12-2009

THE DEVELOPMENT OF A MECHATRONICS AND MATERIAL HANDLING COURSE: LABORATORY EXPERIMENTS AND PROJECTS

James Shirley
Clemson University, jrshirl@gmail.com

Recommended Citation
Shirley, James, "THE DEVELOPMENT OF A MECHATRONICS AND MATERIAL HANDLING COURSE: LABORATORY EXPERIMENTS AND PROJECTS" (2009). *All Theses*. 673.
https://tigerprints.clemson.edu/all_theses/673

THE DEVELOPMENT OF A MECHATRONICS AND MATERIAL HANDLING COURSE: LABORATORY EXPERIMENTS AND PROJECTS

A Thesis
Presented to
the Graduate School of
Clemson University

In Partial Fulfillment
of the Requirements for the Degree
Master of Science
Electrical Engineering

---

by
James Ralton Shirley III
August 2009

Accepted by:
Ian Walker, Co-Committee Chair
Randy Collins, Co-Committee Chair
John Wagner

ABSTRACT

Mechatronic systems integrate technologies from a variety of engineering disciplines to create solutions to challenging industrial problems. The material handling industry utilizes mechatronics to move, track, and manipulate items in factories and distribution centers. Material handling systems, because of their use of programmable logic controllers (PLC), PLC networks, industrial robotics, and other mechatronic elements, are a natural choice for a college instructional environment. This thesis offers insight and guidance for mechatronic activities introduced in a laboratory setting. A series of eight laboratory experiments have been created to introduce PLCs, robotics, electric circuits, and data acquisition fundamentals. In-depth case studies synthesize the technologies and interpersonal skills together to create a flexible material handling system.

Student response to the course and laboratory material was exceptional. A pre and post course questionnaire was administered which covered topics such as teamwork, human factors, business methods, and various engineering related questions. Quantitative scores resulting from these questionnaires showed a marked improvement by students, especially in regards to technical/engineering questions. The responses from students generally indicated an excitement about course material and a thorough understanding of the various syllabus topics. In this thesis, the multi-disciplinary mechatronics (and material handling systems) laboratory will be presented. An in-depth examination of each laboratory will be offered as well as the discussion of two material handling case studies. The Appendixes contain the PLC and robot code for a order fulfillment case study.

ACKNOWLEDGMENTS

I would like to extend my sincere thanks to Dr. E. Randolph Collins for his tremendous guidance and educational assistance. Without his help, my graduate studies at Clemson University would not have been possible. Also, I would like to thank Dr. John Wagner, who I worked closely with in developing this laboratory. Finally, I would like to thank Dr. Ian Walker whose willingness to work on my unique situation regarding the multidisciplinary committee structure was immensely helpful.

I would like to thank Harish Chaluvadi, Bharath Sridhar, Daniel Fain, and Curtiss Fox and the others affiliated with the Power Quality and Industrial Applications Laboratory for their advice, assistance, and occasional distraction.

Finally, thanks to my family and friends who have kept me going on this long journey.

TABLE OF CONTENTS

Table of Contents (Continued)

Page

LIST OF TABLES

Table Page

LIST OF FIGURES

List of Figures (Continued)

List of Figures (Continued)

Figure Page

List of Figures (Continued)

List of Figures (Continued)

Figure Page

CHAPTER ONE

INTRODUCTION

Mechatronic systems combine various engineering disciplines to create a synergistic operation. Often mechanical, industrial, electrical, and computer engineering skills must be combined to successfully create a mechatronic system. Industrial factories across America rely extensively on these systems and engineers that can incorporate them into a functioning cell. Due to the varied skills necessary, teams of engineers are employed to create these systems. One large task will be divided into many smaller units, each with its own team, making interpersonal skills, communication, and teamwork essential qualities of a successful mechatronics engineer.

The material handling and logistics industry is a $156 billion market [1] which encompasses the movement, control, and storage of products in both manufacturing and distribution environments. The industry utilizes the mechatronics field to achieve precise product movement.

Colleges and universities have been hesitant to incorporate this field into their curriculums due to a variety of reasons. Expensive equipment, dwindling laboratory space, few educational resources, and the breadth of multi-disciplinary topics are some of the obstacles that engineering programs must overcome in creating a course that effectively instructs students in mechatronics.

The presentation of mechatronic system concepts, within a material handling framework, allows practical classroom exercises, laboratory experiments, and design projects. The associated classroom materials introduce sensors, actuators, control theory, human factors, electric power, electronics, electric motor, and systems integration as encountered in typical manufacturing scenarios. Further, students learn and practice leadership, team building, collaborative learning, and project management skills to help accomplish the laboratory and project activities. A series of laboratory assignments have been developed for students to gain hands-on experience with electronics, programmable logic controllers, industrial robots, conveyors, instrumentation, and data acquisition. The initial exercises establish a basis to program and network multiple PLCs, command the movement of a robotic arm, and then integrate these elements into a smart conveyor system under automated control for product distribution. The remaining laboratory activities focus on electronic circuits, and vibration experiments with accompanying data acquisition and theoretical analysis. Lastly, a case study offers an open-ended multi-faceted opportunity to apply a robotic arm, conveyors, bar code reader, color sensor, and networked PLCs to accomplish the tasks of identification, sorting, and conveyor transport or to fulfill other material handling tasks.

This thesis thoroughly discusses the eight laboratory experiments and two case studies associated with the newly created Mechatronics and Material Handing Course at Clemson University. Chapter Two offers a detailed examination on six of the eight laboratory experiments, with a broad overview of an order fulfillment case study. Chapter Three discusses two separate laboratory experiments involving data acquisition techniques and equipment. Chapter Four focuses on the pedagogy of the course, and how the laboratory experiments are a building block for particular case studies. Chapter Five offers a summary and conclusion. The Appendix contains source code for the PLC software and Staubli Industrial Robotic arm utilized in the order fulfillment case study as well as the procedure for each laboratory exercise.

CHAPTER TWO

MECHATRONICS LABORATORY EXPERIMENTS AND CASE STUDY

Introduction

Modern industrial systems and components typically feature various sensors, actuators, and controllers integrated into complex configurations that incorporate skills from various engineering disciplines. To design and service this equipment, global companies often use engineering teams familiar with mechatronic system technologies (refer to Figure 2.1). Some of the key technical skills include mechanical, electrical, computer, and industrial engineering as well as control systems, computer simulation, robotics, and human factors. Although the term "mechatronics" may be widely applied to engineering systems, it certainly describes material handling processes which encompass the controlled movement of items through a define sequence of events. For example, different types of conveyor and robotic elements may be applied to transport materials, assemble components, and then move the finished goods within a manufacturing facility. Due to the prevalence of material handling systems and accompanying mechatronics expertise requirements, this industry segment may be emulated in a laboratory setting to offer students real world challenges. A fundamental understanding of various system components and their integration into a functional process is an important objective for laboratory accomplishments.

A number of universities have established classes and laboratories that focus on mechatronic systems. Khan [2] highlighted the importance of international abilities in mechatronics while discussing micro-controllers, programmable logic controllers (PLCs), transducers, and mechanical/manufacturing engineering. Merckel and Fisher [3] offered a two-week hands-on PLC experience at Rose-Hulman with two different laboratory demonstration stations. Chiou *et al.* [4] discussed an internet-based mechatronics course created at Drexel University that featured industrial robots, machine vision systems, PLC modules, webcams, and sensors. Lee and Park [5] utilized a computer controlled robotic laboratory in an undergraduate course at Purdue University to teach system integration concepts. Marsico [6] reported the availability of three Pennsylvania State University courses that covered fundamental topics in manufacturing, materials processing, and production design. Erickson [7] presented four scaled industrial processes at the University of Missouri-Rolla that featured robotic arms, conveyor assembly and inspection, pH neutralization, and operator interfaces. Stormont and Chen [8] discussed the use of mobile robots in a mechatronics course at the Utah State University. Ghone and Wagner [9] reviewed a multi-disciplinary mechatronics laboratory created at Clemson University which contained electronic circuits, PLCs, servo-motors, and pneumatic/hydraulic actuators. A materials handling system with robotic arm experiment was introduced by Bassily *et al.* [10] to accompany the existing mechatronic laboratory activities. Vermaak and Jordaan [11] summarized a mechatronics course at the Central University of Technology, Free State that focused on material handling systems with accompanying laboratory. Finally, the Material Handling Industry of America (MHIA) [12] periodically offers educational activities in collaboration with the College-Industry Council on Material Handling Education (CICMHE).

Today’s engineer must be able to function in a global industrial environment as a team member responsible for a product, process, or intellectual activity [13]. A multi-disciplinary mechatronics (and material handling systems) course was created that allows students to learn and experience mechatronics engineering within the context of material handling systems. This thesis describes the development of this course. As shown in Figure 2.1, mechatronics incorporates aspects from different engineering fields such that product teams are typically composed of many individuals. Consequently, contributing as a team member is crucial. In this course, students have an opportunity to review and practice personal skills through classroom activities, laboratory experiments, and design project. This chapter is organized as follows. An overview of classroom topics that provide the technical knowledge and skills needed to create a mechatronics system will be presented, as well as a description of six laboratory experiments which explore electronic circuits, PLC networks, and robotic/conveyor systems. An integrated material handling system environment which facilitates student design projects will be examined, and lastly, a summary is presented.

Classroom Topics

A multi-disciplinary mechatronics engineer should ideally have a set of technical talents to accomplish the given engineering task and accompanying business and interpersonal skills. The required engineering skills include mechanical, electrical, and industrial engineering with computer programming and testing experiences. Given that students may have a range of backgrounds, the course focuses on both systems engineering and general professional skills. The technical content includes control systems, PLCs, robots, actuators, sensors, electronics, circuit reading, mechanical systems, electric power, electric motors, material handling, pneumatics, hydraulics, system integration, and human factors. When covering these concepts, emphasis is placed on the practical aspects of the technology as motivated by typical manufacturing and material handling environments. The completion of these topics ensures that the students have sufficient information to complete the laboratory experiments and design projects.

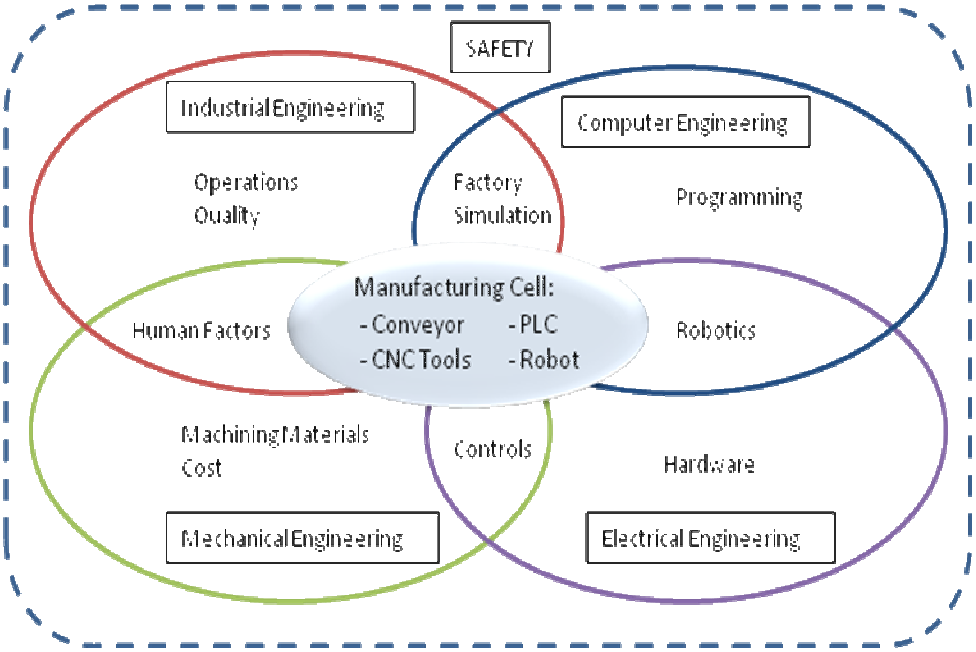


Figure 2.1: Engineering competencies and technical skills to support a general purpose robotic manufacturing cell with conveyor system for material handling

The course also presents important professional (non-technical) skills to better prepare students for successful careers in the workplace. As shown in Figure 2.2, some of these topics include team building, collaborative learning, leadership, communication skills, project management, procurement, and ethics. The first lecture cluster focuses on team dynamics such as team building activities, project management, proper communication techniques, and leadership. Next, students learn how to properly procure materials and equipment, and review general ethics. Finally, the classroom introduction of professional skills can be practiced and utilized in the team-based laboratory experiments and projects.

To reinforce the learning concepts, periodic multi-week homework assignments have been assigned for completion by student teams. Although not currently required, the student teams might be changed for each assignment to facilitate team building skills. Lastly, a midterm exam features an in-class test, laboratory practical, and take home open ended problem. To assess the general performance of student learning throughout the course, frequent surveys and pre/post course questionnaires may be administered.

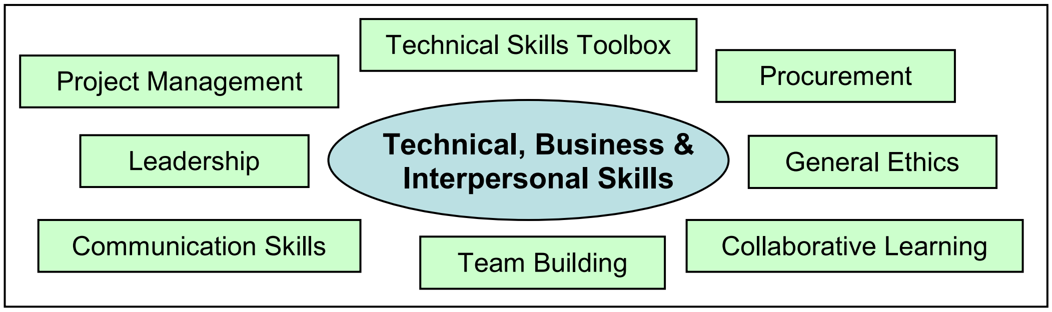


Figure 2.2: Select topics introduced in mechatronics and material handling system course

Laboratory Experiments

The mechatronics laboratory allows students to explore sensors, actuators, robotics, PLCs, conveyors, and system integration. A representative sampling of the experimental modules will be presented with learning objectives, procedure, and materials list.

Programmable Logic Controllers

PLCs are used in most industrial processes to control product manufacture and movement. Two laboratory modules are available that feature PLC programming basics and networked PLCs targeted for conveyor system control.

Physical Security System

The students create an alarm system (refer to Figure 2.3) through the wiring of security components and designing ladder logic to accomplish prescribed security functionality. This module allows students to gains hands-on experience with PLCs using common safety hardware. An Allen Bradley Micrologix 1000 PLC has been selected. The system features four inputs: motion detector, magnetic contact, vibration detector, and panic button. All four devices are wired internally as a normally closed (NC) circuit. Once a device is activated, the internal contacts open and power stop flowing back to the PLC. These sensors are pre-mounted and wired to a second terminal block. Four on/off toggle switches emulate an input keypad for the security system. The system outputs include one light stack unit (green, yellow, and red lamps).

Learning Objectives

The student will understand how PLCs operate and typical signal configurations. A selection of input and output devices will be introduced, wired, and integrated into ladder logic instructional blocks. With these skills mastered, the second laboratory module will create a network connecting multiple PLCs.

Laboratory Procedure

1. Design an alarm system to detect an introducer while offering the home or business owner conveniences for arming and disarming it as needed.
2. Connect the inputs and outputs using terminal blocks and wires.
3. A ladder logic program will be created to function in the following manner:
    a. System armed by placing all toggle switches to ‘open’ position with green light illuminated.
    b. Once an input has been triggered, the yellow light will turn on for a period of 5 seconds. Before this interval is completed, the toggle switches must be changed to a ‘code’ that will deactivate the alarm (e.g., 1010).
    c. If the proper code is entered within 5 seconds, the yellow light will turn off.
    d. Once the switches are put back to 0000, the system will arm itself again.
    e. If the proper ‘code’ is not entered in a timely manner, the red light on the light stack will switch on and the alarm will sound.
    f. Once the alarm has been tripped, the system cannot be reset by the switches.
4. RSLogix500 and RSLinx will be used to create the ladder logic and download the program to the PLC. The security inputs will be monitored with “Examine If Open” (XIO) instructions, while the ‘code’ will require both XIO and “Examine If Closed” (XIC) instructions. The lamp outputs will use “Output Enable” (OTE), “Output

Latch" (OTL), and "Output Unlatch" (OTU) instructions. Also, timers will be introduced and their respective status bits set for a five second period.

Materials

The laboratory materials include a motion detector (Optex #FX-40), panic button (Omron #A22-MR-01M), MicroLogix 1000 (Allen-Bradley #1761-L32BWA Series E FRN 1.0), magnetic contact (Honeywell #943WG-WH), vibration detector (Enforcer #PAT-14658), switches (McMaster #7343K184), and light (Patlite #XEFB-D).

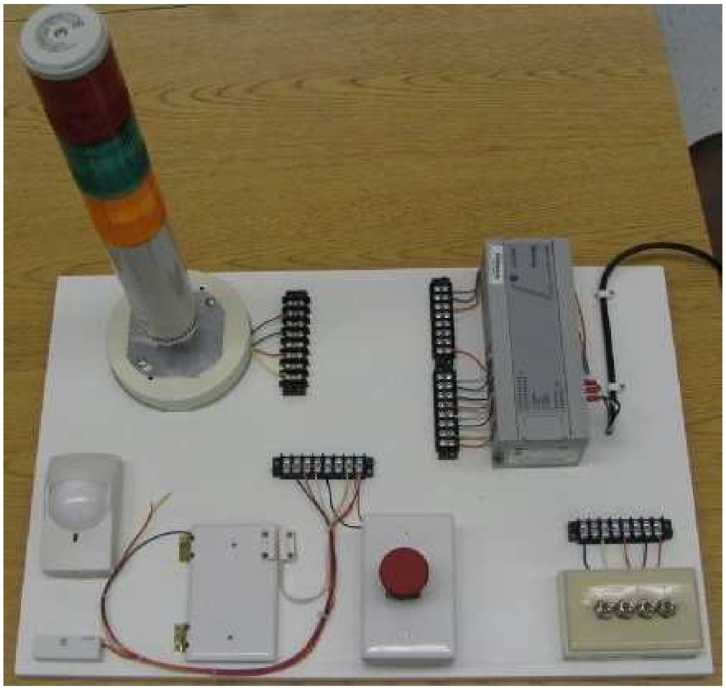


Figure 2.3: Security system with motion, vibration and entry sensor, light stack, horn, panic button, four binary switches, and programmable logic controller

Networked PLCs for Distributed Architecture

In a typical manufacturing environment, multiple PLCs are networked together for communication and the coordination of events. Although there are different network protocols (e.g., DH-485, DeviceNet, EtherNet), an understanding of one network protocol can be extrapolated to others. This laboratory module creates a network; PLC1 governs the material handling system direction while PLC2 powers the rollers to operate a modular conveyor system. Each PLC is a MicroLogix 1500 connected to individual ENI modules via RS-232 cables. These modules convert messages sent by the PLC to the EtherNet protocol, and then translate the messages sent by the network to the PLC. The network (ENI modules, network switches, CAT5 network cable, PC) was connected to allow the PC to access the PLCs as shown in Figure 2.4. Using the security system experiment, the toggles switches and red/green lamps on the light stack were wired into the inputs/outputs of PLC1. For the second PLC, a single conveyor segment is connected which featured five powered rollers and seventeen gravity idle rollers. Along the edge, mounted infra-red sensors determine the position of materials. The sensors and powered rollers have been pre-wired into PLC2. A connectivity chart summarized how the rollers and sensors are connected to the PLC input/output channels.

Learning Objectives

The student will gain an understanding of PLC networks with the ability to configure a network. Specifically, they will establish communication between two PLCs over a prototype network interfaced to a conveyor system with integrated sensors to control material movement. Further, this experiment shall reinforce basic skills in the programming and operation of PLCs.

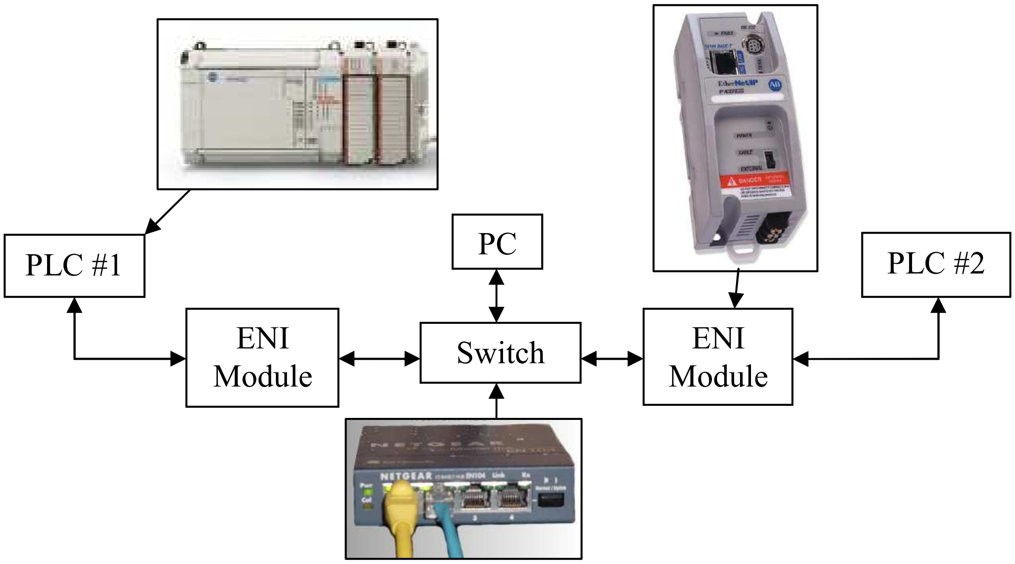


Figure 2.4: Two programmable logic controllers (PLCs) with Ethernet modules and central network switch connected to a computer work station for programming

Laboratory Procedure

1. The first PLC is connected to the toggle switches and light stack. Then, PLC1 and PLC2 are connected to their respective ENI modules. Finally, the ENI modules and PC are interfaced to the network switch to permit PLC programming via PC.
2. Algorithms are created for the PLCs to perform the five tasks listed below. Most instructions are familiar. However, the Message (MSG) instruction sends data in an integer (N7) address from one PLC to another. By changing the N7 register bits, data can be communicated between two PLCs. For example, PLC1 can change two bits (based on the toggle switches) and monitor two other bits that control lights. Similarly, PLC2 will monitor two toggle switch bits and change two light bits.

a. When one switch (connected to PLC1) is activated, the conveyor system (powered by PLC2) will turn on and move a tool pallet down the line

b. While the pallet is moving, the red light (connected to PLC1) will turn on.

c. Once the pallet reaches the last sensor on the line, the conveyor will stop.

d. When the second toggle switch is activated, the conveyor will switch directions and move the pallet back to its original destination.

e. Once pallet reaches this point, the green light connected to PLC1 will turn on.

Materials

The laboratory materials include MicroLogix 1500 (Allen-Bradley #1764-24BWA), ENI Module (Allen-Bradley #1761-NET-ENI), and Network Switch (Standard 5 Port 10/100 Mbps Fast Ethernet Switch).

Robot Programming and Sensor Integration Experiments

Many factories use fixed base and/or mobile industrial robots with computer controlled actuators to accomplish a variety of manufacturing and material handling applications. Some typical operations include part “pick and place” operations and general component assembly. In the next two laboratory experiments, students gain experience with programming and utilizing a standard industrial robot. The students move the robotic arm to specific points and assemble a piston (piston, connecting rod, wrist pin) for an internal combustion automotive engine.

