Design and Development of a Sensor/Actuator Module to Enhance Programmable Logic Controller (PLC) Laboratory Activities

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1. Abstract

In industry, Programmable Logic Controllers (PLCs) are used to automate industrial processes or machines [1]. Typically, the processes or machines being automated perform a series of steps that require the activation of actuators based on feedback from sensors. PLCs are programmed to carry out these steps or sequences [2]. To effectively teach students how to automate a process or machine using a PLC, an apparatus with a set of actuators and sensors that interact with each other is needed. This paper presents the design and development of a compact Sensor/Actuator Module to be used with an existing PLC trainer. The module will expose the students to four different sensor types that interact with a pair of DC motors with bi-directional drive. The sensor types include inductive proximity, capacitive proximity, retroreflective photoelectric, and through-beam (opposed) photoelectric.

2. Introduction

ENGR 382 SCADA Systems Design is an upper-division course taught to students in the Engineering Department as an elective or required course, depending upon the program. The following are the course learning outcomes:

1. Understand common Industrial Automation concepts, methods, and control algorithms.
2. Understand sensors and actuators used in Industrial Automation tasks.
3. Design Piping & Instrumentation Diagrams (P&IDs) for simple process systems.
4. Understand Programmable Logic Controller (PLC) components, signal interface methods, and applications.
5. Design and write PLC control programs. Recognize other control program language formats defined in the IEC 61131-3 standard.
6. Design and program suitable Human Machine Interface systems.
7. Understand of common industrial networking topologies, protocols, and hardware.

Most of the laboratory activities for ENGR 382 involve programming a programmable logic controller (PLC) that is part of a PLC Trainer. The PLC Trainer only has switches and one analog sensor as input devices and relays and LEDs as output devices (see Figure 1). While these are sufficient input/output devices for learning about PLC programming, the laboratory experience could be enhanced with a set of sensors and actuators that interact with each other.

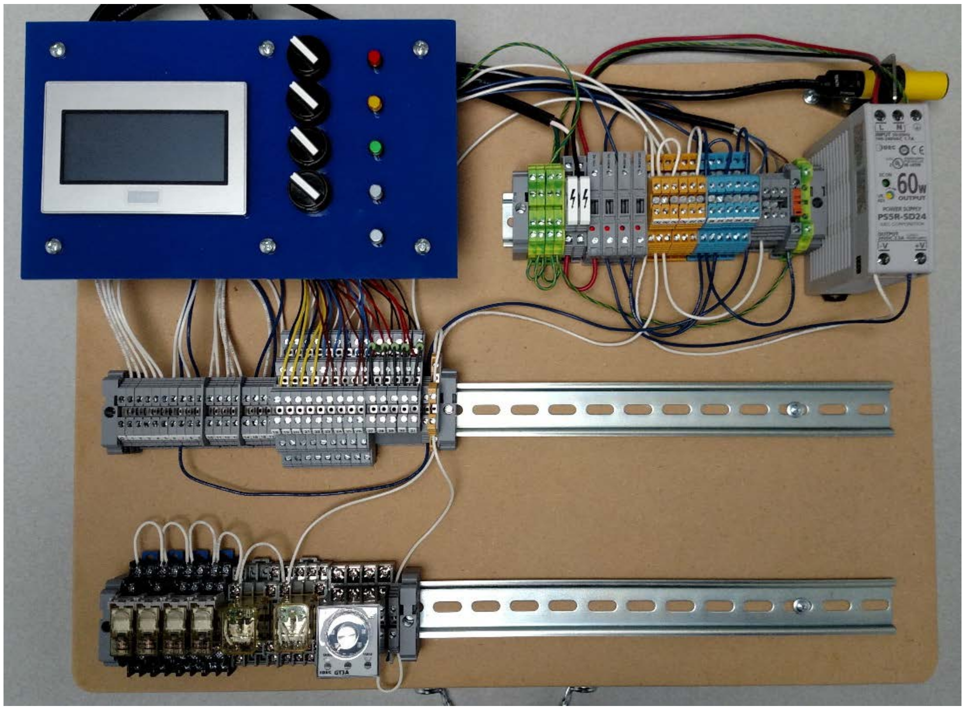

Figure 1: PLC Trainer with IDEC PLC

This paper presents the design and development of a Sensor/Actuator Module to be used with the existing PLC trainer. To provide a better learning experience for the students, the module was designed to have actuators with motion and sensors that interact with the actuators.

The actuators are two DC motors with bidirectional control that each have an aluminum disk with a hole. Four different sensors were selected (two for each disk): inductive proximity sensor, capacitive proximity sensor, through-beam photoelectric sensor, and retroreflective photoelectric sensor. Each sensor uses different methods of detecting either the hole or the absence of the hole.

The two bidirectionally driven motors and four sensors in the module enable the module to be used in several laboratory activities that explore the behavior of the sensors, programming of sequences and loops, exploring timers and counters, and so on. While these sensors are discussed in the lecture and the students see samples of the sensors, being able to use the sensors in a system will enhance their understanding of the sensors.

3. Existing PLC Trainer

The PLC trainer that is used for laboratory activities is custom designed and built (see Figure 1). The PLC used in the trainer is the IDEC FT1A SmartAXIS Touch [3] that includes a human machine interface (HMI) with a color touch screen. The PLC has eight sinking digital inputs, four sourcing digital transistor outputs, two analog inputs, and two analog outputs.

The input devices include four two-position selector switches, five momentary push buttons, and an analog ultrasonic distance sensor. The output devices include five LEDs (inside the momentary push buttons), six relays, and a timer relay.

A 24 V DC, 60 W power supply powers all devices on the trainer.

All PLC inputs, PLC outputs, switches, push buttons, LEDs, the ultrasonic sensor, 24 V DC, and ground are connected to terminal blocks. All relays are mounted in sockets with screw terminals. Each PLC trainer includes a kit of wire jumpers terminated with ferrules and screw drivers so that students may build the circuits needed for the laboratory activities.

4. Module Requirements

The following are the requirements for the Sensor/Actuator Module.

1. The module must contain sets of actuators and sensors that interact with each other.
2. The module must contain a variety of sensor types.
3. The actuators must provide motion as their output.
4. The speed of motion of the actuators must be slow enough that a person may observe changes in the states of the sensors that interact with the actuators.
5. The actuators and sensors must be powered with 24 V DC.
6. The module will receive power from the PLC Trainer.
7. The power requirement of the module must not exceed the capability of the PLC Trainer.
8. The module must have a wiring harness long enough to connect it to the PLC Trainer.
9. The actuator inputs must be of the sinking type.
10. The sensor outputs must be of the sourcing type.
11. The footprint of the module must fit within 12 in X 12 in (304.8 mm X 304.8 mm).
12. The enclosure for the module must be clear so that the components are visible.
13. The relays and terminal blocks must be DIN rail mount.
14. The sensors must be cylindrical with the same diameter.

5. Component Selection

5.1 Actuators

Each motor has an aluminum disk with a hole in it. The motor/disk combination provides visible motion at a low speed as well as providing a means of interaction with non-contact sensors. The module will have inputs to allow each motor to be driven clockwise or counterclockwise using a set of relays. The relay consumes 400 mW.

Each motor/disk combination has two sensors that interact with it. For the left combination, proximity sensors were selected: inductive proximity and capacitive proximity. For the right combination, photoelectric sensors were selected: retroreflective and through-beam.

The motor/disk combination satisfies requirements 1., 3., 4., 5., 7., 9., 11., and 13.

See Appendix A for the detailed electrical design and Appendix B for the detailed mechanical design.

5.1.1 DC Gear Motor

The motor selected for the module is a Zhengke 24 V DC, 5 rev/min gear motor, model ZGA37RG 627i [4] (see Figure 2). The motor has a diameter of 37 mm, is 63.8 mm long (not including output shaft or terminals), and consumes 1.9 W (no load). The module contains two of these motors.

Figure 2: DC Gear Motor (uXcell)

5.1.2 Relay

The relay selected for the module is a TE Connectivity DPDT (double pole double throw) relay model RT4S4LC4 [5] (see Figure 3). The relay coil is rated for 24 V DC and consumes 400 mW. The module contains four relays (two per motor).

Figure 3: Relay (TE Connectivity)

5.2 Sensors

All the sensors are non-contact type with two of them being proximity sensors and the other two being photoelectric sensors. All the sensors are cylindrical, have a diameter of 18 mm, and are powered by 24 V DC.

The sensors satisfy requirements 1., 2., 5., 7., 10., 11., and 14.

5.2.1 Inductive Proximity Sensor

The AutomationDirect PBK-AP-2H inductive proximity sensor [6] has an 8 mm sensing distance and consumes 360 mW (see Figure 4).

Figure 4: Inductive Proximity Sensor (AutomationDirect)

An inductive proximity sensor senses ferrous and non-ferrous metals [7]. This sensor has a normally open output, so the output is on when it senses metal. Thus, the sensor output will be off when the hole in the disk is in line with the sensor.

