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Board 393: Supporting Hardware Engineering Career Choice in First-Year Engineering Students

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Introduction

The semiconductor and digital electronics field is undergoing rapid changes with continuous progress in integrating Artificial Intelligence (AI) [1], expanding the Internet of Things (IoT) [2], enhancing cybersecurity [3], and prioritizing sustainability [4]. These developments have profound implications for various industries and the capabilities of electronic devices. Hardware engineers play a crucial role in driving these advancements, as they are responsible for designing the physical components and systems at the core of these technologies [5]. However, there is a notable shortage of hardware engineers entering the job market due to a tendency among many first-year computer science and computer and electrical engineering students to gravitate towards software-related career paths, often because of limited exposure to hardware-related topics [6].

To address this issue, our project, funded by the NSF Improving Undergraduate STEM Education (IUSE) program, aims to cultivate an early interest in hardware engineering to motivate students to view it as a promising career option. We are developing a hands-on and gamified curriculum to simplify fundamental hardware concepts such as binary numbers, logic gates, and combinational and sequential circuits. These concepts serve as a stepping stone for delving into the complexities of AI hardware and edge computing. We utilize hardware platforms such as low-cost Field Programmable Gate Arrays (FPGAs) and microcontroller and sensor-based IoT boards to facilitate this learning journey by introducing an additional abstraction layer. This approach is particularly beneficial for students with limited prior knowledge or experience with hardware, as it enables them to engage with these concepts, grasp their fundamental principles, and apply them to real-world situations. Our curriculum is rooted in inclusive practices, incorporating Universal Design for Learning (UDL) [7] and Culturally Sustaining Pedagogy (CSP) [8] principles. We also include experiential learning and inquiry-based learning pedagogies. Our primary goal is to provide a curriculum that resonates with all students, fostering self-efficacy, building expectations for positive outcomes, triggering and supporting interest, and guiding career choices in hardware engineering.

Our project employs a design-based research (DBR) [9] methodology to improve the curriculum through iterative analysis, design, development, and implementation. This report will outline the evolution of the curriculum following three implementations: a pilot test involving high school students, a summer residential program with high school students, and an elective course within the Electrical and Computer Engineering (ECE) department for undergraduate students in a large R1 institution in the southeastern US. We have collected data for specific purposes during each implementation, and the results are analyzed to refine our approach. Our overarching goal is to foster the development of a hardware engineering identity and sustained interest in the field, particularly focusing on addressing the needs of underrepresented groups.

Keywords: STEM education, hardware engineering, interest, situated learning.

Conceptual framework

Our curriculum's conceptual framework [10] is driven by the need to support engineering identity development through situational and individual interest theories [11], engineering persistence through self-efficacy theories [12], and engineering outcome expectations [13]. Renninger and Hidi [14] conceptualized interest as the dynamic interaction between an individual's engagement with specific content and their enduring motivation to engage with it over time. This perspective acknowledges that interest evolves over time, with researchers commonly distinguishing between situational interest, influenced by short-term external factors, and individual or personal interest, which is intrinsic and enduring [15]. Interest is closely intertwined with engineering identity, which encompasses a student's self-perception and conception of themselves as an engineer, including their beliefs, attitudes, and values towards the field [16]. Within an educational context, fostering interest among students can contribute to the cultivation of a robust engineering identity.

Conversely, self-efficacy pertains to an individual's confidence in their ability to effectively accomplish a task or attain a goal [12]. In the realm of engineering education, self-efficacy denotes a student's confidence in their aptitude to excel in engineering studies and eventually succeed as a proficient engineer. Studies have demonstrated that students with heightened self-efficacy are inclined to persist in their engineering pursuits [12]. This stems from the fact that students who possess confidence in their abilities tend to harbor a positive disposition toward their academic endeavors, exhibit heightened motivation to learn, and perceive a greater degree of control over their academic achievements [12]. Finally, an individual's outcome expectations are rooted in their beliefs about the results they anticipate from engaging in a specific endeavor [13]. Positive outcome expectations not only enhance motivation but also shape goal-setting, guide decision-making, and bolster self-efficacy beliefs [13].

