Immersive Quantum Phenomena Laboratories: principle of light and polarization

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Abstract: Teaching quantum physics concepts and phenomena can be facilitated through experimental practices. However, these practices are often costly and require dedicated space, making them unfeasible for low-resource educational institutions. Given these limitations, the use of virtual and augmented reality technology has emerged as an intermediary mechanism and teaching resource for quantum physics teaching. This study presents the preliminary development of the designed artifact and the applicability of an immersive laboratory to demonstrate the phenomena of polarization and the principle of light. This research follows the design science research (DSR) approach, proposing the initial development of the artifact and indicating its applicability as a quantum physics teaching tool, specifically for quantum optics phenomena. The proof-of-concept was developed within the UNITY engine and tested with the Meta Quest 3 and 3s headsets. As a result, an immersive, interactive, and functional environment was created for testing, evaluation, and use as a teaching tool. This work contributes to the development of a mobile and reusable teaching laboratory, proposing innovation in the educational path of quantum technologies.

Keywords: quantum immersive, virtual reality, optical physics, polarization, superposition, light principles

1. Introduction

Understanding quantum physics phenomena remains a challenging task. Keeping students engaged and reducing difficulties in assimilating abstract ideas, both in the classroom and in laboratory learning contexts, remains a challenge [1]. Gaps in information transmission, coupled with the limited content that stimulates abstract thinking in beginners, contribute to low active and meaningful student participation in experimental space activities [2]. Due to the limited equipment available, its high cost, and its sensitive handling, many students remain observers, while only a few actively participate [1, 3].

Learning quantum technologies is a challenging task [4], as it requires mastering foundational concepts that underpin more advanced phenomena. Topics such as wave–particle duality, the quantization of light into discrete photons, and the control of their polarization [5] are central to quantum physics and often present significant conceptual barriers to newcomers [6, 7]. These phenomena unfold at the nanometric scale, far beyond the reach of the naked eye, and often defy everyday intuition: photons, for instance, can exhibit both particle-like and wave-like behavior, a duality that challenges our classical understanding of nature [7]. Because they are abstract and not directly observable, such concepts require a high level of abstraction, making their teaching challenging, especially at introductory levels [4, 5].

In the context, the use of virtual reality (VR) to represent abstract concepts through virtual simulations can potentially replace physical experiments, which would be costly, complex, or imperceptible to the naked eye [5, 8]. Furthermore, it also enables remote access and interaction with content. Thus, building a laboratory that fosters the ability to think at multiple levels of abstraction can help students develop their skills [9, 10].

A large-scale study found that learning outcomes after completing tasks in remote labs were as high as or superior to those in in-person labs [11]. This illustrates the potential of implementing VR technologies as a tool to overcome obstacles [12, 13] and help expand experiences beyond the classroom, as the use of these resources potentially increases the chance of a positive impact on students and reinforces their use of this tool [14].

This study presents the preliminary development of the designed artifact and the applicability of an immersive laboratory to demonstrate the phenomena of polarization and the principle of light.

The paper is structured into three sections: Section 2 outlines the materials and methods adopted, Section 3 examines the findings, and Section 4 offers our conclusions and recommendations for future studies.

2. Materials and Methods

Design Science Research (DSR) [15] was adopted to combine applicable solutions and the generation of scientific knowledge, highlighting the particular relevance of research in the areas of quantum technologies, immersive technologies, and education, which are relevant domains for the project, through the proposed methodological approach and real-world applications related to the research problems and opportunities. The specific objectives of the study are: (1) develop a functional virtual laboratory focused on teaching quantum technologies; (2) visually design, in a VR environment, the properties of light; (3) implement interactive visualization of the polarization phenomenon in VR; and (4) present an initial digital model of the components that make up the immersive laboratory. To achieve the proposed objectives, the method followed the six DSR stages: (1) problem identification; (2) defining the solution's objectives; (3) model design and development; (4) demonstration of the developed model; (5) model evaluation; and (6) communication of the results to the scientific community and the manufacturing sector. In the first and second stages of the DSR, the problem was identified and the solution's objectives were defined based on an analysis of the research context and the limitations of traditional quantum technologies teaching approaches [6, 16]. An exploratory review was conducted to obtain an overview of current knowledge on the development of VR laboratories for quantum technologies. We searched Google Scholar, CAPES, and Scielo databases for works published since 2015 using the keywords: ("Virtual Reality" AND "educational VR laboratory" AND "VR learning" AND "abstract VR learning" AND "quantum light principle" AND "quantum polarization phenomenon"). Of the articles found, we analyzed eight systematic reviews, the results of which will be discussed later.