5.2.2 Capacitive Proximity Sensor

The AutomationDirect CK2-CP-1H capacitive proximity sensor [8] has an 8 mm sensing distance and consumes 530 mW (see Figure 5).

Figure 5: Capacitive Proximity Sensor (AutomationDirect)

A capacitive proximity sensor senses metals and non-metals [7]. This sensor has a normally closed output, so the output is off when it senses metal. Thus, the sensor output will be on when the hole in the disk is in line with the sensor.

5.2.3 Photoelectric Retroreflective Sensor

The AutomationDirect FBP-DP-0E retroreflective sensor [9] has a 2.5 m sensing distance and consumes 480 mW (see Figure 6).

Figure 6: Retroreflective Sensor and Retroreflector (AutomationDirect)

A retroreflective sensor emits light that is reflected back to it by a retroreflector [7]. This sensor has a dark-on output, which means that its output is on when the light beam is broken by an object that is between the sensor and the retroreflector. Thus, the sensor output will be off when the hole in the disk is in line with the sensor.

5.2.4 Photoelectric Through-Beam Sensor (Emitter and Receiver)

The AutomationDirect FBE-00-0E through-beam emitter [10] and FBR-LP-0E through-beam receiver [11] have an 8 m sensing distance and each consumes 190 mW (see Figure 7).

Figure 7: Through-Beam Emitter and Receiver (AutomationDirect)

A through-beam (also called opposed) sensor system consists of an emitter that emits light and a receiver that senses the light [7]. The emitter and receiver are mounted facing each other. This receiver has a light-on output, which means that its output is on when the light beam is not broken. Thus, the sensor output will be on when the hole in the disk is in line with the sensor.

6. System Definition

The Sensor/Actuator Module is connected to the PLC Trainer through a 24 in (610 mm) long wire harness from the module. Figure 8 shows the context diagram.

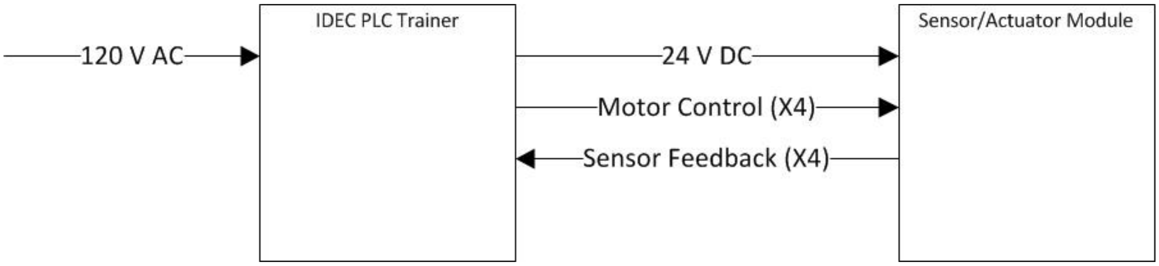

Figure 8: Context Diagram

The module's system definition satisfies requirements 1., 6., and 8.

The system diagram (see Figure 9) for the module shows the electrical connections for power, inputs, and outputs. A total of ten wires must be connected to the PLC Trainer.

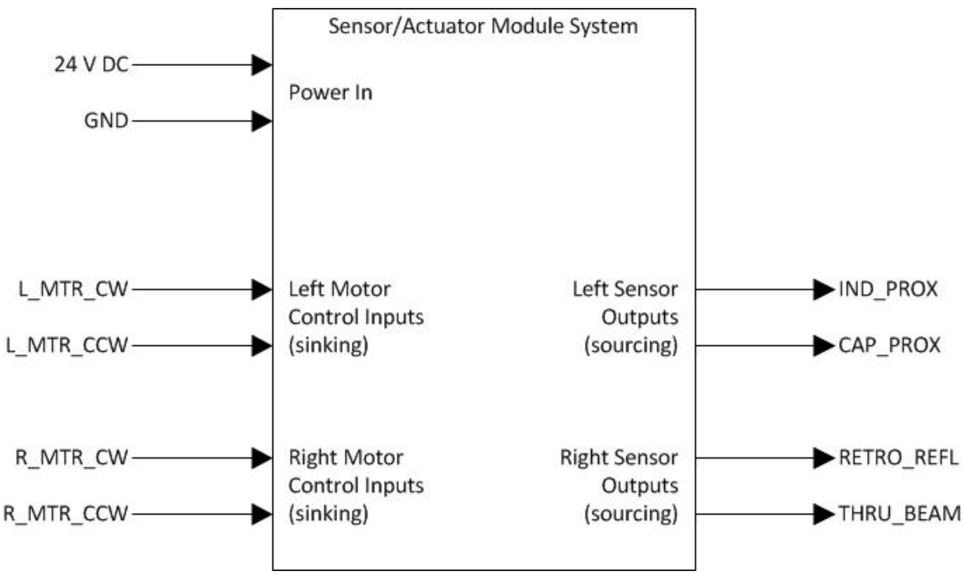

Figure 9: System Diagram for the Sensor/Actuator Module

The system architecture consists of two subsystems; one for each motor/sensor combination (see Figure 10).

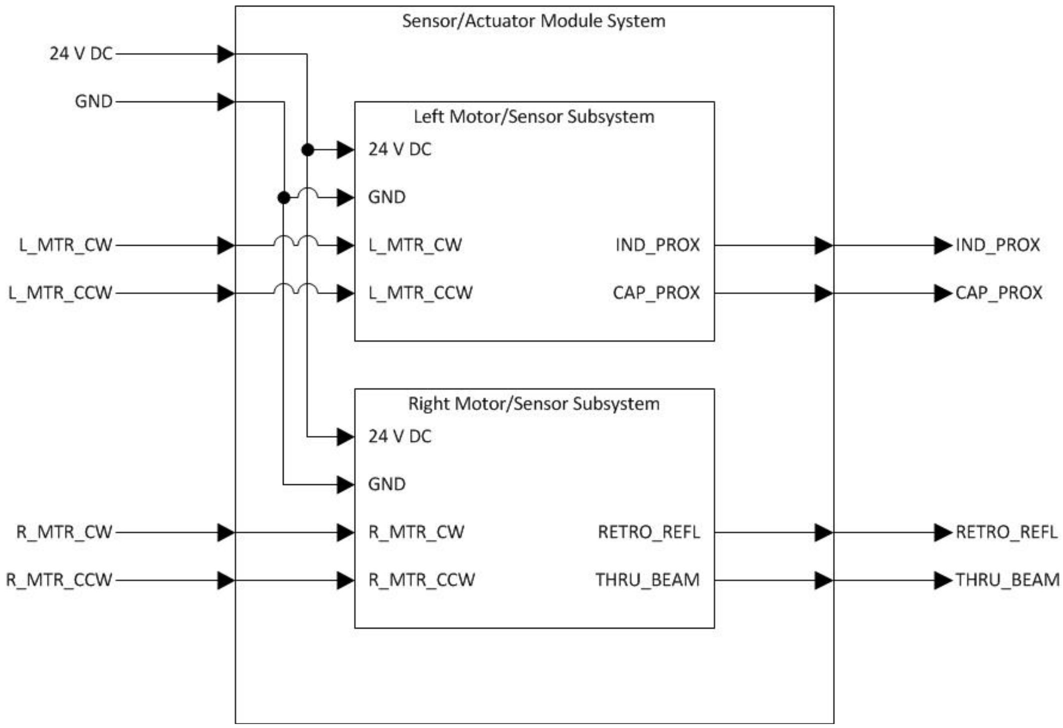

Figure 10: System Architecture

Figures 11 and 12 show how each subsystem is further divided.

