MAKÜ | MMF
MÜHENDİSLİK-MİMARLIK FAKÜLTESİ

Uluslararası Mühendislik, Tasarım ve Teknoloji Dergisi, 2025, 7(1), Sayfa: 31-41
International Journal of Engineering, Design and Technology, 2025, 7(1), Page: 31-41

Araştırma Makalesi
Research Article

VR-eLAB: A virtual reality platform for electronics education

VR-eLAB: Elektronik eğitimi için sanal gerçeklik platformu

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Abstract: Virtual laboratories have gained importance due to the high costs of traditional labs, the need for constant technological updates, and limited usage time. This study introduces a Virtual Reality-based Electronics Laboratory (VR-eLAB) to overcome these challenges in engineering education. The VR-eLAB allows students to design and simulate circuits in a virtual environment, leveraging 3D-modeled circuit components created in Blender and integrated using the Unity game engine. This virtual lab application is integrated into Oculus Quest 2 VR headsets to test interactive and dynamic circuit modeling to enhance the learning process. A comparative experiment was conducted to assess the effectiveness of traditional and virtual laboratories. Following the experiment, a survey revealed that 81.1% of participants found the VR-eLAB more effective than traditional labs, while 88.2% emphasized its usefulness for time management. Students reported enriched learning experiences due to the interactive nature of the virtual environment. These findings highlight the potential of virtual reality in making electronic laboratories more accessible and efficient, improving students' understanding and engagement. The study demonstrates VR's transformative role in education, offering a cost-effective and flexible alternative to traditional methods while fostering practical skills development.

Keywords: Virtual Reality, Education, Electronics, Engineering, Unity, Three-Dimension

Özet: Geleneksel laboratuvarların yüksek maliyetleri, sürekli teknolojik güncelleme ihtiyacı ve sınırlı kullanım süresi nedeniyle sanal laboratuvarlar önem kazanmıştır. Bu çalışmada, mühendislik eğitimindeki bu zorlukların üstesinden gelmek için Sanal Gerçeklik Tabanlı Elektronik Laboratuvarı (VR-eLAB) tanıtılmaktadır. VR-eLAB, öğrencilerin Blender 'da oluşturulan ve Unity oyun motoru kullanılarak entegre edilen 3B modellenmiş devre bileşenlerinden yararlanarak sanal bir ortamda devre tasarlamalarına ve simüle etmelerine olanak tanır. Bu sanal laboratuvar uygulaması, öğrenme sürecini geliştirmek amacıyla etkileşimli ve dinamik devre modellemesini test etmek için Oculus Quest 2 VR başlıklarına entegre edilmiştir. Geleneksel ve sanal laboratuvarların etkinliğini değerlendirmek için karşılaştırmalı bir deney yapılmıştır. Deneyin ardından yapılan bir anket, katılımcıların %81,1'inin VR-eLAB'yi geleneksel laboratuvarlardan daha etkili bulduğunu ortaya koyarken, %88,2'si zaman yönetimi için yararlılığını vurgulamıştır. Öğrenciler, sanal ortamın etkileşimli doğası nedeniyle zenginleştirilmiş öğrenme deneyimleri yaşadıklarını bildirmişlerdir. Bu bulgular, sanal gerçekliğin elektronik laboratuvarlarını daha erişilebilir ve verimli hale getirme, öğrencilerin anlayışını ve katılımını artırma potansiyelini vurgulamaktadır. Çalışma, sanal gerçekliğin eğitimdeki dönüştürücü rolünü ortaya koymakta ve pratik becerilerin geliştirilmesini teşvik ederken geleneksel yöntemlere uygun maliyetli ve esnek bir alternatif sunmaktadır.

Anahtar Kelimeler: Sanal Gerçeklik, Eğitim, Elektronik, Mühendislik, Unity, Üç Boyut

1. Introduction

Laboratory experiences are vitally important in engineering education (Hernández-de-Menéndez et al., 2019). Lessons offered in the laboratory facility allow students to apply theory to practical experience. Overall, such a format provides an opportunity for students to learn the basics of engineering, how to apply them in real life, and develop critical skills as well (Felder and Brent, 2004). Although students are developing their manual skills in a laboratory setting, they also put into practice their experimental design, data analysis, and problem-solving skills (Azevedo et al., 2024). They will also get acquainted with experimental research methodology and develop their skills with respect to the handling of measuring and testing equipment. Students, through laboratory work, will be able to experience how to handle real problems that might occur in engineering (Çivril, 2017).

With the very rapid development of technology today,

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Geliş / *Received*: 20.11.2024, Revizyon / *Revised*: 06.12.2024
Kabul / *Accepted*: 13.12.2024

Burdur Mehmet Akif Ersoy University Press

https://doi.org/10.70669/ijedt.1588581

education is taking a new turn (Johnson et al., 2016). Central to these changes are virtual reality-based laboratories developed as alternatives to traditional physical laboratories. Virtual reality (VR) technology allows users to disconnect from the physical world by immersing them in a fully digital and interactive environment. VR systems, typically equipped with head-mounted displays (HMD) and motion sensors, engage the visual and auditory senses. It is used in many fields such as education, gaming, health, and industry. The main advantage of VR is that it allows users to safely gain experience in simulated environments. However, high hardware costs, difficulties in content production, and physical discomfort such as dizziness or motion sickness for some users are among the limitations of this technology (Porcino et al., 2020). While virtual reality opens access to experiences that were hard for students to imagine, it is nonetheless no less than a revolutionary form of education disposition (Brinson, 2015). In this respect, virtual reality-based labs have a number of advantages in comparison with physical labs (Makransky and Lilleholt, 2018).

