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An interactive augmented reality framework to enhance the user experience and operational skills in electronics laboratories

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Abstract

Augmented reality (AR) stands as a widely embraced technology that significantly enhances learning experiences for students. AR offers an instructional approach supported by technological design, thereby fostering enriched learning interactions. This research proposes an interactive AR framework, intended to create an augmented reality learning environment (ARLE) for the specific needs of electronics engineering laboratory hardware operations. The ARLE functions as an active learning system designed using a user-centered methodology. It offers interactive 3D models of laboratory equipment, providing learners with preliminary training in equipment operation. The real-time connection between the laboratory apparatus and the AR environment is established using the Arduino board. This interface empowers users to control the AR simulation through the laboratory equipment seamlessly. An experimental study involving 80 engineering students was conducted to evaluate the impact of AR intervention on user experience, usability, and operational skills. The participants were divided into two groups: the experimental group (N = 40) and the control group (N = 40). The experimental group underwent electronics equipment training using ARLE, while the control group followed instructions from a standard instrument handbook. To assess the usability and user experience of ARLE, the system usability scale (SUS) and the user experience questionnaire (UEQ) were employed (N = 40). The findings revealed an SUS score of 80.9 for ARLE, categorizing it as "good" according to SUS ratings. Additionally, the UEQ results demonstrated significantly favorable scores across the six scales when compared to the benchmark dataset. The study's outcomes demonstrate that AR intervention offers learners significant pedagogical value, resulting in a substantial positive impact on operational skills in electronics laboratories.

Keywords: Augmented reality, Engineering laboratory, Learning environment, System usability, User experience

Introduction

In the past decade, there has been a significant development in the field of information and communication technologies (ICTs) that has allowed academicians, learners, and educators to explore smart learning methodologies (Mercader & Gairín, 2020). ICTs have the power to present information in interesting and innovative ways that help learners easily understand concepts. ICT also enables learners to access information anytime and anywhere (Martín-Gutiérrez et al., 2015; Yeh et al., 2019). With the development of ICTs, educational trends are shifting from traditional teaching methodologies to modern learning techniques such as e-learning and m-learning (Tlili et al., 2022; Wu et al., 2013; Yip et al., 2019).

Augmented and virtual reality (VR) approaches have a significant impact on student attention because they provide an instructional approach supplemented by technology design, which offers a unique learning experience to the learner (Cubillo et al., 2014; Di Serio et al., 2013). While AR has great learning prospects, it also presents challenges for educational researchers in designing unique learning experiences. Augmented reality combines the real world with virtual objects, allowing learners to visualize complex concepts and theories. It also enhances learners' spatial abilities (Avilés-Cruz & Villegas-Cortez, 2019; García et al., 2016; Santos et al., 2014).

According to Milgram et al. (1995), augmented reality (AR) is a combination of virtual information and a real environment, with the latter being more predominant than the former. On the other hand, Augmented virtuality refers to the integration of real-world objects into virtual environments, where virtual information takes precedence over real-world objects (Azuma, 1997; Odeh et al., 2013; Singh & Mantri, 2015; Yang & Liao, 2014; Muneeb et al., 2023). AR lies between the real and virtual environments, providing a comprehensive view of 3D registered virtual information in the real world.

Past research has demonstrated that technology has the potential to enhance both learning and teaching experiences (Ahmad et al., 2016, 2017, 2021, 2023b). AR in particular has a significant impact on the student experience by providing additional virtual information in conjunction with the real environment (Hu et al., 2015; Perez-Sanagustin et al., 2014; Sugimoto, 2011; Zseby et al., 2016). AR has a wide range of applications in fields such as entertainment, medicine, the military, training, and education. In the education sector, AR provides an engaging and interactive learning experience for students (Huang et al., 2019a; Kapici et al., 2019; Wang & Tseng, 2019). By utilizing AR-based learning environments in education, the integration of the real world and virtual information can be achieved. Researchers have developed a variety of AR educational applications to teach difficult concepts and lessons to students (Efiloğlu Kurt & Tingöy, 2017; Nguyen et al., 2018; Singh et al., 2019).

The LearnAR Resource Centre (Bower et al., 2014) offers a package of marker-based AR applications for biology, mathematics, physics, chemistry, religion, and languages. LearnAR aims to provide interactive and independent learning opportunities for students on specific topics. Ferrer et al. (2013) developed an AR learning system called AR-SEE for passive solar energy education. This system is designed to teach students about solar energy design issues and energy usage efficiency. AR-SEE is a mobile phone-based learning application that provides interactive visualizations of solar simulations and Brownian motion, while also computing building performance in a simulated environment.

Klopfer and Squire (2008) have developed a learner-centered educational game that incorporates AR technology to offer an immersive experience of scientific phenomena, including chemical reactions. Xie et al. (2007) have designed several AR learning environments that enable students to interact with virtual models of the solar system and visualize the process of photosynthesis. Similarly, Matcha and Awang Rambli (2012) have developed an AR application that investigates the relationship between current and resistor. This application utilizes a camera to capture the real environment and markers. The computer then calculates the position of the markers in order to display corresponding 3D graphics on specific markers. The 3D graphics are designed to simulate a real experiment, with the bulb lighting up when the circuit is complete, and the intensity of light varying based on the value of the resistor. Additionally, an ammeter is used to measure the current flowing through the circuit, which is determined by the resistor and dry cell that are connected. Ibanez et al. (2016) have developed an AR-based simulation and learning tool called AR-SaBEr. This tool is designed for ninth-grade students to comprehend the fundamentals of electricity.

Barata et al. (2015) have developed a VR learning tool to help comprehend and visualize the operation of transformers in an electric power station. This system is a virtual technical system created to train individuals in the operations of transformers in electric power substations. Cadenas et al. (2015) designed a virtual system that operates on the Linux platform to teach assembly language programs for ARM-based processors. Chan et al. (2011) developed a dance training system based on VR, which incorporates optical motion capture technology to enhance students' dance skills. Terzidou et al. (2016) proposed an AI-supported approach for a collaborative educational game that offers various agents and interfaces to enhance the learning experience in a 3D environment. The research shows that AR has the potential to enable ubiquitous learning experiences through the use of remote laboratories, computer and web-based simulations, and interactive learning using 3D models or virtual objects.

Alvarez-Marin and Velazquez-Iturbide (2021) presents a systematic review discussing the impact of AR on engineering education, exploring various studies, experiments, and implementations. It is advised to evaluate AR apps using objective measures and more formal frameworks. It has been stated that most engineering domains have not employed AR extensively, and that there is potential to fully exploit AR technology in engineering education. Lu et al. (2022) gives a systematic analysis of the literature that characterizes the methodological features of usability studies on educational and learning technology. According to the findings, most of the usability research focuses on technological usability, with very few studies addressing educational and socio-cultural components of usability. The review emphasizes the importance of user-centered design and significance of optimizing interfaces and interactions in educational technology for enhanced usability and learner engagement.

