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Integrating PLCs with Robot Motion Control in Engineering Capstone Courses

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Abstract

Robotic motion control methods and Programmable Logic Controllers (PLCs) are critical in engineering automation and process control applications. In most manufacturing and automation processes, robots are used for moving parts and are controlled by industrial PLCs. Proper integration of external I/O devices, sensors and actuating motors with PLC input and output cards is very important to run the process smoothly without any faults and/or safety concerns. Most traditional electrical and computer engineering (ECE) programs offer high level of motion theory and controls but little hands-on exposure to PLCs which are the main industrial controllers. This paper provides a framework for a hands-on project to integrate PLCs in robot arm motion control, troubleshooting, and testing the real sensors and motors with PLC experiments which complements the virtual calculations and theory. This PLC with Robot Arm Motion control integration concept idea was introduced and tested in a 600-level graduate capstone project class. By the end of the semester long class, the students used their PLC hardware and software skills to wire a robot arm sensing elements and actuating motors to pick and place objects from one location to a bin. The assessment demonstrated that the course learning objectives were met.

Introduction

Different motion control profiles for industrial robots that are typically integrated with PLCs are used in a wide variety of fields such as manufacturing automation, sorting, and packaging in large warehouses to name a few. Besides robotic control, The PLC based control system are used in other types of applications including utilities, rides in theme parks, traffic control systems, railroad, aviation, and a variety of transportation modalities [1-6]. Traditionally, control using PLCs is not taught in a ECE undergraduate or graduate curriculum. However, an electrical and/or mechanical engineer needs these skills to work in a variety of industries. Typical ECE curriculum includes control theory, analog and digital electronics but seldom include courses in PLCs and integrating them with different equipment. This missing link led to the development of PLC and industrial instrumentation related courses in remote learning and technology programs [7]-[10], but ECE students rarely take these courses from technology departments. A survey of the courses offered in the ECE curriculum by the four year universities in Virginia list no courses in PLC based control. However, there are numerous reports on innovative approached to teach PLC in engineering technology programs [11-12]. To offset these missing skills in ECE graduates, a capstone project as a pilot course was introduced in this work. The PLC based control can effectively be taught in a hands-on laboratory setting which is the focus of this paper. . Hardware and software integration using PLCs, and active lab-based learning is more effective in these types of courses for engineering students [13], [14].

Use of industrial robots in manufacturing industry paved the path to improved productivity and innovation of new products. However, the education and workforce training in these areas are lagging. All levels of education and workforce development (EWD) nationwide don't have relevant courses in this area, especially in ECE and Mechanical Engineering programs. The robotics related curriculum development has many challenges because robots need to be integrated with other equipment such as PLCs and other controllers to teach these topics more effectively, and these challenges are explained well in reference [15]. The benefits of early exposure of children to robotics technologies are discussed in reference [16]. The statistical information [17-19] related to workforce development in robotics, manufacturing and automation areas are available in different U.S departments data bases. This statistical information provides a big picture on how traditional engineering curricula and industry needs in the areas of robotics and PLC integration have a wide gap. This gap is more evident in ECE related curricula, hence there is a need to include industry driven course development in ECE programs with focus on PLCs, sensors, motor control, robotics, instrumentation and most importantly the integration of these devices in different engineering applications.

This paper focuses on how a robot arm motion control devices can be integrated with PLCs. The project was implemented in one of the graduate capstone classes in a ECE graduate engineering program. The emphasis is on PLCs integration skills they learned in class to a real engineering experiment. The main parts of integration include wiring the hardware, software development, and fault detection methods. If the undergraduate/graduate students from ECE or Mechanical engineering degree get exposed to PLCs, industrial instrumentation, and industrial motion control methods, it will improve their working skills in the real world.

