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TOPICAL REVIEW

Applications of Augmented and Virtual Reality in Electrical Engineering Education: A Review

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ABSTRACT Augmented Reality and Virtual Reality are one of the key advances in technology in the last decade. Their usage is rapidly increasing across various contexts. The COVID-19 pandemic and the pressing need for remote learning tools that imitate as close as possible real training environments motivated more research and investigation of AR/VR tools. We present in this work a review of the applications of Augmented Reality (AR) and Virtual Reality (VR) in electrical engineering education. We apply a methodological review of all available publications in this area and classify them according to the application. We ask key research questions regarding these publications. We present recommendations for researchers and educators who want to apply these promising technologies.

INDEX TERMS Augmented reality, electrical education, electrical laboratory, virtual reality.

I. INTRODUCTION

Society is currently undergoing the fourth industrial revolution, which is defined as the era where disruptive technologies are affecting the way people live and work. Examples of such technologies include Augmented and Virtual reality (AR/VR), artificial intelligence (AI), and cloud computing [1]. Similarly, education is also moving from the World Wide Web and knowledge-production education using pedagogy, to using innovative ways for education such as AR/VR technologies and Internet of Things (IoT). This is referred to as Education 4.0 [2]. What is common between the two sectors is AR/VR technology, which has been a popular topic for the past decade and continues to make an impact [3].

The official definition of AR stated by Ronald Azuma in 1997 is the technology that combines real and virtual content, interactive, and registered in live 3D. The virtual information is fixed according to the user's location in the real world [4]. AR applications can be installed on smartphones using its camera (referred to as mobile AR) or can be experienced through a computer screen. Mixed Reality (MR) is similar to AR but uses a head mounted display (HMD) to display virtual information (such as the Microsoft Hololens) [5]. AR uses image processing, computer graphics and vision, and target tracking techniques using the device's camera to render virtual objects in the real world. Target tracking can be vision-based, sensor-based (using Inertial Measurement Units such as accelerometer, gyroscope, magnetometer, and many more), or both. Vision-based tracking is made up of two kinds: marker-based and markerless tracking. Marker-based AR relies on a marker (such as a QR code or a 2D image) to display the virtual content whereas markerless AR displays

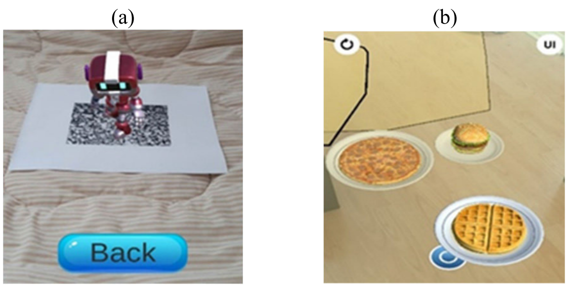

FIGURE 1. Types of AR experiences; a) Marker-based AR and b) Markerless AR.

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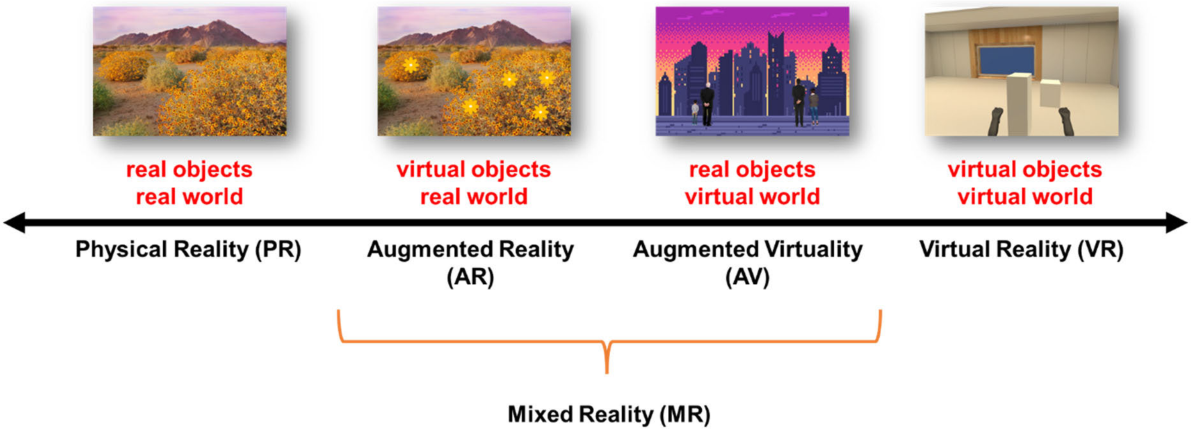

FIGURE 2. Reality-Virtuality (RV) continuum.

virtual information based on the user's preference without the need of a marker [6].

Unlike AR, VR employes computer technology to create the effect of an interactive three-dimensional world in which objects have spatial presence [7]. In simpler terms, it is a computer-generated environment that users can interact with using some of their senses [8]. Another definition in the literature is the I^3 definition, which stands for Interaction + Immersion + Imagination [9]. The two main kinds of VR are non-immersive (referred to as Desktop VR or DVR) and immersive VR (IVR) [10]. DVR is experiencing VR through a computer screen whereas IVR blocks peripheral vision using VR HMD such as Oculus Quest, HTC Vive, Playstation VR, and many others. VR uses a display, head tracking algorithms, and controllers such as HMD controllers or Data Gloves for user navigation and haptic feedback vibrations.

Another interpretation of AR/VR is the Reality-Virtuality continuum (Figure 2) developed by Milgram and Kishino [11]. There is always a trade-off between cost and computational power in AR/VR. High performance HMDs are expensive whereas using smartphones and desktops is cheap but with lower computational power [12].

AR/VR technologies are used widely in training in many areas including military, medicine, surgery, manufacturing, and others [13], [14]. From a learning perspective, AR/VR is also used in mathematics [15] and engineering education. In [16], a framework for adopting VR/AR in the field of Field Programmable Gate Arrays (FPGAs) was developed. The authors in [17] conducted a systemic review on the applications of AR in engineering education. They found that the top three engineering applications are engineering visualization of 3D geometric objects, electronics for placing components and building electrical circuits, and visualization of building construction. Reference [18] reviewed 17 studies between 2015 and 2019 looking at applications of VR in engineering education and observed that the top four streams were civil engineering, mechanical engineering, electrical engineering, and industrial engineering.

To the authors' knowledge, there is no record of a complete and systemic review that focuses on the applications of AR and VR in electrical engineering education. Electrical engineering is one of the disciplines that deal with abstract concepts and thus can benefit from such technology. From a general engineering education context, there are four AR reviews [17], [19], [20], [21], four VR reviews [12], [18], [22], [23], and one AR and VR review [24]. These mentioned reviews cover applications from an academic standpoint by only looking at scientific databases.

The aim of this paper is to review the applications of AR and VR in electrical engineering higher education from academic and industrial perspectives. This is achieved by searching through scientific databases and deployed apps in the Google Play Store. We analyzed the applications by asking five main questions. These questions address the engineering streams handled using AR and VR, the hardware and software tools used, how the AR and VR applications were evaluated, and the pros and cons of using AR and VR applications. The answers to these questions are presented.

The research tool used for this review is the content analysis method, which is the retrieval of key words present in a text [20]. This tool analyzes journal articles, conference papers, and deployed applications and identifies repeating themes and keywords. The authors initially identified the type of technology used in the paper, which are categorized into marker-based AR, markerless AR, non-immersive VR, and immersive VR. Then the abstract, title, or the description of the deployed applications were read thoroughly to categorize the electrical engineering stream the AR/VR application targets. The software and hardware tools used were then identified in the method section of every reviewed paper. Then if there were any experiments conducted by researchers in the literature, the number of participants and the statistical tools used were recorded. Finally, the results of these experiments or the literature's opinion about the technology developed were recorded.

The rest of the paper is structured as follows. Section II covers the background. Section III covers the methodology and selection process of the review. Section IV covers the discussion of the findings. Section V provides recommendations for future AR/VR researchers. Finally, Section VI is the conclusion and Section VII is the limitations of the study.

II. BACKGROUND

Our review included over 80 references and applications. In specific, we found 15 review papers on applications of AR and/or VR in education from 2017 till 2022. None of these review papers are focused on electrical engineering education.

Lai and Cheong [25] performed a scoping review on AR/VR in mathematics education. The authors focused on providing a technical and pedagogical framework for a successful AR/VR application. Applying AR technology in physics education was conducted in [26] by reviewing 100 articles from 2017 till 2021. Reference [17] reviewed 42 articles and investigated the engineering streams that use AR technology. Huang and Roscoe [22] reviewed 47 papers about the advantages, applications, and research opportunities of head-mounted display virtual reality (HMD VR) in engineering education. HMD VR is used to improve students' understanding of teaching content, gain engineering skills, and as a motivation tool to pursue engineering. 17 studies were reviewed in [18] looking at the application of virtual reality in engineering education. VR technology is explored in engineering education because of the advantages of remote learning and immersive learning.

Reference [12] reviewed 72 articles about the advantages of using virtual reality in engineering education as a tool for blended learning as opposed to the traditional approach of teaching. VR has advantages in engineering education for blended learning such as accessibility, immersivity, costs reduction, safety, and university recognition. Kamińska et al. [27] discussed the application of virtual reality in various types of education, its advantages, and disadvantages.