First, virtual reality-based labs have great merits in cost-effectiveness and accessibility (Asare et al., 2023). Virtual laboratories eliminate the costs associated with buying, maintaining, and securing expensive equipment that needs to be set up in traditional laboratories (Bačnar et al., 2024). This makes it much easier for educational institutions, despite their limited budgets, to let more students have access to it. Moreover, virtual labs allow students to access them at any time and from any place, making this whole education process more flexible (Valtonen et al., 2021).

Secondly, virtual reality-based laboratories stand out for their ability to best mimic the real-world experience. In a virtual environment, students get the feel of handling actual equipment and putting theoretical concepts into practice. This, in turn, enhances students conceptual learning and problem-solving skills. In addition to all the above benefits, the hazards associated with actual laboratory experiments are eliminated, and virtual laboratories provide a safe learning environment for students (Küçüksille and Çatak, 2022).

Thirdly, virtual reality-based laboratories may increase student motivation. Through virtual environment interactivity and immersion, students' attention will be drawn to the learning process, making it more interesting. Virtual labs make the learning process more efficient by allowing students to immediately identify, observe, and correct their mistakes. This provides immediate feedback that increases student success.

Globally effective pandemic processes such as COVID-19 (Belciug et al., 2020; Ciotti et al., 2020; Kilinç et al., 2023), have significantly accelerated the use of VR technologies in education in recent years. Due to COVID-19, face-to-face education was restricted for an extended period, leading to a search for effective and practical alternatives within the framework of distance learning (Ewais et al., 2024; Sharma et al., 2023). In this respect, VR technologies have contributed so much to students' education, especially in some fields related to practice, such as laboratory studies and field applications. VR has recreated virtual environments that students could not physically get, making learning immersive and interactive and helping to continue education. As a result, the pandemic has accelerated the broader adoption of this technology by demonstrating the potential for VR in education (Sadek et al., 2023).

Based on these views, the research presented here introduces Virtual Reality Based Electronics Laboratory (VR-eLAB), a simulation software that provides an electronics laboratory experience without physical constraints. In VR-eLAB, students can effectively place and assemble circuit components and construct circuits using software and hardware tools. They can then observe the results in real-time, significantly enhancing the accessibility of the electronic laboratory experience and contributing to student learning.

The developed application makes important contributions to the literature. These contributions can be summarized as follows;

- Integration of VR Technology: VR-eLAB fills the existing gap in this field by integrating VR technology into the field of electronic education. This increases the opportunity for students to interact with modern educational tools.

- Hands-on learning experience: The application allows students to put theoretical knowledge into practice by providing practical experience in electronic education. This demonstrates the potential of VR technology in education.

- Innovation in education: VR-eLAB contributes to the development of modern training methods in the field of electronics by offering an innovative approach to education. This is an element that encourages going beyond traditional training methods.

- Student motivation and engagement: By providing an interactive and immersive learning environment, VR-eLAB increases student motivation and participation. This is a factor that supports the wider use of VR technology in education.

- Safe and accessible learning environment: By providing a secure learning environment, the application reduces the risks of electronic education and allows a wider range of students to benefit from this technology.

The paper is structured as follows: Section 2 reviews previous studies in the literature. Section 3 describes the materials and methods used in the study. Section 4 introduces the developed VR-eLAB application and details the implementation processes. Section 5 analyses the results of the study. Finally, section 6 summarizes the conclusions of the study and provides recommendations for future studies.

2. Related Works

In recent years, virtual reality-based laboratories have become widespread in various educational fields. Many studies in the literature examine their effects on education.

In the study by Nicolaidou and colleagues, a significant increase in vocabulary performance was observed in students who used VR, and these students received high scores in participation, immersion, and depth. However, VR applications did not show superiority over mobile applications (Nicolaidou et al., 2023).

In the study by Küçükkara et al., VR technology was used to overcome the difficulties of accessing historical structures in restoration courses for architecture students. The historical Safranbolu Tabakhane building was transferred to a virtual environment, and students were able to work interactively with virtual measuring tools; survey results showed that 88.62% of students had a positive view of this system (Küçükkara et al., 2024).

In the study by Udeozor et al., a virtual reality-based game was designed and implemented to reduce the difficulties that chemical engineering students and professionals may encounter in business life. The survey results revealed that both students and professionals had positive attitudes towards virtual reality-based games, with students valuing entertainment and ease of use, and professionals valuing usability and ease of use (Udeozor et al., 2021).

Pletz et al. involved mechanical and plant engineers in virtual operator training to assess the practical applicability of virtually learned content and the development of an effective virtual environment. According to the results of the post-training survey and actual machine application, evaluating the knowledge learned in the virtual environment through practical errors and difficulties provided important revision options for the development of the virtual learning environment (Pletz and Zinn, 2020).

Borsci et al. developed a VR simulator to demonstrate and practice the stages of the automotive joining process. These virtual environments were developed on the HoloVis game engine, supporting devices such as Oculus Rift, Cave, and zSpace holographic 3D interactive desktop displays to interact with CAD data. Using different controllers in several training sessions, participants interacted with objects in a virtual environment by wearing different devices (Borsci, 2016).

