*A*dvanced Topics in Embedded Systems Design

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Abstract

This project focuses on building a new course for the University at Buffalo coined CSE 479: Advanced Topics in Embedded Systems Design. This course serves to be the successor to the course CSE 379: Introduction to Microprocessors. Entirely in ARM Assembly language, students learn to build drivers for multipurpose applications using a variety protocols that were not discussed in the introductory course. Topics include Floating Point, Direct Memory Access (DMA), Pulse Width Modulation (PWM), the Serial Peripheral Interface (SPI), Inter-Integrated Circuit (I^2C), Digital to Analog Conversion (DAC) as well as Analog to Digital Conversion (ADC). These topics are reinforced by Texas Instruments (TI) Tiva LaunchPad and EVP+ Alice daughter board. Near the end of the course, students create a final project, up to their choosing, about a topic that was not covered in the course, using the base knowledge that was taught.

1 Introduction

Microcontrollers (MCUs), such as TI's Tiva TM4C123GH6PM, are widely used in embedded systems due to their low power consumption, small form factor, cost-effectiveness and massive communication support. Today, microcontrollers are not only used for simple interactions. Many other sensors, chips, and other controllers are used to create the overall embedded system.

This project aims to encourage students to learn the more advanced microcontroller techniques that are used in industry system devices today. While learning these subjects, the importance of reading and understanding documentation is heavily emphasized since every microcontroller is different with how its registers and bits are configured.

2 Motivation

At the University at Buffalo (UB), one of the courses in the Computer Science & Engineering (CSE) department is CSE 379: Introduction to Microprocessors. This course teaches the fundamental building blocks of microprocessors and how they work. The course is taught entirely in ARM assembly language and uses direct register manipulation to control each piece of hardware discussed in the course.

Currently, in the introduction class, time only allows for the following peripherals to be used:

- **Universal Asynchronous Receiver Transmitter (UART):** Allows for serial communication with a computer or another device.
- **General Purpose Input Output (GPIO):** Utilizes the pins on the microcontroller to either read or write a single voltage line. This allows LEDs, motors and buttons to be monitored.

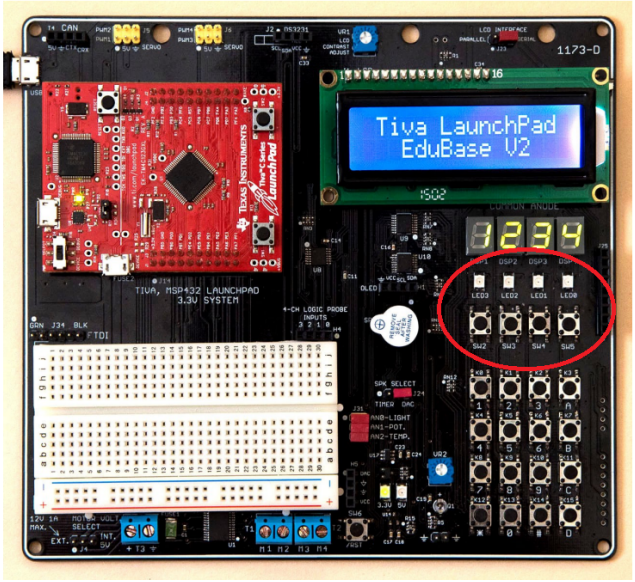

Figure 1: EVB+ EduBase-V2 Trainer

- **Interrupts:** Allows for processor to run code when specific actions happen instead of constantly polling flags and waiting. Interrupts are defined for UART, GPIO and Timers.

To convey these topics, an educational trainer board is used for easy access to a multitude of peripherals shown in Figure 1. The trainer board used for this class is the EVP+ EduBase Board. The peripherals used in the introductory course are the four LEDs and the four push buttons which are circled in red in Figure 1. In the Spring of 2023, the sixteen button keypad was used in labs but was retired due to some boards that rendered inoperable during the development process by some students.

Despite the amount of peripherals that are on the board, the trainer board was not being used up to its full potential. So little of the trainer board's functionality was used that one could remove the trainer entirely ans still have the same functionality with the peripherals, as if they were connected to the trainer. This essentially nullifies the use case for the trainer board altogether.