To support interest, self-efficacy and outcome expectations, our activities emphasize equitable practices, experiential [17] and inquiry-based learning [18], collaboration, reflection, and gamified learning experiences [19]. Each lesson is divided into activation, mini-lesson, gameplay, student-led work time, and debriefing. In addition, each lesson features equity spotlights, including Universal Design for Learning (UDL) [7] and Culturally Sustaining Pedagogies principles (CSP) [8].

Additionally, educators' self-efficacy influences their confidence in teaching hardware concepts [20]. In our framework, this confidence is further sustained by the integration of teacher implementation strategies and educative materials, which are informed by the Technological

Pedagogical Content Knowledge (TPACK) framework [20]. Through this alignment, educators' self-efficacy serves as a bridge connecting their confidence levels with the instructional strategies and materials provided in each lesson. These connections among theoretical foundations are depicted in Figure 1 and are integrated into the design and development of the curriculum modules.

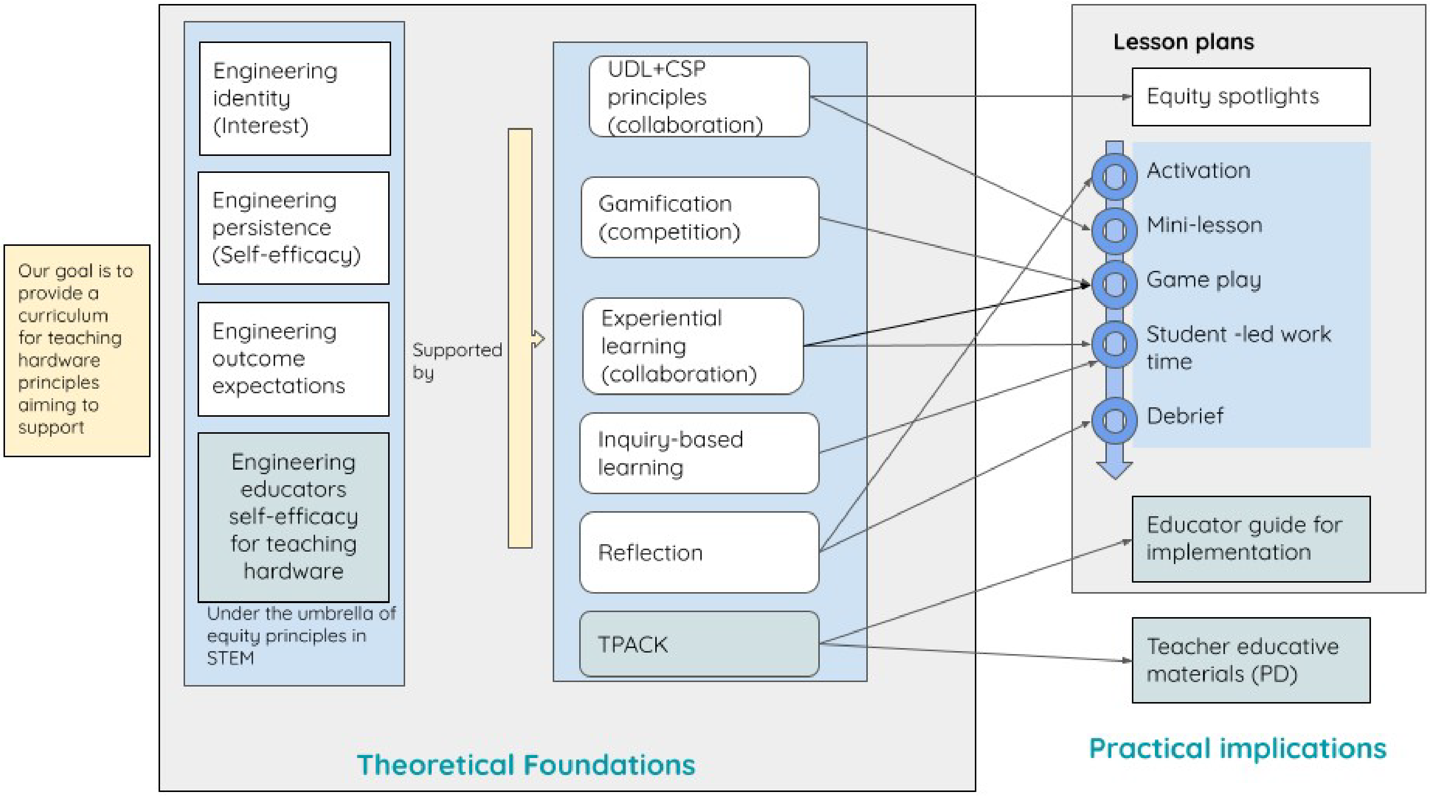

Figure 1. Curriculum conceptual framework

Method

Utilizing a Design-Based Research (DBR) framework [9], we aim to systematically investigate the effective conditions for designing and implementing our curriculum to cultivate situational interest and learning in hardware engineering. Our DBR approach employs a range of mixed and relevant methods, such as phenomenology, comparative case studies, and pre-posttest analyses, to gather diverse perspectives and insights.

Within the DBR program, the data gathered during each research cycle is essential for shaping the conceptualization, design, and implementation of our curriculum, as well as guiding subsequent cycles. This iterative process guarantees that our interventions are consistently refined and guided by empirical evidence. We have implemented our curriculum three times, as depicted in Figure 2.