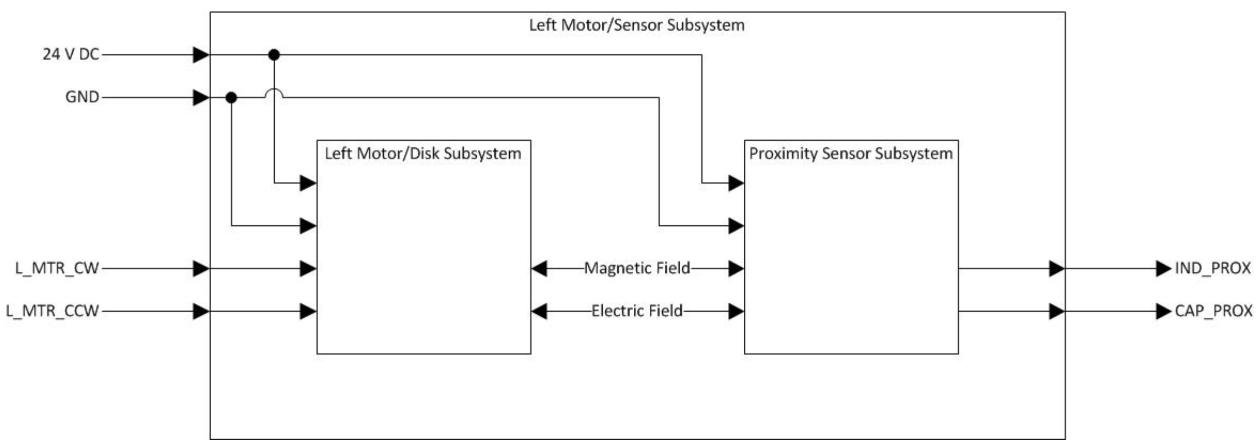

Figure 11: Left Motor/Sensor Subsystem

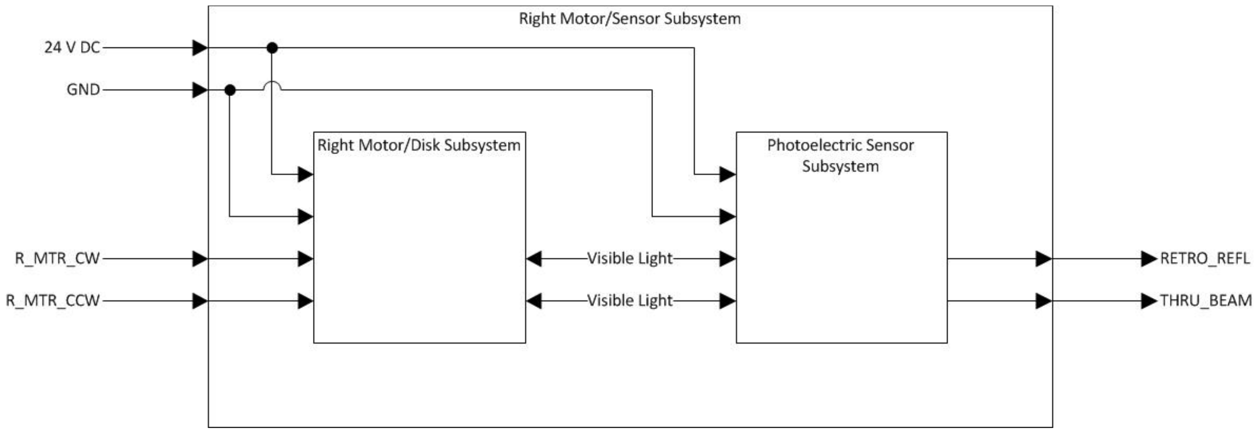

Figure 12: Right Motor/Sensor Subsystem

The detailed electrical design is found in Appendix A and the detailed mechanical design is found in Appendix B.

7. Assembled Module

Figures 13 to 15 show an assembled module without the wiring harness attached. Note that the plates seen in the figures are earlier versions that have additional holes that have since been removed. The footprint of the module is 8 in X 10 in (203 mm X 254 mm).

The mechanical design satisfies requirements 11. and 12.

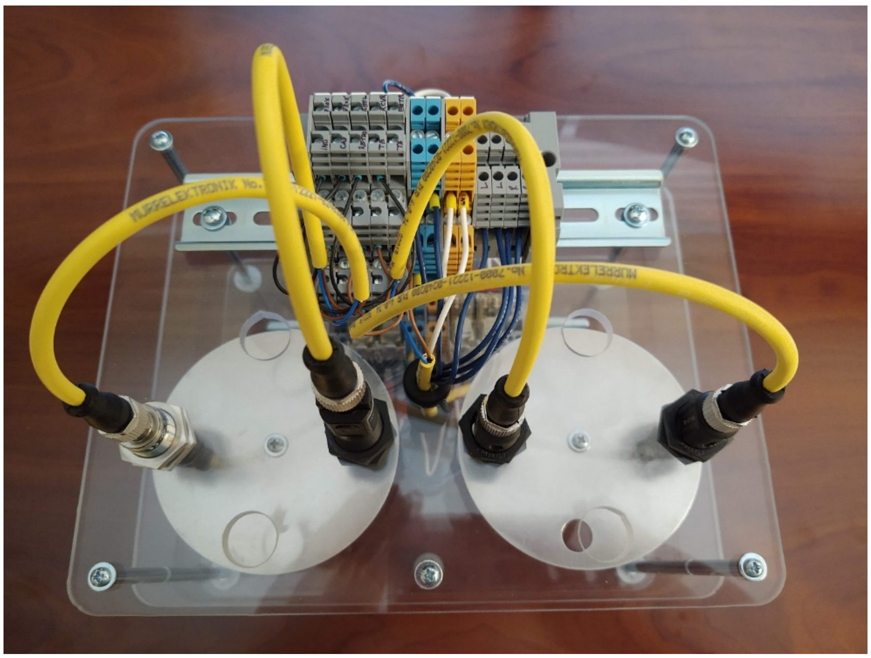

Figure 13: Top View

Figure 13 shows the top plate of the module with terminal blocks that provide connections for the wiring harness going to the PLC trainer. All sensor components, except for the retroreflector and through-beam emitter, are mounted to the top plate.

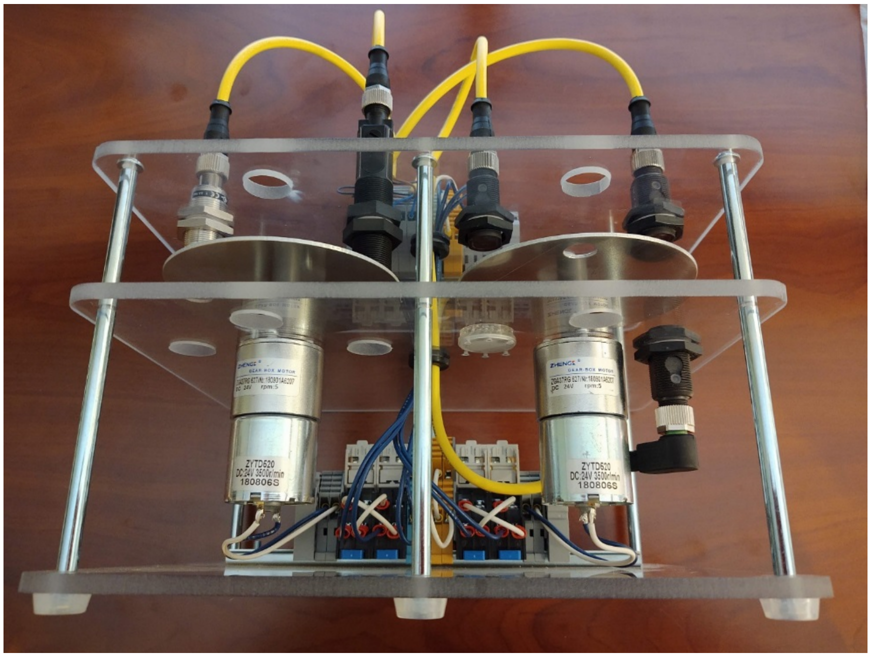

Figure 14: Front View

Figure 14 shows the motors, retroreflector, and through-beam emitter are mounted to the middle plate. The relays and terminal blocks for the motor connections are mounted to the bottom plate.

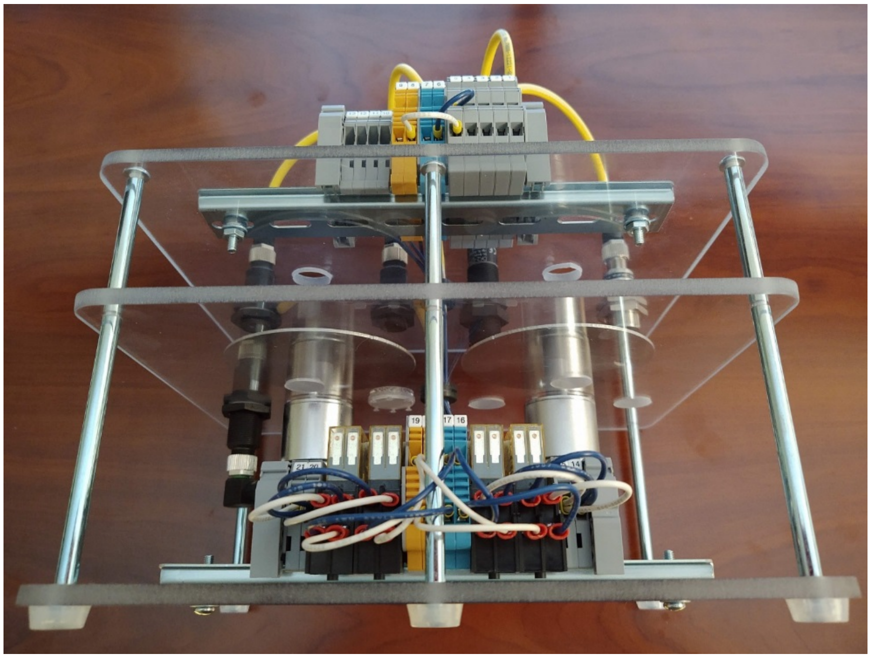

Figure 15: Rear View

The wiring harness that goes to the PLC Trainer (not shown) attaches to the terminal blocks on the top plate at the rear of the module (see Figure 15).

