Transforming the Microprocessor Course: Enhance Learning Objectives with Embedded Processors

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Abstract

For the past two decades more and more universities have adopted embedded microprocessors in their Electrical and Computer Engineering Curriculum. The reasons are twofold. First nowadays embedded microprocessors become more and more popular and can be found in almost everybody's daily lives. Second embedded microprocessors allow more flexibility in low level port accessing and interfacing with other external chips.

This paper presents the redevelopment of a junior level introductory microprocessor/microcontroller course, ECE 362 – Microprocessor Systems and Interfacing. The course development transforms the current Intel x86 family processors to the ARM Cortex microprocessors. The course development includes both the lecture and the laboratory experiments. This transformation is aiming at enhancing the students' learning objectives with more hands-on experience on interfacing the microprocessor with various peripherals. The learning objectives are mapped into course outcomes for assessment. Students' course outcome assessment was conducted in the end of the Fall 2014 semester. The assessment results showed that the outcomes were all achieved.

1. Introduction

Microprocessor architecture is a core subject in both electrical engineering and computer engineering curricula. Introductory microprocessor courses aim at providing students with enough background so they will be able to interface, design and program microprocessor based systems. The lectures complement the laboratory experiments; they introduce basic concepts that help students complete the laboratory projects. Thus a critical feature of an introductory microprocessor course is that it is a laboratory-oriented course. The laboratory experiments play a very important role in preparing students for work in industrial applications.

Since there is large variety of microprocessors in the market, faculty in charge of a microprocessor course have to pick the ones they believe will prepare best their students. Because of fast changes in microprocessor technology, laboratory courses associated with this topic have to be continuously updated. Engineering programs worldwide have investigated on different microprocessors and then developed experiments that use the ones they pick[1]. Some of these efforts have been limited to assembler based software experiments e.g., Microsoft Macro Assembler (MASM)[2]. While MASM is a good tool for students to experiment with Intel X86 assembly instructions, it does not provide a meaningful hardware interfacing experience. Other institutions teach microprocessor architecture that lean heavily on hardware interfacing experiments[3]. Some other institutions, realizing that both software and hardware experiments are important for learning basic microprocessor architecture have shifted from a traditional microprocessor course, based on software experiments (e.g. using X86 assembly instructions), to one that uses a PIC microcontroller and then provided their students with software/hardware experiments[4].

Before the fall of 2014 our school used the Intel X86 family of microprocessor systems under the premise that Intel has been the leading manufacturer of microprocessors since 1970s. Prior to 2005, the digital I/O board used for the input/output operations in our experiments was designed for the ISA (Industry Standard Architecture) bus. Around the year of 2000 the PCI (Peripheral Component Interconnect) bus became dominant and squeezed out the ISA bus from most motherboards. By the year of 2005 it was almost impossible to find a computer equipped with an ISA expansion slot. To expose students to contemporary technology, in the fall of 2005 a new set of experiments were developed that use a PCI board on topics dealing with digital input/output operations, analog-to-digital (A/D), and digital-to-analog (D/A) conversions[5]. These experiments were performed mainly in software level using high level C program language. Specially defined C functions provided in the Universal Library that came with the PCI DAQ board were used to perform digital input/output, DAC and ADC. Although students get exposed to how the interfacing can be realized using high-level language, such as C/C++, students are missing the practice to perform direct low level port accessing for the interfacing.

Assembly language and a high level language, such as C/C++, are two different tools for embedded system design. Each has advantages and disadvantages. Without a “mysterious” intermediate compiler, assembly programming is faster and clearer. On the other hand a high level language accomplishes a given task in a more general way regardless of the differences between the assembly instruction sets of different microprocessors. Portability is of extreme importance for embedded systems. Thus using assembly language can be problematic. Due to fast changes in microprocessor technology, new designs may not use the same processor architecture and/or the same compiler as previous designs. Therefore, anytime one writes software in assembly language, the ability to reuse the code is greatly diminished. That’s why most industrial applications prefer to use C or C++ these days. However learning assembly programming is still an important objective for the introductory microprocessor source. Therefore, the laboratory experiments should expose students both to the assembly programming and C programming in embedded microprocessors.

For the past two decades more and more universities have adopted embedded microprocessors in their Electrical and Computer Engineering Curriculum. The reasons are twofold. First nowadays embedded microprocessors become more and more popular and can be found in almost everybody’s daily lives. A large field that current ECE graduates work at is embedded systems. Teaching embedded microprocessors in the ECE curriculum is a must. Second, for the past several years, in our department different kinds of embedded microprocessors, such as ARM, PIC, and etc., have been chosen in the majority of ECE senior design projects and some multidisciplinary projects. Hence, teaching embedded microprocessors will definitely provide students with more appropriate technical skills in delivering more successful projects. Embedded microprocessors also allow more flexibility in low level port accessing and interfacing with other peripheral chips.

