Custom Microcontroller Peripheral Platform Design and Build: A Unique Hands-on Experience for an Undergraduate Student

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Abstract

Using the project based learning teaching method in an undergraduate computer engineering course provides students with valuable hands-on experience in addition to theoretical knowledge of the subject. The effectiveness of this method is realized when a student can take this experience and carry out a project from a concept to a finished design. We at Grand Valley State University's School of Engineering were able to witness this first-hand when we had an undergraduate student undergo this unique experience of design and build. Student was entrusted the responsibility to fulfill our need in our senior level embedded systems course for a hardware peripheral platform that would integrate with the Texas Instrument's MSP432 development board.

The paper first talks about the need for an MSP432 peripheral hardware platform. Then, we talk about taking this need and engaging an undergraduate student, engineering staff mentor, and a faculty member in the design and development of the hardware platform. Topics discussed in this section include creating design specifications, project timeline, brainstorming, hardware and software prototyping, manufacturing, debugging, and working within a budget to produce a final fully functional platform. The undergraduate student was expected to collaborate with the mentor and faculty member through multiple design reviews, as well as meet milestones throughout the semester long project.

The paper then talks about the various kinds of laboratory exercises and projects that can be implemented on this platform by the students in their senior-level embedded systems course. We further include student assessment data that shows that the students appreciated the use of this hardware peripheral platform to solve practical engineering problems. Finally, we conclude the paper with lessons learned and ideas for an improved learning experience.

I. Introduction

Microcontrollers in the classroom have become the mainstay of digital systems courses at the university level. Microcontrollers offer a unique opportunity to learn computer architecture and its applications, as well as hands-on learning through projects and laboratory exercises. Traditionally, engineering schools would expose students to a certain level of theoretical knowledge with minimal real-world applications; however, the new trend is shifting towards a mixture of theory and projects. Project Based Learning (PBL) is a relatively new educational approach, and many universities have adopted this to better prepare students for the real world[1].

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While microcontrollers continue to be an effective PBL learning tool in the classroom[2], the full potential is not realized until peripheral devices are added. There are many different sensors and actuators that can be added to the system to achieve this result, however, this usually involves designing a circuit around the sensor or actuator. In a computer engineering course, the outcome of the course is to become proficient in microcontroller applications, not circuit design. Therefore, a unique plug-and-play peripheral platform was desired.

Instead of purchasing an off-the-shelf sensor platform, a faculty member and a staff mentor took advantage of the opportunity to design and build a custom peripheral platform with the aid of a junior computer engineering student. The student was selected for the project based on the following criteria, (i) motivation to learn new design tools and learn a multitude of new topics, and (ii) experience in writing low-level microcontroller drivers or experience in Printed Circuit Board (PCB) design. The first criterion was required so that the student would take ownership in the design and be self-motivated to deliver a successful product. The second criterion was important so that the student could mainly focus on one area (hardware or software) and not have to learn everything from the ground-up. This project included numerous learning opportunities for all involved in the project. The student gained invaluable knowledge of hardware and software, the engineering design process, budget constraints, and debugging. While the engineering staff mentor gained experience in project management and leadership, and the computer engineering faculty member learned topics of circuit design and hardware design.

The paper is organized as follows: the next session discusses the need for a custom peripheral platform for a microcontroller, phasing out an old development platform, and limited funds available to execute the project. The paper then describes the extensive design and build of the platform through multiple phases, and the sense of ownership gained from the student after achieving project milestones. The paper then describes the development of our laboratory and learning exercises and how they build towards the project assigned to students. We further include student assessment data that supports our approach and shows that the students appreciated this intellectual way of learning microcontrollers. We finally end the paper with our concluding remarks.