The authors in [28] reviewed 38 articles on the applications of VR in higher education. In [29], a review on the advancements of AR and VR in general education between 2010 and 2019 was presented. They outlined what has been observed in terms of educational levels, fields of education, pedagogical methods and learning approach, learning outcomes, and challenges facing AR and VR along with recommendations if tasked to implement an AR or VR application.

Gandolfi [10] provided an overview of the applications of AR and Immersive Virtual Reality (IVR) in K-12 education. Reference [24] reviewed 37 articles from 2004 to 2020 on the methods used to measure the impact of AR and VR on student learning in engineering education. No standardized testing approach was found for evaluating AR/VR effects on teaching and learning, regardless of the engineering stream. An outline of the various engineering streams that apply AR, benefits of AR, and opportunities and threats of AR technology in engineering education was portrayed in [19].

The authors in [20] looked at the general characteristics of AR-STEM (Science, Technology, Engineering, and Mathematics) studies, advantages of AR-STEM studies, and challenges observed in AR-STEM studies. Reference [30] reviewed the advantages of using AR technology in higher education. The main advantages were the increase of learning satisfaction and acceptance, improving learning process in difficult courses, increasing motivation in learning, better collaboration and interactions, and improved visualization ability. The uses of Virtual Reality in engineering education as well as its pros and cons were analyzed in [23].

III. METHODOLOGY

In this section, the method of retrieving the articles is explained. The methodology used by [17] is adopted in this systematic review.

A. RESEARCH QUESTIONS

The following five research questions will act as a guide to investigate the various applications of AR/VR technology in electrical engineering education:

1) What electrical engineering streams is AR/VR technology used for?
2) What are the software and hardware tools used to create AR/VR experiences in electrical engineering education?
3) How are AR/VR applications evaluated in electrical engineering education?
4) What are the advantages of using AR/VR in electrical engineering education?
5) What are the challenges of using AR/VR technology in electrical engineering education?

B. SEARCH DATABASES

The two main search databases utilized in this work are IEEE Xplore and Google Scholar. Google Play Store was also used to search for deployed AR or VR applications. Our review covers peer-reviewed journals, conference proceedings, and deployed AR applications in the context of electrical engineering education.

C. SEARCH STRINGS

The search string that was used for IEEE Xplore was the following: (''Document Title'':Virtual reality) OR (''Document Title'':Augmented reality) AND (''All Metadata'':engineering education) OR (''All Metadata'':electrical engineering education). The abstracts and titles were carefully analyzed.

The search string that was used for Google Scholar is the following: ''Engineering education'' ''virtual reality'' OR ''augmented reality'' ''electrical engineering education'' -mechanical -civil.

Several searches were made in the Google Play Store to identify AR and/or VR applications. The following searches were used: ''AR electrical'', ''AR engineering education'', ''AR electrical circuit'', ''VR electrical'', ''VR engineering education'', and ''VR electrical circuit''.

TABLE 1. Paper selection criteria.

Inclusion Criteria	Exclusion Criteria
Must be between 2017-2022	Papers that do not have AR and/or VR implemented
Must have augmented, virtual, AR, or VR in the title and/or abstract	Used in K-12 education or young children education
Must be electrical engineering-related	
Used in higher education	
Journal paper, conference paper, or deployed applications	

TABLE 2. Selection process summary.

Stage Number	Number of Publications
1) Result of IEEE string search	26,342
2) Applying paper selection criteria	52
3) Removing duplicates	**48**
4) Google Scholar string search	320
5) Applying paper selection criteria	176
6) Removing duplicates from IEEE	112
7) Removing duplicates from same authors and further screening	**32**
8) Google Play Store search	7
9) Applying selection criteria	5
10) Testing the apps	1
Total	**81**

D. SELECTION OF STUDIES

An inclusion-exclusion criteria was created to select the studies covered in this work as illustrated in Table 1. Applications and papers were selected from 2017-2022 to identify the current state-of-the-art as AR/VR technology is always evolving [10]. One of the challenges in selecting the studies was differentiating between ordinary desktop applications and non-immersive VR applications. Therefore, the criteria of including virtual or VR in the title and/or abstract had to be added.

Initially, search was conducted using the IEEE Xplore database. The search string resulted in 26,342 publications. Using the selection criteria, only 52 publications were identified. Duplicate articles from the same authors were removed and this resulted in 48 publications. The only two exceptions were [31] and [32], that addressed different DVR applications, and [33] and [34] that covered the same application, but one is DVR and the other is IVR respectively.

Using the Google Scholar search string resulted in 320 publications. The selection criteria reduced the number of publications to 176. Duplicate papers from the IEEE Xplore database were removed and this reduced the number to 112 results. After removing duplicate papers from the same authors and with further screening of title and abstracts, 32 publications remained.

The Google Play Store search resulted in seven AR apps and no VR apps. After applying the selection criteria, five applications remained. The applications were then tested on a Samsung Galaxy A50 and resulted in only one functioning application. The other applications were eliminated due to either missing markers or crashing of the application. Thus, the final analysis includes 81 publications. Table 2 summarizes the selection process.

E. OVERALL SUMMARY

Out of 81 publications, 31 are journal articles, 49 are conference papers, and one is a deployed Google Play Store application. The selected publications and applications distribution per year and type of technology is displayed in Figure 3. This trend follows the covid-19 lockdown period from 2019 till 2022 [35] as many educational institutions had to temporarily shut down and offer remote learning choices. Many institutions came up with innovative educational ways to deliver a suitable learning experience for their students. Starting 2018, AR applications are observed to be more than VR applications. This is because Google released its software development kit called ARCore, which allows developers to build their own AR applications on smartphone devices [36]. It can also be noted that there are 81 publications but 82 AR/VR applications due to one publication that has one AR and one VR application [37].

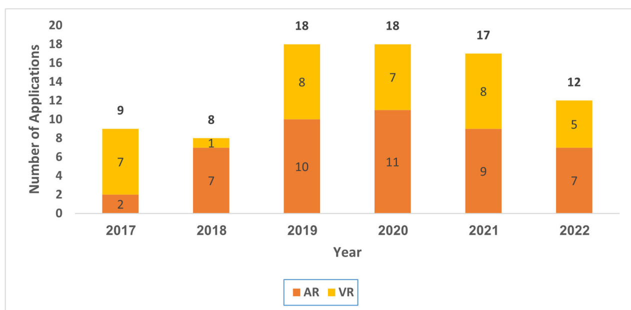

FIGURE 3. Number of selected applications per year and type of experience.

IV. DISCUSSION OF FINDINGS

This section analyzes 82 AR/VR applications, which are found in [2], [6], [31], [32], [33], [34], and [37], [38], [39], [40], [41], [42], [43], [44], [45], [46], [47], [48], [49], [50], [51], [52], [53], [54], [55], [56], [57], [58], [59], [60], [61], [62], [63], [64], [65], [66], [67], [68], [69], [70], [71], [72], [73], [74], [75], [76], [77], [78], [79], [80], [81], [82], [83], [84], [85], [86], [87], [88], [89], [90], [91], [92], [93], [94], [95], [96], [97], [98], [99], [100], [101], [102], [103], [104], [105], [106], [107], [108], [109], [110], and [111]. The results of the five research questions are presented as well as a discussion for each research question. Comparison between

TABLE 3. Streams that applied AR technology.

Stream	Number of applications	References
Electrical Circuits (Analog and/or Digital)	17	[38]-[54]
Electrical Laboratory	6	[55]-[60]
Computer Engineering	5	[61]-[65]
Power Engineering	9	[2], [66]-[73]
Electromagnetism	1	[74]
Electric motor and power	2	[75], [80]
Control Systems	1	[6]
Electrical Lighting	1	[76]
Wireless Network	1	[77]
Electrical Wiring	1	[78]
Fuel Cell	1	[79]

the findings of the present paper and previous review papers is also presented.

A. RESEARCH QUESTION 1): WHAT ELECTRICAL ENGINEERING STREAMS IS AR/VR TECHNOLOGY USED?

1) AR TECHNOLOGY IN ELECTRICAL ENGINEERING STREAMS

AR technology has been applied in analog circuit analysis [38], [39], [40], [41], [42], [43], [44], [45], [46], [47], [48], digital circuit analysis [49], [50], [51], both analog and digital [52], and in circuits using passive components or for placing components on a breadboard [53], [54].

ARCC [38] is an AR application that explains electrical circuit concepts and clarifies misconceptions by analogies. For example, the bicycle chain analogy explains chain's speed as current and energy transfer to the back wheel as the battery transferring energy to the load. The water pipe analogy shows current as water particles' speed, pipe diameter as resistance, and wheels as sources or loads. Waterfall analogy represents water speed as current, waterfall height as electrical potential, and wheel speed as power. The authors in [39] developed an application that allows students to understand how current intensity and brightness of a light bulb changes as you increase the resistance using a potentiometer. Alkurdi [40] developed an application with the same idea but using a switch that the user can press to observe the electrons flowing from a battery to a light bulb. In [41] a sophisticated mobile markerless application was developed that computes the voltage, current, and power across resistors in a resistive circuit. A mobile marker-based application where users can build DC circuits made up of batteries, resistors, and light bulbs in any configuration was created in [42]. The voltage and current are computed across every component in real time. The authors in [43] developed an application that utilized AR and sensor boxes that represent different electrical components. The components are connected using wires. Voltage and current measurements are rendered on each box. Virtual Circuits [44] is a proof-of-concept marker application that displays plots of voltage, power, current, and resistance across a variable resistor, which is useful in studying concepts such as Thevenin's theorem. An AR and machine learning application was developed in [45] to identify electric components by scanning physical circuits or circuit images. The authors in [46] developed a marker-based application for DC circuits representing a battery, switch, motor, or a light bulb. Students can place them in different positions to see how different circuits operate. In [47] an AR and machine learning application was created to compute the voltage, current, and power across every component of a hand drawn electrical circuit. This application is limited to only resistors, capacitors, inductors, DC voltage sources, and current sources. Villanueva et al. [48] discuss a teleconsulting robot called RobotAR that aids students in constructing circuits using AR. The robot acts as a virtual communication link between students and the instructor.

