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Transforming Embedded Systems Education: A Novel Approach to Hands-On Learning in a Virtual Environment

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Transforming Embedded Systems Education: A Novel Approach to Hands-On Learning in a Virtual Environment

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Abstract

The COVID-19 pandemic posed significant challenges to traditional hands-on learning in embedded systems education, particularly during the fall of 2020, as students were forced into remote learning environments. This paper presents a project aimed at mitigating these challenges by providing students with hardware and hands-on experiences through the development of a take-home lab experiments kit. As a core requirement of the course, students designed and assembled the kit themselves, enhancing their engagement with real-world electronics practices. The project involved students designing a low-cost Printed Circuit Board (PCB) that would host all the electronic components required for both lab experiments and final projects. The initiative began with an introduction to the fundamentals of PCB design, production requirements, and industry standards. Upon completing their designs, the PCBs were manufactured in China and distributed to the students. Students living off-campus received the kits by mail, while others collected them locally. Each kit included the PCB and the necessary electronic components, enabling the students to solder the components and proceed with their lab work. This hands-on experience provided students with critical skills, such as PCB design and soldering, while also enabling them to complete seven remote lab experiments and three final projects. The flexibility of remote learning combined with hands-on kit usage resulted in a learning experience that surpassed the traditional classroom setting in terms of practical exposure. Due to the project's novelty, creativity, and effective innovation in transforming teaching and learning in dynamic educational environments, it was awarded the Rowan University President's Award for Excellence in Innovative Teaching. The project not only succeeded in adapting to the constraints of remote learning but also demonstrated a forward-thinking approach to embedding practical, real-world skills in the curriculum, serving as a model for future education strategies in embedded systems and other hands-on disciplines.

1. INTRODUCTION

The COVID-19 pandemic in 2020 fundamentally disrupted educational systems worldwide, forcing a sudden shift from in-person to remote learning. For engineering disciplines like embedded systems, which rely heavily on hands-on laboratory work and real-time hardware-software integration, this transition posed unique and significant challenges. The inability to access physical tools and collaborative environments risked undermining the experiential learning that is central to the discipline [1], [2]. This paper explores how these challenges were addressed in an Embedded Systems course offered during the Fall 2020 semester, highlighting the adaptations and innovations employed to ensure students achieved the desired learning outcomes.

The transition to remote learning demanded significant modifications to course delivery and content, particularly for project-based learning and laboratory sessions. Tools and strategies had to be reimagined to replicate the hands-on experience that is central to Embedded Systems education.

While technical constraints such as access to hardware, tools, and reliable internet connections posed hurdles, these challenges also presented opportunities for creative solutions.
Existing literature has explored various remote learning solutions, such as virtual labs and remote desktop access to on-campus resources [3], [4], [5], [6], [7], [8], [9], [10], [11], [12], [13], [14], [15]. However, these approaches often fall short in replicating the tangible, interactive experience of working with real circuits and components, have significant design overhead, and have little to no room for collaboration. Additionally, many rely on generic platforms like Arduino kits, which limit the depth and breadth of learning opportunities in embedded systems.

This paper addresses these gaps by presenting an innovative approach to remote embedded systems education implemented during the Fall 2020 semester. Through the development of take-home lab kits and project-based learning, students were empowered to engage with real-world engineering practices despite the constraints of remote learning. By designing and assembling custom Printed Circuit Boards (PCBs) AKA Booster Packs, students not only gained practical skills but also experienced a learning environment that exceeded traditional classroom settings in some respects.

This paper aims to share these strategies, reflect on the lessons learned, and provide a framework for future remote or hybrid teaching scenarios in embedded systems and related fields.

2. COURSE OVERVIEW

The *Introduction to Embedded Systems* course, designed for junior-level students, provides a comprehensive foundation in microcontroller architectures, C programming, and hardware interfacing. The course emphasizes experiential learning through hands-on activities, including the use of the TI MSP-EXP430F5529LP development board and a PCB workshop to introduce students to real-world engineering practices.

Key topics covered in the course include MSP430 architecture, interrupt processing, input/output operations, and peripheral components of embedded microprocessors. Table 1 outlines the topics covered and the corresponding laboratory experiments, showcasing the integration of theoretical and practical learning.

