A Multi-Level Curriculum in Digital Instrumentation and Control based on Field Programmable Gate Array Technology

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Abstract – Currently, on one hand courses in digital instrumentation focus on the general principles and the utilization of off-the-shelf equipment without addressing the design issues of safety critical environments. On the other hand, the use of FPGA in education is mostly limited to a small scale digital circuit design or computer architecture concepts. This might be due to the misconception of insufficient FPGA densities or the lack of easy to learn design tools that students can comprehend within a single course. However, thanks to the advances in FPGA technology and the initiatives taken by the FPGA industry, more FPGA-based educational components can be developed. Our innovative idea is to effectively combine digital instrumentation and control with FPGA design course using hardware description language. This will be accomplished using multi-step integrated curriculum components, with industrial collaborative linkages, offered at appropriate points starting from sophomore level, and extending to senior levels.

Keywords: Digital Instrumentation & Control curriculum, multidisciplinary components, FPGA design courses.

INTRODUCTION

Digital Instrumentation and Control (I&C) plays an increasingly essential role in monitoring, control and protection of modern industry. Modern industry in the USA is in the process of replacing aging analog systems with digital I&C. Digital I&C technologies are known for high processing capabilities, which allow them to perform intelligent on-board computing that supports functionality such as self-checking. They also provide for improved accuracy, flexibility and easy calibration. However, digital I&C poses some challenges for sensitive environments such as nuclear power plants, or biomedical applications. Such challenges require special skills, knowledge and awareness from engineers in the design, operation and maintenance.

With the inevitable upgrades to the aging analog I&C, there is a growing demand for engineers who understand the special nature of the safety critical digital I&C and are capable of meeting the challenges of the industry. Moreover, with the advent of new promising technologies such as FPGA, the design of digital systems has undergone tremendous change. However, no electrical engineering curricula that fully integrate FPGA in digital I&C system design for safety critical applications is known to exist. The increasing demand on digital I&C requires competent new graduates and well trained professionals, which is not completely satisfied as of yet.

The use of software and general purpose processors is a principal difference between digital and analog I&C systems. The development of safety critical industrial products utilize complex software that is often designed by multiple parties and/or at various sites; and is developed typically over a long period of time. Hence, Configuration Management (CM) tools need to be installed on the developing computers; and are connected to a centralized server

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that keeps track of different versions of generated code. This required CM system adds to the complexity of modern safety critical industries, and is subject to problems as well (such as operating system portability and assured network connectivity). One way to reduce the CM problems as indicated by the National Research Council (NRC) report on digital I&C in safety critical industries is the use of Field Programmable Gate Arrays (FPGAs) and similar technologies [AREVA, 1].

NEEDS FOR CURRICULUM CHANGES

A report by the NRC [NRC, 2] identified several key concerns about the utilization of digital instrumentation and control in safety critical industries including:

- Common-mode Software failure
- Configuration management
- Safety and Reliability
- Functional Diversity

Some key design issues have also been noted in the same report as important issues in the design of digital I&C. These include:

- Sequential and Concurrent operations,
- Multitasking and Multiplexing,
- Memory sharing and Data communications,
- Real time processing and Data storage.

Embedded computing is gaining national and global interest. This interest is shared by large embedded computing industry that is accounting for 10% of the gross national product of the United States, more than the automotive industry [NRC, 2]. Modern FPGAs enable efficient embedded computing at both the hardware and software level. FPGAs offer a multitude of performance improvements in terms of speed, reduced circuit size, light weight, and low cost of the product, due to the close integration of hardware/software functionalities on the chip. It also simplifies the execution of application logic such that operating systems or application software can be eliminated or minimized [William and Malcolm, 3]. Hence, FPGA modern technology could have a significant impact on strengthening the Nation's economy.

In addition to its performance advantages, it is clear that the safety critical industries will benefit from FPGA due to its simplified configuration management model. One main feature of FPGAs is their reconfigurability, that is, they can be reshaped to have various software/hardware components at various times. At any point of time, an FPGA can be reconfigured by a host computer that is installed with FPGA configuration tools. These tools are portable, and perform similarly on various operating systems. In addition, this re-configuration can be done in real time, while the FPGA is connected to the target system. Since the host computer and the FPGA are separate, the configuration management of the FPGA can be relatively simpler compared to software only non-FPGA systems.

Moreover, it is worth mentioning that application software can be automatically or custom converted to an equivalent hardware in the FPGA technology using Hardware Description Languages (HDL). For example, a software segment that adds elements of an array can be converted to a hardware register file, with an adder and an accumulator using HDL. Hence, a number of well-known companies such as AREVA in the USA [Westinghouse, 4] and France [AREVA , 5], Triconex in England [Ajay, 6], and Westinghouse in the USA [Westinghouse, 4] are looking into adopting FPGA in the design of new digital I&C equipment for nuclear reactor instrumentation. Westinghouse in the USA, have adopted FPGA-based instrumentations in their Boiling Water Reactors in Neutron Monitoring System [Westinghouse, 4].