Kumar et al. (2022) developed an AR-based interactive tabletop environment to teach the fundamentals of microcontroller-based embedded systems to engineering students in a collaborative learning mode. The AR-based learning environment utilizes the Arduino UNO development board for the hands-on exploratory study. The study outcomes indicate a significant improvement in the practical knowledge and collaborative skills of the students using AR technology. Tuli et al. (2022) developed an AR-based laboratory manual to help engineering students perform practical laboratory experiments in electronics engineering. The AR-based laboratory manual is a mobile-based game that provides 3D visualization of electronic hardware components like breadboards, ICs, LEDs, resistors, batteries, connecting wires, and switches. The students can interact with the electronic components and connect the electronic circuit by following step-by-step instructions from the AR game. The study outcomes reveal that AR intervention has a significant positive impact on the academic achievement and learning attitude of the students. Dutta et al. (2023) designed an AR-based learning environment to help students learn about logic design using the Karnaugh-map (K-map) technique in a digital electronics course. The AR-based mobile application provides step-by-step instructions to the students to solve the Boolean expression using the K-map technique and helps them get the correct logic design. It also provides interactivity with an AND-OR-INVERTER logic diagram for any Boolean expression. The study outcomes reveal that AR technology has a significant positive impact on the knowledge gain, and critical thinking skills of the students.

Engineering laboratory experience is crucial for developing problem-solving skills, critical thinking abilities, and project-based learning among students. Laboratory experience instills confidence in graduates to work on live or field projects in the industry (Bautista, 2016). However, students often face challenges and difficulties while working with laboratory equipment, especially when they have no prior knowledge or experience with it. Electronics engineering laboratory training faces hurdles due to the complexity of equipment, limited access to resources, safety risks, and challenges in engaging students effectively. AR addresses these issues by simplifying complex concepts, providing access to a wider range of tools virtually, offering a safer learning environment, and engaging students through interactive, hands-on experiences. It is crucial to enhance the learning experience of engineering students. ARLE can provide a better learning experience for novice students who lack prior equipment experience. This paper proposes an AR framework for developing a learning environment and discusses the design aspects of the ARLE. ARLE is designed to assist learners in operating laboratory equipment, especially oscilloscopes and function generators, in engineering laboratories. The design takes input from academic faculty members who have previously taught electronics laboratory courses.

This research aims to answer the following questions:

- RQ1: How does the use of AR technology in the electronics laboratory affect system usability and user experience?
- RQ2: How does the use of ARLE affect users' operational skills when learning about electronics engineering laboratory equipment?
- RQ3: Does the use of ARLE in electronics engineering laboratories significantly impact students' critical thinking skills?

This paper is organized as follows: in "Development of augmented reality learning environment (ARLE)" section describes the development process of ARLE. "Methodology" section presents the research methodology and evaluation. "Result analysis" section presents the data analysis and associated results. "Discussion and conclusion" section outlines the discussion and conclusion of the study outcomes.

Development of augmented reality learning environment (ARLE)

3D modeling

Figure 1 illustrates the sequential process of ARLE development. This section describes the design process for creating 3D models of laboratory equipment that are used as virtual objects in ARLE. To create these models, Autodesk Maya, a 3D modeling software,

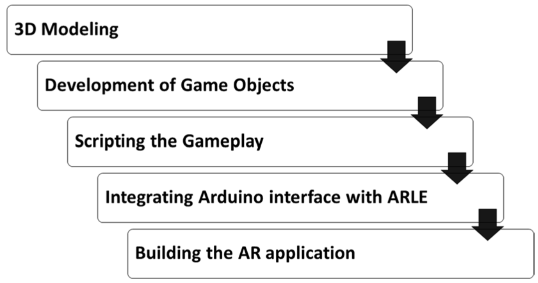


Fig. 1 Development process of ARLE

is used. The steps involved in developing these models are presented in Fig. 2. To ensure that the 3D models provide an immersive experience for students, it is crucial to analyze the physical object from all angles. Thus, the developer manually collects reference images and videos of the object from various perspectives. This helps in verifying the accuracy of the 3D models throughout the development process.

Once the reference material has been collected, the 3D modeling of laboratory equipment can begin. Initially, wireframe models of 3D objects are developed. Afterwards, textures are added to these models. Texturing is critical for defining the surface texture and color details of 3D models, which are necessary for creating realistic objects (Huang et al., 2019a, 2019b). Figure 3 presents the oscilloscope model without textures, while Fig. 4 shows the same model with textures applied.

The process of lighting involves using lights to enhance the realism of 3D models. It involves defining the light sources, their intensity, and color. Lights are crucial for visualizing 3D models during rendering (Dere et al., 2010). Global illumination was used as the lighting technique for this study. This technique simulates the way light bounces off every object in the environment, similar to natural light. It provides realistic lighting to the objects in the environment, as opposed to the simple lighting provided by a light source that travels in a straight path. After setting up the lighting, the next step was animation, which involves adding movement to static 3D models. In the 3D representations of laboratory equipment, linear and rotational movements were assigned to buttons and knobs, respectively.

Finally, the rendered images were extracted from the Autodesk Maya software. During the process of 3D modeling, a mesh can often consist of a significant number of vertices and faces, resulting in a substantial increase in file size and longer rendering times. To reduce rendering time, mesh optimization was performed by eliminating unnecessary vertices and edges that do not affect the model's shape (Hoppe et al., 1993; Valdez

