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Circuit Tutor AR App using Unity3D

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Abstract : *Grasping electrical circuit analysis often proves difficult because abstract 2-D diagrams feel disconnected from real-life implementation. This paper presents **CircuitTutorAR**, an application built in Unity3D that transforms textbook sketches into interactive 3-D breadboard views layered over the user's physical environment. Unlike traditional tools that focus solely on connectivity, our approach integrates an image-processing pipeline to detect components and a **Circuit Analysis Module** to support theoretical rules like Mesh and Nodal analysis. By converting flat drawings into "touchable" digital prototypes, the system provides a hands-on pedagogical tool that bridges the gap between theoretical representation and practical realization. The result is a system that reduces cognitive load and enhances conceptual clarity for undergraduate engineering students.*
Keywords - *Augmented reality, breadboard visualization, circuit analysis, electrical education, image processing*

I. INTRODUCTION

Electrical circuit analysis is the foundation for electrical and EXTC engineering students. Topics such as mesh analysis, Thevenin’s theorem, and superposition theorem are essential for understanding complex electrical systems. However, these concepts are traditionally taught using 2-D circuit diagrams and mathematical formulas, which many students find difficult to visualize and relate to practical circuit construction. The lack of interactive and practical visualization often results in reduced conceptual clarity and learning effectiveness.

Traditional learning methods rely heavily on static diagrams, textbook illustrations, and limited laboratory exposure. While physical breadboards are used in laboratories, students frequently struggle to translate schematic diagrams into correct physical connections. There is a gap between theoretical representation and practical implementation which remains a major challenge in engineering education. Existing circuit simulation tools provide numerical analysis but do not effectively demonstrate real-world circuit assembly or understanding of component placements.

Advancements in Augmented Reality (AR) technology have opened new possibilities for interactive and immersive learning experiences. AR enables the overlay of virtual objects onto the real-world environment, allowing users to visualize abstract concepts in a more interactive and engaging manner. Integrating AR with circuit education can significantly enhance students’ ability to understand circuit structure, connectivity, and analysis.

This project proposes an AR-based Circuit Tutor application that accepts simple electrical circuit diagrams as input and converts them into an interactive virtual breadboard representation. By combining image processing, circuit mapping, and AR visualization, the system aims to bridge the gap between theoretical circuit diagrams and practical circuit realization. The proposed solution enhances learning by providing real-time visualization, improved conceptual understanding, and an interactive educational platform suitable for undergraduate engineering students.

II. LITERATURE SURVEY

This study addresses the limitations of physical laboratory access, particularly highlighted during the COVID-19 pandemic, by proposing a virtual laboratory system for digital circuits. The authors utilized the Unity 3D engine and Blender to create realistic component models, implementing a web-based interface that allows students to perform experiments remotely. The system was tested for performance efficiency, specifically monitoring processor and memory consumption (resource utilization) and time behaviour to ensure smooth simulation speeds on standard computing hardware. The results indicated that the virtual platform provides a flexible and repeatable experimental experience that matches the learning outcomes of traditional labs while offering superior visual interactivity. [1]

Patel et al. developed a mobile Augmented Reality (AR) system designed to assist undergraduate engineering students in understanding resistive electric circuits. The application uses a smartphone camera to capture a physical breadboard circuit and overlays virtual information—such as theoretical voltage and current values—directly onto the real-world components. By integrating real-time data from measuring instruments with a markless tracking method, the system calculates discrepancies between theoretical and measured values, displaying error metrics instantly. This approach helps students visualize invisible electrical concepts and bridge the gap between abstract circuit theory and physical implementation. [2]

Focusing on novice learners, this paper introduces an AR-based simulator specifically for DC circuit connections. The tool allows beginners to practice circuit assembly without the risk of damaging components or causing short circuits, which are common issues in introductory electronics. The application utilizes mobile AR to project correct wiring guides and component placements over a physical workspace. The study emphasizes the reduction of cognitive load for beginners, demonstrating that AR guidance significantly lowers the barrier to entry for understanding basic series and parallel circuit topologies compared to traditional 2D schematic diagrams. [3]

This comprehensive systematic review analyzes the application and effectiveness of AR in higher education over a two-decade period. The authors conducted a meta-analysis on 60 experimental studies, revealing a large overall effect size ($g = 0.896$), which suggests that AR significantly boosts learning outcomes compared to traditional methods. The review categorizes findings based on instructional function, technical affordances, and discipline, noting that AR is particularly effective in engineering and science education. It concludes by offering four key implications for educational practice, emphasizing the need for robust instructional design to fully leverage AR's interactive capabilities. [4]

