HANDS ON PROGRAMMABLE LOGIC CONTROLLER (PLC) LABORATORY FOR AN INDUSTRIAL CONTROLS COURSE

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Abstract

The instruction of industrial controls employing programmable logic controllers (PLCs) is vital for many industries including manufacturing, mining, and production. PLCs are self-contained industrial grade microcontrollers with user-friendly input and output buffering. They are typically programmed using a visual ladder logic based language.

In response to requests from our constituents, we implemented an industrial control course based on both PLC and microcontroller technology. In developing the course, a graduate student worked closely with an industrial control company to develop a series of practical, hands on laboratory exercises to educate students on the fundamentals of PLC application design and implementation. In conjunction with development of laboratory courseware, an Industrial Control Laboratory was developed and equipped with state-of-the-art PLC and control instrumentation and test equipment.

This paper discusses the development and content of the laboratory exercises and physical laboratory. We have now taught this course twice and have gathered student perceptions on the quality and utility of the Industrial Control course. Students have requested additional emphasis in this area. We conclude the paper with plans for future course enhancements.

Overview

The Electrical and Computer Engineering Department at the University of Wyoming was contacted by one of our alumnus in the Spring of 2008 concerning development of an industrial controls course. The alumni had graduated in the early 1980's developed a highly successful industrial control company that provided service to the chemical, mining, oil, petrochemical, gas, and automotive industries [1]. The alumnus was interested in supporting the development of a course that emphasized the design of programmable logic controller (PLC) based systems vital to a wide range of industries and to support the ongoing demand for engineers educated in industrial control concepts and applications. Further, the alumnus pledged financial support to develop a physical laboratory and the required instrumentation to stand up an industrial controls laboratory. His motivation was to honor the memory of the late Professor R. Kenneth Beach who taught in the ECE Department for 38 years and who had a profound impact on his education and professional development [2].

At the time of the alumnus request, the ECE Department had a modest educational program in PLC-based system design. A course had been recently developed that emphasized the control of industrial devices and processes using state-of-the-art programmable logic controllers (PLCs) and microcontrollers. Equal time was spent between PLC-based and microcontroller based control of industrial equipment and processes. In the course, students investigated control algorithm design in detail and also discussed sensors, transducers, and interfacing. Students used state-of-the-art design and troubleshooting tools to apply control theory to a series of hands on laboratory exercises.

In response to the alumnus request a team was formed to make the course, laboratory exercises and the physical laboratory a reality. The team consisted of the faculty member currently teaching the industrial controls course, a graduate student who would be developing the laboratory exercises for his graduate project, the alumnus, the department staff engineer and the department senior technician who would plan and supervise the laboratory renovation and laboratory equipment purchase.

In this paper we describe the overall process to make the industrial course a reality. We begin with a brief review of PLC technology, a description of the team approach employed for the project, the curriculum and laboratory exercises developed for the course, the physical laboratory developed, the launch of the new course, dedication of the new laboratory, results of the course, and plans for course improvement based on student feedback.

Background

Programmable logic controllers or PLCs are special purpose industrial grade computers designed for use in the control of a wide variety of manufacturing applications. The PLC industry began when Dick Morley conceived the PLC concept early in 1968. Since its early beginnings, PLC based control has become a 6.5 billion dollar business with over 110 PLC vendors worldwide [3].

PLCs are industrial grade computers that have been specifically designed to work in harsh environments on the factory floor, process control environments, and mining applications. Typically PLC based systems are self-contained, rack-mounted control systems. The PLC rack contains a host power supply and a backplane that accepts circuit cards to provide for the central processing unit (CPU), protected input/output terminals, timing modules, communication modules, etc. Many PLCs use the 8051 microprocessor as the host CPU for the

control system [3]. The processor may be programmed using five different programming languages based on the IEC 61131 standard; however, a visually based ladder logic approach is popular [3,4].

As its name implies ladder logic programming bears a striking resemblance to the diagram of a ladder. It is a PLC graphical programming that was first introduced with PLC technology. Each rung on the ladder represents a program step that logically links system inputs to outputs. The logic on a specific rung graphically represents the algorithmic link between the inputs and outputs. The IEC 61131 standard provides instructions program timing, counting, basic arithmetic and move instructions, data conversion instructions, and program control instructions. The rungs are sequentially processed from the top to the bottom of the ladder diagram. When the ladder logic is compiled, it is converted in to machine code appropriate for the host processor [3].

For this project we used the Allen-Bradley SLC 500 line of PLCs. The SLC 500 line provides a wide variety of AC and DC input/output modules, timing modules, and communication modules [3, 5].

