



Teaching PLC Programming and Industrial Automation in Mechatronics Engineering

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Abstract

This paper presents an approach to teach programmable logic controller (PLC) programming and industrial automation to students in Mechatronics Engineering program at Vaughn College of Aeronautics and Technology. The first course, i.e. PLC Programming, introduces texted languages, such as instruction list and structured text, according to IEC61131-3 standard so that students can learn a fundamental concept about PLC hardware and software using the standards-based programming languages. The advanced course, Industrial Automation, focuses on teaching students the sequence control concept and problem solving strategy, where Sequential Function Chart, Ladder Diagram and Function Block Diagram are used to put the design of industrial manufacturing assembly line into operation. The classes have been taught in project based approach and the kinesthetic learning style has been adopted throughout all laboratory sections. From students' comments, the teaching approach was very successful. By the end of the academic year, students have developed their own various projects using the knowledge they learned from PLC Programming and Industrial Automation courses. Some of the projects have been further advanced as a student research paper published at the college technology day conference, ASEE regional conferences or the Latin American Caribbean Conference for Engineering and Technology. Moreover, these courses are intended to enhance career opportunities for the students in Mechatronics Engineering program. Currently some of our graduates have chosen their careers in the area of PLC programming and industrial automation.

Keywords: PLC Programming, Sequence Control, Industrial Automation.

Introduction

Programmable Logic Controller (PLC) is an industrial computer which takes in data from sensors and sends commands to actuators to implement complex industrial controls. Since PLC controllers are highly configurable and reliable, they have been widely used in various industries ranging from automotive¹, nuclear power and energy systems², material handling³ to food manufacturing⁴. Due to higher demands in industries, PLC programming course as well as the fundamentals of industrial automation has been introduced and taught by many universities and colleges with addressing various applications and practical issues^{5,6}.

PLC programming has been taught using Ladder Diagram since PLCs were introduced in earlier 1970s. The programming technique was designed following two-wire relay control logic schematics. The process begins with entering the first rung to satisfy the first output requirement and the rungs are continually entered until the solution to the problem under investigation is reached. The special programming approach makes the electricians who are responsible for the maintenance of a PLC control system easy for troubleshooting and updating programs due to the similarity between the relay control hardware and software schematic. However, for the students in Mechatronics Engineering at Vaughn College, although they have taken a 3-credit DC/AC Circuits course and a 3-credit Electronics course (including laboratory exercises), their knowledge in electrical engineering is still very limited since they need to learn courses from mechanics, thermal science and material science as well as computer engineering. Therefore, the relay control schematic is a new topic for the students in understanding the hardware and software programming.

On the other hand, the students in the program have had some knowledge in texted programming languages since they learned MATLAB programming through the computational method course in mechanical engineering and assembly language through the microprocessors course in computer engineering. Under the circumstance, teaching the logic programming in PLCs can be easier if starting from texted languages. Therefore, the texted languages designated by the IEC61131-1 standard, such as Instruction List (IL) and Structured Text (ST), have been taught in the first course, PLC Programming, at the college. After students have mastered the fundamental knowledge needed for programming industrial automation devices, the Sequential Function Chart (SFC), Ladder Diagram (LD) and Function Block Diagram (FCB) are taught in the advanced course, Industrial Automation, where Siemens Step 7 PLCs have been used. Particularly, the SFC chart has been taught as an approach of developing a complex algorithm so that students can first develop the pseudo code as an SFC-like diagram and then implement it in LD or FCB diagram⁷.

The courses, PLC Programming and Industrial Automation, have been taught at the college since 2010. As a result, students have developed various course projects which aim to solve problems in the real world using PLCs. The corresponding educational research papers have been successfully presented in several conferences. Furthermore, a number of students have landed jobs in the industry as control and automation engineers.

This paper will present the result that we got from teaching the courses, which is organized as follows. In Section 2, the course schedule for the first course PLC programming is introduced.

The course layout for the advanced course, Industrial Automation, is presented in Section 3 and the course survey as well as the students' papers in conferences are discussed in Section 4, respectively. The approach to teach PLC programming and industrial automation is concluded in Section 5.

