Development of a Programmable Logic Controller Training Unit for Engineering Technology Curriculum

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Abstract

The Electronics Engineering Technology (EET) Program at Central Washington University (CWU) offers courses in Programmable Logic Controller (PLC) applications. The program previously relied on out-of-date, rack-mounted PLC equipment to support this class. While this provided the students with a procedural introduction to PLCs, it did not allow for a conceptual understanding or real world experience with the equipment. The EET Program recently developed an updated set of PLC units utilizing the Allen-Bradley CompactLogix® L30ER controller that allowed an open platform for the laboratory component of the class while fostering a conceptual understanding of the topic.

This paper presents an overview of the development cycle of the PLC training units created to support the engineering technology courses. It also summarizes curriculum developments supporting the associated courses using the PLC units. Finally, assessment results indicating that the new equipment has notably improved the educational experience and learning outcomes of the students is presented.

Introduction

Programmable logic controllers serve as the cornerstone in many industrial process control and automation operations[1]. They provide the ruggedness required for continuous operation in industrial environments, the computing power necessary for control of manufacturing processes, and the re-configurability needed when transitioning from one process to another. Responding to this important and widespread use of PLCs in industry, as well as to recommendations made by the program's industrial advisory board, the EET program developed a course entitled Programmable Logic Controller Applications in the mid-1990s. The topic proved to be so central to engineering technology education at Central Washington University that it was later incorporated into the Mechanical Engineering Technology (MET), Industrial Technology (IET), and Master of Science in Engineering Technology (MSET) Programs as well.

The initial PLC training units were based on the Automation Direct DL205 controller. The controller was configured with a single 8-point DC input module, a single 8 point relay output module, a combination analog module with four input channels and two output channels, and a RS-232 serial port available by way of an RJ-11 connector on the processor module. A series of toggle switches and push buttons provided five discrete inputs to the PLC while four status indicators served as outputs. In addition, a potentiometer functioned as the single input to the analog module while two test points were connected to the analog output channel thus allowing students to measure the analog output voltages. Finally, a human machine interface (HMI) was connected to the PLC through the serial port.

This configuration, while not necessarily appropriate, was adequate for an introductory course. The primary disadvantage of the original system was that the hardware was entirely pre-configured, thereby representing a closed-box training unit. As a result, the students were only responsible for developing the ladder logic and did not develop any ownership of the training system itself. This resulted in many missed learning opportunities that could have been designed into the lab activities or introduced by the students themselves. Additionally, since the course was essentially a programming class, the importance of the PLC was limited due to the "software only" approach to the lab. Further, the original curriculum was developed around a procedurally written lab. While it was acceptable to use procedural instructions in some instances for learning activities, it generally did not support conceptual learning of the material. This was articulated well by Eiriksdottir et al. who stated that: "Specific instructions help initial performance, whereas more general instructions, requiring problem solving, help learning and transfer."[2] Finally, because the system was originally developed in the mid 1990's, the hardware and software were both out of date and difficult to support. Not only had the limited maintenance resulted in hardware failures, but the software was problematic with a significant number of errors in the programming interface. This resulted in considerable frustration to the students, and alternative approaches were frequently required to overcome software limitations and associated errors. It should be noted that this DirectSoft32 software was originally developed for Windows XP and was not supported in newer versions of Windows[3]. This suggests that some of the issues encountered with the software were likely related to compatibility. Because of these limitations, a needs analysis was performed to determine how to rectify these issues.

Lab Equipment Requirements and Availability

The needs analysis determined that to provide a hands-on learning environment for the students; the following criterions were required of any alternative to the existing training systems.

1. The system had to be "open", meaning that the systems had to be designed so that the students developed "ownership" of the systems and learned not only the software aspects of programmable logic controllers, but the hardware considerations as well.
2. The system had to be up to date. Since the training systems would be used for a minimum of five years, the hardware had to span this generation of hardware. In addition, the software had to be well supported by the manufacturer to avoid issues that would prevent compatibility with operating systems or that would influence the functionality of the development environment.
3. The system needed to be representative of what the students would encounter upon graduation. To address this, the industrial advisory committee was consulted and provided several recommendations.
4. The systems needed to be developed to allow for group configurations so that each student had ample opportunity to work with both the software and hardware aspects of the systems. This was primarily an economic consideration intended to ensure that the course satisfied the learner outcomes while relying only on student fees to support the class.

In addition to these criteria for the training systems, the decision was made to redevelop the lab sequence to minimize the use of procedural instructions in the labs and to encourage conceptual understanding.