Industrial Robot Programming

The Staubli RX-130 robot features six degrees-of-freedom. The control cabinet contains a pendant for manual programming and a terminal for software programming. The teaching pendent allows the student to define specific points needed to control the robot's movement. The controller allows the user to move the specific joints of the robotic arm through the V++ programming language. Using a few basic commands such as OPENI, CLOSEI, MOVES, and DELAY, and by defining points using the pendant, the robot can be controlled to perform various operations. A pneumatic end effect gripper (refer to Figure 2.5) has been installed to grip different objects. This module also introduces students to robot safety issues.

Learning Objectives

The student will understand robot fundaments such as movement (pendant and language programming), motion limitations, and safety concerns. It will be observed that the robotic arm may select different paths between operating points which reinforces the need to remain alert.

Laboratory Procedure

1. Students need to review the safety requirements for the robotic cell.
2. After ensuring that power is disconnected, students enter the cell to stage the necessary parts to assemble and ship the pistons (i.e., pistons, rods, pins, pallet).
3. The appropriate end effect gripper should be installed on the robotic arm and the compressed air supply turned on.

4. The students program the robot to accomplish four tasks which results in a fully assembled piston. First, the arm retrieves a connecting rod from a part storage platform and places it on the assembly jig. Second, the arm moves a piston from the platform and places it on the assembly jig with the wrist pin holes properly aligned. Third, the robot retrieves a wrist pin from the platform and inserts it into the piston and connecting rod. Fourth, the arm picks up the assembled piston and places it into an empty pallet located on the conveyor.

Materials

Staubli robot (CS7 RX-130) with control pendant and computer terminal.

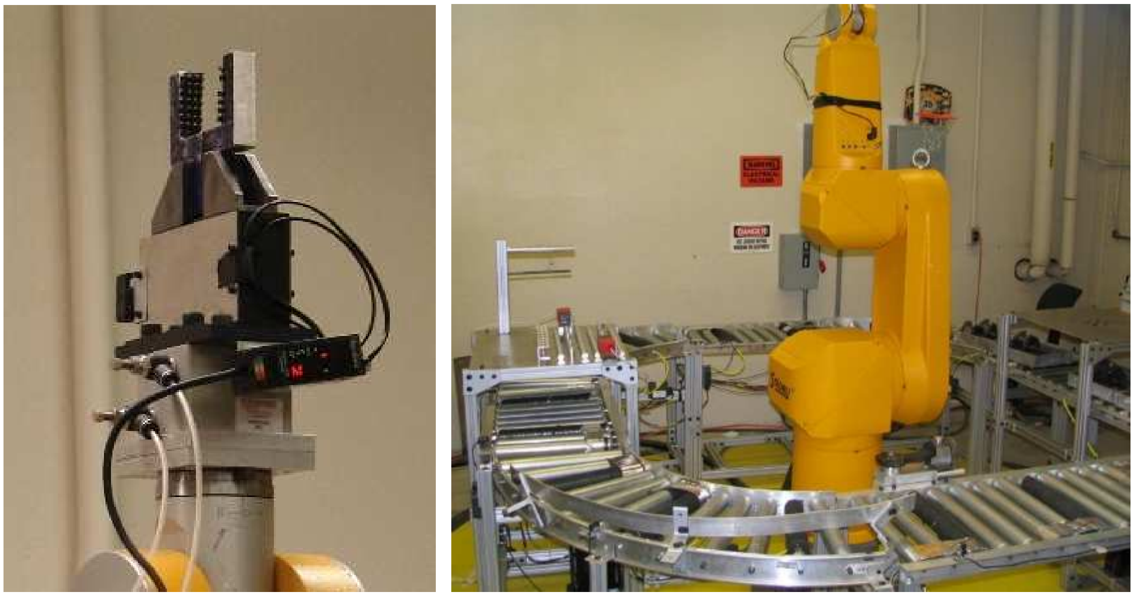


Figure 2.5: Staubli RX-130 industrial robot with (a) end effect gripper for part manipulations, and (b) conveyors in enclosed manufacturing cell

Robot and Conveyor System Integration

This module builds on the knowledge gained regarding the Staubli robot and previous PLC modules to integrate the equipment into a material handling system. A series of conveyor segments, featuring distributed electrical powered rollers with driver modules, are constructed of inner/outer aluminum rails mounted on an aluminum frame with casters. The infra-red sensors, mounted on the edge of the conveyor, permit the position tracking of materials on the conveyor rollers. The Staubli control cabinet features input/output terminal blocks to allow the robotic arm to be integrated into surrounding environment for closed loop operation. The dual PLCs, controlling the conveyor segments, will be interfaced to the robot, for coordinated material movement studies.

Learning Objectives

The student will understand the integration of robotics with material handling systems for product fabrication and transport. A unified architecture will be introduced and implemented which permits multiple PLC interactions with robot arm to assemble and move goods based on user defined algorithms and sensor feedback.

Laboratory Procedure

1. Two robot outputs (e.g., 1 and 2) are connected to PLC1 thereby replacing the two toggle switches used for the network conveyor. Similarly, two robot inputs (e.g., 1010 and 1011) are wired to PLC1 to replace the lights.

2. The robot is now programmed to wait before placing the piston in the pallet until a signal is sent from PLC1 which indicates the pallet is in the proper position based on the infra-red sensors.
3. Once the assembled automotive piston is properly secured in the pallet, another signal is sent to PLC1 by the robot to move the pallet to the end of the conveyor system for subsequent operation by another manufacturing resource.
4. When the pallet reaches this terminal conveyor position, the robot is programmed to return to the "ready" position to resume operation.

Materials

The materials for this laboratory include Holjeron 24VDC brushless dc motor driven rollers, Holjeron #ZL-DK100 driver modules, 8020 T-Slot extruded aluminum, and Takex #GS20SN infra-red sensors.

Electronic Circuits

Electronic circuits are common in manufacturing environments and consumer products which should encourage engineers to understand their basic electronics. Consequently, electronic components and integrated circuits will be introduced and reviewed to acquaint students with their general operation. In the next two modules, several basic circuits will be presented which offer breadboarding opportunities with signal test points. The two circuits feature 'electronic dice' which mimics a real dice using IC chips and a rotational sensor to count rotations of a flywheel.

Electronic Dice Circuit

The electronic dice module introduces integrated circuits with the creation of an electrical system that emulates the functionality of a six sided dice with a digital display. The circuit features a general purpose timer chip, a counter chip, assorted resistors, diodes, a switch, and six LEDs as shown in Figure 2.6. The timer chip is configured to output a high frequency oscillating signal, which is then fed to the counter chip. The counter will count up, until the switch is activated. At this point, the counter's outputs are latched. These outputs are connected to LEDs, in such a way as to resemble a die. Due to the high frequency of the oscillating signal each time the switch is activated, a new number will appear on the die, thus creating a random pattern.

Learning Objectives

The student works with a 555 timer chip and learns how to test basic circuit features. Specifically, they learn how to use breadboards, wire chip inputs/ outputs, and validate circuit functionality using oscilloscopes and multi-meters.

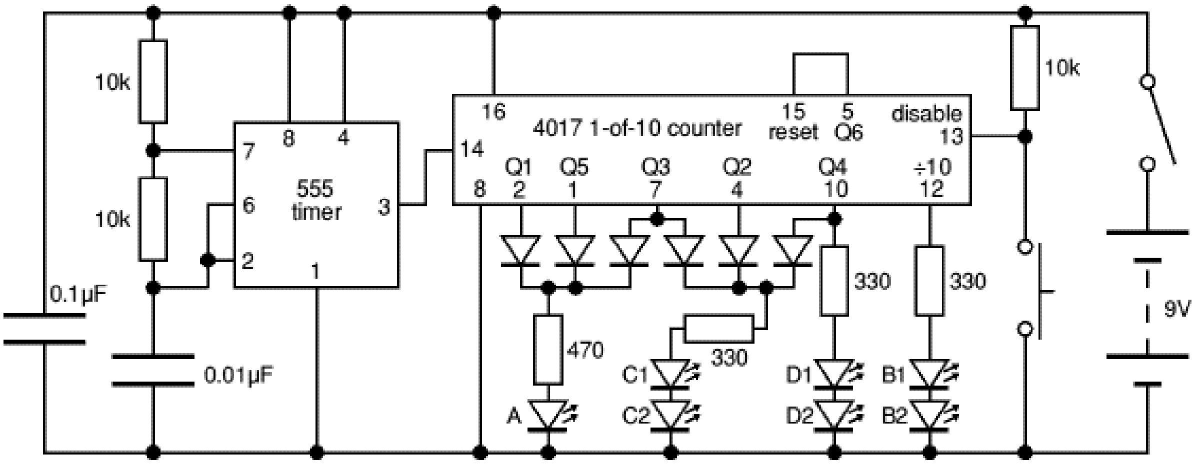


Figure 2.6: Circuit diagram for electronic dice experiment which features a 555 timer, 4017 decade counter, and multiple light emitting diodes (LEDs)

Laboratory Procedure:

1. Insert a 555 timer chip into the breadboard with the number 1 pin in the top left. Connect Pins 8 and 4 to +5VDC and connect pin 1 to ground. Connect one side of a 10kΩ resistor to +5VDC and the other side to Pin 7. Take another 10k Ω resistor and connect pin 7 to pin 6. Use a piece of wire to connect pin 6 to pin 2. Place a 0.01uF capacitor between pin 2 and ground.
2. The timer circuit is now fabricated to operate as an oscillator. Check to determine whether the circuit is properly functioning by connecting the onboard speaker to pin 3 and ground. If you hear a ringing note, it is functioning as expected.
3. Place the 7 LED’s and arrange them on the breadboard in a standard dice configuration (three rows by two columns). Make sure the cathode and anode are not

on the same rail and that no LED shares the rail with another. There should be three sets of LED's in series with the middle LED being alone.

4. Wire a 330Ω resistor to points A, B, and D. Next, connect a 470Ω resistor to point C. Apply +5VDC through the resistors to the LED's and verify that all seven are illuminated. If so, then this circuit section is properly completed.
5. Place the 4017 counter with pin 1 oriented in the top left corner. Connect pin 16 to +5VDC and pin 8 to ground. Wire the 1N4148 signal diodes to pins 1, 2, and 7. Bring the diodes together on one rail and connect this rail to point C using the 470Ω resistor. Connect the 1N4148 signal diodes to pins 4, 7, and 10. Bring the diodes together on one rail and connect this rail to point D using the 330 Ω resistor. Wire pin 10 to point B using a 330 Ω resistor. Connect pin 12 to point A using a 330Ω resistor.
6. Use a 10kΩ resistor to connect +5VDC to pin 13. Wire the switch from pin 13 to ground. Connect pin 14 of the 4017 chip to pin 3 of the 555 timer. Connect a 0.1 uF capacitor to between ground and +5VDC to smooth the power supply.
7. When the circuit is energized, all 7 LED's should be illuminated until the switch is pressed again. At that point, there should be a different number displayed via the LED configuration which resembles the behavior of a thrown dice.

Laboratory Materials

The electronic supplies for the experiment include 330Ω resistors (3), 10kΩ resistors (3), 470Ω resistor, 0.01µF capacitor, 0.1µF capacitor, 555 Timer (Texas Instruments #TLC555CP), 4017 decade counter (Texas Instruments #CD4017BE), toggle switch (C&K Components #GT12MABE), signal diodes (6) (Diodes Inc, #1N4001-T), and LEDs (7) (Panasonic #LN81RCPHL).

Rotation Sensor Electronic Circuit

An electronic sensor circuit will be created to count the rotations of a metal flywheel connected to a servo-motor. A metal test stand holds the dc motor, metal disk with single through hole, and light emitting diode (LED) with photo-resistor sensor as shown in Figure 2.7. An accompanying breadboard circuit (refer to Figure 2.8) interfaces to the LED and sensor to count the flywheel rotations with test points to validate during construction.

Learning Objectives

The student will gain experience with op-amps (compare measured sensor voltage against established threshold value) and a combined counter and display driver integrated circuit (4026 chip) for multiple segment LED display. In addition, a sequential building process that emphasizes frequent validation will reinforce the need to test each subsystem for operation prior to the complete build.

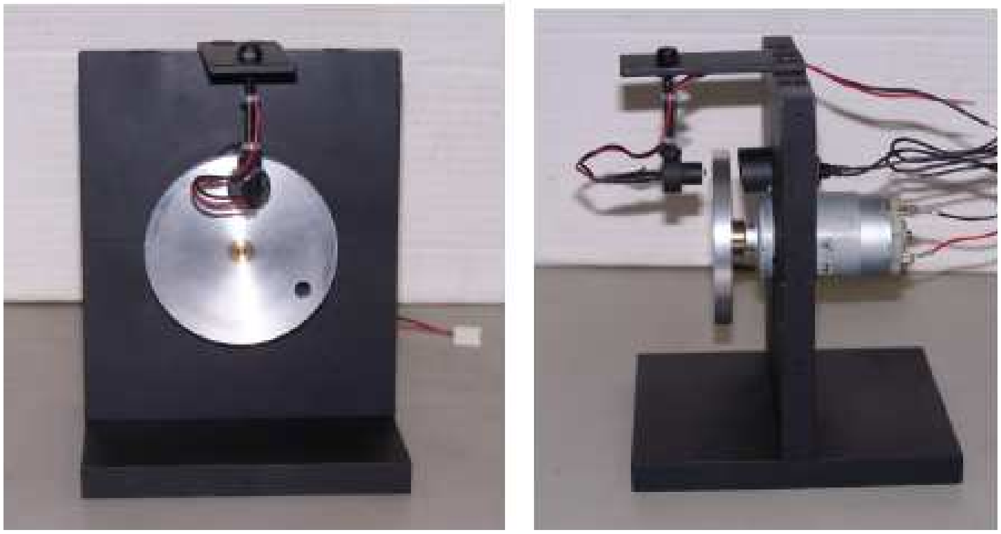


Figure 2.7: Servo-motor driven wheel featuring a single thru-hole with LED lamp and photo-resistor components for rational sensor experiment

Laboratory Procedure

1. Insert the 741 operational amplifier into the breadboard with the number 1 pin in the top left. Connect Pin 7 to +9VDC and connect pin 4 to ground. Take the leads coming from the LDR and connect one to +9VDC and connect the other to pin 3 of the 741 amplifier.
2. Use a 3kΩ resistor to connect one side to +9VDC and the other side to pin 3 of the 741 chip. Connect a 330Ω resistor to +9VDC and connect the other end to the positive lead for the white LED. Attach the other LED wire to ground.
3. Test the circuit. Place a LED with 330Ω resistor to pin 6 of the 741 amplifier. Spin the wheel and check to ensure the LED is flashing when appropriate. If the LED fails to light, increase the resistor to pin 2. If the LED is always on, decrease the resistor to pin 2. Once the circuit is verified, remove the LED and resistor.

4. Place the 4026 IC into the breadboard with the number 1 pin in the top left. Next, connect pins 3 and 16 to +9VDC. Now connect pins 2, 8, and 15 to ground. Finally, place the seven segment display onto the breadboard and follow the diagram to connect the pins. Please include 330Ω resistors in each connection.
5. The 4026 IC pin 1 should be connected to +9VDC; ensure that it counts up one. If the circuit successfully counts up one, then connect pin 1 of the 4026 IC to pin 6 of the 741 op-amp chip.
6. The circuit has been successfully constructed. Connect the servo-motor to a variable output dc power supply to spin the attached flywheel. As the wheel rotates, watch the circuit count the total number of rotations.

Laboratory Materials

The supplies include 330Ω resistors (8), 3kΩ resistor, 741 op-amp (Fairchild Semiconductor #LM741CN), 4026 IC chip (Texas Instruments #CD4026BE), 7 segment display (Lite-On Inc #LSHD-5503), light dependent resistor (Chartland #N5AC501085), LED (Panasonic #LN81RCPHL), and dc motor test stand.

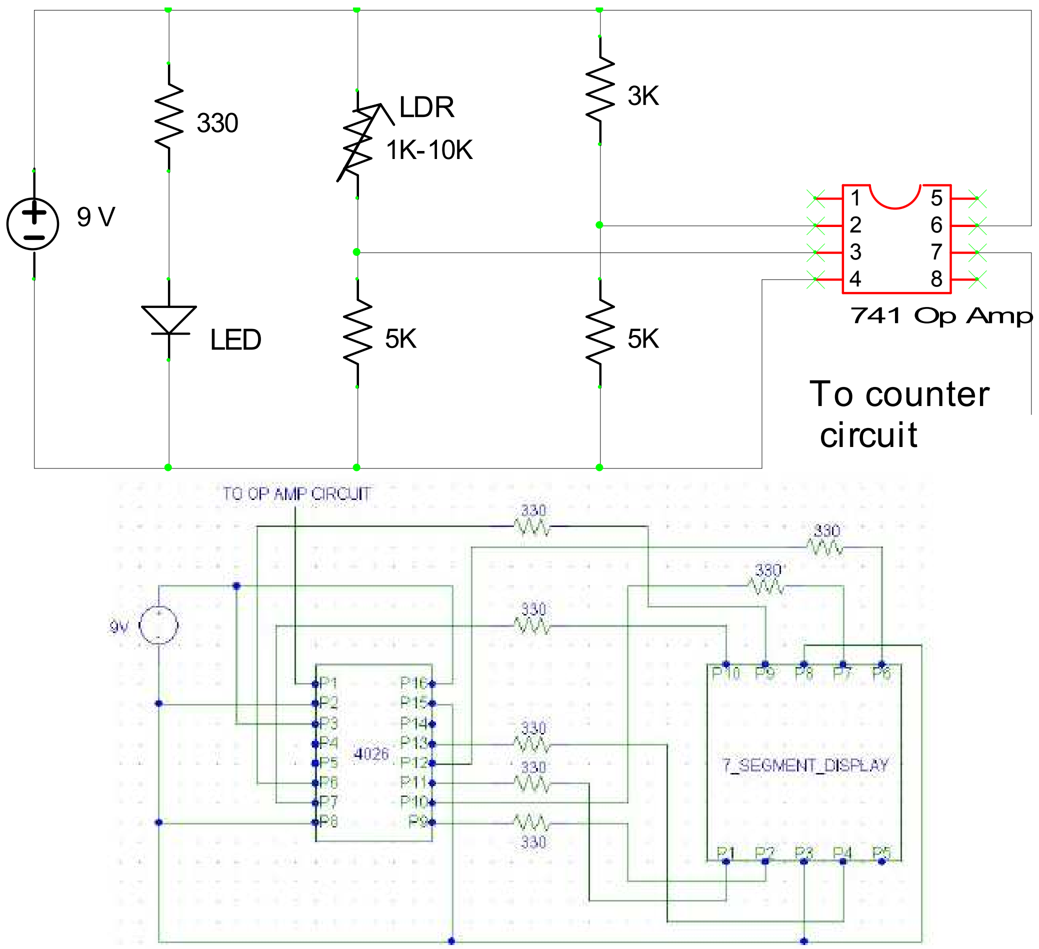


Figure 2.8: Rotational photoelectric sensor circuits - (a) sensor and (b) counter elements

Design Project - Material Handling System with Order Fulfillment

A semester long experimental based design project has been introduced to supplement the classroom activities and laboratory modules. In the laboratory, the robot and conveyor system have been combined on a somewhat 'microscopic' level to execute a specific well-defined task. In contrast, the design project requires student teams to create a larger 'macroscopic' system that encompasses tasks including order identification, fulfillment, and movement in preparation for shipment from the manufacturing facility. The project emphasizes the need for students to divide into teams to accomplish singular objectives that may then be integrated into a collective material handling system which achieves a larger objective. For instance, some of the groups may focus on sensing and sorting, conveyor systems, PLC programming, or robot interaction The team approach allows students to experience how real world problems may be solved with typical group and organization challenges. Finally, the project allows the application of class room and laboratory technical and interpersonal skills to create a mechatronics system.

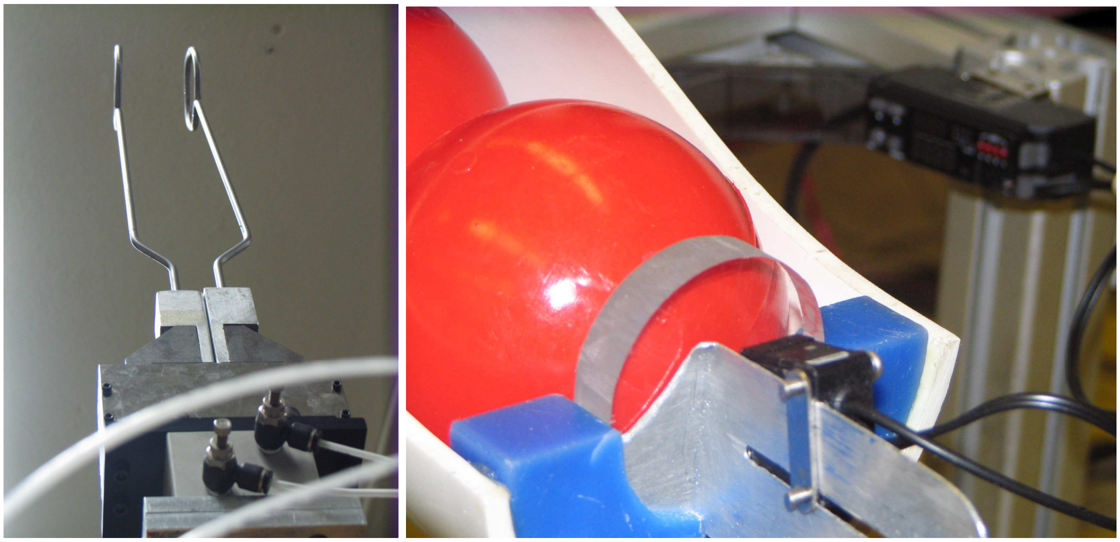


Figure 2.9: Staubli robot with end effector and color balls with sorted single color bin

The design project requires the sorting and packing of colored (blue, green, red, and yellow) multi-sized plastic balls for order fulfillment at a toy distribution center. Specifically, the students use the Staubli robot, conveyor segments, and sensors/actuators to create a small scale material handling system per Figure 2.9. In terms of operation, a bar code on the pallet box side lists the number of colored balls and destination (one of three points) on the conveyor system for subsequent pallet placement. The system reads the bar code using a bar code scanner (Keyence #BL-160). A color sensor (Keyence #CZ-H32) determines the ball color loaded in the main hopper and places the correct number in the proper container (refer to Figure 2.10). The box is then sent down the conveyor system and routed to one of three spurs as commanded by the PLC network. Refer to Chapter Four for a more detailed examination of this design project.

Figure 2.10: Shipping container with ball order fulfilled and complete sorting system

Summary

The growing sophistication and complexity of engineering systems requires broad knowledge of mechatronics (sensors, actuators, and controls with application to consumer products, specialized equipment, and manufacturing environments) as well as general business and interpersonal skills. In this paper, the mechatronics (and material handling systems) course has been described which offers students an experience composed of classroom activities, laboratory experiments, and semester long design project. First, the technical, business, and personal skills covered include electrical, industrial, mechanical, and systems engineering, project management, procurement, team building, and leadership. Second, laboratory experiments allowed students to program networked PLCs, integrate conveyor system components including industrial robot for material movement, and breadboard electronic circuits. Third, a challenging material handling design project offered a learning opportunity for students to synthesize class and laboratory materials in a hands-on team-based endeavor. A comprehensive mechatronic course should help prepare graduates to meet the product design, manufacturing, material transport, and research needs of the 21st century.

CHAPTER THREE

DATA ACQUISITION EXPERIMENTS

Data acquisition techniques can be utilized in industry to ensure product quality or to record measurements of a system process. Two exercises were created to cover these important topics in mechatronics, however were not included in the previous chapters. In the first experiment, students measure the vibration frequency of various length chime rods, while in the second the frequency of a torsional pendulum and a hanging pendulum are measured.