Methods

Team Approach

To launch this project a team was formed to make the course, laboratory exercises and the physical laboratory a reality. The team consisted of the faculty member currently teaching the industrial controls course, a graduate student who would be developing the laboratory exercises for his graduate project, the alumnus, the department staff engineer and the department senior technician who would plan and supervise the laboratory renovation and laboratory equipment purchase. The team met and developed a list of action items for each member:

- Faculty member
  - Coordinate the overall project
  - Select a textbook to support the course
  - Develop the classroom curriculum for the course

- Graduate student
  - Complete an internship with an industrial control company to learn firsthand PLC applications and processes
  - Develop laboratory curriculum for the course based on internship lessons learned
  - Serve as the laboratory teaching assistant for the laboratory portion of the course

- Alumnus
  - Provide a paid internship opportunity to the graduate student to learn PLC applications and processes
  - Provide financial support for the renovation of the physical laboratory
  - Provide financial support to equip the laboratory with four workstations hosting a SLC 500 rack with appropriate modules and basic laboratory instrumentation equipment

- Staff engineer and senior technician
  - Develop plan to renovate existing wet lab to a industrial control laboratory
  - Specify required workstation and laboratory instrumentation
  - Install PCs, laboratory instrument-tation and support software

Curriculum Development

The faculty member developed classroom curriculum based on "Programmable Logic Controllers" by James Rehg and Glenn Sartori [3]. This book was chosen after an exhaustive review of available PLC textbooks. The textbook was chosen because of its "student friendly" approach. The textbook is very readable and well-illustrated with numerous figures and worked examples throughout the text. The textbook was also highly recommended by a student who had taken the early version of the course and was now a practicing field engineer.

From the faculty perspective the textbook is well supported with numerous worked examples, a CD of support material, and course lecture slides available for download from the publisher. Furthermore, the textbook had recently been updated with the release of the second edition.

Laboratory Exercise Development Approach

To get practical experience, the graduate student interned with Infinity Power and Control of Rock Springs, Wyoming. This company is an industrial controls company that works with oil and natural gas companies, such as British Petroleum (BP) and Shell, to install monitoring and control systems on drilling platforms. The following is the graduate student's review of the internship:

"Working as an intern at Infinity, I learned real world applications of industrial controls. The first month I got acquainted with the field work and installation of industrial controllers. My work entailed installing the wiring for the control system from start to finish on an oil drill monitoring station. At the monitoring station, we recorded tubing and casing pressures and temperatures on up to eight drilling stations and transmitted this data to a base station via a FreeWave® radio. We also connected the station to a solar panel and a battery for power.

After my supervisor was confident I understood field work, I started work on installing programs for different projects on diverse PLC configurations. To feel safe about my testing, I had to

understand the software and programming required to create the programs. My testing had to be thorough and complete, both in simulation and actual implementation.

From this experience, they decided to give me the job of reverse engineering the process from creation of the program, to installing the program, configuring the PLC, and finally to installing the PLC and program in the field. I had to create instructions for the technicians and engineers for the project in AutoCAD® drawings, complete with directions for each step in the process. I also had to discuss the details and information needed for each step with the overseeing technicians in the process. In this fashion, I was able to create important and relevant information for the projects.

Along with creating start-to-finish details for the oil drill monitoring station, I created a program for QSI® Corporation's QTERM-G55 handheld programmer that could communicate with a PLC. The handheld was to be used in the field to monitor the relevant information from each different project/location that was installed by Infinity. Overall, the handheld graphically displayed information for three different projects.

After creating and testing the handheld both at the company and in the field, I taught the field technicians how to use and troubleshoot the handheld. I then created a step-by-step instructional manual for programming the handheld and establishing communication with a PLC. This manual is used by both technicians and engineers to operate and develop new programs for the QTERM-G55 handheld at Infinity.

After talking with the engineers at Infinity, I wanted to create laboratory experiments that were relevant to real world industrial applications and teach students to think objectively with any problem they faced. Since industrial applications are always changing, I wanted the students to have a good base to revert back to, but also teach them to expand the base code to more complicated designs. To accomplish this objective, my laboratory exercises consisted of a basic format that gave the students fundamental code to start from and then required the students to expand the code to accomplish more complex tasks."

Based on lessons learned via the internship program, the graduate student developed a series of PLC based laboratory exercises. He developed laboratory exercises to concentrate on the knowledge and design skills needed on the job. The focus of these laboratories included teaching ladder logic through binary logic, timers, counters, binary comparisons, and subroutine basics. Using these techniques, the students learned how to establish communication with an Allen Bradley SLC 500, control a stepper motor, use binary masks to control outputs connected to light emitting diodes (LEDs), and simulate a PLC with graphical monitoring of inputs, outputs, and variables. The laboratories helped expose the students to basic skills that are needed in industrial applications.