Most ECE departments either don't have any PLC related lab equipment or have some equipment that are antiquated when compared to current industry standards. It is always prudent to train the students with the most current PLC equipment to remain relevant in the ever-evolving industry. The project reported in this paper utilized the Rockwell PLC modules, Festo robot arm and Human Machine Interface (HMI) unit, and RSstudio software [20-21]. The capstone course syllabus was developed with learning outcomes that focuses on understanding of different sensors, motors, motor drives, PLC I/O cards, wiring, control algorithms, and how to integrate all these devices and control them with the PLC software. The other important goal was to teach students to troubleshoot the hardware and software issues in the integration process.

The Main Leaning Objectives and Block Diagram of the Project Framework

The capstone projective learning outcomes were divided into two main parts, the first one was to run the robot with manufacturer provided software, without PLC, to understand the working principles and limitations of the robot, and the second part was to integrate the robot with PLC and develop software to control it. All the learning objectives are listed below.

- Run the Festo robot sample exercises using keypad and manufacturer provided standalone software. This objective was included in the syllabus to make sure students understand how robot works before unhooking motors, sensors and connecting them to PLC cards.
- Identify main sensors on the robot that are used in moving the material parts from one station to another station. These sensors include end position sensors, arm joint sensors and other related sensors.
- List out and document all actuators/motors' type, wiring diagram and electrical specifications.
- Do the wiring and connect all the sensors and actuators to PLC input/output cards.
- Do the mathematical calculations for required motion profile to meet the required specifications (such as velocity, acceleration, deceleration, stop procedures) based on how quickly and smoothly the process should be completed.
- Develop a ladder logic program for the given task using appropriate motion profile. Develop HMI program for the user to enter motion profile values, Start/stop the process, implement emergency stop, and program useful display indicators and lights.

The project stages are explained in the block diagram shown in figure 1.

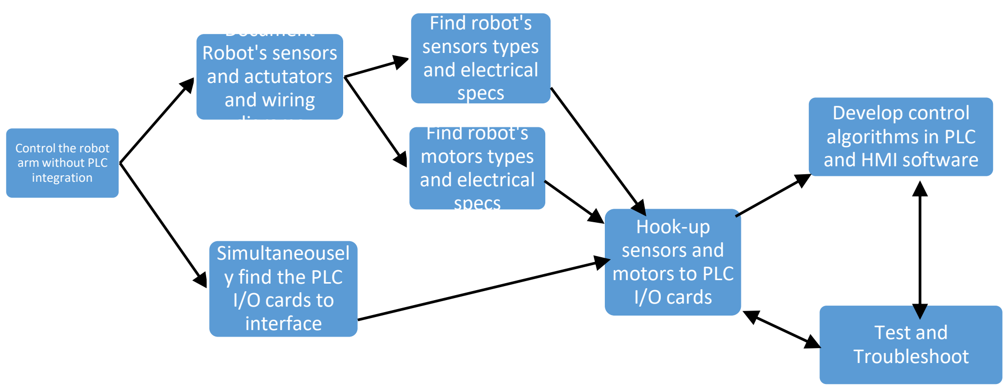


Figure 1 Project Phases Block Diagram

Hardware and Software Requirements and Software Setup

The industrial motion control involves integration of robot control with PLCs, motor drives. sensors and proper software development. The objective is for students to use the PLC integration skills they learned from this class in a real engineering applications. The course project consists of different hardware parts that include a FESTO Robot arm, stepper motors, control drives, various sensors, PLC hardware and HMI device. For successful integration, the students first need to understand robot motors, sensors and wiring diagrams so that these can be connected to the correct PLC I/O cards. One also needs to understand different PLC cards and their wiring methods. Finally, after the robot and PLCs are interconnected, motion control algorithms need to be simulated first and then downloaded into the PLC processor to run the entire automation system. The following sections explain in more detail about these different hardware components that were used in the project.