8. Laboratory Activities

The following are laboratory activities that use the PLC Trainer and Sensor/Actuator Module.

8.1 Sensor/Actuator Introduction

The objectives of the activity include:

1. Demonstrate the ability to find specifications on data sheets.
2. Demonstrate the ability to drive the motors with jog controls.
3. Determine the behavior of each sensor.
4. Create a schematic diagram of a simple automation system.

The students will perform the following in the activity:

1. Summarize relevant specifications for each sensor and actuator in the module.
2. Write a ladder logic program that has jog controls using the push buttons to manually drive each motor clockwise and counterclockwise. The program must provide monitoring of the sensor outputs.
3. Use the program to observe the behavior of the sensors with respect to the aluminum disk. They are to summarize the behavior.
4. Create a schematic diagram of the system (PLC, buttons, sensors, and actuators).

8.2 Sequential Programming and Looping

The objectives of the activity include:

1. Demonstrate the ability to create a sequential program to automate a set of steps.
2. Demonstrate the ability to make a sequential program loop.
3. Produce a well-documented program.

The students will perform the following in the activity:

1. Write a sequential programming ladder logic program to implement the following steps: When the Start button is pressed, drive the left motor clockwise. When the hole in the left disk reaches the capacitive proximity sensor, drive the left motor counterclockwise. When the hole in the left disk reaches the inductive proximity sensor, stop the left motor and drive the right motor clockwise. When the hole in the right disk reaches the through-beam sensor, drive the right motor counterclockwise. When the hole in the right disk reaches the retroreflective sensor, stop the right motor. Pressing the Stop button must stop any step. All rungs must be commented.
2. Convert the previous program into a looping program. Remove the Done step. All rungs must be commented.

8.3 Counters

The objectives of the activity include:

1. Demonstrate the ability to create a basic human machine interface (HMI) for a control system.

2. Demonstrate the ability to use adding counters.
3. Demonstrate the ability to use up/down counters.
4. Demonstrate the ability to use data comparisons.

The students will perform the following in the activity:

1. Design an HMI screen and write a ladder logic program to drive the left motor clockwise for five revolutions and then drive the right motor counterclockwise for three revolutions. Use counters to determine the number of revolutions based on sensor feedback. The HMI must show the current counts for the two counters. Use sequential programming and the buttons of your choice for start and stop actions. All rungs must be commented.
2. Design an HMI screen and write a ladder logic program to drive one of the motors clockwise or counterclockwise while keeping track of the number of revolutions. Driving clockwise must increment the count while driving counterclockwise must decrement the count. Use a counter capable of counting up and down. Stop the motor if the count reaches zero or ten (use comparison operators). All buttons must be implemented through the HMI and the screen must display the current count. All rungs must be commented.

8.4 Timers

The objectives of the activity include:

1. Demonstrate the ability to create a human machine interface (HMI) with multiple screens.
2. Demonstrate the ability to use timers.
3. Demonstrate the ability to use math operations.

The students will perform the following in the activity:

1. Design HMI screens and write a ladder logic program to drive one of the motors and determine the speed of the motor using sensor feedback and a timer. One HMI screen will allow the user to set the number of revolutions to run the motor for a test. The other HMI screen will start or abort the test and display the current time and current revolution counts along with the speed.

9. Conclusion

All of the requirements for the module have been met by the design. Labs have been designed to use the module that give students experience with inductive proximity, capacitive proximity, retroreflective photoelectric, and through-beam photoelectric sensors; motors with bidirectional drive; basic ladder logic programming, sequential programming, looping, counters, and timers.

The module could be used with laboratory activities that require more advanced sequences, programming (such as subroutines or jumps), or HMIs. Numerous combinations of behavior are possible given that there are two sets of actuators with sensors and each bidirectional actuator has two sensors providing feedback.

The module, which has motion, should prove more interesting to work with over the current PLC Trainer alone which only has relays and LEDs.

10. Future Work

Create additional laboratory activities as suggested in the conclusion.

Explore other types of non-contact sensors that could be added to the module to provide an even greater experience for the students.

Appendix A

Detailed Design – Electrical

The following are the schematic diagrams of subsystems in the module. The behavior of each subsystem is described.

Actuators

Figures A.1 and A.2 show the schematic diagrams for the left and right motor/disk subsystems.