II. Need for Hardware Platform

Recently, the Electrical and Computer Engineering programs in the School of Engineering switched development platforms from an AVR based platform to the Texas Instruments MSP432[3] ARM development platform. The senior-level microcontroller course taught in the computer engineering program had been using the Texas Instruments Stellarisware platform that was at the end-of-life, and decided that the MSP432 platform would be an adequate replacement. The Stellarisware platform had to be checked-out to students due to its lack of availability, whereas the MSP432 was a cost-effective platform that was readily available for purchase.

The course covered topics ranging from assembly programming and low-level driver development to real-time operating system fundamentals along with dedicated learning exercises, laboratory assignments and projects targeting the StellarisWare platform. To keep the same essence of the course, it was required to revise the laboratory exercises, assignments and projects to target MSP432 platform. In effort to make course projects more exciting and interesting, peripheral devices such as motors and displays were desired. Instead of having students build their own circuits around the peripheral devices and risk damaging expensive components, a turnkey peripheral platform was deemed the best option.

The need for the proper student to place on this project was paramount in order to achieve a successful final product. The computer engineering student selected to design the platform was highly motivated to learn circuit and hardware design. Having already taken the introductory digital systems and the circuit analysis course, we felt confident that the student could handle the hardware involved in the project since Grand Valley State university's PBL teaching method prepares students for projects of this magnitude.

III. Design and Build

In order to keep the student on-track for a successful completion at the end of the semester, the project was broken down into phases with hard deadlines. The phases included brainstorming, specification design, prototyping along with driver development, schematic design, PCB design, manufacturing, and finally testing and debugging. The project began with a preliminary brainstorming session in order to define the peripheral platform specifications. All of the peripheral devices to be added to the platform were specified in the session. The grant funds for the project allowed the purchase of "***breakout board***" versions of the peripheral devices used in the design. The student was tasked with developing software drivers for each of the peripheral devices as a prototype and proof-of-concept for the final design. Some of the peripheral devices chosen included, but not limited to the following: Pololu MC33926 dual motor driver module[4], ESP8266 Wi-Fi module[5], and an Adafruit 1.8" TFT color LCD module[6]. Figures 1a, 1b, and 1c below are examples of the "***breakout boards***" used.

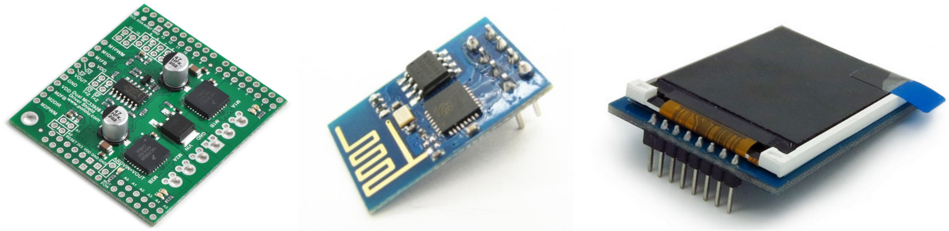

Figure 1 (a, b and c): Breakout boards used for prototyping and driver development

After the drivers were developed and tested, a final design was discussed between the student, mentor, and faculty member. The final design would consist of RGB and green LEDs, push buttons, buzzer, SD-Card reader, accelerometer, gyroscope, and the items from Figure 1. The board would also be designed for modularity. Some of the peripherals could be disabled if not needed and those pins could be used for other purposes. The board was designed to mate to the MSP432 like a shield so the pins can pass through the board and be reached by external devices. Figure 2 below shows a finished peripheral platform mated to an MSP432 board.

Figure 2: Mating of the peripheral platform and an MSP432 microcontroller board

The first challenge faced was limited I/O ports on the MSP432 board. Since it was desired to have expansion ports available for off-board sensors, the LED and switch count had to be reduced. Another challenge faced was the power requirements. There was a mix of 3.3V low-current devices and 5V high-current devices. Motor drivers demand a high current source, which a USB port on a PC cannot provide. A circuit was designed to isolate the motor drivers from the USB power source and use an external power source such as a battrery pack or a wall plug. The student designed a logic-level shifting circuit, 3.3V power supply, and a high-current input protection circuit. This may seem trivial for some, but for an undergraduate computer engineering student, this was a great learning experience. The greatest challenge faced was the embedded Wi-Fi antenna as they are rather difficult to design. The student sought out help from high-speed PCB design faculty member to ensure the best possible chance of success.