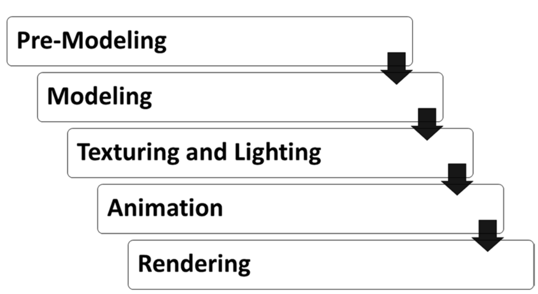


Fig. 2 Steps for 3D model development

Fig. 3 Oscilloscope model without the textures

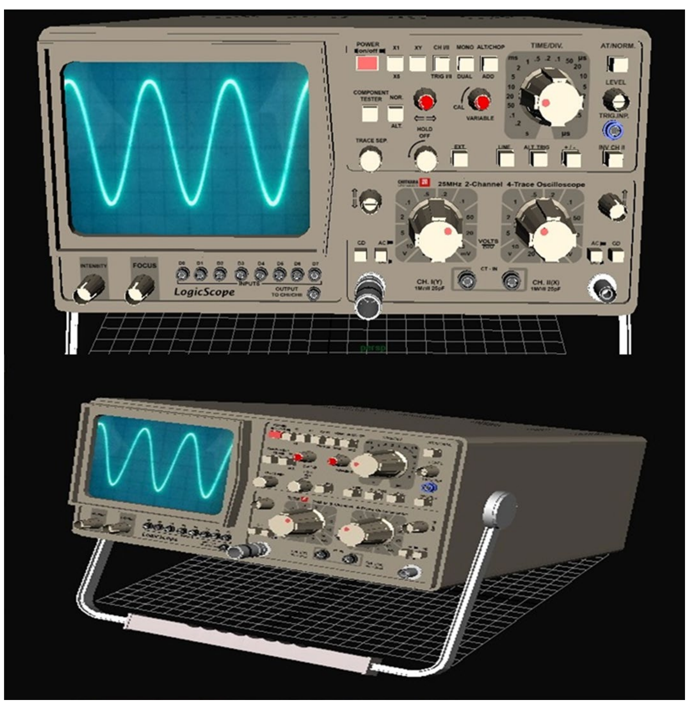


Fig. 4 Oscilloscope model with the textures

et al., 2015). The polygon reduction technique was used to decrease the overall number of polygons in the mesh. Figure 5 presents the rendered image of the 3D model of the oscilloscope.

Development of game objects

Game objects are essential entities that represent various objects in a game. Students can generate various waveforms, including sine, triangular, and square waves, using the function generator. These waveforms are then generated as virtual game objects within the Unity 3D game engine using the Vectrosity toolset. Vectrosity provides a comprehensive solution for drawing lines and curves in Unity. The three waveforms, sine, square, and triangular, are designed based on amplitude and frequency, allowing for the adjustment of waveform parameters. These waveforms are superimposed on the model of an oscilloscope, as demonstrated in Fig. 6. Furthermore, the 3D models of the oscilloscope and function generator, created using Autodesk Maya, are exported as game objects into Unity 3D.

Scripting the gameplay

Scripts play a crucial role in controlling game components in augmented reality (AR) games. They specify the actions of game objects during gameplay (Dichev & Dicheva, 2017). In the ARLE (augmented reality learning environment), control scripts were integrated to manage the switches and knobs of 3D models of laboratory equipment. These scripts were written using the C# programming language and the Unity editor. In AR simulations, students can adjust the frequency and amplitude of waves by turning the corresponding knobs on the equipment. Moreover, they can regulate the signal voltage and time-period on the oscilloscope by using the relevant knobs and buttons. By pressing the switch on the 3D model of the function generator, waveforms such as sine, square, and triangular waves are generated on the 3D model of the oscilloscope.

The user interface (UI) for the AR environment was designed with students in mind, allowing them to interact with and perform actions on virtual models of laboratory equipment using the computer mouse. The students can press the button on the 3D model of the equipment using the left mouse click function and rotate the equipment knob using the scroll function of the mouse. Additionally, information regarding the significance of buttons and knobs on the equipment is provided at the top of the screen. This helps students operate the equipment more efficiently.

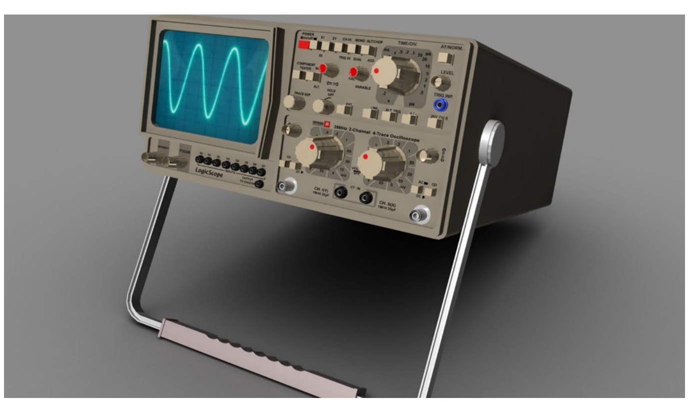
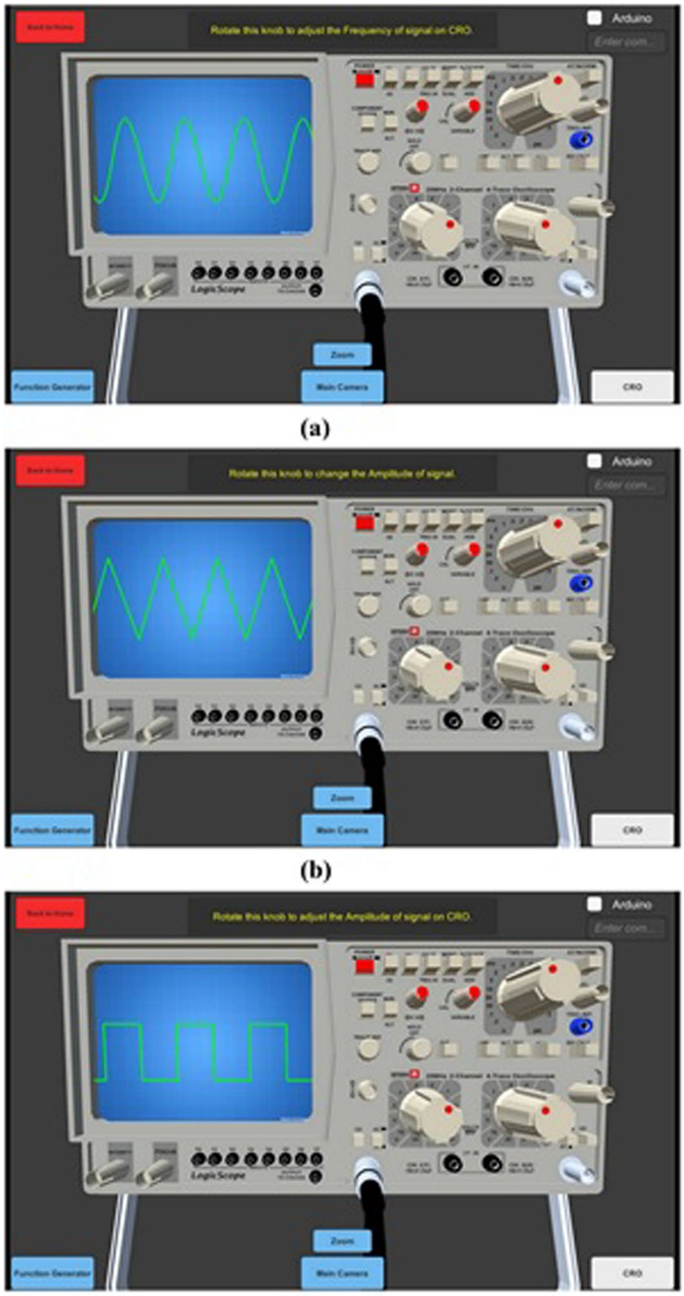