Kaminska et al. prepared a VR simulation in order to be used in mechanical and electronic engineering education. This virtual environment, created by three-dimensional modeling of all electrical and hardware parts of a washing machine, was thus further targeted at the learning process of the students about modern technologies. Authors have tested the developed simulation and obtained results that show a virtual reality-based mechatronics laboratory would improve higher education quality and efficiency (Kamińska et al., 2017).

Singh et al. developed a virtual reality-based learning environment to provide engineering students with information about electronic laboratory equipment and to measure their readiness. 65 students were divided into experimental (N=33) and control (N=32) groups. The experimental group received virtual reality and the control group received traditional education. The results showed that virtual reality increased students' knowledge and motivation, and the use of virtual equipment provided a safe learning environment (Singh et al., 2021).

The comparison of our study with other studies is given in ▶**Table 1**.

Table 1. Comparison of virtual electronic laboratories in the literature

	Developed Simulator	Singh et al., 2021
VR support	✓	✓
Circuit elements	✓	x
Dynamic work	✓	x
Immersion Technology	✓	✓
Interactive experiment sheets	✓	x
Equipment used	Quest 2 remote control	Mouse
Routing notifications	✓	✓
Interactive learning	✓	✓

A review of the literature shows that virtual reality-based applications are widely used in many different fields such as defense, health, and engineering. However, it is notable that the number of studies on the use of this technology in more specific areas, such as electronics laboratories, is insufficient. Electronic laboratory education is crucial for providing students with practical skills and experimental learning, and for putting theory into practice. Given the limitations of traditional laboratory environments, such as cost and capabilities, virtual reality-based solutions can play a significant role in overcoming these issues. In this context, a virtual reality-based electronics laboratory environment has been designed to meet such needs in electronics education and to provide students with a new learning environment. This lab attempts to fill an important gap in education by providing ample opportunities to perform various experiments safely and efficiently, thereby offering a realistic and providing cost-effective experience for students.

3. VR-eLAB Development

This section provides information about the laboratory components and software of the developed VR-eLAB application. In the VR-eLAB application, certain restrictions have been imposed in order to provide students with a solid theoretical background and practical experience within the electronics course. The circuit elements to be used were carefully selected in accordance with the course objectives and limited to basic electronic circuit elements (resistors, capacitors, transistors, diodes, etc.). The experiment sheets have been prepared taking into account the weekly learning objectives The experiment sheets have been prepared taking into account the weekly learning objectives of the students and structured with experimental procedures appropriate to these objectives. This arrangement is considered to play a crucial role in ensuring that students understand the basic principles of electronic circuits and reinforce them through practice. In addition, each experiment has been designed to provide students with the skills to build circuits from scratch, make measurements, and analyses circuits, and has been planned in accordance with the curriculum requirements. In addition, students are given the freedom to dynamically design and operate circuits of their own choice, independent of the experiment sheets.

3.1. Three-Dimensional Modeling of Electronic Circuit Elements

In the first phase of the VR application for the electronics lab, three-dimensional (Gabrijelčič Tomc et al., 2021) solid models of objects to be used were created and textured using open-source software called Blender (Rajamani and Iyer, 2024). Blender is an application that uses solid modeling, texturing, animation, kinematics, particle effects, and physics rules, among other features.

▶Figure 1 shows a solid model of the breadboard, modeled in three dimensions. This model is designed to visualize the physical structure of the breadboard and the layout of the components in detail. The solid model simulates the breadboard's construction, connection points, and possible circuit layouts in the most realistic way, providing a basis for experimental studies in a virtual environment. Students and engineers can improve their ability to build and analyze a circuit without using a real breadboard.

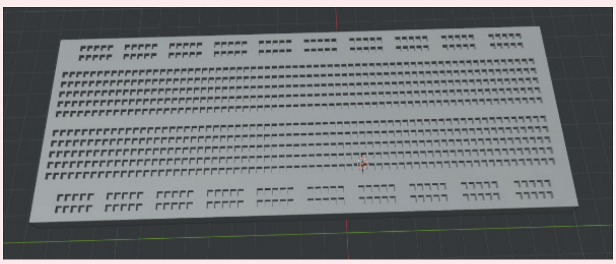

Figure 1. The solid-state of the Blender model

The models on the board were created using Blender software. **▶Figure 2** visually shows the finished texture overlay and the circuit elements placed on the breadboard such as: resistor capacitor, diode, led, ldr, ntc, ptc, potentiometer, voltmeter, fan, and how these circuit elements can interact with each other.

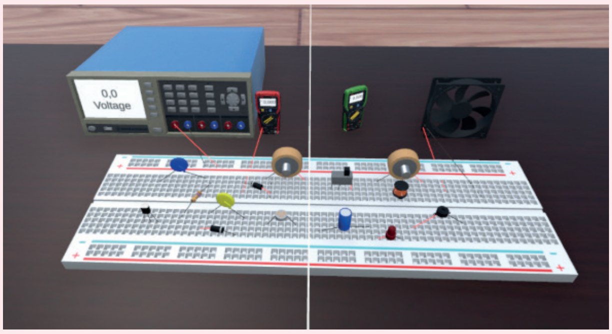

Figure 2. Textured state of circuit elements

3.2. Development of VR-eLAB software

The VR-eLAB application allows users to visually examine electronic circuit elements, build circuits using these elements, and then take the necessary measurements. This application aims to make the process of circuit design and analysis more accessible, inspiring users with its educational value. The lab environment was developed using Unity software (Technologies, 2023), which allows the creation of various digital projects such as 2D and 3D games, simulations, VR, and augmented reality (AR) applications, and the application's functionality was implemented using the C# programming language. In this way, users can design electronic circuits step by step, build circuits, and turn their theoretical knowledge into practical experience, feeling motivated and inspired by the educational journey.