The authors in [49] presented a marker-based application to teach students about various logic gates and how to build logic circuits. Martin et al. [50] developed a marker-based application where the user scans markers that discuss logic gates, combinational systems, and sequential systems. The user can interact with the inputs of the system to see the output logic. The application has a trivia game where the user finds the marker that displays the correct digital circuit. Two marker-based applications were developed in [51] to teach students about the Karnaugh-Maps (K-Maps). The first one teaches two variable K-Maps while the second teaches three and four variable K-Maps. In [52] a marker-based application was developed that better teaches students the behavior of N-type MOSFETs.

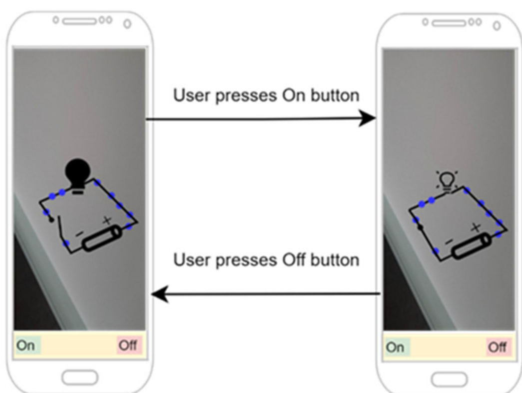

FIGURE 4. The AR implementation in [40].

The authors in [53] developed a marker-based application for students to learn about various kinds of circuits such as linear DC circuits, single-phase and three-phase circuits, non-linear electrical and magnetic circuits, and transformers. An application that can place virtual electrical components on a real breadboard was developed in [54]. The developed algorithm can track the breadboard with an error between 2.13% and 4.88% (see Figure 5).

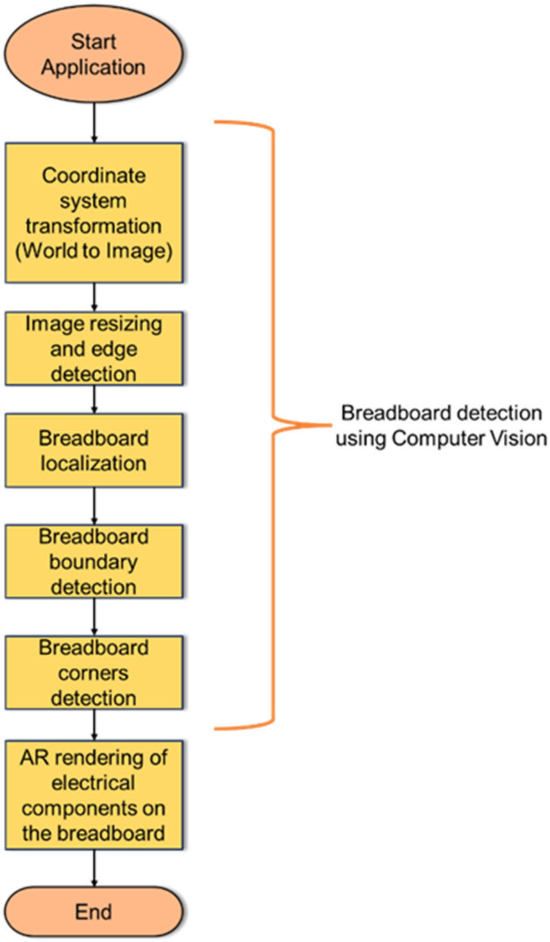

FIGURE 5. The flowchart of application in [54].

AR technology is also applied to teach students how to use laboratory equipment such as oscilloscopes, multimeters, function generators, etc. The authors in [55] developed an application that integrates AR and deep learning neural networks to identify wave generators, multimeters, power supplies, and oscilloscopes. The application then projects a virtual representation of the equipment in the real environment followed by how to operate them. Alptekin et al. [56], [57], [59] contributed the most in this stream by developing three different applications. The first is a marker-based application to train students on how to use laboratory equipment. It also assesses whether students can identify, compare and contrast, and operate equipment. The second is a markerless application where students can interact with virtual laboratory equipment by following an onboarding process. The third is a markerless application that uses a gamification approach by adding game elements such as a story, avatar, varying levels of difficulty, points and badges, and leader board. In [58] a tabletop marker-based application was developed to assist students in learning how to operate oscilloscopes and function generators in electronics laboratories in India (see Figure 6). Eduvance [60] is a deployed marker-based application on the Google Play Store that educates users on voltmeters, ammeters, oscilloscopes, function generators, soldering irons, among other things.

FIGURE 6. Students can interact with the virtual oscilloscope and function generator on the screen using the computer mouse. The mouse left click to press the buttons and the scroll to rotate the knobs. Source: Adapted from [58].

AR technology is used to detect computer hardware components, perform experiments on FPGA boards, and educate users on network wiring. In [61] a marker-based AR application that detects computer hardware components was developed. The authors in [62] developed an application integrated with a board recognition algorithm to identify pins on the FPGA board and render experiment instructions. A network wiring application was developed in [63] by comparing various systems tutoring wiring. The systems were mobile AR, HMD AR, and two dimensional wiring tutor to better prepare students for industry. The authors in [64] developed a tabletop marker-based application to teach students how data registers operate in an Arduino Uno board by observing a LED circuit. Hutahaean et al. [65] discussed a mobile marker-based application that teaches students in a university in Indonesia the basics of computer networking and the various utilized components (see Figure 7).

The application of the AR technology to power engineering is exculsively marker-based. It mostly explains electrical components and their function. In [66], a mobile marker-based AR application was developed. It displays the operation of a transformer for electrical engineering students (see Figure 8). Bazarov et al. [67] developed an application to explain components in a laboratory complex (such as circuit breakers and tumblers) through animation and descriptive text on the side. The authors in [68] used markers to display images or videos aiding students on how to conduct power engineering experiments before students attend the laboratory. Hatmojo et al. [69] developed an application to identify components in a distribution station workbook in Indonesia.

The operation of a motor and its parts can be visualized using AR technology. For example, in [70] a marker-based application was developed for students to study induction motors in the laboratory. Once the marker is scanned, a video

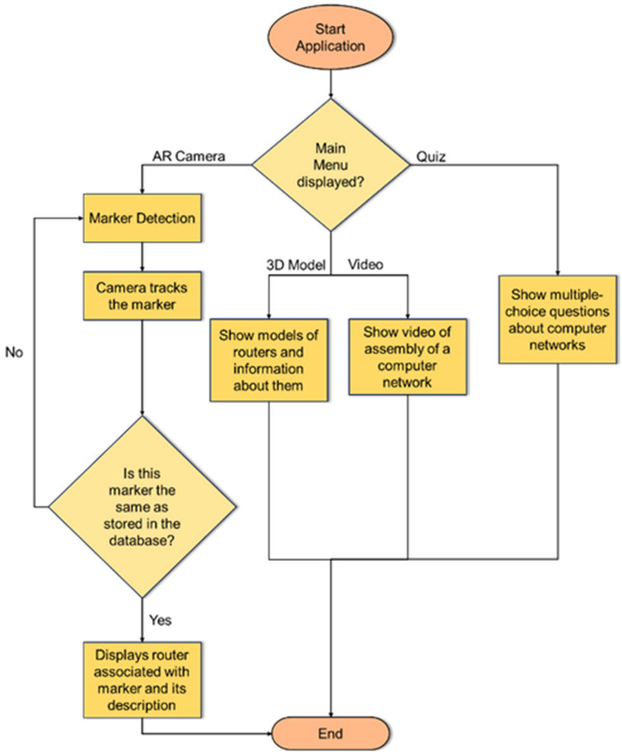

FIGURE 7. The AR main application flowchart in [65].

FIGURE 8. The setup of the application in [66]. User scans the marker and the transformer is rendered in the real world.

is projected on the students' phones showing a 3D model of the motor and an explanation of each part of the motor. Reference [71] developed an AR visualization technique of the current and voltage waveforms called metaveillography on Sequential Wave Imprinting Machines (SWIMs). Pogodaev et al. [72] developed a marker-based application to understand the working principles of a squirrel cage induction motor, its history, and the different parts of the motor.

Sandoval Pérez et al. [73] developed a marker-based power electronics circuits application for higher education students and industry professionals. The user scans markers for RLC circuits and the buck-boost converter. The application displays the underlying equation governing the circuits. It also explains how to build those circuits on a virtual breadboard and displays the battery voltage plots through animations. Carlos et al. [2] presented a platform called Power Electronics Experiment (PELE) that optimizes the traditional experiment procedure in a power electronics laboratory in Brazil. The platform integrates AR for electrical components identification and IoT to save test data results (such as total harmonic distortion and RMS values). It also mimics an oscilloscope by retrieving voltage waveforms.

