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Programmable Logic Controllers: What Every Controls Curriculum Needs to Cover

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Abstract

The field of automatic control has been undergoing a transformation over the past thirty years. The number of control engineering positions in manufacturing has been dramatically increasing to the point that the majority of new control engineering positions is now in manufacturing and involves programmable logic controllers (PLCs). The typical college or university has been slow to recognize this trend. This paper describes three courses that were developed to satisfy this demand. All three courses present the subject of programming PLCs with an emphasis on the engineering and the design of the programs. These courses contain an integral laboratory component that solidifies the concepts presented in the lectures. Best practices for PLC design and the application of standards are also key content elements. The philosophy and pedagogical features of the three courses are first described, followed by the structure of the lecture and the laboratory exercises. The paper concludes with assessment results. In the author‘s opinion, every university that teaches control system courses should have at least elective one course devoted to PLC programming, the basic one described in this paper.

Introduction

All three courses are electives in our curriculum. The first course, "Basic PLC," covers the basics of PLC ladder logic programming and its application to manufacturing control, including PID control. The major component of the second course, "Advanced PLC," is a class-wide project configured to run like a multi-team industrial project. This course also covers other PLC languages (function block diagram, structured text, and sequential function chart), factory communications, and control system security. The third course, "PLC Motion Control," concentrates on the control of servo motors and drives in applications such as coordinated multi-axis motion (robot arm or Deltabot) and a flying shear. This course also covers automation safety and safety PLCs. These courses are cross-disciplinary and are applicable to chemical engineering, computer engineering, electrical engineering, industrial engineering and mechanical engineering.

All courses take an engineering approach, emphasizing the design of the PLC programs. Beyond teaching one how to program the PLC in its languages or for certain applications, the courses emphasize the more general problem: “Given a set of operational specifications, how does one develop the PLC program?” This emphasis is beyond what is covered in the typical engineering technology program. The first course addresses these topics with the ladder logic programming language only. The second course extends the material to cover other languages, more sophisticated applications, and an engineering approach to multi-team projects. The motion course covers servo motion control applications and safety. All three courses present the design process: the tasks involved, breaking the program into manageable pieces, standard code for the various parts, and handling the sequential parts of the problem.

All three courses have the following pedagogical features:

- An emphasis on good design practices, not just the programming language.
- Good design practice using standards (for example, safety standards and the National Electrical Code).
- Lecture is heavily application-oriented, working through example problems instead of emphasizing the theory.
- Laboratory exercises are an integral part of the course and the lecture topics are closely coordinated with the laboratory schedule.
- Laboratory exercises are small versions of real processes and use real commercial PLC equipment, not simulations.

By incorporating standards into the courses, the students become accustomed to the reality that in the work environment, their designs must follow appropriate standards.

The courses use active learning activities throughout. The particular framework is the scaffolded knowledge integration framework proposed by Linn [1]. This framework describes knowledge integration as the process of linking, organizing, and structuring students' ideas, views, and theories to form a specific concept. With this framework, Linn [2] proposed the knowledge integration environment (KIE) principles and guidelines on how to design learning activities, which are:

- Make content accessible – use personally-relevant problems and connect new and existing knowledge.
- Make thinking visible – provide visual representations
- Help students learn from each other – design social activities to promote collaborative interactions.
- Promote lifelong learning – encourage students to take responsibility for their own learning

Activities in the PLC courses that support these principles are the following:

- Make content accessible – Many manufacturing processes are relevant to the students' personal lives, such as water bottling and food packaging. Videos of manufacturing operations are used in the lectures and scaled versions of real processes are used in the laboratory exercises. Engineering students are often interested in how things are made and programming a system to do a real operation, not just manipulating a computer simulation. Ladder logic programming is also connected to their digital logic and/or computer programming courses.
- Make thinking visible – Ladder logic is a highly visual language and is basically represented as a wiring diagram. Though the concept can be presented simply, it is capable of highly complex solutions.
- Help students learn from each other – Students work in teams of two on the laboratory exercises. The laboratory exercises span 3 to 4 weeks and the teams are expected to collaborate on the exercises between lab periods (or it is very likely the team will not complete the exercise). In the Basic PLC course, organized group sessions with the instructor for the first 7 to 8 weeks of the semester promote collaborative interactions when working on the homework exercises.

- Promote lifelong learning – One part of the first Basic PLC laboratory exercise – construct the logic to make two lamps to alternately flash at a given period – requires the student groups to think. No solution is given to them and it is not covered in the prior course lectures, though the lab teaching assistant will help them to figure out the solution. In addition, at the end of each laboratory exercise, the students ask a series of reflection questions to help them evaluate their performance and what they could do better.