Acoustics Laboratory

In the first laboratory students were tasked to measure the vibrating frequencies of several chime rods, each with varying lengths. This lab contained two different sections; the first part involves using a microphone to determine the frequency of resonance of each rod, while the second section utilizes an accelerometer to determine the frequency. Several different technologies are introduced, such as a pre-amplifier (refer to Figure 3.1) and an accelerometer, as well as specific testing locations, such as an acoustic chamber (refer to Figure 3.2).

Figure 3.1: Audio amplifier

Learning Objectives

Students should understand how various sensors and other equipment, in conjunction with data processing technology, can be utilized to describe properties of objects. Experience with Matlab and SigLab are also gained.

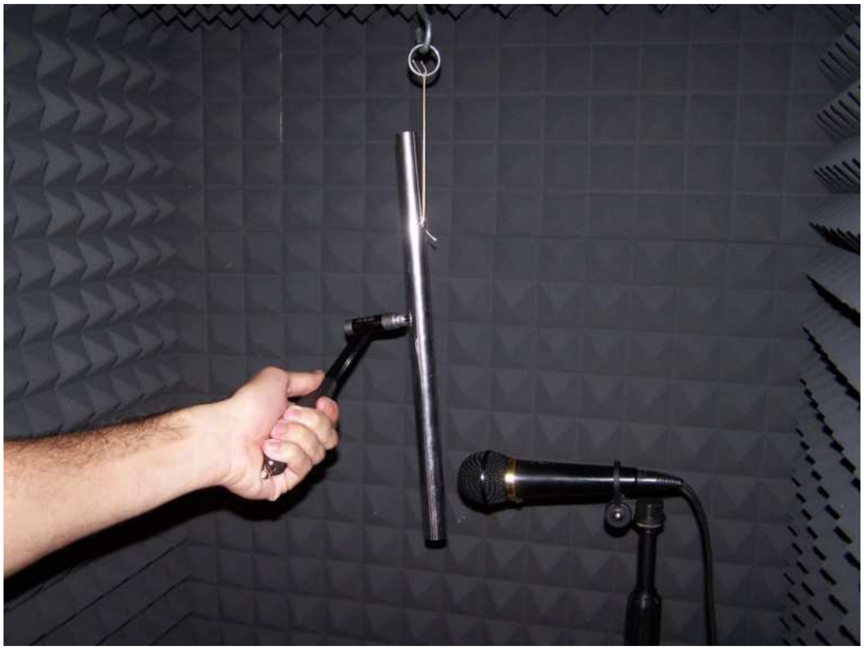


Figure 3.2 Set up for acoustic experiment

Procedure – Acoustics Experiment

1. Hang chime rod on the rear hook inside semi-anechoic chamber.
2. Place the microphone on the stand.
3. Connect the microphone to input 1 on Audio Buddy pre-amp box.
4. Connect the red cord from output 1 on Audio Buddy to the computer (microphone input).
5. Set microphone inside semi-anechoic chamber as close to the chime rod as possible without touching it.
6. Open Sound Recorder from Windows start menu.
7. Press Record and strike the chime rod.
8. Press Stop after collecting sound data.

9. Save Sound Recorder file as chime.wav in the MATLAB folder.
10. Open wavanal.m file in MATLAB.
11. Run the program and observe the resulting graphs of the spectrum analysis and frequency of the chime rod.
12. Repeat experiment using a different chime rod. Observe any differences in the spectrum analysis and frequency graphs.

Procedure — Vibration Experiment

1. Install accelerometer (100mV/g) on chime rod. Hang chime rod on the rear hook inside semi-anechoic chamber as shown in Figure 3.3.

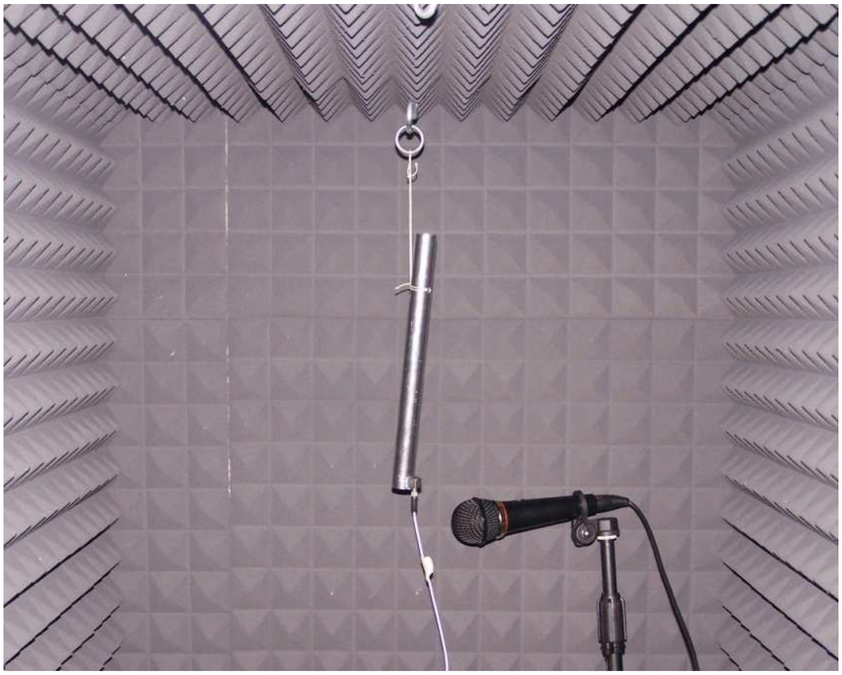


Figure 3.3 Rod with accelerometer in the chamber

2. Connect the accelerometer cable to channel 2 on SigLab per Figure 3.4.

3. Connect the impact hammer cable to channel 1 on SigLab.

Figure 3.4 Connections at Siglab

4. Type “sigdemo” on the command window of MatLab.
5. Press VNA (Virtual Network Analyzer) button in Siglab.
6. Open MechatronicsLab.vna file in SigLab (parameters for this experiment are saved in this file).
7. Hit “AVG” and strike chime rod using impact hammer. Observe for changes in the graphs.
8. Hit “STOP”.
9. Copy the plots (impulse response from the hammer and FFT response from the accelerometer) or export data to be analyzed later.
10. Detach the accelerometer from the chime rod and install it on the next rod to be tested. Repeat procedures 7-9 until all the 5 rods have been tested.

Materials

A standard Chime Rod set with five varying lengths of chime rods were used. The first section utilized a microphone connected to an amplifier, which was then connected to a PC equipped with MatLab. For the second section, an accelerometer was attached to the chime rod, and connected to a SigLab box. An impact hammer was also attached to this box. A software program connected to this SigLab device allowed for data acquisition.

Pendulums Laboratory

The pendulum is a classic device to study motion and the concept of energy. In this experiment, two different types of pendulums are used to understand data acquisition as shown in Figure 3.5. In the first, a Hall Effect sensor is used. This type of sensor is able to detect small changes in magnetic fields. For the second pendulum, an accelerometer is utilized.

Learning Objective

Students will understand how various sensors can be connected to a data acquisition card, which can then be utilized by LabView. Students will also gain experience in working with a Hall Effect sensor, as well as an accelerometer. Finally, higher level concepts such as noise and data collection errors should be understood.

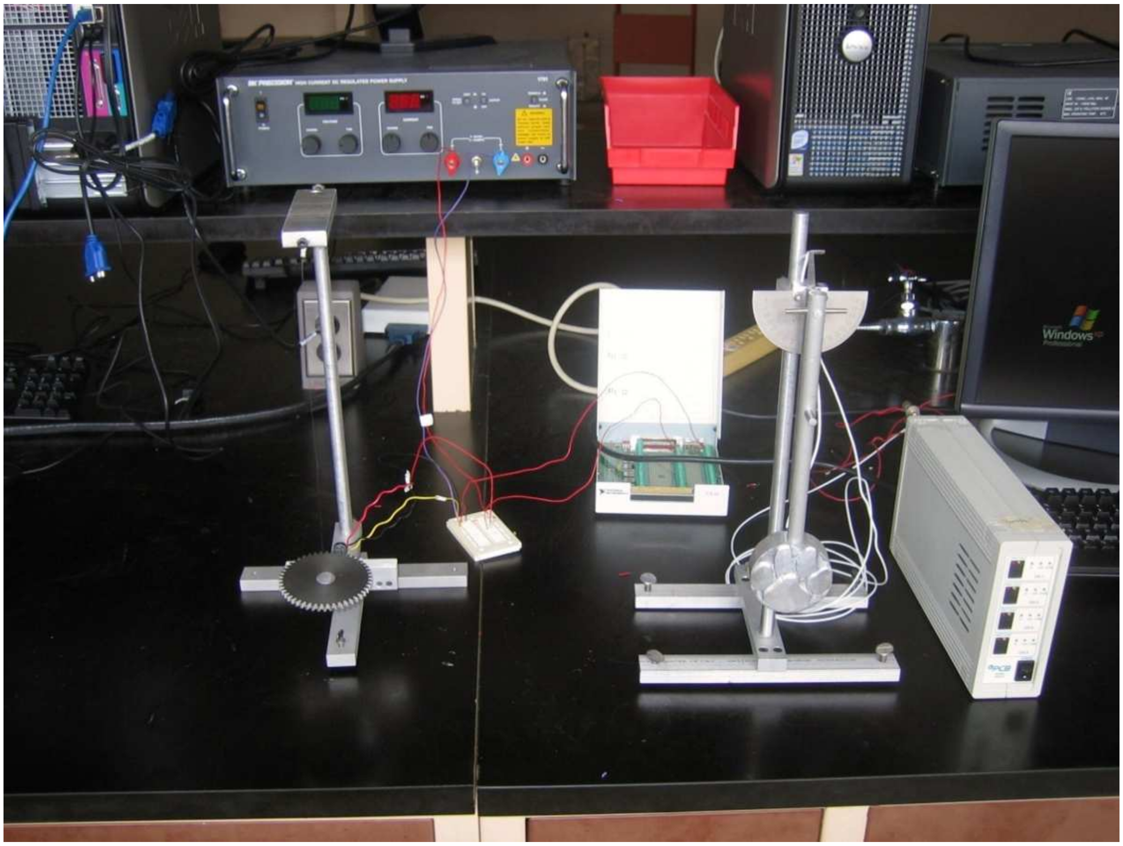


Figure 3.5 Pendulum experiment setups

Procedure – Torsional Pendulum

1. Connect the torsional pendulum to the test stand. Assure that the pendulum is secured and the Hall effect sensor is in an adequate position to measure data.
2. Ensure that the Hall Effect circuit is set up and connected correctly to both the power supply and the sensor.
3. Turn the power supply on and set it to 3 volts.
4. Wind the pendulum 3-5 full rotations in either direction. Release the pendulum and, using the DAQ, record at least one full oscillation.
5. Calculate the angle per tooth on the gear to which will be used to determine the angular displacement.

6. Transfer data to Excel. Differentiate the data from the accelerometer to go from acceleration to velocity to displacement. Then integrate the data from the magnetic variable reluctance sensor to go from displacement to velocity to acceleration. Compare the two results.

Procedure – Swinging Pendulum

1. Connect the swinging pendulum to the test stand and mount the rotational potentiometer to the swinging joint.
2. Turn on the constant current PCB amplifier.
3. Rotate the pendulum to about 45º and release. Using the DAQ, record a minimum of five full oscillations.
4. Transfer data to Excel. Integrate the data from the accelerometer to obtain velocity and displacement. Compare the two results with those of the torsional pendulum.

Materials

Two types of pendulums were used; a torsional (comprised of a metal gear on a thin wire) and swinging Pendulum (weight attached to a rod). A Hall Effect sensor or an accelerometer was attached to collect data. In either case, the sensor was connected to a pre-amplifier, which was then connected to a computer with LabView software. The software was programmed to output data collected from the sensor to an excel file which could be manipulated to determine desired data.

These two laboratory experiments help to solidify the understanding of data acquisition. Several types of sensors are used, as well as two different computational programs; Matlab and LabView. Students learning various data acquisition environments and different programs ensure they will be more adequately prepared upon graduation.

CHAPTER FOUR

A MECHATRONICS AND MATERIAL HANDLING SYSTEMS LABORATORY

Introduction

Modern industrial systems rely on core technologies such as programmable logic controllers (PLCs), computer networks, industrial robots, conveyor systems, and a variety of sensors and actuators to assemble and move products within flexible work cells. In many instances, these devices must be integrated to realize a computer controlled mechatronics solution. To create and maintain these systems, engineering teams must apply their individual and collective skill sets. Material handling systems offer a great subset of processes to demonstrate how mechatronic solutions are designed and implemented to move, track, and manipulate products. Mechatronic technologies can be used to read a barcode, divert products off a conveyor line, place items in a container, and perform other material handling tasks. While these devices are common in industry, universities do not typically offer formal courses of instruction which explore their operation and integration.

A brief literature review will be presented on academic mechatronic programs. Acar and Parkin [14] provided an overview of mechatronics and select programs from universities around the world. Pennsylvania State University has created three courses that provide students with fundamental concepts in materials processing, production design, and manufacturing [6]. Merckel and Fisher [3] at the Rose-Hulman Institute of Technology created a two week PLC experience, which utilized two separate PLC stations for student ‘hands-on’ experience. Erickson [7] described a University of Missouri-Rolla laboratory which used four industrial processes featuring robotic arms, assembly and inspection, pH neutralization, and operator interfaces. Carnegie Mellon University utilized a robotics laboratory that supplied the students with ‘hands-on’ experience [15]. Chiou *et al*. [4] at Drexel University have developed a mechatronics course that controls industrial robots over the internet using machine vision systems, PLC modules, webcams, and sensors. Some international mechatronic programs have been highlighted by Khan [2] with a review of micro-controller technology, mechanical/manufacturing engineering, transducers, and PLCs. Lee and Park [5] created a computer controlled robotic laboratory which focused on systems integration concepts. The Utah State University used mobile robots for mechatronics education as described by Stormont and Chen [8]. Ghone *et al*. [16] discussed ‘hands-on’ experiences in a multi-disciplinary mechatronics laboratory at Clemson University which contains circuits, pneumatics, hydraulics, and servo-motors [9]. A series of experiments utilizing PLCs, industrial robotics, and electrical circuits which culminated in a mechatronics design project was discussed by Shirley *et al*. [17]. Murray and Garbini [18] reported on the mechatronic capstone design projects at the University of Washington, which featured four classes to teach fundamentals. Ebert-Uphoff *et al*. [19] compared various aspects of mechatronics courses from both a teaching and infrastructure viewpoint. For a graduate level focus, Du [20] offered a thorough review of various laboratory experiments and possible projects.

Creating a firm foundation is critical to future mechatronic applications. In model-integrated mechanics [21], both model-driven architectures and pre-defined function blocks are used to design systems. Finally, Jammes and Smit [22] proposed that service oriented automation, in which mechatronic components exemplify a plug-n-play architecture, should be required to accommodate ever changing manufacturing processes. To ensure students understand basic mechatronic fundamentals, the multi-disciplinary "Mechatronics and Material Handling Systems" course was created at Clemson University to introduce mechatronics systems from an industrial setting and encouraged students to practice team skills. The classroom time focuses on core technologies and improving communication skills. An accompanying laboratory features eight experiments involving PLCs, industrial robotics, data acquisition, and electronic breadboard experiments. A case study encourages students to synthesize class and laboratory concepts into a focused material handling task (refer to Figure 4.1). Teamwork is stressed and practiced in the laboratory experiments and case study.

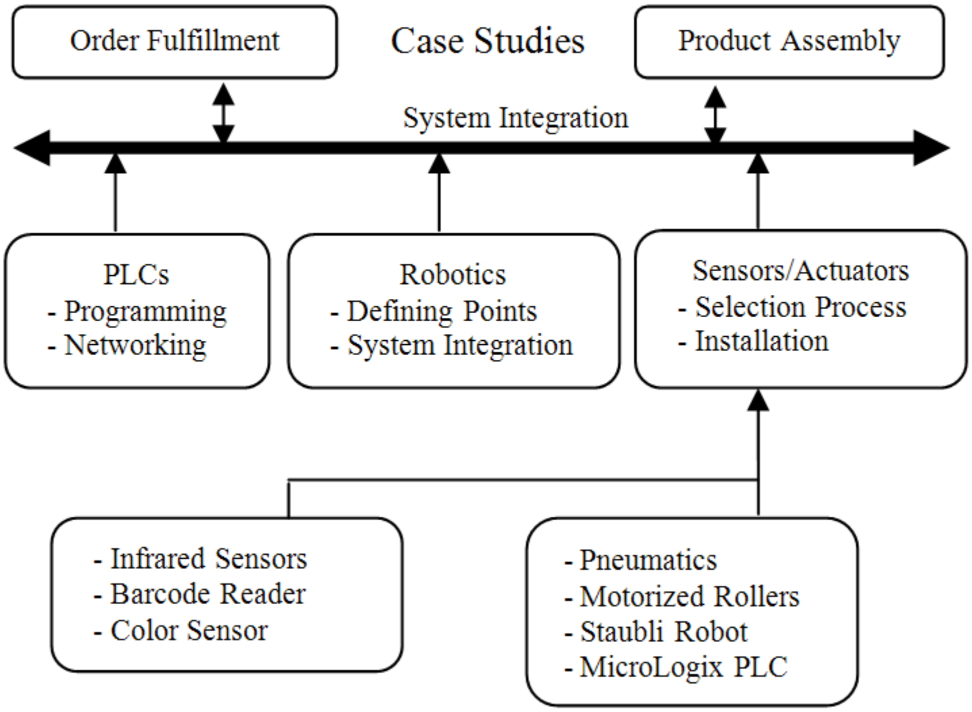


Figure 4.1: Engineering technology topics in the mechatronic and material handling course to support case studies

The remainder of the manuscript is organized as follows. A selection of four laboratory experiments and accompanying technologies will be discussed followed by a presentation of two case studies which focus on assembly and sorting operations. A summary is presented to conclude the paper. The Appendix contains the material lists for the experiments.

<u>Experiments – PLCs and Robotics</u>

Eight laboratory experiments were created which feature four distinct technologies used in industrial mechatronic systems. The experiments cover four different topics: PLCs and communication; industrial robotics; data acquisition; and electronic circuits. These laboratories establish the frame work for system integration activities in the case studies. Four of the eight laboratory modules will be discussed and the accompanying materials listed in the Appendix. The reader is referred to Wagner [23] for information regarding the other experiments.

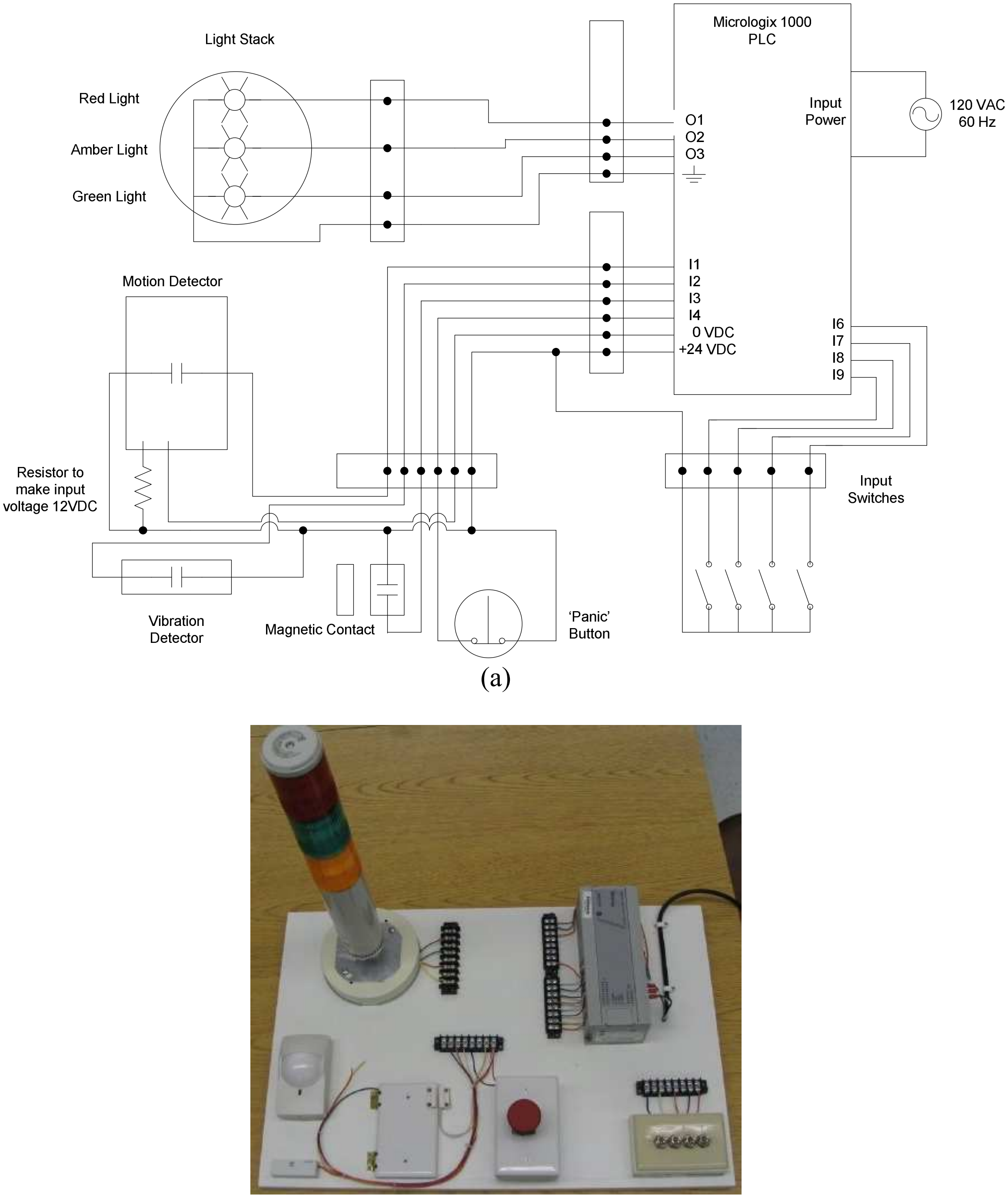
PLC Programming and Communication

An understanding of PLC operation is essential to the design of a manufacturing mechatronic system. The combination of multiple PLCs across a dedicated network can significantly increase the response time and effectiveness of a control system. Two laboratory modules were created that focus on PLC basics and creating a dedicated network. In the first module, fundamental PLC control is taught through the creation of a residential security system, while in the second, a PLC network is implemented to control a conveyor system.

Residential Security System

A modular security system is constructed to help students understand PLC operation. The successful completion of this laboratory should allow students to understand PLC programming and connecting various inputs/outputs to create a mechatronic system. The operational principal behind a security system is common to most students; thus, making it an ideal choice to explain PLC operation and how PLC inputs can control various outputs. A motion detector, a vibration detector, a magnetic switch, a pushbutton, and four switches represent the system inputs, while alarm lights function as the output. A PLC (Allen-Bradley MicroLogix 1000) acts as the controller for the system.

The students wire the inputs and outputs to the PLC and create a program that controls the system operation (refer to Figure 4.2). The security system is to operate in the following manner: when a sensor is triggered, the user has five seconds to input the proper code before an alarm light activates and "locks out" the system. Students are exposed to many programming commands used for ladder logic devices (e.g., Examine-If-Open, Examine-If-Closed, various timer implementations). Proper wiring techniques and PLC operation is also explained. Students are encouraged to discuss in their small groups the most efficient manner to wire and program the PLC.



(a)

(b)

Figure 4.2: Security system experiment - (a) schematic, and (b) photograph with component layout and space for wiring

PLC Network for Conveyor Control

The second module re-enforces basic PLC programming principles and introduces students to PLC networks. A PLC network allows efficient communication between two (or more) PLCs which ensures data sharing. In this experiment, the teams move a “tool” pallet down a conveyor line, wait for an input signifying some action has taken place, and then activate the conveyor to move the pallet back to the original starting location.

