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TLIC PAPER

Expanding Remote Embedded Systems Education: Integrating the MICRO Remote Lab Across Courses and Curricula

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ABSTRACT

Practical training in embedded systems often suffers from resource shortages, scheduling restrictions, and limited accessibility. This article introduces MICRO, a web-based remote laboratory at University of Applied Sciences Mittelhessen (THM) that enables real-time access to microcontroller and FPGA hardware via standardized and scalable *Cubes* and *Assemblies*, replacing error-prone home construction kits with robust setups. MICRO is used extensively in teaching and anchored in the curriculum: from register-oriented programming in the Microprocessor Technology module to FPGA-based logic design in Digital Technology, to IoT-oriented rapid prototyping in Technical Computer Science II, and to the interdisciplinary Computer Science Project connecting the second and third semester, where students design and implement full-stack applications that integrate web technologies, databases, and remotely provided embedded hardware, thereby creating a consistent learning path across levels of abstraction. The article consolidates the curricular anchoring of MICRO across multiple modules, the underlying architecture and technical innovations for scalability and collaboration, and lessons learned together with an outlook on formal effectiveness studies, open-source release, and data-driven assessments.

KEYWORDS

remote lab, microprocessor technology, experiments, programming, embedded systems education, internet of things, engineering computer science, collaborative experimentation, project-based learning, scalability, remote hardware access

1 INTRODUCTION

Engineering Computer Science (ECS) and Computer Science (CS) education increasingly relies on practical training with embedded systems, where students must program, test, and debug real hardware. Traditional laboratory courses

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offer such experiences but face significant challenges, including limited physical resources, scheduling constraints, and barriers to accessibility [1]. The COVID-19 pandemic further underscored the vulnerability of location-bound laboratories and accelerated the adoption of remote and hybrid solutions worldwide [2], [3].

Remote laboratories have since become an established component of higher education, particularly in technical fields such as electronics, automation, and embedded systems. Initiatives such as VISIR [4], Practable (practable.io) [5], GOLDi [6], and LabsLand [7] have demonstrated the feasibility of providing online access to hardware experiments, thereby laying the foundation for scalable and inclusive laboratory education. Despite these advances, many existing platforms remain limited in scope, often relying on simulations or being confined to a single application domain. As a result, they fall short of providing the curricular breadth needed to cover different levels of abstraction within the targeted degree programs.

In response to these challenges, the MICRO remote lab was developed at the University of Applied Sciences Mittelhessen (THM). Conceived initially during the pandemic as a replacement for on-site microcontroller experiments, MICRO has since evolved into a modular platform that now supports multiple courses across the ECS and CS curricula [8]. This paper extends earlier work by presenting both the curricular integration of MICRO and the technical advancements that enable its scalable and collaborative use.

The contribution of this paper is threefold: First, a description is provided of how MICRO has been integrated into multiple modules, ranging from low-level programming to high-level prototyping and FPGA-based digital logic [9]. After which the recent technical advancements, including automated circuit analysis through Electronic Design Automation (EDA) [10], collaborative shared sessions [11], and cost-effective instrumentation [12] will be presented. Lastly, the lessons learned from teaching practice and outlining future directions for research and development shall be synthesized and shared.

2 THE MICRO REMOTE LAB: FOUNDATION

The MICRO remote lab provides remote access to real embedded hardware via a web-based interface, as illustrated in Figure 1. At its core, the platform is built on so-called *Cubes*, compact autonomous units containing a Raspberry Pi, which acts as a host computer, a microcontroller or Field-Programmable Gate Array (FPGA)-based experiment, internally called *Assembly*, including additional components such as sensors and actuators, as well as peripherals like cameras and digital oscilloscopes/function-generators. Students access these *Cubes* by reserving them through a centralized backend; once assigned, the interaction is routed directly between the browser and the host device, ensuring low latency and scalability.

The primary interaction features include:

- **Code Deployment:** Students upload source code (in C/C++, assembly) that is compiled and flashed onto the hardware in real time.
- **Hardware Interaction:** Digital and analog inputs can be emulated, while hardware outputs are observable through video streams, General Purpose Input/Output (GPIO) mapping, or integrated measurement tools.
- **Serial Communication:** A terminal interface enables direct interaction with microcontrollers for debugging and input/output (I/O) operations.