All of these courses were initiated in response to industry demand. In the 1980's, AT&T sponsored a project to develop manufacturing-related courses. The Basic PLC course was one of these courses. The Advanced PLC course was added a few years later because of encouragement by former students and by the companies that hired those that took the Basic PLC course. Likewise, the PLC motion course was recently added in response to industry needs due to the trend toward more sophisticated servo motion applications in the manufacturing industry.

All three courses are moderately popular. The Basic PLC course is taught in both the Fall and Spring semesters with a current enrollment of 60 to 70 each semester. The Advanced PLC and PLC Motion Control courses are normally taught once per academic year, in alternate semesters, and each has a typical enrollment of around 30.

So, why should every university that teaches control system courses have at least one elective course devoted to PLC programming? While a university education prepares students for both positions in industry and for further graduate studies, most graduates secure an industrial position. Graduates that are working in the controls field need to be prepared for the reality that the majority of these positions involve PLCs. For example, scanning the first 50 job postings on Monster.com [3] for a "control engineer," 36 (72%) of them explicitly listed PLC experience as either required or preferred. In addition, most companies can no longer afford to spend 6 months or more to train new graduates. They need graduates that are ready to contribute in a few weeks.

Basic PLC Course Organization

The objectives of the first course are to teach:

- Programming in ladder logic
- How to attack a sequential control problem
- Hands-on experience programming PLCs
- Simple PID control tuning
- Introduction to National Electrical Code

The topics in the first course are outlined in Table 1. This course has two hours of lecture and two hours of lab each week (total 3 semester-hours of credit). For the first course, it is important to get the student into the laboratory as soon as possible. By confining the material to the one (or two) PLCs in the laboratory, basic ladder logic is covered in three hours of lecture. To meet this goal, the laboratory does not meet during the first week of class and each lecture in the first week of class is extended by an additional half-hour.

Table 1. Outline of First PLC Course Lectures

Topic	Num. of Hours
Introduction to factory automation and PLCs	1
Basic ladder logic, discrete I/O and wiring	2
PLC memory,	1
Timers, counters	3
Sequential applications	4.5
Troubleshooting	0.5
Exam 1	1
Analog I/O	0.5
Comparison, arithmetic instructions	4.5
Exam 2	1
PID control	6
Exam 3	1
Introduction to National Electrical Code	4
Communications	1

Many examples are used throughout the course. After briefly presenting a new concept, it is illustrated by working through examples. Also, good design practice is emphasized through examples and showing examples of bad design practice.

Basic PLC Course Laboratory Exercises

The students have three weeks for the first laboratory exercise. By this time, the lectures have covered sequential applications. For the remaining laboratory exercises, the student teams rotate among the other three laboratory exercises (two two-student groups per exercise), spending four weeks on each exercise for the first two rotations. The students are more efficient by the end of the semester, so there are only three weeks for the last laboratory exercise rotation.

Currently, two PLC platforms are used in the laboratory exercises: Allen-Bradley ControlLogix and Siemens S7-1500. The students switch from the Siemens to the Allen-Bradley or vice versa twice during the semester. Typically, one exercise uses Siemens PLCs and the other two exercises use Allen-Bradley PLCs. In a particular semester, at least one lab exercise is primarily sequential in nature, one exercise involves PID controller tuning, and one exercise involves programming an HMI panel. A particular exercise may combine two of these elements, for example PID controller tuning and an HMI panel.

The first laboratory exercise is intended to familiarize the students with the basic ladder logic instructions, the PLC programming software, and simple sequential applications. The students begin by wiring a simple switch and light board to the particular PLC. Although most of them will not be doing wiring after graduation, they will often check wiring done by a technician, so exposure to wiring is important. The ladder logic exercises progress from simple series and parallel logic to timers, counters, flashing lights, Ford Thunderbird turn signal, and culminate in the control for a cereal box filler. The solution to the last part of the exercise is worked out during lecture. The students enter the program and use the switch board to simulate the sensors. The cereal box filler application is a small demonstration of the solution to a short sequential problem – a precursor to the much longer multi-week exercises.

