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Practical Learning in Microcontroller Courses Using Novel MISL-ASE Embedded System Development Boards

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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.

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Abstract

In recent years, the growing demand for mechatronic systems and smart products has fueled a substantial expansion in the global embedded systems market, leading to an influx of high-paying design positions across various industries. Embedded systems education often relies on hands-on learning experiences provided by embedded systems development boards. To swiftly integrate the latest microcontroller techniques into existing microcontroller courses, we have developed, constructed, and tested a novel Modular Integrated Stackable Layer - Analog System Environment (MISL - ASE) board. This board, featuring the MSP430F5438A microcontroller intelligence layer in conjunction with a range of fundamental and advanced analog & digital circuits and modules, serves as major experimental equipment in our embedded systems design education. Through two pivotal microcontroller courses at Northern Kentucky University (NKU), students engage in hands-on exploration of microcontroller architecture, covering registers, memory addressing, subroutines, stacks, peripheral Inputs/Outputs, clock systems, interrupts, timers, as well as advanced microcontroller techniques and real-time operating systems. The proposed practical experiments and course projects, conducted on the MISL-ASE boards, empower students with invaluable insights and skills. Survey results from anonymous student feedback indicate heightened interest in microcontroller courses and improvements in hands-on knowledge and skills relevant to embedded systems design. This paper provides an overview of the introduction of the MISL-ASE board, details of lab assignments and final projects and examines the impacts on students' learning outcomes.

1. Introduction

An embedded system is an electronic system that combines microcontroller hardware and software for monitoring and controlling diverse electro-mechanical systems (e.g., automated industrial machines, robotics, automobiles, airplanes, etc.) and smart devices (e.g., medical and healthcare equipment, smartphones, and household appliances, etc.) [1]. In recent years, a surging demand for those mechatronic systems and intelligent products has driven the fast growth of global embedded systems market, from $88.35 billion in 2020 to $138.45 billion (projected) by 2028 at an annual growth rate of 5.73% [2]. This increased need has resulted in a significant increase in high-paying design positions across diverse industries. Nationally, there are approximately 77,000 vacancies, with around 4,090 openings in the Tri-State area near our university [3]. Notably, embedded systems design roles are integral to electronic product designer positions that leverage microcontroller technologies, contributing to over 163,000 available jobs nationwide [4].

Embedded systems design education in microcontroller courses is predominantly provided by Engineering Technology (ET) programs (e.g., Electrical, Electronics, and Mechatronics ET programs) in the United States. Engineering Technology is an applications-oriented engineering major that emphasizes the application of specific engineering techniques. The author conducted a course survey on the state of embedded systems design education within Electrical and Electronics Engineering Technology Programs nationwide. This survey encompassed various aspects such as participating schools, course codes, microcontroller models taught, and course syllabi, etc. The survey reveals that the ET curricula in many universities typically incorporate a three-course sequence in embedded systems design education. The first course is a 200-level class in C language programming, the sole computer programming course in most engineering technology programs. This class not only imparts essential C programming skills but also exposes students to microcontroller development environments and several basic microcontroller applications. The second course, a 300-level class, delves into the microcontroller architecture, including registers, memory addressing, subroutines, stacks, peripheral Inputs/Outputs, clock systems, interrupts, timers, and more. Additionally, this course introduces interfacing concepts, connecting microcontrollers to external devices like sensors, buttons, LCD displays, and motors.

The final course, a 400-level class, concentrates on embedded systems development methodologies, advanced microcontroller programming techniques, and real-time operating systems, providing students with advanced design skills.