The course is structured around two 50-minute lectures and one 150-minute lab session per week, providing ample opportunity for students to apply classroom knowledge to practical scenarios. A unique feature of the course is the PCB workshop, which equips students with the skills to design and implement custom Printed Circuit Boards (PCBs). Students learn industry-standard practices for schematic capture, component placement, and PCB design, using DipTrace software.

A hallmark of the course is the capstone project, where students work in teams to design and implement innovative solutions. Teams conceptualize project ideas, refine them through instructor feedback, and prepare a Bill of Materials (BoM) for required components. These projects allow students to apply their knowledge to solve practical engineering problems while gaining experience in teamwork and project management. The department supports these efforts by procuring necessary components, ensuring that students can realize their designs.

The traditional structure of this course, including the PCB workshop and hands-on lab experiments, laid a solid foundation for embedded systems education. This foundation became critical during the transition to remote learning in Fall 2020, as it informed the innovations necessary to maintain the course's hands-on focus under pandemic constraints.

Table 1: Course topics and lab experiments before fall 20.

Lecture part topics	Lab experiments
• MSP430 Architecture • MSP430 General Purpose I/O • MSP430 Interrupt • More on Timers and PWM • Analog to Digital Converter ADC • Serial Communication	• General Purpose Input/Output GPIO. • Interrupt based Input/Output. • Timer A: Pulse Width Modulation PWM. • Timer A: Capture/Compare modes. • Analog to Digital Converter ADC. • Closed-Loop light Controller. • Universal Asynchronous Receiver Transmitter. • PCB design workshop. • Final project (students' ideas)

3. REMOTE DELIVERY OF THE COURSE

The transition to remote delivery in Fall 2020 due to the COVID-19 pandemic posed significant challenges for the Introduction to Embedded Systems course, where hands-on practice is a cornerstone of the learning experience. To address these challenges and maintain academic rigor, several approaches were considered, including virtual labs, remote desktop access to on-campus resources, and home lab kits. After evaluating the limitations of virtual tools—such as the inability to provide direct interaction with physical circuits—the decision was made to adopt remote lab kits.

Each kit comprised two main components: the TI MSP-EXP430F5529LP development board and a custom PCB (Booster Pack) designed to host the electronic components required for the lab experiments. Additional components were included to support two moderately challenging projects, allowing students to engage deeply with practical applications. Table 2 outlines the bill of materials for the kits, which cost $22.99 per unit. The university covered the costs of the components, PCB fabrication, and shipping, while students purchased the development boards from the campus bookstore.

To accommodate this new format, the course calendar was adjusted significantly. The PCB workshop was moved to the beginning of the semester, enabling students to design and assemble their custom PCBs early. This adjustment ensured that students could utilize their kits for experiments and projects throughout the semester. Table 3 provides the updated course calendar.

Students were required to demonstrate their work by uploading video demos of their lab experiments and technical reports for their projects to the Canvas learning management platform. This approach ensured accountability and allowed instructors to assess student progress remotely. Additionally, students were encouraged to purchase low-cost lab equipment for at-home use, as shown in Figure 1, further enhancing their hands-on experience.

The remote delivery approach provided students with a unique opportunity to engage in real-world engineering practices, including designing and fabricating PCBs, soldering components, and integrating hardware with software. Despite the challenges of remote collaboration, the course maintained its experiential focus, demonstrating that practical engineering education could thrive even in a virtual environment. This model has potential applications for broader contexts, including scaling to larger cohorts and adapting to resource-constrained institutions.

Figure one: Examples of students' at home lab equipments.