The longer lab exercises are selected from the available exercises. The particular set of exercises changes every semester. Generally, a particular lab exercise appears every third or fourth semester. Exercises that have been used in the past are described in [4]-[6]. Current exercises include:

- Production System (Figure 1) – A puck is extracted from the bottom of a stack, elevated, and conveyed to a table with 4 positions. The table rotates, moving the puck to the next position, a hole is drilled in the puck, the puck is rotated to the next position, a probe checks for the presence of the hole, the puck is rotated to the next position, the puck is picked up with a vacuum and an XY table moves it to the "good" stack if the hole was detected in the puck or to the "bad" stack if no hole was detected in the puck.
- Steel Reheat Furnace (Figure 2) – A scale version of a furnace that heats steel bars in preparation to be hot-rolled into sheet steel and then coiled. Small bars are basically pushed through the furnace that heats them up as they progress through the furnace. The sequential operation consists of raising the exit door, extracting a bar from the furnace, closing the exit door, and then lowering the bar to a roller conveyor that moves the bar out of the station and to the (virtual) hot rolling mill. A second roller conveyor moves a new bar into position and then it is pushed into the furnace and as a consequence all bars in the furnace move one position.
- Case Erector – A small tuck-bottom box blank (flattened) is removed from a stack. The blank is unflattened, the bottom is formed by folding and tucking the flaps, and then pushed out to the next station.
- HVAC pressure/temperature control – The pressure and temperature of a heating duct is controlled with PID control blocks. The students also tune the pressure loop.
- pH control – A combination of sequential control and PID loop control of pH and level. The students also tune the level loop.
- Concentration and level control – A combination of sequential control and PID loop control of colorant concentration and level. The students also tune the level loop.
- Production Filling System – a combination of adding a weigh scale measurement and bar code reading to an existing program that fills plastic beads into a container. The students also program a simple HMI for the process.
- Automation Storage/Retrieval System – a system with 12 product bins. The students modify an existing program to track the number of pallets moving into and out of the system. Most of the exercise is programming a moderately complicated HMI screen for the process.

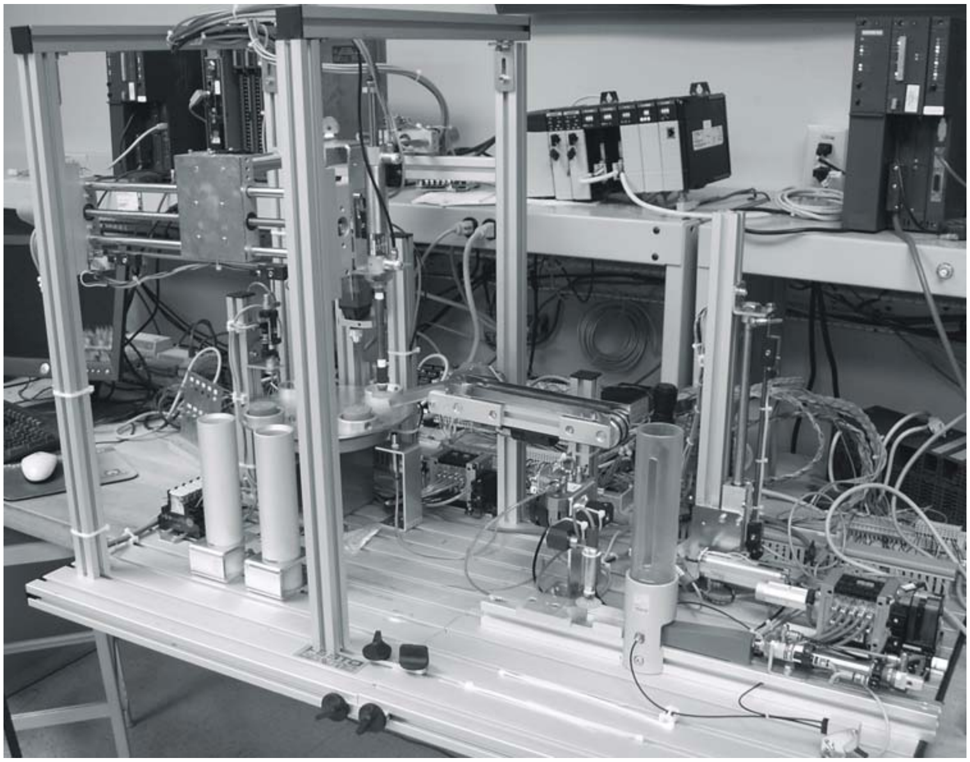
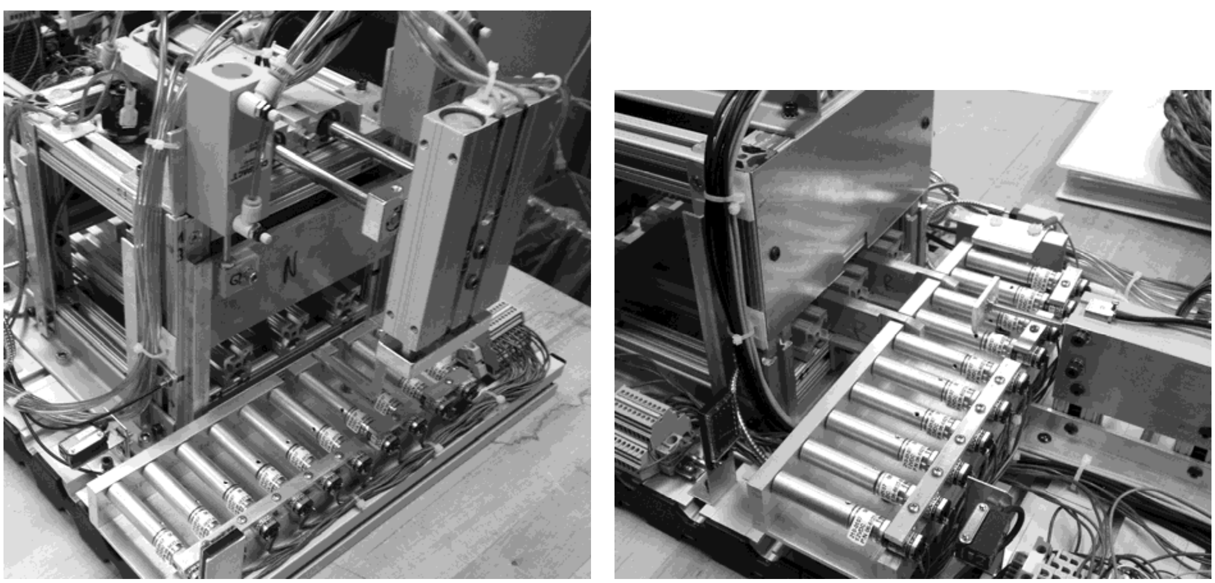


