VR-based implementation of interactive laboratory experiments in optics and photonics education

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ABSTRACT

Within the framework of a developed blended learning concept, a lot of experience has already been gained with a mixture of theoretical lectures and hands-on activities, combined with the advantages of modern digital media. Here, visualizations using videos, animations and augmented reality have proven to be effective tools to convey learning content in a sustainable way. In the next step, ideas and concepts were developed to implement hands-on laboratory experiments in a virtual environment. The main focus is on the realization of virtual experiments and environments that give the students a deep insight into selected subfields of optics and photonics.

Keywords: laboratory experiments, hands-on, augmented reality (AR), virtual reality (VR), research-oriented education optics and photonics

1. INTRODUCTION

Hands-on activities and experiments are an elementary part of the study program. Due to the Covid19 pandemic and the accompanying government regulations, a situation arose in which these important elements of a study program could only take place on an irregular basis under certain conditions. Too often, they even had to be cancelled altogether, since laboratory exercises in particular, in contrast to lectures, place high demands on a laboratory environment. The challenge was and is to create digital interactive possibilities for learners and teachers, such as remote labs or a complete virtualization of laboratory activities.

Within the framework of a developed blended learning concept, much experience has already been gained with a mixture of theoretical lectures and hands-on activities, combined with the advantages of modern digital media. Digital media are used to enhance the established teaching scenarios. Here, visualizations using videos, animations and augmented reality (AR) have proven to be effective tools to convey learning content in a sustainable way. In the next step, ideas and concepts were developed to implement hands-on laboratory experiments in a virtual environment. These are not intended to replace the hands-on experiments, but to complement and extend them. The main focus is on the realization of virtual experiments and environments that give the learner a deep insight into selected areas of optics and photonics. Various experiments have already been implemented and used in teaching. The aim now is to evaluate them and to apply the knowledge gained to the further development of our concept.[1–7]

2. VIRTUALIZATION OF LABORATORIES

As already mentioned, hands-on activities and experiments are an integral part of the studies and, in particular, also within the framework of our teaching concept for media technology. In the appropriately equipped laboratories, the aim is to gain applied experience that deepens the understanding of the theoretical knowledge imparted. Most of the experiments require special hardware, which is why it is not possible for students to conduct the experiments outside the university laboratory. For the preparation and follow-up of the hands-on activities, written tutorials, literature and videos are provided to the students via the e-learning platform used. Set-up and performance of the experiments are described in detail. In order to understand the underlying physical principles and to transfer them into an individual model, the students have to deal with the experimental setup. Different prior knowledge and experience of the students complicate this process. Local access to the relevant experimental setups is also limited in time. A closer look reveals that many students have problems to prepare well for a highly interactive and activity-oriented exercises based on static learning resources such as texts and pictures. For this reason, we decided early on to use simple software simulations to enable students to also perform various experiments virtually.[2–4]

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2.1 Augmented Reality (AR)

We initially focused on easy-to-use augmented reality (AR) applications. The term AR was coined in 1990 and can be described as the concept of augmenting our perception of reality with virtual elements and content. Azuma defines AR, regardless of the technology used, as a method of combining real and virtual elements interactively and in real time in three dimensions.[8] Another popular definition is Milgram's reality-virtuality continuum. This continuum spans between reality and virtuality and allows for any form of mixed reality in between. While AR is closer to reality, augmented virtuality is closer to virtuality, which is also referred to as virtual reality (VR).[9] Basically, however, it should be noted here that a variety of definitions can be found in the literature, most of which refer to the interaction of digital information and the real world. The rapid technological development and availability of mobile handheld devices also has a high influence here.[10]

The success and widespread adoption of handheld mobile devices, such as tablet computers and smartphones, has made mobile AR applications easy to use. Our approach was to utilize an AR app that would allow students to use their own mobile devices to prepare or review experiments and exercises on their own. With mobile devices nearly ubiquitous, students can prepare and learn when and where they want. Ubiquitous learning becomes a real possibility and makes knowledge accessible, but cannot replace the learning process. The simulated virtual experiments and exercises are largely equivalent to the real ones to be performed in the laboratories. We still believe that a simulation cannot be a full substitute for a real experiment, but it can still contribute to the study and understanding of the most important principles.[1] The first experiment implemented was the visualization and simulation of an optical bench to promote understanding of the laws of optics. Students can interactively change features such as lens type, lens curvature, lens diameter, refractive index of the lens, and the position of the instruments in space. An AR application like this is ideally suited to prepare for the actual lab sessions and/or recap the course content.