Fig. 5 Rendered image of 3D model of oscilloscope



(c)

Fig. 6 **a** Sine wave is designed as game object, **b** square wave is designed as game object, **c** triangular wave is designed as game object

Integrating Arduino interface with ARLE

In this step, a real-time interface is developed between a physical oscilloscope and the AR learning system using Arduino as the intermediary. To create the interface, an extension of the Unity 3D game engine known as Uniduino is utilized. This extension enables Unity 3D to establish a connection with an Arduino board and retrieve real-time analog and digital values from any electronic circuit. By establishing a connection between the real oscilloscope and ARLE using Uniduino and an Arduino board, the ARLE can be controlled with the real oscilloscope. The Arduino board is used to monitor real-time changes in the amplitude and frequency values by adjusting the Time/Div. knob and Volts/Div. knob on the physical oscilloscope. The Arduino board transmits these values to Uniduino, which then processes them in Unity 3D and modifies the signal waveforms in the AR environment. The block diagram of the interface is shown in Fig. 7.

When the user rotates the knobs for amplitude control and frequency control on the actual oscilloscope, the voltage level changes in the control circuit of the oscilloscope. Therefore, the real-time values are read from the amplitude control circuit and the frequency control circuit (time base generator) of the oscilloscope using the Arduino board. The Uniduino extension transfers these values to the Unity game engine. A control script is implemented that adjusts the amplitude and frequency of the waveform in the learning environment based on real-time values obtained from the amplitude control circuit and the frequency control circuit of the oscilloscope. This real-time system enhances students' visualization and understanding (Kumar et al., 2022).

Building the AR application

The final stage of the design process involves constructing the learning system within the AR environment. The AR application is designed for the tabletop environment on the Windows platform. The EasyAR software tool is used to enable AR tracking. EasyAR is an AR-SDK available for smartphones and PC platforms that utilizes computer vision techniques to track the target object and overlay virtual content (Tuli et al., 2022). The AR application uses multiple marker-based tracking techniques, and QR codes are employed as markers to superimpose 3D models of equipment (Nguyen & Dang, 2017; Prit Kaur et al., 2018). Figure 8 showcases the ARLE developed for the oscilloscope and function generator.

Methodology

This section presents the methodology adopted for the present study. It consists of participant details, measurement instruments, and an experimental design. Figure 9 illustrates the flowchart outlining the proposed activities to implement the ARLE intervention with engineering students.

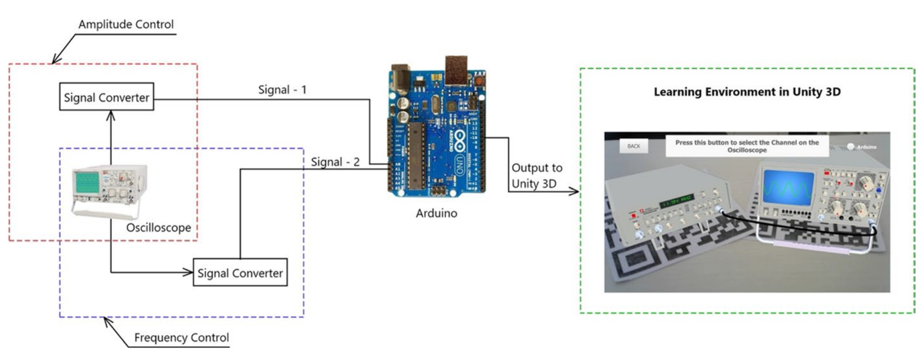


Fig. 7 Block diagram of Arduino interface with Unity 3D

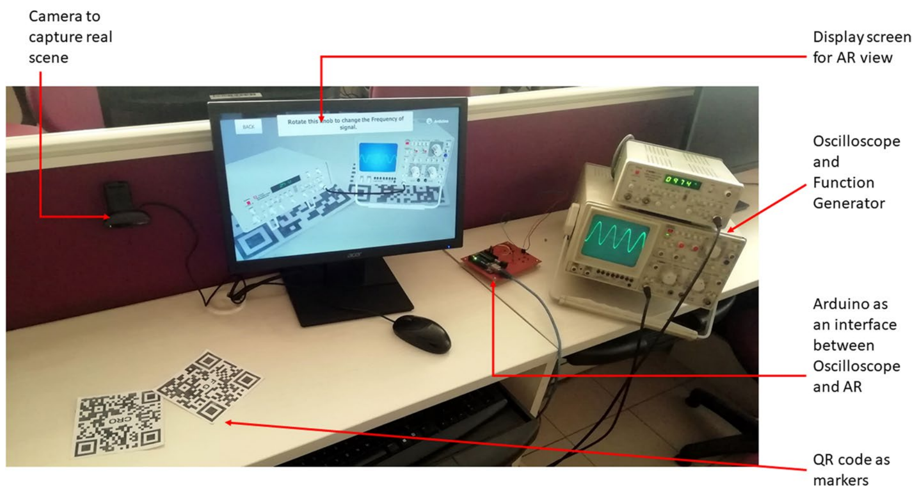


Fig. 8 ARLE for oscilloscope and function generator

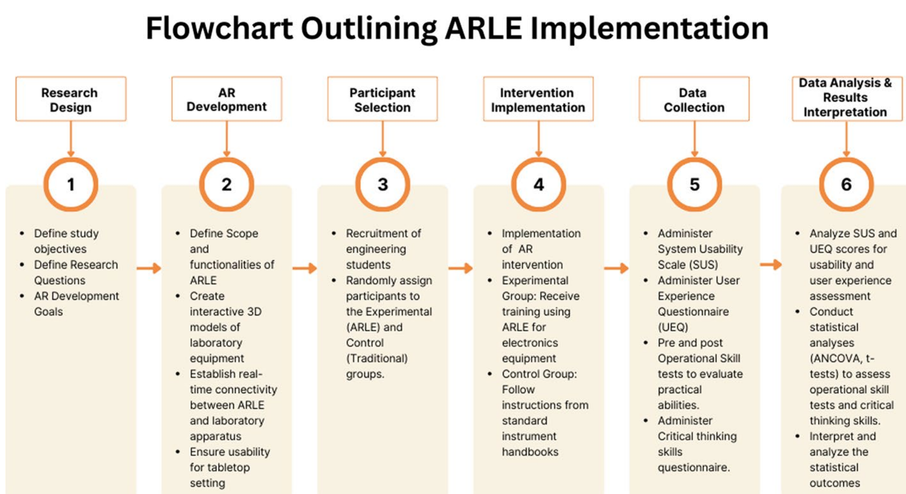


Fig. 9 Flowchart for ARLE implementation

Participants

The presented study recruited 80 s-year electronics engineering students, aged between 18 and 20 years, as participants (see Table 1). These participants were divided equally into two groups, using random sampling: the experimental group and the control group. The experimental group received training on electronics equipment using ARLE, while the control group received instruction using a standard instrument handbook. It's noteworthy to mention that none of the participants had prior experience in using an oscilloscope or a function generator.

