

Enhancing Electronics Education through Augmented Reality and Automated Circuit Verification: A Comprehensive Workflow Design

Aswin A^{1,a}, S M Anzar², N P Subheesh³ and Aby John⁴

^{1&2} *Department of Electronics and Communication, TKM College of Engineering, Kollam, India - 691005*

³ *Teaching Learning Centre, SRM University - AP, Andhra Pradesh, India - 522502*

⁴ *Faculty of Philology, RUDN University, Moscow, Russia*

Corresponding Author: ^aanzarsm@tkmce.ac.in

Abstract—This study presents an innovative workflow designed to enhance electronics education through the integration of augmented reality (AR) with a novel automated circuit verification systems. The proposed workflow, illustrated in a detailed block diagram, encompasses various stages from user authentication to final result analysis, providing a comprehensive and interactive learning experience. By utilizing AR and virtual reality (VR) technology, students can visualize and interact with virtual elements overlaid on real-world components, bridging the gap between theoretical concepts and practical application. The proposed workflow using AR includes steps for project selection, experimental setup, circuit diagram creation, and verification through camera scanning, ensuring accuracy and immediate error feedback. Additionally, the system supports both exam and project-based learning paths, allowing for flexible and tailored educational experiences. This approach not only enhances student engagement and understanding but also fosters a deeper comprehension of electronic circuits. The automated verification process mitigates common setup errors, promoting iterative learning and improvement. This paper provides a comprehensive work flow design, demonstrating its potential to significantly improve academic outcomes in electronics laboratory courses. The findings highlight the efficacy of combining AR with automated circuit verification systems in educational settings, paving the way for future research and implementation in diverse engineering disciplines.

Index Terms—Augmented Reality, Educational Technology, Electronics Laboratory, Immersive Learning, Interactive Learning, Technology Enhanced Learning, Virtual Reality

I. INTRODUCTION

The cornerstone of engineering education lies in the practical application of theoretical knowledge. This is particularly true in fields like electronics and electrical engineering, where students must grasp not only abstract concepts but also the intricacies of physical circuits, current flow, and component behavior. Traditional laboratory environments, while valuable, often face limitations in terms of resource availability, time constraints, and the ability to provide immediate feedback on errors. The growing pervasiveness of technology in everyday life necessitates a parallel evolution in educational methods to

better prepare students for the demands of modern engineering roles [1].

With the rapid pace of technological advancements, educators are presented with an unprecedented opportunity to bridge the gap between theoretical knowledge and practical application. Augmented Reality (AR) and Virtual Reality (VR), once relegated to the realm of science fiction, are now poised to revolutionize the educational landscape. AR overlays digital information onto the physical world, allowing students to visualize components, circuit connections, and even current flow in real-time. VR, on the other hand, immerses students in simulated laboratories, enabling them to experiment with complex circuits in a safe and controlled environment. These immersive technologies hold immense promise for fostering a deeper understanding of digital electronics principles.

Despite the growing interest in AR and VR for educational purposes, a comprehensive understanding of their impact on learning outcomes within digital electronics labs remains elusive. While existing research explores the potential of these technologies in various educational contexts, a focused analysis specifically tailored to the unique challenges and opportunities presented by digital electronics education is lacking. This research gap necessitates a closer examination of how AR and VR can be effectively integrated into laboratory experiences to improve student learning, engagement, and assessment methods.

This study presents a detailed workflow designed to enhance electronics education through the integration of AR and automated verification systems. The proposed workflow involves several stages, from user authentication to result analysis, using AR technology. It allows students to visualize and interact with virtual elements overlaid on real-world components, connecting theory with practice. The steps include project selection, experimental setup, circuit diagram creation, and verification through camera scanning for accuracy and error feedback. The system supports both exam and project-based learning, offering flexible and tailored educational experiences.

II. LITERATURE REVIEW

A. Educational Benefits of AR and VR

Numerous studies have highlighted the educational benefits of Augmented Reality (AR) and Virtual Reality (VR), particularly in STEM (Science, Technology, Engineering, and Mathematics) education. These technologies can enhance spatial understanding, improve problem-solving skills, and increase student motivation and engagement. For instance, a study by Bacca et al. demonstrated that AR applications in education positively affect learning outcomes by providing real-time feedback and interactive content [2]. Their findings suggest that students using AR-based learning tools show improved performance and retention of complex concepts compared to traditional learning methods.