3 Course Structure

Dr. Kris Schindler and I aimed to develop a course that would help both benefit the students and utilize more of the peripherals on the board. The course was structured in the following way:

- **Floating Point:** Utilizes the vector floating point co-processor on the Tiva LaunchPad. Students created a floating point calculator to demonstrate the use of the floating point instruction set,

- **Advanced GPIO:** Advanced GPIO topics were discussed for the keypad on the EduBase Board trainer. Bit banging and advanced interrupt techniques were discussed.
- **Direct Memory Access (DMA):** Discussed how DMA works and the involvement of setting up the DMA controller on the Tiva Lauchpad.
- **Pulse Width Modulation (PWM):** Outlined the PWM module, its use cases and how to set up for the Tiva LaunchPad's GPIO pins. The RGB LEDs were used to create a specific color from user input.
- **Serial Peripheral Interface (SPI):** Discussed the SPI protocol, including its history, conventions nowadays and setup. The SPI module is used by the LCD and the four 7-Segment displays on the trainer board.
- **Inter-Integrated Circuit (I^2C):** I^2C was discussed and used in conjunction with the 12-bit Digital-to-Analog Converter (DAC), MCP4725, to convey both (I^2C) communication and topics on speakers and how to drive analog signals.
- **Final Project:** Students worked on their own specialized projects that they chose, along with their teammates. The students then present to the class about their project and demonstrated what they have accomplished.

Throughout the course, topics were initially introduced to the students at a basic level. This approach allowed the students to preview the upcoming material, with instructions to first research the documentation, on their own, about the peripheral. By doing so, they were better prepared for the lecture, having a foundational understanding of how the module works and how to begin. This method proved effective, as it helped students become more comfortable reading and understanding technical documentations.

At the end of the semester, students selected a final project complete with the Tiva board. The trainer board was not required for their project unless needed, giving students more flexibility. During the final month of the semester, all class days were designated as workdays, where no lectures were held, and students were free to ask questions and work on their projects. Final presentations took place during finals week, where students presented and demonstrated their projects to the entire class.

3.1 Project Duties

3.1.1 Course Setup. This project first began back in June of 2023. I was previously an undergrad teaching assistant for CSE 379, taught by Dr. Schindler. Over the summer, I continued as a teaching assistant which provided me more time and access with the EDUBase Boards. During this time, I conducted extensive research and debugging to decipher the layout of the EduBase Board to determine pin connections. As a result, I was able to get the 16x2 character LCD working in pure assembly utilizing the SPI module on the Tiva. I also created PowerPoint slides that outlining the process for future students.

This process was similar for the 7-Segment Displays. By the Winter of 2024, I had slides for both the LCD and the 7-Segment displays. Dr. Schindler's students proposed holding a special topics course to serve as a preliminary test of CSE 479 in practice. This course was held in Spring 2024, which covered topics such as the keypad, PWM, 7-Segments and a final project. However, topics such as DMA, floating-point arithmetic and analog conversions were not discussed at this point. I participated in this course as a student in the graduate-level special topics course while also assisting the undergraduate students similar to a teaching assistant. Similarly, all students completed a final project and presented at the end of the semester.

In Summer 2024, the course improved significantly. I aimed to extend the curriculum to include topics that are relevant in industry such as DMA and analog conversions. Floating-point arithmetic became a necessary part of the course due to an application of the temperature sensor on the trainer board. This sensor outputs a voltage reading that corresponds to the surrounding temperature, but this voltage needs to be converted to an actual temperature value. Since conversion required floating-point arithmetic, I had to research and develop a library that works with the floating-point co-processor embedded in the Tiva LaunchPad. This addition was beneficial, as it introduced a small but important component to the course content. Floating-point operations also have dedicated instructions, so to ease the students back into assembly programming, floating-point arithmetic was the first topic covered.