The application was developed using the Visual Studio IDE with Unity 2021. It uses the Unity XR Interaction Tool, Oculus XR Plugin (Meta, 2024b), XR Core utilities, and other packages. An example code snippet is shown in **▶Table 2**.

3.3. Hardware used

In order to evaluate the functionality and performance of the VR-eLAB application developed in this study, Oculus Quest 2 glasses, which offer a virtual reality experience, were preferred as a test device. Oculus Quest 2, shown in **▶Figure 3**, is a standalone virtual reality (VR) headset developed by Meta. This device, which allows users to interact with virtual environments, has advanced hardware and software features.

The Oculus Quest 2 features high-resolution imaging, wide-area tracking, and a user-friendly interface. Oculus Quest 2 features a dual LCD with a resolution of 1832 x 1920 pixels. This high resolution allows users to see details in virtual environments clearly. The device is powered by a Qualcomm Snapdragon XR2 processor for high performance and low latency. It also features 6DoF

Table 2. Breadboard operations

Algorithm 1. Breadboard Operations

```
private BoardHole GetCollidingHole(Vector3 position)
  {
    BoardHole minimum = null;
    double minDistance = 100000000000;
    foreach (var hole in holeList)
    {
      Vector3 a = hole.node.transform.position;
      Vector3 b = position;
     double currDistance = Vector3.Distance(a, b);

      if (minimum == null
        || minDistance > currDistance)
      {
        minimum = hole;
        minDistance = currDistance;
      }
    }
    if (minDistance > 1) return null;
    return minimum;
  }
```

(six degrees of freedom) motion tracking, allowing users to move and interact freely in the virtual environment (Meta, 2020).

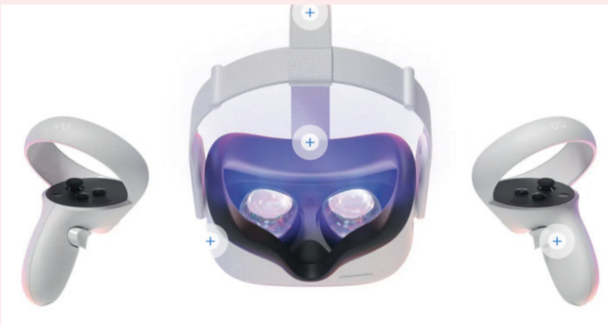

Figure 3. Oculus Quest 2 (Meta, 2024)

4. Testing the VR-eLAB Application

When the application is first opened, a virtual classroom environment welcomes the user as shown in ▶**Figure 4**.

Figure 4. Virtual classroom overview

As shown in ▶**Figure 5**, there is a table in the virtual classroom and interactive experiment pages on the left side. These sheets are designed so that users can follow the experiments they are going to perform step by step and receive the necessary instructions.

The user can select the experiment sheet they wish to use by using the forward and backward orientation options among the interactive experiment sheets presented. The virtual classroom environment makes the learning process more effective and interactive by simulating a real laboratory experience.

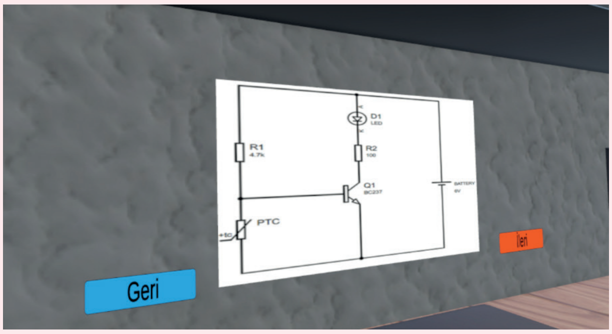

Figure 5. Interactive experiment sheets

Using the VR handles, the user can open a panel to select the circuit elements to be used. When this panel is opened for the first time, it appears as shown in ▶**Figure 6**. The panel is designed to make it easier for the user to design circuits in a virtual environment and provides quick access to all the necessary circuit elements.

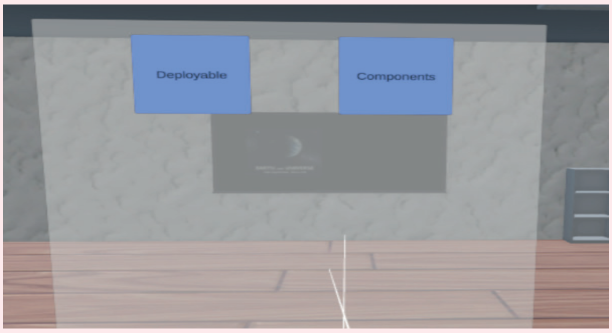

Figure 6. Main menu screen

The Deployable Panel contains general lab instruments which a user may potentially want to use in the virtual laboratory environment. Concretely, this menu have host a breadboard, and power supply with some measurement devices. A user selects these from the menu—breadboard and power supply and drops them into the virtual table. In this way, users have all the facilities that are needed to generate and test virtual circuits ▶**Figure 7**. "Components" panel is the section that unifies the basic electronic components applied in the circuit designs. This includes different circuit elements such as resistors, capacitors, diodes, and transistors. The user can create the virtual circuit by selecting the necessary materials from this screen and dropping them onto the breadboard. The circuit is ready to use by connecting the power supply.