Course Setup for PLC Programming

At Vaughn College, the PLC Programming course is scheduled in the second semester of junior year. As Mechatronics Engineering students in junior year standing, they have learned MATLAB programming, assembly language and C language programming from the courses as MATLAB, C++ Programming, Computational Methods in Engineering, and Microprocessors. With the knowledge background, the main goal for the PLC programming course is to let students understand the fundamental structure of PLC technology and programming skills used in PLCs in the automation and manufacturing industry, such as addressing mode in PLC programming, timers and counters, PLC digital input/output module and analog input/output module, etc. Furthermore, students are required to solve some practical problems through programming the PLCs. By the end of the course, the concept of Sequential Function Chart is taught as an algorithm development approach so that students are ready to be engaged in developing a PLC control logic for a complicated industrial automation system. Based on the goals, the course topics and laboratory project exercises are scheduled as shown in Table1.

Table 1: Course Topics and Lecture Hours Devoted to Each Topic

Week	Hour	Topic
1	2	PLC technique overview.
2-3	4	Addressing mode in PLC programming, basic logic programming in Instruction List and Structured Text languages
4	2	Combination of Boolean operations and storing elements
5	2	Function blocks, edge-triggered functions, timers including switch-on delay, switch off delay and pulse function
6	2	Up counters, down counter, up/down counter with applications
7	2	Programming structure - function calls and jump statements
8	Course Review and Midterm	
9	2	Analog to digital conversion and digital to analog conversion in PLC program.
10	2	Conveyor belt station: basic sensors and actuators in manufacturing industry
11 – 12	4	Sequence control development and programming.
13 – 14	4	Introduction to PLC network communication and PROFIBUS configuration
15	Course Review and Final Exam	

In the laboratory exercise sections, the Uni-trainer as well as the corresponding conveyor belt system, provided by Lucas Nuelle (LN) Ltd⁸, is used, which is shown in Figure1. According to the course topics, the laboratory exercises are arranged as a sequence of small homework

assignments and laboratory exercises with the schedule shown in Table 1. The IL and ST languages are used for the exercises until the conveyor belt station.

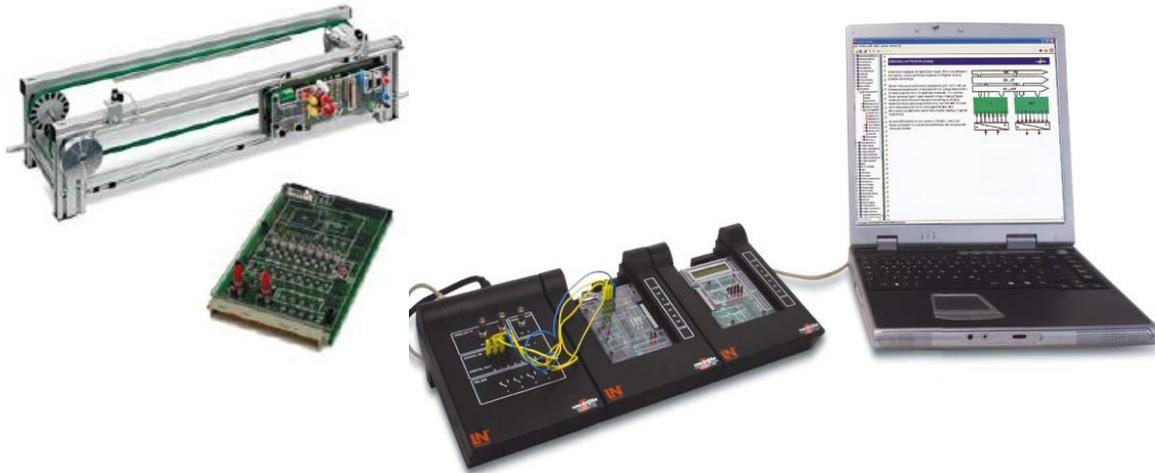


Figure 1: Uni-trainer (a) and Conveyor Belt Station (b) for PLC Programming

During the teaching process, in addition to provide students the basic concepts about PLC programming, such as the programming structure, logic operations, basis concepts as normally open/closed circuit and set/reset dominance latches for storing elements, switch on/off delay timers, up/down counters, we focus on enhancing students' problem solving capability through the kinesthetic learning style. For example, after we teach students the function blocks for times and counters, we require students to solve the problem as follows,