The conveyor line was constructed with both motorized and idler rollers, as well as infrared sensors located at various positions along the rails. Following the completion of this laboratory, students should be able to electrically interface two PLCs together over an Ethernet network, and send/receive data packets to accomplish a given task. Two PLCs (Allen-Bradley MicroLogix 1500) control the system (refer to Figure 4.3). The switch inputs (turn off/on the conveyor) are connected to PLC-1 as well as two output lights to indicate when a task is complete. PLC-2 controls the motorized conveyor rollers and monitors the infrared sensors attached to the conveyor system. The PLCs are networked over a dedicated Ethernet system using two ENI modules from Allen-Bradley.

The network functions in the following manner. An Integer register from one PLC is sent, through the ENI modules, to the other PLC. Information (by using bits) or numbers (by using the entire register) can be transmitted between PLCs by sending these designated Integer registers. All control information (i.e., which Integer register to send to which PLC, which register at the target PLC the information goes to) was stored in a ladder logic function block. The ‘control’ inputs wired to one PLC, and the motorized rollers connected to the second PLC, forces students to comprehend and utilize the network.

Although a variety of PLC networks exists (e.g., ControlNet, DeviceNet, Fieldbus), the current equipment offers sufficient hands on practice for students to grasp the concept. The knowledge gained may then be transferred to more complicated networks with additional PLCs and/or different protocols. Finally, the teams were encouraged to discuss various solutions to problems encountered among the group members.

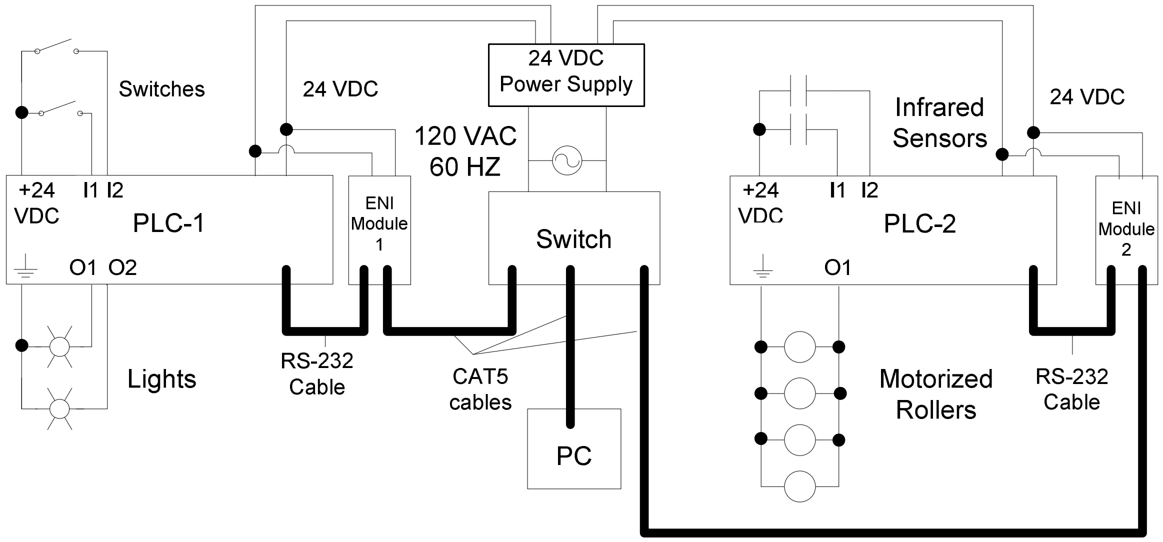


Figure 4.3: PLC network featuring two controllers (regulate lights and rollers) with CAT5 cable network

Robotic Manipulator

Factories utilize fixed and mobile industrial robots to perform specific tasks such as pick-and-place operations, welding, and product manipulation. Two laboratory modules were developed which illustrate the intricacies of integrating an industrial robot into a mechatronic system. In the first module, students program the robot to assemble an automotive piston. The second module integrates this industrial robot with a modular conveyor system for product movement.

Industrial Robot Primer

The Staubli robot/safety review and operation is completed in the third laboratory module. The Staubli RX-130 industrial robot features six degrees of freedom that allows for various pick-and-place operations. Once completed, students should be able to use this industrial robot to complete a complicated task.

The RX-130's movements are created and programmed using the V++ computer language and manual input (pendant) connected to the robot's control cabinet. Students are given instruction in programming basics, including the teaching pendant, defining special locations, and creating code. Once familiar with the robot, the group is tasked to assemble an automotive piston. A previously constructed jig assisted in the assembly process. Students program the various spatial points to maximize efficiency and ensure safety. Most participants were impressed that a complicated task such as assembling an automotive piston could be accomplished by programming a few simple points.

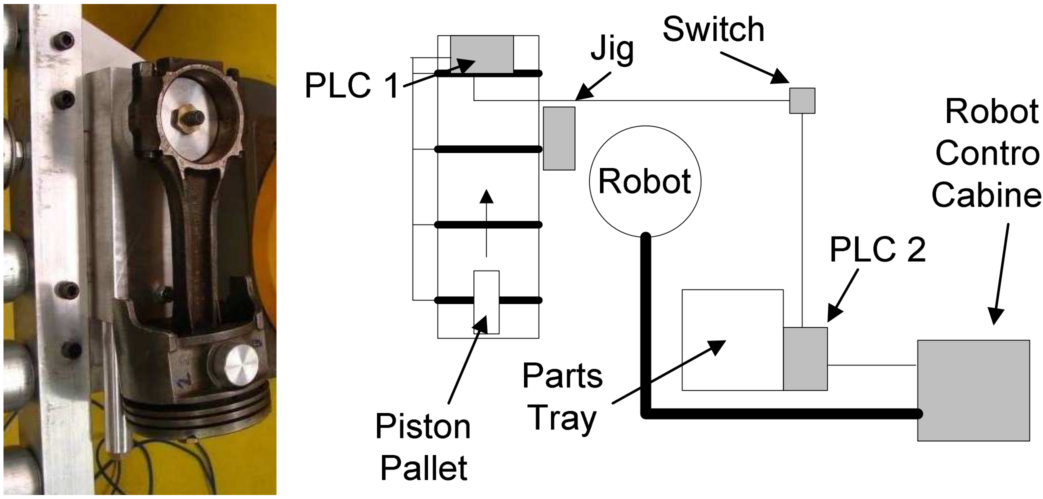
System Integration with Robotic Manipulator

The fourth laboratory module focuses on connecting external inputs and outputs to the Staubli robot control cabinet. Unmodified, the robot operates in an open loop manner with the exception of position information received from each arm joint.

However, the robot is capable of receiving feedback through input/output (I/O) boards allowing environment information to be received. Input from various pushbuttons, sensors, switches, and PLCs can be used in conjunction with internal software programs to increase the robot's effectiveness. Following the completion of this laboratory module, students were able to connect the industrial robot to an external mechatronic system, thereby drastically increasing the system utility and complexity.

The laboratory exercise integrates the PLC network controlled conveyor system with the Staubli robot through the use of two signal wires. One wire transmits a signal from PLC-2 to the robot, while a second wire connects an output from the robot to PLC-2. A four sequence process is implemented: the system moves a tool pallet down the conveyor; a signal is sent to the robot to start piston assembly; the piston is assembled and placed on a tool pallet; and the robot sends a signal to PLC-2 to move the pallet back down the conveyor (refer to Figure 4.4). A light connected to PLC-2 activates when the process is completed.

The conveyor is composed of modules created in-house by students, which offer several advantages over procuring pre-constructed commercial conveyors. The design and construction of the segments creates a practical experience for students and provides cost effective solutions. The segments feature caster wheels, attached to the bottom, to aide in reconfiguring the conveyor. This helps to ensure that the case studies can be changed easily. Sensors are attached along the conveyor segments, notably at the ends, to track product movements.



(a) (b)

Figure 4.4: Automotive piston assembly utilizing system integration - (a) automotive piston construction jig, and (b) schematic.

Case Studies

An in-depth semester long project, viewed as a critical course element, allows students to configure and control mechatronic components to create a material handling system. Each study maintains a focus on material handling while incorporating different technologies (color sensing, barcode, RFID) into the laboratory. In this section, two case studies (construction of automotive piston assemblies; color ball order fulfillment system) will be presented and discussed.

Product Creation – Assembly Operation

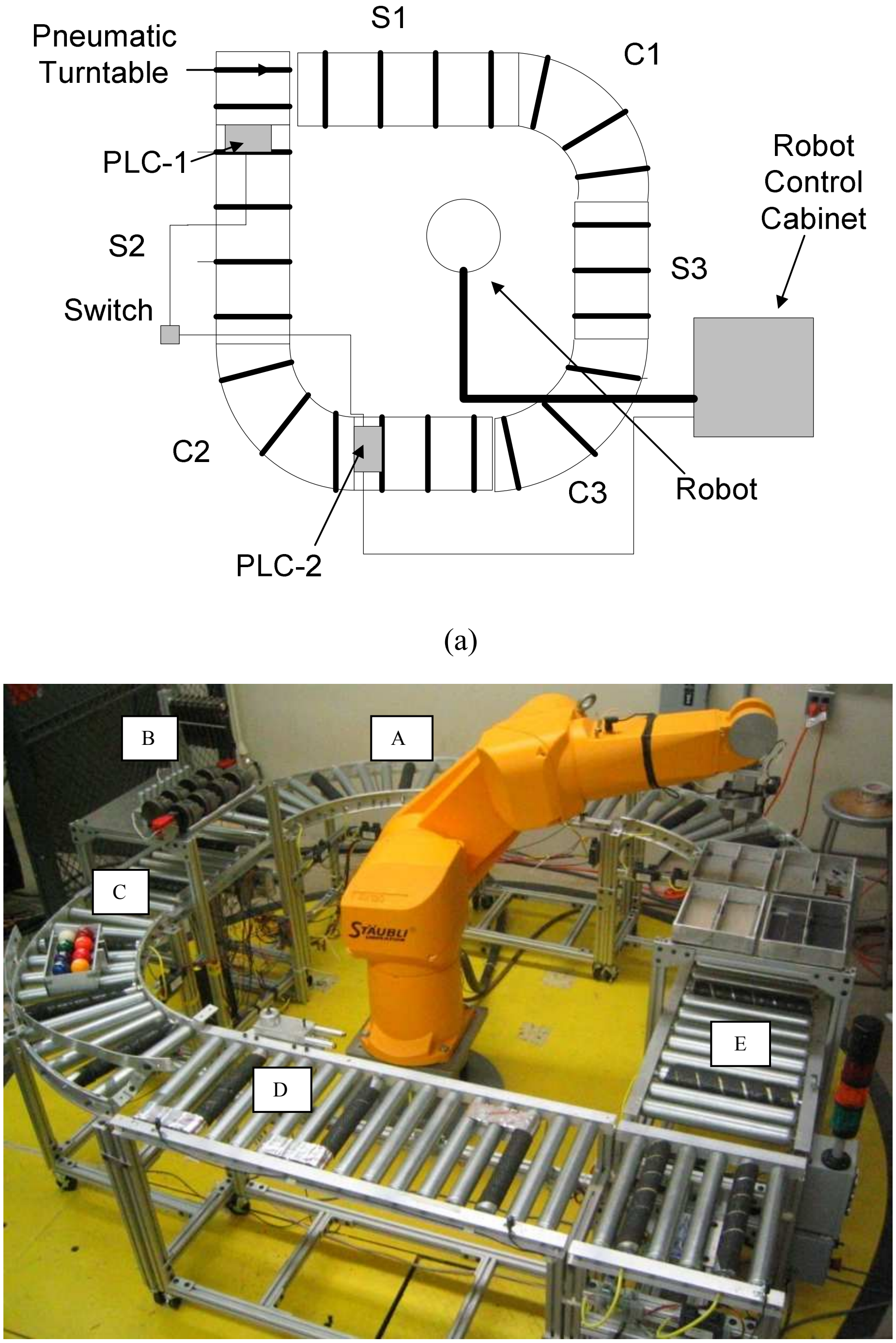
The first study challenges students to create a material handling system to assemble internal combustion engine pistons. To complete this task, teams are required to design, procure, assemble, control, and verify system components. For instance, students fabricate parts, integrate sensors, program the robot, and design the PLC control system. Interpersonal communication skills are practiced throughout the project to ensure the proper timing of events.

In the laboratory space, teams configure the conveyor in an approximately circular shape (refer to Figure 4.5) with three rounded corners and the fourth utilizing a square pneumatic powered 90º turntable. The turntable uses two pneumatic cylinders controlled by solenoid valves and a common manifold; one lifts the rollers up, while the other turns the table 90º. By using the pneumatic cylinders to rotate the table, products can be moved in any direction desired with bi-directional motorized rollers. Two sensors, attached on each end, completed the turn table.

Motorized rollers, powered by individual 24 VDC driver modules, and idler rollers control the movement of objects on the conveyor system. Two control wires from the PLC determined when the given roller is activated and the direction it turns. The powered rollers are wrapped with a friction tape to facilitate object movement. Infrared sensors are attached at various positions along the conveyor.

The operation of the conveyor system is controlled by two Allen-Bradley MicroLogix 1500 PLCs connected over an Ethernet network. Each PLC controls one half of the system. Specifically, PLC-1 controls the segments containing points D and E, and PLC-2 controls the segments containing points A and C. The conveyor modules' inputs and outputs are distributed between the two PLCs. For example, the light stack is connected to PLC-1 while PLC-2 is interfaced to the robot control cabinet. This allows for ‘closed-loop’ operation of the material handling cell. A computer located nearby allows students to program the PLCs and to observe their ‘on-line’ operation.

The system functions in the following manner (refer to Figure 4.5b). First, the robot picks up a pallet from a storage tray and places it on the conveyor at Point A. Next, an infrared sensor connected to PLC-2 indicates that the pallet is securely placed down and activates the conveyor rollers. When the pallet reaches the ‘Queue Point’ (Point C), the program checks to determine if another pallet, or object, is at the ‘Assembly Location’ (Point D). If there is an object present, then the pallet temporarily stops. Once the ‘Assembly Location’ is clear, the system continues to send the pallet down the conveyor. In this manner, a queue is formed resulting in a pallet always being ready for loading with the next piston assembly. Point C (Queue Point) is controlled by PLC-2, while Point D (Assembly Location) is connected to PLC-1, such that communication over the network is necessary to ensure proper queuing. A guard rail is mounted for pallet positional accuracy and orientation as it approaches the ‘Assembly Location’. Once the pallet reaches the ‘Assembly Location’, a sensor connected to PLC-1 is activated, which triggers a signal to the robot via the PLC network. If for any reason the pallet does not reach the ‘Assembly Location’, then the robot does not attempt to load the piston.



(a)

(b)

Figure 4.5: Product creation system - (a) schematic, and (b) robot loading pistons into pallet with start point [A], parts tray [B], queue point [C], assembly point [D], and destination point [E].

The piston parts are available on a “Parts Tray” (Point B), located above one of the conveyor segments due to the robot’s limited reach. A piston assembly jig was created and attached to the conveyor near the ‘Assembly Location’. This jig assists the robot in assembling the pistons. A photoelectric sensor detects the proper placement of the wrist pin. If the wrist pin is not inserted correctly, then the piston could break apart during system operation leading to product damage and a potentially unsafe environment. If the pin is not fully inserted, the sensor does not activate and the robot is programmed to halt and wait for user input. Once completed, the pistons are placed by the robot onto pallets (two pistons per pallet) and a signal is sent to PLC-2, which communicates over the network to PLC-1 to start the conveyor system to move the pallet. The pallet continues to the turntable, and around the corner to the ‘Destination Point’ (Point E).

The complexity of this assignment mandates that the teams work efficiently. Proper communication is critical within and between design teams. Students are able to take pride in their own individual contributions to the overall effort.

Product Fulfillment – Sorting Operation

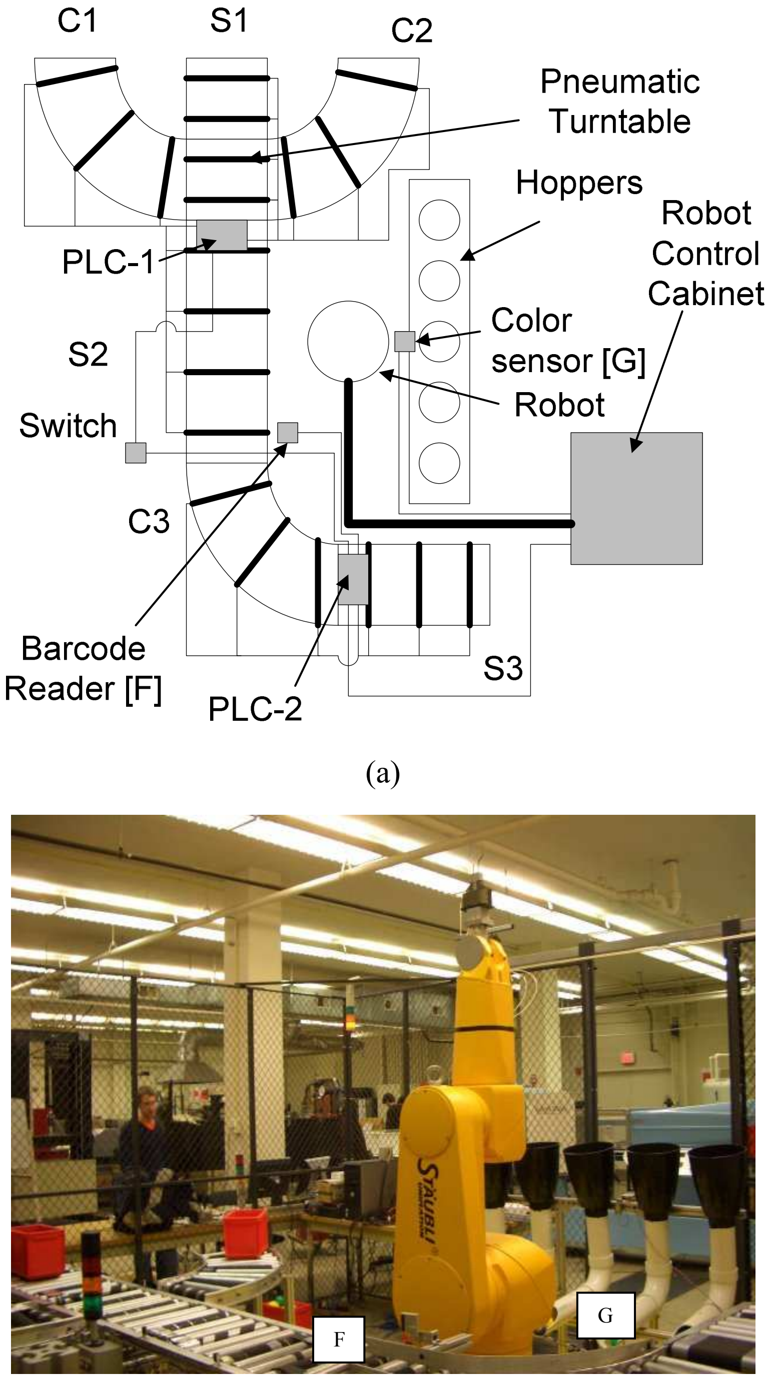
A modular order fulfillment system, in which containers are filled with plastic colored balls, is examined for the second case study. Each container is filled with varying numbers of red, yellow, blue, and/or green balls based on information stored in barcodes affixed to the containers. The conveyor system is configured into a trident shape (refer to Figure 4.6), so that three different destinations can be achieved to emulate a shipping department. The project is divided into two sub-tasks: one team focuses on determining the color of the ball and properly sorting it; the second group controls the conveyor system and utilizes the barcode reader to determine the colored balls that complete a particular order. Again, internal and external team communication skills are essential to ensure that the project is completed satisfactorily.

A pushbutton triggers the system to activate motorized rollers on conveyor segment ‘S3’ to move an order container down the conveyor line (refer to Figure 4.6a). Once the container passes an infrared sensor, PLC-2 activates a Keyence barcode reader (Keyence #BL-180). The reader is connected to a processing unit (Keyence #DV-90), which stores four barcodes in its internal memory. When the reader scans a barcode, the processing unit activates an output that corresponds to that particular barcode. By monitoring these outputs, PLC-2 knows which barcode is scanned and uses this data to fill a container with the proper number of each color ball. After the barcode is read, the conveyor system halts the container at a point within the robot’s reach.

The system is initialized with the multiple sized colored balls randomly located into the main hopper. To increase system efficiency, it was determined that the balls should be pre-sorted into four smaller auxiliary side hoppers; each hopper contains a designated color.

A Keyence color sensor (Keyence # CZ-32) and control module (Keyence # CZ-K1) are connected to the system. The control module conditions the sensor signal, determines the color from a preset list in memory, and activates a particular output. The preset list is manually set so that any one of the four ball colors can be sensed. The color sensor utilizes an LED to observe the reflected light waves; the sensor is mounted behind

Lexan for protection. Once the ball’s color in the output feed of the hopper is determined, it is placed in one of four smaller hoppers by the robot. If the ball color cannot be sensed, either due to the ball not being in the proper location to be sensed or the sensor not being able to get a clean read, the ball is picked up and returned back into the main hopper. The misreading frequency is small enough that this is an acceptable error handling method. The individual color ball hoppers are programmed to accommodate a maximum number of balls. The robot counts the number of balls in each hopper, stores this number in its internal memory, and once all the hoppers are full of balls, the robot transmitted a ‘Balls are Sorted’ signal to PLC-2.



(a)

(b)

Figure 4.6: Order fulfillment system - (a) interconnection of three straight, three curved, and 90º turntable conveyor sections with robot, and (b) photograph with barcode reader [F] and color sensor [G].

When PLC-2 receives the ‘Balls are Sorted’ signal, a binary code is sent back to the robot to specify the ball color to retrieve. The binary code architecture uses three wires to specify four colors (two wires for the binary code; one wire for the ‘Data Ready’ signal). The code is received by the robot, and promptly ‘Acknowledged’ (with dedicated data signal). The robot then retrieves a ball from one of the individual color hoppers and places it in the container. Once the acknowledge signal is sent, the PLC transmits a request for the next color ball. This process continues until the order is filled. Upon order completion, the system transports the filled container on the conveyor line to one of three destinations, per the barcode. The pneumatic turntable is used to change the direction of container transport to one of three destinations. Next, another container is sent down the line, and the process is repeated.

If at any time the number of balls in a hopper goes to zero, then the system pauses and the robot starts sorting balls from the main hopper into the individual hoppers until the maximum number has again been reached. This ensures that there are sufficient balls in the hoppers to complete the given order.

Summary

The mechatronics discipline incorporates principles from multiple engineering fields to create integrated systems that accomplish specific tasks. Typically, universities have offered few courses which introduce these mechatronic technologies and apply them to industrial systems. The laboratory experiments developed for this Mechatronics and Material Handling course introduce students to PLC networking, industrial robotics, and system integration which culminate in a case study. Using a team approach to accomplish these tasks allows students to practice the various skills necessary to successfully complete a multi-disciplinary system. The completion of the laboratory exercises and experimental case study, coupled with team building skills, better equips students for the competitive global marketplace and work environment.

CHAPTER FIVE

CONCLUSION

The prevalent use of mechatronic technologies in industry makes their knowledge and operational understanding critical to present day engineers. Many universities lack the curriculum to appropriately demonstrate specific technologies and possible material handling schemes. Clemson University created the Mechatronics and Material Handling Course and accompanying laboratory to equip students with new skill sets.

