AC 2009-1426: DEVELOPMENT OF A "SMART" SENSOR: AN INTEGRATED INSTRUMENTATION COURSE PROJECT

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Abstract

The instrumentation course at Texas A&M University has and will continue to follow a traditional format, teaching the students about sensor technology, signal conditioning, digitization, and finally signal processing techniques. In addition, with the program's new emphasis on distributed process control, information on smart sensors and industry-standard instrumentation buses is included. However, because the Programs are in the process of developing a strong emphasis in the area of product/system development, the instrumentation course has also been identified as an excellent place to have students bring together for the first time, the knowledge they have been developing in analog, digital and software design. In addition, it is also the best place in the curriculum to introduce the students to product design principles for the first time and have them develop a fully-functional prototype of an electronics product.

To this end, while the lecture portion of the course still covers traditional instrumentation topics, the faculty has developed a new course project that integrates all of these elements into a comprehensive learning experience where the students design, implement and test a networked “smart” sensor. The project not only requires the students to design and simulate a sensor with signal conditioning, they also have to interface their sensor to a microcontroller, interface the microcontroller to an instrumentation bus, and write the software necessary to process their sensor data and communicate via Modbus protocol to a process control supervisory system. In addition, the students use CAD tools to design a printed circuit board for the working prototype they have to build at the end of the course. This paper will present this new course project in detail including the problem statement, the tools/processes used by the students, and the final deliverable required at the end of the course. In addition, lessons learned, student feedback, and future work will be discussed.

Introduction

Over the past five years, the Electronics and Telecommunications faculty have moved the focus of their programs towards product/system development. While the Programs will always deliver a well-rounded curriculum that prepares students for general careers in the Electronics and Telecommunication industries; the faculty believes, like many other programs, in the importance of producing graduates that understand innovation and entrepreneurship as well as the technical/engineering fundamentals.^{1,2} For this reason, the curriculum has been changed over time to provide students with the requisite technical expertise and a strong background in project management that allows them to understand the planning process behind product and system development. Since 2002, the Programs have refined their capstone design course sequence to require all students to: form a team that will function as a small startup company; identify an idea for a product or system; locate sponsorship and find a faculty advisor; plan their efforts using project management principles and develop a formal proposal to sell their idea; and finally implement their design through a working prototype and complete documentation package³.

This process encourages the students to use their education to innovate and solve a complex, real-world problem. Feedback from both graduates and their employers indicate that this experience makes them extremely valuable employees.

Most recently, seniors working on their capstone design sequence have had the option of becoming an E4 team. E4, or Engineering Entrepreneurship Educational Experience is a process developed by the faculty that allows interested students to take the next logical step and commercialize their idea/prototype either through licensing or through a new start-up company⁴. E4 begins by having the students sign an intellectual property agreement with the University. This allows the school to represent their interests, and in return the students become “inventors”, entitling them to share in any royalties derived from the licensing of their capstone design efforts. In addition, E4 teams typically partner with students from the School of Business. While the engineering technology students develop the actual product/system, the business students develop market/feasibility studies and create a business plan. At the end of the capstone sequence, each E4 project can choose to continue their efforts through one of two paths: the new venture path (regional start-ups) or the technology transfer path (licenses). The decision of which path to follow is made by the students and faculty based on their project’s opportunity for success.

Using the technology transfer path, the University works on behalf of the inventors (students and faculty) to negotiate licensing of intellectual property with third party companies interested in commercializing E4 products/system prototypes. To date, this has been the more successful of the two models offered by E4. In fact, over the past two years, five different student projects have been pursued by the private sector, and three of those have actually been licensed. The alternate path, the creation of a new venture, has been more difficult to support. This has been for two reasons. First, most students have been preparing for four years to graduate and take a position with an existing company. While they enjoy the E4 experience, they are not ready to accept the risk and responsibilities associated with starting a new company. Second, the University still has legal challenges with creating an on-campus incubator for use by faculty and students. However, as E4 takes hold, the attitudes of both the students and the University administration are shifting.