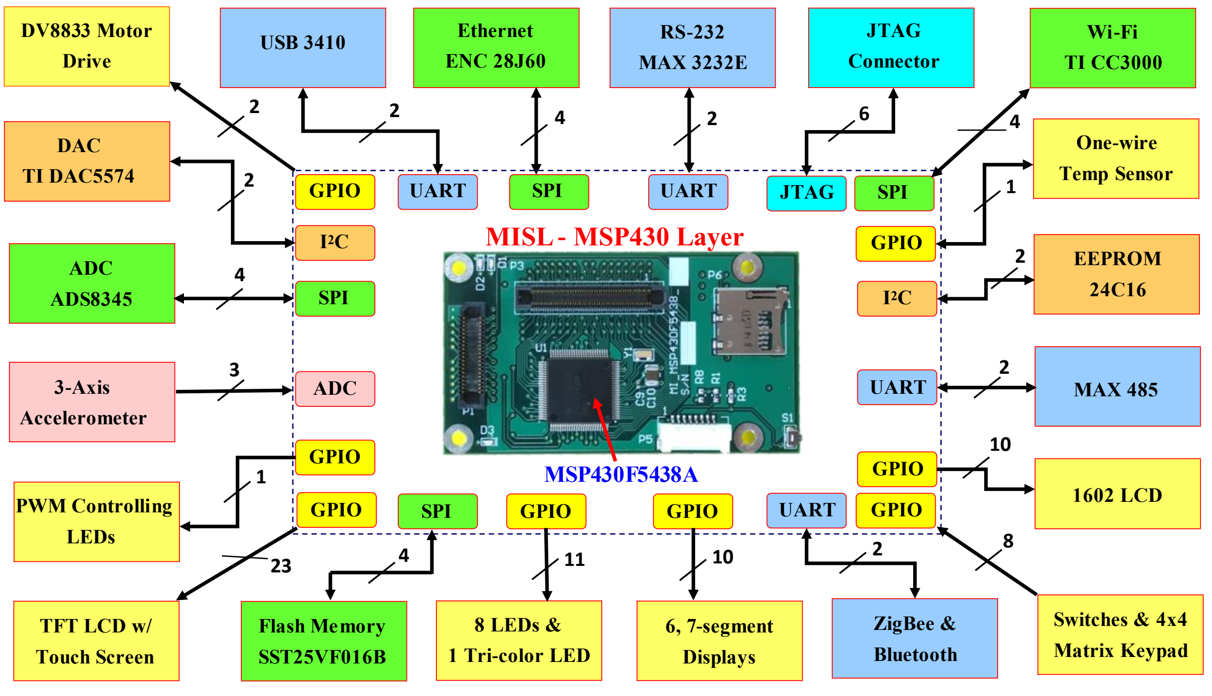
In embedded systems education [1, 4-11], students primarily acquire hands-on learning experiences through experiments and course projects conducted on development boards, such as Texas Instruments Launchpad kits, Arduino, Freescale, TI-ARM, PIC, Motorola and Intel-8051 experimental boards, etc. The Texas Instruments LaunchPads offer limited hardware resources, with only a handful of basic lab examples accessible for download from the TI website. In practice, students often replicate the code for lab assignments, reducing the overall learning experience. While Arduino provides a cost-effective, open-source microcontroller platform designed initially for hobbyists or non-electrical and electronics major students to delve into embedded systems design, its capabilities fall short when dealing with the intricacies of large, advanced, and real-time systems. In addition, Arduino lacks support for harsh operational environments typical in aerospace, automotive, medical, and communication systems prototyping [12]. The PIC and Motorola experimental boards [6-7, 13] often lack support for new industrial communication and control protocols, and their power is not very sufficient. At Texas A&M University, embedded systems development in C utilized a three-board MISL stack [12]. However, students working with the MISL stack found themselves spending considerable time wiring and debugging circuitry, diverting their focus from designing, testing, and documenting their programs.

To expeditiously incorporate the latest microcontroller techniques into the creation of cutting-edge real-time embedded systems, a novel Modular Integrated Stackable Layer - Analog System Environment (MISL - ASE) board has been developed, constructed, and validated. This board is designed for students and product design engineers seeking to delve into advanced microcontroller technology and explore a broad range of new digital, analog, and communication modules. This paper outlines the experiential learning process of embedded systems design using the innovative MISL-ASE boards and examines the impacts on students' learning outcomes.

2. Materials and Methods

2.1 Introduction of the MISL-ASE Embedded System Development Boards

The MISL-ASE embedded system development board project was supported by Texas Instruments, NASA Johnson Space Center, ECETDHA (US Electrical & Computer Engineering Technology Departments Heads Associate), and university faculty development funds from Texas A&M University and Northern Kentucky University. Picture 1 displays the overall Functional Block Diagram (FBD) of the MISL-ASE board.



Note: the digit indicates the wire number of each cable.

Figure 1: Overall functional block diagram of the development board.