Before the student was allowed to start the PCB design, a final schematic review was conducted to ensure that nothing was overlooked. After a couple of edits, the student was tasked with designing the circuit board. This phase turned out to be the longest phase of the project simply because of the lack of eexperience the student had on the subject. Due to the high power requirements of the motor drivers and other peripheral devices, a four layer board with internal power planes was needed. Multi-leayer PCB design was also something that the student hadn't experienced before this project. The student faced many challenges in the PCB design stage due to the complexity of the design. There were many sensitive data signal traces, high-power traces, and RF traces that all had to reside on the same PCB while maintaining optimal signal integrity. Before finalizing a design, component specifications were conducted to ensure a cost effective design. Finally, a round of design reviews was conducted prior to sending out the board for manufacturing.

While waiting for the PCB to be manufactured, the student put together a cost analasys for reproduction of the platform. Since the intention of this platform was to be used in the classroom, we needed a cost estimate to manufacture and assemble multiple boards. During this waiting time, student also worked on the generation of a user manual and a design specification document for future use. The user manual included pinouts, peripheral descriptions, and sample circuit schematics for future students to use.

The next phase was the assembly of the PCB. At Grand Valley State University, we have an electronics assembly lab where stencil work and reflow can be done. The student used this lab to stencil on the solder paste, place the components on the PCB, and then reflow the PCB. Figure 3 shows the stencil and the unpopulated board used for this phase.

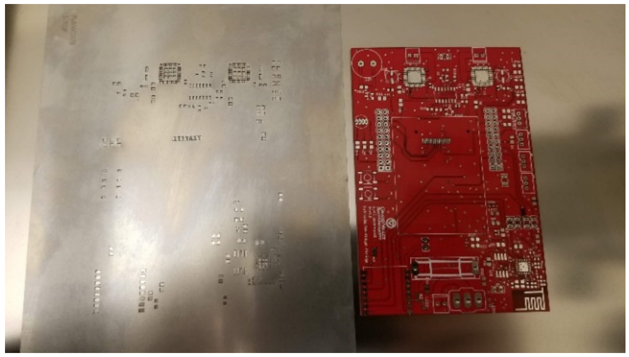

Figure 3: PCB assembly

At the end, the testing and debugging phase was conducted. Prior to powering up the PCB, continuity checks were performed on all of the traces to ensure there were no short-circuits or open circuits. This is a common problem faced when hand-placing and reflowing components is done. The student was then able to power up the PCB and start testing indiviual circuits with the drivers written in a previous phase. Each successful circuit descovered provided the student with a sense of pride and ownership over the design. At the end of the debugging, the platform was deemed 100% operational and a huge success. Figure 4 below shows the finished design with descriptions of the peripheral devices.

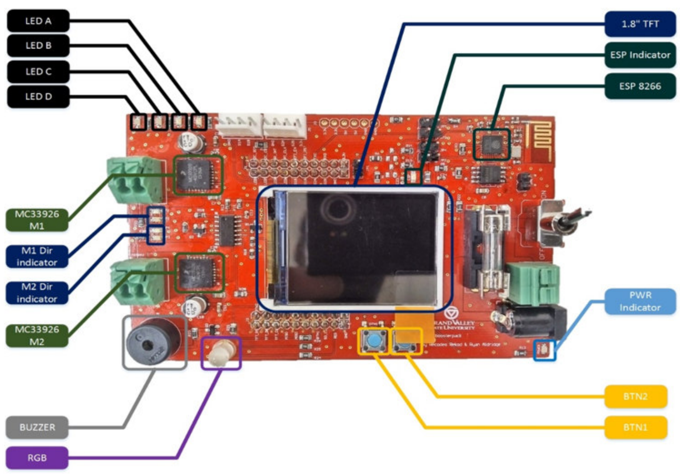

Figure 4: Finished peripheral platform

IV. Sample Laboratory Assignments and Project

The course laboratory exercises are meant to help students design and understand the use of microcontroller in an electro-mechanical system. The course laboratory exercises involving this platform are structured as several assignments and one project. They cover the following topics: introduction to the microcontroller platform; general-purpose input output; timer peripherals; interrupt mechanism, analog-to-digital conversion and working with several interfaces such as

