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# Exploring the Impact of Hands-on Learning in Embedded Systems on Undergraduate Research Experiences

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# Exploring the Impact of Hands-on Learning in Embedded Systems on Undergraduate Research Experiences

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## Abstract

With the growing demand for embedded systems expertise in fields like consumer electronics, healthcare, and robotics, Engineering Technology programs in the U.S. have increasingly integrated practical learning into embedded systems education. Although a number of embedded systems learning and development tools are available, very few are fully capable of meeting both academic and industrial R&D needs. The Modular Integrated Stackable Layer-Analog System Environment (MISL-ASE) board was designed and developed to support a hands-on approach across six embedded systems design courses at several universities. These courses range from basic microcontroller programming to advanced embedded systems design, real-time operating systems, and system integration. Through a series of hands-on lab exercises and three funded research projects in embedded system design, this study explores how hands-on learning in the classrooms with MISL-ASE boards impacts undergraduate research experiences, including their understanding of embedded systems, research skills, and career interests. Results from an anonymous survey indicate that all undergraduate research students found the practical learning experiences highly beneficial, significantly enhancing their understanding of embedded systems and their ability to contribute to research. Additionally, all research students expressed confidence in applying the skills acquired through hands-on learning to research projects, with many reporting increased interest in pursuing careers or further research in embedded systems design. Furthermore, the study highlights the importance of integrating PCB (Printed Circuit Board) design, system debugging, and industry collaboration into the embedded systems curriculum to maximize student learning outcomes. As the demand for embedded systems engineers continues to grow, equipping students with practical, hands-on experiences through tools like the MISL-ASE board is crucial for preparing the next generation of engineers.

## 1. Introduction

The field of embedded systems plays a pivotal role in the development of modern electronic and computer technologies. With applications spanning from consumer electronics - such as smartphones, medical and healthcare equipment, and household appliance to electro-mechanical systems like automated industrial machines, robotics, automobiles, and aerospace systems, expertise in embedded systems is a critical skill for electrical engineers pursuing careers in electronic product development using embedded systems technologies. Recent market analysis [1] projects a compound annual growth rate of 5.73% for embedded systems over the next five years, along with the creation of over 112,000 jobs related to electronic product design nationwide [2].

The rapidly growing demand for embedded systems expertise has driven significant advancements in embedded systems education in the United States. Many Engineering Technology programs now include a three-course sequence focused on embedded systems design. The first course introduces C programming, the primary language used for microcontroller programming, along with fundamental microcontroller concepts and applications. The second course delves into microcontroller architecture, covering topics such as registers, memory addressing, subroutines, stacks, exceptions, peripheral I/Os, clock systems, interrupts, timers, and more. It also covers assembly language to provide a deeper understanding of microcontroller architecture. The third course expands on digital interfacing, analog electronics, communication protocols, development tools, and real-time operating systems, equipping students with advanced skills in embedded system design. Although a number of embedded systems learning and development tools are available [3-8], few fully meet both academic and industrial R&D needs. As an instructor in Electrical, Electronics, and Mechatronics Engineering and Technology, my primary teaching focuses on embedded engineering design and industrial automation. Since 2013, I have taught five embedded systems courses at Texas A&M University (TAMU) and Northern Kentucky University (NKU). To integrate the latest microcontroller techniques and methodologies into the curriculum while providing hands-on laboratory experiences, I redesigned the curriculum and developed the Modular Integrated Stackable Layer - Analog System Environment (MISL-ASE) board [9]. Hands-on learning with the MISL-ASE boards has been shown to significantly enhance student engagement and skill acquisition.

Additionally, I have secured research funding from industry, government, and professional associations to support projects focused on product development using embedded systems technologies. These projects—such as the development of embedded systems design kits with modular interchangeable hardware architecture, a MISL-based CubeSat instrumentation system, and a GSM-based intelligent monitoring system—have provided undergraduate student researchers with opportunities to apply their classroom knowledge to real-world design challenges, including embedded system hardware and software design, as well as system integration.

A review of the literature reveals that few studies have explored the relationship between undergraduate students' hands-on learning in embedded systems design and their participation in related research projects. Through close engagement with students and careful observation of their progress, two key questions have emerged: (1) How does hands-on learning using the MISL-ASE boards and lab assignments influence undergraduate research experiences? Specifically, to what extent does participation in hands-on learning improve students' knowledge and practical design skills in embedded systems research projects? (2) How can insights gained from student research advising enhance my teaching and better prepare students for future career challenges? This paper explores the impact of integrating hands-on learning with the MISL-ASE boards into embedded systems education, focusing on its influence on undergraduate research experiences. Also, the potential areas for further enhancement of the embedded systems design curriculum are identified.