Most importantly, it is believed that educating students about the state-of-the-art technology connects the curriculum with students' real life [Wright, 7]. It is extremely important for students to know, through experiments, how new technology works [Dugger, 8], [Grewe, 9]. This paper focuses on presenting how we utilize the new FPGA technology to involve the students in experiential learning of hardware and software issues of digital I&C. Students, at various levels, will use FPGA to learn simple concepts (e.g., concurrent hardware versus sequential software operation) to sophisticated design concepts (i.e., multiplexed data acquisition or multitasking of real-time software components) through a gradual and guided increase of complexity. The ability to implement such concepts efficiently is gained by the maturity that FPGA technology has reached, and its new design technology of Systems-on-Programmable-Chips (SoPC), which allows the integration of multiple system components (software and hardware) on a single programmable and reconfigurable chip.

PROPOSED CURRICULUM

Bloom’s taxonomy will serve as a guide to develop the presented learning methodology in a manner appropriate to students’ progression through their engineering education. This methodology is of multi-steps. At the earliest levels of learning (step 1), students acquire basic knowledge and engage in basic applications in the sophomore level introduction to digital systems course. As the students progress through the curriculum encountering varied digital design and experiment courses (steps 2, 3), they increase their skills in application, synthesis and analysis. Finally, analysis and evaluation are reinforced in the senior capstone design courses (step 4).

As previously mentioned, combining digital I&C with embedded systems design courses using hardware description language and FPGAs will be introduced in multidisciplinary multi-step integrated curriculum components, with industrial collaboration linkages, offered at appropriate points starting from sophomore to senior level (as shown in figure 1) courses. This will be achieved by the following steps (1-4):

Step 1: Development of a new lab for Digital I&C using FPGA & SoPC: This lab would be utilized by multiple courses throughout the proposed curriculum in order to provide a hands-on experience to undergraduate students. In this task, a more capable laboratory facility will be prepared. A ubiquitous FPGA board released by Altera (Altera DE2 board) will be used to implement to curriculum enhancements. The Altera design must be installed in the utilized lab. Experiential demonstrative exercises will be developed, and tested on all workstations. The authors have prior experience with Altera DE2 board, and chose it due to its various capabilities and well established University Program support.

Step 2: Development of Digital I&C components to be integrated in existing sophomore to senior level courses with the goal of spurring interest in students and laying foundation for senior level courses. These components include the introduction of the FPGA technology in the ECE 2110 Introduction to digital systems course. It also includes adding new experiments that are based on Verilog HDL code for the ECE 3160 Laboratory. These experiments will be carried out in the lab equipped with the Altera DE2 boards mentioned earlier. Some experiments will be added to ECE 3160 to introduce the new Altera platform and programming tools, and introduce students to simple input output interfaces, such as LEDs, switches and sequential components such as counters.

Step 3: Development of a new senior level elective undergraduate course in Digital I&C focusing on utilizing FPGA. The new course would be integrated into the curriculum of students with emphasis in Instrumentation and Control. This course (henceforth named the new ECE 4150- FPGA based Digital I&C course) will be taught every fall semester twice during the project period, and adjusted as needed to meet the project goals and objectives before its second offering (as detailed in Section 3). It will have various pre-requisite courses as outlined in Figure 2. The course will be offered at the senior level as a 3 credit-hour-course (2 hours lecture and 3 hours lab). The new ECE 4150 course will require students to have knowledge of the "C" high level programming language and digital systems. It will introduce FPGA technology and Verilog HDL (which is a C-like language). This course will utilize FPGA in teaching Digital I&C concepts such as data acquisition (DAQ) and processing, data storing, and input output interfacing both at the hardware and software levels. First, the FPGA platform will be used to allow students to experience hardware based digital I&C concepts such as synchronization between analog to digital converters and data multiplexing, buffering of acquired data, adjustable clock timing and on-chip bus management. Then, the FPGA platform will be used to experience various software design choices such as sequential operation versus multitasking, and memory sharing versus message passing. In the process, students will be taught how to integrate hardware and software components on the FPGA chip. Hence, they will have the opportunity to experience and assess the difference between achieving the various digital I&C functions on hardware or software. Through critical thinking, students will address some of the several key concerns, (listed in Section 2: Needs for curriculum changes), of Safety Critical digital I&C such as functional diversity to achieve reliability. This new course will be the core of the new area on digital I&C at to satisfy these needs.