Singh and Ahmad propose an interactive AR framework aimed at improving user experience (UX) and operational skills in electronics labs. Drawing on cognitive absorption theory, the study utilizes Partial Least Square-Structural Equation Modelling (PLS-SEM) to analyze data from university students. The research identifies that factors such as enjoyment, control, and curiosity significantly influence the "perceived usefulness" and "ease of use" of the system. The findings suggest that AR does not just serve as a visual aid but mediates immersive experiences that directly enhance cognitive processing, making it a viable tool for improving psychomotor skills in handling electronic equipment. [5]

This paper presents a deep-learning workflow to automate the conversion of circuit schematic images into machine-readable netlists. The authors decompose the problem into three detection tasks: component recognition (e.g., resistors, diodes), line/junction detection, and text recognition (OCR for values/labels). Using a dataset provided by Microchip, they trained models to fuse this visual information into a netlist that can be automatically validated against design rules. The approach addresses the manual bottleneck in validating legacy schematics, showing high accuracy in reconstructing circuit connectivity from static PDF or image files. [6]

Hu et al. introduce a bottom-up graph encoding model to parse analog integrated circuit topologies from images, a task traditionally difficult for standard optical character recognition (OCR) methods. The study proposes a Graph Attention Network (GAT) combined with a port localization algorithm to accurately predict connections between components. By treating circuit components as nodes and wires as edges in a graph structure, the model effectively learns the connectivity patterns of analog circuits. The authors demonstrate that their method outperforms comparative algorithms in both recognition accuracy and speed, facilitating the rapid digitization of paper-based analog designs. [7]

To support synchronous and remote physical computing education, this article introduces "BlinkBoard," an augmented breadboard system. The hardware features LED arrays embedded along the breadboard rows that light up in specific patterns to guide students on where to place components and wires. It includes I/O pins to sense voltage levels, allowing the system to provide real-time feedback on the circuit's state. The study highlights the system's ability to facilitate remote instruction by allowing instructors to push wiring configurations directly to student devices, thereby reducing assembly errors and improving engagement during remote lab sessions. [8]

This conference paper proposes a comprehensive workflow that combines AR with automated circuit verification to streamline electronics education. The system guides students through project selection, experimental setup, and circuit diagram creation using AR overlays. Crucially, it employs camera scanning to verify physical circuit connections against the design, providing immediate error feedback. The authors argue that this workflow supports both exam-based and project-based learning paths, bridging the gap between theoretical circuit design and practical implementation while reducing the burden of manual verification on instructors. [9]

Cao et al. propose a "layered framework" for extracting information from electrical diagrams, aiming to overcome the limitations of existing methods that struggle with diverse diagram styles. The framework sequentially processes the image in three layers: the element layer (using an enhanced YOLOv7 model with attention mechanisms), the text layer (using domain-adapted PaddleOCR), and the connection relationship layer. This separation allows for more robust handling of complex wiring structures and varying component sizes. The results demonstrate that this layered approach significantly improves recognition accuracy and adaptability across different types of electrical schematics. [10]

Gupta explores the pedagogical shift toward "Augmented Learning," where digital overlays are used to reduce the cognitive distance between abstract engineering theories and their physical counterparts. The paper argues that for subjects like circuit analysis, the primary benefit of AR is not just visual appeal but the spatial mapping of information, which helps students internalize the "flow" of electricity in a 3D space. This research provides a theoretical foundation for why transforming 2-D schematics into 3D breadboard views is essential for long-term conceptual retention. [11]

Sharma investigates the future of interactive pedagogy, specifically focusing on how real-time feedback systems can be integrated into engineering classrooms. The study suggests that the next generation of educational tools should move beyond static simulations to "closed-loop" systems that can detect user errors during the assembly process. This supports the future scope of the CircuitTutorAR project, emphasizing the importance of transitioning from simple visualization to an active guidance system that corrects student mistakes as they occur. [12]

2.1 Methodological Synthesis

Researchers have utilized diverse technologies to enhance laboratory learning:

2.1.1 Virtual Environments:

Engines like Unity 3D and Blender have been used to create web-based virtual labs that allow for repeatable experimentation without physical hardware.

2.1.2 AR Overlays:

Mobile AR systems can capture physical breadboards to overlay theoretical values, helping students visualize "invisible" electrical data.

2.1.3 Automated Extraction:

Deep-learning workflows using YOLOv7 and Graph Attention Networks (GAT) have been developed to convert static schematic images into machine-readable netlists by treating components as nodes and wires as edges.

2.2 Identification of Research Gaps

While these individual components are powerful, a critical gap remains in the synthesis of analysis and assembly. Most existing AR simulators focus on either pure data visualization of a pre-built circuit or simple wiring guides for beginners. There is a lack of systems that can take a raw diagram as input and generate both the physical layout (breadboard mapping) and the step-by-step analytical solution (mesh/nodal analysis) simultaneously. CircuitTutorAR addresses this by combining image recognition with an analysis engine to support the full educational lifecycle.