In each laboratory experiment students were required to complete pre-laboratory readings and exercises to prepare for the laboratory assignment. Students were required to record pre-laboratory exercises in their laboratory notebook. During the course of the laboratory exercises students were provided introductory tasks to acquaint them with the PLC subsystem under study. Students were then challenged to expand on the basic design given in the

introductory tasks with increasingly more challenging follow on tasks. In these more challenging tasks, students were often required to add more functionality to the system.

After completing the laboratory, students were to post their ladder logic in their laboratory notebook. The notebook could then be used as a reference later on the job. Also, students were required to discuss their final design and problems they had throughout the laboratory. This allowed the students to further contemplate about what they did in lab and how they went about solving the different problems encountered.

Laboratory Exercises Developed

Each laboratory was designed to further the knowledge and skills of every student. To accomplish this, the laboratories gradually increased in difficulty and complexity of instructions. Each laboratory focused on a different set of instructions and concepts, which gave the students new skills that could be applied to industrial applications.

- **Laboratory exercise 1: Programmable Logic Controller Software and Fundamentals.** The purpose of this laboratory experiment was to become familiar with the operation of the SLC 500 programmable logic controller (PLC). The students constructed a simple circuit to interface with the PLC and use some of the outputs to power LEDs. The students used a two way switch to imitate a fault in the system and a button to start a theoretical motor. To show that the system was working correctly, the students illuminated an LED to indicate the motor was running and another LED to indicate a fault/no fault in the system. In the final task, the students had to add another button that indicated another motor. This laboratory could be accomplished using basic bit logic and latches.

- **Laboratory exercise 2: Controlling a Stepper Motor.** The purpose of this laboratory experiment was to control a stepper motor (Jameco #224022-42BYG016) using ladder logic. The PLC was used to control the basic functions of the stepper motor: forward and backward steps and step to a specific location. The basic goal of this laboratory was to get the students acquainted with the operation of a stepper motor. To accomplish this laboratory, the students learned more about bit comparison and adding/subtracting. This laboratory was a more challenging for the students than expected and required an additional laboratory session to finish.

- **Laboratory exercise 3: Stepper Motor Speed Control.** The purpose of this laboratory was to control a stepper motor's speed. The laboratory used the same stepper motor as the previous exercise. The basic goal of this laboratory was to teach the students how to use PLC timer features to control the stepper motor's speed and verify the operation of the motor.

- **Laboratory exercise 4: Basic Traffic Controller.** The main focus of this laboratory was to learn how to use subroutines to perform actions that are frequently repeated. Since subroutines can be challenging to understand for the first time user, the laboratory was conducted using basic circuitry already used in previous laboratories. To get the students acquainted with subroutines, students were required to describe how to use subroutines and the instructions involved in the pre-laboratory exercises. Students were also introduced how to create new program files where subroutines could be stored and the use of bit masks to set outputs.

- **Laboratory exercise 5: Emulation and Graphical Control.** The purpose of this laboratory was to use an emulated PLC to test code. The students also designed a graphical control panel that was used to both control the PLC and display the current state of different variables. Through emulation and a graphical control panel, students were shown how it is possible to accomplish extensive testing without every using a PLC. This technique saves time and money by implementing design faster and without the possibility of damage to the PLC. Although testing should always be done on a real PLC before actual implementation, this technique helps the students troubleshoot their program and make sure it is as safe as possible before installation. The laboratory used many of the same instructions introduced previously so the students could concentrate on new topics being introduced. At the end of this laboratory, students were required to determine how to make the code go into incorrect operation (or "break" the code). Getting to know the instructions and the program more in-depth helped the students learn the true operation of the instructions. This also helped improve the student's troubleshooting abilities.

Physical Laboratory Development

In conjunction with the development of classroom and laboratory curriculum, an industrial control laboratory was developed from an existing wet laboratory that had not been used in some time. The renovation required removal existing lab benches, gas and water lines, and air handling equipment. Once the dated laboratory facilities had been removed, the laboratory room was renovated with new wall covering. Also, workstation benches were installed. The laboratory was also equipped with four workstations with the following complement of test equipment:

- Personal computer
- Programmable logic controller instrumentation
  - Allen-Bradley SLC 500 programmable logic controller rack
  - Allen-Bradley 1747-UIC USB-to-DH485 interface converter – communication cable linking PC to SLC500
  - Allen-Bradley 1746-IB16 Input DC Sink Module
  - Allen-Bradley 1746-OB8 Output DC Source Module
  - Allen-Bradley 1747-DCM Direct Communication Module
  - Allen-Bradley Rockwell Automation RSLinx software tools
- Tektronix TDS2012B, 2 channel, 100 MHz digital storage oscilloscope
- Instek GDM-8135 digital multimeter
- Agilent 33210A 10 MHz function/arbitrary waveform generator
- B&K Precision 1823A 2.4 GHz universal frequency counter
- Mastech HY3003D-3 DC power supply
- Digiview TechTools PC-based logic analyzer

A laboratory illustration is provided in Figure 1.