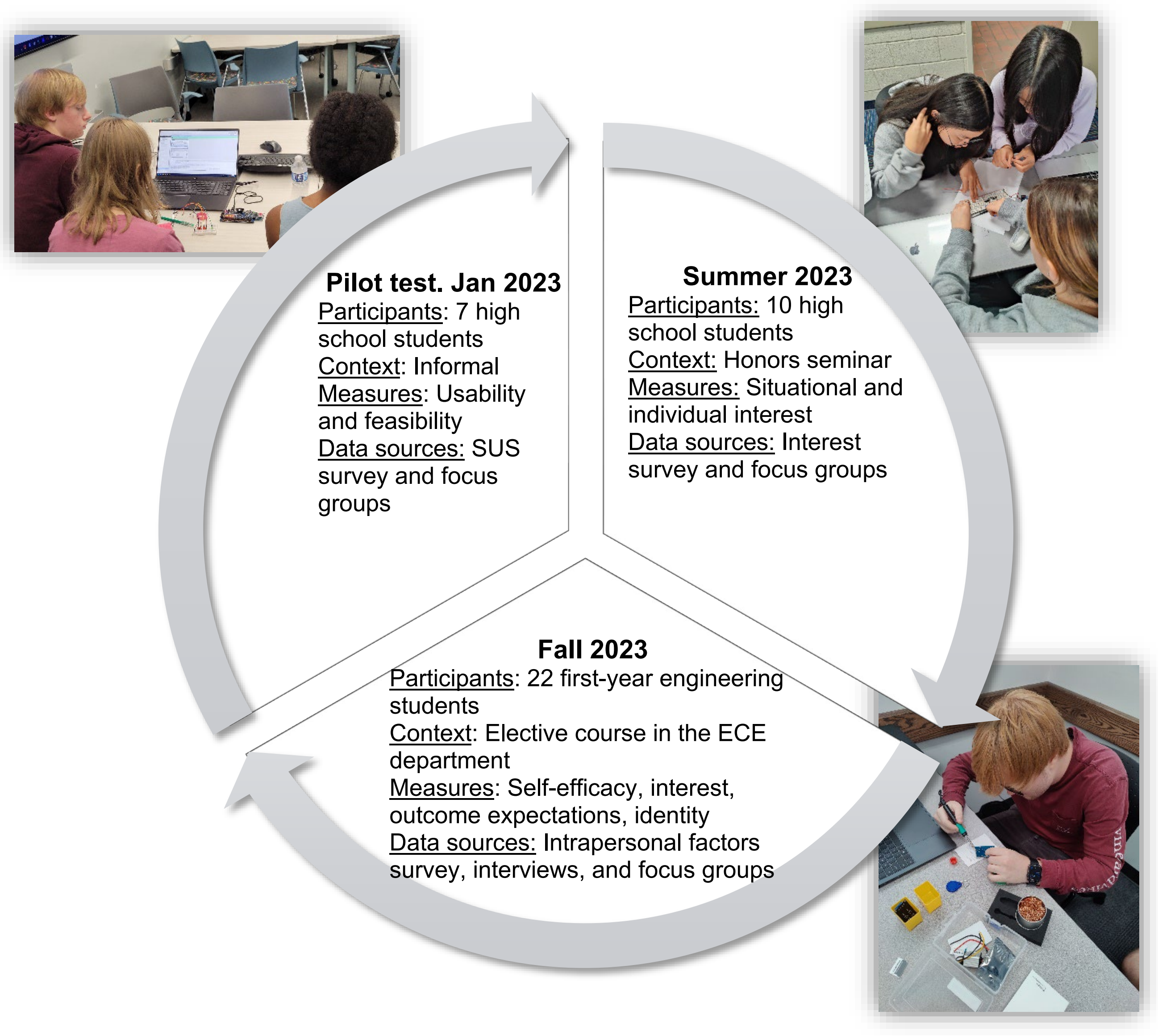

Figure 2. Cycles of implementation

Pilot test. January 2023

Participants

Six girls (n=6) and one boy (n=1) in grades ten and eleven participated in the usability testing as an after-school activity.

Instructional approach

One of the project's main aims is to create various games and activities that help reinforce fundamental concepts about computer hardware. Each game focuses on one or multiple hardware concepts and involves hands-on tasks.

In this implementation phase, participants were engaged with the initial two games from the curriculum utilizing a Digilent Artix-7 FPGA, as depicted in Figure 3. The games covered topics on binary numbers and Boolean logic. During the activity, students uploaded necessary files onto the FPGA and set up the board as per the game's requirements (the first game required a two-digit seven-segment display, while the second game called for a breadboard with LED lights). Because there was no expectation of prior knowledge, the students received a brief, interactive lecture on the relevant topics. The games were structured to foster both competition and collaboration among the participants.