The MISL-ASE board encompasses the MISL - MSP430 microcontroller intelligence layer and various fundamental and advanced analog & digital circuits and modules. The fundamental circuits consist of LEDs, 7-segment displays, 1602 LCD, switches, keypad, A/D conversion, multiple analog signal generators, and RS-232/485 serial communication, etc. The advanced features that other existing embedded systems development tools may not have are also included, e.g., TFT LCD with touch screen, Ethernet Lan network, battery life density measurement, 3-axis accelerometer, high-resolution external ADC converter, motor drive, remote control, etc. Moreover, new communication interfaces and protocols are available on the MISL-ASE board, such as UART (USB, RS-232/485, Bluetooth, and Zigbee), SPI (Ethernet, 2.4 G Wi-Fi, Micro SD card, and flash memory), I^2C (DAC and EEPROM), and 1-wire communication devices.

The whole MISL-ASE embedded system development board can be divided into four major sections: (1) MISL architecture and MSP430 intelligence layer section; (2) GPIO (General Purpose Input & Output) section; (3) Signal conversion section; and (4) Wired & wireless communications section. Figure 2 depicts the version II ASE board interfaced with the MISL-MSP430 intelligence layer. The ASE board is demarcated by the red dashed line, while the MSP430 embedded intelligence layer is delineated by the yellow dashed line.

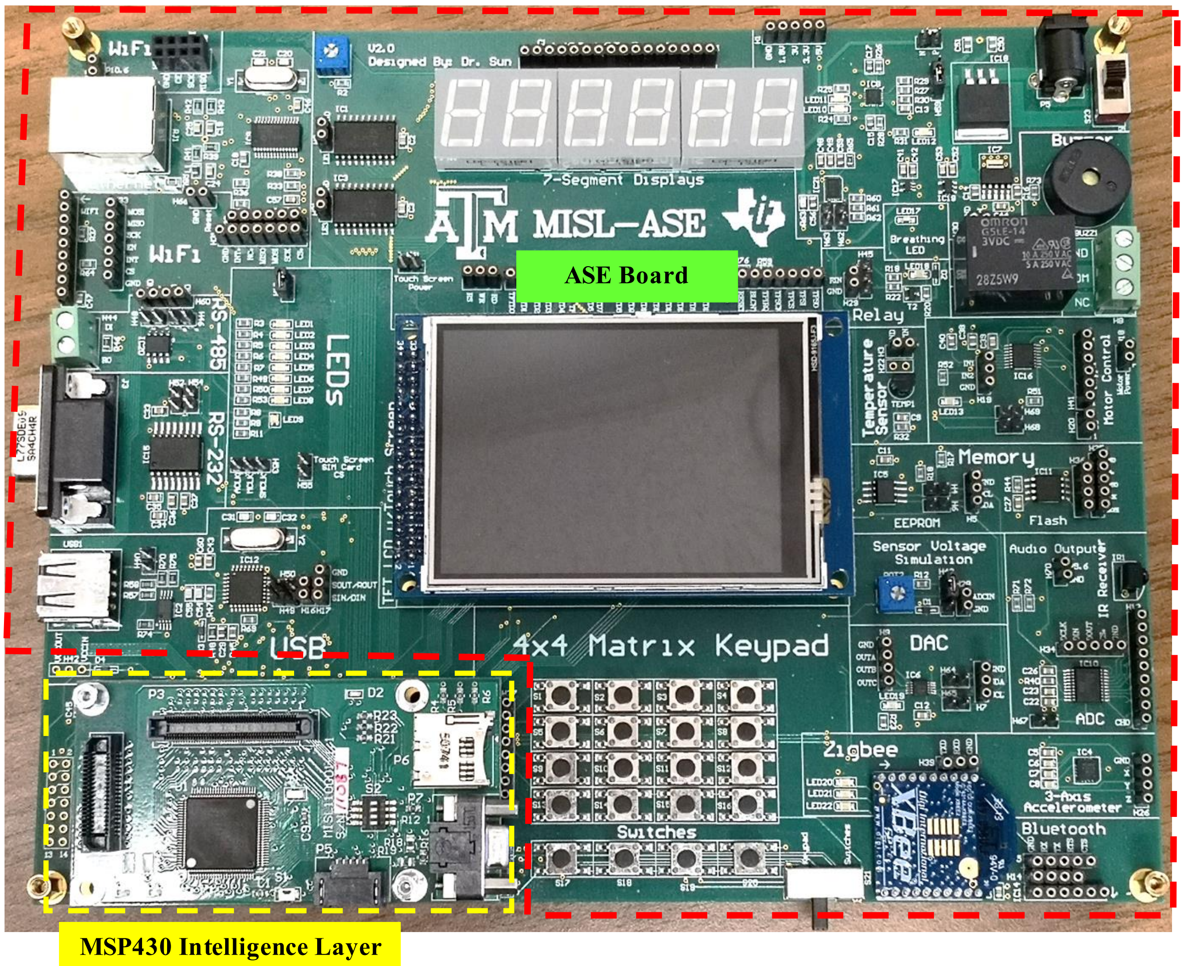


Figure 2: The version II MISL-ASE embedded system development board.

