Framework for Server-Side Image and Circuit Analysis for automatic Student Feedback

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1. Motivation

Electrical-engineering programs in Germany face strong challenges: dropout rates have risen from 35 % in 1995 to 60 % by 2020, and freshman enrollment is declining [1][2]. Exit surveys attribute this trend in part to overly abstract theory, limited hands-on experimentation, and insufficient opportunities for immediate self-assessment [1]. Although hands-on labs can address these issues, they require instructor guidance and labor-intensive inspection of student-built circuits and measurement data to provide a timely feedback to the students. Advances in digitalization are transforming engineering education: computer vision (for OCR and 2D-code decoding), inexpensive multi-node data acquisition, and scriptable SPICE/AI engines now make a fully automated, end-to-end evaluation pipeline feasible. This project will leverage these technologies to deliver real-time, data-driven feedback on student circuits, thereby reinforcing theory-practice links and improving learning outcomes.

2. State of the Art and Existing Infrastructure

Several research strands converge to enable an automated evaluation framework. Remote-lab platforms such as VISIR have demonstrated the pedagogical value of anytime-anywhere access to real experiments, but they lack the tactile engagement of physical components and impose substantial maintenance overhead [3]. In contrast, the MEXLE system provides a modular lab-in-a-box for hands-on experimentation in conventional on-site labs [4]-[6], see fig. 1. Building on this foundation, the upcoming MEXLEfirst hardware upgrade embeds sensors and microcontrollers on the carrier board, allowing real-time measurement of every nodal voltage and branch current [7]; the first units will be available in August 2025.

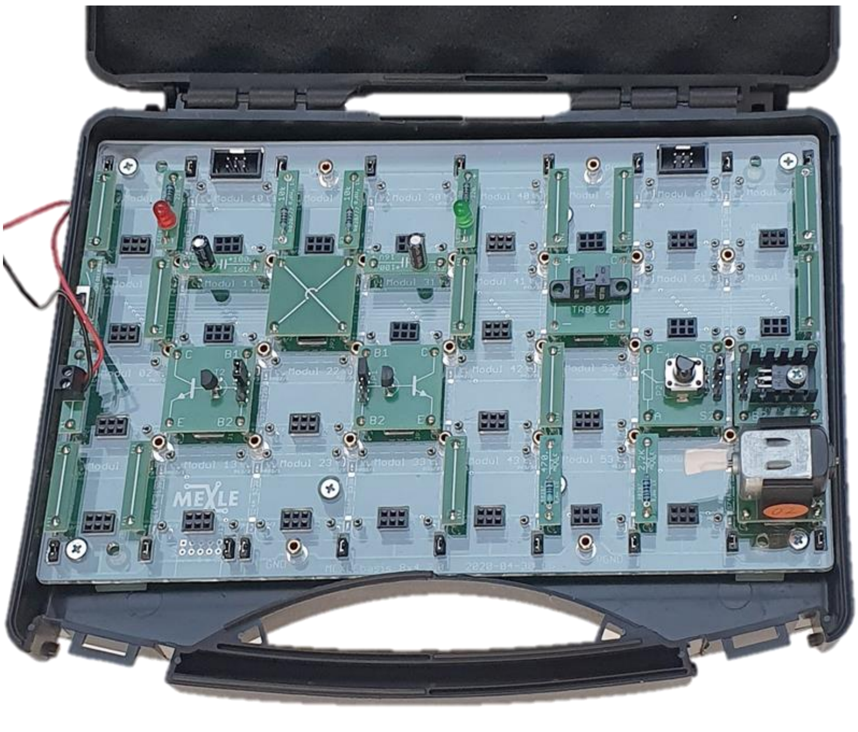

Fig. 1. Already available MEXLE carrier board with different modules for the electronics lecture. [7]

On the computer-vision front, standard libraries can decode pixel codes and alphanumeric silkscreen text in ideal conditions, but student-captured images might suffer from blur, small or skewed codes, uneven lighting, and partial occlusion — conditions under which off-the-shelf solutions are challenged [8]-[10].

This project will build on the upcoming MEXLEfirst infrastructure — comprising carrier boards with unique 2D barcodes on each module, a local institutional server hosting the Web App, and mobile-device clients for data submission—to bridge these gaps. What remains unexplored, however, is the seamless integration of robust computer-vision routines with a SPICE-driven, server-based analysis engine to close the loop between image capture, circuit recognition, and simulation.

3. Project Objectives

By combining mobile-device image capture with advanced vision and circuit-analysis algorithms, the project will translate a student's physical layout into a SPICE-compatible netlist. The resulting simulation will detect misplacements, connectivity errors, or electrical faults, and instantly deliver targeted, data-driven feedback. Students will receive instantaneous, targeted feedback on their circuit via a web app (fig. 2, left).