3.1.2 Course TA. Throughout the fall semester of 2024, I served as the teaching assistant and grader for the course. I attended most lectures to assist with answering questions. I also delivered a few formal lectures and participated in in-class grading. This meant that I went to each student and ask them to provide a demonstration of their projects. This had the benefit of a faster grading experience for both the student and grader. Additionally, I created skeleton code for each of the projects, allowing students to gradually assemble the necessary configuration for each module. Lastly, I kept track of the trainer boards used by students. Since it was not always feasible for students to come to the lab to use the hardware, some students requested to take the trainer board home. As these boards were lab property, I was responsible for monitoring which student had which board.

One day, we decided to try a new approach. We asked a student with a bug to project their screen and demonstrate the issue. This idea was intended to reinforced debugging techniques with everyone in the class rather than having one teaching assistant visit each student individually to provide the same debugging advice.

3.1.3 Exams. Although the first exam was administered a bit later than expected, I contributed to creating exam questions for both the midterm and the final. Both exams were conducted online, with a time limit but students had a designated time frame to take them. Exams were given to further the proposition of this special topics course as a legitimate class.

3.2 Course Results

This course was received well by the students from this semester. Many of the concerns raised were not having enough time for the final project and covering Analog-to-Digital Conversions (ADC).

3.2.1 Projects. In total, there were 13 students that took the course. 7 of the 13 were in a group of 2 or more while the other 6 worked alone. Final project were up to the students but must include a new topic or idea that wasn't covered in class to enforce reading documentation. The projects that were chosen by the students are:

- **Audio Visualizer:** Audio is received by microphone and the intensity of volume is shown on an LCD display.
- **LED controller via Bluetooth:** A webpage is set up to connect to the connected Tiva and will wirelessly light up the corresponding color to the other Tiva.
- **Conway's Game of Life:** Conway's Game of Life shown on an 8x8 addressable LED matrix. This uses DMA and PWM to send the bytes through the matrix without using the CPU.
- **Walkie-Talkie:** Records audio on one Tiva and the other Tiva outputs the recording on the other side.
- **Thermometer:** Uses kitchen probes to detect the temperature of the tray.
- **SD card E-Reader:** Uses SD-card protocol to read and display text on the LCD.
- **Plant Incubator:** Monitors the plants environment including temperature and soil moisture.
- **Reflex Game with Leaderboard:** Uses the EEPROM module on the Tiva to save the scores of the top player in the game. This saves over power cycles.
- **Remote-Control Mini Fan with Adjustable Speed:** Uses the motor controller on the EduBase Board to control a fan. PWM is used to vary the speed on the fan and an IR sensor is used to turn off an on the fan.

3.2.2 Feedback. The students generally liked the course but had many feedback to give us.

With the question: *"What, if anything, do you think should be eliminated from our offering of CSE 410 in the future?"*, one of the most frequent responses was removing floating-point and PWM utilizing a general purpose timer. Students felt that both of the topics did not need to be covered and would give them more time to either cover another topic or have more time for the final project.

For the following question: *"Give your thoughts about CSE 410. Any feedback not given in the previous questions would be appreciated and would benefit future offerings."*, the following were included in the majority of the comments given.

- More use cases
- Allocating time for an actual lab
- More time for final project

4 Trainer Board

The EduBase trainer board was planned to be discontinued in August 2024. Throughout my time with the 410 course, I worked on creating a new trainer board that can be used for both courses Introduction to Microprocessors & Advanced Topics in Embedded Systems Design.

This new board I have named as the Juliet board, inspired by two main ideas. First, the original was called the "Alice" trainer board, evoking the story "Alice in Wonderland." During the development of the new board, I attended the play "& Juliet", which imagines what would happen if Juliet survived the events of "Romeo and Juliet". This situation can be seen in parallel with the transition from the Alice trainer board, which has been discontinued, to the Juliet trainer board, which is here to stay. The schematic, printed circuit board (PCB) layout and initial prototyping testing was completed