B. AR and VR in Electronics Education

In the field of electronics education, the application of AR and VR has shown promising results. These technologies can simulate complex electronic environments, allowing students to visualize and manipulate electronic components and circuits in a 3D space. This capability leads to a deeper understanding of both theoretical concepts and practical skills. For example, research by Krüger et al. [3] and Kim et al. [4] highlights the immersive and interactive nature of VR, which enables students to engage with electronic circuits in a controlled, virtual environment, thus enhancing their comprehension and operational skills.

C. Design and Development of AR and VR Experiences

The educational landscape is undergoing a significant transformation with the emergence of innovative technologies like AR and VR. These technologies hold immense potential to revolutionize how students learn, particularly in practical fields like electronics engineering. Maunder and Carmigniani et al. [5] provide a clear distinction between AR and VR: while VR creates a fully immersive, virtual environment, AR overlays digital information onto the real world [6], [7]. This distinction is crucial in designing educational experiences, as each technology offers unique benefits. AR's contextuality and interactivity allow students to see real-time overlays on physical components, whereas VR's immersive environments facilitate comprehensive explorations of complex systems without physical constraints.

D. Empirical Evidence of Effectiveness

A growing body of research supports the positive impact of AR and VR on learning outcomes in electronics engineering education. Studies by Beck [8], Chen et al. [9], Gudoniene and Rutkauskiene [10] have demonstrated that these technologies can significantly enhance student engagement and understanding. For instance, Beck found that VR simulations allowed students to virtually explore complex electronic systems, leading to improved cognitive skills and practical knowledge. Similarly, Gudoniene and Rutkauskiene reported that AR applications provided real-time information overlays

that enhanced students' ability to visualize and understand circuit functionalities.

E. Challenges and Considerations

Despite their potential, the implementation of AR and VR in electronics labs faces several challenges. Nguyen et al. highlight the high costs of hardware and software, which can be a significant barrier for educational institutions [11]. Additionally, Biswas et al. raise concerns about accessibility, noting that not all students may have access to the necessary equipment [12]. Scavarelli et al. emphasize the need for scalable content that can keep pace with rapid technological advancements, ensuring that AR and VR applications remain relevant and effective [13].

F. Practical Applications and Case Studies

An illustrative example of AR applications in electronics labs is provided by [14] that addresses challenges faced by students in a laboratory course on experimental physics. This study proposed an AR-based solution to issues such as insufficient preparation, difficulty in transferring written instructions to practical application, and errors in measurements. The AR system provided interactive 3D visualizations, real-time feedback, and step-by-step guidance, which significantly improved student performance and understanding.

Further evidence for the effectiveness of AR comes from experiments where engineering students were introduced to various electronic measuring instruments. The results indicated that students trained with AR-based tools outperformed those using traditional manuals, highlighting AR's potential to enhance operational skills and learning outcomes.

G. Impact on Student Engagement and Motivation

The literature also underscores the positive impact of VR on student engagement and motivation. A study in [15] developed a VR learning environment for operating electronics engineering equipment, revealing that VR can significantly improve students' knowledge, cognition, and motivation to learn. This suggests that VR environments can create engaging and interactive learning experiences that foster deeper understanding and enthusiasm for the subject matter.

H. Research Gap

The reviewed research presents a promising picture for the design and development of AR and VR in electronics labs. These technologies offer numerous benefits, including enhanced visualization, improved understanding of complex systems, increased student engagement, and better learning outcomes. However, challenges related to cost, accessibility, and content scalability must be addressed to ensure successful implementation. By leveraging the strengths of AR and VR and overcoming these challenges, educators can create innovative and effective laboratory environments for electrical and electronics engineering students. Future research should focus on developing comprehensive assessment strategies tailored

to AR and VR learning experiences to fully understand their impact on educational outcomes.

III. THEORETICAL FRAMEWORK

The effectiveness of AR and VR in electronics education is underpinned by established learning theories that emphasize active engagement and experiential learning. Constructivism, a prominent educational theory, posits that learners actively construct knowledge through interaction with their environment [16]. In the context of a digital electronics lab, this theory translates to students manipulating circuits, observing responses, and building their understanding through hands-on exploration. AR and VR technologies, by providing interactive visualizations and simulations, align directly with constructivist principles. These technologies enable students to see the impact of component changes in real-time within an AR overlay or to experiment with complex circuits virtually, actively constructing their knowledge of digital electronics.

Furthermore, experiential learning theory, championed by John Dewey, emphasizes the importance of learning through experience [17]. Traditional labs provide valuable hands-on experience with physical circuits; however, they are limited in scope and safety considerations. AR and VR can significantly expand experiential learning by allowing students to interact with intricate circuits or conduct experiments that would be impractical or hazardous in a physical lab. For instance, AR and VR simulations can enable students to "virtually dissect" a complex circuit, examining its inner workings and component interactions in a safe and controlled environment. This immersive experience aligns perfectly with experiential learning principles, fostering deeper understanding and knowledge retention.