Initially, a proposal was presented to purchase the PLC training systems from an outside vendor, with the two primary vendors identified being Lab-Volt and Hampden. Lab-Volt, for instance, has two trainers available, models 5930 and 5930-A[4], that were considered and reasonably well suited for the needs of the course. Similarly, Hampden produced a PLC trainer, model 1200[5], which was adequate for the course and had basic DC motor control features. These three trainers were based on Allen-Bradley Logix® controllers which would satisfy the need for the systems to be up to date and the software would be well supported. Unfortunately, none of these systems provided an open platform. In addition, since all three trainers featured PLC's that were integrated rather than modular, concerns were expressed pertaining to the cost of potential equipment failure which could require replacement of the entire PLC rather than a single module. Finally, while product and pricing information was readily available from Lab-Volt, similar information from Hampden was not available.

Development of PLC training unit

The development of the training units was based on the criteria described above. First and foremost, the unit had to be open. This meant that while the necessary hardware was available in the training unit, the students were left to develop the system to achieve the outcomes described in the lab activities. This allowed students the opportunity to learn trade skills such as industrial wiring, troubleshooting, and safety, while developing technical knowledge and conceptual understanding of hardware and software. Secondly, the units had to be representative of the current state of technology and capable of adequately representing technology during the system's life cycle. The Allen Bradley CompactLogix® 1769 platform[6] was therefore selected because it was affordable and representative of PLC's used in local industry. Additionally, the instructor assigned to develop the trainers and update the curriculum had significant industrial experience with Allen-Bradley controllers and was therefore able to relate relevant experience to the class. Further, based on feedback from the industrial advisory committee and faculty of the Mechanical Engineering Technology and Industrial Technology programs, it was desirable for the trainers to incorporate an adjustable speed drive. Finally, an adequate number of units had to be available to support the class to achieve a combined enrollment of 32 students. By design, groups were intended to include two students; therefore at least sixteen units were required to support the class.

To satisfy these objectives, the following system configurations were established for each trainer. (See Figure 1.)

- Allen Bradley CompactLogix® 1769 PLC
    - 5370 L3 Controller: 1769-L30ER
    - Input Module: 1769-IQ16
    - Output Module: 1769-OW8
    - Analog Module: 1769-IF4XOF2
    - Terminator: 1769-ECR
- Allen Bradley PowerFlex® 4 Adjustable Frequency AC Drive[7]
- Allen Bradley 24V Power Supply
- Three-Phase motor starter relay
- Four General Purpose relays
- Seven Momentary push buttons
- Five Indicators

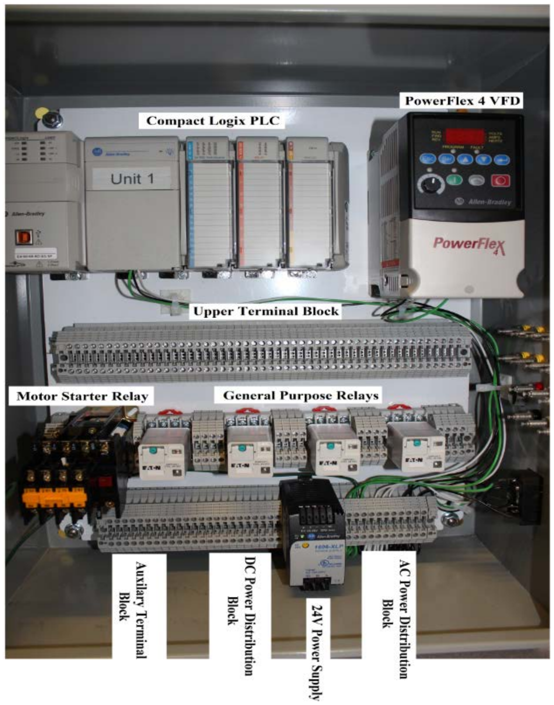

Figure 1. New PLC Trainer.

The system was constructed in a control cabinet as illustrated in Figure 1. All AC connections are preconfigured to prevent the risk of electrical hazard. Minimum recommended clearances were achieved in all instances except between the PLC and the VFD. It is noteworthy that while a larger cabinet was originally requested, a smaller, slightly less expensive alternative was purchased. Based on the configuration shown, each unit was estimated to cost approximately $2250 to build. While this cost did not account for future changes to the equipment, it does account for the stipend afforded to the faculty member charged with design and construction of the units. By comparison, the Lab-Volt model 5930 and 5930-A trainers were priced at approximately $6600 and $8100 respectively.

Based on the estimated cost, funding was provided from several underspent departmental budgets, generous support from the department chair, and the Rockwell Automation's Educational Discounts program. This provided the sixteen units required to support the demands of the course as well as a unit used by the professor for demonstrations and three units reserved for student based projects such as those associated with the capstone sequence.