The Festo Robot Hardware and Wiring

The FESTO robot, shown below, is a 6-motor robot with 5 degrees of freedom and an end effector of a gripper. These degrees of freedom include:

1. Base rotation clockwise and counterclockwise
2. Shoulder raising and lowering
3. Arm extending and retracting
4. Wrist yaw control
5. Wrist Rotation control

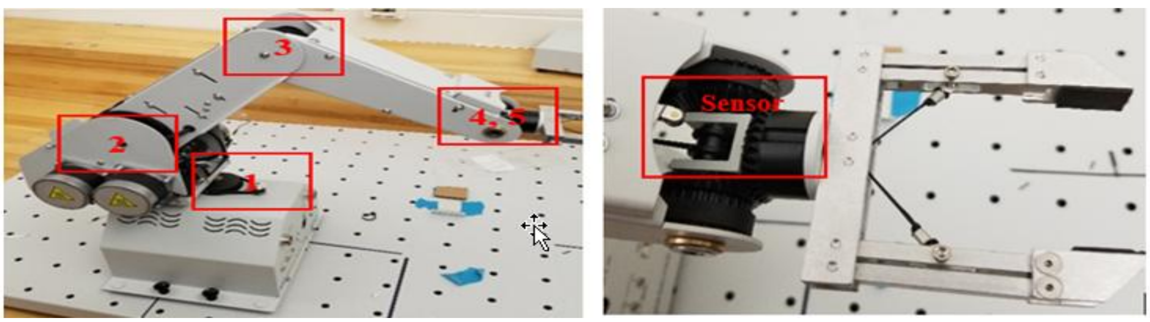


Figure 2 FESTO Robot and Gripper

To support the robot's base level of control there are also 4 sensors. These sensors are solely used to determine the position of each motor and are not used for preventing self-damage to the robot. These sensors are shown in the following figures.

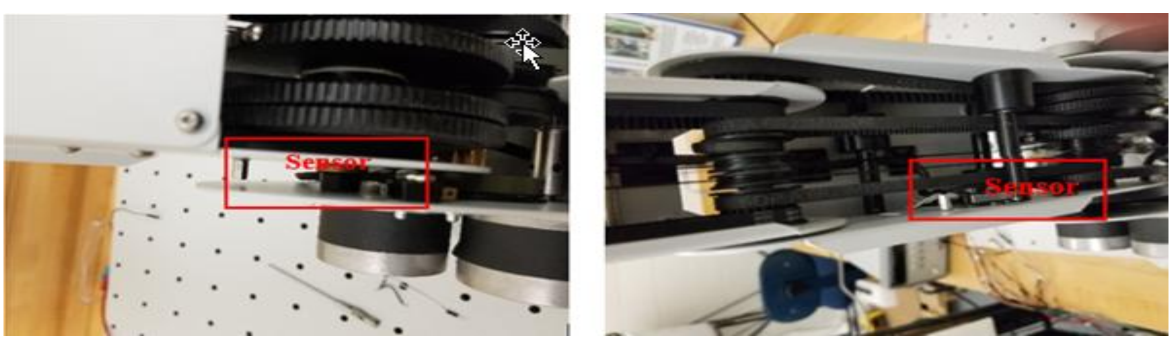


Figure 3 Shoulder and Arm Sensors

For the gripper motor there is no sensor to determine if the gripper is fully open or fully closed. Instead, what the robot has is a screw in the gear wheel assembly which prevents the gripper from opening too far or trying to close once fully closed. This screw is shown in figure 4.

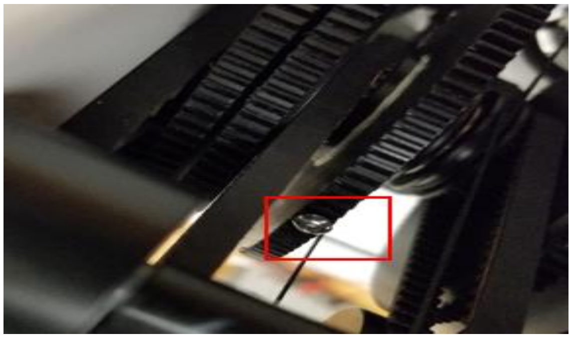


Figure 4 Gripper Screw

All design work that was done takes just these limitations into account to build a program that is capable of controling motors and defines the outline for fine tuned control.