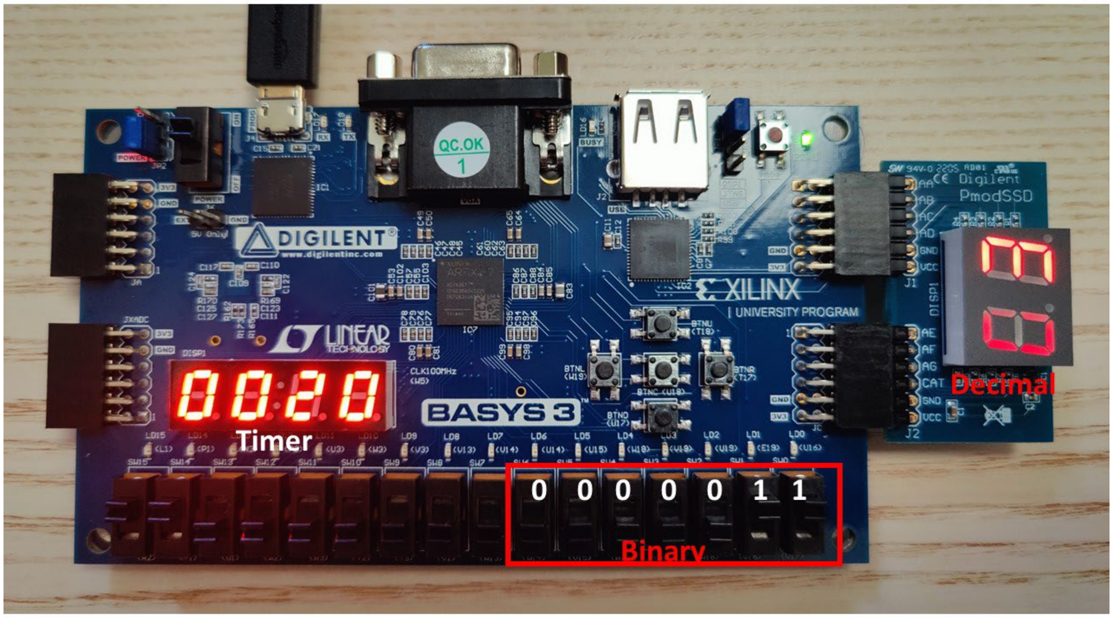

Figure 3. FPGA-based activity. In this game, students were prompted to convert a decimal number to binary and send their response using the seven switches highlighted in the red box. They could then confirm their answer on the two-digit seven-segment display located on the right side of the board. The timer was utilized to determine the winner.

Measures and data sources

After playing both games, students completed a Systems Usability Score (SUS) survey. The SUS is a widely recognized questionnaire utilized to assess the perceived usability of both software and hardware products [21]. We added two open-ended questions to the survey aiming to expand on the main points of the like/dislike aspects of the games. Also, we developed an observation protocol to validate students' behavioral, cognitive, and emotional engagement. Finally, we conducted a semi-structured focus group to gather participants' opinions, suggestions, and aspects of how they enjoyed interacting with the hardware boards.

Results

The average SUS score for all participants was 61. SUS scores range from 1 to 100. According to the literature, scores below 68 are considered below average [22]. To complement the findings from the SUS survey, we analyzed the categorized open-ended responses, along with the results from observations and focus groups. From this analysis, we derived the following design considerations for the games in the curriculum:

1. Minimize the external components connected to the FPGA.
2. Adjust the collaboration scope while retaining the competitive aspect.
3. Enhance the complexity of the concepts and incorporate more real-life applications.
4. Balance the games with activities that require more student involvement in the design of circuits.

Summer program June 2023

Participants

We scaffolded the curriculum activities to meet the needs of high school students attending an honors seminar during a summer residential program at a large R1 institution in the southeastern US. Our seminar, titled "Hands-on Introduction to Computer Hardware: A Game-Based Approach," occurred in person twice a week for six weeks, with each session lasting an hour and a half. Ten (n=10) students participated in the seminar. Among them, six (n=6), consisting of two (n=2) self-identified girls and four (n=4) boys, gave informed consent. These students came from various high schools across the United States.

Instructional approach

The seminar's activities aimed to balance simulations, real-life circuit design, FPGA-based games, and collaboration to develop FPGA-based projects to address real-world challenges. Examples of these challenges include integrating FPGAs with sensors to achieve intelligent home energy management or optimizing air conditioners for precise temperature control. The overarching goal was to explore a range of science and math concepts, such as binary arithmetic, Boolean logic, combinational circuits, finite state machines, and memory read-and-write processes. Additionally, students had the opportunity to engage with guest speakers who are experts and role models in the field of computer hardware engineering.

Measures and data sources

Before and after the seminar, students completed Romine et al.'s [15] Student Interest in Technology and Science (SITS) survey. The SITS instrument assesses individual interest in science and technology, specifically to understand students' ideas about learning, careers in science and technology, and computer engineering. We adapted the SITS instrument, designed initially to gauge individual interest in biotechnology, to focus instead on computer hardware engineering.