SPI and I2C. These laboratories expose the students to become familiar with the microcontroller platform and learn to program a microcontroller to perform the desired functions. Each laboratory has a set of deliverables; typically including the successful demonstration of a working design, source code with comments, and a brief report.

The following is an outline of some of the laboratory assignments that we offer in the course:

- **Laboratory #1**: The purpose of the laboratory was to introduce students to the microcontroller platform that they use in the course. The laboratory teaches students to write and upload C programs using a mix of built-in functions that is available through the open source database and their own custom functions that provides the same functionality.

- **Laboratory #2**: The purpose of the laboratory was to teach students to work with general-purpose input and output (GPIO) available on the peripheral shield such as pushbuttons, switches, LEDs and RGB LEDs.

- **Laboratory #3**: The purpose of the laboratory was to teach students to work with built-in timer peripherals and interrupt controller mechanism on the MSP432 platform.

- **Project #2**: Project #2 is spread over several weeks where students learn about pulse-width modulation, analog-to-digital (A/D) conversion and various bus interfaces like SPI and I2C based on the kind of projects they are assigned. The students are given several weeks to design and implement the project by using pre-designed components from the laboratory assignments and/or creating new components from scratch.

In Summer 2018, we had to use StellarisWare platform for Project #1 and Project #3 and the new peripheral platform for Project #2. Moving forward it would be ideal to use the new peripheral platform for all the three projects to avoid any confusion among students.

V. Assessment

The course "***Design of Microcontroller Applications***" introduced the aforementioned hardware peripheral platform for the first time in Summer 2018 with an enrollment of 15 students. In order to obtain finer-grained feedback from the students, at the end of the semester we encouraged the students to complete a customized anonymous questionnaire to learn the benefits of using the peripheral platform and help improve the efficiency of the platform usage for future semesters. All of the students filled out the questionnaire to identify their actual impressions of using peripheral platform in this course. The peripheral platform was called ***Wifi-Boosterpack*** shield.

Questions

The students were asked four questions as well as they were given the opportunity to include written comments. The questions were rated on a five point scale, where '1' indicates "***not at all***" and '5' indicates "***a great deal***". The questions were:

1. Did you enjoy working with ***<u>Wifi-Boosterpack</u>*** shield?

2. Was the provided documentation (technical datasheet) regarding the ***Wifi-Boosterpack*** shield appropriate to use?

3. Was there any benefit in using the ***Wifi-Boosterpack*** shield over hand-wiring the peripherals to the MSP432 on a breadboard?

4. Would you have benefitted from covering technical aspects of the Wifi-Boosterpack shield during lecture rather than just reading the datasheet and extracting information yourself?

5. Please provide comments/suggestions as to how the experience can be made more beneficial in future offerings.

<u>Questionnaire Results</u>

Figure 5 shows the graphical representation of the feedback received from the students. Each bar in the graph represents the question number in the questionnaire and the bar shows the average ratings by the students for each question asked.