Table two: Bill of Materials

Qty	Desc	URL
1	PCB (student custom designed)	-
4	1x10 LaunchPad Conn	https://www.mouser.com/ProductDetail/474-PRT-11376
1	WiFi module	https://www.sparkfun.com/products/17146
1	2x4 WiFi conn	https://www.digikey.com/en/products/detail/harwin-inc/M20-7830446/3727759
1	MEMS Mic module	https://www.mouser.com/ProductDetail/485-2716
1	1x5 MEMS Mic conn	https://www.mouser.com/ProductDetail/855-M20-7820546
1	#2-56 x 0.75" machine screw	https://www.mcmaster.com/91772A084/
3	#2-56 nut	https://www.mcmaster.com/96537A110/
1	22 pin break-away header for FTDI and selection pins	https://www.mouser.com/ProductDetail/Molex/22-28-4221?qs=qNWTS1i2F3YqAvqPvx8JHw%3D%3D
5	jumpers, shunts	https://www.digikey.com/en/products/detail/sullins-connector-solutions/QPC02SXGN-RC/2618262?utm_adgroup=Shunts%2C%20Jumpers&utm_source=google&utm_medium=cpc&utm_campaign=Shopping_Product_Connectors%2C%20Interconnects_NEW&utm_term=&utm_content=Shunts%2C%20Jumpers&gclid=CjwKCAjwgISIBhBfEiwALE19Sc-z3eKjMm-EtFSZlg72iWezVqru-rExilbFIYeuwL_Vo1yqfi_QRBoC6AEQAvD_BwE
6	3mm LEDs	https://www.mouser.com/ProductDetail/Lite-On/LTL-4291?qs=hwwi6K77lY0mRqALuL4%252BkA%3D%3D
6	330 Ohm 0.25W resistor	-
1	10 KOhm 0.25W resistor	-
1	100 KOhm 0.25W resistor	Match to LDR below
1	light sensitive resistor (LDR)	https://www.amazon.com/eBoot-Photoresistor-Sensitive-Resistor-Dependent/dp/B01N7V536K/ref=asc_df_B01N7V536K/?tag=hyprod-20&linkCode=df0&hvadid=242033424131&hvpos=&hvnetw=g&hvrand=14327938443129206506&hvpone=&hvptwo=&hvqmt=&hvdev=c&hvdvcmdl=&hvlocint=&hvlocphy=9003792&hvtargid=pla-397676869569&psc=1
1	push button switch	https://www.mouser.com/ProductDetail/Alps-Alpine/SKHHAMA010?qs=%2Fha2pyFadujOP02hD5NbdXjJUo97HkYyT5yCPdM2hOo%3D
1	0.1 uF cap	https://www.mouser.com/ProductDetail/Vishay-BC-Components/K104Z15Y5VE5TL2?qs=sGAEpiMZZMuMW9TJLBQkXvgYvLiRA5NjwUgVmrrdr7g%3D
1	10 uF cap, alum +B17B15:B19C11B16:B19B14:B19B15:B19	https://www.mouser.com/ProductDetail/KEMET/ESK106M010AC3AA?qs=%2Fha2pyFaduh414j3d5VxUBeQVJEfyB9wfCbzb4buokLVL3Pu%252BGgJIw%3D%3D

Table Three: Course Calendar in fall 2020

Week of	Monday Class	Tuesday lab	Wednesday Class
Sep. 1	NO Classs	PCB workshop	Group work on PCB workshop
Sep. 7	Group work on PCB workshop	PCB workshop	Group work on PCB workshop
Sep. 14	Introduction to ESP-01 WiFi module	PCB workshop	Introduction to MSP430F5529-part one
Sep. 21	Introduction to MSP430F5529-part two	PCB workshop	2. Introduction to C programming-part one
Sep. 28	MSP430F5529L GPIO + CCS	lab1 GPIO and CCS introduction	Interrupts lecture
Oct. 5	Quiz one	lab2 interrupts	Timer A Introduction
Oct. 12	Introduction to Timer A	lab3 Timer A (software PWM)	Quiz 2
Oct. 19	Timer A PWM	PCB board soldering	lab4 Timer A (PWM)
Oct. 26	Timer A Capture mode	lab4 Timer A (Button based delay using capture mode)	lab4 capture mode (additional time).
Nov. 2	lab3 Timer A (software PWM) discission	Lab 4 more discussion + Quiz 3	ADC
Nov. 9	ADC (review of registers)	lab5 ADC (assignment)	ADC lecture 2
Nov. 16	UART	lab6 ADC	UART
Nov. 23	Introduction to lab7	lab7 UART	WiFi project
Nov. 30	UART review	project	Quiz 4 (UART)
Dec. 7	Review of ADC registers.	project	Review of Timer A
Dec. 14	Final Exam		