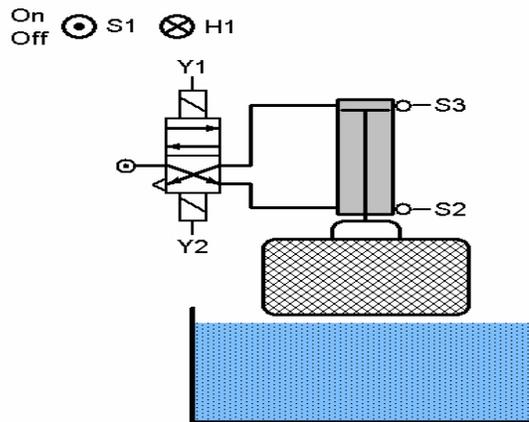


Figure 2: Schematic of a Cleaning Plant with Hydraulic Mechanism

A cleaning plant shown in Figure 2 is used to clean metal components in a cage. The cage is lowered into the cleaning plant for 5 seconds by a hydraulic mechanism and then raised up for 1 second. The process is repeated for three times and finally the cage will return to the original position. Switch S1 is used to start a new cleaning cycle and the indicator H1 lights up during

the cleaning procedure. Draw the block diagram to analyze the procedure and Program in IL and ST, respectively, to implement the control procedure.

To order to do the exercise, we discussed with students (1) the type of function blocks should be used to solve the problem, such as counter, switch-on delayer timer, set-reset flip flops, and rise edge trigger; (2) what inputs and outputs each block should have; (3) what we should notice in the programming. After the program was written, students discussed in groups on how the program solve the the problem.