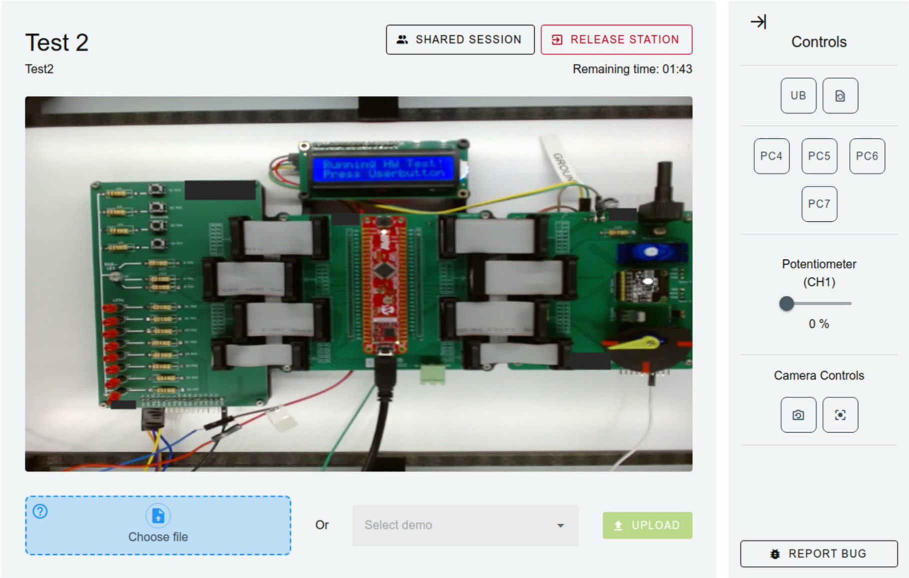

Fig. 1. The MICRO web interface, showing code upload and control interfaces

By abstracting away error-prone circuit assembly and device setup, MICRO ensures consistent and reliable conditions for all students. At the same time, it preserves the authenticity of hardware interaction, distinguishing it from purely simulation-based environments.

From a technical perspective, MICRO combines decentralization with modularity. Each *Cube* is capable of autonomous operation, minimizing backend load and allowing the system to scale with student cohorts. Each experiment is provided as a modular *Assembly*, enabling flexible provisioning of the required hardware in response to changing demands. This architecture also facilitates future extensions, as demonstrated by the later integration of FPGA-based experiments, tailored to their unique requirements.

3 CURRICULAR INTEGRATION ACROSS MODULES

The MICRO remote lab has been deliberately designed not as an isolated tool for a single course, but as a flexible digital infrastructure that supports multiple stages of the ECS and CS curricula. Its integration extends across introductory, intermediate, and advanced modules (as shown in Figure 2), thereby providing students with a coherent and progressively deepening experience in embedded systems.

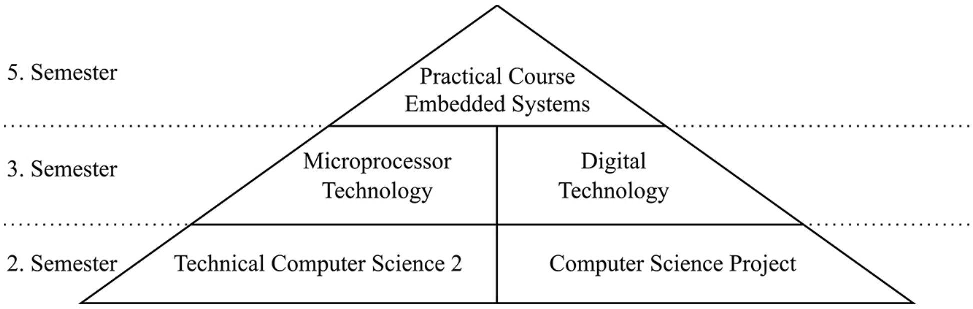

Fig. 2. Curricular integration of MICRO across modules in the engineering computer science program. Adapted from [8]

3.1 Microprocessor Technology

The Microprocessor Technology (MPT) module represents the first dedicated course in embedded systems, typically offered in the third semester. It introduces students to low-level programming using the AVR128DB48 microcontroller, employing both C/C++ and assembly languages. Experiments are carefully sequenced, beginning with basic register-level manipulations and gradually extending to more complex interactions with peripherals such as displays, sensors, and communication interfaces [8]. The remote environment preserves the essential interactions of the original course, as shown in Table 1, including visual inspection via a camera stream, digital and analog input emulation, and Universal Synchronous/Asynchronous Receiver/Transmitter (USART)-based communication, except for audio perception.