The integration of technology in education has been extensively explored by scholars such as Mayer [18], Dalgarno and Lee [19]. Mayer's Multimedia Learning Theory emphasizes the importance of presenting information through multiple channels (e.g., visual and auditory) to enhance learning outcomes. AR and VR, by combining visual overlays or immersive simulations with traditional lab activities, adhere to this principle by engaging multiple senses simultaneously. On the other hand, Dalgarno and Lee highlight the necessity for technology to be pedagogically sound, meaning it should be purposefully integrated into the curriculum to achieve specific learning objectives. This research explores how AR and VR can be effectively designed and implemented within the digital electronics curriculum, ensuring these technologies transcend mere novelty to become powerful tools for enhancing learning.

In summary, the theoretical framework supporting the use of AR and VR in electronics education is robust. Constructivism and experiential learning theories provide a solid foundation for the pedagogical benefits of these technologies. Additionally, principles from multimedia learning and pedagogically sound integration emphasize the need for thoughtful implementation to maximize educational outcomes. This research aims to demonstrate how AR and VR can be seamlessly

incorporated into the digital electronics curriculum, enhancing student engagement, understanding, and retention of complex concepts.

IV. METHODOLOGY

The integration of AR and VR technologies in engineering education has shown significant potential to enhance learning outcomes. This study presents a detailed workflow, depicted in Figure 1, is designed to improve electronics education through the use of AR and automated verification systems. The diagram illustrates a structured approach encompassing user authentication, project selection, experimental setup, verification, and result analysis, thereby providing a comprehensive educational experience.

A. Block Diagram Explanation

1) Login

- Purpose: Secure authentication of users.
- Function: Users enter their credentials to access the system, ensuring authorized access to the educational platform.

2) Project Selection

- New project: Users starting a new project proceed by defining and setting up their project.
- Project: Alternatively, users can choose to work on a project, initiating the project workflow.

3) Exam

- New Exam: Users can opt to take an exam, leading them through a series of questions relevant to their coursework
- Question: Exam takers proceed to answer questions designed to assess their understanding of the subject matter.

4) Experiment Selection

- Select the Experiment: Users select a specific experiment from a provided list, which customizes subsequent steps to match the chosen experiment's requirements.

5) Camera Scanner

- Detection of Breadboard: The system uses a camera scanner to detect the breadboard setup, ensuring that the physical configuration aligns with the experiment's requirements.
- Camera Scanner for Verification: The camera scanner verifies the correctness of the experimental setup, checking for accurate component placements and connections.

6) Circuit Diagram

- Creation/Upload: Users create or upload a circuit diagram that represents the experiment's theoretical framework.