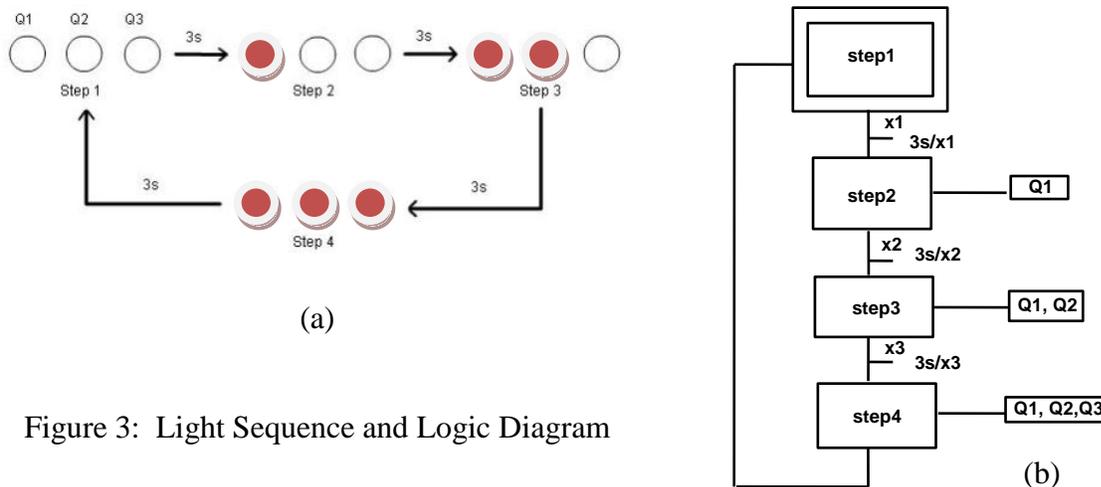


Figure 3: Light Sequence and Logic Diagram

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VAR
Q1   AT %QX2.7 : BOOL; (*Lamp 1*)
Q2   AT %QX2.6 : BOOL; (*Lamp 2*)
Q3   AT %QX2.5 : BOOL; (*Lamp 3*)
INIT AT %IX0.7 : BOOL; (*Initialisation button*)
STEP1 : RS;   (*Instance of step 1*)
STEP2 : RS;   (*Instance of step 2*)
STEP3 : RS;   (*Instance of step 3*)
STEP4 : RS;   (*Instance of step 4*)
TIMER1: TON;  (*Instance of timer 1*)
TIMER2: TON;  (*Instance of timer 2*)
TIMER3: TON;  (*Instance of timer 3*)
TIMER4: TON;  (*Instance of timer 4*)
END_VAR
(*Step1*) TIMER1(IN := STEP4.Q1, PT := T#3s);
STEP1(S := INIT OR STEP4.Q1 AND TIMER1.Q, R1 := STEP2.Q1);
(*Step2*) TIMER2(IN := STEP1.Q1, PT := T#3s);
STEP2(S := STEP1.Q1 AND TIMER2.Q, R1 := STEP3.Q1 OR INIT);
(*Step3*) TIMER3(IN := STEP2.Q1, PT := T#3s);
STEP3(S := STEP2.Q1 AND TIMER3.Q, R1 := STEP4.Q1 OR INIT);
(*Step4*) TIMER4(IN := STEP3.Q1, PT := T#3s);
STEP4(S := STEP3.Q1 AND TIMER4.Q, R1 := STEP1.Q1 OR INIT);
(*Command for Lamp 1*) Q1:=STEP2.Q1 OR STEP3.Q1 OR STEP4.Q1;
(*Command for Lamp 2*) Q2:=STEP3.Q1 OR STEP4.Q1;
(*Command for Lamp 3*) Q3:=STEP4.Q1;
(*The program is implemented in a systematic way*)

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Figure 4: Implementing Light Sequence in Structured Text Language

Finally, the program was implemented on the Uni-trainer and the result was examined. Through the learning process, students know how to apply timers and counters to solve the problems which require time delay and repeated operations.

After students were familiar with the PLC programming logic, they were further taught the sequential control which links multiple stages of operations in a sequence. At the beginning, students were provided the problem on how to turn on the lights shown in Figure 3(a) one by one with three second interval. By the analysis of control steps, the logic diagram similar to the sequential function chart shown in Figure 3(b) was developed to represent the control process in sequence. Next, students were guided to implement the logic using set-reset flip flops, timers and counters. Figure 4 shows the implementation of the logic diagram of Figure 3(b) in ST language. Again, the program had to be tested on the Uni-Trainer. If the result was not correct, students should re-program until the correct solution was reached.

Course Setup for Industrial Automation

The goals of the Industrial Automation course are to familiar students with the design procedure of industrial manufacturing systems, which includes (1) understanding the fundamental structure of manufacturing automation, including the working principles of various sensors and actuators; (2) being able to design and implement the manufacturing process in sequence control and finite state machine approaches; (3) practicing advanced programming in SIMATIC S7 in Ladder Diagram and Function Block Diagram languages, respectively; (4) being able to effectively communicate the system design of the manufacturing process orally and in writing.



Figure 5: Industrial Mechatronic System From LN Company

Toward the educational objectives, the Industrial Mechatronic System (IMS) developed by Lucas Nuelle (LN) Ltd⁹ has been used for the laboratory project exercises, which is shown in Figure 5. The IMS system contains eight stations: sorting, assembly, processing, testing, handling, storage, routing and buffering. The IMS sub-systems are connected with a Siemens PLC S300 PLC via the PROFIBUS.

For substations, each of them can be controlled by a PLC emulator embedded in a Uni-Trainer.

Hence, students can first develop a PLC program and download it to the Uni-Trainer emulator of each substation to examine the control performance. Particularly, the LN company provides the program converter to transfer the program written in the Siemens SIMATIC Step7 to IL language and run it under the Uni-Trainer emulator. Using the courseware, students can directly write a program in Siemens SIMATIC Step 7 and run it to control the IMS system as well as each substation of the IMS system. Course topics and lecture hours devoted to each topic are listed in Table2 and the corresponding laboratory project arrangement is shown in Table 3.