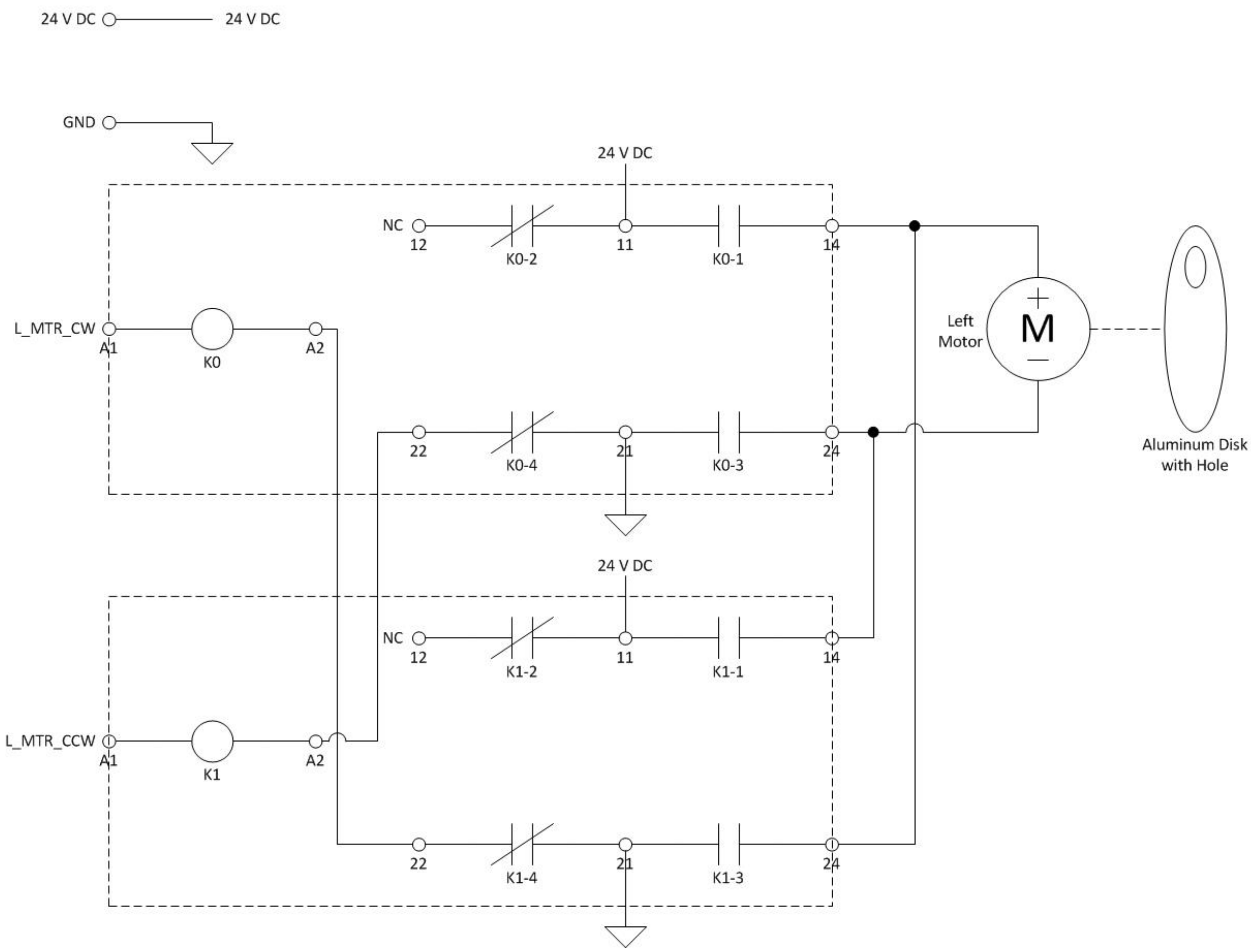

Figure A.1: Left Motor/Disk Subsystem Schematic Diagram

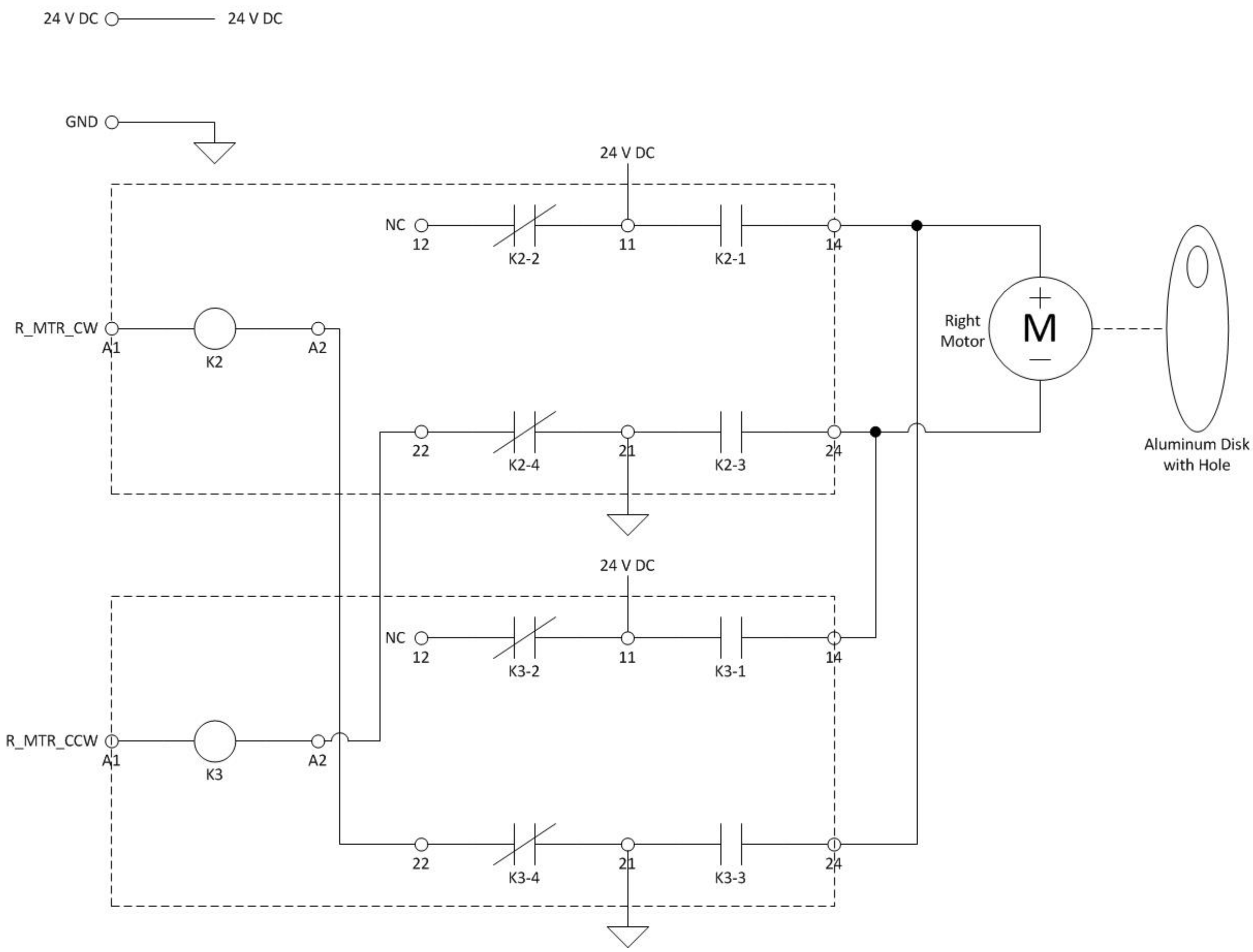

Figure A.2: Right Motor/Disk Subsystem Schematic Diagram

The two subsystems have identical designs. Two DPDT (double pole double throw) relays are connected in an interlocking fashion so that if both the CW (clockwise) and CCW (counterclockwise) control lines are energized at the same, the power supply will not be shorted out.

The two control lines permit bidirectional control of the motor, which is attached to an aluminum disk with a hole in it. Each disk has two different types of sensors that interact with it.

Sensors

Figures A.3 and A.4 show the schematic diagrams for the proximity and photoelectric sensor subsystems.

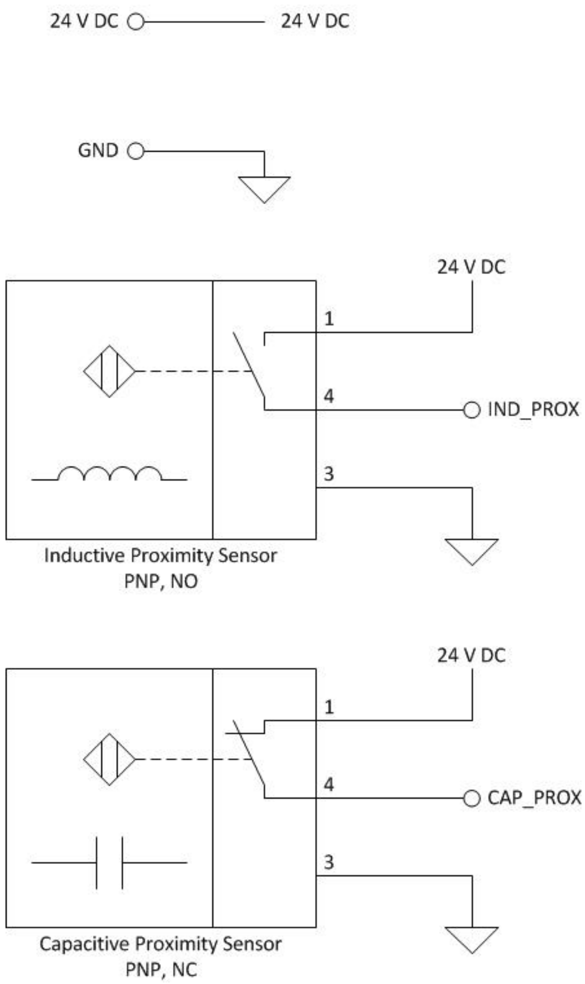

Figure A.3: Proximity Sensor Subsystem Schematic Diagram

Both sensors have PNP (sourcing) outputs.

The inductive proximity sensor is normally open and senses metallic objects with a magnetic field.

The capacitive proximity sensor is normally closed and senses both metallic and nonmetallic objects with an electric field.

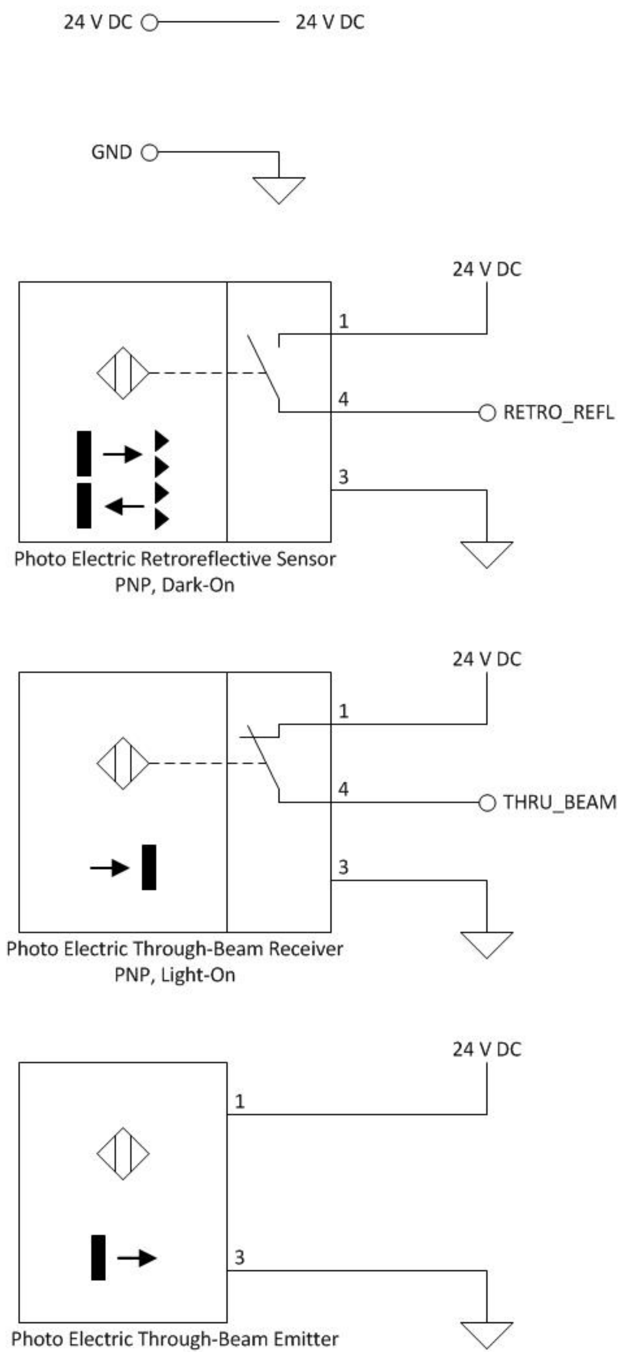

Figure A.4: Photoelectric Sensor Subsystem Schematic Diagram

Both sensors have PNP (sourcing) outputs and produce visible light.