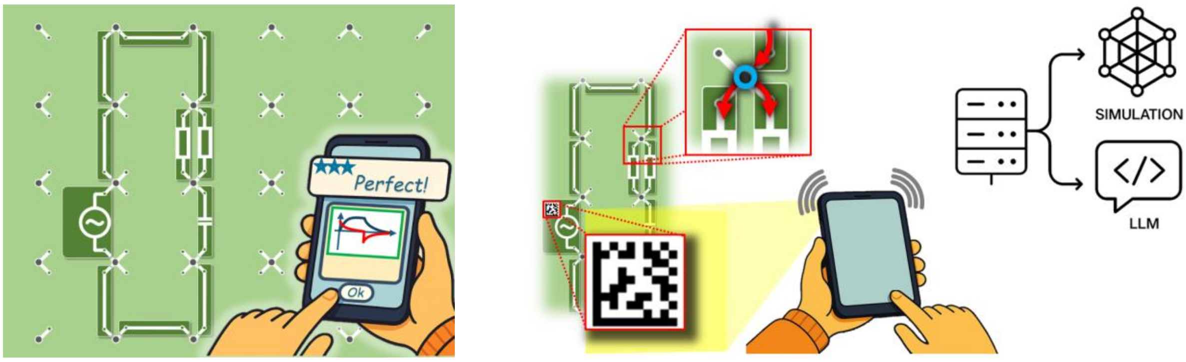

Fig. 2. Sketches of the proposed development: The student's perspective (left) shows the students' circuit and the feedback on a mobile phone. For the analysis, coded modules and measurement on all of the nodes will be used (right).

Specifically, the research will:

- **Image Analysis Pipeline:** Design and implement algorithms to (a) detect and decode 2D Data Matrix or similar codes from modules, (b) recognize alphanumeric silkscreen markings, and (c) map image coordinates to the carrier's node grid, all under variable imaging conditions, like student-captured images.
- **SPICE Model Interface:** Design a method to automatically translate the recognized circuit layout into a SPICE netlist for simulation.
- **Nodal Analysis** (see fig 2, right)**:** (a) sampling the 45 node voltages and >120 current measurements, (b) injecting a voltage-sweep in the student's hardware, (c) automatic approximation of the two-pole and four-pole components.
- **Automated Feedback Mechanism:** Establish a feedback loop where simulation results are compared against predefined benchmarks. When discrepancies are found (e.g., voltage irregularities or connectivity errors), the system provides targeted suggestions to the student.
- **Scalability and Inclusivity:** Ensure that the solution supports a wide range of mobile devices and can be easily integrated into existing educational platforms without imposing significant additional costs.

4. Methodology

The methodology comprises four main stages: image processing and component recognition; netlist generation and SPICE simulation; feedback-loop implementation; and evaluation through iterative testing.

- **Image Processing and Component Recognition:** Utilize established computer vision techniques (e.g., feature detection, pattern matching) to identify modules, connectors, and unique barcodes on each component. The algorithm must accommodate variations in lighting and orientation.
- **Netlist Generation and SPICE Simulation:** Develop an interface that maps the recognized circuit layout to a SPICE-compatible netlist. Integrate a SPICE engine on the server to run simulations in real time. Errors or deviations (such as voltage drops or signal integrity issues) are then automatically identified.
- **Feedback Loop Implementation:** Implement a web-based interface that displays simulation outcomes alongside actionable feedback. This includes error messages like "Voltage discrepancy at Node 3 – please verify resistor values" and recommendations for corrective actions.
- **Evaluation and Iterative Testing:** Conduct controlled experiments with a group of first-year engineering students. Use pre- and post-tests, along with system usage metrics (e.g., error correction rates, time-to-feedback), to evaluate the system's effectiveness and identify areas for improvement.

5. Expected Contributions and Scientific Impact

This project aims to contribute to the field of engineering education by delivering a scalable, automated evaluation system that combines image analysis and circuit simulation. We will generate empirical benchmarks for OCR and code-scan performance under adverse imaging conditions, quantify the impact of real-time feedback on student learning and retention, and demonstrate a resource-efficient model that can be replicated across engineering curricula. We anticipate publishing the findings in journals such as IEEE Transactions on Instrumentation and Measurement. Further publications are expected in the field of OCR/code-scan benchmarks under adverse imaging conditions.

6. Sustainability and Future Directions

In the long term, this platform can be integrated with standard learning-management systems (e.g., ILIAS) and extended to support more advanced experiments, including digital-logic circuits and microcontroller labs. By serving as a blueprint for automated feedback in other engineering domains, it promises to reduce instructor workload, democratize access to timely assessment, and foster more engaging, practice-oriented curricula across STEM education.

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