In the third stage, which involves the development of the artifact and design applications, we then conducted an exploratory focus group with our interdisciplinary team of senior researchers, experts, and students in quantum technologies and immersive technologies. We identified functional and non-functional requirements and success criteria for representing the quantum light and polarization principles in VR [17]. This study combines design strategies and digital tools, such as Blender v4.1, for 3D modeling and importing into Unity Engine for the development of a responsive application. The proof of concept in a simulated educational environment is part of the fourth stage of the DSR, where participants explored and interacted with the immersive laboratory of the principles of light and polarization. The fifth stage of the DSR focused on artifact validation by collecting qualitative and quantitative data through user feedback. The Presence Questionnaire (PQ) was used to assess usability, sense of presence, and user immersion within the immersive environment [18]. The Likert scale also be used as an evaluation method to administer objective questionnaires to assess the proposed learning before and after the immersion. Feedback from interactions with the immersive environments provided by participants be collected and used to improve the development of the laboratory and the quantum technologies teaching process. The sixth stage of the DSR method involved the communication of results obtained from the work.

3. Results and Discussion

Appropriate, user-centered design requires identifying all considerations and limitations for more assertive guidance and aligning expectations [19]. In this sense, for the initial development of the artifact, the goal is for the immersive experiment to operate with clear functional execution, a lower-cost proposal that does not negate the role of the physical laboratory, but rather offers a complementary option [20]. One of the objectives outlined for this study is the pursuit of cost reduction compared to a physical laboratory. The costs of acquiring and maintaining traditional experimental equipment are significantly high [20]. In the following sections, we present our findings, as well as the proposed guidelines related to scenarios, equipment, experimental design, and initial construction of the proposed immersive laboratory.

3.1. Choice of technologies

The Unity Engine was chosen for its intuitive extensions that support the development of VR environments [21]. Additionally, applications can be tested directly on headsets or using head-mounted displays (HMDs). It significantly contributes to its robust documentation, simple and fast C# programming, and reduced build size. Compared to other free engines, such as Unreal Engine, Unity Engine is lighter, allowing applications to achieve higher frame rates, which is essential to avoid discomfort when using HMDs in this early prototyping phase [22]. The Meta Quest 3 and 3s headsets stand out as the most affordable available on the market, meeting the demand for a cost-effective solution [23]. Both options support immersive experiences with good performance, positioning themselves as a viable alternative for educational environments, virtual labs, and applications that prioritize cost-effectiveness. Both feature external cameras that allow for real-world environment scanning and the definition of safe zones, allowing users to move freely without the need for resetting when changing locations [24].

3.2. Virtual scenario planning

The scenario planning stage sought to identify likely interactions between the user and the immersive laboratory so that the simulation would stimulate learning. Digital tools designed for teaching quantum physics Physics Education Technology (PhET) and Quantum Flytrap were tested, analyzed and observations were made about them. PhET is a simulation that allows users to visualize the phenomenon and interact with the experiment in a 2D visual format, aimed at young people who already have prior exposure to quantum physics. Its interface contains a wealth of specific information; there are no step-by-step instructions or a small gamified system for an introductory educational tool [25]. Quantum Flytrap, which also uses 2D visualization, is aimed at younger audiences and researchers. To simplify simulations, the platform uses imaginative symbols to represent optical devices, creating recognizability and a welcoming introduction to quantum physics [26].

The adoption of storyboarding tools serves as a means of narrative illustrations that help sketch out ideas that aim to generate empathy with users in the face of the challenges posed, indicating necessary details even before 3D development [27]. Figure 1 demonstrates the division of three frames into beginning, middle, and end. This results in a structure in which the user begins the experience in the immersive laboratory, its operation and interaction with the environment, and how to end the experience.