Measurement instruments

System usability scale (SUS)

To evaluate the usability of ARLE, the system usability scale (SUS) was utilized. The SUS, developed by John Brooke in 1996, composes 10 items (see "Appendix 1"). These items

Table 1 Participant details

Gender	Number of students		Total
	Experimental group	Control group	
Male	26	23	49
Female	14	17	31
Total	40	40	80

include statements such as “I think that I would like to use this system frequently” and “I found the system unnecessarily complex”. Participants were asked to respond on a five-point Likert scale, where 1 indicated strong disagreement and 5 indicated strong agreement. The following steps are followed to calculate the SUS score:

Step 1 Calculate the average of the responses collected for each question asked in the survey.

Step 2 For even-numbered survey questions (1, 3, 5, 7, and 9), calculate the System Usability score by subtracting one from the user response.

Step 3 For odd-numbered survey questions (2, 4, 6, 8, and 10), calculate the System Usability score by subtracting the user response from five.

Step 4 Sum up the newly obtained System Usability scores for all questions.

Step 5 Multiply the sum by 2.5 to obtain the final System Usability score as a percentage.

Step 6 The System Usability score now falls within the range of 0–100.

According to John Brooke’s system usability scale (SUS) questionnaire, a product or system’s usability is considered acceptable if the overall system usability percentage exceeds 55% (Kumar et al., 2020).

User experience questionnaire (UEQ)

To evaluate user experience with ARLE, the User Experience Questionnaire (UEQ) was utilized (details given in “Appendix 2”). The UEQ, developed by Martin Schrepp (2014), consists of 26 items comprising six scales: attractiveness, perspicuity, efficiency, dependability, stimulation, and novelty. Attractiveness evaluates the overall impression of a product and how much users liked or disliked it. Perspicuity refers to the ease with which a product can be used or learned. Efficiency refers to the level of ease with which users can successfully accomplish their tasks without having to exert unnecessary effort on the system. Dependability can be defined as the user’s perception of control over the system’s interaction. Stimulation refers to the user’s excitement and motivation to use the product, while novelty measures a product’s ability to be innovative, creative, and grab the user’s interest. The Cronbach’s alpha value of the six scales is above 0.70, indicating a high level of internal consistency for the survey scale.

Operational skill test

All the participants of the experimental and control group were instructed to undertake the operational skill test, as a pre and post experiment test. The operational skill test had a maximum score of 40 points, and participants were given 20 min to complete it.

During the operational skill test, participants were asked to perform the following tasks on laboratory equipment:

- Connect the output port of the function generator to the input port of the oscilloscope.
- Generate various signals (sine wave, square wave, and triangle wave) using a function generator with specific amplitude and frequency settings.
- Adjust the oscilloscope controls to observe the signal waveform on an oscilloscope.
- Measure the peak voltage and time-period of the signal using an oscilloscope.

The rubrics for the operational skill test are detailed in "Appendix 3".

Critical thinking questionnaire

The students' critical thinking abilities were assessed using a modified survey questionnaire designed by Chai et al. (2015). The questionnaire consists of six items, and participants were asked to respond on a five-point Likert scale. The Cronbach's alpha of the survey questionnaire was 0.782, indicating a reliable internal consistency.

Experimental design

The experiment was conducted in the electronics laboratory, where engineering students were introduced to essential electronic measuring equipment, such as oscilloscopes, function generators, multimeters, and more. The experiment aimed to develop an Augmented Reality Learning Environment (ARLE) to assist students in operating electronics laboratory hardware.

To begin the experiment, an introductory session was conducted to give the students an overview of the electronic equipment. Following the introductory session, a pre-test of operational skills was conducted for both groups under the supervision of an instructor. After the pre-test, participants from the two groups received 2 weeks training on electronic equipment using different learning interventions. The experimental group received ARLE-based training first and then operated the actual instrument. On the other hand, the control group was instructed to carefully read the standard instrument handbook while operating it in the presence of a teacher.

After completing the training, both groups underwent a post-test of operational skills in the presence of an instructor. Additionally, participants were asked to complete a questionnaire on their critical thinking skills and classroom engagement. The students in the experimental group were also asked to complete the SUS and UEQ. The experimental design flow is illustrated in Fig. 10.

Result analysis

ANCOVA and t-test were applied to the collected data from the experimental study to determine the outcomes of the study. The SPSS software package was used for data analysis.

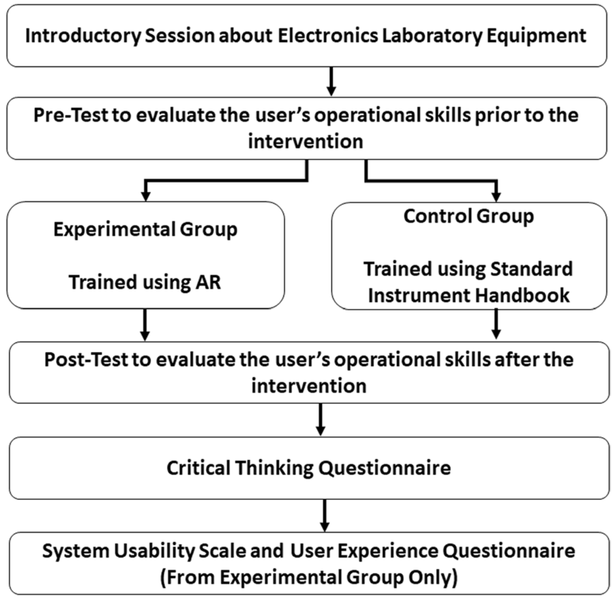


Fig. 10 Experimental design

System usability scale (SUS) score

The SUS survey was administered to participants from the experimental group following their use of the ARLE. The accumulated SUS score for ARLE is 80.9 which indicates good system usability according to the SUS rating (Brooke, 1996).

User experience questionnaire (UEQ) analysis

The collected data was analyzed using the UEQ data analysis tool to evaluate the user experience of ARLE. The UEQ provides analysis through 26 items across 6 scales, which include attractiveness, perspicuity, efficiency, dependability, stimulation, and novelty. Figure 11 presents the distribution of responses for each item of the UEQ on a 7-point Likert scale.