Before the adoption of MICRO, lab assistants provided students with individual hardware kits to conduct experiments at home. While these kits offered flexibility, they also introduced significant challenges: circuit assembly errors, maintenance overhead, and inconsistent learning experiences. By replacing these with standardized, remotely accessible setups, MICRO has reduced the logistical burden while ensuring continuous availability and uniform conditions for all students. Additionally, this enables automated monitoring of experiments, scalable delivery, and allows multiple students to access the hardware in parallel.

Table 1. Experiments in the MPT module and corresponding student interactions. Excerpt from [8]

Experiment	Visual	Audio	Digital	Analog	USART/ USB
GPIO Control: LEDs and Buttons	✓		✓		
PWM Control	✓			✓	
Analog-to-Digital Conversion & USART Communication	✓		✓	✓	✓
I^2C Sensor Integration	✓				
Digital-To-Analog Conversion - “Build your own Piano”	✓	(✓)	✓	✓	

3.2 Technical Computer Science II

In contrast to the low-level focus of MPT, the second-semester course Technical Computer Science II (TCS2) emphasizes higher-level programming and system integration. Here, students work with ESP32-based platforms and the Arduino framework. The didactic aim is not to master register-level programming, but to understand the principles of embedded systems within broader software projects, often with an orientation toward Internet of Things (IoT) applications.

MICRO has been adapted to support this higher-level learning context by providing Arduino-ready stations that enable rapid prototyping, abstraction of hardware complexity, and simplified code deployment. This integration demonstrates the versatility of the MICRO architecture, which can support both detailed, hardware-centric courses and more application-oriented modules. From a curricular standpoint, TCS2 helps prepare students for interdisciplinary projects by introducing them to the practicalities of working with microcontrollers in user-facing applications.

3.3 Digital Technology

A further extension of MICRO addresses the Digital Technology (DT) module, also taught in the second semester. This course introduces students to digital logic design using FPGAs. Traditional webcam-based observation was replaced in MICRO with a low-latency simulation-driven feedback loop (shown in Figure 3): GPIO signals from a Lattice iCE40 FPGA are routed via FTDI FT232H Serial-to-USB interfaces into a simulation layer running on the host computer. These simulation environments range from a water tank control system to a seven-segment counter or a traffic light controller, each requiring a finite state machine to achieve the expected behavior. Students can thus observe the direct effects of their designs without the delays and ambiguities of camera-based feedback [9].

Fig. 3. Example of an FPGA-based experiment in the DT module

This FPGA integration highlights a distinct pedagogical strength of MICRO: the ability to tailor hardware-software interactions to the learning objectives of each course. For DT, the system emphasizes timing, state-based control, and debugging of sequential logic, complementing the software-oriented focus of MPT and TCS2.

3.4 Computer Science Project

Beyond the dedicated embedded systems modules, MICRO has also been incorporated into the interdisciplinary Computer Science Project (CSP) course, which bridges the second and third semesters of the ECS and CS degree programs. In this setting, students work in teams to design and implement full-stack applications that integrate web technologies, databases, and embedded hardware components. Recent examples include the development of a custom *Simon Says* game and, more recently, a quiz game that utilizes a hardware controller to interface with a browser-based application.

These projects demonstrate how MICRO can serve as a unifying platform that links embedded programming with higher-level software engineering, fostering cross-disciplinary competencies.

4 TECHNICAL ADVANCEMENTS SUPPORTING INTEGRATION

While the curricular integration of MICRO demonstrates its pedagogical value, the system's scalability and adaptability are equally dependent on a series of technical advancements. These developments were implemented in parallel to course integration and form the technological backbone that enables MICRO to be used consistently across diverse teaching contexts. Three significant areas will be highlighted: automated circuit analysis and assessment, synchronous collaboration through shared sessions, and the integration of cost-effective instrumentation for interaction and measurement.

4.1 Automated EDA integration

One of the challenges in scaling remote laboratories lies in documenting and evaluating complex experimental setups. To address this, the MICRO team developed the *Creation Assistant*, a service that automatically processes Fritzing diagrams used for experiment documentation. The tool converts graphical circuit descriptions into structured netlists in YAML format, extracting information about components, pins, and connections, which is then stored in a relational database as shown in Figure 4. Through this, MICRO enables automated configuration of experiments and, crucially, lays the foundation for automated testing procedures [10].