The authors in [74] developed a marker-based application so students can understand Fleming's rule in electromagnetism. AR technology was used in [75] and [80] to perform ''telepresence'' remote electric machines and photovoltaic experiments using equipment in a physical laboratory. In [6] a tabletop marker-based application was developed for students to understand stability analysis of linear control systems through the pole-zero plot (see Figure 9). Iskandar et al. [76] applied AR technology in lighting installation for vocational schools. The authors in [77] used AR technology to teach students about wireless network security through various kinds of Wi-Fi attacks and their causes. WireGuide [78] is a marker-based application that teaches students how to connect electrical wires using the industry's best practice. The application provides instant feedback to users when a mistake was made with remedy suggestions. Sendari et al. [79] developed a markerless application called Robo-PEM that teaches students about fuel cells and how they can be connected in a system.

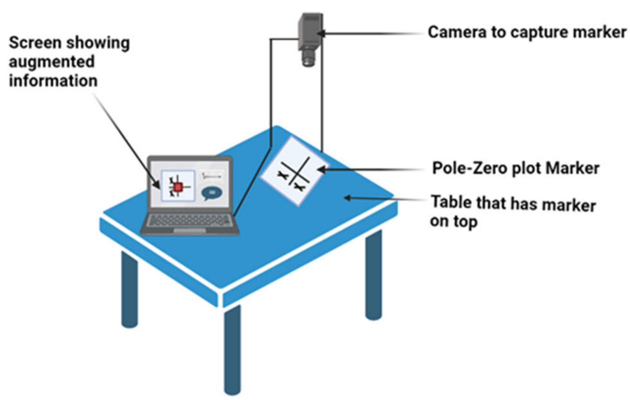

FIGURE 9. The AR application setup in [6].

2) VR TECHNOLOGY IN ELECTRICAL ENGINEERING STREAMS

In this section, we investigate the different areas within electrical engineering that utilize VR technology. In addition, benefits and potential uses of VR are stated for each stream. Table 4 summarizes the number of publications that addressed VR technology.

TABLE 4. Streams that applied VR or both AR and VR (black border) technology.

Stream	Number of applications	References
Power Engineering	17	[81]-[97]
Electric Circuits (Analog and Digital)	10	[31], [32], [98]-[105]
Electrical Laboratory	2	[106], [107]
Telecommunications	2	[33], [34]
Electrical machines	1	[108]
Simulation	1	[109]
Virtual Laboratory	1	[110]
Energy Harvesting	1	[111]
Robotics	1	[37]

VR technology is used in power engineering to provide students tours in laboratories that normally cannot be accessed or to teach them different power concepts. The authors in [81] developed a non-immersive VR application to educate first year engineering students about photovoltaic cells, solar modules, and solar array installation using cloud-based architecture.

VR technology is also applied in industry to train employees in a specific environment or to teach them about high voltage equipment. Reference [82] discusses a non-immersive application developed by the european company E.ON. The application educates electrical engineering students about high and medium voltage substations. It provides them with the necessary theory and practical skills to work in E.ON. In [83] a virtual assembly VR industrial application was created to assemble and view a control cabinet of power transformers and its components using multisensory channels. These channels provide collision detection, ability to grab objects, and real-time video interaction between training instructor and staff. Liegmann et al. [84] developed a digital twin of a grid control station to train employees under various conditions such as transformer failure and back feed in electrical grids. A VR tool was developed in [85] to train employees on how to assemble a transformer along with the various components with low training time to save on costs during the COVID-19 pandemic. The authors in [86] used VR technology to train employees on the procedure of the 10 kV line breaker for relay protection. Tanaka et al. [87] trained electricians in Brazil using an immersive VR appliocation on transformers, circuit breakers, and switches. Liu [88] used immersive VR to create a hydropower station where users can learn how to maintain the station, practice emergency procedures, and diagnose faults. A non-immersive application was created in [89] to train medium tension live-line operators over 40 maintenance procedures to reduce the number of power line accidents. The authors in [90] developed a

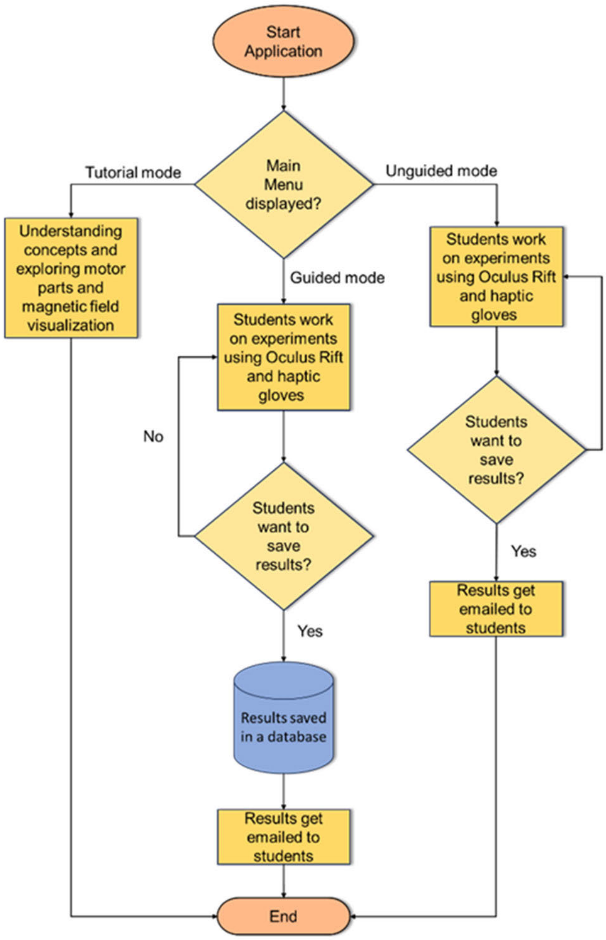

FIGURE 10. VR main application flowchart in [93].

training tool for electricians to maintain and service electrical systems. In [91], an operator training application on a 500kV substation was created using non-immersive VR.

Kvasznicza [92] developed a 3D VR application that teaches students about the operation of asynchronous machines. An immersive VR electric machines laboratory simulator called V-LAB [93] was developed where students can learn about motors, their parts, and one-phase transformers (see Figure 10). The authors in [94] developed an immersive technology to teach students about condition-based maintenance of induction motors. Oliveira et al. [95] developed a VR system using a gamification approach for motor maintenance training for a Brazilian mining company. Mahdi et al. [96] taught students the various parts involved in making an electric motor for mechatronics engineering students using immersive VR. VD-Circuit [97] is a desktop VR application that teaches students the operation of full wave rectifier circuits. The authors evaluated the effectiveness of VR technology as compared to traditional classroom teaching and learning.

The authors in [98] developed a non-immersive application for analog circuits design. A 3D non-immersive environment

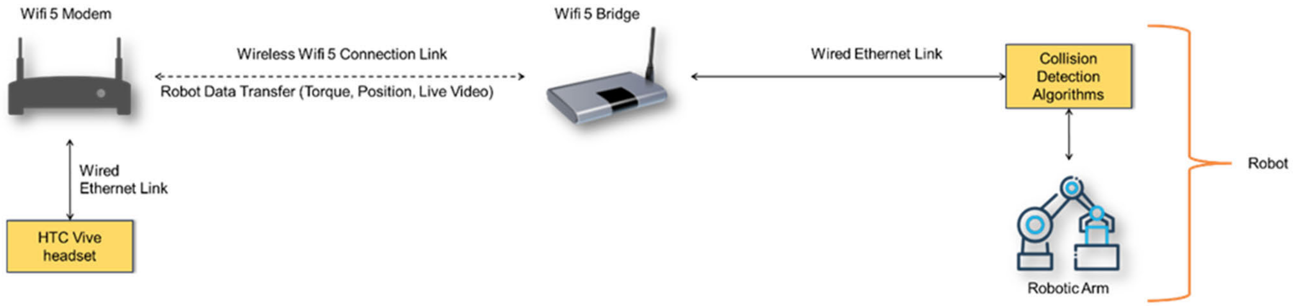

FIGURE 11. Process flow in [101]. The HTC Vive headset and the robotic arm are connected via Fifth Generation Network (5G).

was developed in [32] for students to conduct electrical laboratories and submit reports during the COVID-19 pandemic. The same authors also developed another web-based VR application that uses cloud architecture to build analog electrical circuits [31]. Reference [99] discusses an immersive application that allows students and teachers to perform electrical experiments without damaging real components. Rozell et al. [100] developed Circuit World, an immersive VR experience that allowed users to appear in the environment as avatars to build circuits without the need to be present in-person. Rakshit et al. [101] applied an immersive near-presence approach by allowing a robot to perform circuit measurements. The user wears an HMD and controls the robot's arms remotely (see Figure 11). The authors in [102] taught students electronics engineering concepts using Metaverse platforms such as Second Life, EON-XR, and Minecraft. A VR environment was developed in [103] using a smartphone to teach students about logic gates in digital circuits. Reference [104] investigated the effect of HMD VR simulations as compared to Desktop VR in terms of problem-solving learning for circuit design. Valdez et al. [105] developed a Desktop VR application called VEMA (Virtual Electric Manual) for students to learn circuit theory and promote distance learning.

The authors in [106] applied VR technology for students to tour the solid state electronics laboratory in Arizona State University and learn about safety apparatus and location of tools in the lab. Luzuriaga et al. [107] discussed a work in progress on immersive VR for freshmen year electrical engineering to learn about circuit laws and how to use laboratory equipment. The application targets remote and disabled students.

Only two VR technologies were reported in the field of telecommunications. The web-based non-immersive VR simulator in [33] trains field service engineers. The training focuses on operating a base band unit and a remote radio that supports 5G technology. The same authors developed another immersive application with the same features [34]. The authors compared the two applications by conducting an experimental study that involved six participants. They concluded that the immersive VR application offers a more realistic experience than the web-based application. The movement controls, however, were harder in immersive than non-immersive VR.