UEQ also allows for comparing the measured user experience of ARLE with the benchmark dataset of various existing products. UEQ offers a benchmark dataset that includes data from 20,190 participants from 452 studies (Schrepp et al., 2017). Comparing the UEQ results of ARLE with the benchmark data enables us to evaluate the relative quality of ARLE in comparison to other existing products. The benchmark classifies each scale of UEQ into five categories: Excellent, Good, Above Average, Below Average, and Poor. Table 2 presents the analysis and comparison of six scales of UEQ with benchmark data.

A comparison was conducted between the measured user experience of ARLE and the benchmark dataset across 6 scales. The results are presented in Table 2 and Fig. 12, and they are briefly explained as follows:

- The mean value of attractiveness of ARLE falls in the "Good" category($\mu = 1.61, \sigma = 1.15, \sigma_{\underline{x}} = 0.18$). This suggests that users have a positive overall impression of ARLE, and they enjoy using the system.

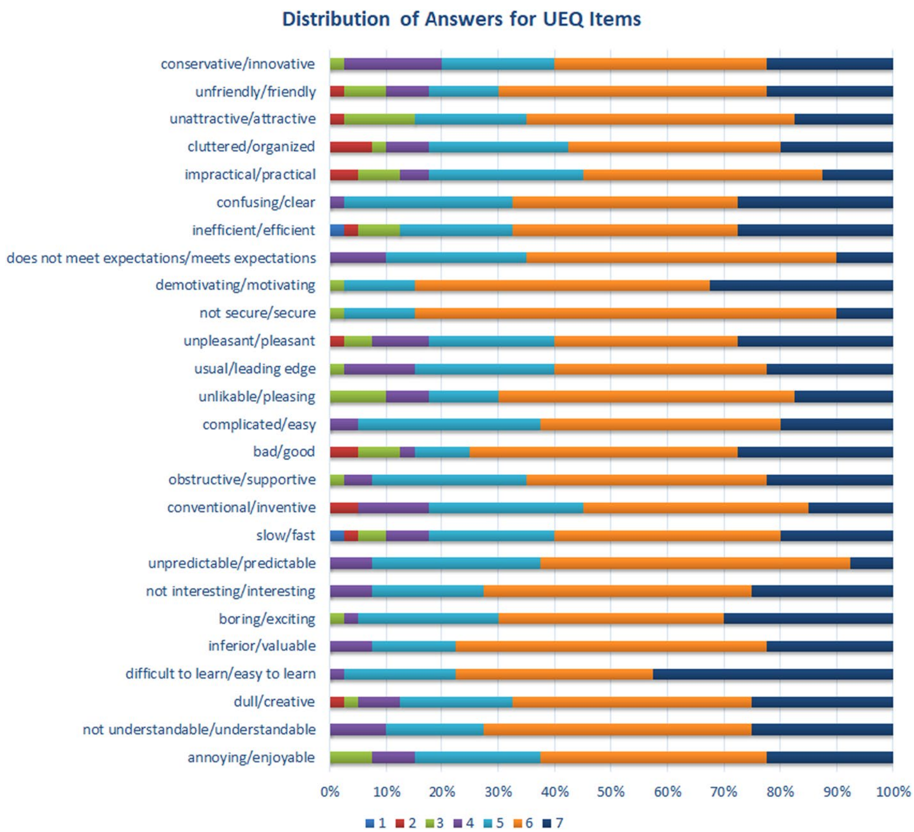


Fig. 11 Distribution of answers for each UEQ item

Table 2 UEQ analysis and comparison to benchmark dataset

Scale	Mean	S.D	Cronbach's alpha	Comparison to benchmark	Interpretation
Attractiveness	1.61	1.15	0.96	Good	10% of results better, 75% of results worse
Perspicuity	1.94	0.71	0.86	Good	10% of results better, 75% of results worse
Efficiency	1.46	1.08	0.79	Above average	25% of results better, 50% of results worse
Dependability	1.74	0.63	0.81	Excellent	In the range of the 10% best results
Stimulation	1.97	0.68	0.81	Excellent	In the range of the 10% best results
Novelty	1.60	1.00	0.92	Good	10% of results better, 75% of results worse

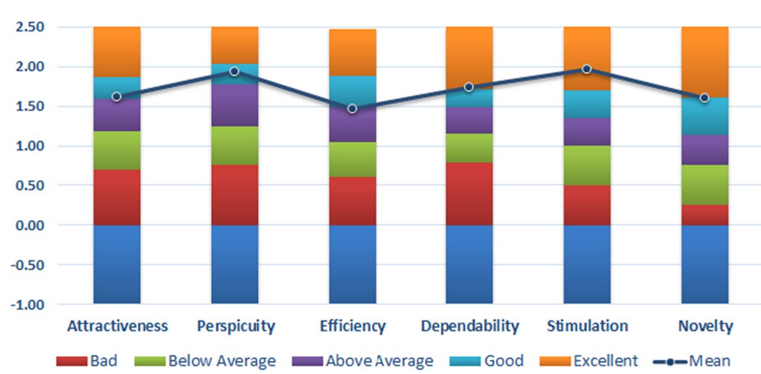


Fig. 12 UEQ comparison with benchmark dataset

- The mean value of perspicuity of ARLE falls in the "Good" category($\boldsymbol{\mu} = 1.94, \boldsymbol{\sigma} = 0.71, \boldsymbol{\sigma}_{\underline{x}} = 0.11$). This indicates that ARLE is easy for users to understand and learn.
- The mean value of efficiency of ARLE falls in the "Above Average" category($\boldsymbol{\mu} = 1.46, \boldsymbol{\sigma} = 1.08, \boldsymbol{\sigma}_{\underline{x}} = 0.17$). This suggests that ARLE is easy to use with minimal effort for users.
- The mean value of dependability of ARLE falls in the "Excellent" category($\boldsymbol{\mu} = 1.74, \boldsymbol{\sigma} = 0.63, \boldsymbol{\sigma}_{\underline{x}} = 0.09$). This suggests that ARLE provides flexibility to users to control the interaction.
- The mean value of stimulation of ARLE falls in the "Excellent" category($\boldsymbol{\mu} = 1.97, \boldsymbol{\sigma} = 0.68, \boldsymbol{\sigma}_{\underline{x}} = 0.10$). This indicates that users found ARLE to be exciting, motivating, valuable, and interesting.
- The mean value of novelty of ARLE falls in the "Good" category($\boldsymbol{\mu} = 1.60, \boldsymbol{\sigma} = 1.00, \boldsymbol{\sigma}_{\underline{x}} = 0.15$). This suggests that users found ARLE to be creative and innovative.

Analysis of operational skills

In the initial phase of statistical analysis, the pre-test operational skills scores of both the experimental and control groups were analyzed using regression coefficient to accurately assess the homogeneity of the groups (F-value = 0.002, p = 0.967). Thus, the post-test operational skills scores of both groups can be considered comparable and conclusive.