Hardware Wiring and Hook-up

The robot comes with a built-in control board which scans different sensors and controls motors. However, using this control doesn’t teach students how to integrate this to PLC, hence the control board was unplugged and rerouted into the PLC.

Figure 5 Robot Wiring

To be as close to as real-world industrial example, not only the pictures of wiring were taken but also a data repository of different hardware components and wiring connections was made. The table 1 shows the wire mapping which can also be used to identify how the wires should be reconnected in the event the PLC connections are removed.

Table 1 Wire Mapping

Wire mapping		
Label	***Usage***	***PLC usage***

A (J19)	Sensors + power	Top cable provides 15v source others are for sensors
B (J18 and J17)	TTL inputs	None
C (J13)	Motor 2 (Gripper)	Motor control (white wire is ground)
C (J12)	Motor 3 (Wrist)	Motor control (white wire is ground)
C (J11)	Motor 5 (Wrist)	Motor control (white wire is ground)
C (J10)	Motor 4 (Arm)	Motor control (white wire is ground)
C (J9)	Motor 6 (Shoulder)	Motor control (white wire is ground)
C (J8)	Motor 1 (Base)	Motor control (white wire is ground)
C (J7)	TTL Ground	None

PLC I/O Requirements

The first step for hooking up the components was to determine what would need to be hooked up and allocate a corresponding number of I/O cards. The main components to be wired are four sensors and 6 motors. Each motor requires four inputs to individually control each of its windings. This leads to the following (table 2) requirements for the PLC IO configuration.

Table 2 PLC Card Requirements

PLC Cards		
PLC Output	***Slot***	***Number of used channels***
IB16	8	4 (sensors)
Ow16I	2	12 (Motors 2, 3, 5)

OW16I	5	12 (Motors 1, 4, 6)
EN2T	9	HMI/Laptop IP: 192.168.0.10

The first set of components that were connected were the sensors. These sensors are sourcing sensors and must be supplied with at least 10V but less than 24 V. To also support the power requirements for motors a 15v power supply was used. The supply is provided by the red cable shown in figure 6 which was labeled as input pin 1.

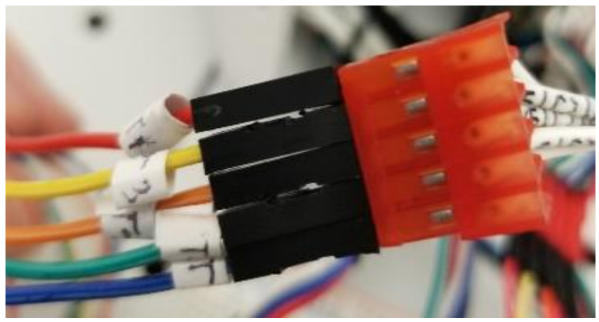


Figure 6 Sensor connections

Sensors to PLC Cards

The remaining pins and how they connect to the PLC can be determined from the list of sensors shown in table 3. These were used in the PLC project to both determine a homed state of the motor and to prevent it from going into an unsafe condition, as defined by the sensing direction. A note from this table is that the robot does not have a sensor for every motor, and nor does it have a sensor for more than one direction for the motors that do have a sensor. This can lead to many unsafe or extreme scenarios. The key motor that does not have a sensor is the gripper, which uses a screw on the gear assembly to prevent motion, and caution should be used when commanding this motor to prevent excessive stripping of the gears in the assembly.