The retroreflective sensor is the dark-on type and has a retroreflector positioned opposite of the sensor. Light is reflected to the sensor while the hole in the disk is lined up with the sensor.

The through-beam sensor has two components: a receiver that is the light-on type and an emitter. The receiver and emitter are positioned opposite of each other. Light falls on the receiver while the hole in the disk is lined up with the emitter and receiver.

Appendix B

Detailed Design – Mechanical

Figure B.1 shows the motor coupling that attaches the motor disk to the motor output shaft. The coupling is produced on a 3D printer.

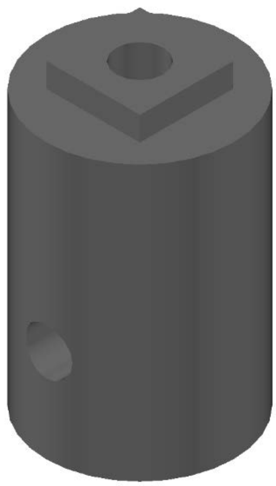

Figure B.1: Motor Coupling

Figure B.2 shows the motor disk that the sensors interact with. The disk is made of 0.063-in thick 6061 aluminum and is cut out on a waterjet. The disk has a diameter of 4 in (102 mm) and the hole has a diameter of 0.5 in (13 mm).

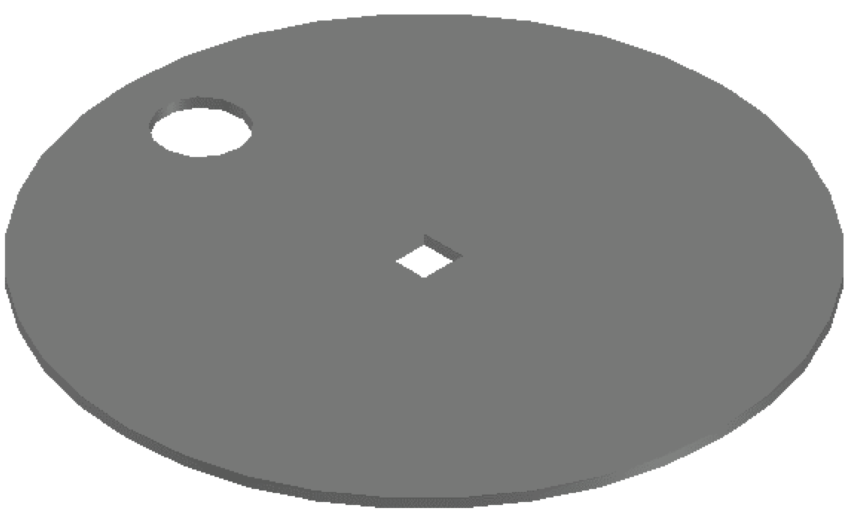

Figure B.2: Motor Disk

Figures B.3 to B.5 show the top, middle, and bottom plates. The plates are made of 0.25-in thick acrylic and can be cut out on a waterjet, laser engraver, or CNC mill.

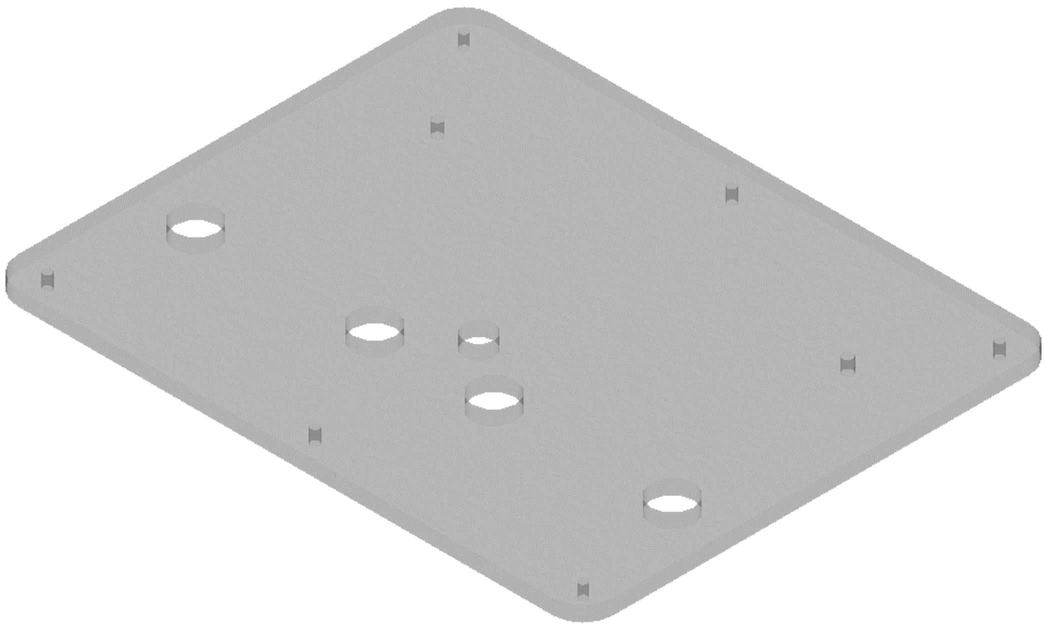

Figure B.3: Top Plate

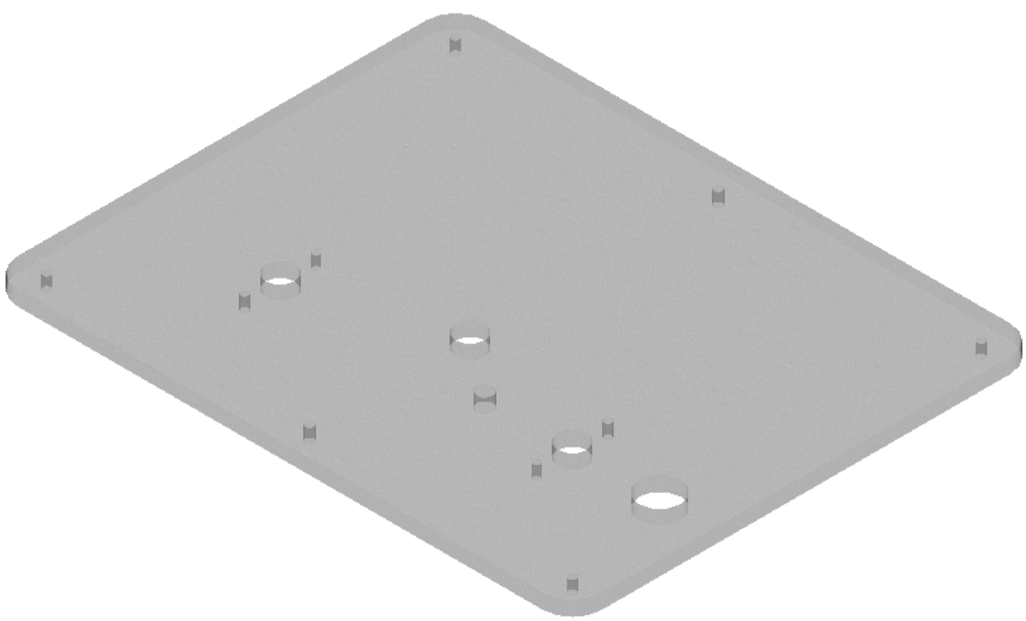

Figure B.4: Middle Plate

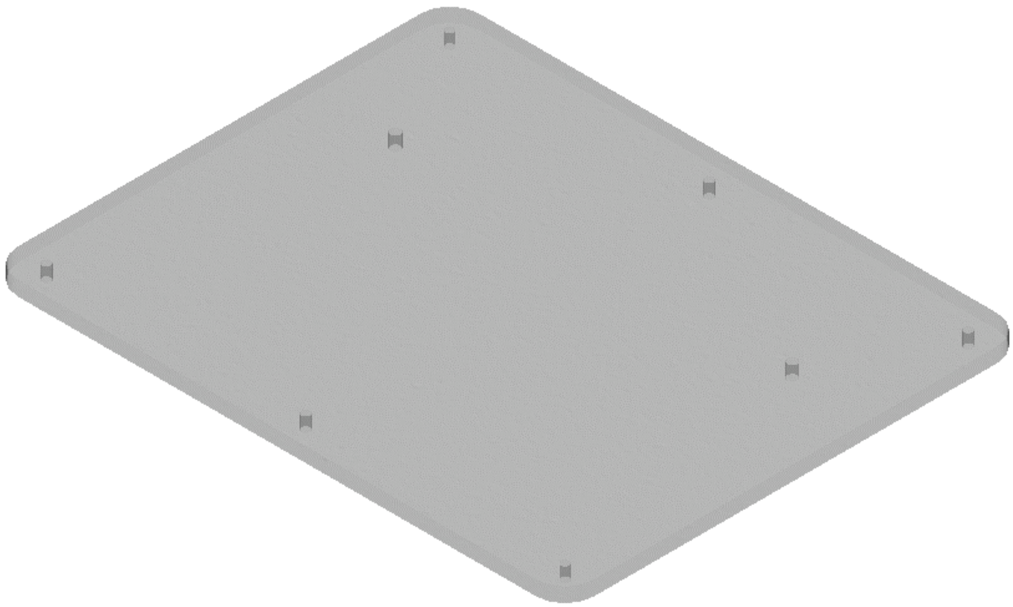

Figure B.5: Bottom Plate

Appendix C

The following figures show the ladder logic programs for the laboratory activities. For brevity, only programs for the first two laboratory activities are included.