7) Checking the Correctness of Circuit

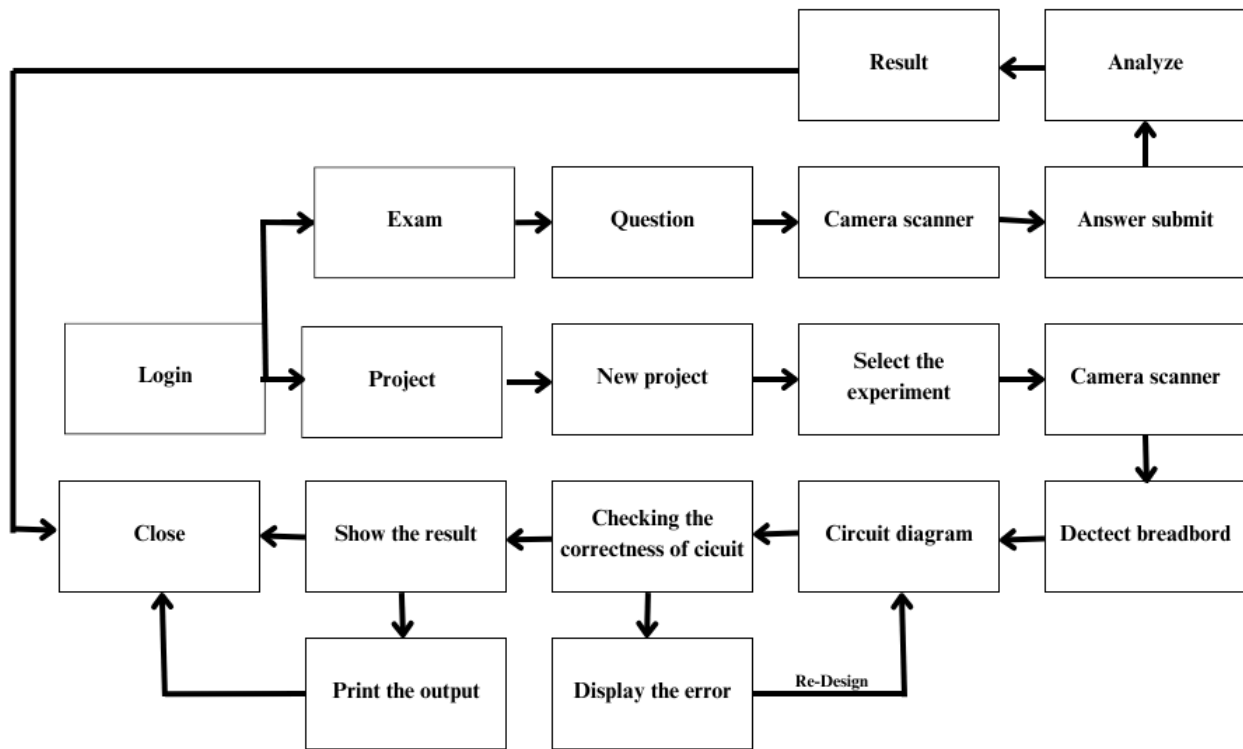


Fig. 1: Proposed System

- Validation: The system compares the circuit diagram with the detected physical setup to validate accuracy. Any discrepancies trigger error notifications.
- 8) Display/Error
 - Error Feedback: If errors are detected, they are displayed to the user for correction, allowing immediate rectification and learning.
 - 9) Show the Result
 - Result Display: Upon successful validation of the circuit, the system displays the results of the experiment.
 - 10) Print the Output
 - Documentation: Users can print the output, providing a tangible record of their work and results for further analysis or reporting.
 - 11) Close
 - Session Termination: The workflow concludes with closing the session, ensuring all user data is securely saved and the system is ready for subsequent users.
 - 12) Answer Submission
 - Exam Path: Exam takers submit their answers for evaluation, transitioning the workflow into the analysis phase.
 - 13) Analyze
 - Data Analysis: The system analyzes the submitted answers or experimental data to generate meaningful

insights and feedback.

14) Result

- Final Output: The final results, derived from the analysis, are presented to the user, offering comprehensive feedback on their performance.

15) Re-Design (if necessary)

- Iteration: If errors are found during the experiment validation, users can redesign their circuit diagram and repeat the verification process.

B. Working Mechanism

The workflow begins with user authentication to ensure secure access. Users can then choose between taking an exam or working on a project. For project work, users select and set up an experiment, utilizing AR and camera scanning technologies to verify the correctness of their physical setup against the theoretical circuit diagram. Errors are immediately displayed, allowing users to correct them and learn from their mistakes. Once validated, the system generates and displays results, which can be printed for documentation. For exams, users answer questions, submit them for analysis, and receive detailed feedback on their performance. The iterative redesign process further enhances learning by encouraging users to refine their setups until they achieve correct results.

V. SURVEY ANALYSIS

We conducted a survey to evaluate the effectiveness of AR for teaching and learning electronic circuits. The survey