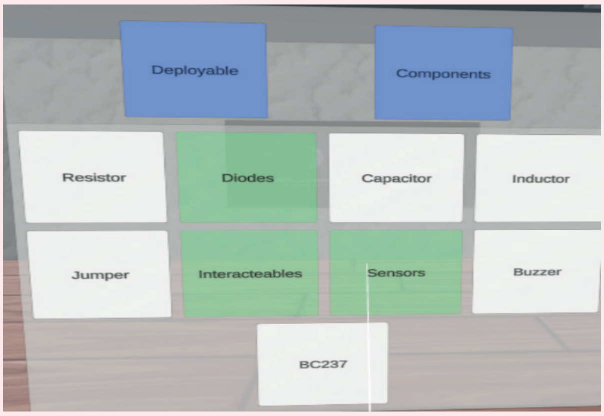

Figure 7. Component panel

As ▶**Figure 8** shows, the virtual lab environment provides a sophisticated circuit model. The participants, within this environment, choose from the "component" panel and carefully place the circuit elements they want onto the virtual board. Once the elements are positioned in the appropriate place, participants build the circuit using virtual cable connections. They choose the power supply from the "deployable" panel that allows the circuit to work, set it on the desktop, and connect it to the board, making the circuit workable. These steps provide students with a realistic and interactive electronic circuit design experience in a virtual laboratory environment. This allows users to apply theoretical knowledge practically and enhance the learning process through real-time feedback in a virtual environment.

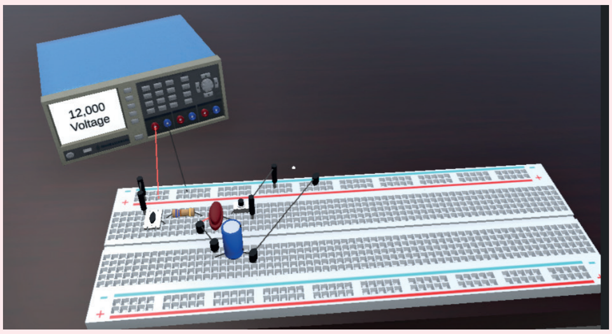

Figure 8. Circuit setup

▶**Figure 9** presents the operation of the prepared circuit. By changing the values of the circuit elements added in the virtual laboratory environment, students can do different operations on this circuit. This brings flexibility to the circuit design, and the students can see various options. Also, some simulations have been added to introduce real-life behavior of the designed system, such as the failure of an LED when excessive current is passed through it. These are the kinds of simulations that enable students to test real circuit behavior in a virtual environment and allow the deepening of the learning process by spotting potential mistakes.

In this way, the virtual laboratory contributes not only to the practical implementation of theoretical knowledge but also to an understanding of the dynamics of complex circuits.

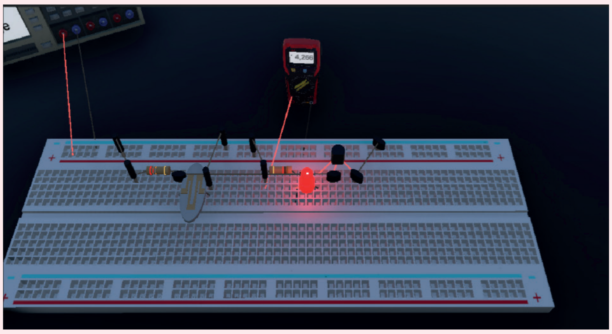

Figure 9. Circuit operating status

The visuals of the tests of the developed VR-eLAB application with the students are presented in ▶**Figure 10**. These images visually reveal the different stages of the application and the interaction of the students in the simulation environment. ▶**Figure 10(a)** shows the process of placing the circuit components; ▶**Figure 10(b)** shows the circuit assembly in the virtual environment and ▶**Figure 10(c)** shows the students' experiences and learning processes during their interaction with the virtual laboratory. These visuals provide important visual support to better understand the impact of VR-eLAB application in education.

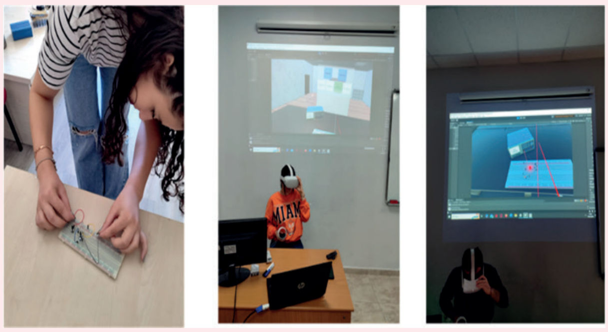

Figure 10. a) The process of placing circuit b) Circuit assembly performed in c) Circuit interaction in virtual environment

In VR-eLAB, the responses of circuit elements to applied voltages are modelled to provide a realistic experience. In addition, the damage (explosion) of circuit elements such as LEDs under overvoltage is visually simulated for the user. ▶**Figure 11** shows the damaged LED simulation.

In addition, in case of an incorrect connection of the circuit elements, the circuit fails and the user is given feedback via a warning light. ▶**Figure 12** shows the visualization of the designed screen.