## 2. Materials and Methods

### 2.1 The MISL-ASE Boards

The development of the MISL-ASE embedded system board was supported by Texas Instruments, NASA Johnson Space Center, and the ECETDHA (American Electrical & Computer Engineering Technology Departments Heads Association). The MISL-ASE board consists of four main components: the MISL architecture and TI-MSP430 intelligence layer, the General Purpose Input/Output (GPIO) section, the signal conversion section, and the wired and wireless communications section. Figure 1 provides an illustration of the MISL-ASE board and its features.

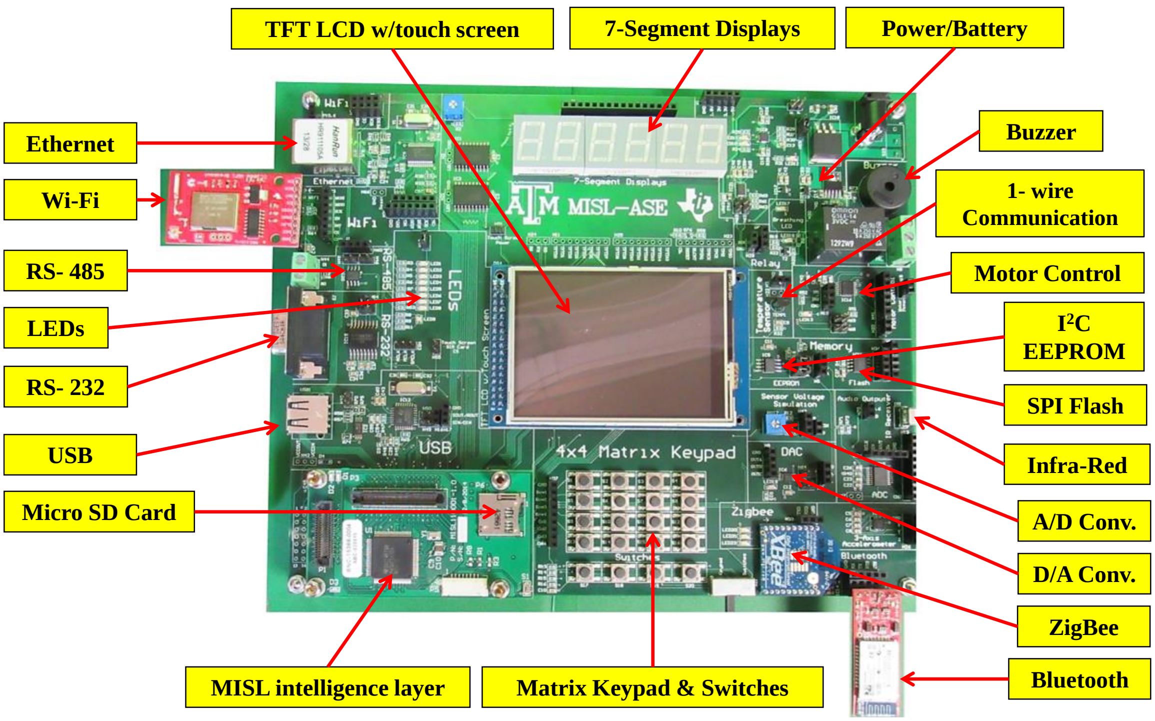


Figure 1: The MISL-ASE embedded system development board.

As shown in Figure 1, the board integrates the MISL-MSP430 microcontroller intelligence layer with a variety of essential and advanced analog and digital circuits and modules. The fundamental components include LEDs, 7-segment displays, a 1602 LCD, switches, keypads, A/D conversion, multiple analog signal generators, and serial communications, etc. Moreover, the board features advanced capabilities not typically found in other embedded systems development tools, such as a TFT LCD with touch screen, Ethernet LAN network connectivity, battery life density measurement, a 3-axis accelerometer, a high-resolution external ADC converter, motor drive functionality, and remote-control capabilities. Furthermore, the MISL-ASE board supports a variety of new communication interfaces and protocols, including UART (USB, RS-232/485, Bluetooth, and Zigbee), SPI (Ethernet, 2.4 GHz Wi-Fi, Micro SD card, and flash memory), I$^2$C (DAC and EEPROM), and 1-wire communication devices.