Figure C.1: Ladder Logic Program for Sensor/Actuator Introduction

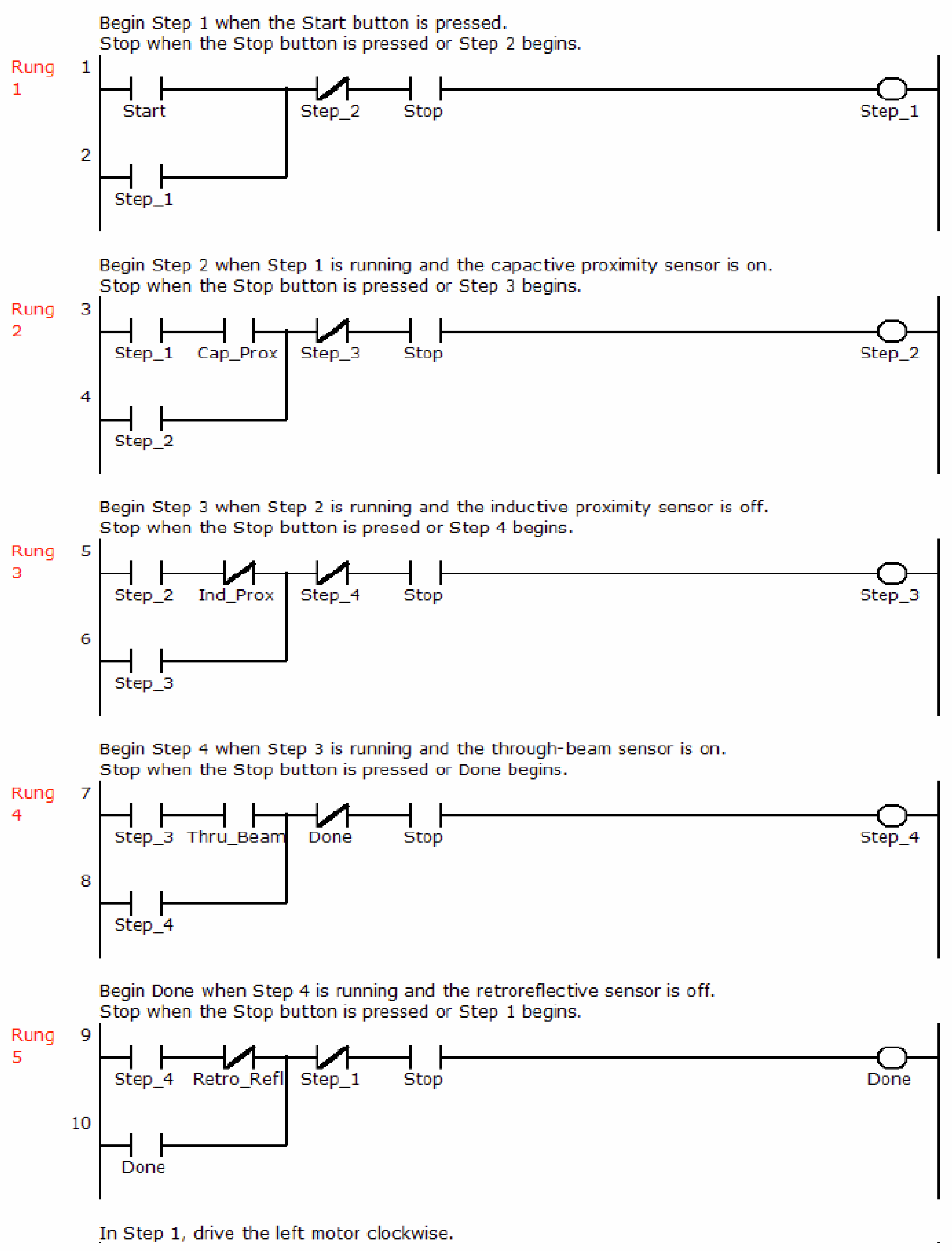

Figure C.2.a Ladder Logic Program for Sequential Programming

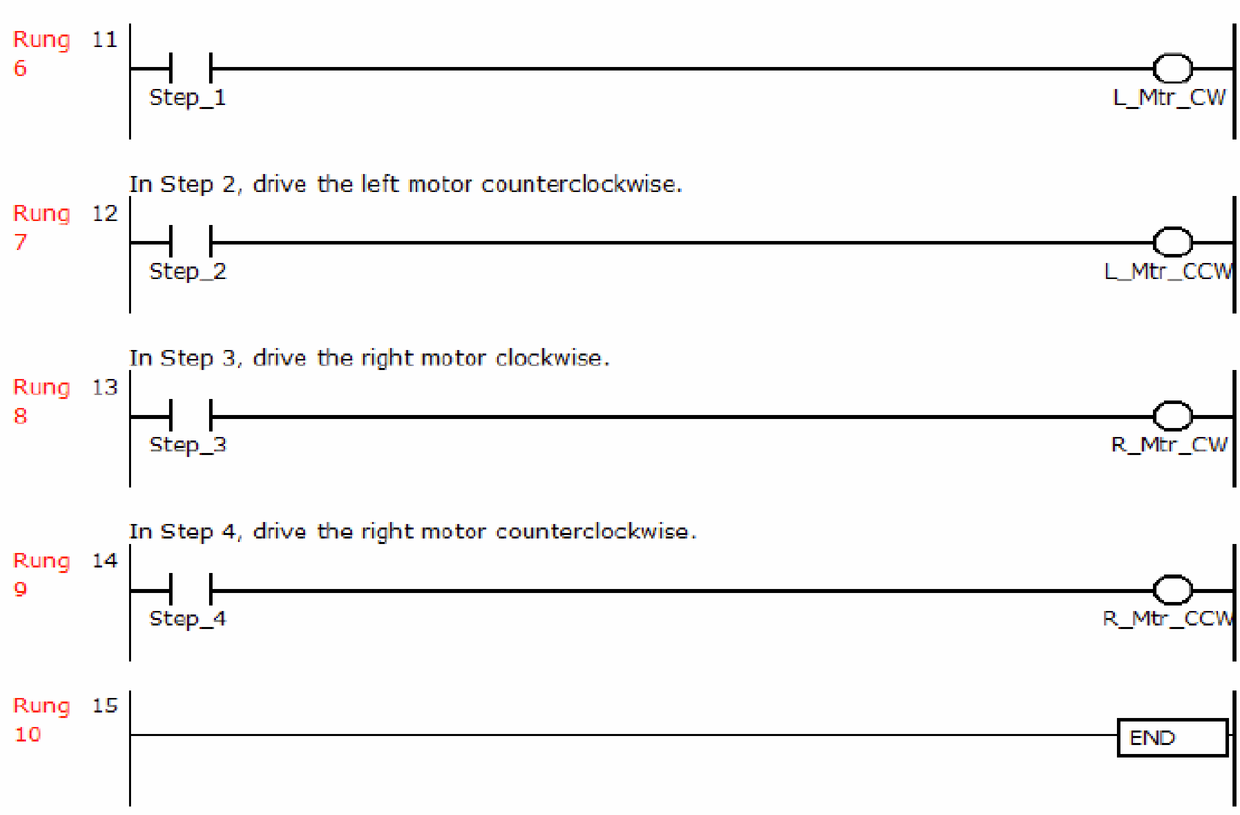

Figure C.2.b Ladder Logic Program for Sequential Programming

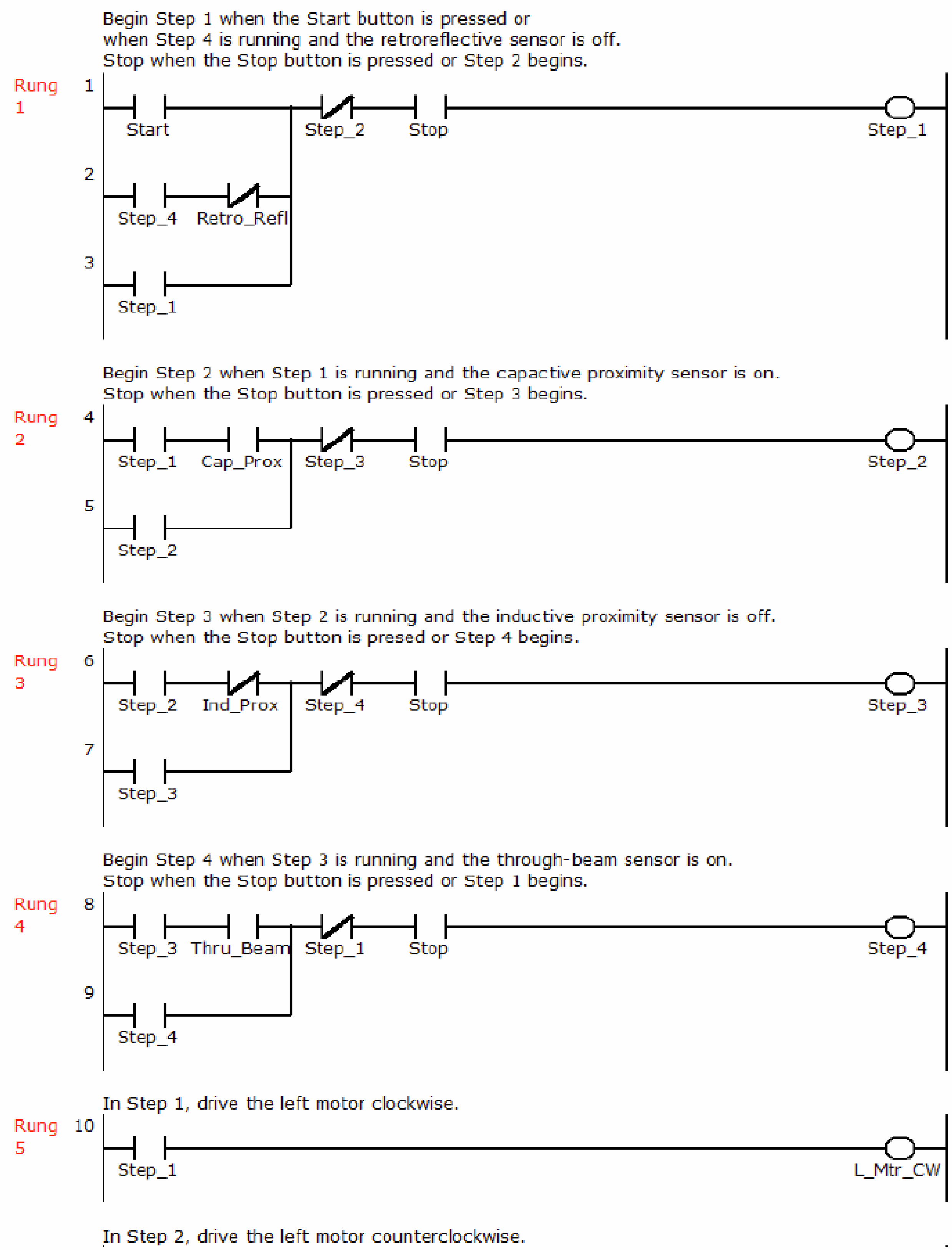

Figure C.3.a Ladder Logic Program for Looping

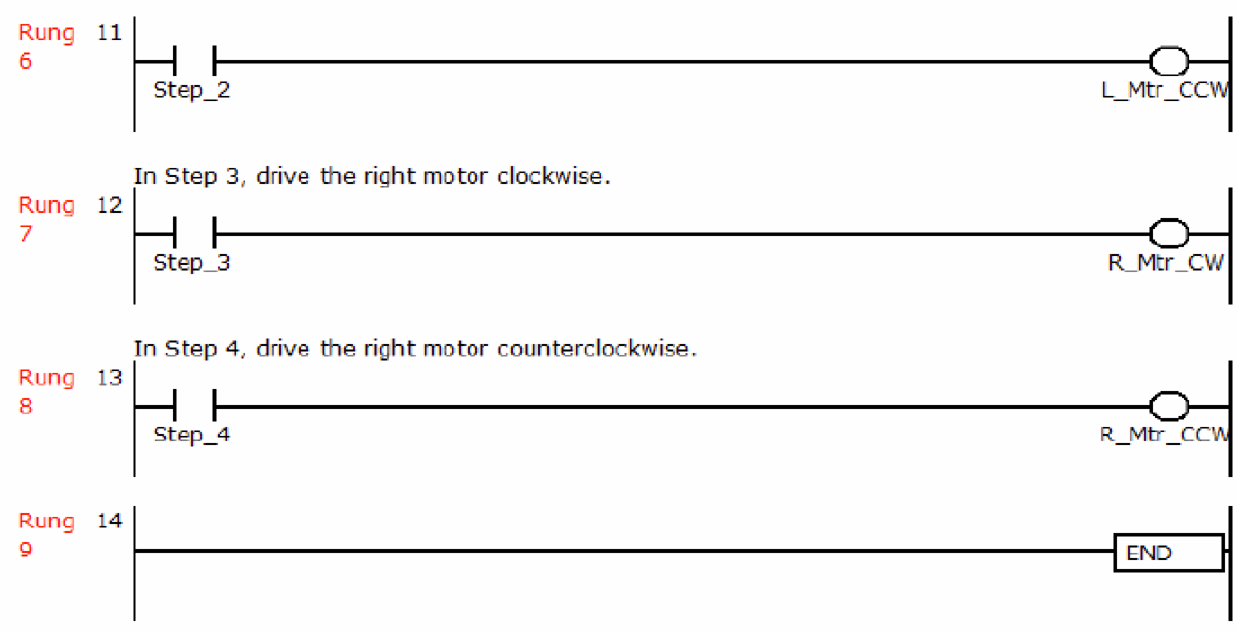

Figure C.3.b Ladder Logic Program for Looping

References

[1] J. Rehg and G. Sartori, *Programmable Logic Controllers, Second Edition*. Upper Saddle River, NJ: Pearson Prentice Hall, 2009.

[2] J. Stenerson, *Fundamentals of Programmable Logic Controllers, Sensors, and Communications, Third Edition*. Upper Saddle River, NJ: Pearson Prentice Hall, 2004.

[3] "SmartAXIS Touch," *IDEC*. [Online]. Available: http://us.idec.com/Catalog/ProductSeries.aspx?SeriesName=10_SmartAXIS_Touch &FamilyName=40_PLC_HMI. [Accessed: 02-Feb-2020].

[4] "ZGA37RG: ZGB37RG," *Zhejiang Zhengke Electromotor Co., Ltd*. [Online]. Available: https://www.zhengkemotor.com/product/ zhengkemotor_product_Dc_Gear_Motor_37mm_ZGA37RG_ZGB37RG.html. [Accessed: 02-Feb-2020].

[5] "RT4S4LC4," *TE Connectivity*, 03-Jan-2018. [Online]. Available: https://www.te.com/ usa-en/product-1-1415073-1.html?q=RT4S4LC4&source=header. [Accessed: 02-Feb-2020].