With all of these improvements, the faculty still feels like the approach the curriculum has taken to emphasize product/system development is still somewhat adhoc. For this reason, industrial experts from several different market sectors were approached to find out how their companies pursue product development. This led to the “Product Development Summit”, a meeting where industry was asked to help answer the following questions:

- Can undergraduate students in electronics/telecommunications engineering technology be successful in the area of product/system development?
- What are specific careers in the area of product/system development? (i.e., test, design, product engineering, sustaining engineering, etc...)
- What does the product/system development process look like in industry?
- What are the attributes of a product/system development engineer?
- What skills/toolsets are necessary for a product/system development engineer?
- Are there existing materials in the area of product/system development that EET/TET can leverage?

Several actions on the part of both industry and academia were established as outcomes of this meeting. In fact, a future paper is planned to discuss the overall product development emphasis and its status. However, an immediate action was the development of a more holistic approach to product development. Industry suggested that while the current capstone design sequence was an excellent experience, a true product development emphasis required early and continued exposure of the students to the best practices and tools used by the product/system development industry. The efforts of the faculty to implement this suggestion have led to a pair of papers at the 2009 ASEE conference. This paper discusses the creation of a course project for use in a junior-level instrumentation course that guides students step-by-step through the product development process and the results achieved to date. The project involves the design and implementation of a “smart-sensor” which is then integrated into a larger instrumentation and control process. The students must develop a set of specifications and product requirements, design a system (hardware and software) that achieves those requirements, implement the design through printed circuit board (PCB) design and manufacturing processes, and finally test their system to ensure it meets specifications. A second paper can also be found in these proceedings that discusses how product design tools are taught to the students throughout the curriculum in order to prepare them for this type of project.

The Instrumentation Course

The Electronic System Interfacing course is a four credit hour instrumentation course with primary topics that include measurement systems, sensors, signal conditioning, and ADC/DAC. Students in the Electronics Engineering Technology program typically take this course in their junior year after taking Circuit Analysis I and II, Digital Electronics, Digital Logic Circuits, Electronic Devices & Circuits, and Microprocessors. It is a technical course that allows students to combine the basic knowledge they have learned in previous semesters and apply it to the field of instrumentation. In fact, while the primary objective of the laboratory is to introduce students to the concepts in instrumentation, it has also had a secondary objective of integrating the analog and digital concepts learned in previous courses. Since instrumentation is a critical part of control systems and all the senior design projects need some type of instrumentation, the Electronic System Interfacing course is one of the key courses in the Program.

Traditionally, the Electronic System Interfacing course (ENTC 359) has covered sensors, signal conditioning, ADC/DAC and instrument communication buses. While not specific to instrumentation, the Programs have also relied on ENTC 359 to teach students about the importance of system testing and validation, as well as techniques for creating good technical documentation. In addition, minor changes have recently been made in the emphasis of the course as part of an effort to develop a new Power Engineering Technology program. Whereas the class originally focused on discrete instruments for monitor and control, it now discusses instrumentation from a more process control aspect, focusing on smart sensors, distributed sensor networks, and digital instrumentation and control systems. Thus, the course still covers the basics of sensors and instrumentation design but with a focus on distributed instrumentation systems that use digital backbones for communications and control.

A New Course Project

Most recently, after a careful review of current program directions, industry needs, and faculty interest, a new emphasis for the Electronics and Telecommunications programs in the area of product/system development has been created. Not only is this closely aligned with current and future job opportunities for the students but it also fits well with the concept of securing the United States' competitive edge through a knowledgeable workforce that understands innovation and entrepreneurship. As part of this new initiative, the Programs held a "Product Development Summit" where industry experts were brought in to discuss best practices. The insight from this meeting resulted in several action items, one being that the students need more exposure to product development concepts over and above their capstone experience. To begin incorporating best practices throughout the curriculum, the faculty identified the Instrumentation course as a good starting point since it is the first place that the students have enough background to engage in a meaningful product development experience. Through the addition of a six week course project (see Figure 1), student teams are now required to develop a set of product requirements, design/implement/package a system, validate that their design meets a set of specifications, and finally document their "intellectual property" completely.