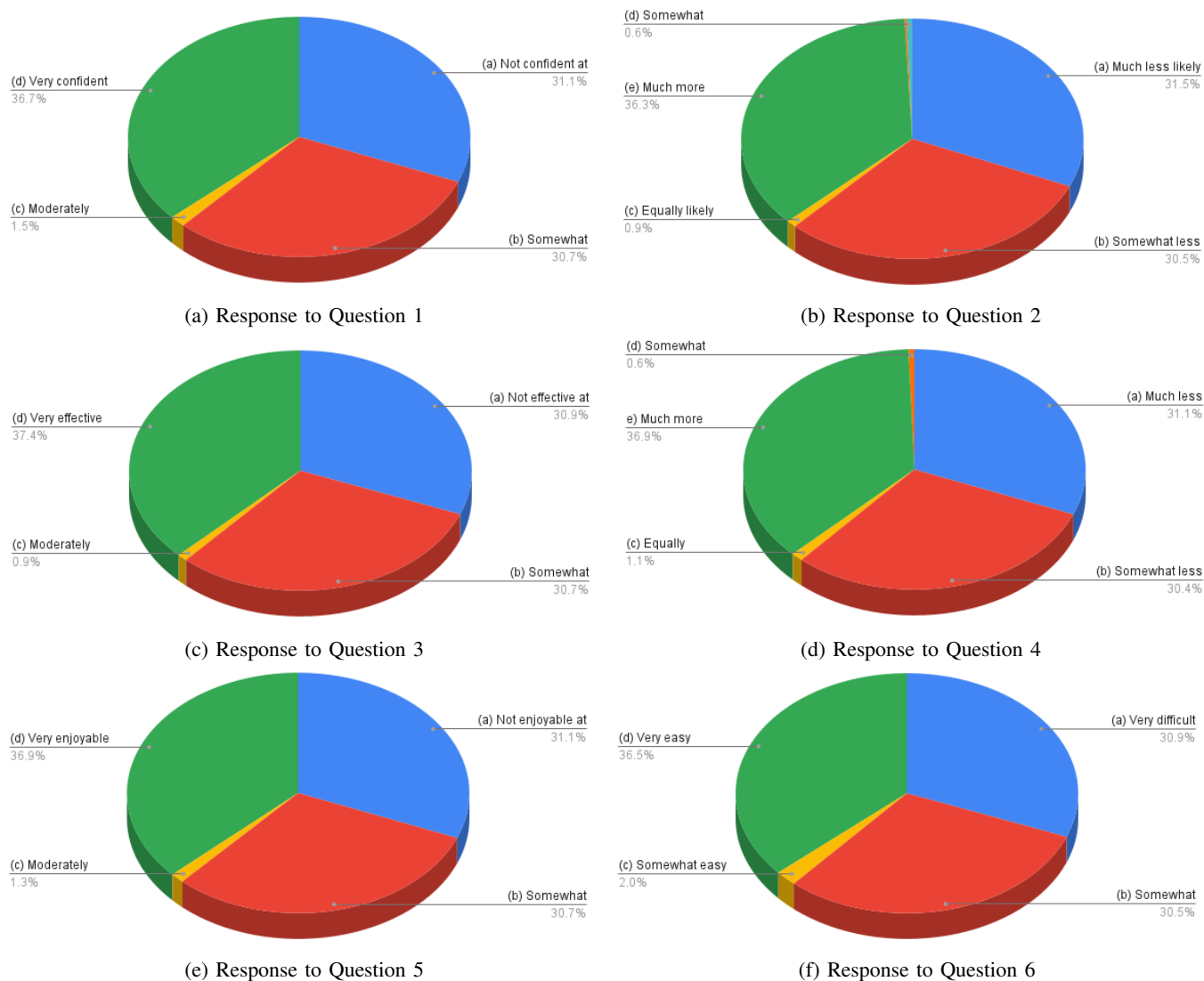


Fig. 2: Survey Analysis: Response to Questions 1-6

was conducted through Google Forms and targeted a diverse group of participants, including both individuals familiar with AR and those new to the technology. Participants were asked to share their experiences and perceptions regarding the use of AR in learning electronic circuits. The survey included questions designed to gauge:

- The level of understanding of electronics circuits after using AR.
- The engagement and enjoyment of the AR learning experience.
- The ease of use of the AR technology.
- Comparisons between AR-based learning and traditional educational methods.

This mixed-method survey used both quantitative and qualitative questions. The quantitative questions gathered structured data on participants' experiences, while the qualitative ques-

tions allowed for detailed insights and elaboration on opinions.

A total of approximately 512 survey responses were collected. The responses to survey questions 1-6 and 7-10 are shown in Figures 2 and 3, respectively. The results indicated a strong positive reception towards the use of AR in learning electronics circuits.

A. Survey Questions

Q1 If AR is introduced, how confident are you now in understanding electronics circuits?

Q2 How likely are you to remember information about electronics circuits learned through AR compared to traditional methods?

Q3 How effectively did AR help you solve practical problems related to electronics circuits?

Q4 How do you think your level of engagement with learning about electronics circuits using AR compares to tradi-