The authors in [108] developed a prototype VR application for learning electrical and mechanical concepts by looking at a machine (e.g. washing machine) in the virtual world. The user can disassemble it and observe the physical and mathematical models to understand how the machine operates. Zhou [109] applied VR for electrical engineering students in the context of simulation teaching. Authors in [110] used non-immersive VR that acts as a visual aid to students in the areas of physics, electronics, and electrical engineering. PV-VR [111] is an immersive application that provides a virtual tour to a photovoltaic research and testing laboratory. It also educates students on various solar technologies. A mobile markerless AR application and a desktop VR application were developed in [37] that teach students about robotics design. The AR application was used to understand the function of two robots, TurtleBot2 and RACECAR MN, by looking at their various parts. The VR application allowed students to view the depth camera readings and the LIDAR sensor by moving the RACECAR MN using arrow keys.

3) DISCUSSION

The results indicate that there were 11 electrical engineering streams that used AR technology, eight used VR technology, and one that used both AR and VR technology. The top three streams that used AR were electric circuits (38%), power engineering (20%), and electrical laboratory (13%). The top three streams that used VR technology were power engineering (47%), electric circuits (28%), and electrical laboratory and telecommunications (6%). The work that combined both AR and VR technologies was in the field of robotics.

Industrial VR applications were more frequent than industrial AR applications. This is possibly due to the nature of VR technology that allows users to escape reality and focus more on the task at hand. The authors in [81] state that the more immersive the environment used to train individuals on a skill, the longer the retention of that skill.

In line with the results obtained in [16], AR academic applications were mostly in a laboratory setting as students focused on a specific concept in depth. VR academic

TABLE 5. The 3d modeling software used for AR.

3D Modelling Software	Number of applications	References
3Ds Max	1	[52]
Autodesk Inventor	1	[53]
Blender	7	[42], [64], [66], [73], [77], [78], [79]
Maya	3	[40], [58], [64]
SolidWorks	2	[77], [37]

TABLE 6. The 3d modeling software used for VR.

3D Modelling Software	Number of applications	References
3Ds Max	6	[83], [85], [91], [95], [105], [108]
Blender	4	[84], [94], [99], [111]
Maya	2	[86], [111]
SolidWorks	2	[111], [37]

applications targeted improving students' knowledge in electrical engineering and gaining more skills, which is aligned with the results obtained in [21].

Fields such as nanotechnology and photonics also applied AR/VR technologies. However, the publications in this area are outside the time frame covered by this study.

B. RESEARCH QUESTION 2): WHAT ARE THE SOFTWARE AND HARDWARE TOOLS USED TO CREATE AR/VR EXPERIENCES IN ELECTRICAL ENGINEERING EDUCATION?

Out of 81 publications, 75 stated the hardware and/or software tools used to develop the AR/VR experience. To develop an AR or VR application, it is crucial to consider the software programs that are required to model the virtual objects, create animations, audio files, and develop the AR/VR application. Moreover, equipment that act as inputs to the AR/VR software are required to create the AR/VR experience. In this section, the various hardware and software tools used to create AR/VR applications in electrical engineering education are discussed.

1) 3D MODELING SOFTWARE

3D modeling software is used to create 3D models to be projected in the AR/VR environments. It was observed that the software used were few. 12 out of the 45 AR applications reported the 3D modelling software used. Blender software is the most used modeling software, followed by Maya and SolidWorks (see Table 5). In [66], Blender was used to build the transformer 3D model with steps. Blender was also used in [42] to build the battery 3D model, resistors, and light bulbs. There were 14 out of 36 VR applications that reported the 3D modeling software used. 3Ds Max is the most used modeling software followed by Blender and with equal percentages, SolidWorks and Maya (see Table 6). Kamińska et al. [108] used 3Ds Max to build the washing machine 3D model. Authors in [83] used 3Ds Max to model the various power transformer parts.

2) DEVELOPMENT SOFTWARE

Reference [17] categorized development software into three categories: game engine development software, outsourced development software, and in-house development software. The most common category in this review is game engine development software. We found that Unity is the most common software in both AR and VR applications (see Tables 7 and 8). Unity is an engine that develops desktop, mobile, web, and console applications. It is also used to develop AR and VR applications using the C# scripting language. Another common engine is Unreal, which uses C++ scripting language. Unreal engine was used in [87] and [94] to develop their VR applications. Outsourced development software is the usage of third-party applications to develop AR/VR experiences. Examples include BlippAR [70], HP Reveal [68], EV Toolbox [53], [72], Mastersoft Tech [97], Minecraft [102], Maxwhere [82], and Breadboard Simulator [104]. In-house development software is the usage of programming languages to create an application. Examples are Python3 [54], [77], OpenCV [77], JavaScript [75], [105], and PHP [110].

In mobile AR applications, tracking applications are also required so that virtual objects are placed accurately in the real environment, regardless of whether the application is marker-based or markerless. The most common tracking application is Vuforia, which runs on Android and iOS devices. It allows developers to view the AR experience on their laptop [112]. Some applications used ARCore [73], which runs on Android devices, and ARKit [40] which runs only on iOS devices. In VR applications, tracking algorithms are implemented in the development software through programming for non-immersive applications and in the HMD for immersive applications.

3) HARDWARE

The most used hardware for AR development are smartphones (see Table 9). This shows how technology has advanced from experiencing AR in a headset to smartphones that individuals carry everyday [64]. Some applications used hardware tools along with the AR software. For instance, Reyes-Aviles et al. [41] measure the voltage and current values of a circuit using an Arduino MEGA board connected to the smartphone through Bluetooth. RobotAR [48] uses a teleconsulting robot as a communication link between students and instructors. The robot communicates to the smartphone via the TCP/IP protocol. Hardware such as webcam and laptop screens were used as a setup for AR experiences, which is known as tabletop. Kaur et al [6] used a webcam, workbench, and a laptop screen for the AR experience

TABLE 7. The development software used for AR.

Development Software	Number of applications	References
Game Engine Development Software	25	
Unity	24	[6], [38], [39], [40], [42], [43], [44], [45], [48], [50], [51], [52], [55], [58], [59], [61], [64], [66], [67], [73], [74], [76], [78], [79]
Android Studio	1	[62]
Outsourced Development Software	4	
HP Reveal Studio	1	[68]
BlippAR	1	[70]
EV Toolbox	2	[53], [72]
In-house Development Software	5	
IoT	1	[2]
Machine Learning (Capsule networks)	1	[47]
Python3	2	[54], [77]
Java	1	[75]
No mention	13	[41], [46], [49], [56], [57], [58], [60], [61], [63], [65], [69], [71], [80]

TABLE 8. The development software used for VR.

Development Software	Number of applications	References
Game Engine Development Software	18	
Unity	16	[33], [34], [111], [83]-[86], [90], [91], [93], [95], [96], [99], [100], [103], [108]
Unreal	2	[87], [94]
Outsourced Development Software	4	
Mastersoft Tech	1	[97]
Minecraft, EON-XR & Second Life	1	[102]
MaxWhere	1	[82]
Breadboard Simulator 1.0	1	[104]
In-house Development Software	3	
PHP & MySQL	1	[110]
Javascript & HTML5 & CSS	1	[105]
Google Cloud Platform (GCP)	1	[81]
No mention	10	[31], [32], [88], [89], [92], [98], [101], [106], [107], [109]

as well as Singh et al. [58]. Other kinds of hardware are AR headsets such as Hololens [43], [63] and AR smart glasses [62].

There is a myriad of headsets used in immersive VR experiences and non-immersive VR that rely on desktop computers. Headsets made by HTC, Google, and Meta Oculus are used. See Table 10 for a summary of the usage of these headsets. Hardware kits that are used in VR applications were mostly to enhance the user's immersion in the virtual environment. In [93] haptic gloves were used for haptic feedback in the environment. Similar to AR applications, hardware components were used to communicate with VR software such as Bluetooth controllers with smartphone Google cardboard VR application [106] and sensors [109].

TABLE 9. The hardware used for AR development.

Hardware	Number of applications	References
Smartphone	28	[2], [37], [39], [40]-[42], [44], [47]-[51], [53]-[57], [59], [60], [63], [65]-[67], [69], [70], [72], [73], [76], [79]
Tablet	4	[38], [50], [52], [78]
Hardware Tools (microcontrollers, wires, robots)	7	[41], [43], [45], [48], [51], [64], [75]
Tabletop	3	[6], [58], [64]
Head Mounted Displays (Hololens and AR glasses)	3	[43], [62], [63]
Other (Laptop and a camera)	1	[77]
Not mentioned	6	[46], [49], [61], [68], [71], [74]

TABLE 10. The hardware used for VR development.

Hardware	Number of applications	References
Head Mounted Display	4	[84], [87], [99], [100]
Desktop/Laptop	14	[31]-[33], [37], [81], [82], [89], [91], [97], [102] [104], [105], [110], [111]
Oculus	9	[34], [83], [85], [90], [93]-[96], [111]
HTC	5	[86], [90], [101], [104], [108]
Hardware kit	5	[88], [93], [101], [103], [109]
Google Cardboard	1	[106]
Not mentioned	3	[82], [98], [107]

4) DISCUSSION

It was observed that 63% of the AR applications are marker-based and the rest were markerless. This result agrees with the findings in [17] and [18]. It was also observed that 57% of the VR applications are immersive and the rest were non-immersive.