4. COURSE PROJECTS

Students were tasked with designing a Booster Pack PCB compatible with the MSP-EXP430F5529LP development board. The PCB design needed to meet the following specifications:

- Host an SPW2430 MEMS microphone and an ESP8266 Wi-Fi module (802.11).
- Include a power selection jumper for each module, enabling ON/OFF control.
- Feature LED indicators to display module power status.
- Provide pin headers for external line data monitoring and solder pads for unused development board header pins.
- Incorporate ample prototyping pads.
- Adhere to a 2-sided PCB design with dimensions ≤ 99 x 99 mm.

Four online lab sessions were dedicated to PCB design, using the academic free version of DipTrace software. Students learned to create custom component libraries, validate designs, and follow industry standards. Once finalized, designs were submitted to the university's resource center, which facilitated fabrication through PCBWay. Fabricated boards were shipped within two weeks, with on-campus students collecting them locally and off-campus students receiving them via mail.

Students soldered components onto the PCBs with guidance provided through YouTube tutorials. On-campus students used lab kits, while off-campus students purchased soldering kits using recommended Amazon links. Figures 3 and 4 show completed Booster Packs, and Figure 5 illustrates a PCB designed by one team coupled with the MSP-EXP430F5529LP board.

A challenge arose when a few teams failed to follow the required file naming conventions for submitting their designs, leading to not sending their designs to fabrication facility. These teams utilized spare boards from other groups as the minimum order size of five PCBs per design. This highlighted the importance of clear communication and precise instructions in remote environments.

4.2 IoT Project

In this project, students utilized the MSP-EXP430F5529LP development board and the ESP8266 module to create an IoT system for monitoring light intensity in a Weed Science Laboratory. The system performed the following functions:

- Measured voltage across a photoresistor every 15 minutes.
- Uploaded the data to MathWorks ThingSpeak, an open IoT platform for data storage and analysis.

This project introduced students to IoT integration and data visualization, enhancing their understanding of sensor-based systems and cloud connectivity.

4.3 MEMS Microphone Project

Students used the MSP-EXP430F5529LP development board and the SPW2430 MEMS microphone to develop a system that:

- Connected the microphone's AC and DC outputs to two ADC12 inputs.
- Displayed instantaneous data from these inputs using either LabVIEW or MATLAB.

This project enabled students to explore analog signal acquisition and processing, critical skills in embedded systems applications.

The course projects demonstrated the students' ability to design, fabricate, and implement functional hardware systems in a remote learning environment. By working collaboratively on these projects, students gained practical experience that mirrored real-world engineering challenges, fostering adaptability and resilience. These projects not only bridged the gap between theory and practice but also prepared students for industry scenarios where multidisciplinary skills and teamwork are essential.