A questionnaire was created to track student knowledge over a broad range of mechatronic topics. Eight of the twenty one questions focused on engineering topics covering various disciplines such as electrical, mechanical, and industrial engineering. Other questions focused on teamwork, personal leadership, and prior education. Questions ranged from “Do you prefer to work in a group or individual setting? Why?” to “What type of motor would be used for a residential ceiling fan?” A five point scale was used to grade the questions, with a five being correct. The average for the engineering questions for the pre-course questionnaire was 3.08. The average for the post-course questions increased to 4.58. While engineering showed the greatest increase, each subject showed significant improvement. An end of course survey indicated students enjoyed the laboratory and appreciated the opportunity to create such unique systems. The few negative comments were focused on the changing course requirements, which were typical of a class being taught for the first time. An independent Technical Advisory

Panel (TAP) comprised of seven industry engineers agreed with the core fundamentals being taught. Requests for new technologies and stricter limits (i.e., costs and time) were the only suggested improvements.

In this thesis, eight laboratory experiments were examined in which students explore different mechatronic technologies. Once completed, the students integrate various mechatronic components to create a material handling case study. This semester-long project allows students to visualize how a device specific function is integrated into a system and the power of combining multiple units together.

The laboratories and the case studies were designed such that teamwork and communication were critical to accomplishing the given task. This reinforced the group concept which is required due to the complexity of mechatronic systems. All materials used in the laboratory experiments were devices commonly used in industry, and often times at the forefront of available technology. Focusing on a specific task, such as a material handling process, allows for proper techniques of creating a system to be developed, which can be transferred to a wide range of systems in the future. The advantage of the Mechatronics Laboratory lies in its ability to assist students in applying mechatronic solutions to real world problems.

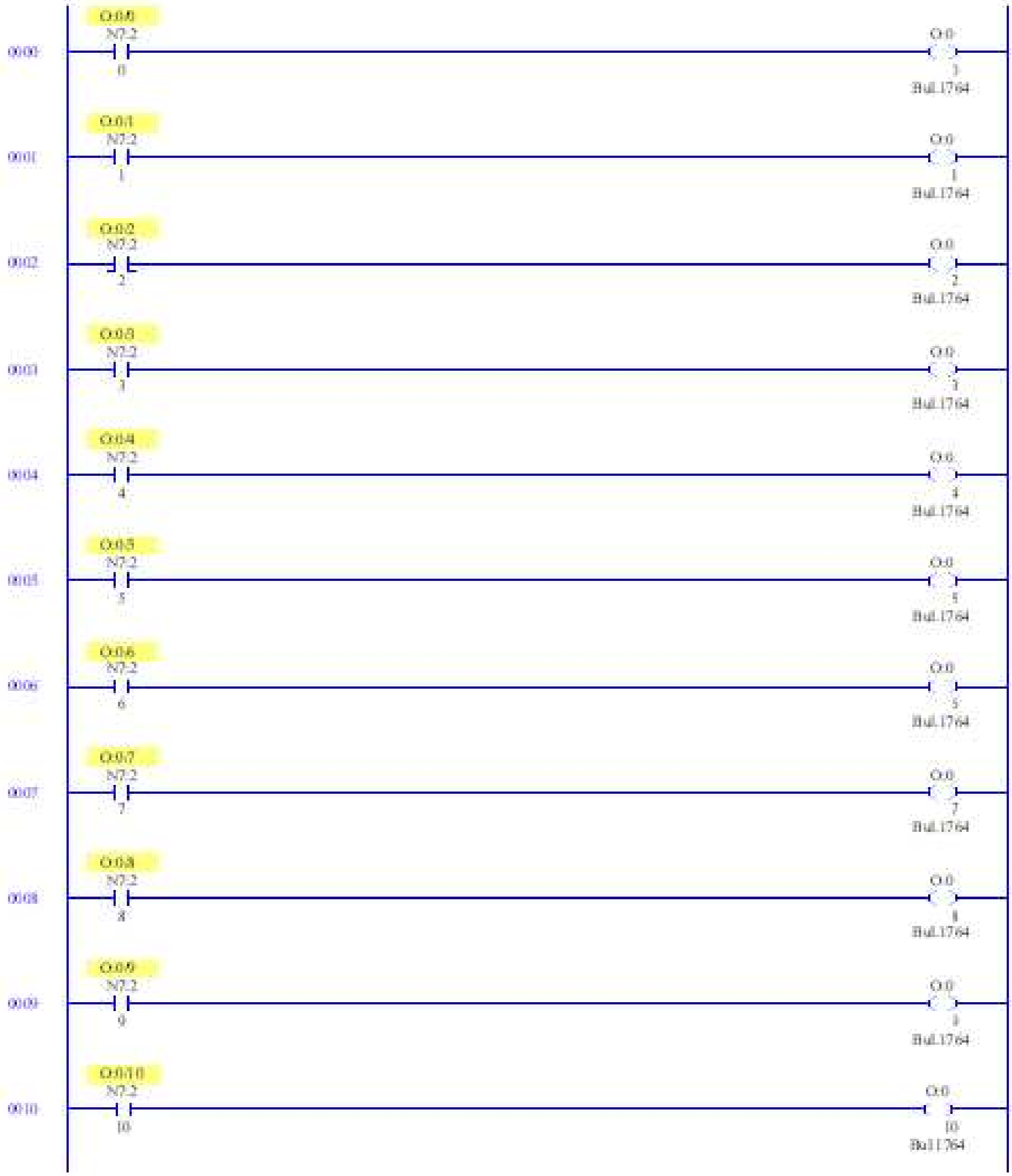
APPENDICES

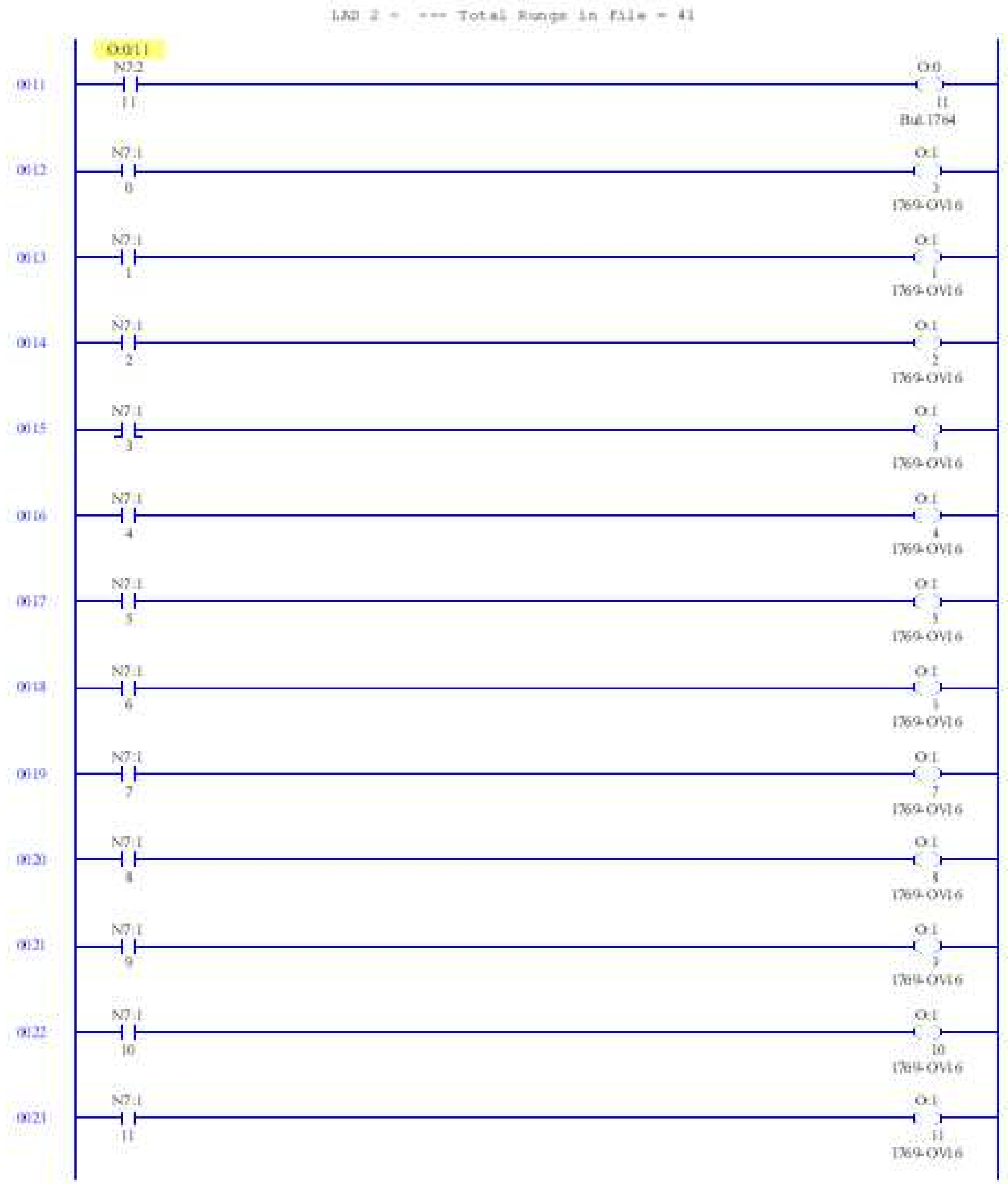
Appendix A

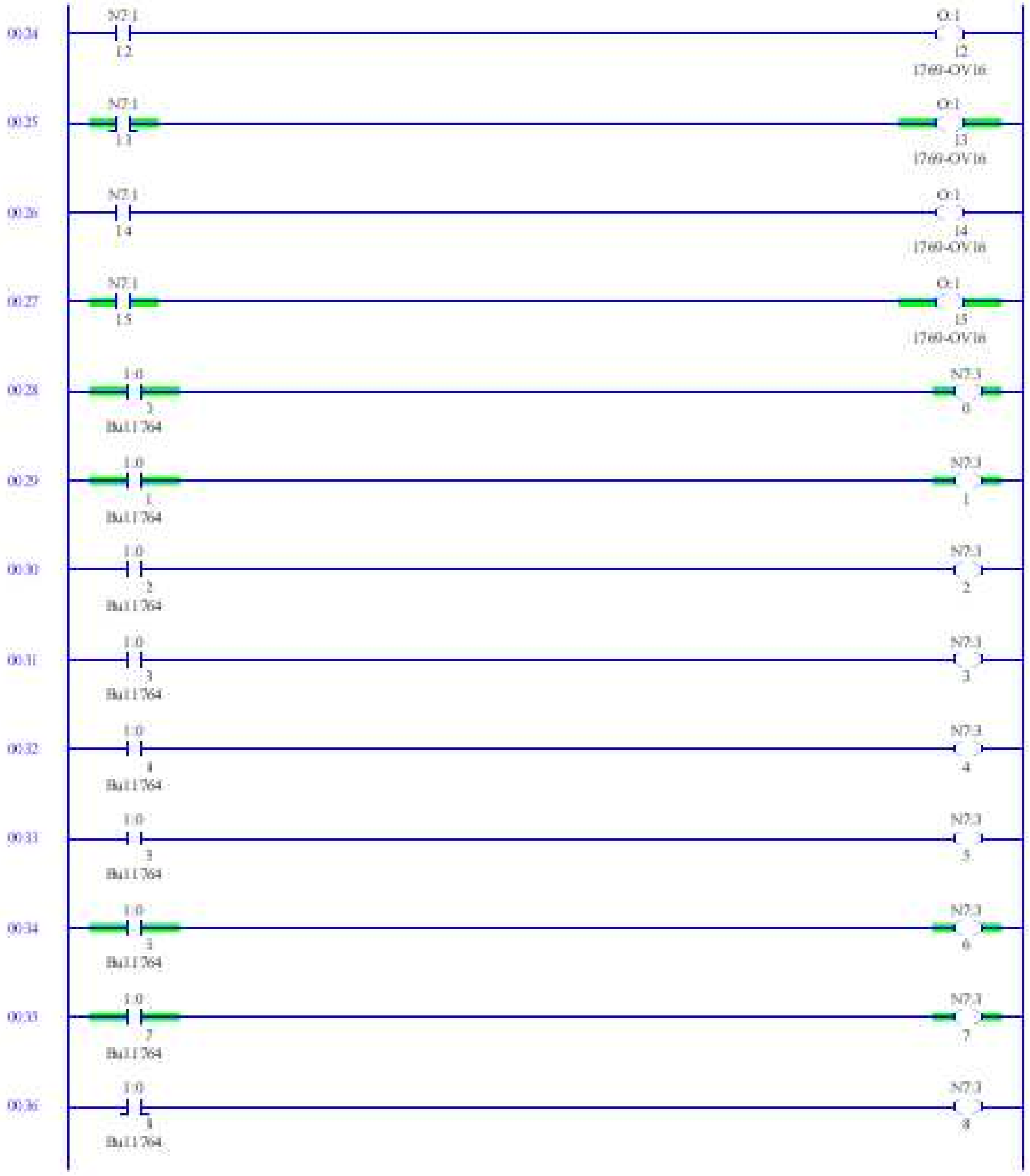
PLC Code for Order Fulfillment System

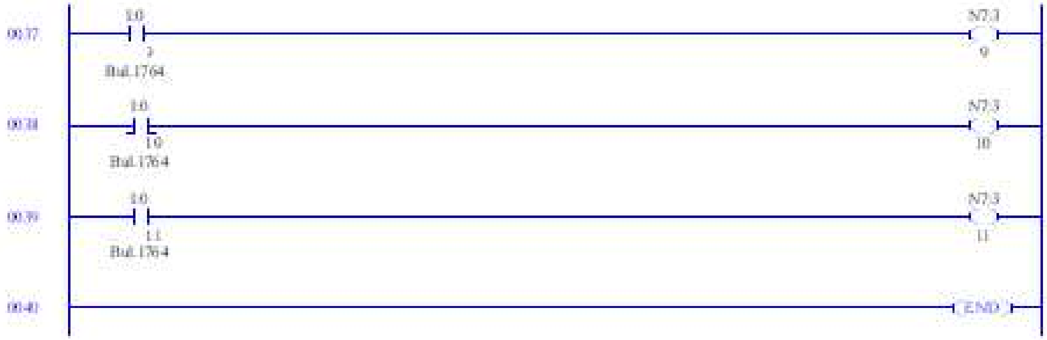
The following code is for two PLCs connected together through an Ethernet/IP Protocol Network. The first PLC code shown transfers all inputs and outputs to an Integer file, which is then transmitted to the second PLC. This PLC then contains the control program, which uses its own inputs and outputs, in conjunction with the transmitted data, to determine the color of ball needed to fulfill an order. This second PLC is also connected to a barcode reader which informs the system on the specific colors needed for the order. The code was written by Tate Boulware with assistance from Trey Shirley.

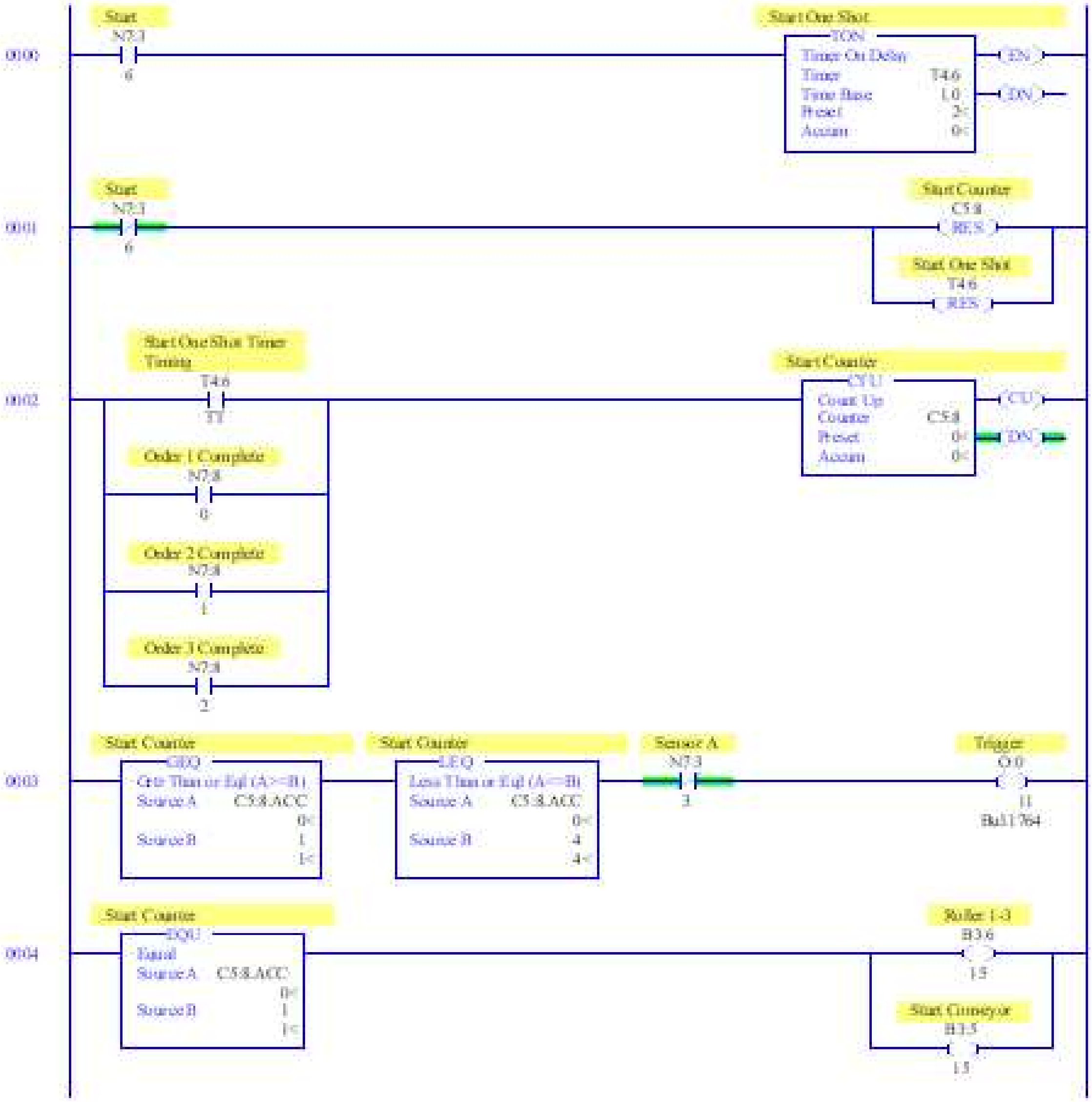
LAD 2 - --- Total Rungs in File = 41

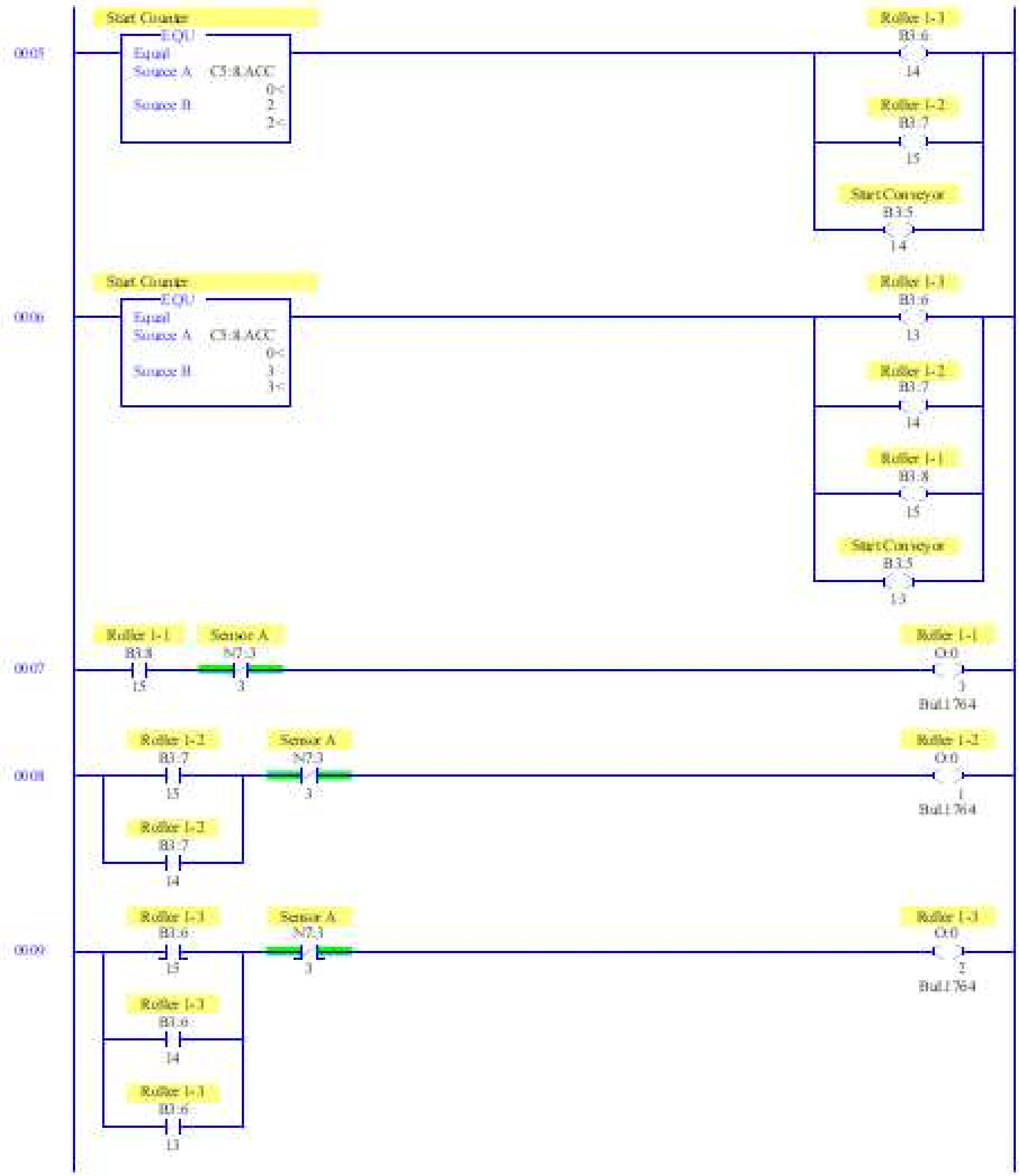


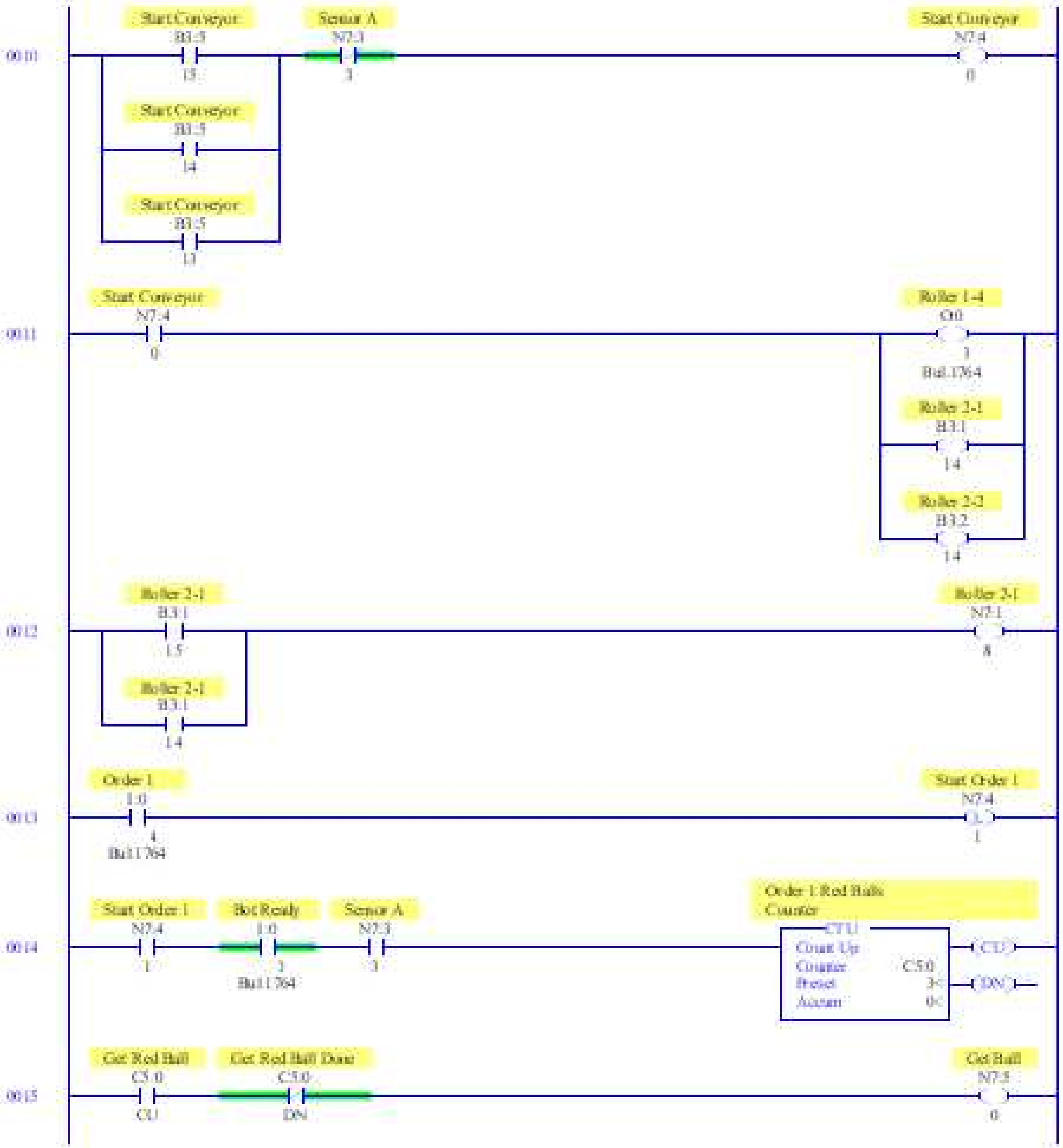

LAD 2 - --- Total Rungs in File = 41
O:0/11
0011
N7:2
11
O:0
11
Bul.1764
0012
N7:1
0
O:1
0
1769-OV16
0013
N7:1
1
O:1
1
1769-OV16
0014
N7:1
2
O:1
2
1769-OV16
0015
N7:1
3
O:1
3
1769-OV16
0016
N7:1
4
O:1
4
1769-OV16
0017
N7:1
5
O:1
5
1769-OV16
0018
N7:1
6
O:1
6
1769-OV16
0019
N7:1
7
O:1
7
1769-OV16
0020
N7:1
8
O:1
8
1769-OV16
0021
N7:1
9
O:1
9
1769-OV16
0022
N7:1
10
O:1
10
1769-OV16
0023
N7:1
11
O:1
11
1769-OV16