Figure 1. Production system laboratory exercise.



(a) (b)

Figure 2. Steel reheat furnace laboratory exercise: *(a)* exit end; *(b)* entrance end.

Advanced PLC Course Organization

The objectives of the second course are to teach:

- Working on engineering teams for large control system projects
- Other PLC programming languages (sequential function chart, function block diagram, structured text)
- Putting a system together – Specifying a system bill of materials from a system specification

The topics in the second course are outlined in Table 2. As for the first course, this course has two hours of lecture and two hours of laboratory each week. Since the students already have programming experience from the first course, the laboratory exercises start immediately. After covering the classwide project background topics (communications, simulation, standard code), the other PLC languages (function block diagram, structured text, sequential function chart) are covered. These languages are the subject of the only exam in the course. After the exam, the students are taken through the process of starting with a specification that lists the number and type of input/output channels, specify the bill of materials suitable for quoting the system cost and then obtain a quote. This topic was added to the course (and some other topics were removed) as a direct result of feedback from former students and the companies that hire them. The course concludes with the important topic of security in an automation control system and current trends in the development of HMIs.

Instead of a final exam, the students write a 3-4 page paper and give a 5-10 minute presentation about a topic related to PLCs in one of three categories: (1) PLC products from a company whose equipment is not in the laboratory, (2) a possible process for a lab exercise, and (3) an unusual application of PLCs.

Table 2. Outline of Advanced PLC Course Lectures

Topic	Num. of Hours
Communications and MSG block	2
Process simulation with PLC	2
Classwide project, standard code (concurrent with lab exercise)	2
Other IEC languages (SFC, ST, FBD)	13
Exam	1
Specifying system components	5
Security of automation systems	1
Human Machine Interface	1
Presentations	2

The students are heavily exposed to standard industry practices. For example, simulating a process using the available PLC without any physical I/O is covered early and used throughout the course. This practice of testing a program before installing it in the real process is common in industry. Also, the students experience the process of remotely programming/testing a PLC, another common industry practice. Many of the homework exercises involve programming and testing the solution on one of the lab PLCs, including simulating the physical process being controlled. These exercises are not done as part of the scheduled laboratory time, so the students access the programming software through a pool of virtual machines, or remote desktop into one of the lab PCs (when labs are not in session). In either case, the students access the laboratory PLCs via the campus network. It is not uncommon for an engineer in his/her office 200-km (or across the country) from the actual process to modify the PLC program while the process is in operation.

A class-wide project is a significant part of the course. This exercise is modeled after the author's experience in industry and involves multiple student teams. The process consists of multiple interconnected units, typically chemically-oriented. For example, the process consists of units such as raw material storage/handling, blending, reacting, ion exchange, product storage, and product loadout. Each team is assigned one unit. To do this exercise effectively, there are multiple PLCs that communicate with each other and multiple computers for the HMI screens. Each team is assigned its own PLC. The project involves some coordination between PLCs so that PLC-to-PLC communication is required. The students are also required to simulate the actual process in the PLC. The students are given a narrative that describes the operation and control equipment of each unit and a piping & instrument diagram (P&ID) for each unit. In addition, the students are required to follow a programming guideline (like a corporate standard) that dictates how sequential operations, alarms, motors, valves, and PID loops are coded in the PLC and in the HMI device.