After a thorough evaluation over embedded microprocessors from different manufacturers, the ARM microprocessors by ARM holdings are chosen for the course transformation. ARM microprocessors are popularly used in handheld devices, Robotics, Automation, and Consumer Electronics. Examples are Apple iPhone and many other smartphones, Lego Mindstorm Robotics Kit, Graphics Calculators, and many handheld game consoles. ARM processors are best known for their low power consumptions and high processing power, thus are very competitive in the embedded system market.

Therefore, starting from Fall 2014 the intro-level microprocessor course: ECE 362-Microprocessor System and Interfacing, in our school made the transition from Intel x86 architecture to ARM Cortex-M3 embedded microprocessors, which are also used in two other senior level advanced ECE courses, ECE 485 and ECE 437. The transformation is aiming at enhancing the students' learning objectives with more hands-on experience on 1) interfacing the microprocessor with other peripheral chips such as UART (universal asynchronous receiver/transmitter), ADCs (analog-to-digital converters), DACs (Digital-to-analog converters), and etc. 2) assembly programming in RISC (Reduced Instruction Set) architecture which is used popularly in embedded systems.

2. Course development

The microprocessor system and interfacing course at our school is a 4 credit hour course, including a 3 credit hour lecture and 1 credit hour laboratory. The lecture meets twice a week for 75 minutes each. The laboratory session meet once a week for 2 hour and 50 minutes. This course introduces the basic microprocessor architecture, assembly programming, and how the microprocessor can be interfaced with other peripherals. The accompanying laboratory allows students to perform hands-on activities with assembly programming and microprocessor hardware interfacing. ECE 362 is a required course for both Electrical Engineering and Computer Engineering students here at our school. It is pre-requisite for three senior level ECE courses: ECE 465 – Embedded Microprocessors, ECE 485 – Embedded Real time operating systems, and ECE 437 – Computer System Design and Prototyping. With this course transformation, these three courses all use the ARM microprocessors. These three courses are all required courses for Computer Engineering curriculum. They are also technical elective courses for Electrical Engineering Curriculum. ECE 362 is also the pre-requisite course for the Capstone Senior Design course in both programs. The course is currently offered every Spring and Fall semester.

Using the same family microprocessor for these three courses will bring the following benefits to students and the ECE program.

1. To students, covering more than one type of microprocessors in the curriculum allows students to get exposed to a wide range of microprocessors, thus provides students with the opportunity to implement the basic microprocessor knowledge into different types of microprocessors. On the other hand, teaching the same family microprocessor will save times for the learning curves as compared to using different kinds of microprocessors in

different courses. Currently students learned the Intel x86 architecture and assembly instruction set in ECE 362. When students take the two senior level microprocessor related courses, they need to spend at least one third of the semester learning the ARM architecture and assembly instructions set. Thus the time left for learning the application using the microprocessors is limited.
2. To the Electrical and Computer Engineering programs, using the same family microprocessors in different level microprocessor related courses allows the instructors to cover more materials in depth for the senior level courses.
3. For the past several years, different kinds of embedded microprocessors have been chosen in the majority of ECE senior design projects and some multidisciplinary projects. Hence, teaching embedded microprocessors in ECE 362, which is the pre-requisite course for the senior design projects, will definitely provide students with more appropriate technical skills in delivering more successful projects.

The course development is conducted under the principle that the lecture prepares students for the laboratory and the laboratory complements the lecture. The lecture covers the architecture and the instruction set of the ARM Cortex-M3 microprocessor as well as various analog and digital interfacing components. The main topics discussed in the lecture are listed in Table 1 along with the approximate duration. ARM Cortex-M3 core are adopted by many microcontrollers in the market. The experimental platform chosen for our laboratory use LPC1768[6] microcontroller made by NXP.

Table 1. The main topics covered in ECE 362

Topic	Duration (approximation)
Review of number systems	1 week
Instruction set of the ARM Cortex-M3 microprocessor	5 weeks
ARM based MCU and GPIO	1 week
Memory Interfacing	1 week
Peripherals - Serial transmission:LPC17xx UART - A/D and D/A conversion - LPC17xx Timer - LPC17xx PWM - Interrupt	5 weeks

The newly developed laboratory experiments are performed on Keil MCB1760 Board[7] which is supported by Keil ARM-MDK, the leading ARM development environment. The board is based on LPC1768, an ARM Cortex-M3 processor-based Microcontroller. A total of 13 laboratory experiments were developed to provide students with hands on experience on assembly programming as well as interfacing microprocessor with other peripherals, such as UART, ADC, Timer, and PWM (pulse width modulation) signal generation. Table 2 showed the details of these 13 experiments. Lab 1 is a tutorial for the software development environment students will use throughout the whole semester. The Keil MDK- ARM Microcontroller Development Kit is free to download from the Keil website, which provides students the opportunity to perform the pre-lab in their home computer. Lab 2-7 are experiments with the ARM assembly instruction set in basic arithmetic operations, conditional coding, flow control and subroutine call. Lab 8-13 are experiments using the peripherals including GPIO, interrupt, serial transmission, A/D and D/A conversion, timer, and PWMs.