It is recommended for future researchers to investigate markerless AR. Markerless AR relies on visual and depth perception to estimate the camera's position and rotation in the real world while simultaneously identifying features and mapping the real world. This technique is called Simultaneous Localization and Mapping (SLAM), which is currently a hot topic of research [113].

The 3D modeling software used in AR and VR applications were the same. It can be noted that none of the published work that mentioned the utilized modelling software did not use websites that publish 3D models such as Sketchfab [114]. This is because there is a lack of engineering models on the web and thus the need to create them from scratch [17]. One solution is to use primitive objects present in the development software to build complex objects. For example, Unity has cubes, spheres, capsules, cylinders, planes, and quads as default objects.

Smartphones are commonly used for AR development in electrical engineering education due to their convenience and portability [47]. The study in [115] found that 555 undergraduate students preferred using smartphones for e-learning. However, when it comes to VR applications, HMDs are typically used for industry training, while desktop computers are used for academic education. This is likely due to the high cost of HMDs, which can be prohibitive if they are needed for every student to conduct laboratory experiments [17].

C. RESEARCH QUESTION 3): HOW ARE AR/VR APPLICATIONS EVALUATED IN ELECTRICAL ENGINEERING EDUCATION?

The reviewed publications contained experiments to test the AR/VR applications. There are two main kinds of experiments: experiments that involve participants (46 out of 81 publications) and experiments that do not involve participants (6 out of 81 publications). The rest of the publications did not mention any conducted experiment and only explain the features of the application and how it was implemented (see Figure 12). Out of the 46 publications that involved participants, 87% mentioned the number of participants that were involved in the experiment. The percentage of publications based on the number of participants are summarized in Figure 13. The average number of participants is 76. The maximum number of participants of 800 [109] and the minimum is three [76].

There were three publications that compared various hardware. Reference [61] compared an AR network wiring tutor application using the smartphone and Microsoft Hololens. Reference [34] compared the immersive VR to the desktop VR used in [33] for field service telecommunication engineers training. Reference [90] compared the Oculus Rift CV1 and HTC Vive.

In terms of experiment structure, publications fell into either control group learning without the technology and experimental group using the technology (such as [49], [73]), quasi experiments (such as [80], [97]), or neither (such as [52], [67]). Data collection methods, data analysis tools used, and assessed variables will be investigated to answer the research question.

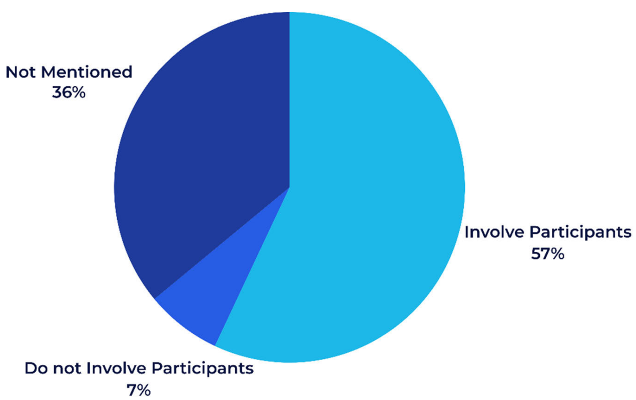

FIGURE 12. Types of experiments.

1) DATA COLLECTION METHODS

The data collection methods that were observed in the AR/VR publications were the following (see Figure 14):

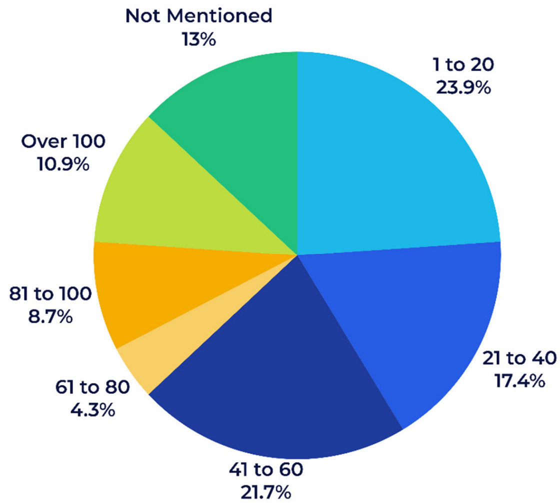

FIGURE 13. The percentage of publications based on number of participants.

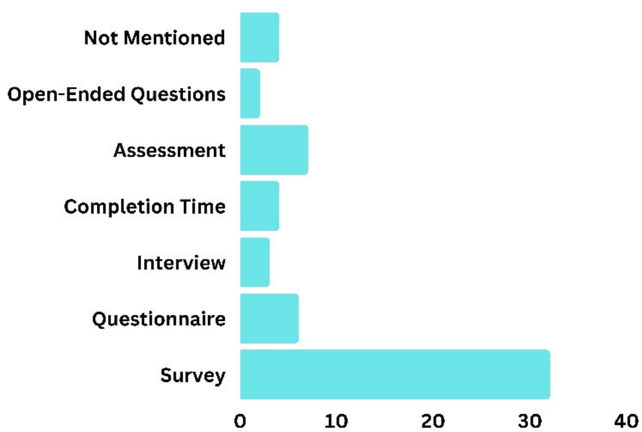

FIGURE 14. The data collection methods used in AR/VR applications.

Surveys: The participants answer statements by choosing one of five options from a Likert scale, giving a rating from 1-10, or other variations. They are mostly used after the experiment is conducted. There were 19 AR publications ([41], [42], [43], [44], [46], [48], [49], [51], [52], [58], [63], [64], [67], [68], [69], [70], [73], [74], [78]) and 13 VR applications ([32], [33], [34], [81], [84], [90], [93], [95], [99], [104], [106], [109], [111]) that used surveys.

Questionnaire: The participants would answer a series of questions that involved writing. There were three AR publications ([38], [49], [78]), two VR publications ([94], [107]), and one publication that contained an AR and VR application [37] that used questionnaires as a data collection tool.

Interview: The research team would take participants in a separate room from the experiment and questions would be asked about their feedback of the technology and experiment. One AR publication [76] and two VR publications ([83], [108]) used this method.

Completion Time: The research team would record the amount of time a participant would take to perform a specific task. Only VR publications employed this method of data collection ([83], [86], [90], [104]).

Assessment: The participants take a test after the experiment to test their knowledge. Two AR publications ([44], [49]), five VR publications ([33], [37], [81], [104], and [106]) used assessments.

Open-ended Question: This is a question where participants can freely express their opinion about an experiment. One AR publication [68] and once VR publication [104] used this method.

Experiments that did not involve participants were all AR-based [45], [47], [55], [61], [62], [79]. The testing was on the performance of the application under various conditions and parameters. For example, references [45] and [47] looked at the accuracy of the model being able to identify electric components. Reference [55] tested various lighting conditions and distance between the phone's camera and electrical equipment to be detected. Reference [61] tested, under various lighting intensities, the distance between the smartphone's camera and marker, corner detection, and closing 20% or 50% of the objects. Reference [62] varied the angle between the board under test and the EPSON BT-200 AR glasses. How various Android versions and the amount of Random Access Memory (RAM) on a smartphone affect the performance of the application was explored in [79].

2) DATA ANALYTICS TOOLS

Figure 15 shows the data analytics tools used in AR/VR applications. The majority of the studies used descriptive statistics ([32], [33], [37], [38], [41], [42], [44], [46], [48], [51], [52], [57], [58], [63], [67], [70], [74], [78], [83], [94], [99], [106], [108], and [111]) and content analysis ([34], [64], [65], [68], [69], [77], [84], [86], [87], [90], [95], [107], [109]). Descriptive statistics is the usage of mostly the mean and standard deviation and percentages to compare results between experimental groups. Content analysis is the brief analysis of results without using basic statistics. One publication [97] used ANCOVA test. Five publications ([49], [51], [58], [74], and [97]) used t-test statistics tools. Three publications ([37], [49], [63]) used correlation test and three publications ([43], [49], [57]) used Cronbach's alpha to determine the reliability of the data collection method and consistency of the assessed variables. Shapiro-Walk and Wilcoxon Signed-Rank was used by [48], Whitney-Mann U test was used by [78], and Kolmogorov-Smirnov two sample test was used by [81]. Reference [104] used ANOVA, Omega squared, and Chi squared tests, and [73] used ANOMA method. Two references ([76], [93]) did not mention the data analytics tool used.

3) ASSESSED VARIABLES

Figure 16 shows the variables that were assessed in the AR/VR experiments. There are 13 variables that have been observed in the reviewed articles:

Usability: This parameter evaluates the performance of the application in terms of features and ease of use. It was the most assessed and was used in 22 AR applications ([37], [38],

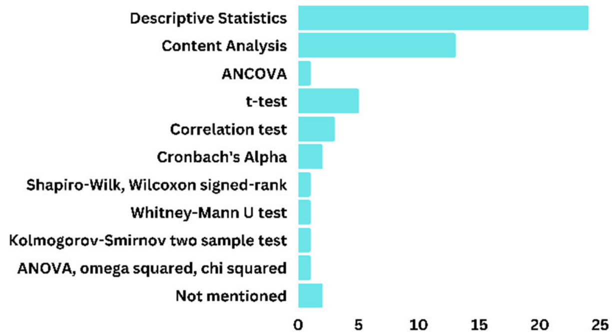

FIGURE 15. The data analytics tools used in AR/VR applications.