Advanced PLC Course Laboratory Exercises

The majority of the laboratory sessions are spent on the classwide project described above. The project is 7 weeks long and proceeds in stages. Each team first produces the sequence diagrams for their unit, and then implements the sequential control by using a “class standard” ladder logic with code libraries, moves on to programming an HMI screen for their unit and then starts testing. The students start testing parts of their code by the third week. Week 6 is the big unit test, conducted like a Factory Acceptance Test (FAT) with a published test plan, much like what happens in a consulting engineering firm’s office before the project is commissioned in the real manufacturing facility. The seventh week is the test of the inter-unit communication and coordination, like the second-stage FAT. Again, there is a previously published plan for this test.

The students do other exercises during the remaining 6 weeks. The project starts on the second week of the semester. The laboratory exercise for the first week is to program communications between two processors to exchange 100-integer arrays and then set up a “heartbeat” between them. After the project is finished, the students have five remaining lab sessions and can choose from a list of possible exercises including

- Advanced HMI
- Configuring remote IO networks

- Working with VFDs over a network
- Program a PLC not covered in the courses (GE, Modicon, Rockwell Micro 800, EZ Automation)
- Configure a vision system to measure object width and program a PLC to extract that information from the vision system and display it on a simple HMI

PLC Motion Course Organization

The objectives of the PLC Motion course are to teach:

- Understand and implement standard motion control applications
- Be familiar with the PackML state model
- Understand and implement integrated motion control in a PLC application
- Experience with motion control hardware and software from Rockwell and Siemens
- Safety in control systems

The topics in the PLC motion course are outlined in Table 3. As for the first course, this course has two hours of lecture and two hours of lab each week. As for the advanced PLC course, all of the students have prior programming experience, and so there is no review. The first week of lectures introduces the students to the PackML standard state machine model [7], [8] for machine control and the motion blocks for both Rockwell and Siemens processors. Then while the students are working on the simple motion control laboratory exercise, servo loop tuning is shown with live demonstrations during the lecture. Then while the students continue to work through the first laboratory exercise, the conceptual background to the longer laboratory exercises is presented. These lectures include programming a position cam, virtual axes, safety PLCs, and the extension of the simple PackML state machine presented earlier for one axis to a machine with multiple axes. The students are heavily exposed to standard industry practices.

Table 3. Outline of PLC Motion Course Lectures

Topic	Num. of Hours
Intro to motion control	1
Basic motion, PackML, and servo loop tuning	5
Lab exercise scenerios – conceptual solutions	3
PackML for multiple axes	2
Sizing servo drives	7
Exam	1
Incorporating safety into control	7
Camming with Rockwell	1
Variable frequency drives	2
Presentations	2

After the laboratory background has been presented, the lecture moves through sizing servo motors and drives and that is the subject of the only exam in the course. In the latter part of the course, incorporating safety into the machine control in the context of the ISO 13849 [9] standard is covered. The safety topics include safety relays, safety sensors, safety PLCs, and safe-torque-off for servo drives. The course concludes with controlling variable-frequency drives from a PLC.

Instead of a final exam, the students find a YouTube video of a machine and write a 3-4 page paper about the machine operation and give a 5-8 minute presentation about it. The video of the machine operation is expected to be a part of the presentation. The machine must have at least 3 axes of motion and at least two of the axes must be obviously controlled by a servo motor.

PLC Motion Course Laboratory Exercises

The equipment for the laboratory exercises is a combination of purchased and fabricated components. The equipment supports the following laboratory exercises:

- Simple motion control
- Rotary knife (cut web material to length while in motion)
- H-Bridge gantry (virtual axis and safety PLC)
- Deltabot (multi-axis coordinated path control)

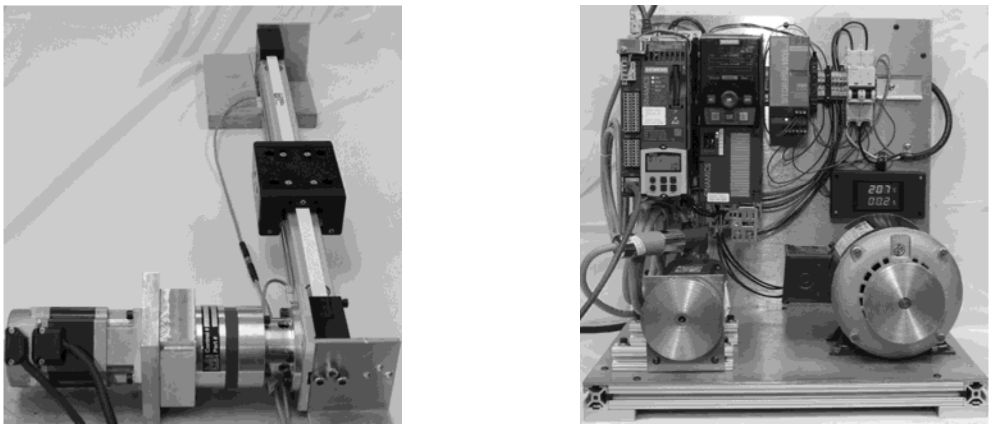
The students spend four weeks on the simple motion control exercise, two weeks with a Siemens servo system and two weeks with Rockwell servo system. After the first four weeks, the students rotate among the three longer labs, spending four weeks on the first one and then three weeks each of the remaining two exercises.