Two versions of the MISL-ASE board were designed, developed, and tested, along with a series of laboratory assignments and course projects. A total of 250 boards were procured and assembled. These boards have served as key laboratory equipment for five courses in the Electronic Systems Engineering Technology (ESET) program at Texas A&M University, as well as in the Electronic & Electrical and Mechatronics Engineering Technology (EEET and MET) programs at Northern Kentucky University.

### 2.2 Implementation of Hands-on Experiments

Prior to enrolling in embedded systems courses, students must complete prerequisite classes in C computer language programming and Digital Electronics. These courses provide foundational knowledge in C programming and digital logic design, which are essential for success in subsequent embedded systems coursework.

Embedded Systems Design Course 1 (names could include Microprocessor, Microcontroller Architecture, Microcontroller Applications, Introduction to Microcomputers, etc.) offers an in-depth exploration of microcontroller architecture and key interfacing concepts. In this course, students are able to: 1) understand microcontroller architecture, including components like the processor, ALU, memory, registers, stacks, logical operations, and instruction sets; 2) program microcontrollers using embedded C; and 3) design basic embedded systems using digital GPIOs, timers, interrupts, and external peripherals. The course includes eight hands-on assignments and a final three-week project using the MISL-ASE boards. These lab assignments cover topics such as registers, memory addressing, subroutines, stacks, peripheral I/O, clock systems, interrupts, and timers. In the final project, students use the TI MSP430F5438A microcontroller, four switches, the Timer A0, and two 7-segment displays to build a functional stopwatch. This project allows students to apply both theoretical and practical knowledge gained from lectures and labs to create a real-world embedded system, reinforcing concepts like microcontroller architecture, GPIOs, clock systems, interrupts, timers, and display interfacing.

Embedded Systems Design Course 2 (names could include Advanced Microprocessor, Embedded Systems Software, Advanced Microcontroller Engineering, Embedded and Real-Time Systems, Advanced Microcontroller and Embedded System Design, etc.) builds on the foundational knowledge from Course 1, focusing on advanced microcontroller techniques and the use of real-time operating systems. The lab component includes four projects and a comprehensive four-week final project using the MISL-ASE board. The four projects cover interfacing an LCD with the microcontroller, keypad programming, UART serial communications, and $I^2C$ (Inter-Integrated Circuit) programming. The final project integrates techniques learned throughout both embedded systems courses, culminating in the development of a real-time signal measurement system. Key tasks include programming the internal Analog-to-Digital Converters (ADC12) to sample analog signals from sensors, convert them into binary values (ranging from 0000 to 4095), and display these values on 7-segment displays or an LCD. Additionally, the system transmits the data to a computer screen via UART serial communication. This project also introduces students to Real-Time Operating Systems (RTOS), specifically the uC/OS-III or freeRTOS kernel, which enables task management with varying priorities (signal sampling, display management, UART communication, and keys/switches handling). Through this project, students deepen their understanding of RTOS concepts such as task scheduling, interrupt handling, task management, and timers, while gaining practical experience with RTOS features like semaphores, mailboxes, and message queues.

### 2.3 Research Projects Related to Embedded Systems Design

In this paper, three funded research projects are discussed to explore the impact of hands-on learning in embedded systems design on undergraduate research experiences.

- Embedded Systems Design Kits with Modular Interchangeable Hardware Architecture *(funded by ASEE, American Society for Engineering Education and CINSAM research grants)*: The MISL-ASE boards have generated significant interest from multiple universities, students, and product development engineers. However, individual student acquisition of the boards remains a challenge due to their relatively high cost, exceeding $1500 per unit. To address this issue, I and undergraduate research assistants, developed a cost-effective embedded systems design kit [10].

  A survey revealed that various microcontroller families (e.g., TI-MSP430, ATMEL-AVR, Microchip-PIC32, Silicon-8051, and ARM) are being taught at universities across the United States. A literature review indicated that existing development boards are typically designed for a specific microcontroller model. If students wish to explore multiple microcontroller families or brands, they must purchase separate development boards for each, significantly increasing their financial burden. To overcome this limitation, our project introduced a novel modular interchangeable hardware architecture, allowing popular microcontrollers (e.g., TI, Atmel, and Microchip) to interface with the same main board. This design enables students to learn various microcontroller families using consistent devices and peripherals by simply swapping the modular microcontroller layer. Figure 2 illustrates the embedded systems development kit with modular interchangeable hardware architecture. This solution maintains essential analog, digital, and wired/wireless devices while significantly reducing both cost and size.