Table 3. Sensor Information

List of Sensors					
Location	***Tripped State***	***Direction (relative)***	***Motor Direction***	***PLC Input Channel***	***Robot Outputs***
Wrist	Closed	Raising Wrist	Positive	0	2

Arm	Closed	Retracting Arm	Negative	2	3
Shoulder	Closed	Raising Shoulder	Positive	4	4
Base	Open	Rotating CW	Negative	6	5

Motors to PLC Cards

Once the sensors were connected the next step was to connect each motor. In general, these motors are all rated at 30V, 2A. However as described in the previous section, a power supply voltage of 15 V was used for both the sensors and motors. Therefore, the motors were set to operate at 15 V and 1 A. The table 4 identifies each motor (as labeled on its cabling) with which pins it was connected to on the internal circuit board (for easy reconnection), and how it was connected to the PLC.

Table 4. Motor Information

List of Motor				
Descriptive Name	***Board Connection***	***Motor Number***	***Positive Direction***	***PLC Output Channels***
Gripper	J13	M2	Open gripper	Card 1 0-3
Wrist M1	J12	M3	Rotate CCW	Card 1 5-8
Wrist M2	J11	M5	Rotate CW	Card 1 10-13
Arm	J10	M4	Extend	Card 2 0-3
Shoulder	J9	M6	Raise	Card 2 5-8
Base	J8	M1	Rotate CCW	Card 2 10-13

Each motor uses the same set of connections (figure 7) for its outputs from the PLC. The first connection (the white wire) is always connected to a common ground. After this the color of the wires native to the robot follow the same pattern and are hooked up as listed below in table 5.

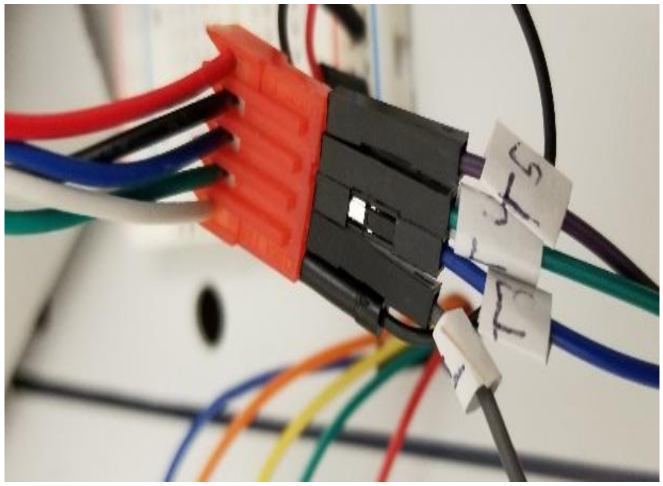


Figure 7 Motor Connection

Table 5. Motor Wiring

Motor Wiring	
PLC Output	***Motor Connection***
Output 1	Pin 3 (Blue)
Output 2	Pin 4 (Black)
Output 3	Pin 5 (Red)
Output 4	Pin 2 (Green)
Ground	Pin 1 (white)

Results and Discussions

Once the wiring was completed for robot sensors and motors to proper PLC I/O cards, control algorithms/methods were developed and implemented in PLC ladder logic program. The other goal of this project was to teach students how to program PLCs to control external automation devices such as industrial robots in manufacturing shop floor.

Initial Motor Control

Each motor in the system is a 4-pole stepper motor. This means each motor has 5 cables: one for a ground and one per motor winding. To control a stepper motor the winding must be energized in the correct order. This means turning on the next motor before de energizing the current winding. This causes the motor to make a 1/4 turn rotation per winding. To complete a full rotation each winding must be energized once. The figure 8 below outlines the general control signals. Note all outputs were at 15V and the different levels are only to aid visualization of each signal.