The equipment for the simple motion control exercises consists of a Rockwell or Siemens drive with corresponding servo motor driving a load. Each student team works with a Rockwell servo and a Siemens servo. For the Rockwell system, the load is a linear belt-drive actuator (Figure 3*a*) and for the Siemens system, the load is a rotary wheel (Figure 3*b*). The goal of the first exercise is to become familiar with the configuration, programming and tuning of one motion axis for each platform (Rockwell and Siemens).

The rotary knife system (Figure 4) consists of a small conveyor with an added rotary knife axis. The conveyor and rotary knife are driven by servo motors. A registration mark on the conveyor belt is sensed and the rotary knife is controlled so that the “knife” starts from the home position, meets the line (for the “cut”), tracking the conveyor velocity one radian before and after meeting the line. Then the knife rotates back the starting home position. The knife motion is defined by a position camming profile that is synchronized to the conveyor motion as soon as the registration mark is sensed.

The H-bridge gantry (Figure 5) consists of a Parker OSPE H-bridge gantry driven by Rockwell servos with a 300mm x 300mm x 100mm working envelope. The goals of this exercise are (1) to properly program a virtual X axis to drive the real left X and right X axis motors for movements in the X direction, and (2) integrate the safety light curtain and E-stop switch into the motion control to drive the safe-torque-off of the drives to immediately stop motion when the safety is tripped.

The Deltabot (Figure 6) is programmed to do a pick-and-place operation. Starting from the home position, the end effector is moved to a position to pick up a part with a vacuum cup, the part is moved to a new position with a 180 degree rotation in the middle of the move, the vacuum is released, and the end effector is moved back to the home position. The challenge of this exercise is properly program the axis transformation from the XYZ coordinates of the move commands to the rotational coordinates of the Deltabot servo motors.



(a) (b)

Figure 3. Simple motion exercise: *(a)* linear belt drive; *(b)* rotary (left side).

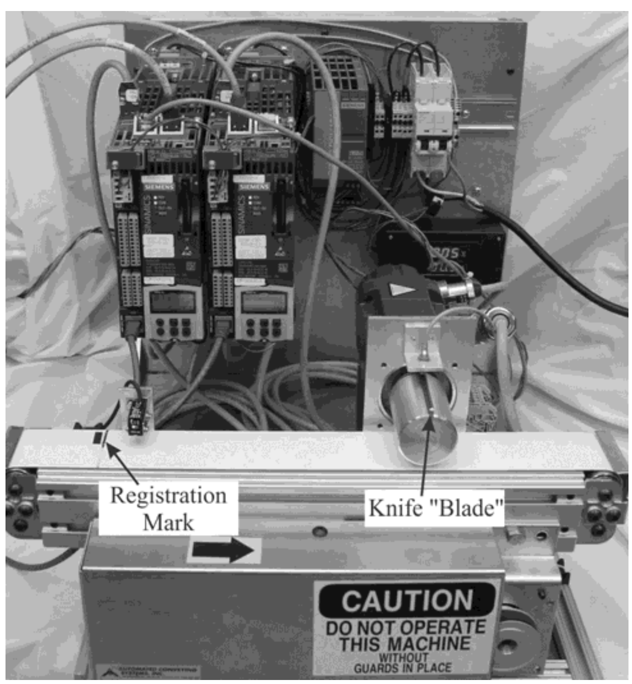


Figure 4. Rotary knife system.