Figure two: On Campus delivery process

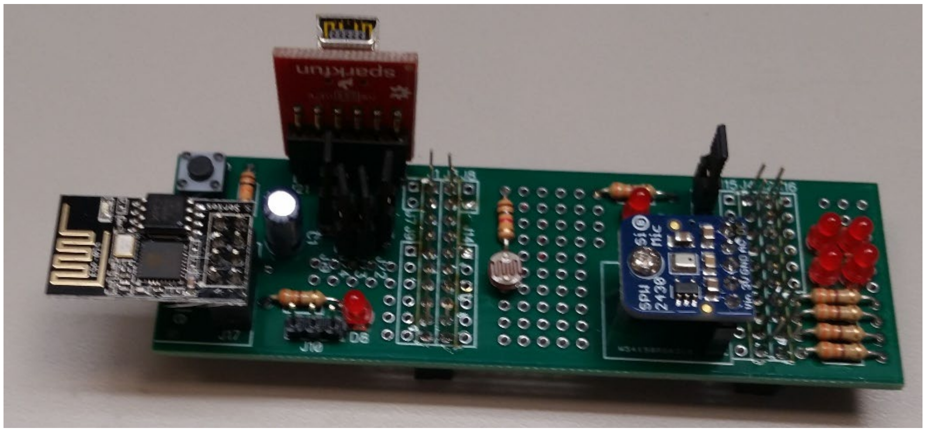

Figure three: Top view of the booster pack

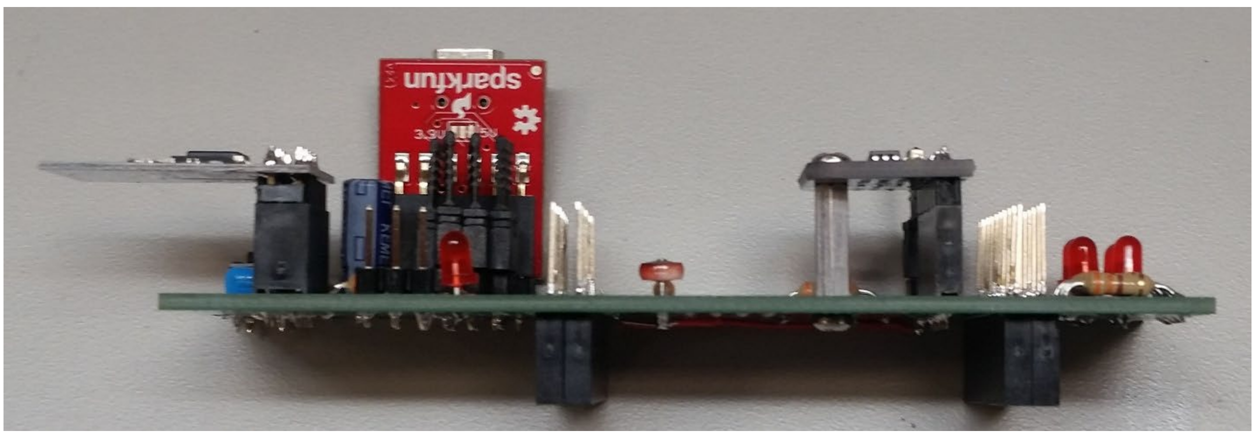

Figure four: Side view of the booster pack.

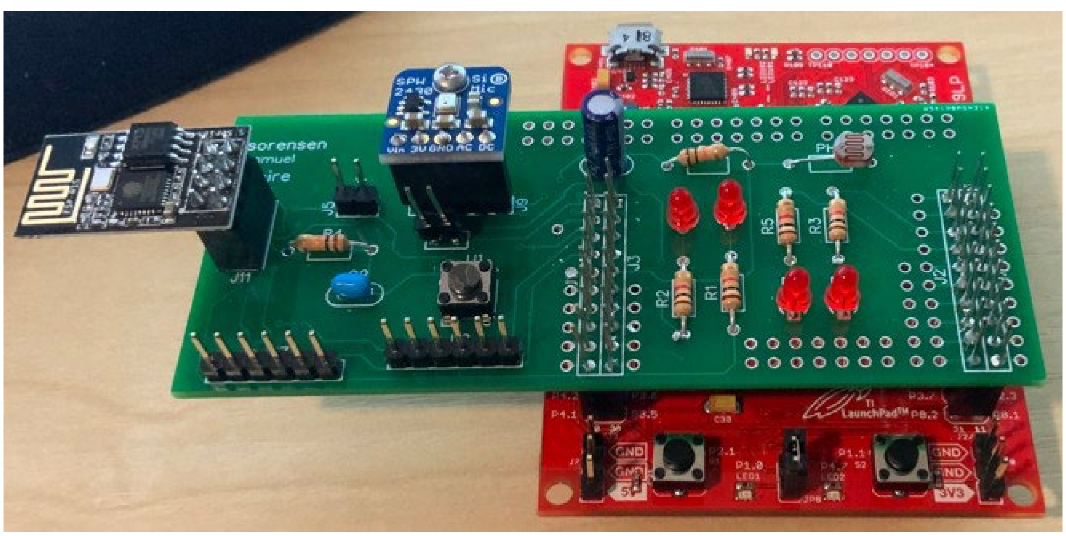

Figure five: A booster pack coupled with the MSP-EXP430F5529LP development board

5. RECOGNITION AND IMPACT

The project's innovation in teaching and learning was recognized with the Rowan University President's Award for Excellence in Innovative Teaching. Beyond its immediate success, the project received enthusiastic feedback from students, highlighting its transformative impact, the following comments were mentioned in the students' evaluation of the course:

- "Doing PCB design was easily the highlight of the course for me."
- "My favorite project was the PCB project where we actually built a PCB and did labs with it. It was very interesting and cool and it taught a lot about real-world engineering."
- "Dr. Al-Quzwini was one of my favorite professors this semester. The class was project-based and did not focus on tests. The class was still challenging but in a very good way. This helped me to learn the information much more effectively and I wished more professors did this. The PCB project was a great addition to the class, since many engineering students don't get the opportunity to create a PCB for a class. I hope more classes start adapting to a similar format."
- "The final project with the PCB was one of my favorite parts. I enjoyed creating the schematic and soldering the board. I wish we had some lessons on soldering though."
- "Last semester I had a wonderful experience with Dr. Al-Quzwini in Introduction to Embedded Systems. Within his class, the students were assigned three large projects which included designing and assembling our own PCB interface board to interact with an MSP430 and with a Wi-Fi module and MEMS Microphone. Even while doing his class remotely, I still mailed my board and parts and was able to build a PCB right in my home that I then did labs with. His class was awesome! I felt like I learned so much and had a lot of fun."
- "Throughout this project, I learned a lot about designing, customizing, and manufacturing PCBs. With this project, I was allowed to do something that I have never done before which was take client specifications for a project and turn it into a reality. This allowed me to get a taste of what real-world engineering is like."
- "Designing a PCB with a team remotely was useful in a few ways. Learning to work as a team remotely was an exposure to what many people have had to deal with in the real world due to the pandemic."
- "The PCB project provided a good foundation for generating printed circuit boards, and the processes involved in generating a PCB, such as schematic capture and generating gerber files. This project also provided good fundamentals in the PCB design software, Diptrace, and gave industry knowledge on prototyping."
- "Many projects gave me a feeling of 'I finally feel like an engineer.' However, this PCB project was a standout because of its realistic engineering elements—from client requirements to design constraints to assembly. Seeing my name on a functioning product was incredibly rewarding."
- "This was an interesting project for me to work on and build a PCB. I learned a lot through this project as this was the first time I soldered. I gained a lot of knowledge in this area and now have some solid experience using a program like Diptrace all the way through to putting it together."

6. CONCLUSIONS

This paper details the innovative strategies implemented to transform the Introduction to Embedded Systems course into a remote learning format during the Fall 2020 semester, addressing the challenges posed by the COVID-19 pandemic. By introducing take-home lab kits and project-based learning, the course maintained its experiential learning focus, ensuring that students continued to develop critical skills in designing, fabricating, and integrating hardware and software systems.

The take-home lab kits empowered students to engage in real-world engineering practices, such as PCB design, soldering, and IoT integration, while fostering creativity and collaboration in a virtual environment. These strategies successfully bridged the gap between theoretical learning and hands-on application, providing students with a comprehensive understanding of embedded systems. The positive feedback from students, coupled with the recognition of the Rowan University President's Award for Excellence in Innovative Teaching, underscores the effectiveness and transformative impact of this approach.

Several key lessons emerged from this experience. First, providing clear instructions and robust communication channels is critical for the success of remote learning environments. Second, early exposure to foundational skills, such as PCB design, prepares students to tackle complex projects and enhances their confidence in applying engineering concepts. Finally, integrating project-based learning into the curriculum fosters engagement and adaptability, essential qualities for future engineers.

Moving forward, the strategies outlined in this paper offer a scalable framework for remote and hybrid education in embedded systems and other hands-on disciplines. These approaches not only address the immediate challenges of remote learning but also provide a foundation for leveraging technology to enhance accessibility and practical skill development in diverse educational settings. Based on the positive experience gained in Fall 2020, the author has continued to offer an online version of the Embedded Systems course that provides similar experience, activities and goals of the in person one. In Spring 2025, the enrollment of the online version of the Embedded Systems course was exactly the same as the enrolment of the in person version.