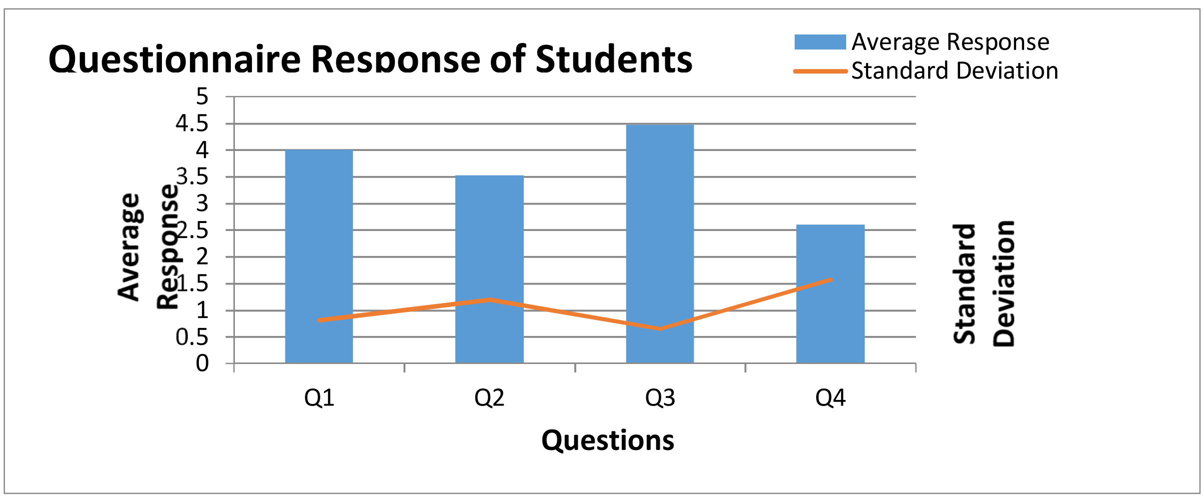

Figure 5: Student Questionnaire Results

The results indicate that the students felt that they benefited from this exercise. Furthermore, the students feel that the use of the autonomous robots would be improved if the robots are introduced earlier in the course and that they had more time to work with it. Students would also like to learn about the RF communication and try to write the communication code themselves rather than working with the provided code template.

Written Comments

As previously noted, this was students' first introduction to the peripheral shield and majority of the students appreciated the opportunity. However, the students indicated that the technical documentation regarding the shield could have been made better. Students did appreciate the fact that using shield helped them save time since they did not have to wire all the components. Students were able to utilize the time saved by writing efficient code and debugging code rather than debugging wiring of the components. These views are reflected in the sample student comments below:

"I enjoyed using the shield but I think there was not enough documentation in the datasheet. It would have been nice to use all the peripherals on the shield."

"Having everything there without the need of hand-wiring was nice. Datasheet was more than sufficient for everything I needed on the board. I enjoyed it and would recommend keeping it."

"The shield was helpful, it decreased the amount of time wiring things and double-checking. The documentation should be more thorough."

"I didn't really get to use it. I used it for the first MSP lab but other than that everything we did could be done without the shield. I would have liked to experiment with it more."

"The shield was professionally done and easy to work with. It would have been nice to learn more about the shield during lecture but there was limited time."

These written comments support the findings that we have already mentioned.

VI. CONCLUSION

The outcome of Project Based Learning is one of high reward for the student as well as the teaching staff invlolved. The staff are able to witness the effectiveness of this technique through these types of projects. It would have been easy to just purchase an inexpensive off-the-shelf peripheral platform, but the the knowledge and experience gained by the student is invaluable. The student was able to go through the entire engineering design process from idea to finished product. The student was able to learn-on-the-fly and seek assistance from the appropriate people to design this platfrom, even though hardware design was not the students area of study. The effectiveness of Project Based Learning truly stands out in this case.

The junior computer engineering student was able to successfully develop a complete and functional product that fits the design specifications given. The student assembled fifteen total peripheral platforms and they were used during the Summer 2018 semester with huge success. In the assessment, student reaction to using peripheral shield in the course was positive apart from little inefficiency such as lack of enough documentation in the datasheet and not being able to use the shield to its maximum potential. We conclude by stating that in our experience, giving students this opportunity with some modifications to remove inconsistencies is an intellectual way of imparting the required knowledge and experience to the students.

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