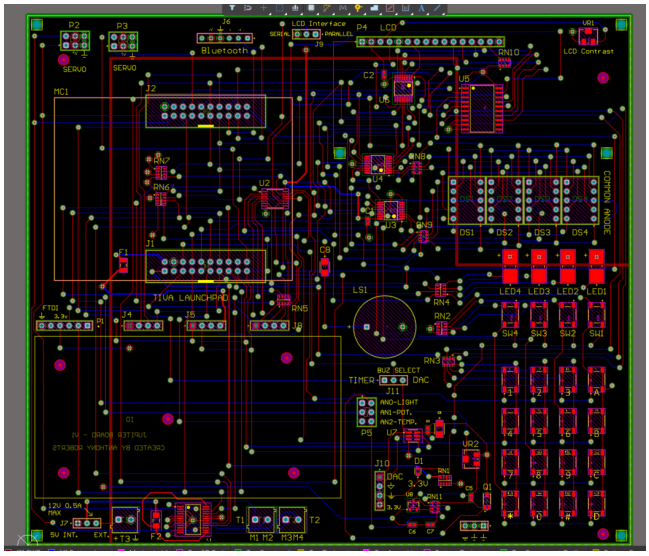

Figure 2: Juliet Trainer Board PCB traces in Altium Designer

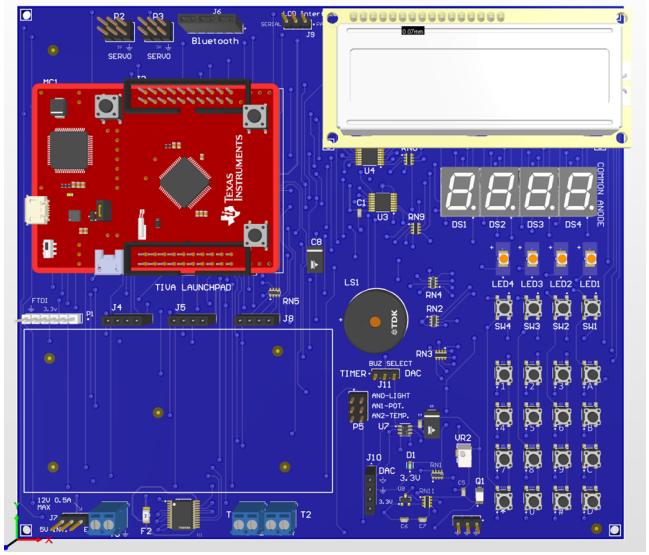

Figure 3: Juliet Trainer Board PCB Assembly in Altium Designer

in Fall 2024. Final assembly of the boards will come in late December, followed by further testing to ensure that all the components function as expected.

5 Conclusion and Future Work

Although this project is unconventional, it was incredibly rewarding to create and see that the students benefited from my efforts. Since the course was well received by students, it has the potential to be offered in the future as a legitimate course under the course number CSE 479: Advanced Topics in Embedded Systems Design.

As for future work, Dr. Schindler and I will continue to work on a formal proposal to the Department of Computer Science & Engineering of the CSE 479 course. Futher testing and improvements are necessary for the new trainer board as there are already some changes that need to be made. Since this special topics course has been successful with the student projects, the Juliet trainer board can be revised to meet student interests and allow for more possibilities with projects. One last thing to consider is that a teaching assistant would need to be available for the class in the near future if this course is offered again. This can be achieved by choosing an exceptional student in CSE 379 in the spring, have them learn the CSE 479 material through the summer so that they're prepared to help in the fall semester. This and a dedicated lab time may be also considered to give students more time with the hardware.

6 Acknowledgments

I would like express my deepest gratitude to Dr. Kris Schindler who has been completely supportive of this idea of a new course from the very beginning which was three years ago. This course and project has grown me as a student, researcher and instructor and he has been instrumental in that process.

I would also like to thank Radhika Jois for pushing me to learn more and for the support for the 7-Segment displays. I hit a breaking point where I could only get one display to light up at a time or all of them with the same segments on. She both wanted to learn and pushed me to learn how to make the displays work correctly which ultimately gave me the push to start at CSE 479 course.

Finally, I am profoundly thankful to all the students that have taken part in this journey with me for this project. Whether you were in the spring or fall offering of the course, I learned and continue to learn so much from everyone's contributions to the course. This course nor project would not be at all possible without your engagement and seriousness of the course.

Thank you all for making this experience engaging, enjoyable and memorable!

References

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