Table 2. Laboratory experiments in ECE 362

Number	Experiment
1	Keil MDK-ARM Microcontroller Development Kit Tutorial
2	Basic Arithmetic Operations
3	Arithmetic and Debugging Tools
4	Conditional Codes and Prime Number Tester
5	Flow Control and String
6	Stack, Function Call Convention
7	Stack, Function Call Convention, Interface between C and Assembly
8	LED Blink, Register Header File, and System Tick
9	System Tick, Polling vs Interrupt, Predefined header file, CMSIS Standard
10	UART Polling vs Interrupt
11	Analog-to-Digital Converter-Polling and Interrupt
12	LPC17xx Timer
13	LPC17xx Pulse Width Modulator

3. Assessment

The learning objectives of ECE 362 are

1. to become familiar with the architecture and the instruction set of a microprocessor.
2. to learn the design of various types of digital and analog interfaces.
3. to provide practical hands-on experience with microprocessor software applications and interfacing techniques

The course transformation will not affect the learning objective 1 and 2. Students will still learn the basic architecture and the instruction set of a microprocessor. Different types of digital and analog interfaces will also be learned. The learning object 3 will be greatly enhanced with more labs in interfacing the microprocessors with other peripherals.

The learning objectives of ECE 362 are assessed through the following three course outcomes. The letter outcomes in brackets are the mapped ABET course outcomes. Learning objective 3 are assessed through the course outcomes 2 & 3.

1. an ability to program a microcontroller to perform various tasks [a,e,k]
2. an ability to interface a microcontroller to various devices [a,b,c,e,g,k]
3. an ability to effectively utilize microcontroller peripherals [a,k]

In Fall 2014, there were a total of 10 students taking this course. The course outcome assessment was conducted during the last week of the semester. The instructor was required to be absent during the assessment. Students were asked to rate the outcomes in a scale of 1(not achieved) to 4 (achieved). Table 3 provides the assessment results. The results showed that all three course outcomes are achieved.

Table 3. Results for students course outcome assessment

Course Outcomes	Average scores
1. an ability to program a microcontroller to perform various tasks	3.4
2. an ability to interface a microcontroller to various devices	3.2
3. an ability to effectively utilize microcontroller peripherals	3.3

In the previous version of ECE 362 where the Intel x86 family microprocessors were taught, there are four course outcomes:

1. Understanding of the Intel 8086/8088 architecture. (a, k)
2. Knowledge of the 8086/8088 instruction set and ability to utilize it in programming. (a, g, k)
3. Understanding of the Intel 8086/8088 real mode memory addressing. (a, k)
4. Ability to interface various devices to the microprocessor. (a, b, c, e, g, k)

The first three outcomes emphasizes on the architecture/instruction set of a microprocessor, where the last one is about interfacing microprocessor with other peripherals. The last time when the course outcomes for ECE 362 were assessed is Fall 2013. The average score for outcome 4 is 3.4, which is comparable to the current outcome assessment score (3.2, 3.3).

Another measurement for the effectiveness of the course development is students' performance. Table 4 below shows the faculty assessment of the course outcomes based on students' work, such as lab reports, homework assignments and exams. The assessment results show that the course outcomes are strongly achieved.

Table 4. Faculty assessment of the course outcomes

Outcomes			Faculty Assessment						
			Tools Used			Course Outcome	Criteria Used		
	Course	ABET	1	2	3	Achieved?	criterion	Limit	Value
1)	an ability to program a microcontroller to perform various tasks [a,e,k]		Lab Report(s)	Homework	Midterm(s)	Yes, strongly	criterion 1	75%	85%
2)	an ability to interface a microcontroller to various devices [a,b,c,e,g,k]		Lab Report(s)			Yes, strongly	criterion 1	75%	90%
3)	an ability to effectively utilize microcontroller peripherals [a,k]		Lab Report(s)			Yes, strongly	criterion 1	75%	90%

criterion 1: The average of students in the assessment tool is equal to or greater than 75%

4. Conclusions

This paper presents the course development of a junior level introductory to microprocessor/mirocontroller course. The redevelopment transforms the previously taught Intel x86 family processors to the ARM Cortex –M3 embedded microprocessors. The development includes both the lecture and the laboratory experiments. This course transformation is aiming at enhancing the students' learning objectives with more hands-on experience on interfacing with various peripherals. The assessment results in the fall of 2014 showed that the three course outcomes are all achieved with the first time implementation of the new materials.

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