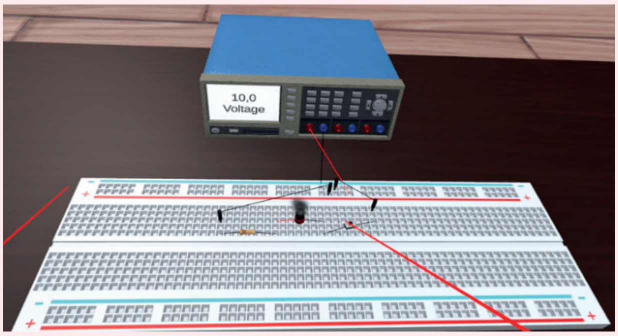

Figure 11. Damaged LED simulation

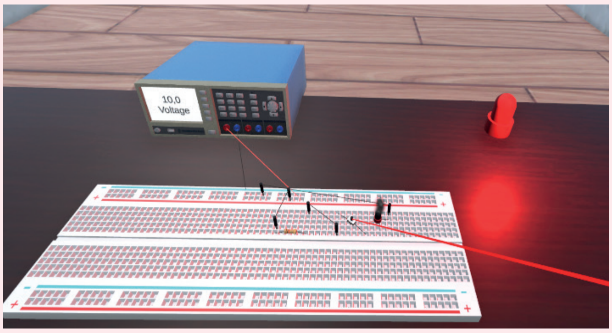

Figure 12. Error warning status

5. Result

In this section, the methodology of the research on virtual reality based electronic laboratory design is explained in detail. The research was carried out using a descriptive design. The research group consisted of 127 students who participated in the study. As a data collection tool, a questionnaire was used for the students who experienced the developed virtual reality-based electronic laboratory application. This questionnaire consists of questions to measure the students' laboratory experience, ease of use, and the contribution of the application to the educational process. The data were analysed using SPSS software, and the findings related to the virtual laboratory experiences of the participants were obtained. The experimental study consisted of two stages. In the first stage, participants were asked to construct a specific circuit in a traditional laboratory environment. This process was designed to give students hands-on experience with physical circuit elements. Students completed the circuit by assembling the circuit elements (resistors, capacitors, integrated circuits, etc.) in a specific order. At this stage, criteria such as completion time, error rates, and overall student satisfaction were carefully recorded. ▶**Figure 13** shows the circuit designed in a conventional laboratory environment.

In the second stage, the same circuit was built in a virtual reality environment using the VR-eLAB application. In this phase, the students interacted with the circuit ele-

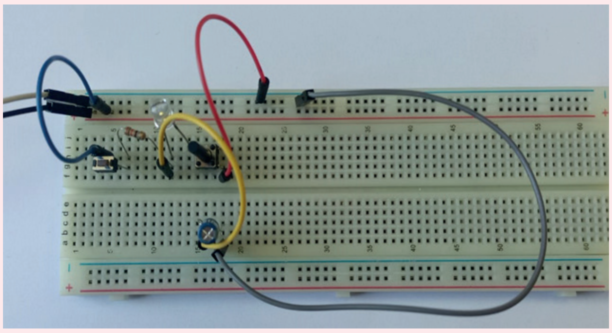

Figure 13. Application in traditional laboratory

ments integrated into the virtual environment through Oculus Quest 2 virtual reality glasses. In the virtual environment, students could see the circuit elements in 3D and perform the placement and assembly of these elements. The user-friendly interface allowed students to easily select and edit circuit elements, while realistic simulation features enhanced the naturalness of the circuit assembly processes. ▶**Figure 8** shows the circuit designed in the virtual lab environment.

At the end of the experimental phases of this study, a questionnaire was administered to evaluate the students experiences. The questionnaire developed by Bektaş (Bektaş, 2020) was applied to 127 university students enrolled in electronics courses at Burdur Mehmet Akif Ersoy University Ağlasun Vocational School, and the participants opinions about their experiences in both traditional and virtual laboratory environments were systematically collected. The purpose of the survey was to determine the impact of VR-eLAB implementation compared to traditional laboratory experiences and to measure student satisfaction. The survey used a 5-point Likert scale to measure participants views. This scale consists of the options 'Strongly Disagree', 'Disagree', 'Undecided', 'I Agree', and 'Strongly Agree' to assess the extent to which participants agree with the statements. Necessary ethics committee approvals were obtained for the questionnaire used (AC:81/3, June 2024).

As a result of the questionnaire we administered to the students, the effects of the virtual reality-based electronic laboratory application on student satisfaction, anxiety, and desire were evaluated. As a result of the analyses, the Cronbach alpha reliability coefficient of the scale was determined to be 0.814.

Table 3. Cronbach Alpha results

Cronbach Alpha	N of Items
0.814	19

This result, shown in ▶**Table 3**, shows that the scale used is quite reliable Interdimensional correlation analyses there was a low negative correlation between satisfaction and anxiety (r=-0.25) and a medium positive correlation between satisfaction and desire (r=0.45). No statistically significant relationship was identified between anxiety and desire. When the knowledge levels of the participants about virtual reality were analyzed, according to the result shown in ▶**Figure 14**, it was seen that 42.5% of them answered 'I have very little knowledge', 39.4% as 'I knew', 14.2% as 'I had no knowledge' and 3.9% as 'I knew very well'.