Figure 1 – Overview of Instrumentation Course Project

In general, the project requires the students to develop a microcontroller-based sensor that can communicate bi-directionally through a digital instrumentation bus to a master that uses the data to control a process. While the actual sensor and bus standard can be different from semester to semester, the overall process is the same and includes:

- Developing of a set of requirements based on the system that the final product must interface with.
- Designing the sensor signal conditioning circuitry, microcontroller circuitry, and bus interface hardware. The students must simulate their design using Multisim and demonstrate that it works before implementation.

- Writing microcontroller software to process data from their sensor and communicate it through the designated protocol (RS-232, Modbus, etc...)
- Laying out a printed circuit board, having it manufactured, and populating their circuit. The students use Ultiboard for the layout and must use surface mount technology where possible.
- Packaging their system professionally.
- Testing and validating that their circuitry not only works, but interfaces seamlessly with the overall system. This includes ensuring that the device can communicate with the system's master controller.
- Documenting their design in such a way that it could be duplicated by a third party.

Through this process, the students develop their own set of best practices so that they are truly prepared for a very rigorous and time intensive capstone design sequence. In addition, while they have seen most of the design tools before, this experience prepares them to use the tools professionally. Finally, this new project also gives the students a deeper understanding of process control and digital instrumentation, a secondary goal that is part of the new Power Engineering Technology initiative.

Work to Date

Spring 2008 - During the Spring 2008 semester, three EET/TET faculty members agreed to work collaboratively on the redesign of the course project for the junior-level instrumentation course and associated laboratory experience. The overall requirements of this project were to have the students design a complete system-level specification for a multi-level data acquisition and control system. A model of an industrial curing chamber was chosen as the target environment to be controlled. The control system was designed as a master controller with two slaves; one to monitor the environment and the other to control multiple attributes of the chamber. The master included a graphical user interface running on a desktop computer to permit user input of system performance parameters, control of the overall operation of the system, and graphically display in near real time the overall status of the system. The second system component was an intelligent sensor capable of measuring an environmental variable and reporting this information to the system-level controller. The third unit was implemented on a laptop computer and was responsible for controlling the operation of multiple system functions to control the target system.

Once the overall architecture of the system design was finalized, a phased approach was established to bring the design to full operation. During the Spring 2008 semester, student teams were assigned tasks to design and implement the smart sensor slave. The slave was designed to measure and communicate the operational temperature of the curing chamber to the master. This work included the evaluation and selection of the temperature sensor together with empirically determining the transfer function for the device. Once determined, the student then designed a complete signal conditioning circuit which included the use of a Wheatstone bridge to translate change in resistance to change in voltage, an instrumentation amplifier for signal gain, an offset amplifier to translate the voltages to the proper range, and a filter to eliminate unwanted noise prior to the analog to digital conversion. A PIC 24 microcontroller was selected as the embedded controller for this slave. Using the Microchip development environment, the students

generated the code necessary to properly configure the PIC processor, accept the analog input from the signal conditioning circuitry, convert it to a digital value, process multiple observations to produce a reading and then communicate this reading to a master via a serial communications protocol. For this first class, standard RS232 serial communications was employed with a send only data packet to the master. The students were also required to accept these temperatures reading and display the readings using LabView running on a laptop computer. Although the students used a protoboard to debug their hardware design of the intelligent sensor slave, teams were required to produce complete schematics and PCB layouts so that they could have a PCB professionally manufactured that they then populated, tested, and demonstrated.