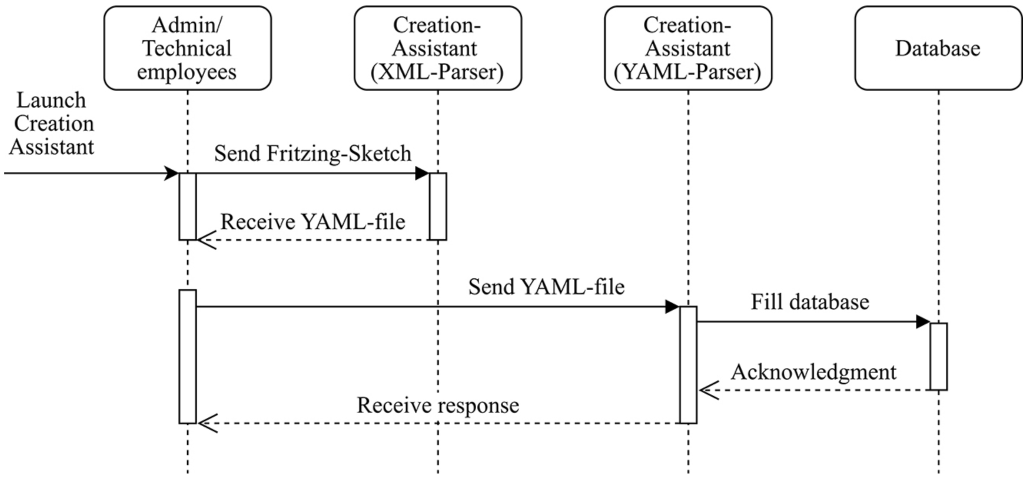

Fig. 4. Fritzing diagrams are processed into YAML netlists and stored in a database. Adapted from [10]

This integration allows instructors to reduce repetitive tasks and enables consistent feedback. Beyond scalability, such automation paves the way for objective assessment strategies that align with competence-oriented learning outcomes.

4.2 Shared sessions and collaborative experimentation

Traditional remote labs often follow a single-user reservation model, which limits opportunities for authentic collaboration. In response, MICRO introduced *Shared Sessions*, a feature that enables multiple students to access and interact with the same experiment simultaneously. Shared Sessions utilize different session keys, allowing for role-based permissions and enabling the session owner to manage collaborators. Achieve this through Server-Sent Event communication to the backend, facilitating session management, and WebSocket communication to the station, enabling simultaneous inputs and outputs across all users in real-time [11].

This functionality supports contemporary pedagogical practices such as pair programming, collaborative debugging, and instructor-led walkthroughs. By embedding synchronous collaboration directly into the lab infrastructure, MICRO not only mirrors authentic teamwork scenarios in professional engineering but also enables instructors to intervene and guide students within the same experimental session. This development enhances competence-based and cooperative learning formats that surpass the limitations of single-user remote labs.

4.3 Enhanced instrumentation for interaction and measurement

A third technical advancement concerns the integration of low-cost multi-function instruments into MICRO (see Figure 5). Devices such as Digilent's Analog Discovery and Digital Discovery provide oscilloscope, function generator, and logic analyzer capabilities at an affordable cost. Their integration into MICRO enables students to generate both digital and analog signals (e.g., simulating button presses or potentiometer adjustments) and to remotely analyze communication protocols such as USART, Serial Peripheral Interface (SPI), or Inter-Integrated Circuit (I^2C).

From a didactic perspective, this extension enhances the authenticity of remote experiments by providing students with access to standard laboratory instruments that they would otherwise encounter only in on-site settings. At the same time, the uniform integration of such tools across multiple MICRO stations ensures consistency and scalability. Technically, the implementation relies on a dedicated service running on the host machines, which interfaces with the instruments via the WaveForms SDK and communicates with the web frontend using REST and WebSocket protocols, utilizing the information provided by the EDA pipeline.

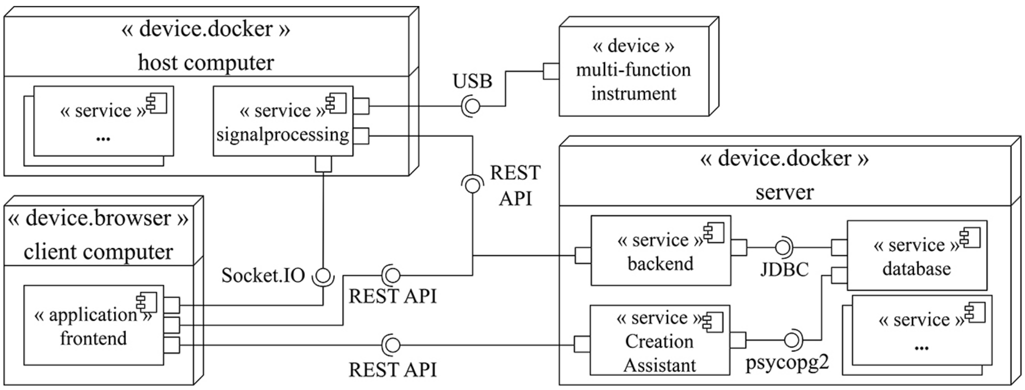

Fig. 5. Integration of low-cost multi-function instruments into MICRO, supporting signal generation and analysis. Adapted from [12]