2.1.1 The MISL architecture and MSP430 intelligence layer section

The ASE board integrates the MISL architecture, initially designed by the Control and Data Handling Branch at the NASA Johnson Space Center in Houston, Texas (Yim, 2012). As shown in Figure 2, the ASE board features data and power bus connectors positioned in the left bottom corner, allowing seamless integration with the MSP430 intelligence layer. This robust design ensures compatibility with various microcontroller models (such as Atmel, PIC, Stm32, Intel microcontrollers) on different embedded intelligence layers.

The ASE board incorporates many features that directly interface to the MSIL-MSP430 intelligence layer. The chosen TI-MSP430F5438A microcontroller is because this advanced microcontroller contains a powerful 16-bit RISC CPU, 16-bit registers, and constant generators, contributing to optimal code efficiency. Additionally, it encompasses three 16-bit timers, high-performance 12-bit analog-to-digital converters, up to four universal serial communication interfaces (USCI), hardware multiplier, DMA, real-time clock module with alarm capabilities, and up to 87 general-purpose I/O pins. All circuits and modules on the ASE board are meticulously controlled by this microcontroller through a network of wires.

2.1.2 The GPIO (General Purpose Input & Output) section

GPIOs are one of the most valuable resources in embedded systems, providing the capability to communicate with the external world through digital lines configured as either inputs or outputs. GPIO outputs control external devices such as LEDs, 7-segment displays, relays, buzzers, and LCDs. On the ASE board, various LEDs, including eight red-color LEDs, one tri-color LED, and one PWM-controlled breathing LED, along with six common-cathode 7-segment displays, indicate on/off status and display numerical digits and characters. Due to GPIOs' drive strength limitations, two octal D-type latches (74HC573) are employed - one for controlling 7-segment display a~dp segments and the other for display selection. Both latches are managed through latch enable pins to prevent them from overriding each other. Additionally, a 3.2" TFT LCD is interfaced with the ASE board for graphic information display. For GPIO inputs, the board incorporates four pushbuttons and a 4x4 matrix keypad as typical GPIO input examples.

2.1.3 The Signal Conversion Section

Embedded systems frequently engage in measuring external analog signals, such as temperature, pressure, flow rate, level, and density. These signals are converted into digital signals for microcontroller comprehension. Conversely, there's a requirement to convert digital signals from microcontrollers into analog signals. The signal conversion section comprises: a) A potentiometer: This component simulates a varying analog input voltage that will be fed into one of internal 12-bit analog-to-digital (A/D) converters. It provides students with a practical platform for learning and implementing A/D converter programming; b) A 3-axis MEMS acceleration measurement system (ADXL335): This system measures both dynamic and static acceleration, finding applications in home healthcare devices, hearing aids, and motion-enabled metering devices; c) An external 16-bit, 8-channel, high-speed ADC (ADS8345): it is placed on the ASE to enhance the measurement system's capabilities. Operated through a Serial Peripheral Interface (SPI), this high-resolution ADC ensures precise results matching its resolution. With a low-power and high-speed multiplexer, the ADS8345 is particularly well-suited for battery-operated systems such as portable multi-channel data loggers; and d) An 8-bit Digital-to-Analog converter (DAC5571): With an I^2C interface, this low-power DAC allows dynamic control of LED density by altering the output voltage from 0 V to Vcc (power supply). Moreover, the ASE board includes reserved PCB terminal blocks for connecting typical analog sensors, converting their outputs into digital signals via internal A/D converters within the microcontroller.

2.1.4 The Communications Section

The MISL-ASE board incorporates a variety of advanced communication interfaces and protocols, including the Four-wire communication networks (SPI), Two-wire communication networks (UART and I^2C), and One-wire communication networks (DS18B20).