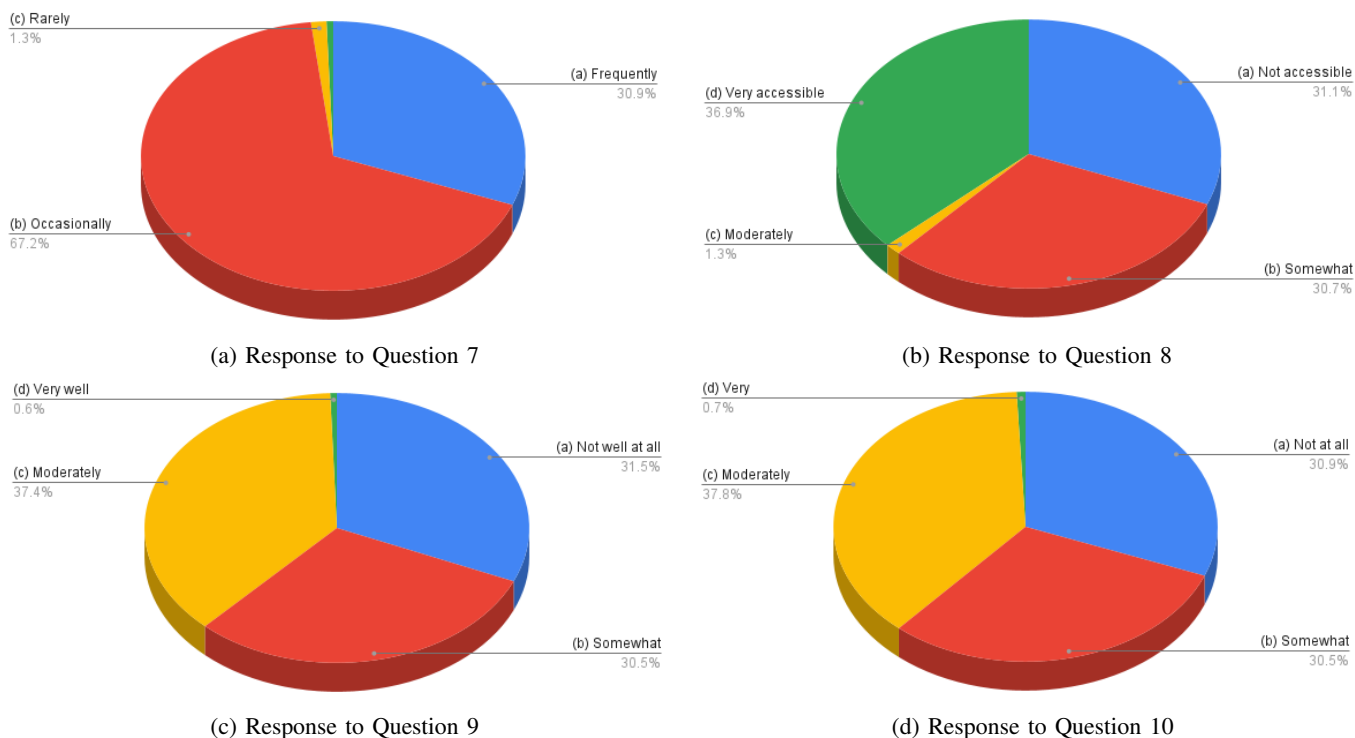


Fig. 3: Survey Analysis: Response to Questions 7-10

tional learning methods?

- Q5** How enjoyable did you find learning about electronics circuits using AR?
- Q6** How easy was it for you to use the AR software and tools (e.g., mobile applications)?
- Q7** Did you experience any technical difficulties (e.g., lag, software crashes) while using the AR system?
- Q8** How well do you think the AR learning tools are accessible to students with disabilities?
- Q9** How well did the AR experience align with the learning objectives for electronics circuits?
- Q10** How much did the AR experience complement your existing learning materials (e.g., textbooks, lectures)?

B. Survey Findings

The survey findings can be listed as follows:

- **Understanding:** 70% of the participants reported a better understanding of electronics circuits through AR compared to traditional learning methods.
- **Engagement:** A significant majority found the AR experience highly engaging and enjoyable, noting that the interactive 3D models and the ability to manipulate circuit components enhanced their learning experience.
- **Ease of Use:** Most respondents found the AR technology easy to use, with intuitive controls and seamless integration of digital and physical elements.
- **Comparative Effectiveness:** A large proportion of participants believed that AR offered a superior learning

experience over traditional methods, citing the interactive nature and visual appeal as major factors contributing to this preference.

C. Validation of Survey

To validate the survey results, a diverse group of participants was carefully selected, comprising both individuals familiar with AR and those who were new to the technology. This diverse sampling provided a balanced perspective on the effectiveness of AR in learning electronic circuits. A mixed-method approach was utilized, with quantitative questions to gather structured data and qualitative questions to capture detailed insights and participant experiences. This comprehensive approach ensured that the survey findings accurately reflect the potential impact of AR in electronics education.