Additionally, students participated in a focus group at the end of the program. The focus group protocol was designed to explore students' perceptions of the activities and whether they triggered situational interest in hardware computing and provided meaningful engagement toward the topic.

Results

Survey results indicated that the six-week seminar increased participants' overall individual interest. Table 1 contains descriptive statistics, including the means (M), medians (Mdn), and standard deviations (SD) for each survey factor pre-seminar and post-seminar. The results for ideas about careers and computer hardware portrayed the greatest increase between pre and post. This finding suggests that the hands-on activities with FPGA boards and simulated circuits implemented during this 6-week summer seminar are effective in enhancing students' inclination to pursue further studies in hardware-related topics.

Table 1. Summer descriptive statistics

	Pre			**Post**		
	M	**Mdn**	**SD**	**M**	**Mdn**	**SD**
Ideas about learning	3.73	3.80	.34	4.00	4.00	.00
Ideas about careers	3.42	3.50	.31	3.85	3.85	.10
Ideas about computer engineering	3.77	3.90	.29	4.00	4.00	.00
Ideas about computer hardware	3.08	3.00	.58	3.83	4.00	.26

Analysis of the focus group discussions supported the quantitative results as students displayed traits suggesting a shift from an initial triggered situational interest to a more sustained level of individual interest.

From this implementation, we derived the following design considerations for the activities in the curriculum:

1. Ensure a balance between FPGA boards, simulations, and circuits while also exploring more advanced applications like Artificial Intelligence IoT (AIoT) and Edge AI.
2. Utilize the FPGA-based games to cover basic topics and provide students with opportunities for deeper exploration of FPGA manipulation for more complex hardware subjects.
3. Introduce students to the hardware design process, enabling them to manipulate both hardware and software used for FPGA programming.
4. Increase the use of simulations to streamline the setup process for hardware boards.

Fall semester 2023

Participants

During the Fall semester of 2023, we implemented our curriculum as an undergraduate course within the ECE department at a large R1 institution in the southeastern US. The elective class involved twenty-two (n=22) first-year engineering students, with seventeen (n=17) granting informed consent—four women (n=4) and thirteen (n=13) men. Students were asked to complete pre- and post-surveys and participate in focus groups and interviews.

Instructional approach

In this cycle, we expanded the curriculum to include activities involving sensor-based IoT boards in addition to those used in previous implementations, such as FPGAs and circuits, as depicted in Figure 4. Students were encouraged to utilize various sensors, including motion, weather, heart rate, ultrasonic, and light sensors, to collect environmental data. This data was then analyzed using machine learning algorithms to make predictions about different conditions. This curriculum's implementation included Artificial Intelligence Internet of Things (AIoT) and edge AI topics. Towards the end of the module, students collaborated in groups on a project utilizing the IoT learning board sensors and machine learning algorithms to develop a real-world solution.

Measures and data sources

At the beginning and end of the semester, students completed a survey on intrapersonal factors to measure changes in self-efficacy, interest, outcome expectations, and hardware engineering identity. This survey was adapted from Neiderhauser and Perkmen's [23] Intrapersonal Technology Integration Scale (ITIS). According to Social Cognitive Career theory approaches, these intrapersonal factors are strongly linked to career intentions [24]. Additionally, students participated in focus groups and semi-structured interviews after the semester.