(a) SPI: SPI (Serial Peripheral Interface) is a synchronous serial bus standard supporting full-duplex communication between the embedded intelligence layer (acting as the master) and various slave peripheral devices. The slave peripheral devices encompass an Ethernet, 2.4G Wi-Fi modules (TI-CC3000 and nRF24L01), a Micro SD card, and a flash memory (SST25VF016B). Utilizing SPI, the embedded intelligence layer can remotely access, monitor, and control diverse external devices over the internet and Wi-Fi. Examples include web-based home automation and remote environmental monitoring, etc.

(b) UART: UART (Universal Asynchronous Receiver/Transmitter) is a crucial microcontroller feature for serial data communication with computers or devices. The ASE board incorporates standard UART interfaces (RS232, RS485, and USB) and also introduces new wireless communication standards (ZigBee and Bluetooth) via UART interfaces.

(c) I^2C: I^2C (Inter-Integrated Circuit bus) is a synchronous serial communication protocol supporting on-board interconnection of integrated circuit devices. I^2C utilizes two lines (SDA and SCL) to establish a half-duplex communication bus between the master (embedded intelligence layer) and two slave devices: a 16K EEPROM (24C16) and a D/A converter (DAC5574).

(d) One-wire communication: A digital thermometer (DS18B20) is employed to develop distributed temperature monitoring systems through a one-wire communication bus. This approach replaces traditional methods involving temperature sensors, signal conditioning circuits, and A/D converters.

2.2 Experiential Learning of Embedded System Design in Microcontroller Courses

Two versions of the MISL-ASE board were designed, developed, and tested, accompanied by the creation of a series of laboratory assignments and course projects. A total of two hundred fifty boards were procured and populated. These boards have served as major lab equipment for five courses in the Electronic Systems Engineering Technology (ESET) program at Texas A&M University (ESET 349 - Microcontroller Architecture and ESET 369 - Embedded Systems Software course) as well as in the Electronic & Electronic, and Mechatronics Engineering Technology (EEET and MET) programs at Northern Kentucky University (NKU). This paper primarily explores students' experiential learning in two microprocessor courses at NKU: EGT 367 (Microprocessor) and EGT 467 (Advanced Microprocessor). Before enrolling in these classes, students are required to complete the prerequisite course EGT 267 (C Programming for Engineering Applications) to acquire essential C programming knowledge and skills, and EGT 245 (Digital Electronics) to ensure a strong foundation in digital logic and electronic circuits.

EGT 367 (Microprocessor, a 3-credit course) delves into the microcontroller architecture, covering registers, memory addressing, subroutines, stacks, peripheral Inputs/Outputs, clock systems, interrupts, timers, and more. The course also introduces interfacing concepts. By the end of EGT 367, students can: 1) understand microcontroller architecture, including processor, ALU, memory, registers, stacks, logical operations, and instruction sets; 2) program microcontrollers using embedded C language; and 3) design basic embedded systems using digital GPIOs, timers, interrupts, external peripherals and devices. In the lab component, students gain hands-on experience through eight laboratory assignments and one three-week final project, including:

- Labs 1 and 2 focus on reviewing electronic circuits and fundamental C programming that will be used in this class, encompassing digital electronics topics such as number systems conversions, logic gates, Karnaugh maps, and functions of combinational logic, as well as essential C programming concepts like variables, data types, operators, expressions, statements, decisions and branching, looping, programmer-defined functions, arrays, pointers, and structures. These review labs, offered in the first two weeks of the semester, are designed to refresh students’ memory, particularly for those who may face challenges in computer programming.

- Lab 3 introduces the MISL-ASE board and the Integrated Development Environment (IDE) - Code Composer Studio (CCS). CCS is a comprehensive IDE supporting TI's microcontroller and embedded processors portfolio. It contains an optimizing C/C++ compiler, source code editor, project build environment, debugger, profiler, and various other features crucial for developing and debugging embedded applications. Students will compose their initial microcontroller program using the embedded system development board within the CCS IDE.

- Lab 4 typically serves as the first hands-on experience for beginners in embedded systems education. Students program the GPIOs of the MSP430F5438A microcontroller to make LEDs blink. Tasks include flashing LEDs, RGB LEDs, and designing a light flow system to control the LEDs, making them successively flash like lights on Christmas trees.