Together, these advancements—automated circuit analysis, collaborative shared sessions, and enhanced instrumentation—form the technological foundation that enables MICRO to operate as a scalable, flexible, and pedagogically diverse remote laboratory platform.

5 EVALUATION AND LESSONS LEARNED

The integration of MICRO across multiple modules has been accompanied by ongoing evaluation through informal student feedback, teaching observations, and comparative reflections from instructors. While a formal quantitative study is still in preparation, several lessons can already be drawn from the deployments in MPT, TCS2, DT, and CSP.

5.1 Student feedback and observations

Across modules, students consistently highlighted the value of MICRO in terms of accessibility and flexibility. The ability to access real hardware at any time was perceived as a significant improvement over traditional laboratory settings, which are bound to fixed schedules. In MPT, students emphasized that the removal of error-prone manual circuit assembly allowed them to concentrate on programming and debugging tasks, thereby deepening their understanding of low-level microcontroller concepts [3]. In TCS2, students appreciated the seamless integration of Arduino-based workflows, which enabled them to prototype higher-level applications more efficiently. Here, the remote lab helped to bridge the gap between abstract software concepts and tangible embedded hardware. In DT, the simulation-driven FPGA interface was particularly valued for its responsiveness and clarity of the provided simulations, linking a visual interpretation to the code execution, as well as the reduced barrier of entry by removing the need to install entire toolchains [9]. In the CSP, especially among non-engineering computer science students, the reduced entry hurdle to incorporating microcontroller-based systems into their software projects was valued.

5.2 Challenges and lessons learned

Despite these positive outcomes, several challenges have also been observed. First, the technical robustness of the platform remains a critical factor: occasional instabilities, especially in shared network environments, can disrupt remote sessions, requiring ongoing improvements in reliability. Second, while MICRO lowers the barrier to hardware interaction, students sometimes miss the tactile experience of physically wiring circuits. This aspect requires complementary on-site components in hybrid teaching scenarios.

From a didactic perspective, a key lesson is that MICRO functions most effectively when embedded into a coherent curricular sequence. By spanning from higher-level systems prototyping to low-level programming and hardware design, the platform creates continuity in learning experiences. This continuity fosters competence development across abstraction levels and highlights MICRO's role as a unifying digital infrastructure in embedded systems education.

6 CONCLUSION AND OUTLOOK

This paper has presented the curricular and technical evolution of the MICRO Remote Lab at the THM. Building upon its initial deployment in the MPT module [8], MICRO has since been extended into multiple courses, including TCS2, DT, and the CSP.

These integrations demonstrate that a single remote laboratory architecture can support diverse learning objectives ranging from low-level register programming to high-level prototyping and digital logic design. The platform thereby provides students with a coherent and progressive learning pathway in embedded systems education.

On the technical side, MICRO has been enhanced through automated EDA integration for circuit analysis [10], collaborative shared sessions [11], and the incorporation of low-cost, multi-function instruments [12]. These features significantly expand the pedagogical reach of the platform, enabling scalable operation, authentic teamwork scenarios, and richer experimental interactions.

Several lessons emerge from these efforts. MICRO's curricular integration demonstrates the importance of continuity across abstraction levels, as students benefit from encountering the same platform in different contexts. At the same time, challenges such as technical robustness and the limited tactile component of remote experimentation underline the continued relevance of hybrid approaches.

Looking ahead, the MICRO initiative will pursue several directions. First, formal evaluation studies are planned to assess learning outcomes across modules systematically. Second, the platform is being prepared for open-source release, which will enable adoption by other institutions and foster international collaboration. Third, future work will focus on integrating automated assessment and learning analytics to support competence-based education further. Finally, MICRO is increasingly being used in interdisciplinary project-based learning formats, such as the CSP. A detailed account of these experiences will be provided in forthcoming works.

In summary, MICRO has evolved from a pragmatic solution to pandemic-related constraints into a scalable and flexible educational infrastructure. By linking technical innovation with curricular breadth, the platform contributes to making embedded systems education more inclusive, accessible, and future-oriented.

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