Table 2: Course Topics and Lecture Hours Devoted to Each Topic

Week	Hour	Topics
1-2	4	Control system design procedure, proximity sensors and pneumatic actuators, sequence control and implementation in Function Block Diagram
3-4	2	Assembly station programming and advanced sequence control
5	2	Multiple sensors with pneumatic actuator, programming Ladder Diagram
6	4	Conductive, inductive, and optical sensors in testing station
7-8	4	Serial and parallel process control in handling station
9	Course Review and Midterm	
10	2	Branching structure in buffering station
11-12	4	Conditional statements and counters in Ladder Diagram, storage station: deposition/withdraw along the Z-axis; deposition/withdraw along the X axis
13	2	Profibus configuration for routing station
14	2	Project development
15	Course Review and Final Exam	

Table 3: Laboratory Project Exercises and Hours Devoted to Each Topic

Week	Hour	Topics
1-2	4	Program sorting station
3	2	Program assembly station
4	2	Quiz1: basic sensors/actuators and FBD programming
5	2	Program processing station
6	2	Program testing station
7	2	Program handling station in parallel operations
8	2	Quiz2: multiple sensors/actuators and handling station in serial operations
9-10	4	Quiz3: buffering station structure and programming
11-12	4	Conditional structure programming, storage station: deposition/withdraw along the Z-axis; deposition/withdraw along the X axis
13	2	Quiz4: routing station programming
14	2	Project development
15	2	Project Presentation

For the laboratory project exercises, five high-quality laboratory project reports are required to be written plus a course project report. The topic of the course project can be chosen by students. The problems existed in industries are encouraged to choose and solve. In addition to the course project report, a course presentation will be held by the end of the semester. Students are required to present the project design and demonstrate the successful implementation of the developed PLC program.

The lecture of each substation focuses on certain new knowledge, for example new sensors or pneumatic/hydraulic actuators with various types of valves, new programming language or new programming skills, such as parallel programming and conditional structure. For each substation, students develop the PLC program and test it by the following steps: (1) Examine the functionality of the station and the corresponding inputs and outputs; (2) Identify the number of stages to complete the procedure and develop the logic diagram or table to represent the stage commands and conditions; (3) Program according to the logic diagram; (4) Test the program and troubleshoot.

As an example, we show how students worked on the sorting substation as follows: in the first step, students understood the process of the substation as a carrier moved right till the sorting slot, a part was dropped by the sorting cylinder and then the carrier continually went right till the right end of the conveyor belt was reached. Two sensors were (1) B3 indicated the stop cylinder at the top position and (2) B4 detected the magazine filled with parts, and two actuators were the stop cylinder and sorting cylinder. The conveyor belt had two inputs as left and right end proximity sensors and three outputs as turning the DC motor forward, backward or creep mode, respectively. Together with the start signal and reset (initialization) signal, an input/output table is listed in Table4.

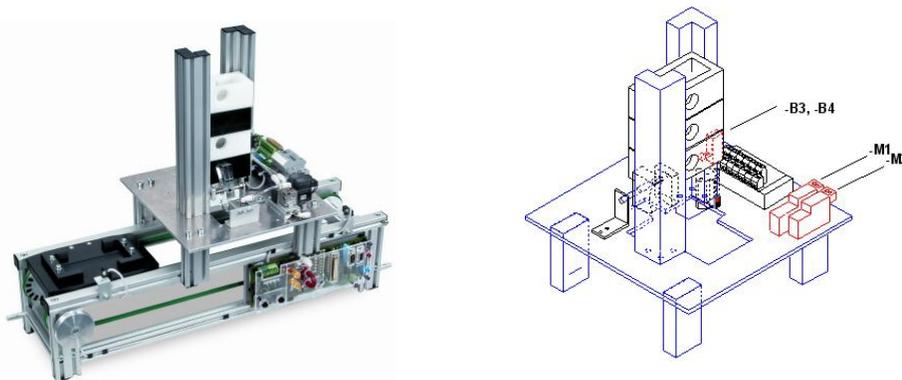


Figure 6: Sorting Substation

Table 4: Inputs and Outputs of Sorting Substation

Address	Type	Designation	Label	Address	Type	Designation	Label
I0.2	Input	Stop cylinder in top position	-B3	I1.4	Input	Right position	-B2
I0.3	Input	Magazine in filled level	-B4	Q1.0	Output	Motor moves forward	-QR
Q0.0	Output	Move stop cylinder	-M1	Q1.2	Output	Motor moves in creep mode	-QS
Q0.2	Output	Open sorting cylinder	-M2	I2.2	Input	Start button (normally open)	
I1.3	Input	Left end position	-B1	I3.1	Input	Initialize the sequence	

The second step of the design was to separate the number of stages to complete the duty: there are six stages to complement the task: 1. initialization; 2. the carrier moves forward; 3. the carrier moves in creep mode; 4. sorting action; 5. waiting for the stopper cylinder up; 6. the carrier moves forward. Similar to the logic diagram shown in Figure 3(b), the sequence and commands to implement the station were analyzed and listed in Table 5.