Summer 2008 - While the Spring 2008 student teams were completing all of these activities, the faculty surveyed industry to determine what the appropriate interface and protocol should be to implement a master/multi-slave system. Although Foundation Fieldbus is a predominant and growing standard, the faculty also learned that this standard comes with a steep learning curve and high cost. The industry contacts then suggested the use of the Modbus protocol which is also used throughout industry, is an open and free standard, and has a more reasonable learning curve. In addition, it was recommended that a four-wire RS-485 interface be used to support the master/slave communications. From these recommendations, a complete system design specification was developed as well as an implementation strategy.

The lessons learned during the Spring 2008 semester were used to guide the continued development of the course project during the Summer 2008 semester. Because the class met four days per week during the summer semester, a higher level of interaction and integration was possible. Based on the overall system design and implementation strategy, the faculty agreed that the student teams should continue to design and fabricate the temperature sensor slave unit. The laboratory instructor was tasked to implement the master using the LabView Modbus Virtual Instrument (VI) hosted on a desktop computer. Although the students were not responsible for the software operating on the master, they had to collect detailed information on the exact protocol that the LabView VI implemented to insure proper communications in both directions. Finally, the faculty members implemented the environmental control capability using a laptop and the LabView development environment which included the Modbus communications VI. To support master-slave communications, a fully terminated four wire RS-485 bus was created that allowed easy attachment of the various units for development, testing, and demonstration.

Figure 2 depicts a conceptual-level diagram of the curing chamber master/slave environmental control system that was developed during the Summer 2008 semester which includes a picture of a populated PCB. In addition, the user interface running on the master computer is shown in Figure 2. A block diagram of the intelligent temperature sensor design is shown in Figure 3 and the four wire RS485 bus structure is depicted in Figure 4.

Fall 2008 - An attempt was made in the Fall 2008 semester to implement the Modbus master/slave control system in an industry sponsored project so that students could work on a real-world problem. The basic project requirements were very similar to those used in the Summer 2008 semester with the addition of a digital low pass filter design component. Students were required to develop a Modbus slave that is able to measure the temperature of the system

and communicate with a LabVIEW Modbus master on a desktop. The teams had an opportunity to go through the system design process. They also completed the PCB design and ordering process, built part of the PCB, and tested with an in-house PIC24 development board. But due to the delayed delivery of the test stand and problems with ordering parts, no team was able to complete the project.

Figure 2 – Overall block diagram of course project

Figure 3 – Block diagram “smart sensor”

Figure 4 – RS485/Modbus communication bus

Based on the lessons learned from this failed attempt, the course project was modified to include multiple stages for Spring 2009 semester. The Modbus communication course project using the desktop curing chamber is now divided into four stages. In the first stage, students modify the NI Modbus VI to control the fan speed, and the heating units inside the curing chamber. A temperature sensor and signal conditioning circuit (on a breadboard) are connected to the NI Modbus slave (a desktop computer). The temperature reading is passed to the master (a laptop computer) via Modbus. The master compares the temperature with the target and varies the speed of fan and the on/off condition of the heating units. The objective for this stage is for students to learn the basics of Modbus communication using the existing LabVIEW VI. In the second stage, students design a PCB using MultiSIM/Ultiboard to replace the functionality of the temperature sensor, signal conditioning circuit, and the NI Modbus slave, i.e., everything inside the dotted box in Fig. 5.

Figure 5. Stage 2 Configuration.

The objective of this stage is for students to learn the hardware design, simulation, and become familiar with the ordering process. In the third stage, students create software code in a PIC microprocessor on a development board for Modbus communications. The objective of this stage is for students to learn to write software for Modbus communications. In the last stage, a PCB is ordered and a prototype is built and tested.