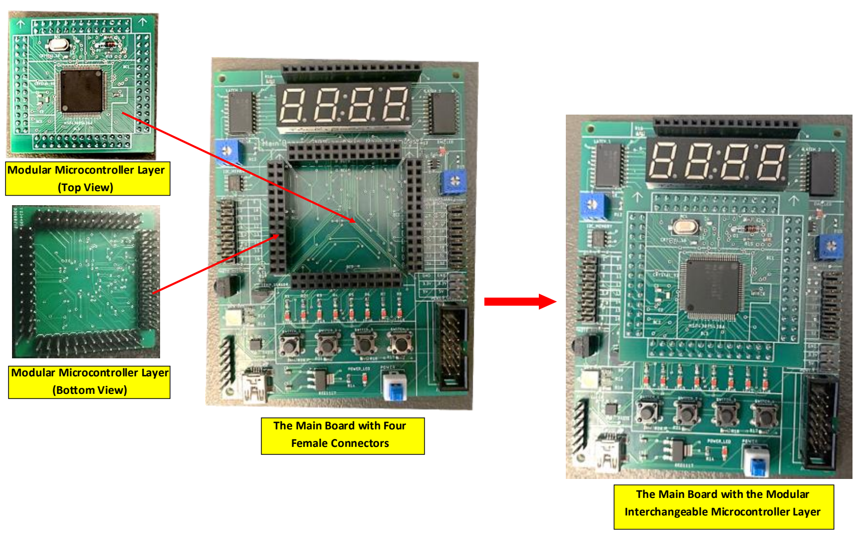


Figure 2: The embedded systems development kit.

- A MISL-based CubeSat Instrumentation System (*funded by the NASA-EPSCoR grant*): CubeSats are miniaturized nanosatellites designed for deployment in Low-Earth Orbit

(LEO) for space science research. With the growing emphasis on microgravity scientific studies conducted in outer space, there is an increasing demand for cost-effective and reliable instrumentation platforms capable of supporting a wide variety of research experiments aboard CubeSats. This project leveraged a NASA-standard, space-qualified MISL hardware structure to develop a low-cost, modular, and scalable instrumentation system for experimental data acquisition, storage, and communication in a microgravity environment. The system features the new MISL-DAQ (Data Acquisition) layer, designed for multi-channel, high-resolution data sampling, conversion, processing, and storage, alongside the MISL power and MSP430F5438A intelligence layers. This integration aims to address NASA mission directorate challenges in space science research and produce cutting-edge technologies for public use in LEO experiments and services. Figure 3 showcases the MISL-based CubeSat instrumentation system with the DAQ layer.

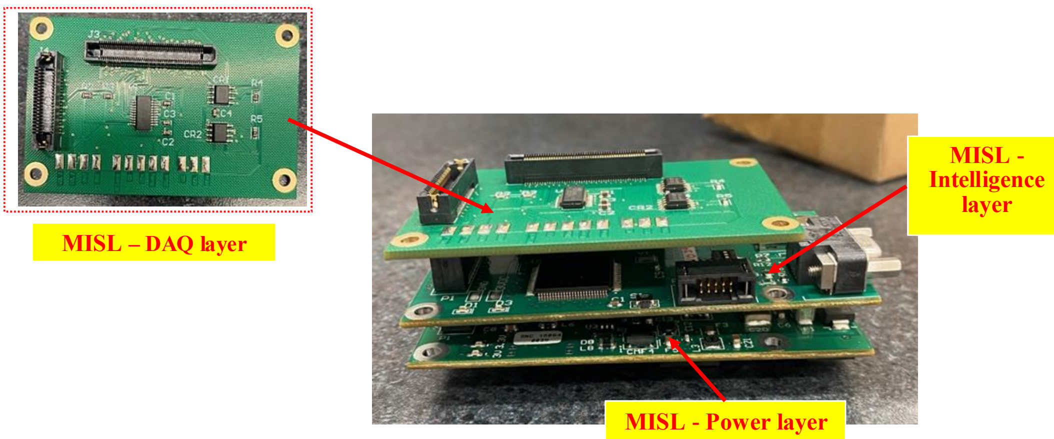


Figure 3. A MISL-based CubeSat Instrumentation System.