Table 5: Implementation of Sequence and Control for the Sorting Substation

Stage	Sequence (conditions from i-1 th stage to i th stage)	Commands (actions at i th stage)
1	B2=1 (*Carrier at right hand end position*)	none
2	(1) B1=1 (*Carrier at left hand end position*) (2) B4=1 (*The magazine is loaded*) (3) Start button = 1.	QR = 1 (*motor moves forward*) M1:= 1 (*stopper is downed*)
3	1 second delay	QS =1 (*motor moves in creep mode*)
4	1 second delay	M2=1 (*sorting action*)
5	1 second delay	M1:=0 (*Reset the stopper*)
6	(1) B3=1 (*stopper at top position*) (2) 1 second delay	QR=1 (*motor moves right*)

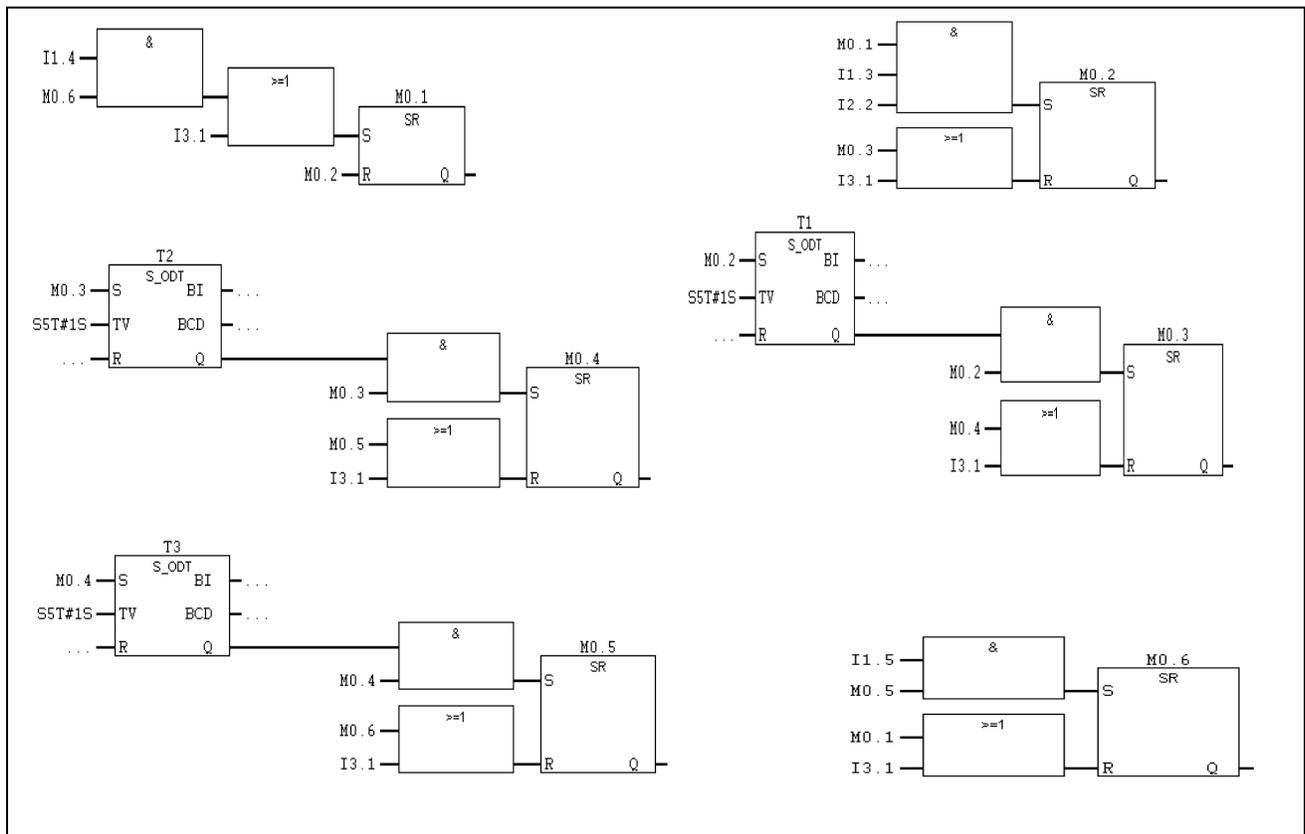


Figure 7: Function Block Diagram to Implement the Sequence for Sorting Station

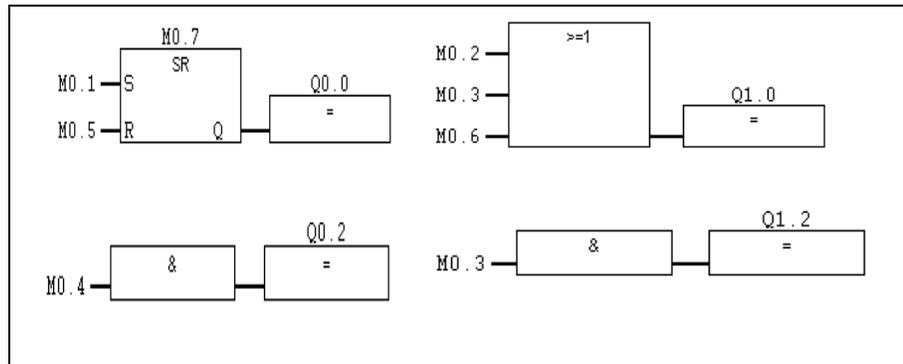


Figure 8: Function Block Diagram to Implement Commands for Sorting Station

Based on the steps of sequence and control shown in Table 5, students programmed in the Function Block Diagram as shown in Figure 7 and Figure 8 in Siemens SIMATIC Step 7, respectively. Finally, the program was transferred into the IL language and downloaded to the LN IMS substation and the result was examined.

In the Spring and Fall semesters of 2014, there were nine students who enrolled in the two classes. By the end of the course Industrial Automation, students have successfully developed their own course projects: (1) Automated car parking system - the system can store and retrieve cars in an optimal way based on the requirement of a car owner; (2) Testing, identifying and storing - a product can be firstly identified by the color and building material and then the PLC system can store them in different locations of a big storage unit; (3) Manufacturing assembly line - the assembly process of several stations