Lab Sequence

The original lab manual was limited to a procedural introduction to various functionalities of PLCs and was constrained by having only eight available training units. Because the typical class had approximately 30 students, each group generally had three to four people. This limited the participation of all group members to very little actual hands-on time spent with the trainer.

In redeveloping the lab sequence, the first two labs necessarily emphasized some procedural exercises. Establishing communications with the PLC, working within the Studio 5000® environment, creating basic relay logic circuits, configuring a power distribution point, or incorporating safety standards associated with industrial wiring and control, for example, are skills necessary to complete the rest of the course. The follow-on labs, however, placed a priority on developing student problem solving skills rather than their ability to follow a procedure.

The first lab introduces basic wiring techniques used within industrial control panels and basic relay logic circuits that serve to demonstrate the need for a programmable platform. The lab begins by introducing the students to NFPA 79, the standard set forth by the National Fire Protection Association that provides "safeguards for industrial machinery to protect operators, equipment, facilities, and work-in-program from fire and electrical hazards."[8] This is used throughout the course to set the minimum level of acceptable workmanship. The lab subsequently requires students to interface the pushbuttons and EMO circuit on the front panel to the upper terminal block. This requires students to apply the NFPA standards discussed in the early part of the lab and provides the instructor an opportunity to correct poor lab practices early in the course. Thereafter, the students can interface the pushbuttons in various configurations to implement basic relay logic circuits. This provides an early introduction to relay logic and latching operations and demonstrates the need for a flexible reprogrammable platform.

The second lab continues by interfacing the pushbuttons from the upper terminal block to the PLC, followed by interfacing the general purpose relays and motor starter first to the upper terminal block, then to the output module of the PLC. This is intended to reinforce the NFPA and workmanship standards expected in the class. Subsequently, the students are provided a short procedure for establishing communications with the PLC for the first time. Once the communications are established, the students work with the Studio 5000® environment for the first time to create a 'test' program that configures the input and output modules, creates the initial controller and program tags, and tests the functionality of the hardware. It is left to the students to recognize that this program can be used as a template, thereby eliminating the need to define the I/O configuration and create the tags each time a new program is created.

The third lab finalizes the hardware by interfacing the status indicators to the general purpose relays. Once the hardware meets the NFPA standards and is approved by the instructor, the students implement the first logic circuits in the Studio 5000® environment. Basic logic circuits are introduced and implementation of combinational logic circuits is then developed using the Sum of Products Method. This is intended to limit the scope of logic circuits so that the MET and IET students are not required to have a background in digital circuit theory prior to this course. Beginning in this lab, MSET are required to develop solutions not only in ladder logic, but also in either the structured text or function block diagrams programming languages.

Lab four introduces safety interlock circuits and Boolean simplification techniques. The lab requires students to develop a "machine active" rung that prevents active outputs whenever the safety interlock circuit is active. This circuit is subsequently required in all programs. After the interlock circuit is developed, students are required to simplify a series of logic circuits expressed in a truth table through the use of common Boolean Identities. Because the implementation of combinational logic circuits was introduced using the Sum of Products Method, only a handful of identities are required to significantly reduce the complexity of the resulting logic expressions.

The fifth lab introduces timers and sequential timing circuits. It introduces students to the "TIMER" data type that, unlike earlier data types, includes two DINT (Double Integer) data types containing the preset value and accumulator value, as well as three Boolean status flags. This allows for a gentle introduction to more complex data types introduced in subsequent course modules. The lab begins by providing an initial procedural approach to defining a timer tag and implementing it in a ladder logic program. It then requires the student to develop several sequential timing circuits culminating in a cross walk circuit using a sequential timer layout.

Lab 6 revisits timer circuits by implementing the same programs as lab five, but with a series of comparisons, rather than sequential timers, thereby providing an introduction to program efficiency, math operations, and comparison instructions. It also introduces program organization and requires the students to implement a series of independent tasks as routines that are called from the main routine. The count up (CTU) instruction, incremented within the main routine to select the appropriate routine, is also introduced.

The final lab introduces analog to digital conversions and the AC Drive. It requires students to interface a photovoltaic (PV) cell to the analog input of the PLC. This input is algebraically manipulated through a series of comparisons and operations to produce the discrete start and stop signals along with the analog frequency signal that are sent to the Allen Bradley PowerFlex® 4 AC Drive which drives a ¼ hp, three phase motor.

This lab sequence develops student problem solving skills by providing projects with clearly defined objectives. The material is also sequenced to develop conceptual understanding by presenting progressively more challenging tasks. While procedural instructions are included in several lab sections, they are limited to specific tasks that require a step by step approach.