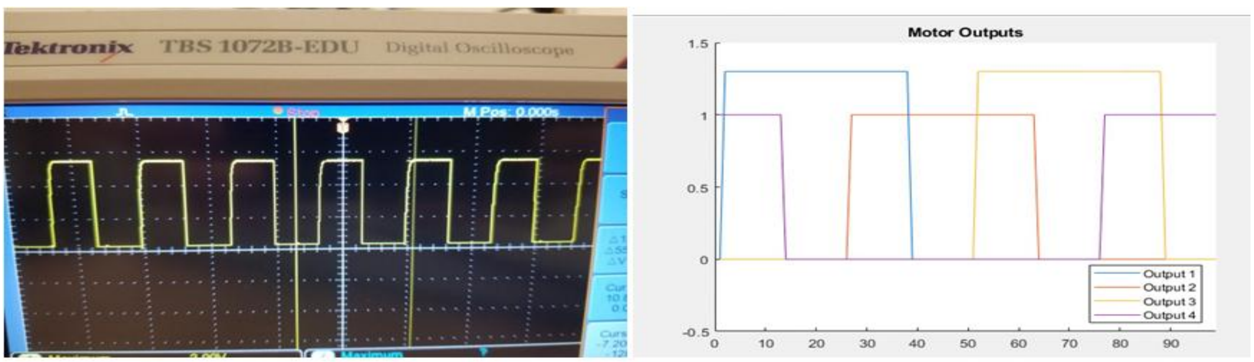


Figure 8 Measured Output Signal and generated PLC output waveform

The general algorithm to calculate this is to first determine the desired frequency for every signal. Based on the measurements, the base speed from the robot's control is on the order of 10 ms. Due to limitations in the PLC, the fastest speed was restricted to around 25 ms to allow the output card time to de-energize before turning back on. The logic then divided the frequency into 4 components with duration equal to $3/8^{th}$ of the full duration. Each is placed such that during one pulse the previous pulse will overlap for $1/8^{th}$ the total duration, and the next pulse will overlap for $1/8^{th}$ the total duration. After spacing each pulse, the next step was simply to control the ordering such that the direction could be controlled: forward for a plus direction and backwards for a negative direction. From this algorithm the following parameters can be controlled in the PLC:

1. Frequency via tag Motor Speed
2. duty cycle via AOI parameters of
3. Direction via plus or minus directional commands
4. Output ordering in case wiring errors were introduced.

The final set of measurements were the power requirement for the motors. The robot itself uses 30 V and 2 A, but that was not possible with the given power supply. From testing it was determined that 15 V was enough to control most motors and would use only 1 A. This led to an issue though as one motor in particular, the shoulder motor, required the full 2A but the power supply could not provide it. As a result, the setup was unable to fully raise or lower the shoulder as the motor could not overcome gravity. To get around this, a 2^{nd} power supply could be added in parallel to provide the required amperage. As it stands, the control operation has been verified under less load.

Wrist Control

With simple motor control programmed installed, the next step was to get the motors to work together. For this the main problem is the wrist motors which must always be controlled in tandem. To manage this the PLC takes the higher-level commands such as rotating the wrist or raising/ lowering it to individual motor commands. This guaranties that the 2 motors are controlled in tandem even if they are moving in opposite directions. This decision also leads to allocating all gripper and wrist motors on the same output card such that if the card fails the entire wrist motion stops.

Sensor Safety

Once all motors could move in synch, the next step was to add safety features. This is the first step that diverges from the original control. This safety feature is designed to protect the robot from trying to drive into itself. Under the normal control scheme, the sensors were only used to home the robot for point-based control. This change guarantees that if the sensor is tripped the command to that motor(s) will be inhibited in the unsafe direction. This has led to a new questionable feature for the arm motor. Namely if the arm retracts back into its sensor, it will stop and then bounce off, which leads to sporadic motion. To get around this a denounce timer was added just for the arm sensor to make the motion smoother when trying to home that motor.

Graphical User Interface Development: HMI Work

To support easier control of the robot, a Factory Talk HMI has been coded. This HMI supports jog functionality and the ability to see the state of corresponding sensors. This has not been loaded onto the panel view and has only been tested on a connected laptop. A quick layout of the buttons and indicators can be seen below.