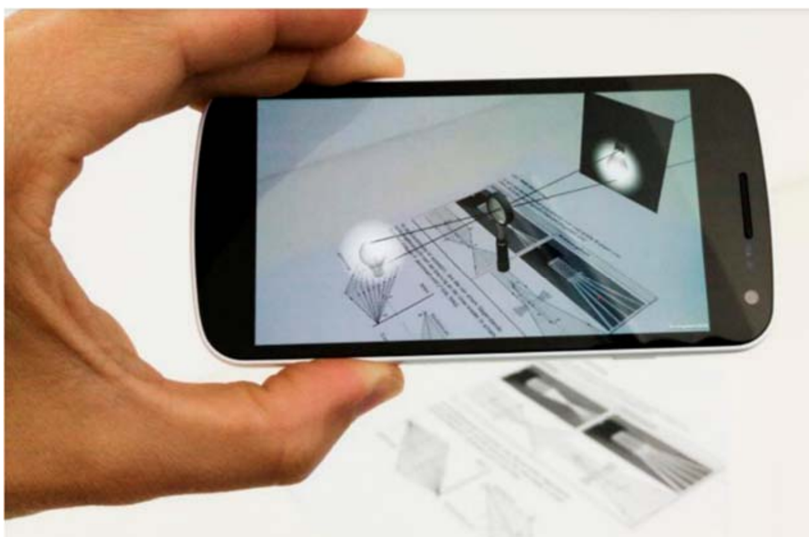

Figure 1. AR lens experiment app running on a smartphone.

2.2 Virtual Reality (VR)

Virtual reality (VR) is the representation and simultaneous perception of an immersive, artificially constructed reality in a real-time computer-generated, interactive virtual environment and is typically limited to head-mounted display (HMD) based applications.[10] With the entry of HMDs into the mass market, the possibilities of using educational and training applications to represent teaching materials and practical work have been significantly expanded. Therefore, to expand our blended learning concept, we have increasingly focused on the realization of experiments and environments in virtual reality. By means of an HMD, the user is offered the possibility to view the experiment from different angles and to make adjustments through interactive control functions. Within the VR application, additional contextual information is displayed. For each visible object in the view frustum, the specific graphics and texts are loaded and supplemented at the appropriate place. Thus, complex facts are supported in an informative way. The application areas for VR technologies are very broad and range from medicine, technology, education, entertainment, as well as art and culture, where they are already used with considerable success as a development technology. [6, 7]

Various experiments with different levels of difficulty have been developed and implemented so far. A simple measurement experiment in electrical engineering focuses on the construction of resistor networks and the subsequent measurement of voltages and currents. By implementing a VR environment, the use of various virtual laboratory objects becomes possible. The objects include the passive resistors as well as the controllable measuring devices, such as a multimeter. This environment is currently being supplemented with additional measuring devices and electrical components. This will significantly expand the experimentation possibilities. The goal is to provide a virtual environment that has as high a recognition value as possible to the hands-on laboratory experiments.[6, 7]

Figure 2. a) The VR laboratory environment b) The VR laboratory set-up

But also considerably more complex experiments and measuring devices are to be implemented in a virtual environment. The experiment with the so-called teltron tube is an experiment that demonstrates the acceleration and deflection of electrons in the magnetic field. It will be possible to determine the mass of an electron. An electron beam is generated in a glass vessel with a hydrogen atmosphere of low pressure. Single electrons of the beam strike hydrogen atoms and excite them to glow. This makes the electron beam visible. A pair of Helmholtz coils is placed in front of and behind the glass vessel. When current flows through the two coils, there is a magnetic field in the center plane of the Helmholtz coils. This field is directed perpendicular to the center plane and has largely the same magnitude in it. To carry out the experiment, it must be possible to adjust the heating voltage applied to the hot cathode, the accelerating voltage applied between the cathode and anode, and the current flowing through the Helmholtz coils. In this way, various tasks can be processed and answered. We are currently working on the digitization of the experiment. The next milestone is the transfer of the experiment into a three-dimensional environment. This 3D environment will be developed as a separate application for desktop, VR and AR HMDs. A first design of the virtual teltron tube can be seen in Figure 3.