is arranged in a pipeline approach so that when one product is finished from one substation, the next product will fill in the substation. Among them, the first project was implemented using ST programming language whereas the second third projects were implemented using the Ladder Diagram.

Program Outcomes and Course Survey

At Vaughn College, the Mechatronics Engineering is a new program which received ABET accreditation in August 2014 with retroactively extending to 2011. From 2011 to 2014, we have a total of 13 graduates. All of them have landed a job or pursued an advanced degree. Three students have studied towards a master degree in System Engineering, Mechanical Engineering and Business Administration (MBA), respectively. Nine students have been hired as Control, Test, Mechatronics, Product Design, or Project Development Engineers. Of the five Control Engineers, three of them are directly working with PLC programming and automation system designs. Before the students graduated from the college, they had developed and presented the following papers at national and international conferences.

"Automated Sorting Using PLC Technology", 2013 Mid-Atlantic ASEE Engineering Conference, April 27, 2013, New York City, New York.

"A PLC Automated Security Checkpoint", Ninth LACCEI Latin American and Caribbean Conference (LACCEI'2011), Engineering for a Smart Planet, Innovation, Information

Technology and Computational Tools for Sustainable Development, August 3-5, 2011, Medellín, Colombia. (The paper has won the second place at the college's technology day conference.)

"Innovative Cargo Screening Using a PLC System", 2011 ASEE St. Lawrence Conference, April 18-19, Albany, New York. (The poster has been awarded as the best poster of the conference.)