- Labs 5 and 6 focus on the control of static and dynamic 7-segment displays. Lab 5 requires students to program the MSP430 microcontroller to successively exhibit sixteen Hexadecimal numbers (ten digits 0~9 and six alphabetic characters A~F) on all on-board 7-segment displays. Through this lab, students will master GPIO control of display circuits and understand coding sections related to “what to display” and “which one to display”. In Lab 6, students will apply the time-multiplexing approach to address multiple displays control using only one GPIO port. They program the microcontroller to showcase various digits and characters on different 7-segment displays.

- Lab 7 instructs students in programming the TI microcontroller interrupts to configure the Watchdog Timer (WDT) as an interval timer. Students will gain hands-on experience setting up WDT registers, selecting appropriate time intervals, and establishing interrupts. The lab also guides students in writing interrupt service routines and related programmer-defined functions.

- Lab 8 explores the programming of built-in hardware timers, teaching students how to set up timer registers and interrupts. This enables them to control the on-board LEDs, making LEDs flash in a specific rhythm.

The EGT 367 final project involves the utilization of the TI MSP430F5438A microcontroller, four switches (S17~S20 on the ASE board), the internal Timer A0, and two 7-segment displays to create a stopwatch. This project provides an opportunity for students to apply the knowledge and skills acquired in EGT 367 lectures and lab assignments to develop a real-world electronic product. It integrates concepts such as microcontroller architecture, GPIOs, clock systems, interrupts, timers, and display interfacing into a comprehensive term project.

- Increment switch (S17): Connected to the P2.0 GPIO pin, pressing S17 increments the displayed value by one.

- Decrement Switch (S18): Connected to the P2.1 GPIO pin, pressing S18 decrements the displayed value by one.

- Reset Switch (S19): Connected to the P2.2 GPIO pin, pressing S19 resets the displayed value to zero.

- Stopwatch Switch (S20): Connected to the P2.3 GPIO pin, pressing S20 initiates the microcontroller to count seconds using the internal Timer A0. Pressing S20 again stops the counting. The two 7-segment displays show a sequential count from 0s to 59s, returning to 00s, and repeating the cycle.

EGT 467 (Advanced Microprocessor, a 3-credit course) focuses on advanced microcontroller techniques and real-time operating systems, providing students with advanced embedded systems design skills. In the lab, students engage in four laboratory projects and one four-week course final project, which comprise:

- Project 1 involves interfacing an LCD with the MSP430 microcontroller to display two lines of 16 characters each. The first line on the LCD displays “EGT Department”, while the second line shows the university website address, “www.nku.edu”. Students will learn how to understand the LCD hardware interface and timing diagram, configure the LCD, and write several programmer-defined functions.

- Project 2 explores keypad programming and interfacing, which is a fundamental practice in embedded systems. This lab project focuses on controlling a 4x4 matrix keypad (S1-S16 on the ASE board) using the P2 port of the MSP430F5438A microcontroller. Each key on the keypad represents either a digit (0-9) or a character (A-F), and pressing these keys results in the corresponding values being displayed on the 7-segment displays.

- Project 3 encompasses designing a serial communication system based on UART for transmitting data between the microcontroller (MSP430F5438A) and the computer. Students will explore and visualize the effects of various factors, such as baud rates and endianness, on serial communications.

- Project 4 requires programming one of the timers within the microcontroller to accurately measure elapsed time and display the timer value (ranging from 00 to 59 seconds). The timer value will be stored in the AT24C16 (a two-wire 16Kbits serial EEPROM, with a device address of 0xA0) using I^2C technology to ensure data persistence in case of power loss. Students will need to write several functions or subroutines related to I^2C, such as Start, Stop, Write_byte, Read_byte, and Acknowledge functions, for writing and reading data to or from the EEPROM.

The EGT 467 final project integrates almost all the microcontroller techniques learned in two embedded systems design courses to develop a real-time signal measurement system. The primary tasks involve programming internal analog-to-digital converters (ADC12) to sample analog signals from sensors at regular intervals and convert them into corresponding binary numbers (4 digits, ranging from 0000 to 4095) displayed on 7-segment displays. In addition, via UART serial communication, the converted voltage measurements are displayed on a computer screen. Furthermore, the project introduces Real-Time Operating Systems (RTOS), specifically the uC/OS-III real-time kernel. This kernel manages multiple tasks with different priorities, including signal sampling and conversion (high priority), data output on UART (medium priority), 7-segment display/LCD (medium priority), and keys (low priority). Through this project, students gain a deeper understanding of embedded real-time kernel and operating system concepts, such as interrupts, task and state management, task switching, and timer operations, etc. They also demonstrate their ability in using RTOS features such as semaphores, mailboxes, deadlocks, and message queues. Figure 3 shows NKU and TAMU students engaged in their labs and final projects using the MISL-ASE embedded system development boards.