Conclusions and Next Steps

As stated in the introduction, industry highly recommended that a more holistic approach to product development be pursued, and that the EET/TET Programs continue to expand their emphasis of industry-grade development tools and best design practices throughout the curriculum. The redesign of the junior-level instrumentation course and associated laboratory experience has responded well to these recommendations. In so doing, the programs have

recognized both positive and negatives in the work done to date. On the positive side, students do gain significantly from an approach that starts with the development of a complete system specification and requires them to design a portion of that system using both hardware and software design tools. The integration of hardware and software design, implementation, testing and documentation are skills that come with experience, and applying these skills to instrumentation, control, and communications builds a strong understanding that will serve the students well as they move forward in their education. On the negative side, it is much more difficult to support a course that has such a critical timeline for student success.

This difficulty is clearly seen when examining the history of the past three semesters. In Spring 2008, of the five teams of students, three teams were able to complete the project successfully and on time. With the fourth team, one student was found to have completed the project on his own and so his partner was required to complete the project by himself. The fifth team also had team interaction issues and had to be split into two individual projects. All three of these students were given an incomplete and were required to finish the project after the semester was over. All three finished the project successfully with an extension of three weeks. Through this initial offering, many lessons were learned about the level of oversight required to ensure that all students were working at the pace required to finish on time. In the Summer 2008, a new set of three teams were each able to successfully complete all of the requirements of the project in a six week semester.

Finally, in Fall 2008, a different faculty member took over responsibility for the course. He had the students attempt a similar course project but added a level of difficulty (the development of a digital filter) which ultimately caused the students to run out of time on the hardware implementation. While these issues have been rectified for the Spring 2009 semester, this clearly shows how the success of a time intensive project can be affected. Problems such as team dynamics, untested changes in the project statement, hardware/software issues, and even component failure during testing are just a few things that can negatively impact the overall success of a student team. All of these must be dealt with in such a way that the problems are resolved with minimal impact to the project. However, even with such difficulties, the faculty agrees that the learning experience offered by such an intensive project warrants the additional effort required.

The success of a redesigning the instrumentation course has added significant value to the EET/TET Capstone Design Sequence. Beginning in Fall 2008, students entering this two-course sequence have a much better appreciation of what is required to move from a conceptual system-level design to a fully functional prototype. Through the lessons learned in participating in hardware and software design processes while in the junior-level course, significant experience is carried forward to the Capstone courses. By having more complete design reviews, the teams are achieving major project deliverables at an earlier point in their projects with far better quality. Having experiential knowledge of the factors that can impact board design and fabrication as well as software development prior to beginning their capstone experience results in far fewer unexpected pitfalls as the team moves from idea to fully functional prototype. The instrumentation course also underscores the need to understand all communications interfaces and protocols down to the lowest level. Gaining an appreciation of what one bit incorrectly assigned can do to full fledged protocol such as Modbus generates a new awareness in the

Capstone teams on how to develop, test and document the overall operation of their prototype and how it should be interfaced to other components in a major system.

On the software development side, the experience gained in the instrumentation course makes the capstone teams more aware of the need to establish early on in the project, the specific requirements their designs will have to meet. These students have experienced the problems and issues that result from unclear or incomplete specifications and pay more attention to these factors as they interface and interact with their customer/sponsor during their Capstone experience.

The teams also come away from the instrumentation course with a new respect for signal characterization as well as clear definitions of test requirements. Each of these are sources of error and time delay during the system design in the instrumentation course, and these lessons are not soon forgotten when the students transition to their Capstone courses. By characterizing all inputs and outputs early on in their projects, fewer redesigns are required due to faulty assumptions. Incompatibility of signals is better understood based on the system design of the instrumentation course. By applying this knowledge to the Capstone project, potential costly mistakes are avoided.

A major step function has been realized in the test plan and reports which are an integral part of the Capstone projects. Although some of this improvement comes from building on the preceding semesters work, the redesigned instrumentation course makes the students aware of the need to design to the test requirements not test to the design capabilities. By placing a higher premium on this aspect of the project, the teams do a better job in understanding and meeting their customer's needs and requirements.

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