- A GSM-Based Intelligent Monitoring System for Improving Robotics Laboratory Safety *(funded by the CINSAM research grant)*: Incorporating industrial robots into robotics curricula has become a key element in engineering and technology programs. Toyota Motor Engineering & Manufacturing North America donated a Kawasaki ZB150S industrial robot to Northern Kentucky University. While the entire Kawasaki robot system was housed within a safeguard cage, the cage was not always effective in preventing unauthorized students from entering the robot's working area. As a result, the lab manager and staff identified an urgent need for a smart tool to monitor and prevent unauthorized access, thereby enhancing laboratory safety. To address this need, we designed and developed a GSM-based intelligent monitoring system to ensure a safe operating environment for students in the robotics lab [11]. The system was divided into two subsystems: the Embedded Laboratory Environmental Monitoring and Robot Power Control (ELEMRPC) subsystem and the GSM communication subsystem. The ELEMRPC subsystem detected presence signals from light curtains at the cage entrance and automatically disarmed the robot’s power supply when unauthorized individuals were detected. Additionally, it monitored lab environmental parameters (e.g., temperature, relative humidity, and light level). The GSM subsystem transmitted text messages (such as lab safety information) to designated cellular phones, alerting lab staff and managers in real time. These notifications enable immediate action to prevent potential accidents within the robot's safety cage. Figure 4 illustrates the GSM-based intelligent monitoring system, displaying the system status (Disarmed) and laboratory environmental parameters on the OLED.

Figure 4. The GSM-Based intelligent monitoring system.

## 3. Evaluating the Impact of Hands-on Learning

To assess the impact of hands-on learning in embedded systems design courses on undergraduate research, an anonymous student survey was conducted using the SurveyMonkey platform. The survey aimed to examine how practical learning experiences influenced undergraduate research and to gather insights from student research advising that could enhance my teaching practices. The anonymous survey included nine questions: six multiple-choice questions and three open-ended questions. These are as follows:

1) Overall, how would you rate your experience in our embedded systems courses that incorporated hands-on learning through the MISL-ASE board?
   A. Excellent B. Good C. Fair D. Poor
2) How confident do you feel in applying the skills acquired from the embedded systems courses to research projects related to embedded systems design?
   A. Very confident B. Confident C. Somewhat confident D. No confident
3) Which aspects of hands-on learning and related research projects were most beneficial to your understanding of embedded systems? (Select all that apply)
   A. Practical experiments with the MISL-ASE board
   B. Final course projects
   C. Conducting research projects related to embedded systems design
   D. Collaboration with peers on research projects
4) To what extent did hands-on learning in embedded systems courses enhance your ability to contribute to research projects?

A. Significantly enhanced my contributions
B. Moderately enhanced my contributions

C. Had little impact on my contributions
D. Did not impact my contributions
5) Did working with the MISL-ASE board in the embedded system courses improve your understanding of the electronic product development process (e.g., hardware/software integration, software debugging, etc.)??
A. Yes, significantly B. Yes, moderately C. No, only slightly D. Not at all
6) How did the hands-on learning experience influence your interest in pursuing further research or a career in embedded systems design/electronic product development?
A. Increased my interest significantly
B. Increased my interest moderately
C. Had no effect on my interest
D. Decreased my interest
7) What challenges did you encounter while applying hands-on learning in the embedded system courses to work on research projects?
8) What additional topics, tools, or resources would you suggest incorporating into the course or research projects to enhance the hands-on learning experience?
9) Please share any other feedback on how hands-on learning has influenced your skills, confidence, or interest in embedded systems design research.

<u>Data Analysis and Findings</u>: Since 2017, I have advised a total of 28 NKU undergraduate research students on my research projects, including 12 who participated in the three embedded systems design projects mentioned above. All these 12 students received research stipends; 10 have graduated, and 2 are currently senior students. The survey results clearly indicate that all participating students found hands-on learning in embedded systems design highly beneficial to their research experiences.