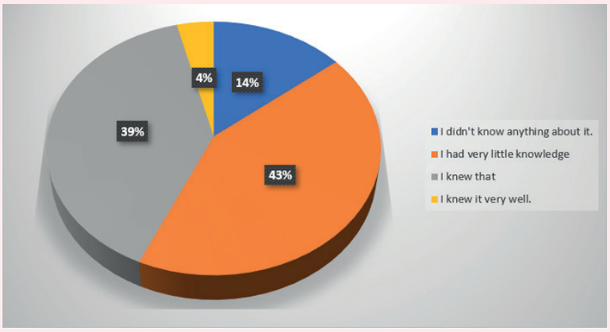

Figure 14. Did you know about VR before?

Furthermore, when analyzing the VR experiences of the students, according to the result shown in ▶**Figure 15**, 51.2% of the participants have used virtual reality glasses before, while 48.8% have not had this experience.

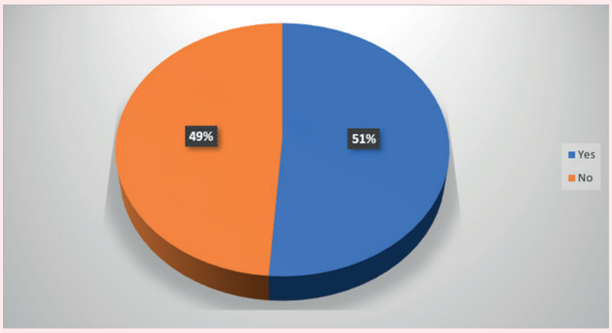

Figure 15. Have you used VR?

The results of the data analysis presented in ▶**Table 4** show that the KMO test performed to assess the suitability of the sample was 0.910 and that the data set was suitable for exploratory factor analysis. Bartlett's test showing significance at p < 0.05 level (chi-square value = 2744.903, standard deviation = 253) also supports this finding.

Table 4. Kaiser-Meyer-Olkin

Kaiser-Meyer-Olkin Measure of Sampling Adequacy		0.91
Bartlett's Test of Sphericity	Approx. Chi-Square	2744.9
	df	253
	Sig	0

When analyzing the total variance explained in ▶**Table 5**, three factors with initial eigenvalues greater than 1 were identified. The contribution of these factors to the total variance was calculated to be 69.252%. The scale is composed of three main dimensions: 'the satisfaction dimension', 'anxiety dimension', and 'desire dimension'. These results underline the potential for the application of virtual reality-based laboratories in education.

▶**Figure 16**, response results from the participant survey. The results provide important information regarding the comparative advantages of virtual labs over physical labs. As many as 89% of the respondents believed that the VR-based lab was able to provide an experience similar to actually performing the lab experiments. This suggests that VR technology can indeed create simulations that match the experiential learning found in traditional laboratory environments.

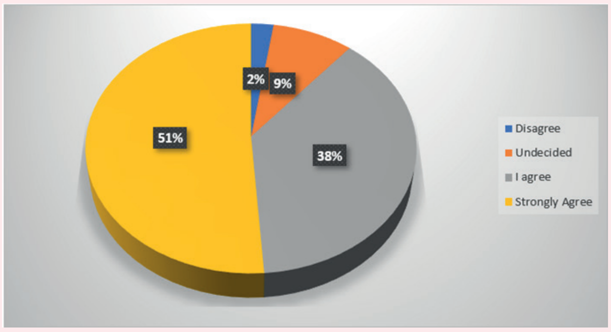

Figure 16. The virtual reality-based laboratory provided an experience similar to real laboratory experiments.

▶**Figure 17** shows that in terms of time management, 88.2% of the participants found the use of the VR lab useful.

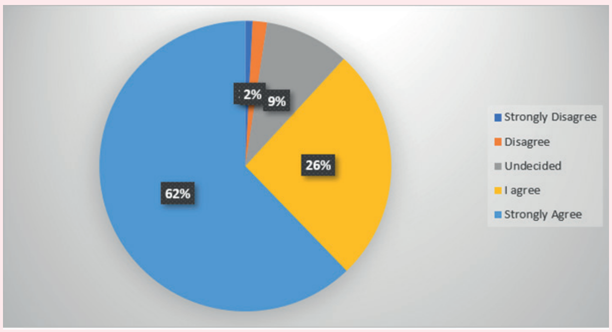

Figure 17. Using a virtual reality laboratory is advantageous in terms of time management.

This corresponds with available literature suggesting that VR contexts enable faster access to experimental environments and reduce time spent on logistical issues related to traditional set-ups, such as cleaning up and preparing equipment. Consequently, the potential for improved time efficiency in VR laboratories could lead to more focused and productive learning experiences.

Table 5. Total variance

Component	Total	% of Variance	Cumulative %	Total	% of Variance	Cumulative %	Total
1	11.941	51.917	51.917	11.941	51.917	51.917	10.151
2	2.786	12.114	64.031	2.786	12.114	64.031	5.161
3	1.201	5.221	69.252	1.201	5.221	69.252	9.836
4	0.975	4.237	73.489				
…							
23	0.078	0.341	100				

As ►**Figure 18** shows, 81.1% of the participants found the virtual reality labs more advantageous when compared to a physical lab. These findings have significant implications in terms of accuracy and user interaction. Virtual labs very often minimize the chances of human error inherent in physical experiments by providing accurate, realistic simulations of what happens when the variables around them are manipulated. In addition, the immersive nature of VR increases user engagement and motivation, further enhancing the effectiveness of learning.