From 2010 to 2014, the number of students in the PLC programming and Industrial Automation classes have grown from 2-3 students to 12 students in the Spring semester of 2015. In the Spring and Fall semesters of 2014, the classes had 9 students. By the end of Fall 2014, a course survey was conducted in order to assure the continued success of the Mechatronics Engineering core courses. The result is listed in Table 6.

Table 6: Course Outcome Survey for the Course Industrial Automation

Question	Strongly Disagree/ Disagree	Neutral	Agree/Strongly Agree
1. The class gives me the information about industrial automation and PLC programming.		1	8
2. Learning multiple PLC languages helps me to efficiently develop a PLC program according to the requirement of a task.			9
3. The sequence control approach helps me think logically and implement a design effectively.			9
4. I know how to program in Ladder diagram, Function Block Diagram, Structured Text and Instruction List.			9
5. I know how to develop a PLC program to connect several stations of an assembly product line.		2	7
6. I know how to write a PCL program given a Flow Chart, such as Sequential Function Chart (SFC).			9
7. I know the working principles of the basic sensors and actuators used in industrial automation.		2	7
8. The course project encouraged me to make a process of asking questions, using resources and develop my lifelong learning skills.		1	8
9. The team work in the course project was positive to improve my skills and knowledge.	1	2	6
10. The class helped me to get a lot of hands-on experiences in building industrial product assembly line.		1	8
11. The class is fun and I have learned a lot. I think the approach to teach the class is correct.			9

General comments as well as suggestions to improve the class

- ✓ Great class! Enjoyed!
- ✓ Please ask Lab Assistant to stay for extra time after class is over to implement code on machine. (in case we need more time.)
- ✓ Make sure the implementation computer is only for testing code. Students who need to modify the code should do it on another computer, allows other students to test their code.
- ✓ The instructor knows how to help students learn programming. It's an amazing hands-on experience.
- ✓ More Quizzes.
- ✓ More time for final project.
- ✓ Enjoyed learning various stations then having Quizzes in between.
- ✓ More algorithms or flow chart creations to supplement the functional logic sequence.

- ✓ Develop emergency stop at earlier stage of the course and develop more troubleshooting exercises.
- ✓ Students need to build up the station by themselves to be able to have hands on it.
- ✓ The course was overall thorough. May need more practices on SFC since the programming was most easily interpreted from SFC or ST language. More experience in logic flow and understanding how to perform an algorithm would be great.
- ✓ It is one of the more fun classes of the semester, probably because programming is my favorite subject. The course using Lucas Nuelle was somewhat easy due to the same hardware being used across stations. Using things like a different PLC controller would add variety.
- ✓ The handout approach is good. It would be great to have them one week before the class.
- ✓ Lab reports take long to write, for old material or application, have a quiz instead.
- ✓ The explanation at station handouts with power points is very good and group discussion at questions is effective.
- ✓ The current approach to teach is good because it is very hands-on and provides an interactive environment.

From the course survey and the program outcomes, it has shown that students are generally satisfied with the teaching approach and the courses provided students necessary knowledge for them to obtain a job in control and industrial automation related areas as well as for their advanced studies. Further improvement will be (1) making more time for the course project and helping students develop teamwork skills; (2) searching industrial connection and offering more time to explain sensors, actuators as well as assembly line programming.

Conclusion

A method to teach PLC Programming and Industrial Automation courses for students in Mechatronics Engineering has been discussed in the paper. According to students' knowledge background, we have scheduled our classes as teaching students the PLC programming in texted languages, such as Instruction List and Structured Text. In the advanced course, Industrial Automation, the graphic languages, such as Sequential Function Chart, Ladder diagram and Function Block diagram, are taught with focus on the enhancement of problem solving skills. The course survey and program outcomes show that the teaching approach, i.e. laboratory project based approach and the kinesthetic learning style, is feasible and effective. Furthermore, since students have practiced five different PLC programming languages in a number of laboratory project exercises, they can flexibly choose a PLC programming language to solve a specific problem at hand. With the knowledge of the PLC programming languages specified by the international standard IEC 61131-3, students are able to work with PLC experts around the world without the limitation of companies and regions.

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