Reflections

During the development of the PLC trainers and associated lab upgrades, a number of possible areas for improvement were identified. The first identified area for improvement was to increase the units' serial communications capability. As mentioned previously, the CompactLogix® L30ER controller has two available Ethernet communications ports as well as a USB port, but lacks support for serial communications through either a RS-232 or RS-485 port. This limits the ability of the units to communicate with serial devices. While this is not an issue in an entry level course, it could limit discussion of some topics in later courses. To address this limitation, the EET program is currently evaluating the 1769-ASCII module to determine its capabilities and to develop labs that incorporate it.

Additionally, since any follow up course will introduce basic control system theory, the program will need to expand the availability of discrete and analog sensors. Sensors will be selected to provide a variety of inputs such as temperature, proximity, and volumetric flow rates, so that different applications can be explored. These sensors will be used as a department resource and therefore will not be a cost directly associated with this project.

Finally, because of the limited space available in the cabinet, a larger cabinet is desirable. As mentioned previously, recommended clearances were not achieved between the PLC and VFD. The addition of the ASCII module and other supplemental devices would further limit the space available. A larger cabinet would allow for future expansions and would not incur a significant expense since most of the hardware could be transplanted to the new cabinets.

Comparison of student feedback

Student feedback was collected from two classes for comparison using a student evaluation of instruction course survey. This survey asked students to rank a series of questions related to the class and instructor on a five point scale ranging from 'Strongly Disagree' (weight of 1) to 'Strongly Agree' (weight of 5). Three questions were selected as being reflective of the survey's results, and are listed below:

To what extend do you agree or disagree that

1. The overall course content was presented in an understandable sequence.
2. The instructions for class activities were clearly communicated.
3. The course activities challenged students to think critically.

The first class selected for analysis was offered during the 2013 spring term using the original equipment and curriculum. The Table 1 data illustrates the mean and standard deviation from both the students participating in this course and a composite across the department.

Table 1. Survey Results From Spring 2013 With Old Trainer.

Question	Course		Department	
	Mean	Standard Deviation	Mean	Standard Deviation
1	4.00	1.26	4.32	0.87
2	4.00	1.26	4.27	0.97
3	4.36	1.29	4.49	0.74

The second class was offered during the 2014 spring term using the updated equipment and curriculum. The Table 2 data illustrates the mean and standard deviation from the students participating in this course and a composite across the department.

Table 2. Survey Results From Spring 2014 With New Trainer.

Question	Course		Department	
	Mean	Standard Deviation	Mean	Standard Deviation
1	4.65	0.57	4.40	0.88
2	4.61	0.58	4.32	1.03
3	4.78	0.42	4.49	0.77

A comparison shows that while the departmental composite mean and standard deviation changed little between the two offerings, the course mean and standard deviation improved significantly. This shows that the average response improved and the variability of the responses decreased which suggests that the redevelopment of the training system and supporting curriculum improved the student experience in the course. It is noted that confounding issues such as the instructor qualifications and class composition could have influenced these results.

Assessment of student learning outcomes

While the student learning outcomes are integrated into all aspects of the course, assessment is performed using intentionally designed instruments that focus specifically on the individual outcomes. The student learning outcomes for this course state that a student will:

- Demonstrate proper implementation of industrial electrical safety standards.
- Implement and simplify logic circuits represented either as algebraic expressions or truth tables in ladder logic.
- Configure and use timers and counters in ladder logic programs.
- Manipulate analog and digital data using mathematical comparisons and operations.

The first learning outcome is assessed in lab on a go/no-go bases. Students are required to follow all guidelines outlined in NFPA 79 to ensure that all electrical safety standards are implemented. During signoff of the first lab, the instructor provides remedial actions that must be corrected before proceeding with the subsequent coursework. If these actions have not been remediated by the completion of the second lab, a no-go is issued and the student is not permitted to proceed with the lab work until remediation has been completed. This approach has resulted in 100% of the class meeting or exceeding expectations for this learning outcome.

The remaining three outcomes were assessed by evaluating weekly homework. These assessment results show a 20% - 30% increase in the number of students who meet or exceed expectations when comparing the results from the spring 2013 term to the spring 2014 term. While it is too early to conclude these improvements are a result of the updated curriculum and equipment, it does suggest that a correlation exists. Future assessment results will be analyzed to further investigate the impacts that these improvements have had on student learning.

Conclusion

The redevelopment of the PLC training units satisfied the objectives identified. First, the new units allow for an open and reliable platform for the students to develop integrated hardware. Secondly, the lab sequence was redesigned to limit the scope of the course and increase the depth of the material to help develop the student’s problem solving skills. As a result of these improvements and revisions, the data suggests that the student experience and student learning in the course has improved significantly which is reflected in both the assessment of the student learning outcomes and the student evaluation of instruction surveys.

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