In the second phase of statistical analysis, the mean score for post-test operational skills in the experimental group was reported to be higher ($\boldsymbol{\mu} = 31.72, \boldsymbol{\sigma} = 1.94, \boldsymbol{\sigma}_{\underline{x}} = 0.303$) compared to the control group ($\boldsymbol{\mu} = 28.45, \boldsymbol{\sigma} = 1.85, \boldsymbol{\sigma}_{\underline{x}} = 0.303$) as mentioned in Table 3. Furthermore, the results of the regression coefficient (F-value = 58.57, $p < 0.05$) indicate a significant difference in the operational skills of both groups. The ANCOVA analysis also suggests that the AR intervention has a significant positive impact on the operational skills of the participants ($\eta^2 = 0.432$, indicating a moderate effect size).

Analysis of critical thinking skills

After the learning activity, participants completed a critical thinking questionnaire using a five-point Likert scale. An independent sample t-test was conducted to determine if there was a significant difference in critical thinking skills between the two groups. As shown in Table 4, the experimental group had a higher critical thinking skills ($\boldsymbol{\mu} = 4.05, \boldsymbol{\sigma} = 0.31, \boldsymbol{\sigma}_{\underline{x}} = 0.049$) than the control group($\boldsymbol{\mu} = 3.20, \boldsymbol{\sigma} = 0.42, \boldsymbol{\sigma}_{\underline{x}} = 0.066$)
.

Table 3 ANCOVA analysis of operational skill test

Group	N	Mean	S.D	Adjusted mean	Std. error	F	*p* value	η^2
Experimental Group	40	31.72	1.94	31.72	0.303	58.57	0.000	0.432
Control Group	40	28.45	1.85	28.45	0.303			

Table 4 t-Test analysis of critical thinking skills

Group	N	Mean	S.D	*t*	df	*p* value	Cohen's d	95% confidence interval of the difference	
								Lower	Upper
Experimental group	40	4.05	0.31	10.249	78	0.000	2.29	0.68825	1.02009
Control group	40	3.20	0.42						

The t-test analysis (t value = 10.249, $p < 0.05$) indicating a significant difference in critical thinking skills between the two groups. The Cohen's d value of 2.29 showing a very large effect size. These findings suggest that individuals who use AR exhibit better critical thinking skills compared to those who do not use AR.

Discussion and conclusion

The study's practical implications highlight that ARLE can revolutionize the way electronics engineering education is taught to teachers, institutions, and students. It provides an innovative teaching tool that improves critical thinking, practical skills, and user experience. Teachers may use it to improve their methods of instructions, institutions can keep up with the latest developments in education, and students can gain skills that are applicable in the real world. The study's methodology highlights the effectiveness of well-established assessment tools such as SUS and UEQ in measuring ARLE's usability and user experience.

RQ1: How does the use of AR technology in the electronics laboratory affect system usability and user experience?

The use of AR technology in education is helping students to better understand difficult concepts. In this study, an interactive ARLE is developed to assist users in operating electronics laboratory equipment. The ARLE was designed using a user-centered approach to actively involve users in the learning process. Within the AR simulation, users can visualize various waveforms generated by the function generator and change waveform parameters by rotating the knobs of a 3D model of the oscilloscope, thus providing an immersive and interactive experience. To evaluate the effectiveness of the ARLE, the user experience of 40 individuals is recorded. The SUS and UEQ is utilized to evaluate the usability of the system and the user experience. Our study results suggest that the ARLE is a relevant and effective learning tool for laboratory hardware education. The SUS score for the ARLE from 40 users was 80.9, which is considered good according to the SUS rating system. This demonstrates that the AR technology implementation was effective in creating an interface that users found intuitive and efficient when interacting with the equipment. These experimental results support previous studies by Dutta et al. (2022), Kumar et al. (2020), and Lin et al. (2015).

Furthermore, the UEQ was used to record the user experience of 40 individuals and compare it to a benchmark dataset. The results of the UEQ indicate that ARLE obtained a satisfactory score on the six scales in comparison to the benchmark dataset. ARLE has great pedagogical value as it provides users with prior training and enhances their technical and operational skills. Using ARLE in laboratories can also reduce equipment damage, as users gain valuable experience in operating equipment within the AR environment. These findings suggest that the ARLE not only provided a usable system but also enhanced the overall user experience, making the learning process more engaging, clear, efficient, and dependable for participants in the electronics laboratory. Feedback from users indicates that they enjoy using the AR system. In conclusion, this study provides evidence that ARLE is an effective tool for enhancing laboratory hardware education. Its immersive and interactive nature offers a unique learning experience that engages users in a way that traditional methods cannot. The development of ARLE offers a promising opportunity to enhance education and training for laboratory equipment operation. Overall, the use of AR technology appears to positively influence both system usability and user experience, contributing to a more effective and engaging learning environment in the electronics laboratory.

RQ2: How does the use of ARLE affect users' operational skills when learning about electronics engineering laboratory equipment?

An exploratory study was conducted to evaluate the impact of augmented reality (AR) technology on the operational and critical thinking skills of engineering students. The ANCOVA analysis indicated a significant positive impact of the AR intervention on operational skills ($\eta^2 = 0.432$, indicating a moderate effect size). This suggests that participants who underwent training using the ARLE demonstrated notable improvements in their practical abilities to operate the laboratory equipment compared to those who followed standard handbook instructions. The operational skill test, which involved tasks such as connecting equipment, generating signals, adjusting controls, and measuring parameters, revealed that participants in the experimental group, who used the ARLE, showed enhanced proficiency in these tasks. This highlights the effectiveness of the ARLE in bridging the gap between theoretical knowledge and practical application, thereby improving users' hands-on operational skills in handling electronics laboratory equipment.

During the experiment, it was observed that the AR group was comfortable operating the actual equipment, as they had visualized the equipment's operating panel in AR. The integration of AR content improved user interaction with laboratory equipment, enabling them to quickly understand the implications of devices. Interaction with 3D models of laboratory equipment in an AR environment enhances user operational skills and knowledge retention (Gargrish et al., 2021; Singh et al., 2019; Sommerauer & Müller, 2014; Zhang et al., 2018). Overall, the use of ARLE appears to significantly enhance users' operational skills, enabling them to perform tasks more effectively and confidently within the electronics engineering laboratory environment.

RQ3: Does the use of ARLE in electronics engineering laboratories significantly impact students' critical thinking skills?