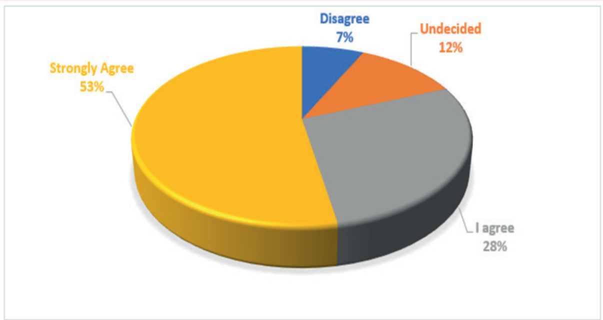

Figure 18. The virtual reality laboratory is more advantageous compared to traditional physical laboratories.

►**Figure 19** shows the responses to how the use of the virtual reality lab facilitates the learning process. A significant 92.1% of respondents agreed that using the VR lab facilitated the learning process.

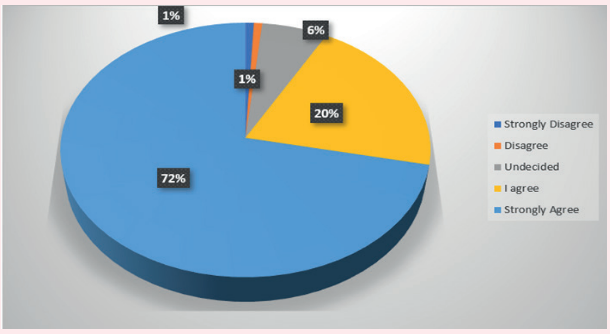

Figure 19. The use of the virtual reality laboratory facilitated the learning process.

This suggests that the interactive and immersive qualities of VR technology can enhance cognitive retention and understanding of complex concepts. The ability to visualize and experiment in a virtual space allows for deeper exploration and experimentation that is often limited in traditional laboratory settings due to constraints such as time, safety, and resource availability. Overall, these results show that VR labs can provide better educational outcomes through a more engaging, efficient, and accurate learning environment than traditional physical labs. As a platform for the use of VR technology in educational practice, it can therefore contribute greatly to improving student experience and organizing learning processes in science subjects.

6. Conclusion

This study developed a virtual reality laboratory application called VR-eLAB, which allows students to build and test electronic circuits in a virtual environment by overcoming physical limitations. The application was developed using the Unity 3D game engine for software and Blender for modeling. The Oculus Quest 2 virtual reality Head Mounted Display (HMD) was preferred for testing the developed application.

The application was tested by conducting laboratory experiments with 127 university students enrolled in the electronics course at Burdur Mehmet Akif Ersoy University Ağlasun Vocational School. At the end of the experiments, a questionnaire was administered to the students and the participants' opinions about their experiences in both traditional and virtual laboratory environments were systematically collected. With this questionnaire, the VR-eLAB application was compared with the traditional laboratory, and the students' satisfaction was measured.

The survey results indicate that VR labs offer substantial advantages over traditional physical labs, with 89% of participants feeling that VR effectively simulates real lab experiences. Additionally, 88.2% found VR beneficial for time management, allowing for faster experimental setups and reduced logistical burdens. A significant 81.1% acknowledged the superior benefits of VR in terms of accuracy and user engagement, while 92.1% agreed that VR enhances the learning process. Overall, these findings suggest that integrating VR technology in education can lead to more engaging, efficient, and effective learning experiences in scientific disciplines.

In conclusion, the implementation of the VR-eLAB application demonstrates the transformative potential of virtual reality technology in educational settings, particularly in the realm of electronics education. The positive feedback from students highlights several key advantages of VR laboratories over traditional physical labs, including enhanced engagement, improved accuracy, and greater efficiency in conducting experiments. The high levels of satisfaction reported by participants underscore the effectiveness of VR in creating immersive learning environments that cater to the diverse needs of students.

In addition, the ability to overcome physical limitations associated with traditional labs such as equipment accessibility and space constraints positions VR as a valuable tool for expanding educational opportunities. As institutions continue to seek innovative ways to improve learning outcomes, the integration of VR technology could not only foster a deeper understanding of complex concepts but also prepare students for real-world applications in a rapidly evolving technological landscape.

Future research may investigate the long-term impact of VR-based learning on student performance and retention in science disciplines, as well as the potential for adapting VR applications for other areas of study. By continuing to refine and expand the capabilities of virtual reality in education, we can open up new possibilities for teaching and learning that are in tune with the digital age. Ultimately, the findings of this study support the assertion that VR has the potential to revolutionize laboratory education, making it more accessible, engaging, and effective for all learners.

Research Ethics

Not applicable.

Author Contributions

Conceptualization: *Mustafa Çatak*, Methodology: *Mustafa Çatak, Ecir Uğur Küçüksille, Kubilay Taşdelen*, Formal Analysis: *Mustafa Çatak*, Investigation: *Mustafa Çatak*, Resources: *Mustafa Çatak*, Data Curation: *Mustafa Çatak*, Writing - Original Draft Preparation: *Mustafa Çatak*, Writing - Review & Editing: *Ecir Uğur Küçüksille, Kubilay Taşdelen*, Visualization: *Mustafa Çatak*, Supervision: *Uğur Küçüksille*, Project Administration: *Mustafa Çatak, Ecir Uğur Küçüksille, Kubilay Taşdelen*, Funding Acquisition: Na.

Competing Interests

The authors states no conflict of interest.

Research Funding

None declared.

Data Availability

Not applicable.

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