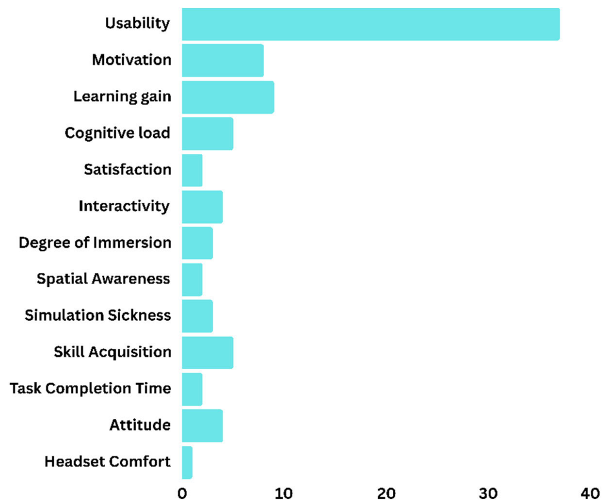

FIGURE 16. The assessment variables used in AR/VR applications.

[41], [42], [46], [48], [49], [51], [52], [57], [63], [64], [65], [68], [69], [70], [73], [74], [76], [77], [78], [80]) and 15 VR applications ([33], [34], [37], [83], [84], [87], [90], [93], [94], [95], [99], [107], [108], [109], and [111]).

Motivation: This variable is used to measure the degree of interest and engagement to learn content using technology. This variable is used in AR publications ([41], [44], [46], [58], [67]) and VR publications ([33], [97]).

Learning Gain: This variable evaluates the impact of AR/VR technology on participants' understanding of content. Five AR applications ([37], [43], [44], [74], [77]) and five VR applications ([37], [81], [95], [107], [108]) investigated this variable.

Cognitive Load: This parameter measures the load on the students to learn how to navigate the environment. References [43], [58], and [73] investigated this variable.

Satisfaction: This variable looks at how the technology might affect the learning process of a subject in the future. References [67] and [68] looked at this variable in AR and [94] in VR.

Interactivity: This parameter analyzes the level of user interaction in the AR/VR environment. Two AR publications

([44], [74]) and two VR publications ([90], [109]) looked at this variable.

Degree of immersion: This variable is only used in VR applications. It is defined as the level of similarity between the objects of the virtual environment to real objects [83]. The higher the degree of immersion, the better the experience. This variable is used in [83], [84], [95].

Spatial Awareness: Only [84] looked at this variable. It is the ability of the user to orient themselves in the virtual environment.

Simulation Sickness: This variable was only investigated in VR applications ([87], [94], [104]). It looks at the degree of dizziness or discomfort the user has in the virtual environment.

Skill Acquisition: This looks at how well the user had understood a specific skill. Three AR ([48], [58], [64]) and one VR [90] looked at this variable.

Task Completion Time: This assessed variable measures how quickly participants can finish a task. References [83] and [86] looked at this variable in VR.

Attitude: This variable works in conjunction with motivation and satisfaction and looks at the overall user's impression of the technology and whether it encourages further research in the topic in study or the technology itself [49]. Three AR references ([42], [46], [49]) and one VR reference [32] looked at this variable.

Headset Comfort: This variable was only looked at in [84].

4) DISCUSSION

The results show that the average number of participants in AR publications was 68 in academic applications and 28 in industrial applications. VR publications, on the other hand, had an average of 130 participants in academic applications and 38 participants in industrial applications. Additionally, we found that marker-based AR had an average of 72 participants, while markerless AR had 44 participants. Immersive VR had an average of 39 participants, and non-immersive VR had an average of 69 participants. This suggests that marker-based AR may be easier to implement than markerless AR. It also suggests that non-immersive VR may be easier to implement than immersive VR. Furthermore, VR is more popular than AR in both academic and industrial settings. Most participants in the academic setting were students rather than educators, which is in line with [16], [17], and [21], indicating that more experiments should be conducted on instructors. The issue of continuity was also highlighted, as some papers did not conduct a second experiment after a period of time to test information retention, as in reference [17].

Surveys were the most popular data collection method, which agrees with the results reported in [17] and [21]. It was recommended to use multiple data collection methods rather than a single method, as this can lead to interpretation issues and lack of information about an experience. In [20] the authors believe that using only the Likert scale can be misleading. Descriptive statistics is found to be the most common statistical tool, as in reference [21]. Using sophisticated statistics tools rather than simply using the mean and standard deviation could provide more insight into the dataset.

The most assessed variables were usability, learning gain, and motivation, which is in line with [16], [17], and [21]. The study also observed that some of the variables had correlations with one another [51], [58], [74], [80]. Some publications used the System Usability Scale (SUS) to measure the usability of a AR/VR application and used learning theories to evaluate the variables. For example, [51] used SUS to measure the usability of an AR application on 90 students, while [37] designed augmented and virtual reality applications using a scaffolding learning approach and integrative thinking to evaluate usability and learning gain.

Utilizing learning theories along with AR and VR applications can further motivate students to use the application [25]. The two most common learning theories used in the reviewed articles were game based [51], [59], [95] and constructivist learning theories [12], [18], [22], [56]. Reference [59] used game-based learning theory by creating avatars, stories, levels, and badges in the AR application. Constructivist learning theory is the ability to perform a task unlimited number of times without restrictions, causing an experience loop [59]. Integrating learning theories help in conducting more valuable experiments using AR/VR technologies as opposed to focusing only on the usability of the application.

D. RESEARCH QUESTION 4): WHAT ARE THE ADVANTAGES OF USING AR/VR IN ELECTRICAL ENGINEERING EDUCATION?

48 out of the 81 publications mentioned advantages of AR/VR technologies where 28 were AR applications and 20 were VR applications. These advantages can be categorized into four areas: attractiveness, educational impact, positive effects on users, and other advantages (Table 11).

The first advantage is that AR/VR are attractive technologies. Reference [111] stated that students found VR technology to be fun to use. Half the participants in [57] found the AR technology creative since they had no experience in using the technology. This is sometimes referred to as the "wow factor" [17]. VR and AR technologies attract generation Z [2], [92] (individuals who are born from the late 1990s to early 2000s [116]) to learn. Shao et al [83] found that VR technology provides an edge to learning because it is immersive. Some participants in [77] found the application attractive and that they would use it outside the experiment. The authors in [34] mentioned the VR application in telecommunication was interesting as the models in the environment had more depth perception.

Another advantage is that AR/VR technologies have an impact on education. In other words, they improve understanding of concepts [94], [109]. Authors in [70] found that AR improved understanding of induction motors. In [41], the AR method is a better analysis tool than traditional analog circuits experiments. The authors in [73] found that

TABLE 11. Advantages of AR/VR technology.

Categories	Number of publications	References
Attractive Technology	9	[2], [34], [57], [63], [77], [83], [86], [92], [111]
Educational Impact	25	[38], [41], [44], [46], [49], [52], [58], [64], [67], [68], [70], [73], [81], [86], [89], [90], [93]-[95], [97], [98], [101], [107], [109], [110]
Effects on User	15	[41], [44], [48], [52], [59], [67], [73], [74], [78], [83], [98], [104], [106], [108], [109]
Other Advantages	19	[31], [33], [41], [44], [45], [47], [51], [56], [63], [68], [74], [75], [81], [87], [92], [93], [95], [107], [109]

AR makes learning concepts easier for participants than the traditional approach. Reference [81] found that VR improves learning about solar energy. In [58], it was reported that AR made learning how to operate electrical equipment easier.

Four references [93], [98], [101], and [107] mentioned that AR/VR technologies promote online education and autonomous learning. An advantage of AR is that the instructor can focus more on harder concepts in class and easier concepts can be explained using AR [67]. This saves teaching time and avoids repeating explanations. In [38], the lecturers found that using AR technology made the concept of resistance in a circuit more tangible. Similarly, [49], [52], and [110] mention that AR and VR technologies help in visualizing abstract concepts that are hard to understand. VR is useful for training in the power engineering field according to [86], [90], and [95]. Reference [68] stated that AR connects theory and practice. In [97], VR provides positive academic performance and better learning experience. There are other publications [44], [46], [64], [89] that mention the same advantage.

The third advantage of AR/VR technologies is that they have positive effects on the individuals using them. The most frequent effect is increasing motivation as mentioned in [41], [44], [59], [67], and [73]. Students were engaged in learning using the AR applications in [48] and [52]. References [73] and [74] concluded that students performed better on tests using AR. In VR applications, participants were more focused on the task using VR [83] [104]. Lian et al. [98] stated that students become more independent learners using VR. References [41] and [78] stated that participants were more confident in performing electrical experiments and electrical wiring, respectively, after they used AR applications. Kamińska et al. [108] stated that VR assists in students' memory recall. Students had more comfort in learning in VR [106] and demonstrated increased engagement [109].

Six references [33], [41], [44], [51], [74], [109] mentioned that AR/VR technology is more interactive than traditional teaching methods. Reference [45] mentioned that AR is intuitive to the brain as the brain likes to store things in 3D and it also complements the real world [75]. In [47], [92], and [93], students were given open access to AR/VR technologies in various platforms. Some publications mentioned that such technologies are safer to use during training in industry or in the laboratory [31], [56], [93], [95]. References [63], [68], [74], and [87] found AR/VR are useful tools to use. AR/VR encourage collaboration according to [81] and [107]. In [33] and [95], VR technology saved on costs for training employees.