3.3. Development of the immersive environment

The development of the immersive environment for visualizing quantum phenomena was based on the experiment kit used in traditional laboratories for simulation of the BB84 protocol [28]. In the BB84 protocol, laser is fired through a small photon gun, passing through half wave plate (HWP) and then directed at a translucent cube called a

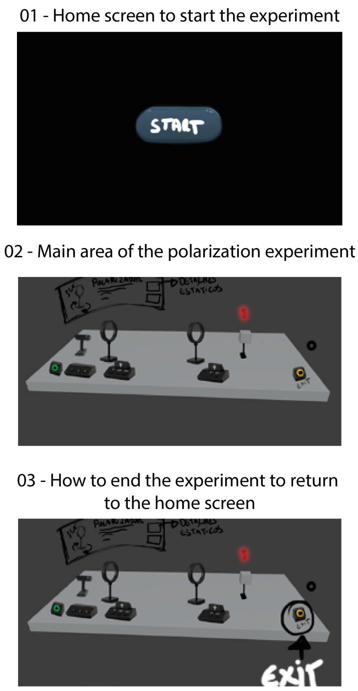

Figure 1: Three-act storytelling draft for developing interaction on how to begin and end the experiment.

polarized beam splitter (PBS), thus directing the light particles toward the photon receivers according to the polarization of photons. In the preliminary environment developed for the proof of concept, photons are represented by red spheres, with eight arrows above them to indicate the polarization vectors. A single arrow represents polarization in only one direction, and two arrows represent polarization in two different directions simultaneously. Figure 2 shows the construction of a virtual demonstration. Each component of the experiment is represented in a simplified 3D format to facilitate user interaction and understanding. The emission of a light particle is represented as a sphere moving at a reduced speed compared to a real photon, to facilitate visualization and understanding of its trajectory and quantum behavior. Also within the VR environment are two HWP's, displayed as circular lenses, which alter the photon's polarization, described by arrows. At the end of the experiment, the polarized light particle passes through the PBS, represented by a transparent cube, thus directing the particle to the quantum gate, indicated as sensors 0 or 1 at the end of the experiment. Positioned on the left, a gray object symbolizes the laser source responsible for emitting a light particle, represented as a sphere.

The buttons on the experiment table serve as different actions for the pieces positioned on the table. The button to launch the laser or particle is labeled START, and the button to pause the experiment and end it is labeled STOP. To select the angle of the polarizing lens, buttons are linked to their respective polarization degrees. The preliminary lab results indicate clear advantages over traditional laboratory setups, revealing a scenario in which sensitive and costly equipment can be preserved from damage due to improper handling, thereby reducing maintenance expenses. By enabling remote interaction with experiments, the platform also offers a scalable model capable of reaching a global audience and broadening access to advanced scientific training. Such accessibility is particularly important in fields like quantum physics, where many foundational concepts are challenging. Quantum phenomena often defy everyday intuition; photons, electrons and other particles can behave both as discrete particles and as waves, a duality famously demonstrated in the

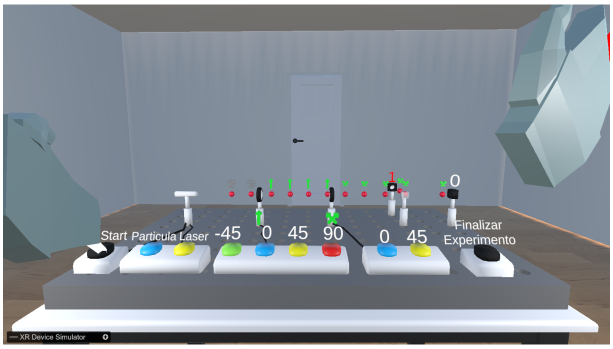

Figure 2: Demonstration of the immersive laboratory with the emission of photons passing through the polarized lenses and directed to port 1 or 0.

double-slit experiment. Incorporating these counterintuitive principles into an interactive, remotely accessible environment not only fosters deeper understanding but also accelerates the dissemination of cutting-edge scientific knowledge.

4. Conclusions

This work sought to present preliminary results of the proof of concept and the applicability of a laboratory with immersive technologies as an educational tool for demonstrating the quantum phenomena of polarization and the principle of light.

Given the identified frameworks and the findings obtained, it is recommended that questionnaires be administered to professionals for visual and didactic validation of quantum teaching. It will also be necessary to administer the questionnaires to students, with and without prior knowledge of quantum phenomena, aiming to improve and refine the developments.

Research in this area could enhance and expand the use of immersive laboratories for educational purposes and as a complement to traditional laboratories.

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