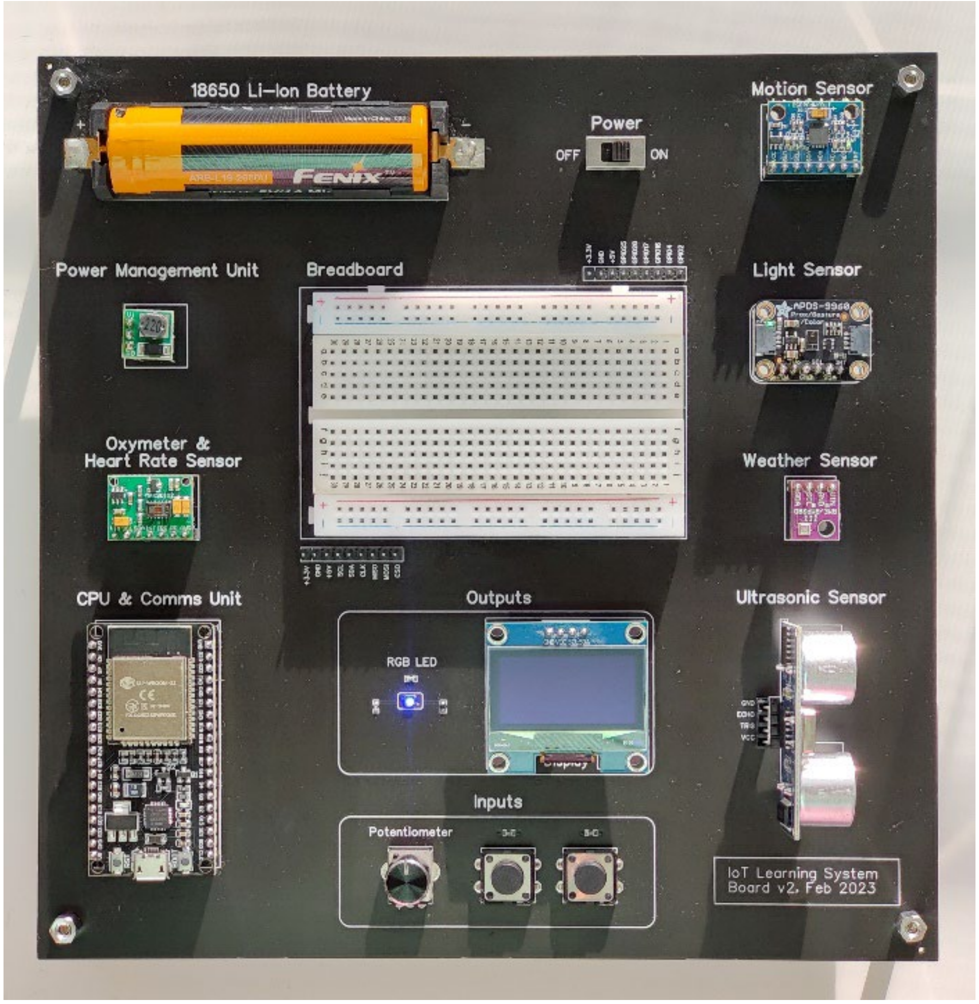

Figure 4. IoT learning board

Results

Findings from the survey indicated significant improvements in students' interest before and after the course ($t_{16} = 2.56, p < .02$), students' self-efficacy ($t_{16} = 3.97, p < .001$), students' engineering identity ($t_{16} = 4.78, p < .001$), and students' outcome expectations ($t_{16} = -2.27, p < .05$). These results are encouraging as they indicate that the curriculum effectively promotes career intentions in hardware engineering, which aligns with the primary objective of our project. The qualitative analysis of the focus groups and interviews is ongoing, and the results will be incorporated into the curriculum's next implementation in Fall 2024.

Future implications

Based on the data collected during the curriculum implementation in Fall 2023, it is crucial to conduct thorough analyses that take into account gender and racial differences. This will allow us to develop targeted and specific supports tailored to address the needs of underrepresented groups, thus promoting a more equitable and diverse workforce in hardware engineering.

Moreover, it is essential to actively involve high school and higher education teachers in refining and testing the curriculum. By engaging educators in this process, we can ensure that the curriculum effectively meets the diverse needs of students and aligns with educational standards. Additionally, creating and disseminating comprehensive curriculum implementation guides is vital to ensuring broad adoption and maximizing the curriculum's impact.

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