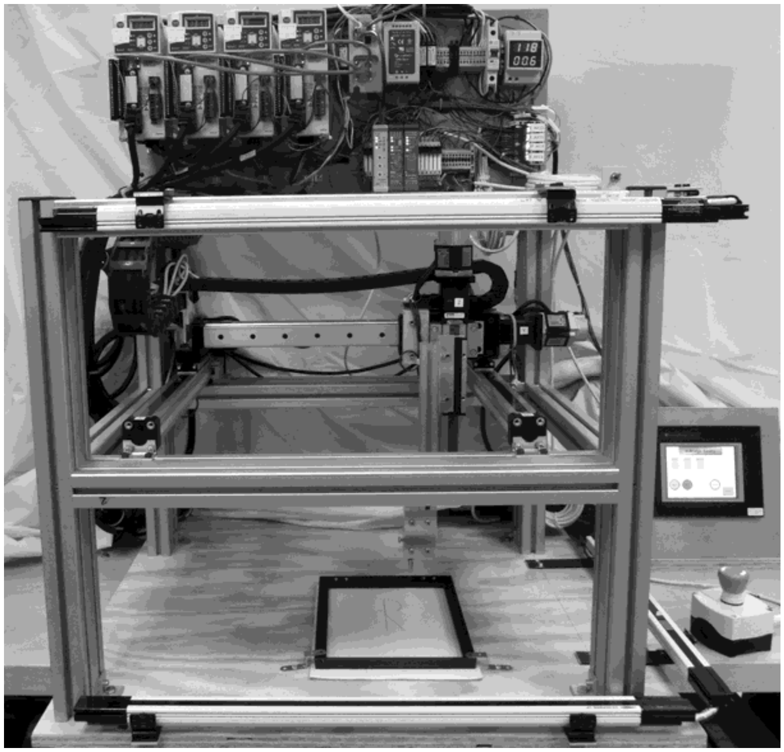


Figure 5. H-bridge gantry exercise.

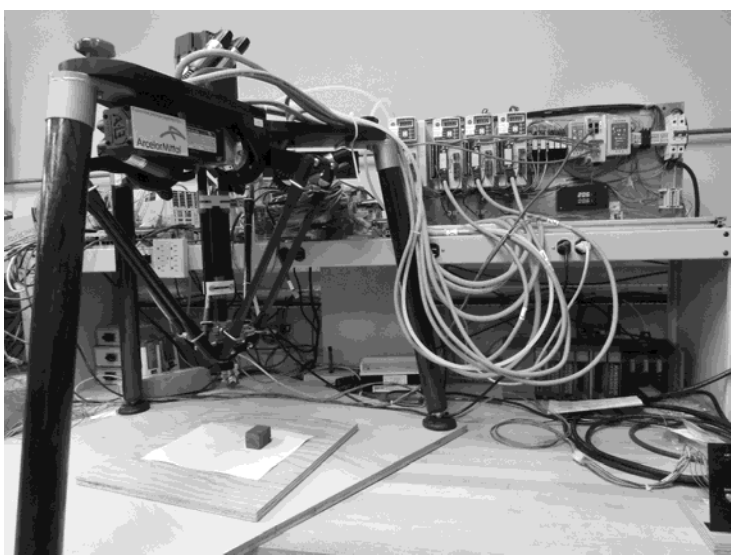


Figure 6. Deltabot pick-and-place exercise.

Assessment Results

The ultimate assessment should come from our customers, those that employ our students. Assessment results include industry feedback and comments from former students (after graduation). Student interest in the courses is assessed by the percentage of students in the first course that take the advanced courses, and their opinion about the relevance of the course material. In addition, the ability of the course to foster lifelong learning is assessed by their responses to reflection questions.

The basic PLC course and advanced PLC course have been taught enough years to establish a reputation among companies in the region looking for control systems engineers. This reputation has come from the students they hire that are ready to work on an automation project from the start. The companies include engineering consulting firms and end users like food and beverage companies, steel mills, tire manufacturers, and cement mills. These companies hire students for summer internships, cooperative training, and full-time positions. During the Spring 2019 Career Fair at our campus, more than 30 (out of 250 total) companies were seeking students with PLC experience. Granted, many of these companies are also filling other types of positions, but of the 30 companies, about 10 companies are engineering consulting firms that exclusively hire students with PLC experience. Generally about 5 companies make a short presentation to at least one of the PLC classes each semester. The presenters are generally those that took the PLC class(es) a few years earlier and they often indicate to the students how the knowledge they learned in the PLC course directly translates to their current position. More than one former student has stated, "What I learned in this class I use literally every day." Many of these companies will first ask a student that approaches them at a career fair, "Have you taken Dr. Erickson's PLC class?" If the student answers "Yes," the interviewer proceeds with further questions. If the student answers "No," the interviewer politely requests them to come back when they have taken the PLC class. A few companies require or strongly encourage those they hire to take the advanced PLC course, as the student is exposed to a typical multi-team project as part of the course. The students in a recent Basic PLC course [10] were polled soon after the campus Career Fair in response to the question, “How many of you found companies at the Career Fair that were interested in you because you are taking this class?” Of the 34 students that attended the Career Fair, 23 (68%) responded affirmatively.