The survey results indicate a strong positive reception of AR-based learning. Specifically, 70% of participants reported a marked improvement in their understanding of electronics circuits, and a majority found the AR experience engaging and enjoyable. The ease of use of AR technologies, with their intuitive controls, also contributed to the participants' favorable perceptions. Furthermore, many respondents highlighted the interactive nature of AR as a key factor in enhancing their learning experience when compared to traditional methods. These responses underscore the potential of AR as a tool for more effective and immersive learning in electronics education.

VI. SUGGESTIONS AND RECOMMENDATIONS

This study demonstrates that AR-based laboratory manuals can significantly enhance student achievement and positively influence learning attitudes in electronics engineering courses. The literature reinforces that AR not only improves academic performance but also enhances student engagement and conceptual understanding. However, scaling the use of AR in education presents certain challenges.

One key challenge is the need for comprehensive training for both educators and students. While AR applications are generally accessible via smartphones and tablets, effective integration into the learning process requires a strong foundation in their use. Therefore, initial training to build proficiency is crucial for maximizing the benefits.

Another challenge is the development of high-quality AR content. Creating immersive and engaging experiences demands specialized skills in game development, 3D design, animation, and rendering. Moreover, professional software tools like Unity 3D, Maya, and Blender often come with significant costs. Financial support from academic institutions and organizations can facilitate the creation of quality AR content and ensure its effective implementation in curricula.

Similarly, Virtual Reality (VR) offers potential for enhancing digital circuit education by enabling immersive environments where students can interact with virtual representations of circuits. VR provides a unique exploration of concepts like electron flow and component interaction. However, VR implementation also poses challenges due to the expense of VR headsets and the advanced technical skills required to develop content, similar to AR.

A. Addressing Technical and Financial Barriers

To make AR/VR implementation more feasible, the following strategies can be adopted:

- 1) **Cost-Effective AR/VR Solutions:** Utilize mobile-based AR applications compatible with existing smartphones and tablets, reducing the need for costly hardware. Tools like Google Cardboard can also offer affordable VR experiences.
- 2) **Open-Source and Free Platforms:** Leverage open-source software such as 'AR.js,' 'BlippAR,' and 'Unity with Vuforia' to develop AR experiences without incurring high costs.
- 3) **Resource Sharing and Lending Models:** Institutions can introduce lending models for AR/VR-enabled devices, ensuring equitable access. Establishing computer labs with shared AR/VR resources can further enhance access for students.
- 4) **Educator Training and Skill Development:** Targeted professional development programs, both in-person and online (e.g., Coursera, Udemy), can build technical skills in AR/VR. Creating peer-learning networks can also help educators share best practices and strategies.

These strategies are aimed at reducing both financial barriers and technical challenges, thereby making AR-based education more accessible and sustainable.

B. Best Free AR Tools for Education

Several free AR tools have proven effective for educational purposes:

- **CoSpaces Edu:** An intuitive tool allowing educators to create interactive AR experiences without programming expertise.
- **Merge Cube:** Provides a tactile learning experience by enabling students to manipulate virtual objects via mobile AR.
- **BlippAR:** Suitable for advanced users, this platform enables the creation of complex AR interactions.
- **HP Reveal (formerly Aurasma):** A user-friendly tool for content creation in AR, making it suitable for diverse educational needs.

These tools are not only cost-effective but also enhance student engagement and facilitate deeper conceptual understanding.

The integration of AR and VR into electronics education offers promising enhancements in student engagement, understanding, and academic achievement. To maximize these benefits, it is crucial to address challenges related to cost, technology access, software integration, and educator training. With continued investment, institutional support, and research, AR and VR technologies can transform the educational landscape, preparing students more effectively for modern engineering roles.

VII. CONCLUSION AND FUTURE SCOPE

This study introduces a comprehensive block diagram of an educational system that utilizes Augmented Reality (AR) and automated circuit verification to enrich learning in electronics courses. Integrating these technologies creates a structured, interactive workflow that effectively connects theoretical knowledge with practical application, resulting in enhanced academic outcomes and a deeper understanding of electronic circuits.

The AR-based educational framework significantly improves real-world classroom experiences by offering interactive, visual, and hands-on learning. With immediate feedback and error correction, the system supports iterative learning, enabling students to grasp circuit functionalities in real-time. This approach not only boosts academic performance but also equips students with practical skills applicable to real-world engineering challenges, better preparing them for modern engineering roles.

Future research should explore the potential of VR in digital circuits education, recognizing the need for financial investment and the development of effective VR learning experiences. By overcoming these challenges, both AR and VR have the potential to revolutionize how students learn about digital circuits and other complex subjects. Providing

the necessary resources and training can ensure that these technologies are effectively integrated into the educational landscape, offering enhanced learning experiences and improved academic outcomes.