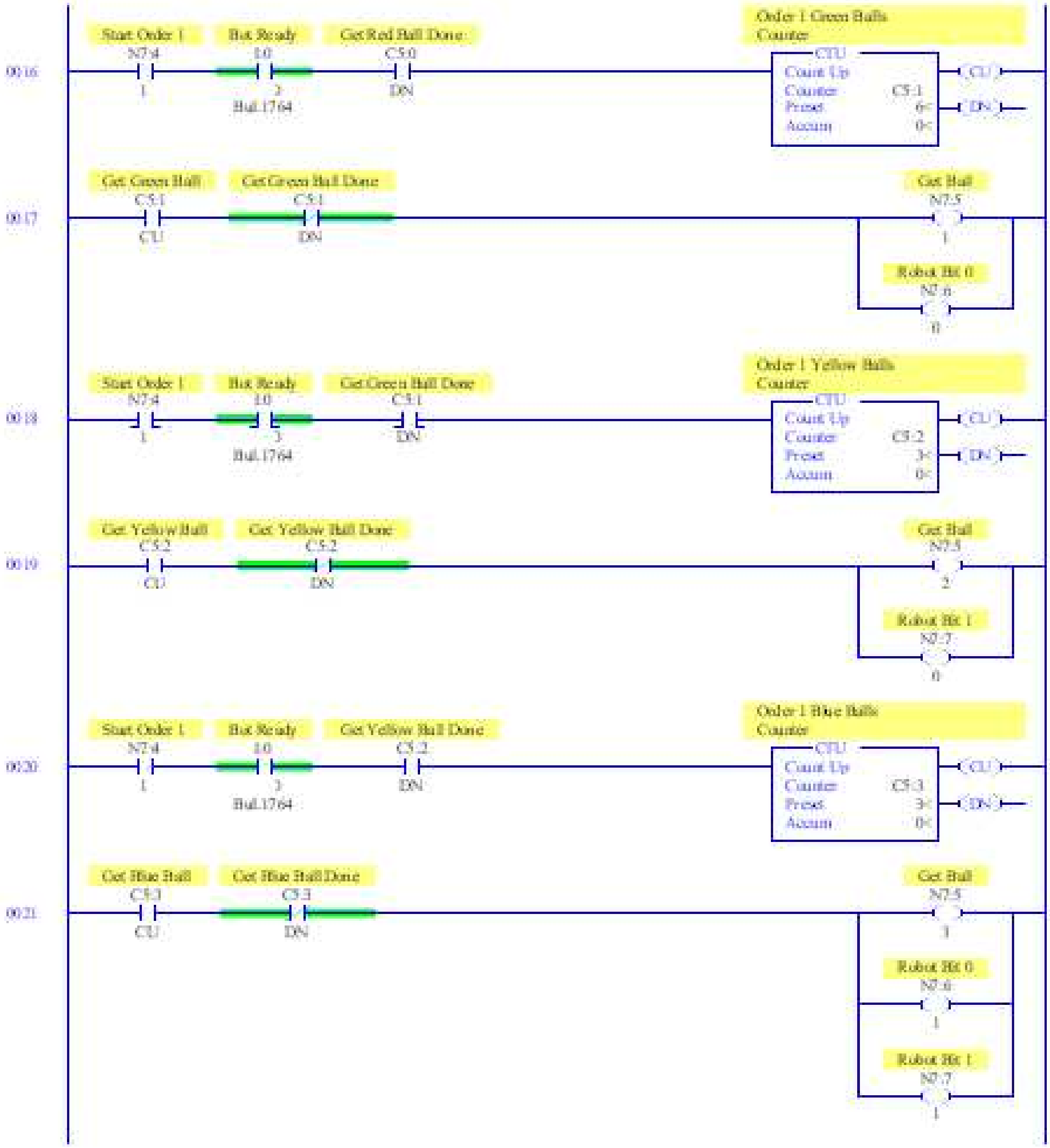

0024
N7:1
12
O:1
12
1769-OV16
0025
N7:1
13
O:1
13
1769-OV16
0026
N7:1
14
O:1
14
1769-OV16
0027
N7:1
15
O:1
15
1769-OV16
0028
I:0
0
Bul.1764
N7:3
0
0029
I:0
1
Bul.1764
N7:3
1
0030
I:0
2
Bul.1764
N7:3
2
0031
I:0
3
Bul.1764
N7:3
3
0032
I:0
4
Bul.1764
N7:3
4
0033
I:0
5
Bul.1764
N7:3
5
0034
I:0
6
Bul.1764
N7:3
6
0035
I:0
7
Bul.1764
N7:3
7
0036
I:0
8
Bul.1764
N7:3
8

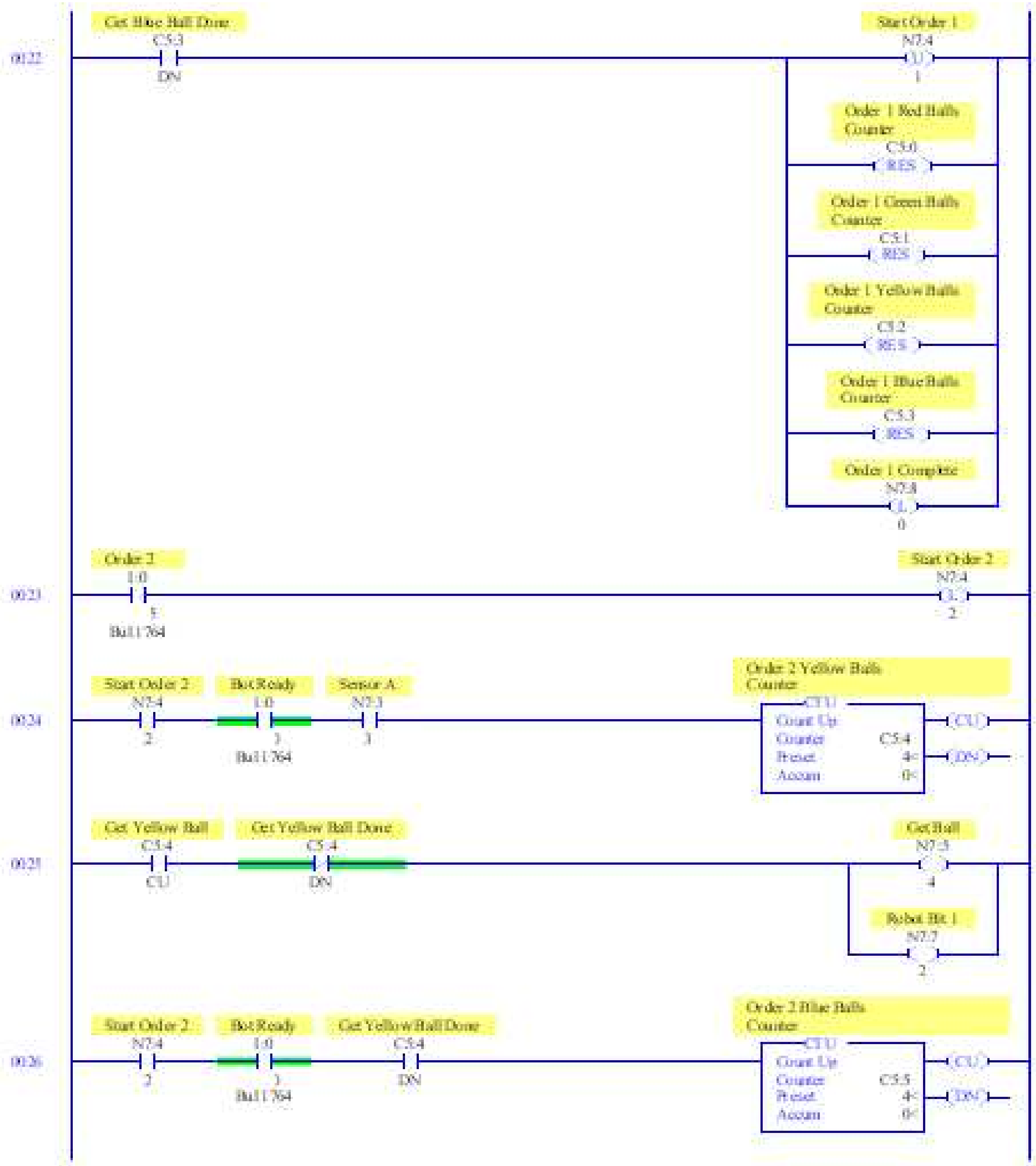

0037
I:0
3
Bul.1764
N7:3
9
0038
I:0
10
Bul.1764
N7:3
10
0039
I:0
11
Bul.1764
N7:3
11
0040
END


0000
Start
N7:3
6
Start One Shot
TON
Timer On Delay
Timer T4:6
Time Base 1.0
Preset 2<
Accum 0<
EN
DN
0001
Start
N7:3
6
Start Counter
C5:8
RES
Start One Shot
T4:6
RES
0002
Start One Shot Timer Timing
T4:6
TT
Order 1 Complete
N7:8
0
Order 2 Complete
N7:8
1
Order 3 Complete
N7:8
2
Start Counter
CTU
Count Up
Counter C5:8
Preset 0<
Accum 0<
CU
DN
0003
Start Counter
GEQ
Grtr Than or Eql (A>=B)
Source A C5:8.ACC
0<
Source B 1
1<
Start Counter
LEQ
Less Than or Eql (A<=B)
Source A C5:8.ACC
0<
Source B 4
4<
Sensor A
N7:3
3
Trigger
O:0
11
Bul.1764
0004
Start Counter
EQU
Equal
Source A C5:8.ACC
0<
Source B 1
1<
Roller 1-3
B3:6
15
Start Conveyor
B3:5
15

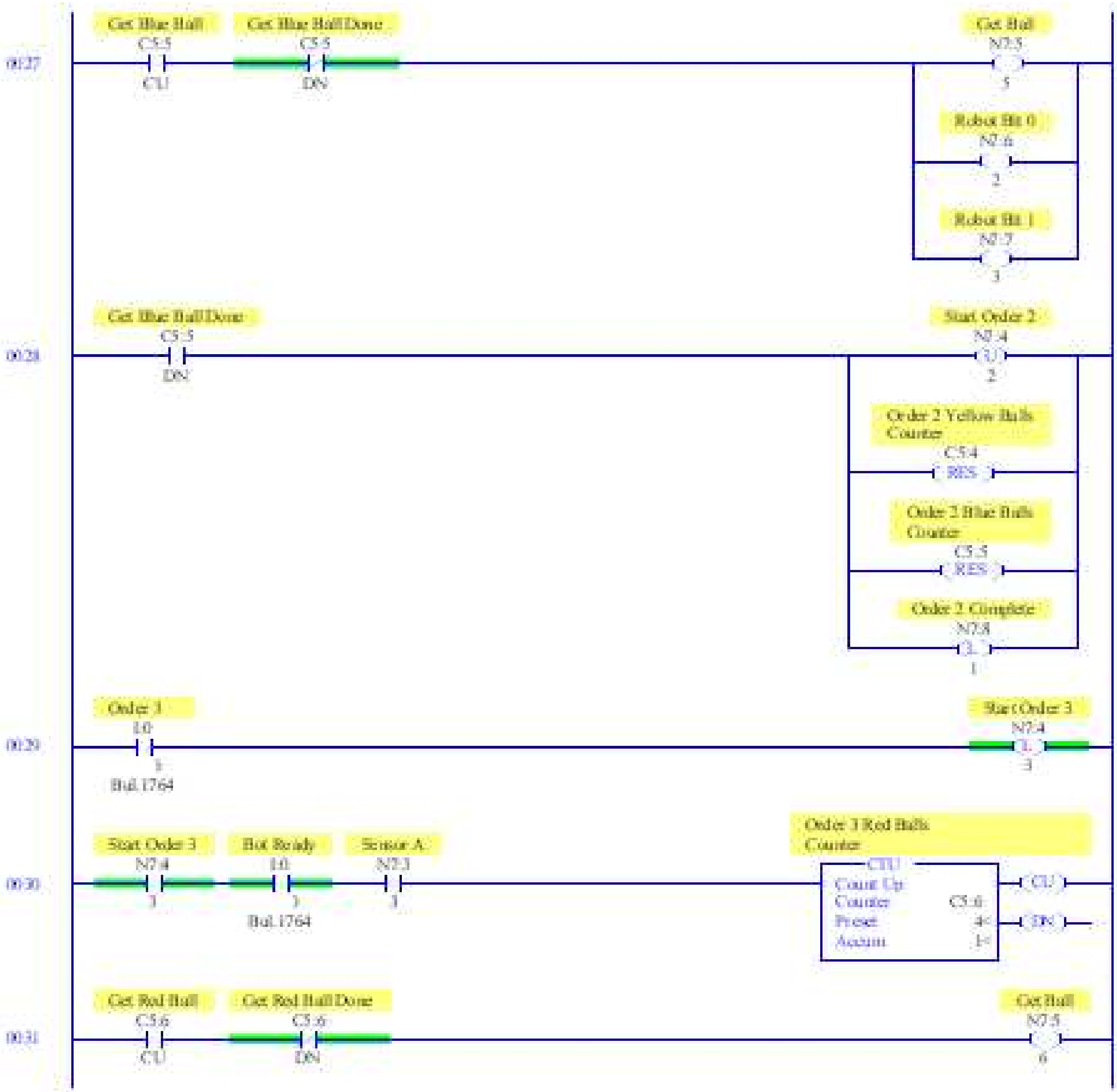

0005
Start Counter
EQU
Equal
Source A C5:8.ACC
0<
Source B 2
2<
Roller 1-3
B3:6
14
Roller 1-2
B3:7
15
Start Conveyor
B3:5
14
0006
Start Counter
EQU
Equal
Source A C5:8.ACC
0<
Source B 3
3<
Roller 1-3
B3:6
13
Roller 1-2
B3:7
14
Roller 1-1
B3:8
15
Start Conveyor
B3:5
13
0007
Roller 1-1
B3:8
15
Sensor A
N7:3
3
Roller 1-1
O:0
3
Bul.1764
0008
Roller 1-2
B3:7
15
Roller 1-2
B3:7
14
Sensor A
N7:3
3
Roller 1-2
O:0
1
Bul.1764
0009
Roller 1-3
B3:6
15
Roller 1-3
B3:6
14
Roller 1-3
B3:6
13
Sensor A
N7:3
3
Roller 1-3
O:0
2
Bul.1764

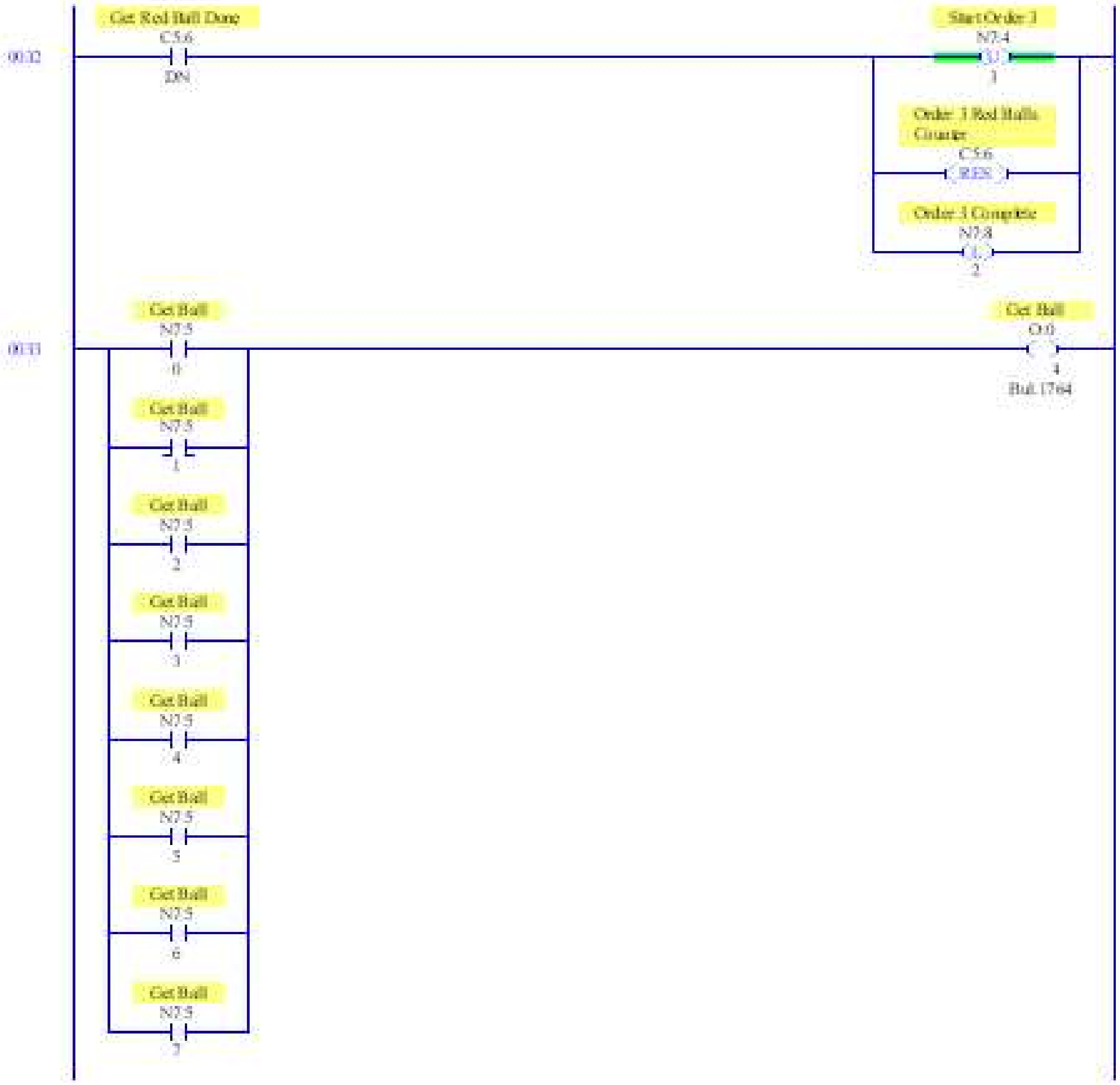

0010
Start Conveyor
B3:5
13
Sensor A
N7:3
3
Start Conveyor
N7:4
0
Start Conveyor
B3:5
14
Start Conveyor
B3:5
13
0011
Start Conveyor
N7:4
0
Roller 1-4
O:0
1
Bul.1764
Roller 2-1
B3:1
14
Roller 2-2
B3:2
14
0012
Roller 2-1
B3:1
15
Roller 2-1
N7:1
8
Roller 2-1
B3:1
14
0013
Order 1
I:0
4
Bul.1764
Start Order 1
N7:4
L
1
0014
Start Order 1
N7:4
1
Bot Ready
I:0
2
Bul.1764
Sensor A
N7:3
3
Order 1 Red Balls
Counter
CTU
Count Up
Counter C5:0
Preset 3<
Accum 0<
CU
DN
0015
Get Red Ball
C5:0
CU
Get Red Ball Done
C5:0
DN
Get Ball
N7:5
0