As another assessment measure, companies regularly contribute funds to the PLC lab to purchase new lab exercises and to periodically upgrade the processors and other PLC modules used for the lab exercises. Companies view this as an investment in their future. For example, in 2014, the approximately $60,000 required for the new motion course lab was funded through a combination of university and external gifts from Anheuser-Busch, ArcelorMittal, Automation & Control Concepts (ACC), Burns & McDonnell, CPM Beta Raven, Intelligrated, McEnery Automation, Nucor, and Siemens (10 total). Subsequent funds from ArcelorMittal and ACC funded the addition of the Deltabot and safety PLCs to the motion laboratory exercises.

As another measure of the success of this course, the percentage of those that complete the basic PLC course and then take at least one of the subsequent courses (advanced PLC and/or PLC motion) during the last few semesters is shown in Table 4. About a third of the students in the class take the basic PLC course during their last undergraduate semester. So the percentages

Table 4. Students Taking Subsequent Advanced PLC Course

Semester	Num. of Students in Basic PLC	Num. of Students Taking Subs. PLC	Percent of Students Taking Subs. PLC
Fall 2018	58	21	36
Spring 2018	57	23	40
Fall 2017	43	16	37
Spring 2017	45	15	33
Fall 2016	38	10	26

listed in Table 4 represent about half of the students that can take the subsequent course, indicating a significant popularity with the material. The enrollment in the subsequent courses is further increased by graduate students. For these students, a short course version of the basic PLC course provides the prerequisite knowledge.

A PLC course at a four-year engineering program is frequently criticized because it is perceived as a “skills-based” course and is more suitable at a technical school, not a university. The companies that recruit students that complete the PLC course would disagree with that criticism, as demonstrated by their interest in the students that complete the class and by their contributions. In addition, the students in a recent Basic PLC course [10] were asked the following question, “Is it worth your time to take a predominately skills-based course?” Of the 45 students in the class, 43 (96%) responded affirmatively. They were also asked to compare the Basic PLC course with a traditional linear control systems course (ChE, EE, or ME). Of the 21 that had already taken or are currently taking a linear control systems course, all (100%) thought they were learning more from the Basic PLC course. These results indicate that the students perceive significant value from a skills-based course.

One of the KIE principles is that of fostering lifelong learning. At the end of each of the long laboratory exercises in the Basic PLC and the PLC Motion class, the students individually answer the following reflection questions:

1. What could you have done better?
2. What would you tell someone just starting the lab exercise?
3. What did you learn about yourself?

Some typical responses to the first question early in the semester are:

"Our group should take more time to focus on the details and study them carefully."

"The first thing we could have done better was to read the entire lab before each lab time."

"More planning in between lab periods would have allowed us to better understand PID loops."

Later in the semester, typical responses were similar, but tended to indicate missing a particular detail in the exercise rather than a general comment about a lack of preparation.

Typical responses to the second question were like the following:

"I would tell them to make sure they read through the instructions several times."

"I would tell someone to make sure they read and reread the instructions for the lab."
"Make sure you have your program to what you believe is completely functional before coming to lab."

Some typical responses to the third question:
"I actually know what I am doing for the most part. It's a good feeling to be able to go through a lab like this knowing the material and how to solve problems that arise."
"I learned that I appreciate the step based method of ladder logic, because it makes it easier to troubleshoot and work with your ladder as you develop."
"I enjoy seeing the results of the labs once we have implemented our code. Seeing the production line in action is very interesting to watch."
Though not typical, some responses were like the following:
"I learned that I am probably not a good candidate for employment in the automation industry. I learned that I have trouble reading instructions thoroughly. I also learned that I definitely work better as part of a team than by myself."

Reflecting on the student responses to the first two questions, most realize they need to spend more time in preparation for the lab sessions, but many do not seem to change their behavior as the semester progresses. I surmise that many still struggle with time management. The typical responses to the third question indicate to me that have learned the engineering techniques I am trying to teach. Also, the course gives enough of a taste of the controls field so that students know whether they will like or dislike a job in the field.

Short Course Version

Some students do not have the time or the desire to have an entire course on PLC programming. In addition, non-EE students, most notably chemical engineering students, realize that the knowledge helps when looking for a job. Therefore, a short-course version of the first course is taught twice per year. This course has about 10 hours of lecture and 14 hours of laboratory time and covers about 1/3 of the first PLC course topics. The material is confined to one PLC, the Allen-Bradley ControlLogix. It is taught during the week before the Fall and Spring semesters so there is minimal disruption to student schedules. The short course is also used as the prerequisite to the advanced PLC course and the PLC motion course for graduate students that cannot take the prerequisite undergraduate basic PLC course due to visa regulations.

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