Due to limited class time, only 40% of assignments and projects can be completed by students during classes. The remaining 60% of labs and projects cover topics such as ZigBee and Bluetooth, Ethernet, Digital-to-Analog Conversions (DACs), PWM, Flash memory, 16-bit, 8-channel external ADC, USB, Wi-Fi CC3000, 3-axis accelerometer, motor drive, remote control, low-power management, and one-wire communication, among others. The MISL-ASE development boards can provide continuous education in embedded systems design, enabling students to practice and explore the aforementioned features and modules.

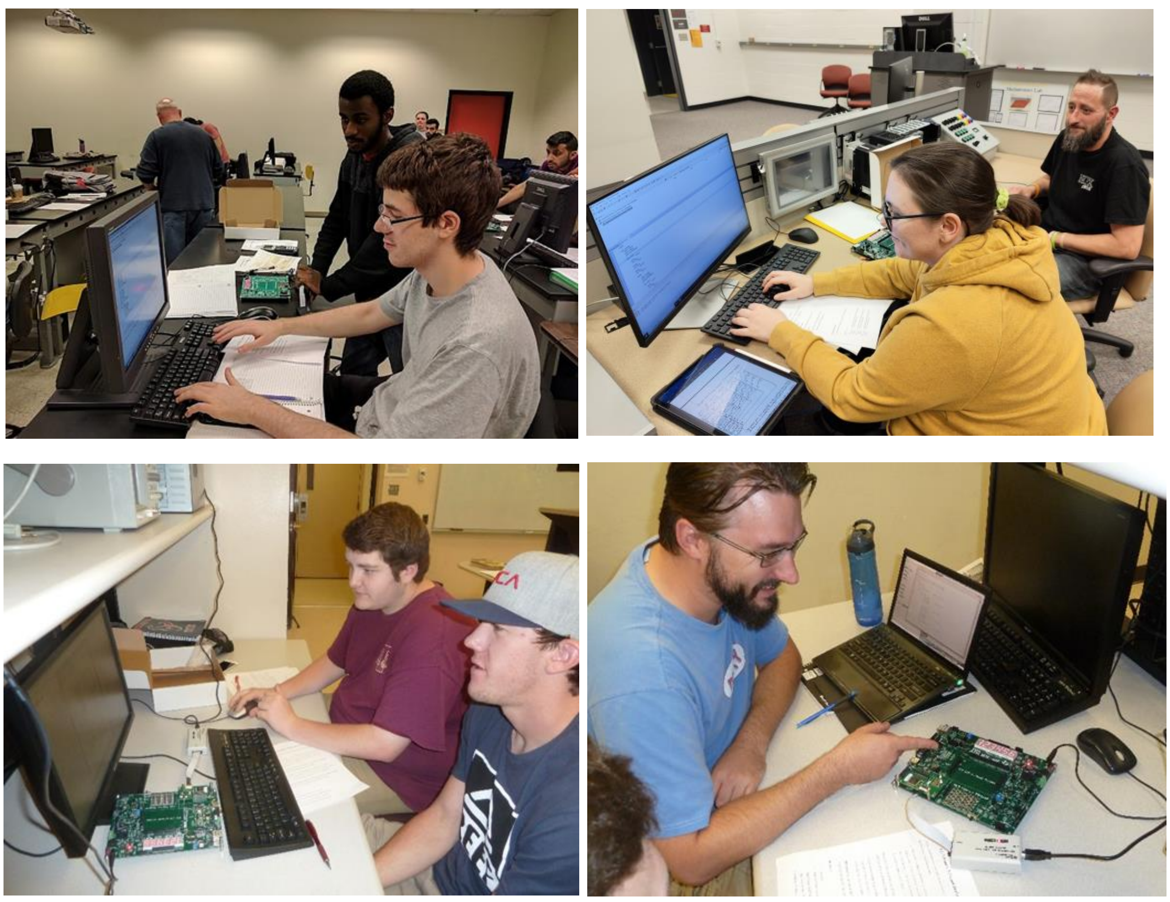


Figure 3: NKU and TAMU students engaged in their labs and final projects using the MISL-ASE embedded system development boards.