<u>Multi-choice question Responses</u>

- Question 1: All undergraduate research students rated their hands-on learning experience in the embedded systems courses as “Excellent”.
- Question 2: All students expressed high confidence in applying the skills acquired from the embedded systems courses to their research projects.
- Question 3: Students identified two key aspects of hands-on learning that were most beneficial to their understanding of embedded systems: practical experiments with the MISL-ASE board and conducting research projects related to embedded systems design.
- Question 4: All students agreed that hands-on learning significantly enhanced their ability to contribute to research projects.
- Question 5: 100% of students reported that working with the MISL-ASE board significantly improved their understanding of the electronic product development process.
- Question 6: The majority of students reported that hands-on learning significantly increased their interest in pursuing further research or a career in embedded systems design and electronic product development. Only one student noted "no effect" on their interest, likely due to his/her different career plan.

Open-Ended Responses

For Questions 7-9, students provided valuable feedback on their hands-on learning and research experiences:

- Question 7: Students identified several challenges encountered when applying hands-on learning to research projects: 1) PCB design: Unfamiliarity with PCB design was noted as the biggest challenge; 2) Debugging and troubleshooting: projects usually did not work the first time, requiring individual troubleshooting; 3) Programming microcontrollers: Students reported a need for stronger programming skills to write code for each project; and 4) Teamwork: Effective collaboration can help transfer lecture knowledge into hands-on applications.
- Question 8: Students suggested incorporating more advanced topics and tools into the course, including: PCB schematic and layout design as well as advanced computer programming topics for embedded systems design.
- Question 9: Students shared positive reflections on the impact of hands-on learning. They reported that it solidified their understanding of key topics. Graduates highlighted how the skills gained in class and lab were directly applicable in the industry. One student specifically mentioned that the hands-on experience significantly benefited their career as an Electronics Engineer, especially in areas such as PCB board assembly and testing.

## 4. Discussions and Conclusions

This research examined the impact of practical learning experiences in embedded systems design courses on undergraduate research experiences. The survey results indicate that all participating students found hands-on learning to be highly beneficial to their research experiences. Specifically, through hands-on learning with the MISL-ASE boards in both classroom and laboratory settings, all undergraduate research students agreed that this practical approach significantly enhanced their understanding of embedded systems. Furthermore, it improved their ability to contribute to research projects and increased their confidence in transferring skills acquired in the courses to their research work.

Additionally, the majority of students reported that hands-on learning significantly heightened their interest in pursuing further research or a career in embedded systems design. However, several challenges were identified, along with my insights from student research advising, that can be used to improve teaching practices in embedded systems courses. Student feedback and performance data suggest the following areas for improvement:

1) PCB Schematic and Layout Design: A notable gap in PCB design instruction exists across most Engineering Technology (ET) programs in the U.S. Incorporating PCB design into the curriculum would address this deficiency.
2) Software Development: Several advanced topics in C programming should be introduced to strengthen students' programming skills, including pointers and arrays applications, data structures (such as linked lists, stacks, and queues), and algorithms (e.g., recursion, sorting, binary search, and backtracking algorithms).
3) System Integration: More emphasis on systems testing, debugging, and the use of related tools is necessary to prepare students for real-world embedded systems design challenges.

While time constraints in the curriculum are a consideration, feasible ways may exist to integrate these improvements without overwhelming students. PCB design instruction could be introduced as a dedicated module within the Embedded Systems Course-2 and capstone design courses, utilizing industry-standard design tools such as Eagle CAD or Altium Designer. To strengthen students' programming skills, additional lab assignments covering advanced C programming topics—such as pointers, data structures, and algorithms—can be integrated into the Embedded C programming class and Embedded Systems Course-2. Additionally, system testing and debugging concepts can be incorporated into final embedded systems projects by requiring students to conduct structured debugging exercises using tools like logic analyzers, oscilloscopes, and embedded system debuggers.

Lastly, collaborating with industry experts to provide workshops on emerging technologies would further enhance the students' learning experience and better prepare them for careers in embedded systems design and electronic product development.

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## Biographical Information

**Dr. Gang Sun** is currently an associate professor of Engineering Technology programs at Northern Kentucky University. His primary teaching areas are digital & analog electronics, embedded systems design, programming for engineering applications, industrial automation, control, and Capstone design. Research interests include designing mechatronic/electronic systems that integrate embedded systems, programmable logic controllers, machine vision, real-time operation system, wired/wireless communication, sensor networks, and actuator control in various industrial, agricultural, and environmental applications. Additionally, his research is concerned with the study of complex dynamic systems using traditional physics-based numerical modeling, big data analytics, and machine learning methods.