Figure 1. Industrial control laboratory configuration.

The laboratory renovation and test equipment purchase for four laboratory workstations was accomplished with a $25,000 gift from the alumnus in honor of his mentoring professor, Professor R. Kenneth Beach. In addition, the alumnus donated all of the Allen-Bradley hardware and software for the four workstations.

Launch of the New Course

The modified version of the course was launched in Spring 2010. As in the previous offering of the course, the course was evenly split between the instruction of controlling industrial processes using microcontrollers and programmable logic controllers. The course was offered as a senior/graduate level elective. A total of fifteen students enrolled in the course.

All but one student successfully completed the course.

Dedication of the New Laboratory

The Industrial Control Laboratory was named in honor of Professor R. Kenneth Beach. To honor his memory and thank the gracious gift from Bruce and Carla Pivic that made the laboratory possible, the laboratory was dedicated in May 2010. Professor Beach's widow was invited to the dedication and cut the ribbon on the laboratory facility. Also students who participated in the course had the opportunity to interact with Bruce Pivic who had worked in the industrial control field for over 25 years. (See Figures 2 and 3.)

Figure 2. Laboratory ribbon cutting ceremony.

Figure 3. Students interacting with industrial control professional.

Results and Discussion

At the completion of the course students were administered a course critique to obtain their perception of the course and recommendations for improvement. Here is a summary of findings:

- *The course provided approximately a 50/50 split between the instruction of the Atmel microcontroller and programmable logic controllers. Is this a good split? Would you recommend a change?* The main feeling of the students was PLCs should enjoy more focus, if not its own class.

- *On a scale of 1 (easy) to 10 (very challenging), how would you rate the difficulty level of the laboratory exercises?* The average of the student's responses was 7.2, which is slightly higher than average but a good indication that the students felt challenged by the laboratories. Overall, we believe the students learned from the laboratory exercises. The student's response on their knowledge level of PLCs before the course was at an average of 2.2; whereas, their average response after the course was 6.1. We believe this is a substantial increase in knowledge and a good indication of the usefulness of the course.

- *We are considering offering this course only as a course in programmable logic controllers. Would you consider this a good idea? Please explain.* To which the student responded: "Yes, I think that the exposure to PLC's is essential for [a] student going into industrial jobs. Especially for students working in the Wyoming region." The student's response shows the overall usefulness and desire of the students for a course that offers PLC training

In light of the student responses, the next offering of the course will concentrate exclusively on programmable logic controllers and their applications. We have already developed two new laboratory exercises to support this venture. The first exercise applies the ladder logic sequencer function in the development of a traffic light system; whereas, the second laboratory provides a linear variable differential transformer (LVDT) interface to the PLC system to measure linear displacement. Our goal is to complete three additional laboratory exercises before launching the course as a PLC only course. Also, to better assess the success of the course, we will provide each student a pre-test and post-test to assess the development of PLC design related course outcomes.

Conclusions

In conclusion we believe the overall project and team approach to implementation was a success. Students were engaged throughout the course and the laboratories and were truly interested in learning how to use PLCs. Students struggled at times through some of the more challenging aspects of the laboratory exercises but they learned some of the best lessons during these times. We also believe the students received a good introduction to industrial control applications and how to approach industrial control problems. Furthermore, we believe the students learned important industrial applications and problem solving skills. During the course of the semester, the students improved on their knowledge of both PLC circuit design and ladder logic. All material described in this paper is available for use by contacting Steve Barrett at steveb@uwyo.edu.

Acknowledgments

the industries of Western Wyoming. Bruce Pivic is the founding member and President of Infinity Power and Control of Rock Springs, Wyoming. This company serves the industrial, oil field and automotive industries around the world.

Dedication

This paper and the laboratory described are dedicated in the honor of the late Professor R. Kenneth Beach. Professor Beach taught in the Electrical Engineering Department until 1984. Ken Beach was a native of Lusk, Wyoming and received the BSEE from the University of Wyoming in 1940. He completed his graduate work at the Illinois Institute of Technology in 1941 and worked for Curtis Wright Aircraft Co. during World War II. Following this service to the country, he returned to the University of Wyoming in 1946 for a teaching career that spanned 38 years. He was awarded the professional EE degree in 1958, was selected the Sigma Tau Outstanding Faculty Member in 1961 and was a past president of the Wyoming Engineering Society. During his tenure Mr. Beach was noted for his dedication to his students and over the years Professor Beach and his wife, Charleen, have made generous contributions to the next generation of engineers through scholarship endowments.

References

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Biographical Information

Amos Purdy, MSEE received the Bachelor of Science and Masters of Science degree in Electrical Engineering from the University of Wyoming in 2009, 2010 respectively. His research interests include industrial control and programmable logic controllers. He is currently pursuing a Masters of Business Administration at the University of Wyoming.

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