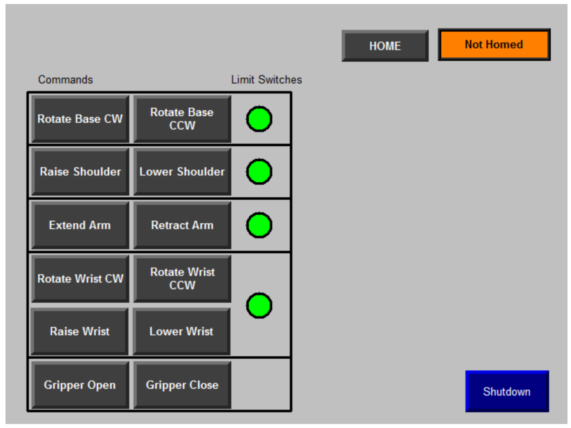


Figure 9 HMI normal and Homed Conditions

For all indicators and buttons all possible states are shown in the following tables (tables 6, 7 and 8)

Table 6 Sensor States

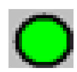
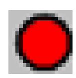
Sensor states	
State	***Display***
good	
tripped	

Table 7 HMI Button States

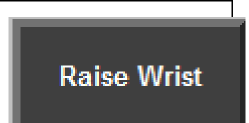
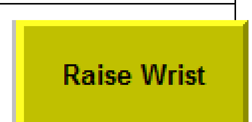
Button states	
State	***Display***
Normal	
Pressed	

Table 8 Homed States

Homed States

State	***Display***
Start up	Not Homed
Homing Shoulder	Homing Shoulder
Homing Arm	Homing Arm
Homing Wrist	Homing Wrist
Homing Base	Homing Base
Homing Gripper	Homing Gripper
Homed	Homed

Project Assessment Criterion

The assessment was based on meeting project milestone set by the instructor. The assement component include evaluation by the project advisor and a project committee. This capstone project was assessed based on the following rubric points:

- Run sample lab assignments without using PLC integration for better understanding of the robot functions.
- Identify all the sensors, actuators, and wring diagrams of the robot.
- Integrate sensors, actuators of the robot to PLC I/O cards.
- Give sample demo to the class and Master's project committee members on robot motion control using PLC program and HMI interface
- Give a formal presentation to the project committee members and class.
- Submit a formal project report to the advising faculty members

Table 9 summarizes the weightage of points when grades were assigned to students.

Table 9 Assessment Weightage Points

Skill Check	Weighted Percentage	Student's Average score
Operate the Robot without PLC	20%	19/20
Demo of controlling the robot using PLC program and HMI interface	30%	28/30
Formal presentation of the project to committee members	25%	24/25
Submit the formal project report	25%	24/25

The average score was 95% and that is why the success rate was 100%. At the conclusion of the course, the instructor managing the capstone projects conducts a student survey of the projects. The comments from the students on this project were very positive. Also, it was evident during the course of the semester, the students were very engaged and completed all tasks on time.

Conclusions and Future Work

A framework is provided for a hands-on project to reinforce the critical concepts of PLC integration in real world situations. The main objective is to introduce industrial PLC control methods through PLC integration with robot motion control to ECE graduate students and was implemented as a pilot project in one of the graduate capstone courses. Traditionally, ECE Engineering undergraduate and graduate students take quite a few electrical, electronics and theory-based control classes but are seldom exposed to PLCs which are the main backbone of industrial controls. To fill this gap and reinforce the use of all electronics and controls skills, this PLCs integration with robot arm and required software were included in this capstone course. SPLCs, motors, sensors and drives are used in every automation process, so reviewing and integrating these methods in courses ensure that students will be ready to handle real world problems after they graduate and work in industry.

This pilot PLC and robotics integration exploratory capstone project was introduced in the ECE program for the first time. The project generated considerable interest amongst students. A methodical approach is outlined in this paper for possible use by other ECE programs. The approach integrates theory, hardware integration along with software development to provide students with a comprehensive learning experience. The student feedback was very good and success rate was 100%. The future work will be to offer this capstone course in coming years for graduate students with different set of objectives that still require PLC integration skills.

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