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Virtual Electrical Labs Powered by AR

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Abstract: Traditional Electrical laboratories require huge investments for Physical equipment and machines and also large infrastructure for laboratories. Augmented reality in electrical transforming solution by enabling portable virtual lab experience, interactive environment, simulation and engagement. This paper presents the design and development of an AR-Based Virtual Electrical Lab that allows students to visualize and interact with electrical lab equipment through marker-based AR technology. By integrating 3D models of instruments with real world environments via mobile devices, the system enhances practical understanding while eliminating the risks and limitations of physical setups. Initial findings suggest that AR can significantly improve learning outcomes in electrical engineering offering a scalable and engaging alternative to conventional laboratory sessions.

Keywords: Augmented Reality. Electrical laboratories, Virtual labs.

I. INTRODUCTION

In electrical engineering it is essential to grasp practical concepts effectively. However, traditional laboratories often face challenges such as high cost, limited space, equipment damage risks, and maintenance overheads. The recent advancement of Augmented Reality (AR) technology opens new opportunities to address these limitations by providing an immersive virtual learning environment.

This research proposes the development of an AR virtual electrical lab that allows students to interact with digital representations of laboratory equipment, promoting deeper conceptual understanding without the need for expensive physical resources.

With the increasing demand for accessible and cost-effective education tools, integrating emerging technologies into the academic curriculum has become more crucial than ever. Augmented Reality (AR), which overlays digital content onto the physical world, has emerged as a powerful medium for enhancing learning experiences in science and engineering disciplines.

In the context of electrical engineering, hands-on experimentation plays a vital role in reinforcing theoretical concepts. However, conventional laboratories are often constrained by issues like equipment unavailability, scheduling conflicts, and wear-and-tear from repeated use. These challenges can hinder students' ability to fully engage in practical exercises, especially in institutions with limited resources.

By leveraging AR, educators can simulate complex laboratory setups in a virtual space, enabling students to explore, visualize, and manipulate electrical components safely and repeatedly. Such interactive learning not only reduces dependency on physical infrastructure but also fosters active learning, error exploration, and concept reinforcement.

This research aims to design and implement a marker-based AR virtual electrical laboratory that can run on standard mobile or web platforms, ensuring ease of access. The proposed system intends to provide real-time interaction with 3D models of electrical equipment, offering an innovative supplement to traditional lab-based learning.

In recent years, Augmented Reality (AR) has transitioned from being a novelty in gaming and entertainment to becoming a transformative tool in education and professional training. Its ability to merge digital content with the real world makes it particularly valuable in fields that require spatial understanding, procedural knowledge, and interactive engagement—such as electrical engineering.

The limitations of traditional laboratory environments—such as dependency on physical presence, limited access to instruments, and constraints on repeatability—pose significant barriers to flexible and inclusive learning. Moreover, the cost of maintaining and upgrading lab facilities often restricts the scope and frequency of practical sessions, especially in institutions with budget limitations.

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II. LITERATURE REVIEW

Various researches and studies have explored the application of AR in education, demonstrating its potential to improve engagement, visualization and retention of complex concepts. previous works such as"AR in Engineering Education" (Smith et al.,2021) and "Virtual Laboratories using AR" (Lee etal., 2020) have shown that students learning through AR environments achieve better academic performance compared to traditional methods.

However, most exciting AR applications are either highly specialized for mechanical engineering or general science. There is limited work specifically targeting electrical engineering laboratories. This gap motivates the development of a specialized AR tool tailored to electrical equipment training. Recent research has begun el al. (2022) developed an AR-based circuit simulator that allowed users to visualize current flow and voltage drop across components in real-time, improving conceptual understanding of electrical circuits. Their findings indicated a significant increase in students' ability to troubleshoot and design basic circuits after interacting with AR systems

In addition, Bhandari et al. (2020) proposed an interactive AR-Based lab manual, enabling students to scan QR codes on lab instruments and access 3d animations and safety instructions. These approaches helped bridge the gap between theoretical knowledge and practical application, especially in institutes with limited lab infrastructure.

AR addresses these concerns by offering a scalable and interactive solution that can mimic real-world electrical experiments without the risks associated with live voltages or fragile components. With AR, students can visualize electric flows, circuit behaviour, and equipment functionality in a more engaging and intuitive way. This allows for enhanced conceptual clarity and fosters curiosity-driven exploration.

Furthermore, the shift towards digital and remote learning—accelerated by global disruptions such as the COVID-19 pandemic—has highlighted the importance of adaptive educational tools. AR-based virtual laboratories can bridge the gap between theoretical instruction and practical application, ensuring continuity of learning regardless of physical constraints.

This research contributes to the growing body of work focused on educational technology by presenting an innovative, low-cost AR-based virtual lab model specifically tailored for electrical engineering students. The solution aims to democratize access to quality practical training while promoting interactive and self-paced learning.

III. PROBLEM STATEMENT

Electrical engineering education often relies on hands-on experience with laboratory instruments, but many institutions struggle with:

- Limited number of lab resources
- High setup and maintenance costs.
- safety risks during equipment handling.
- restricted accessibility outside laboratory hours.

Thus, there is a strong need for a scalable, safe, and cost-effective alternative that ensures practical exposure without physical dependencies.