REFERENCES

- [1] S. Anzar, N. Subheesh, A. Panthakkan, S. Malayil, and H. Al Ahmad, "Random interval attendance management system (riams): A novel multimodal approach for post-covid virtual learning," *Ieee Access*, vol. 9, pp. 91 001–91 016, 2021.
- [2] J. L. Bacca Acosta, S. M. Baldiris Navarro, R. Fabregat Gesa, S. Graf *et al.*, "Augmented reality trends in education: a systematic review of research and applications," *Journal of Educational Technology and Society*, 2014, vol. 17, núm. 4, p. 133-149, 2014.
- [3] J. M. Krüger, A. Buchholz, and D. Bodemer, "Augmented reality in education: three unique characteristics from a user's perspective," in *Proc. 27th Int. Conf. on Comput. in Educ*, 2019, pp. 412–422.
- [4] C. Kim, H. C. Yoon, D. H. Kim, and Y. R. Do, "Spectroscopic influence of virtual reality and augmented reality display devices on the human nonvisual characteristics and melatonin suppression response," *IEEE Photonics Journal*, vol. 10, no. 4, pp. 1–11, 2018.
- [5] R. E. Maunder, "Students' peer relationships and their contribution to university adjustment: The need to belong in the university community," *Journal of Further and Higher Education*, vol. 42, no. 6, pp. 756–768, 2018.
- [6] A. M. Al-Ansi, M. Jaboob, A. Garad, and A. Al-Ansi, "Analyzing augmented reality (ar) and virtual reality (vr) recent development in education," *Social Sciences & Humanities Open*, vol. 8, no. 1, p. 100532, 2023.
- [7] M. Ismael, R. McCall, F. McGee, I. Belkacem, M. Stefas, J. Baixauli, and D. Arl, "Acceptance of augmented reality for laboratory safety training: methodology and an evaluation study," *Frontiers in Virtual Reality*, vol. 5, p. 1322543, 2024.
- [8] D. Beck, "Augmented and virtual reality in education: Immersive learning research," *Journal of Educational Computing Research*, vol. 57, no. 7, pp. 1619–1625, 2019.
- [9] P. Chen, X. Liu, W. Cheng, and R. Huang, "A review of using augmented reality in education from 2011 to 2016," *Innovations in smart learning*, pp. 13–18, 2017.
- [10] D. Gudoniene and D. Rutkauskienė, "Virtual and augmented reality in education," *Baltic Journal of Modern Computing*, vol. 7, no. 2, pp. 293–300, 2019.
- [11] V. T. Nguyen, K. Jung, and T. Dang, "Creating virtual reality and augmented reality development in classroom: Is it a hype?" in *2019 IEEE International Conference on Artificial Intelligence and Virtual Reality (AIVR)*. IEEE, 2019, pp. 212–2125.
- [12] P. Biswas, P. Orero, M. Swaminathan, K. Krishnaswamy, and P. Robinson, "Adaptive accessible ar/vr systems," in *Extended Abstracts of the 2021 CHI Conference on Human Factors in Computing Systems*, 2021, pp. 1–7.
- [13] A. Scavarelli, A. Arya, and R. J. Teather, "Circles: exploring multi-platform accessible, socially scalable vr in the classroom," in *2019 IEEE Games, Entertainment, Media Conference (GEM)*. IEEE, 2019, pp. 1–4.
- [14] F. Lyrath, C. Stechert, and S. I.-U. Ahmed, "Application of augmented reality (ar) in the laboratory for experimental physics," *Procedia CIRP*, vol. 119, pp. 170–175, 2023.
- [15] G. Singh and F. Ahmad, "An interactive augmented reality framework to enhance the user experience and operational skills in electronics laboratories," *Smart Learning Environments*, vol. 11, no. 1, p. 5, 2024.
- [16] T. Mogashoa, "Applicability of constructivist theory in qualitative educational research," *American International Journal of Contemporary Research*, vol. 4, no. 7, pp. 51–59, 2014.
- [17] T. G. Roberts, "An interpretation of dewey's experiential learning theory." 2003.
- [18] R. E. Mayer, "The past, present, and future of the cognitive theory of multimedia learning," *Educational Psychology Review*, vol. 36, no. 1, p. 8, 2024.
- [19] B. Choi and Y. Baek, "Exploring factors of media characteristic influencing flow in learning through virtual worlds," *Computers & Education*, vol. 57, no. 4, pp. 2382–2394, 2011.