1) DISCUSSION

Educational impact is the most common advantage of AR/VR technologies. This surprisingly is not fully in line with the conclusions the previous review papers have found. Reference [12] made several statements about VR. It stated that VR is now more accessible than in the past. VR's immersive nature provides it with a distinct advantage. It also has the potential to reduce liability costs for universities. Moreover, VR can contribute to increasing international recognition for universities. VR promotes distance learning and serves as a source of motivation for students with disabilities. VR/AR technologies allow laboratory experiments to be conducted anywhere and at any time [15]. In [117], AR has an advantage because it does not cause simulator sickness as compared to VR technology. Sırakaya et al. [18] found that the biggest advantage of AR in STEM education is its contributions to the learning process (e.g. increased achievement, motivation, reduced cognitive load, and class engagement). Reference [27] mentioned that AR improves the learning experience in difficult courses. It also increases satisfaction, motivation, collaboration, interaction, and improves visualization ability.

One possible reason is that the previous review papers analyze the applications of AR and VR technologies in general education or in engineering education.

E. RESEARCH QUESTION 5): WHAT ARE THE CHALLENGES OF USING AR/VR IN ELECTRICAL ENGINEERING EDUCATION?

There were 25 out of 81 publications that stated challenges of using AR/VR technologies in electrical engineering education. 16 out of the 25 publications used AR technology and the rest used VR technology. The challenges can be categorized as technical problems, development experience, discomfort and sickness, and other challenges (see Table 12).

The first challenge mentioned in the reviewed papers was technical problems. These range from high light intensity in the environment [6], [61] to smartphone incompatibility [79]. AR applications in [51] and [55] had challenges in recognizing multiple markers simultaneously. Kreienbühl et al. [38] observed that the AR application had reduced scanning speed of the markers and low tracking accuracy in displaying the circuit analogies. Reference [44] stated that students found the AR application's response time slow. The worst drawback of AR according to [68] is that the application crashes, which angered students.

The second challenge is the development experience needed to create applications. Only two publications mentioned this challenge. The authors in [49] mentioned that game design experience is needed to develop an effective AR application. False detection of markers for AR applications was a drawback in [50] as well as the difficulty for instructors to develop such applications. This is because a fundamental understanding of programming languages is required. The authors solved the false detection problem by using patterns on the marker such that they are distinct from other markers.

The third challenge is discomfort and sickness. One AR application and five VR applications address this challenge. Too much information in the AR environment can cause cognitive overload [43]. Reference [83] stated that around 45% of participants experienced cyber sickness in the VR environment. In [87], it was confusing for participants to move in the VR environment and few experienced cyber sickness due to low refresh rate (measured in frames per second). 4 out of 30 Participants in [90] experienced cyber sickness. Wu et al. [104] observed that few participants found the HMD equipment heavy and caused eye discomfort. VR can also cause motion sickness with low resolution display [93].

References [52], [105], and [108] mention that VR applications can be time consuming as it is difficult to create visual content. 3D models must be as close to their real counterpart as possible. Singh et al. [58] elaborate further on that point in the context of electrical laboratory and stated that modeling of virtual equipment affects the user experience using the application. Low participant sizes were an issue in conducting experiments in AR and VR [63], [104]. The participants in [77] mentioned that the AR application works for simple analysis of wireless network security but not for complex analysis and a simulator would be better suited. Evstatiev et al. [32] concluded that the desktop VR application for analog circuits was less interesting than real laboratories and virtual experiments cannot replace real experiments. In [33], participants said that movement in the environment of non-immersive VR is more challenging than immersive VR.

1) DISCUSSION

Technical problems were the most common challenge in AR/VR technology. Reference [18] also found the same conclusion along with instructors' bias towards AR, technical problems (such as GPS, internet connections), lack of features on students' electronic devices, and reduction in imagination. Reference [24] stated the main drawbacks of VR are lack of evaluation, limitation of VR graphics, trade-off between price and computational power, and cyber-sickness and headaches. To overcome lack of evaluations in VR applications, the authors recommend using SUS for evaluating usability of the application and a learning theory from the results of research question 3. Using learning theories will evaluate how motivated students are to use VR applications for learning.

Reference [15] points out that some of the disadvantages of AR and VR are the price and learning curve to master the technology, wrong perception of VR (VR is only for playing games), and lack of willingness by experienced instructors to use new technologies in education. Educational institutions can train instructors how they can integrate AR/VR technologies through information and training sessions hosted by researchers in this field or industry experts. Reference [21] also found that the low number of participants in VR applications is due to a considerable time to perform an experiment.

V. RECOMMENDATIONS FOR RESEARCHERS

Unity is currently the most popular development software used in both AR and VR applications. The decision on what development software to use depends on several factors such as the cost, ease of accessibility of documentation, as well as the intensity of programming required for a VR or AR environment. This is where Unity stands out as a powerful tool as it is free, well-documented, and requires only basic programming knowledge. Additionally, there are various channels available for learning how to program, such as YouTube [118] and LinkedIn Learning [119], which make it easier to get started with Unity development. Unity uses C# scripting language and researchers are highly encouraged to learn C# in the context of Unity. This is because AR/VR applications require strong programming skills to create custom behaviors. Researchers can also collaborate with companies that provide AR and VR solutions to create such custom behavior scripts. This alleviates the burden of complex programming on the researchers and allow them to focus on more important tasks. Another alternative can be to take advantage of current Generative AI solutions to provide

TABLE 12. Challenges of AR/VR technology.

Categories	Number of publications	References
Technical Problems	8	[6], [38], [44], [51], [55], [61], [68], [79]
Development Experience	2	[49], [50]
Discomfort and Sickness	6	[43], [83], [87], [90], [93], [104]
Other Disadvantages	9	[32], [33], [52], [58], [63], [72], [77], [105], [108]

code snippets for various tasks. The most popular example is OpenAI's ChatGPT [120].

When deciding on the hardware to use for developing AR/VR applications, several factors come into play, particularly considering accessibility and interactivity. AR applications can be developed on smartphones, making them highly accessible to a wide audience. However, their interactivity is somewhat limited. On the other hand, VR applications, while offering high levels of interactivity and immersive experiences, are not as accessible to all users due to their relatively high costs. Nevertheless, VR applications have the advantage of including multiplayer features, which can enhance collaborative experiences. Learning how to model parts using 3D modelling software applications is highly recommended. However, the choice of 3D modelling software is dependent on the game engine being utilized for the application. For example, Unity accepts 3D models in either .fbx or .obj format. Thus, it is crucial to conduct thorough research on 3D modelling software that is capable of exporting to these specific file types. Failing to choose the appropriate 3D modelling software may lead to exporting models in different file formats, requiring reliance on paid or online file converters to convert them to the required formats for the game engine. This conversion process can potentially lead to information loss and negatively impact the overall quality of the 3D model.

It is important to understand that when developing AR applications, not all smartphones are compatible for such an experience. This depends on the software development kit that is used, mainly Vuforia, ARCore, or ARKit. A list of supported devices can be found for Vuforia in [112] and for ARCore in [121]. Currently, Unity supports Vuforia, ARCore for android devices, and ARKit for iOS devices. An Apple laptop allows development in both Android and iOS devices. Microsoft laptops, however, allow only development of AR Android applications. This is because to develop iOS applications, an application called Xcode [122] is needed which is only available on Apple laptops.

When developing Immersive VR applications, purchasing the right computer or laptop is crucial. The utilized headset may need different laptop specifications. For instance, to develop VR applications using a Meta/Oculus headset, the minimum required computer/laptop specifications are listed in [123].

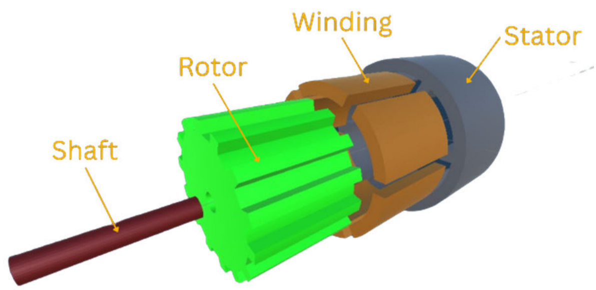

FIGURE 17. The SRM of study.

The authors of this review are developing a work-in-progress mobile AR marker-based application in the power engineering domain. The aim of the application is to visualize the magnetic field of a Switched Reluctance Motor (SRM) in real time by changing motor characteristics using machine learning and AR (see Figure 17). The user can observe the various parts of the SRM by playing and pausing an animation at any point in time. The application has the feature of rotating and scaling the SRM. Unity is the development software being used and ARCore is the software development kit. A demonstration of the application can be found here [124].

VI. CONCLUSION

This review investigated 81 publications (82 applications) in the field of Augmented and Virtual Reality and their applications in electrical engineering education. This is the first review that tackles this technology in electrical engineering. The various electrical engineering streams, hardware and software technologies, evaluation methods, advantages, and challenges encountered in AR/VR applications have been discussed. Although this technology is continuing to grow, utilizing other industry 4.0 technologies such as machine learning and cloud computing along with VR/AR will improve performance and benefit society.

VII. LIMITATIONS OF THE STUDY

There was only one deployed AR application on the Google Play Store that was functional, making it difficult to compare various application features. Moreover, this review paper looked at two databases, IEEE Xplore and Google Scholar. This affects the number of publications available and including more databases will provide stronger conclusions.

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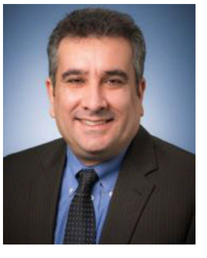

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