IV. ACTUAL METHODOLOGY FOLLOWED

The development of the AR Virtual Electrical Lab followed a structured methodology comprising multiple stages—**requirement analysis, system design, 3D content development, AR integration, implementation, and evaluation.** The primary focus was on creating an interactive and accessible platform for electrical engineering students to visualize and interact with virtual lab equipment in a realistic environment. The steps followed are outlined below:

1. Requirement Analysis

A detailed analysis of conventional electrical engineering lab activities was conducted to identify the core experiments and components most commonly used in undergraduate curricula (e.g., resistors, breadboards, power supplies, mustimeters, etc.). The learning objectives and constraints of physical labs were also assessed to design an equivalent virtual experience.

2. Platform and Technology Selection

Considering accessibility, **web-based AR** was selected to ensure that the virtual lab can run on mobile devices and laptops without the need for expensive hardware. The following technologies and tools were chosen:

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- AR.js or 8thWall / Zap Works for marker-based AR rendering.
- Three.js or Babylon.js for 3D rendering and interaction.
- Blender / Tinker cad for designing 3D models of lab instruments.
- HTML, CSS, and JavaScript for frontend development.
- GitHub / Firebase for hosting and version control.

3. 3D Model Creation
Digital representations of lab equipment were modelled using open-source 3D modelling software such as Blender or Tinker cad. Each component was created with accurate proportions and texture to simulate real-world interaction. Optimized low-poly models were used to ensure compatibility with web-based AR environments.

4. Marker Design and Mapping
Custom markers were designed for each virtual lab component. These markers serve as reference points that the AR engine recognizes through the user's camera feed. Each marker was mapped to a specific 3D object using the chosen AR framework.

5. AR Environment Development
The AR interface was developed by integrating the markers and 3D models into the chosen AR platform. User interaction features, such as zooming, rotating, and component placement, were implemented using JavaScript event handlers. Instructions and component labels were overlaid in the AR scene to aid learning.

6. Simulation of Basic Experiments
Interactive simulations of basic experiments such as Ohm's Law, Series and Parallel Circuits, and Voltage Measurement were implemented. These simulations included real-time feedback, component manipulation, and visual cues for voltage/current flow to mimic real experimentation.

7. Testing and Validation
The virtual lab was tested on various devices (mobile and desktop) to ensure cross-platform compatibility. Usability testing was conducted with a small group of electrical engineering students who provided feedback on the interface, learning effectiveness, and overall experience.

8. Evaluation and Improvement
User feedback and performance data were analysed to identify usability issues and improve the system. Suggestions for enhancement (e.g., adding voice assistance, gamified quizzes, or mustimeter interactivity) were documented for future iterations.

V. SYSTEM DESIGN AND ARCHITECTURE

The system is designed using web-based AR technologies, ensuring cross-platform compatibility without the need for specialized hardware.
Architecture Overview:
1. Users scan printed markers using their device cameras.
2. MindAR detects the marker and overlays the corresponding 3D model.
3. Students can interact with the model (rotate, zoom) and view its functional parts.

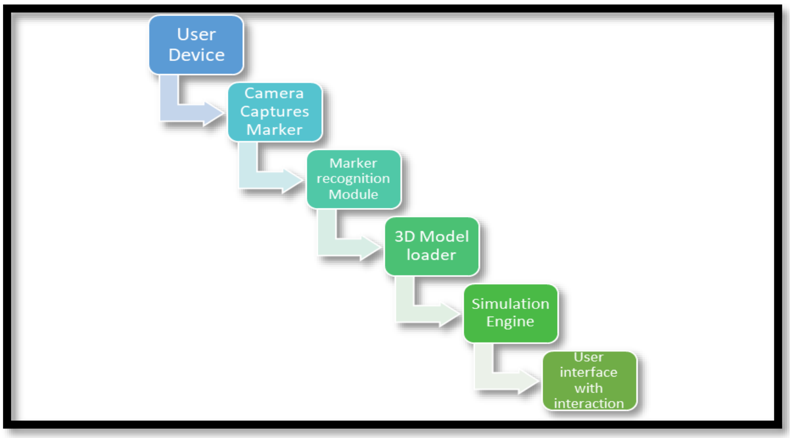

Fig. 1 System Design

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VI. IMPLEMENTATION

- The implementation follows a step-by-step modular approach:

1. Marker Design: Unique markers are created for each lab instrument.
2. Model Development: 3D models are developed using Blender with attention to detail to replicate real-world equipment accurately.
3. Integration: Models are integrated with markers using MindAR.js.
4. Interaction Features: Users can manipulate models (rotation, scaling) for detailed examination.
5. Testing and Validation: The system is tested across multiple devices to ensure stability and user-friendliness.

VII. BENEFITS

- The AR Virtual Electrical Lab demonstrates significant advantages:

1. Students could visualize internal components of instruments that are usually hidden in physical devices.
2. The interactive 3D models helped in better understanding the working principles.
3. Feedback from a small user testing group indicated higher engagement levels and improved retention of technical knowledge.
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5. The system operated smoothly on mid-range smartphones, confirming its accessibility.

However, challenges such as ambient lighting affecting marker detection and the limited interactivity of complex instruments were noted. Future iterations will focus on improving these aspects by integrating real-time simulations and animations.

VIII. CONCLUSION

The AR-based Virtual Electrical Lab successfully addresses the limitations of traditional laboratories by offering a safe, scalable, and engaging alternative for electrical engineering education. Through marker-based interaction and realistic 3D visualization, students gain hands-on exposure to critical lab equipment without the associated costs and risks. This approach not only enhances learning outcomes but also democratizes access to quality technical education across institutions with limited resources. Future enhancements will include more complex simulations, multi-device collaboration features, and AI-driven tutorials for a comprehensive learning experience.

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