III. METHODOLOGY

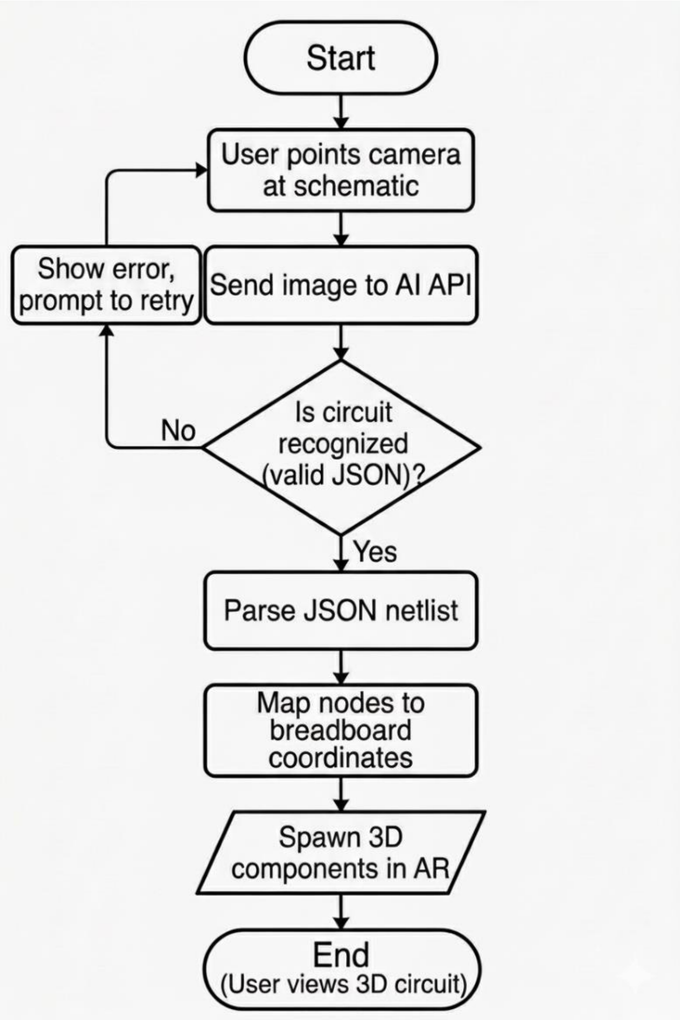

Fig 1 Flowchart of the proposed AR-based circuit tutor system

3.1 The Input Phase (Camera Capture)
User points camera at schematic: This is the starting point. The user has a physical piece of paper with a circuit diagram and opens your Unity AR app to look at it.

3.2 The AI & Validation Phase (The "Eye")
Send image to AI API**:** The app captures a frame from the camera and sends it over the internet to a multimodal AI (like Google Gemini or OpenAI Vision). The prompt asks the AI to convert the drawing into a structured JSON netlist.

Is circuit recognized (valid JSON)? [Decision Block]: This is a crucial safety check. AI can hallucinate or fail to read messy handwriting.

No (Show error, prompt to retry): If the AI returns garbage text, fails to find a circuit, or the JSON is broken, the app catches the error and asks the user to hold the camera steadier or draw clearer. It loops back to the start.

Yes: If the JSON is perfectly formatted, the app moves forward.

3.3 The Logic Phase (The "Brain")

Parse JSON netlist: The app takes that text data and converts it into C# objects using the C# script we wrote. It now mathematically knows what components exist and how they connect.

Map nodes to breadboard coordinates: This is where the heavy lifting happens. The algorithm looks at abstract concepts (like "Node_A" and "Node_B") and translates them into physical reality (e.g., "Node_A is Row 5, Node_B is Row 10"). It also uses the "Column Manager" to ensure components don't overlap.

3.4 The AR Output Phase (Visualization)

Spawn 3D components in AR: The app instantiates your downloaded 3D Prefabs (the resistor, capacitor, breadboard). It scales them to fit the exact distances between the calculated rows and columns, rotating them so they connect properly.

End (User views 3D circuit): The AR Foundation camera tracks the physical table the user is looking at and anchors the 3D breadboard there. The user can now walk around and inspect the circuit from different angles.

IV. CONCLUSION

CircuitTutorAR provides an innovative solution to the visualization challenges in engineering education by synthesizing image processing, circuit analysis, and AR. By transforming static paper diagrams into interactive 3D prototypes, it facilitates a deeper conceptual understanding and reduces the barrier to entry for practical electronics.

Future Scope: While the current system supports simple DC diagrams, future updates will include support for complex designs, including AC analysis and active components like transistors. Additionally, we plan to implement a feedback system where the AR can scan a student's actual physical breadboard and provide real-time error correction against the digital model.

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