The impact of AR on the critical thinking skills of students was analyzed using t-test analysis. The results indicated that the AR group demonstrated better critical thinking skills compared to the control group. The t-test analysis conducted between the group that used the ARLE and the control group suggests a significant difference in critical thinking skills. The t-value of 10.249 with a p-value of less than 0.05 indicates a notable difference in critical thinking abilities between these groups. The Cohen's d value of 2.29 showing a very large effect size. This finding implies that individuals who utilized the ARLE demonstrated better critical thinking skills compared to those who followed standard handbook instructions in the electronics engineering laboratories. While the exact mechanisms behind this improvement may need further exploration, it suggests that the interactive and immersive nature of the ARLE might have contributed to stimulating and enhancing students' critical thinking abilities. Users visualized the front panel of the equipment in ARLE, which reduced their effort when operating the actual equipment. This helped them to think critically about other aspects and explore more features of the equipment during operation. AR familiarized them with laboratory equipment, improving their performance and confidence (Ahmad et al., 2023a; August et al., 2016; Chin et al., 2020; de la Torre et al., 2015; Gómez-Tejedor et al., 2020; Potkonjak et al., 2016; Terzidou et al., 2016).

The use of augmented reality (AR) technology for conducting engineering laboratory experiments is particularly advantageous during the current COVID-19 pandemic, as most universities in India have adopted online teaching methods. The Augmented Reality Laboratory Environment (ARLE) developed in this study is an effective learning tool that enables teachers to provide students with an immersive and interactive learning experience. In the future, the ARLE will be available online to students, enabling them to enhance their skills from home. However, the AR framework presented in this study is designed for a tabletop setting, which requires a specific setup for use in laboratories or classrooms. Nevertheless, efforts are underway to transform the ARLE for mobile phone usage, making it more accessible for every student without any special hardware or setup requirements. The timeline for implementing changes in ARLE involves a 6-month timeline for mobile adaptation and online accessibility, followed by a 6–12-month phase for advanced interactivity and potential wearable integration. Challenges include device compatibility and optimization complexities, content adaptation for mobile screen, user training, and alignment with educational systems. These phases aim to make ARLE accessible, user-friendly, and impactful for engineering education, especially in remote learning setups. The design framework and deliberations presented in this article can assist in the development of AR learning environments for other areas of engineering education.

The ARLE framework is designed for a tabletop setting relies on specific laboratory setups, restricting accessibility outside designated laboratories or classrooms. The current framework demand specialized hardware, such as AR-compatible devices and Arduino interfacing boards. Addressing these limitations will be crucial for ensuring broader accessibility, usability, and effectiveness of the ARLE.

Appendix 1

System usability scale by John Brooke

The participants are asked to score the following 10 items with one of five responses that range from Strongly Agree to Strongly disagree:

1. I think that I would like to use this system frequently.
2. I found the system unnecessarily complex.
3. I thought the system was easy to use.
4. I think that I would need the support of a technical person to be able to use this system.
5. I found the various functions in this system were well integrated.
6. I thought there was too much inconsistency in this system.
7. I would imagine that most people would learn to use this system very quickly.
8. I found the system very cumbersome to use.
9. I felt very confident using the system.
10. I needed to learn a lot of things before I could get going with this system.

Appendix 2

User experience questionnaire (UEQ) by Martin Schrepp

Please assess the product now by ticking one circle per line.

	1	2	3	4	5	6	7		
annoying	○	○	○	○	○	○	○	enjoyable	1
not understandable	○	○	○	○	○	○	○	understandable	2
creative	○	○	○	○	○	○	○	dull	3
easy to learn	○	○	○	○	○	○	○	difficult to learn	4
valuable	○	○	○	○	○	○	○	inferior	5
boring	○	○	○	○	○	○	○	exciting	6
not interesting	○	○	○	○	○	○	○	interesting	7
unpredictable	○	○	○	○	○	○	○	predictable	8
fast	○	○	○	○	○	○	○	slow	9
inventive	○	○	○	○	○	○	○	conventional	10
obstructive	○	○	○	○	○	○	○	supportive	11
good	○	○	○	○	○	○	○	bad	12
complicated	○	○	○	○	○	○	○	easy	13
unlikable	○	○	○	○	○	○	○	pleasing	14
usual	○	○	○	○	○	○	○	leading edge	15
unpleasant	○	○	○	○	○	○	○	pleasant	16
secure	○	○	○	○	○	○	○	not secure	17
motivating	○	○	○	○	○	○	○	demotivating	18
meets expectations	○	○	○	○	○	○	○	does not meet expectations	19
inefficient	○	○	○	○	○	○	○	efficient	20
clear	○	○	○	○	○	○	○	confusing	21
impractical	○	○	○	○	○	○	○	practical	22
organized	○	○	○	○	○	○	○	cluttered	23
attractive	○	○	○	○	○	○	○	unattractive	24
friendly	○	○	○	○	○	○	○	unfriendly	25
conservative	○	○	○	○	○	○	○	innovative	26

Annexure 3

Rubrics for measuring operational skills on oscilloscope and function generator

Activities	Points
Basic connections	
(1) Turn on the devices and connecting oscilloscope and function generator with BNC Cable	4
On function generator	
(2) Generate a sine wave from function generator with an amplitude of 5 V and frequency of 90 kHz	3
(3) Generate a sine wave from function generator with an amplitude of 12 V and frequency of 450 Hz	3
(4) Generate a square wave from function generator with an amplitude of 5 V and frequency of 15 MHz	3
(5) Generate a square wave from function generator with an amplitude of 25 V and frequency of 550 kHz	3
(6) Generate a triangular wave from function generator with an amplitude of 18 V and frequency of 85 Hz	3
(7) Generate a triangular wave from function generator with an amplitude of 8 V and frequency of 5 MHz	3
On oscilloscope	
(8) Adjust the controls of oscilloscope to properly display the sine waveform	3
(9) Measure the amplitude and frequency of a given sine wave on oscilloscope	3
(10) Adjust the controls of oscilloscope to properly display the square waveform	3
(11) Measure the amplitude and frequency of a given square wave on oscilloscope	3
(12) Adjust the controls of oscilloscope to properly display the triangular waveform	3
(13) Measure the amplitude and frequency of a given triangular wave on oscilloscope	3
Total	40 Points

Abbreviations

AR	Augmented reality
ARLE	Augmented reality learning environment
ICT	Information and communication technologies
QR	Quick response
SDK	Software development kit
SUS	System usability scale
UEQ	User experience questionnaire
UI	User interface

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GS has conducted the study, analyzed the results, and written the manuscript. FA has helped in finalizing the study design and improving the manuscript in terms of writing and data analysis.

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Data availability
The datasets used and/or analysed during the current study are available from the corresponding author on reasonable request.

Declarations

Ethics approval and consent to participate
The authors declare that they have taken the ethical approvals and consent from the participants to participate. The university's Vice-Chancellor granted written permission for the execution of the present study involving engineering students. A comprehensive proposal was submitted, outlining the study's objectives, experimental methodology, the instrumentation and technologies employed for the investigation, as well as the potential outcomes of the research.

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