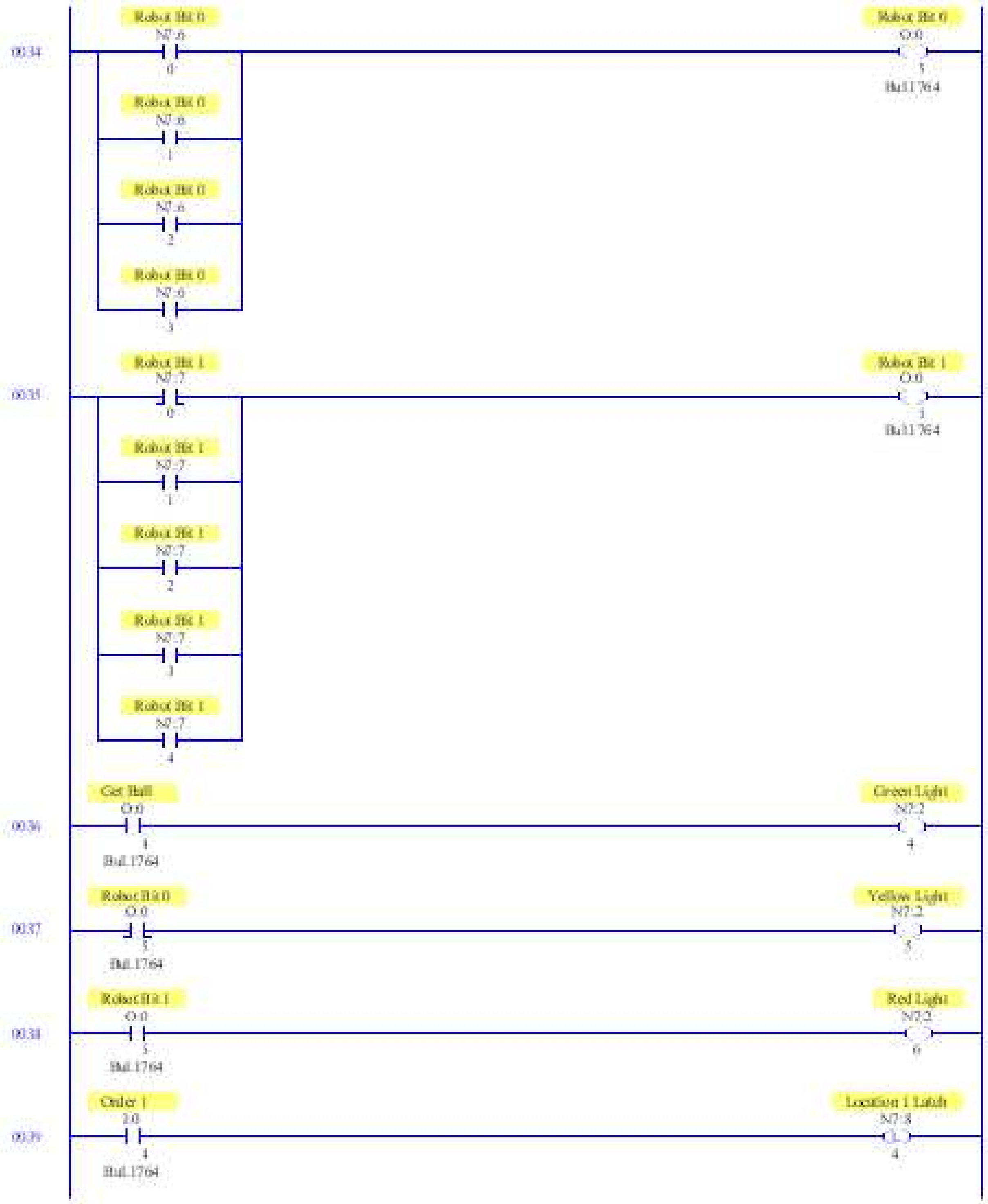

0016
Start Order 1
N7:4
1
Bit Ready
I:0
2
Bul.1764
Get Red Ball Done
C5:0
DN
Order 1 Green Balls Counter
CTU
Count Up
Counter C5:1
Preset 6<
Accum 0<
CU
DN
0017
Get Green Ball
C5:1
CU
Get Green Ball Done
C5:1
DN
Get Ball
N7:5
1
Robot Bit 0
N7:6
0
0018
Start Order 1
N7:4
1
Bit Ready
I:0
3
Bul.1764
Get Green Ball Done
C5:1
DN
Order 1 Yellow Balls Counter
CTU
Count Up
Counter C5:2
Preset 3<
Accum 0<
CU
DN
0019
Get Yellow Ball
C5:2
CU
Get Yellow Ball Done
C5:2
DN
Get Ball
N7:5
2
Robot Bit 1
N7:7
0
0020
Start Order 1
N7:4
1
Bit Ready
I:0
3
Bul.1764
Get Yellow Ball Done
C5:2
DN
Order 1 Blue Balls Counter
CTU
Count Up
Counter C5:3
Preset 3<
Accum 0<
CU
DN
0021
Get Blue Ball
C5:3
CU
Get Blue Ball Done
C5:3
DN
Get Ball
N7:5
3
Robot Bit 0
N7:6
1
Robot Bit 1
N7:7
1

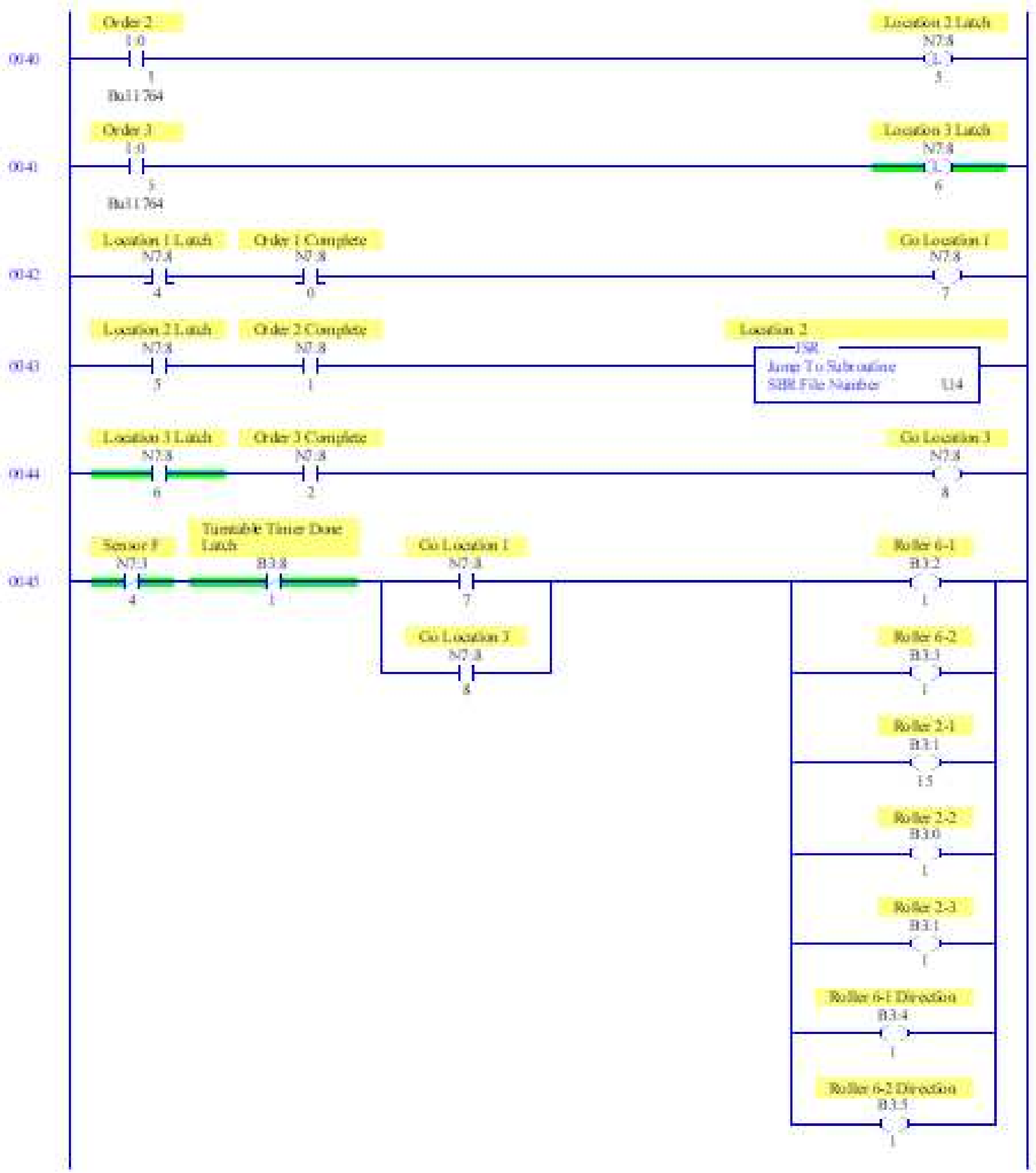


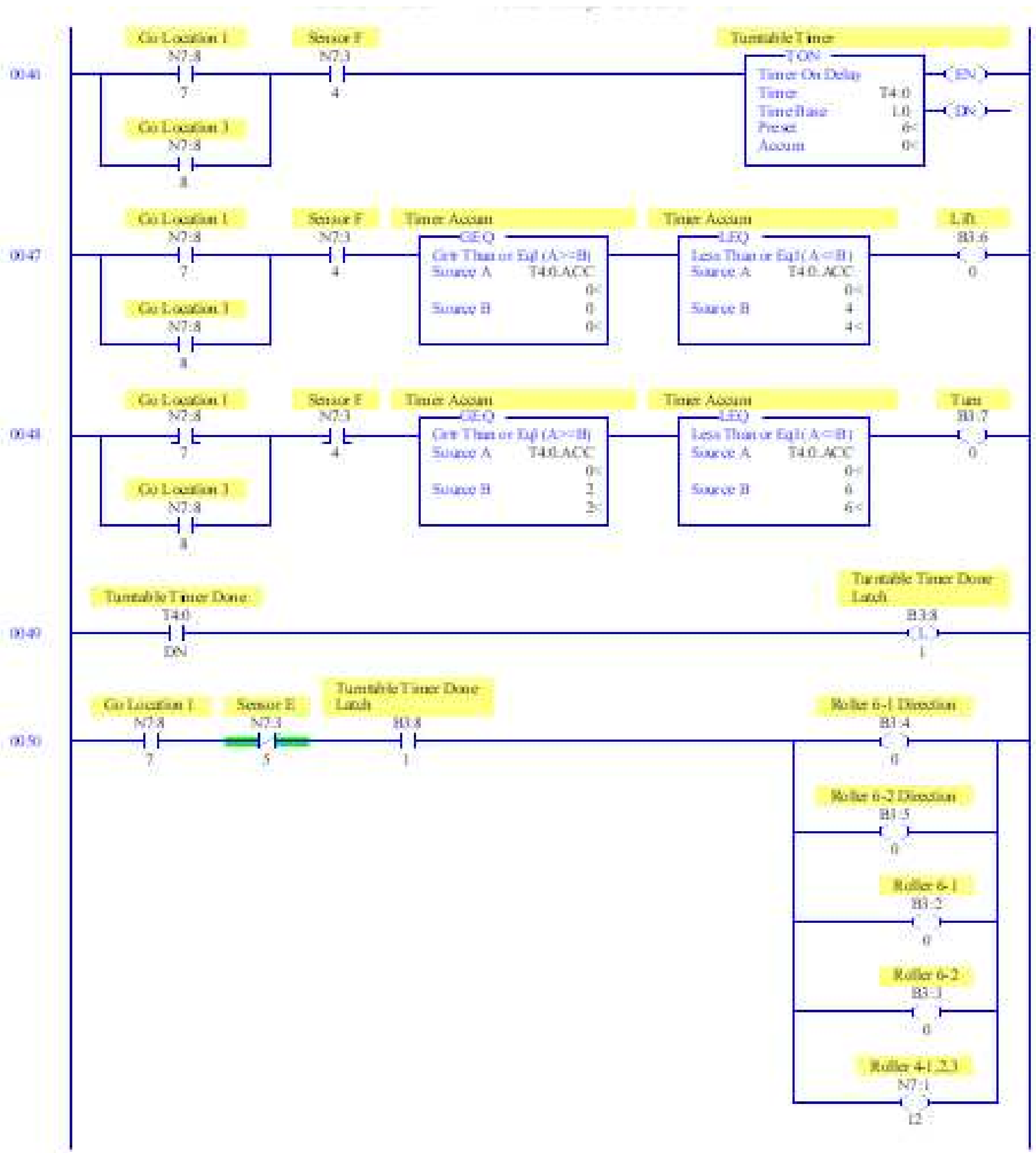
0022
Get Blue Ball Done
C5:3
DN
Start Order 1
N7:4
U
1
Order 1 Red Balls Counter
C5:0
RES
Order 1 Green Balls Counter
C5:1
RES
Order 1 Yellow Balls Counter
C5:2
RES
Order 1 Blue Balls Counter
C5:3
RES
Order 1 Complete
N7:8
L
0
0023
Order 2
I:0
5
Bul.1764
Start Order 2
N7:4
L
2
0024
Start Order 2
N7:4
2
Bot Ready
I:0
3
Bul.1764
Sensor A
N7:3
3
Order 2 Yellow Balls Counter
CTU
Count Up
Counter C5:4
Preset 4<
Accum 0<
CU
DN
0025
Get Yellow Ball
C5:4
CU
Get Yellow Ball Done
C5:4
DN
Get Ball
N7:3
4
Robot Bit 1
N7:7
2
0026
Start Order 2
N7:4
2
Bot Ready
I:0
3
Bul.1764
Get Yellow Ball Done
C5:4
DN
Order 2 Blue Balls Counter
CTU
Count Up
Counter C5:5
Preset 4<
Accum 0<
CU
DN

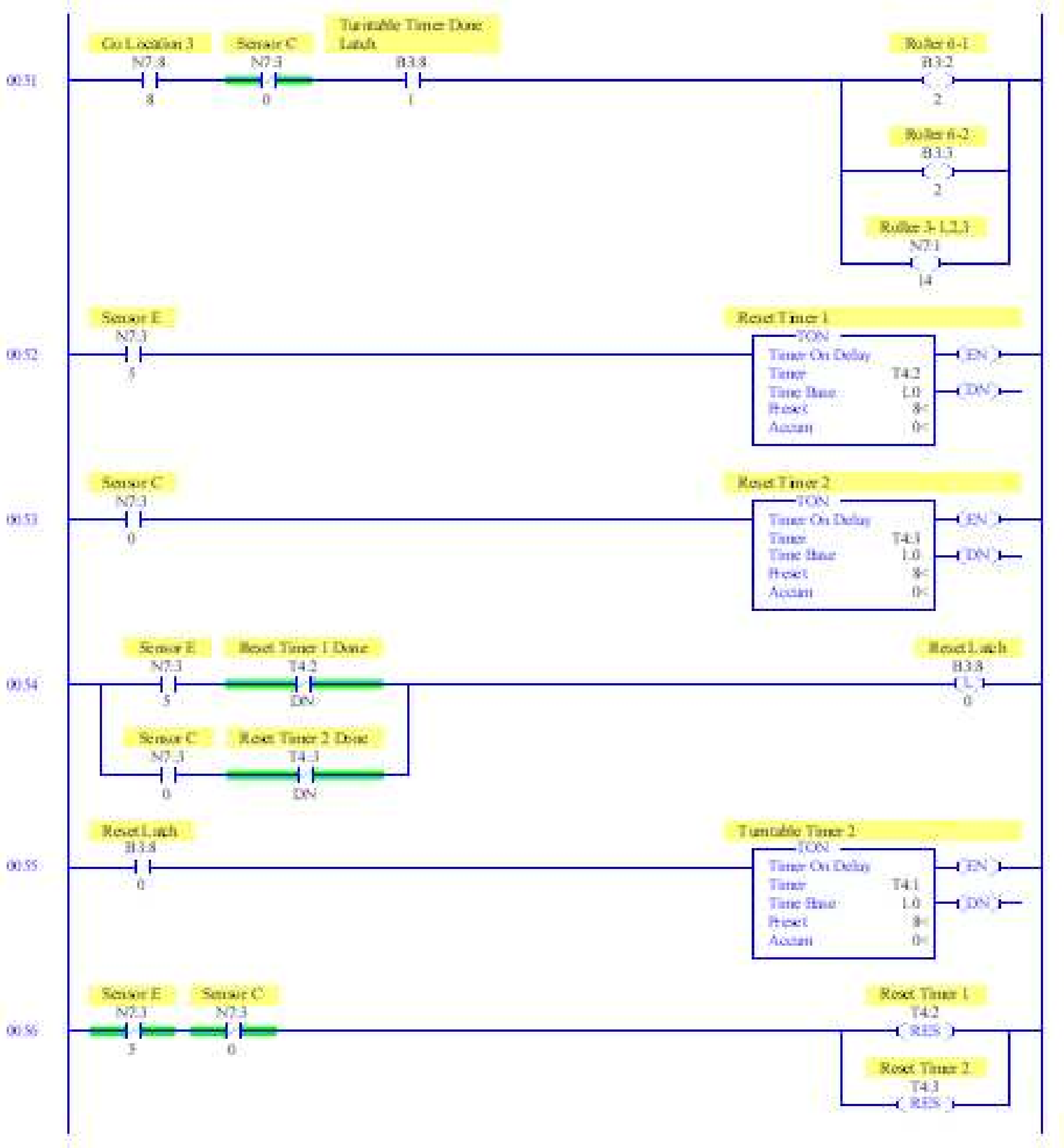

0027
Get Blue Ball
C5:5
CU
Get Blue Ball Done
C5:5
DN
Get Ball
N7:5
5
Robot Bit 0
N7:6
2
Robot Bit 1
N7:7
3
0028
Get Blue Ball Done
C5:5
DN
Start Order 2
N7:4
U
2
Order 2 Yellow Balls Counter
C5:4
RES
Order 2 Blue Balls Counter
C5:5
RES
Order 2 Complete
N7:8
L
1
0029
Order 3
I:0
3
Bul.1764
Start Order 3
N7:4
L
3
0030
Start Order 3
N7:4
3
Bot Ready
I:0
3
Bul.1764
Sensor A
N7:3
3
Order 3 Red Balls Counter
CTU
Count Up
Counter
C5:6
Preset
4<
Accum
1<
CU
DN
0031
Get Red Ball
C5:6
CU
Get Red Ball Done
C5:6
DN
Get Ball
N7:5
6


0032
Get Red Ball Done
C5:6
DN
Start Order 3
N7:4
U
1
Order 3 Red Balls Counter
C5:6
RES
Order 3 Complete
N7:8
L
2
0033
Get Ball
N7:5
0
Get Ball
N7:5
1
Get Ball
N7:5
2
Get Ball
N7:5
3
Get Ball
N7:5
4
Get Ball
N7:5
5
Get Ball
N7:5
6
Get Ball
N7:5
7
Get Ball
O:0
4
Bul.1764

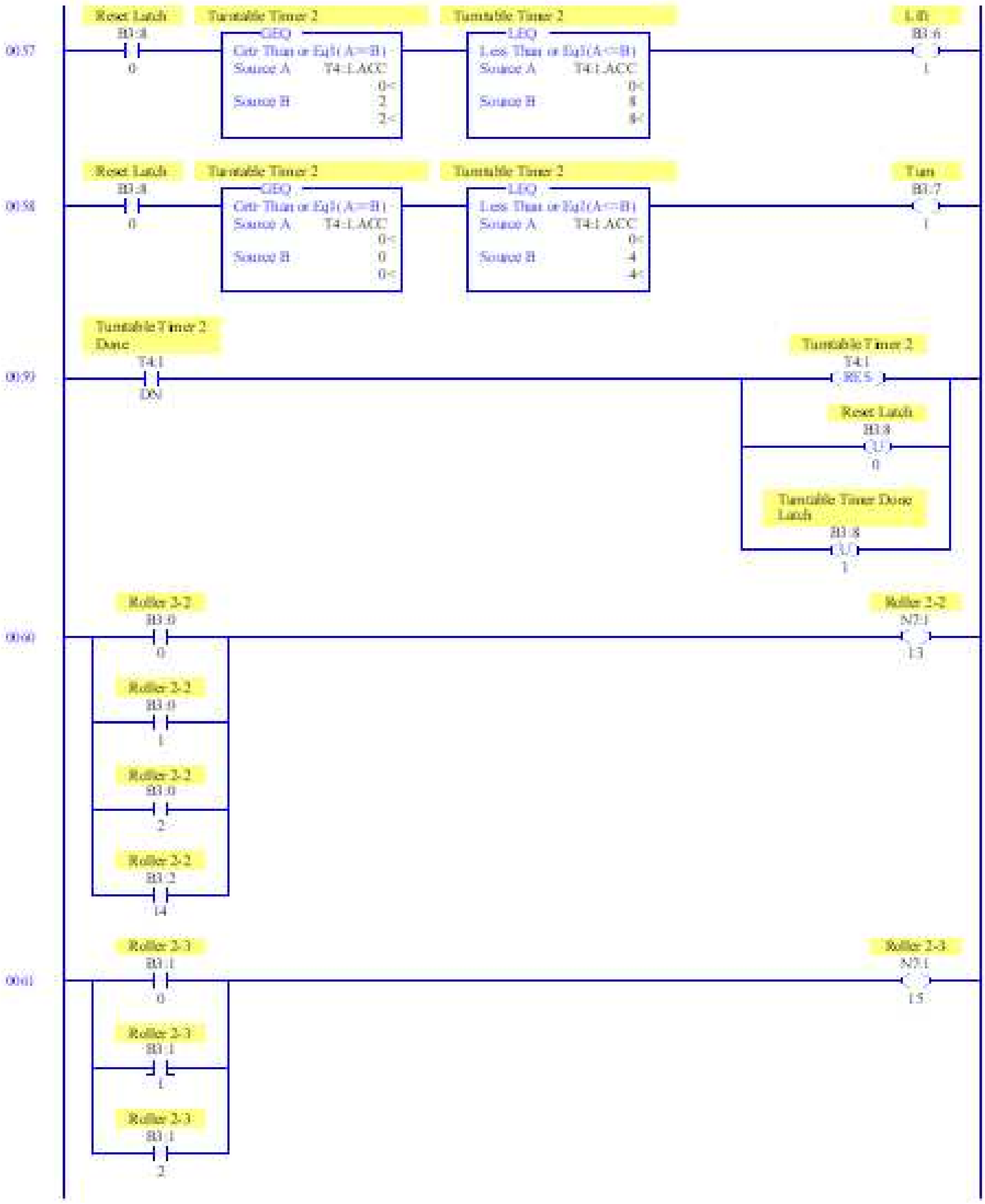

0034
Robot Bit 0
N7:6
0
Robot Bit 0
N7:6
1
Robot Bit 0
N7:6
2
Robot Bit 0
N7:6
3
Robot Bit 0
O:0
5
Bul.1764
0035
Robot Bit 1
N7:7
0
Robot Bit 1
N7:7
1
Robot Bit 1
N7:7
2
Robot Bit 1
N7:7
3
Robot Bit 1
N7:7
4
Robot Bit 1
O:0
3
Bul.1764
0036
Get Ball
O:0
4
Bul.1764
Green Light
N7:2
4
0037
Robot Bit 0
O:0
5
Bul.1764
Yellow Light
N7:2
5
0038
Robot Bit 1
O:0
3
Bul.1764
Red Light
N7:2
6
0039
Order 1
I:0
4
Bul.1764
Location 1 Latch
N7:8
L
4