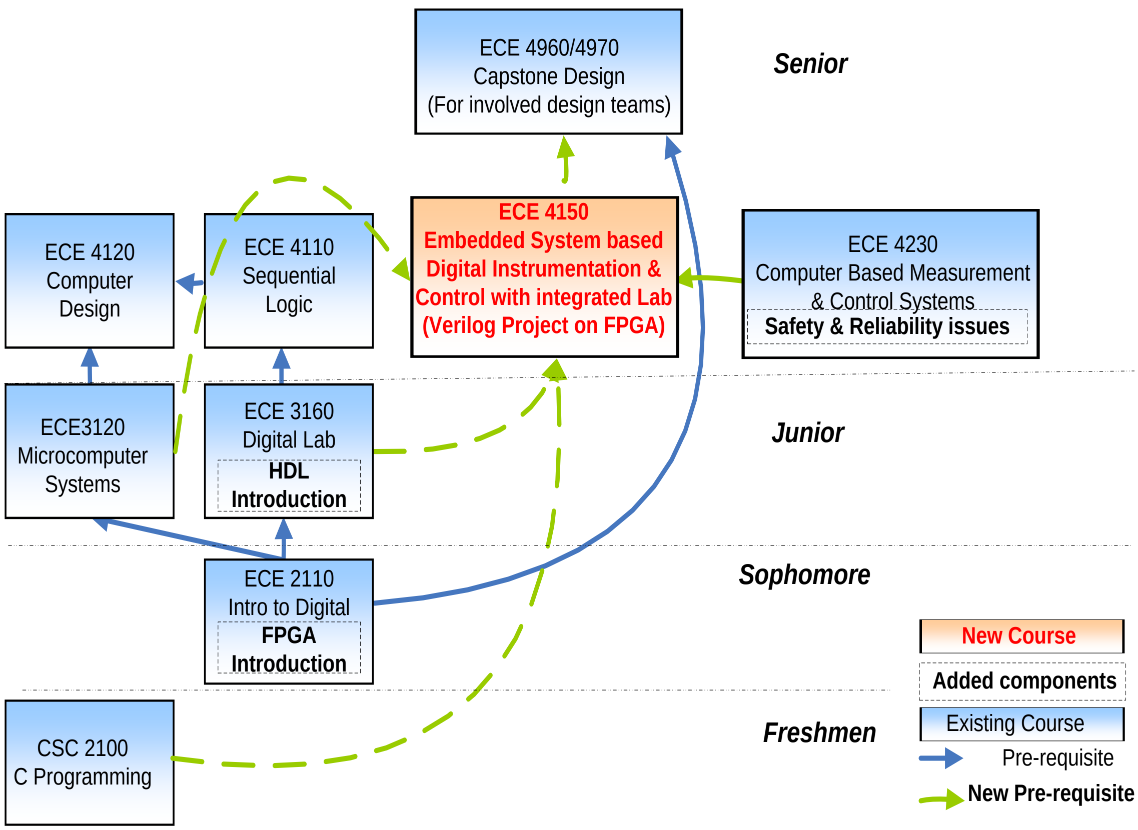

Figure 1: Flow chart of the partial existing curricula of ECE at TTU (solid lines), along with proposed component additions and their linkage to the curriculum (dotted lines)

Step 4: Development of industry linked capstone projects with applications related to digital I&C in Safety Critical industries such as Tennessee Valley Authority (TVA), in Nashville TN. TVA's nuclear power plants contribute about 7000 megawatts of electricity to the USA power grid, and is an integral part of the USA power system. The new ECE senior design activity will include a requirement of FPGA integration within the design (through DAQ, monitoring or control). The FPGA will serve as a tool to clearly show the effect of embedding reconfigurable hardware/software systems within the context of a Safety Critical engineered product. At this stage, students will be engaging their programming skills at the highest levels of learning, synthesis and evaluation. We will solicit senior capstone design challenges relevant to Safety Critical digital instrumentation and control. As senior students approach the challenge, they will be able to engage their software programming skills along with their hardware skills to achieve the highest level of design quality and productivity, and to be able to analyze, synthesize and assess their knowledge acquired throughout the developed emphasis of the Multi-level Digital Instrumentation and Control Curriculum.

CONCLUSION

In this paper, we present how we can enhance the students' design experience and competencies in digital I&C using FPGA and System-on-Programmable Chip (SoPC) Technology, and increase the awareness among Engineering Educators of the design of digital I&C using the state of the art FPGA SoPC design techniques. We aspire to enhance the robustness of such systems and their applicability in sensitive (Safety Critical) environments such as nuclear power plants or biomedical instrumentation.

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