[6] "PBK-AP-2H," *AutomationDirect*. [Online]. Available: https://www.automationdirect.com/adc/shopping/catalog/sensors_-z-_encoders/ inductive_proximity_sensors/18mm_round_industrial_automation/standard_sensing_(18mm)/ pbk-ap-2h. [Accessed: 02-Feb-2020].

[7] T. Bartelt, Industrial Automated Systems: Instrumentation and Motion Control. Clifton Park, NY: Delmar, 2011.

[8] "CK2-CP-1H," *AutomationDirect*. [Online]. Available: https://www.automationdirect.com/adc/shopping/catalog/sensors_-z-_encoders/ capacitive_proximity_sensors/18mm_round_industrial_automation/ck2-cp-1h. [Accessed: 02-Feb-2020].

[9] "FBP-DP-0E," *AutomationDirect*. [Online]. Available: https://www.automationdirect.com/adc/shopping/catalog/sensors_-z-_encoders/ photoelectric_sensors/18mm_round_-_nonmetal/polarized_retroreflective_(ss_-z-_fa _-z-_fb_series)/fbp-dp-0e. [Accessed: 02-Feb-2020].

[10] "FBE-00-0E," *AutomationDirect*. [Online]. Available: https://www.automationdirect.com/adc/shopping/catalog/sensors_-z-_encoders/ photoelectric_sensors/18mm_round_-_nonmetal/through_beam_(ss_-z-_fa_-z-_fb_series)/ fbe-00-0e. [Accessed: 02-Feb-2020].

[11] "FBR-LP-0E," *AutomationDirect*. [Online]. Available: https://www.automationdirect.com/adc/shopping/catalog/sensors_-z-_encoders/ photoelectric_sensors/18mm_round_-_nonmetal/through_beam_(ss_-z-_fa_-z-_fb_series)/ fbr-lp-0e. [Accessed: 02-Feb-2020].