Figure 3. Virtual 3D teltron tube

3. EVALUTION AND FURTHER DEVELOPMENT

The use of new digital technologies to improve teaching is only one part of the approach being pursued. As part of our research, we are deliberately trying to gain new insights in the area of e-learning in conjunction with VR technology. Thereby, we try to answer a core question about the compatibility of the individual media components. For this purpose, we firstly perform direct comparisons between real hands-on experiments and their counterparts in VR environments. Simultaneously, we are expanding the available technology so that in the future we will not only be able to compare existing implementations, but also draw conclusions about the influence of the technology used, such as different HMDs. Different manufacturers typically also mean different developer tools for creating the virtual environment and involve different challenges for implementing suitable control systems.[6, 7]

In addition, an evaluation from the participants' perspective is in preparation to provide helpful information about the usability of the virtual application. But also the learning objectives that we have established considering the taxonomy proposed by Bloom will be reviewed in this way. This consists of three hierarchical models for classifying learning objectives with a view to complexity and specificity. We refer to the cognitive model to structure our learning objectives and curriculum. At this stage, we are very optimistic that through focused development, not only the K4 analysis level (ability to break down ideas and problems into their elements and compare problems, identify differences), but also the K6 evaluation level can be achieved.[6, 7, 11–14]

3.1 Development of a concept for evaluation

Currently, we are working with two very different applications in our research comparing hands-on experiments and experiments in VR environments. The first application is the presented realization of measurements with a multimeter (Figure 2). The electrical engineering experiment simulates a laboratory environment and introduces the use of a multimeter. The second application is the virtual implementation of a research project on visual perception and color measurement. In principle, the VR environment was developed and designed in such a way that the real laboratory environment was implemented as realistically as possible and the execution of the experiment to obtain the measurement data also corresponds to the real hands-on experiment.[6, 7]

HMDs from the manufacturer Oculus VR were used in the first test series. The developer tools from Oculus are mandatory and recommended for use. A high challenge is the graphical adaptation of the user interface (UI) elements to achieve a result comparable to the real laboratory environment. Another challenge was the implementation of a suitable control system. Here, two touch controllers are used and all necessary functions are embedded with a suitable key mapping. The practical implementation involves the analysis and realization of a suitable software architecture that essentially has to handle user interactions. In summary, initial results of the comparisons performed show that the constant and consistently defined measurement setting of the virtual environment offers a significant advantage, which is particularly relevant for optical experiments. Another advantage is a noticeable time saving. Accommodation times are required only one time. Once immersed in the VR experimental setup, the gaze remains accommodated. Under defined conditions, data acquisition of measurements in VR can be performed much more efficiently and quickly.[6, 7]

These initial insights provide a good basis for developing a concept for evaluating the applications developed to date and will be transferred to a research project. An empirical study will thus show to what extent the effectiveness of learning in virtual environments is guaranteed depending on the platform. The cross-platform comparison includes the hands-on experiment, as well as the digital implementation for desktop PC, AR and VR (HMD). All platforms refer to the common experiment and furthermore offer the same range of functions. Only the necessary user interfaces are adapted to the respective device.

The concept for this empirical study is to divide the test participants into several, disjoint groups. Each of these groups runs through the platform-specific experiment used for evaluation in two runs. At the beginning, the groups are supervised by a tutor who has the task of first explaining the experiment and then guiding the participants in its implementation. Once the experiment is completed, relevant empirical data is collected by means of a detailed questionnaire. This is followed by an important stage; the participants' short-term memory is to be filled with new information. This can be done with the help of an entertaining memory game, where the participants have to memorize different things from the scientific field of optics and photonics. Results achieved here are not relevant for the evaluation. But this step makes it possible to check which essential information the participants have stored in their long-term memory during the first run of the experiment. Because in the now following second run no more guidance takes place. Each participant is on his or her own and must repeat the experiment independently. Assistance from the tutor present is possible, but only on the basis of the standardized documents that were already used in the first run for introduction and explanation. With the participants' permission, this run will be recorded on video for later evaluation.[15]

Qualitative and quantitative measurement values are collected throughout the test series. The qualitative data is obtained through the questionnaire and considers the platform-specific impressions of the participants. The quantitative data, on the other hand, are only measured in the second test run. For this purpose, the tutor records, among other things, the time required to complete the test, the number of errors that occurred, and the amount of help given. To supplement this data, the recorded video is then analyzed.

4. PERSPECTIVE

Despite this initial positive feedback and results, we believe that the implementation of the experiments in VR cannot replace the hands-on experience on an equal level. But they can be a significant support in didactics and in the process of practical preparation of experiments. Combined with AR technology, hands-on and VR complement each other and result in an ideal synthesis. Technological advancements in VR are also opening up more and more possibilities. HMDs are becoming smarter and also lighter, which of course increases the comfort for the user and thereby also improves the virtual experience. Both comfort and usability are an important factor for the achievable didactic success of virtual applications. For this reason, we start here with our research and also deliberately integrate it into the curriculum of the study program "Media and Communication". In the concept of our research-oriented education, we give our students the opportunity to work specifically on the realization of digital, virtual experiments and laboratory environments in order to gain new insights in the field of e-learning in connection with AR, VR and MR technology.

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