3. Assessment

Anonymous student surveys were given to students who attended both microcontroller courses starting from Fall 2017, excluding the academic years 2020 - 2021 due to the pandemic and Spring 2022 during my sabbatical. Each survey consisted of 8 questions, with students asked to provide a score ranging from 1 to 5 (1: strongly disagree ~ 5: strongly agree) for each question. The questions related to experiential learning using the MISL-ASE board, along with corresponding statistical results, are presented in Table 1. The average scores for the five associated questions ranged from 4.15 to 4.75, with deviations between 0.45 and 1.02. These high scores indicate that students were satisfied with the MISL-ASE boards, assigned labs, and final projects.

Survey Questions (1: strongly disagree ~ 5: strongly agree)
Q1: Did the MISL-ASE board increase my interest in learning embedded systems?
Q3: Did the MISL-ASE board and related labs help me understand digital and analog interfacing?
Q4: Did the MISL-ASE board and related labs help me understand wired and wireless communication protocols?
Q5: Did the MISL-ASE board and related labs enhance my programming skills for embedded systems?
Q6: Did the MISL-ASE board contribute to the completeness of my embedded systems design education?

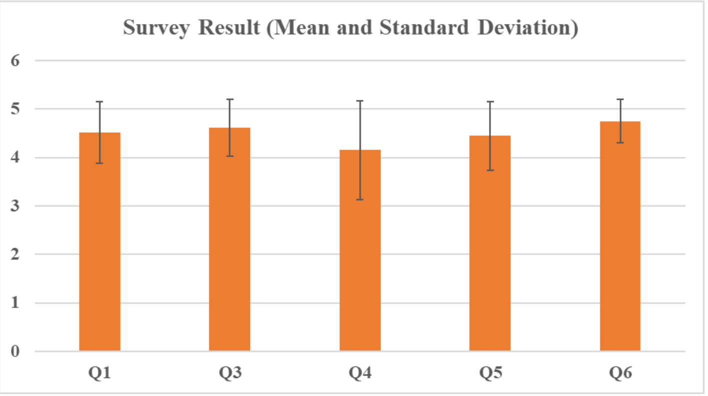


Table 2 provides an overview of my recent teaching scores for both microcontroller courses across various semesters (note: EGT 367 and 467 are offered in Fall and Spring semesters, respectively). The instructor score was based on a 5-point scale, with 5 being the highest score. These scores suggest that students find my courses and my instruction to be valuable.

Term / Course	Spring 2021	Fall 2021	Spring 2022	Fall 2022	Spring 2023	Fall 2023
EGT 367 (Microprocessor)	-	4.73	-	4.77	-	4.89
EGT 467 (Advanced Microprocessor)	4.57	-	4.90	-	Sabbatical	-

4. Conclusions

In the Engineering Technology curricula at NKU, students undergo a comprehensive three-course sequence dedicated to embedded systems design education. This sequence begins with the prerequisite course EGT 267 (C Programming for Engineering Applications), where students acquire essential C programming knowledge and skills. Following this foundation, EGT 367 (Microprocessor, a 3-credit course) delves into microcontroller architecture, exploring topics such as registers, memory addressing, subroutines, stacks, peripheral Inputs/Outputs, clock systems, interrupts, timers, and so on. Through a series of eight laboratory assignments and a three-week final project (making a stopwatch), students gain hands-on experience and solidify their understanding of these concepts. Moving forward, EGT 467 (Advanced Microprocessor, a 3-credit course) builds upon EGT 367 by focusing on advanced microcontroller techniques and real-time operating systems. This course equips students with the advanced embedded systems design skills necessary for complex projects. In the lab component, students engage in four laboratory projects and a four-week final project (designing a real-time signal measurement system), further refining their practical skills.

The proposed practical experiments and course projects conducted on the MISL-ASE boards serve as invaluable learning tools that provide students with hands-on experience and insights into embedded systems design. The results of anonymous student feedback surveys implied increased interest in microcontroller courses and enhancements in hands-on knowledge and skills pertinent to embedded systems design.

Acknowledgement

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Biographical Information

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