By sharing these insights and methodologies, this paper contributes to the ongoing dialogue on best practices in engineering education during times of crisis. It highlights the importance of adaptability, innovation, and a student-centered approach in overcoming educational barriers, ensuring that learning remains effective and relevant in any teaching environment.

REFERENCES

[1] S. Pasricha, "Embedded Systems Education: Experiences with Application-Driven Pedagogy," *IEEE Embed Syst Lett*, vol. 14, no. 4, 2022, doi: 10.1109/LES.2022.3175686.

[2] S. Pasricha, "Embedded Systems Education in the 2020s: Challenges, Reflections, and Future Directions," in *Proceedings of the ACM Great Lakes Symposium on VLSI, GLSVLSI*, 2022. doi: 10.1145/3526241.3530348.

[3] A. Shoufan, "Active Distance Learning of Embedded Systems," *IEEE Access*, vol. 9, 2021, doi: 10.1109/ACCESS.2021.3065248.

[4] I. Angulo, L. Rodriguez-Gil, and J. Garcia-Zubia, "Scaling up the Lab: An Adaptable and Scalable Architecture for Embedded Systems Remote Labs," *IEEE Access*, vol. 6, 2018, doi: 10.1109/ACCESS.2018.2812925.

[5] Y. Wang, B. Mendoza, and F. Zia, "Online Hands-on Embedded System Project in Virtual Classroom," 2024. doi: 10.18260/1-2--38444.

[6] N. ABEKIRI, A. RACHDY, M. AJAAMOUM, B. NASSIRI, L. ELMAHNI, and Y. OUBAIL, "Platform for hands-on remote labs based on the ESP32 and NOD-red," *Sci Afr*, vol. 19, 2023, doi: 10.1016/j.sciaf.2022.e01502.

[7] M. Bharath, J. Indra, and S. Kirubakaran, "Design and Development of Virtual Lab Environment for Embedded System and IoT Applications," in *Proceedings of the 2022 International Conference on Innovative Computing, Intelligent Communication and Smart Electrical Systems, ICSES 2022*, 2022. doi: 10.1109/ICSES55317.2022.9914369.

[8] M. Proske and C. Trodhandl, "Anytime, Everywhere - Approaches to Distance Labs in Embedded Systems Education," 2006. doi: 10.1109/ictta.2006.1684437.

[9] A. Abouhilal, A. M. Taj, N. Taifi, and A. Malaoui, "Embedded electronics applied in remote laboratories using NodeJs," *Iraqi Journal of Science*, vol. 2021, 2021, doi: 10.24996/ijs.2021.SI.1.1.

[10] C. Beck, L. Brodo, C. B. Q. Docmac, S. Henkler, A. Rettberg, and K. Rother, "Introducing a group-based remote laboratory for embedded education," in *IEEE International Conference on Industrial Informatics (INDIN)*, 2023. doi: 10.1109/INDIN51400.2023.10218010.

[11] Y. Wang, B. Mendoza, and F. Zia, "Online Hands-on Embedded System Project in Virtual Classroom," 2024. doi: 10.18260/1-2--38444.

[12] I. Angulo, L. Rodriguez-Gil, and J. Garcia-Zubia, "Scaling up the Lab: An Adaptable and Scalable Architecture for Embedded Systems Remote Labs," *IEEE Access*, vol. 6, 2018, doi: 10.1109/ACCESS.2018.2812925.

[13] A. Shoufan, "Active Distance Learning of Embedded Systems," *IEEE Access*, vol. 9, 2021, doi: 10.1109/ACCESS.2021.3065248.

[14] M. Proske and C. Trodhandl, "Anytime, Everywhere - Approaches to Distance Labs in Embedded Systems Education," 2006. doi: 10.1109/ictta.2006.1684437.

[15] M. Bharath, J. Indra, and S. Kirubakaran, "Design and Development of Virtual Lab Environment for Embedded System and IoT Applications," in *Proceedings of the 2022 International Conference on Innovative Computing, Intelligent Communication and Smart Electrical Systems, ICSES 2022*, 2022. doi: 10.1109/ICSES55317.2022.9914369.