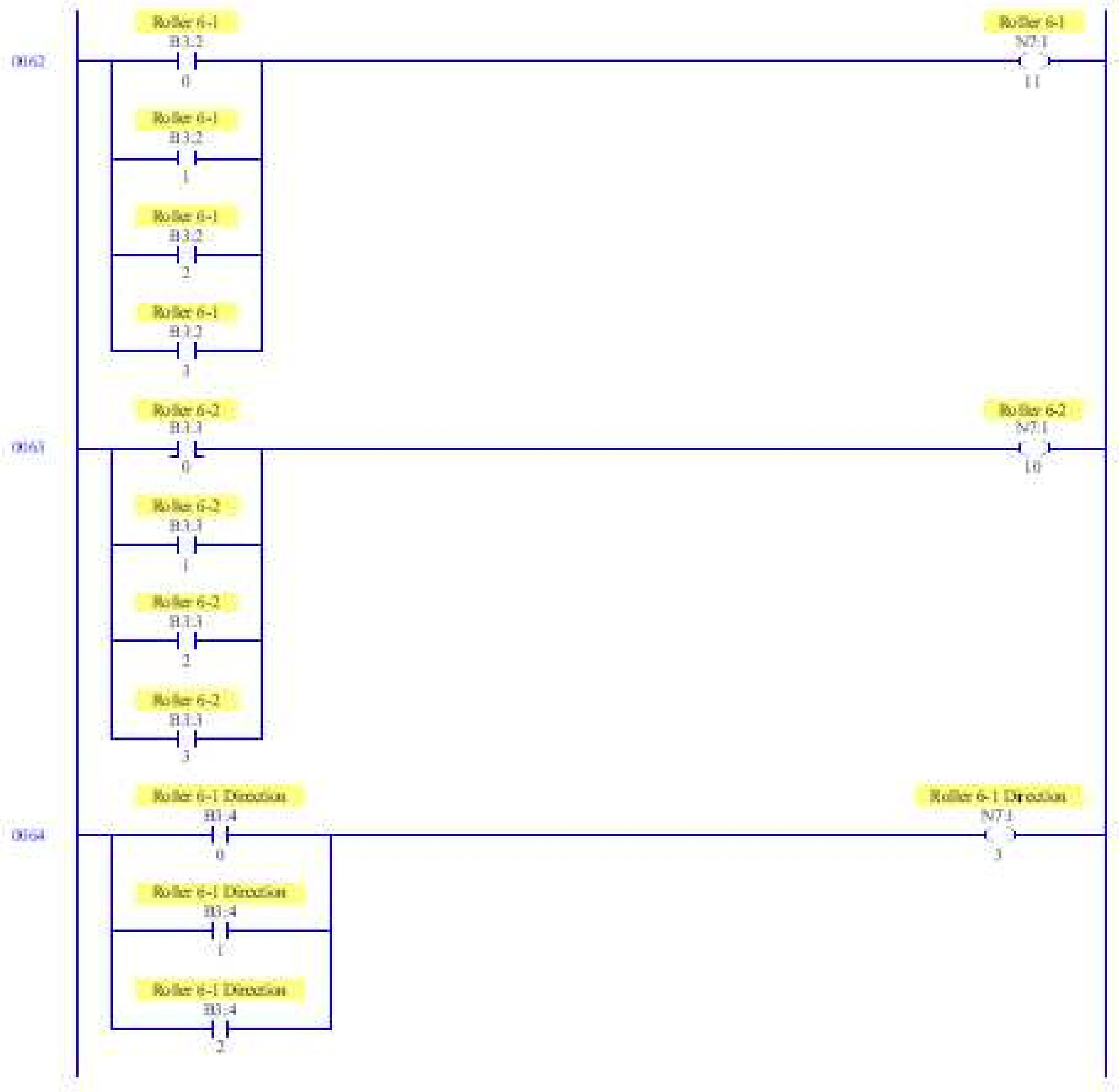

0040
Order 2
I:0
1
Bul.1764
Location 2 Latch
N7:8
L
5
0041
Order 3
I:0
3
Bul.1764
Location 3 Latch
N7:8
L
6
0042
Location 1 Latch
N7:8
4
Order 1 Complete
N7:8
0
Go Location 1
N7:8
7
0043
Location 2 Latch
N7:8
5
Order 2 Complete
N7:8
1
Location 2
JSR
Jump To Subroutine
SBR File Number U:4
0044
Location 3 Latch
N7:8
6
Order 3 Complete
N7:8
2
Go Location 3
N7:8
8
0045
Sensor F
N7:3
4
Turntable Timer Done Latch
B3:8
1
Go Location 1
N7:8
7
Go Location 3
N7:8
8
Roller 6-1
B3:2
1
Roller 6-2
B3:3
1
Roller 2-1
B3:1
15
Roller 2-2
B3:0
1
Roller 2-3
B3:1
1
Roller 6-1 Direction
B3:4
1
Roller 6-2 Direction
B3:5
1

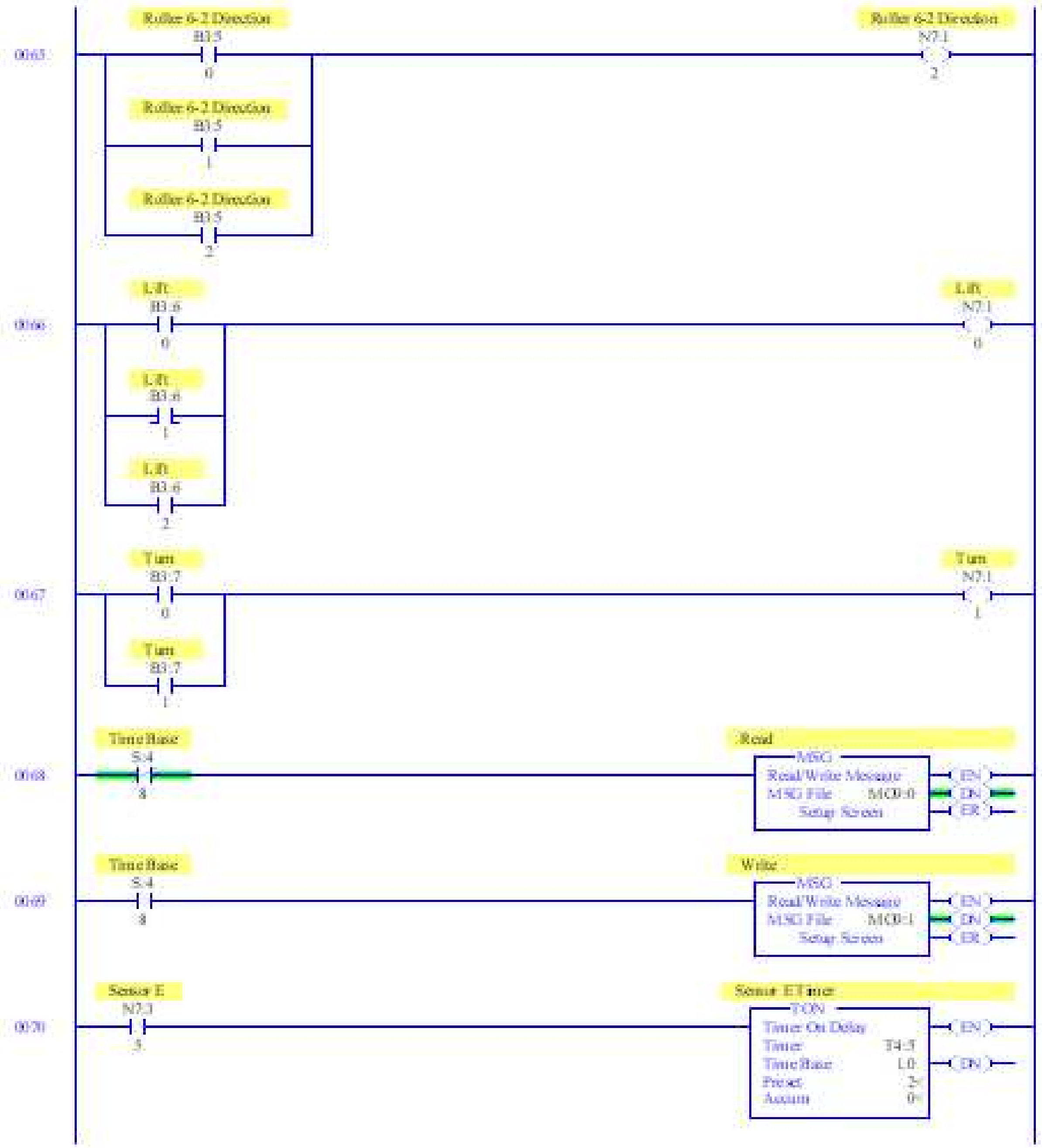

0046
Go Location 1
N7:8
7
Go Location 3
N7:8
8
Sensor F
N7:3
4
Turntable Timer
TON
Timer On Delay
Timer T4:0
Time Base 1.0
Preset 6<
Accum 0<
EN
DN
0047
Go Location 1
N7:8
7
Go Location 3
N7:8
8
Sensor F
N7:3
4
Timer Accum
GEQ
Grtr Than or Eql (A>=B)
Source A T4:0.ACC
0<
Source B 0
0<
Timer Accum
LEQ
Less Than or Eql (A<=B)
Source A T4:0.ACC
0<
Source B 4
4<
Lift
B3:6
0
0048
Go Location 1
N7:8
7
Go Location 3
N7:8
8
Sensor F
N7:3
4
Timer Accum
GEQ
Grtr Than or Eql (A>=B)
Source A T4:0.ACC
0<
Source B 2
2<
Timer Accum
LEQ
Less Than or Eql (A<=B)
Source A T4:0.ACC
0<
Source B 6
6<
Turn
B3:7
0
0049
Turntable Timer Done
T4:0
DN
Turntable Timer Done Latch
B3:8
L
1
0050
Go Location 1
N7:8
7
Sensor E
N7:3
5
Turntable Timer Done Latch
B3:8
1
Roller 6-1 Direction
B3:4
0
Roller 6-2 Direction
B3:5
0
Roller 6-1
B3:2
0
Roller 6-2
B3:3
0
Roller 4-1,2,3
N7:1
12

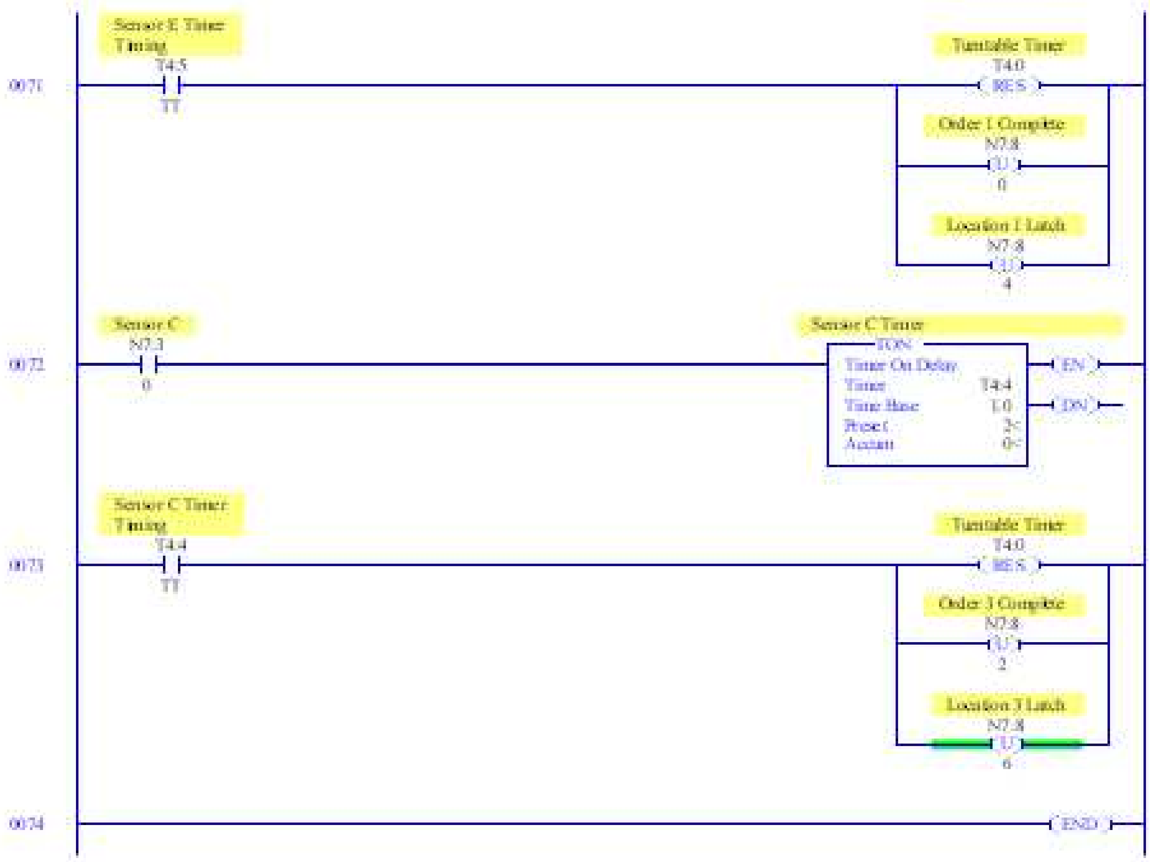


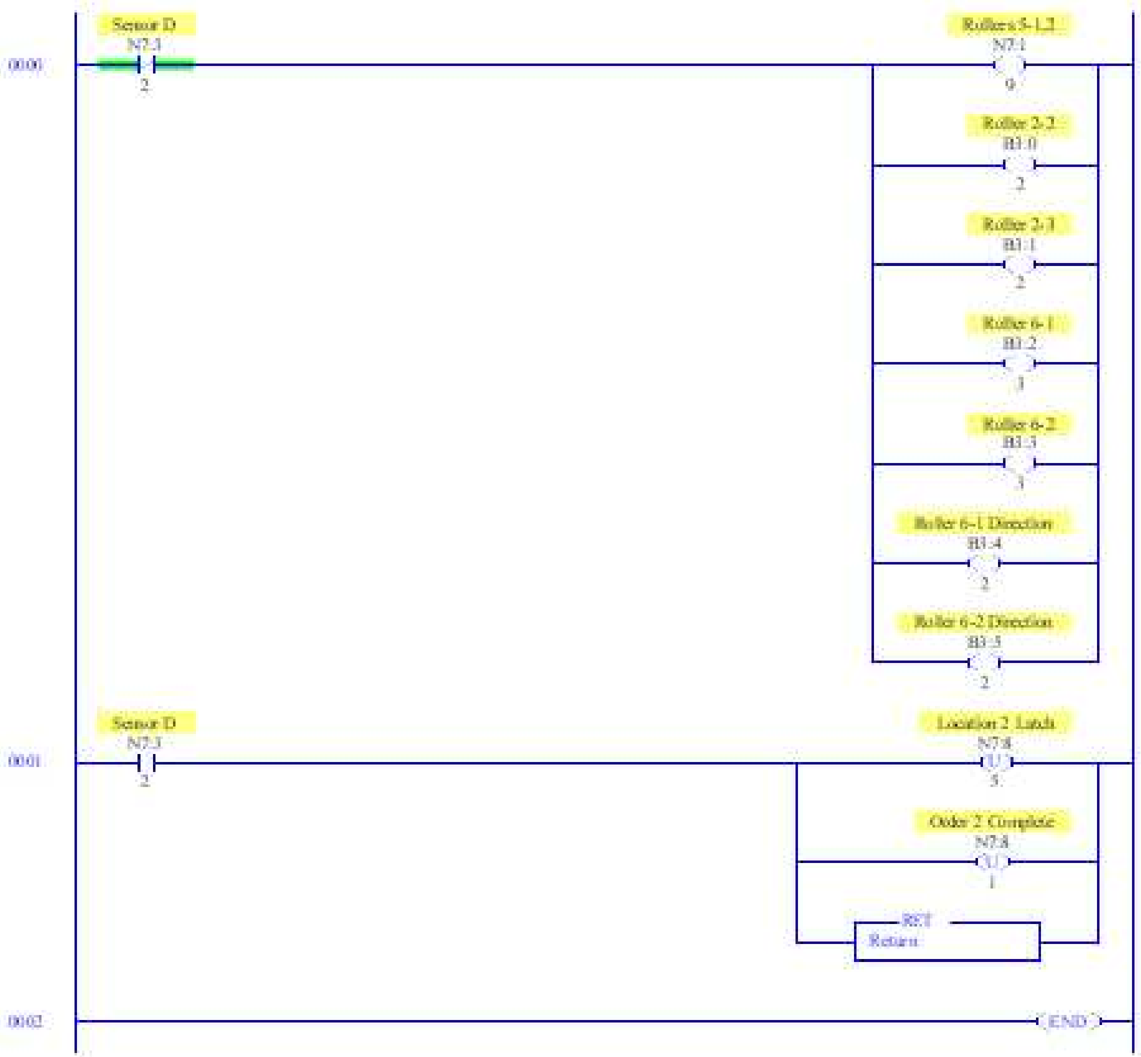
0051
Go Location 3
N7:8
8
Sensor C
N7:3
0
Turntable Timer Done Latch
B3:8
1
Roller 6-1
B3:2
2
Roller 6-2
B3:3
2
Roller 3-1,2,3
N7:1
14
0052
Sensor E
N7:3
5
Reset Timer 1
TON
Timer On Delay
Timer T4:2
Time Base 1.0
Preset 8<
Accum 0<
EN
DN
0053
Sensor C
N7:3
0
Reset Timer 2
TON
Timer On Delay
Timer T4:3
Time Base 1.0
Preset 8<
Accum 0<
EN
DN
0054
Sensor E
N7:3
5
Reset Timer 1 Done
T4:2
DN
Sensor C
N7:3
0
Reset Timer 2 Done
T4:3
DN
Reset Latch
B3:8
L
0
0055
Reset Latch
B3:8
0
Turntable Timer 2
TON
Timer On Delay
Timer T4:1
Time Base 1.0
Preset 8<
Accum 0<
EN
DN
0056
Sensor E
N7:3
5
Sensor C
N7:3
0
Reset Timer 1
T4:2
RES
Reset Timer 2
T4:3
RES


0057
Reset Latch
B3:8
0
Turntable Timer 2
GEQ
Grtr Than or Eql (A>=B)
Source A T4:1.ACC
0<
Source B 2
2<
Turntable Timer 2
LEQ
Less Than or Eql (A<=B)
Source A T4:1.ACC
0<
Source B 8
8<
Lift
B3:6
1
0058
Reset Latch
B3:8
0
Turntable Timer 2
GEQ
Grtr Than or Eql (A>=B)
Source A T4:1.ACC
0<
Source B 0
0<
Turntable Timer 2
LEQ
Less Than or Eql (A<=B)
Source A T4:1.ACC
0<
Source B 4
4<
Turn
B3:7
1
0059
Turntable Timer 2 Done
T4:1
DN
Turntable Timer 2
T4:1
RES
Reset Latch
B3:8
U
0
Turntable Timer Done Latch
B3:8
U
1
0060
Roller 2-2
B3:0
0
Roller 2-2
B3:0
1
Roller 2-2
B3:0
2
Roller 2-2
B3:2
14
Roller 2-2
N7:1
13
0061
Roller 2-3
B3:1
0
Roller 2-3
B3:1
1
Roller 2-3
B3:1
2
Roller 2-3
N7:1
15


0162
Roller 6-1
B3:2
0
Roller 6-1
B3:2
1
Roller 6-1
B3:2
2
Roller 6-1
B3:2
3
Roller 6-1
N7:1
11
0163
Roller 6-2
B3:3
0
Roller 6-2
B3:3
1
Roller 6-2
B3:3
2
Roller 6-2
B3:3
3
Roller 6-2
N7:1
10
0164
Roller 6-1 Direction
B3:4
0
Roller 6-1 Direction
B3:4
1
Roller 6-1 Direction
B3:4
2
Roller 6-1 Direction
N7:1
3


0065
Roller 6-2 Direction
B3:5
0
Roller 6-2 Direction
B3:5
1
Roller 6-2 Direction
B3:5
2
Roller 6-2 Direction
N7:1
2
0066
Lift
B3:6
0
Lift
B3:6
1
Lift
B3:6
2
Lift
N7:1
0
0067
Turn
B3:7
0
Turn
B3:7
1
Turn
N7:1
1
0068
Time Base
S:4
8
Read
MSG
Read/Write Message
MSG File MG9:0
Setup Screen
EN
DN
ER
0069
Time Base
S:4
8
Write
MSG
Read/Write Message
MSG File MG9:1
Setup Screen
EN
DN
ER
0070
Sensor E
N7:3
5
Sensor E Timer
TON
Timer On Delay
Timer T4:5
Time Base 1.0
Preset 2<
Accum 0<
EN
DN


Sensor E Timer Timing
T4:5
TT
Turntable Timer
T4:0
RES
Order 1 Complete
N7:8
U
0
Location 1 Latch
N7:8
U
4
0071
Sensor C
N7:3
0
Sensor C Timer
TON
Timer On Delay
Timer T4:4
Time Base 1.0
Preset 2<
Accum 0<
EN
DN
0072
Sensor C Timer Timing
T4:4
TT
Turntable Timer
T4:0
RES
Order 3 Complete
N7:8
U
2
Location 3 Latch
N7:8
U
6
0073
END
0074


0000
Sensor D
N7:3
2
Rollers 5-1,2
N7:1
9
Roller 2-2
B3:0
2
Roller 2-3
B3:1
2
Roller 6-1
B3:2
3
Roller 6-2
B3:3
3
Roller 6-1 Direction
B3:4
2
Roller 6-2 Direction
B3:5
2
0001
Sensor D
N7:3
2
Location 2 Latch
N7:8
U
5
Order 2 Complete
N7:8
U
1
RET
Return
0002
END

Appendix B

Robot Code for Order Fulfillment System

The following is the program code for the industrial robot utilized in the case study. The robot first sorts the color balls in the main hopper, which are in a random order. The robot is programmed with a maximum hopper size for each individual color hopper. The second portion of code receives a signal from the PLC network for a ball color. This is accomplished through a Binary code system [00 for red, 01 for green, …]. The robot then proceeds to pick up the designated ball and place into the order container. Code was written by Jeff Smith with assistance by Trey Shirley.

```
PROGRAM design()
        redmax=6
        yellowmax=6
        greenmax=6
        blue=6


redquantity=0
        yellowquantity=0
        greenquantity=0
        bluequantity=0
1
2       OPENI
        MOVE #center
```

```
IF (redquantity == remax) AND (yellowquantity == yellowmax) AND
(greenquantity==greenmax) AND (bluequantity == bluemax) GOTO 3

IF SIG(-1007,-1005,-1006,-1008) THEN
            APPRO #ballpickup, 75
            MOVE #ballpickup
            CLOSEI
            APPRO #ballpickup, 75
            MOVE #center
            APPRO #balldropoff, 300
            MOVE #balldropoff
            OPENI
            APPRO #balldropoff, 300
            GOTO 2
END

IF (redquantity < redmax) OR (yellowquantity < yellowmax) OR (greenquantity <
greenmax) OR (bluequantity < bluemax) THEN
MOVE #center
END
```

```
IF SIG(1005) THEN
        APPRO #ballpickup, 75
        MOVE #ballpickup
        CLOSEI
        APPRO #ballpickup, 75
        MOVE #center
        IF (redquantity == redmax) THEN
            APPRO #balldropoff, 300
            MOVE #balldropoff
            OPENI
            APPRO #balldropoff, 300
            GOTO 2
        END
        MOVES #redropoff
        OPENI
        redquantity = (redquantity+1)
        GOTO 2
END

IF SIG(1006) THEN
        APPRO #ballpickup, 75
        MOVES #ballpickup
```

```
                CLOSEI
                APPRO #ballpickup, 75
                MOVE #center
                IF (yellowquantity == yellowmax) THEN
                        APPRO #balldropoff, 300
                        MOVE #balldropoff
                        OPENI
                        APPRO #balldropoff, 300
                        GOTO 2
                END
                MOVES #yellowdropoff
                OPENI
                yellowquantity = (yellowquantity+1)
                GOTO 2
END

IF SIG(1007) THEN
                APPRO #ballpickup, 75
                MOVES #ballpickup
                CLOSEI
                APPRO #ballpickup, 75
                MOVE #center
```

```
        IF (greenquantity == greenmax) THEN
                APPRO #balldropoff, 300
                MOVE #balldropoff
                OPENI
                APPRO #balldropoff, 300
                GOTO 2
        END
        MOVES #greendropoff
        OPENI
        greenquantity = (greenquantity+1)
        GOTO 2
END

IF SIG(1008) THEN
        APPRO #ballpickup, 75
        MOVE #ballpickup
        CLOSEI
        APPRO #ballpickup, 75
        MOVE #center
        IF (bluequantity == bluemax) THEN
                APPRO #balldropoff, 300
                MOVE #balldropoff
```

```
                OPENI

                APPRO #balldropoff, 300

                GOTO 2

        END

        MOVES #bluedropoff

        OPENI

        bluequantity = (bluequantity+1)

        GOTO 2

END

3

MOVE #center

OPENI


IF (redquantity == 0) OR (yellowquantity == 0) OR (greenquantity == 0) OR

(bluequantity == 0) GOTO 2


SIGNAL (4)

DELAY 1


IF SIG(1010,-1011,-1012) AND (redquantity > 0) THEN

        SIGNAL (-4)

        APPRO #redpickup, 75
```

```
                MOVES #redpickup

                CLOSEI

                APPRO #redpickup, 75

                MOVE #center

                MOVE #boxdropoff

                OPENI

                redquantity = (redquantity-1)

                GOTO 3

END


IF SIG(1010,-1011,-1012) AND (yellowquantity > 0) THEN

                SIGNAL (-4)

                APPRO #yellowpickup, 75

                MOVES #yellowpickup

                CLOSEI

                APPRO #yellowpickup, 75

                MOVE #center

                MOVE #boxdropoff

                OPENI

                yellowquantity = (yellowquantity-1)

                GOTO 3

END
```

```
IF SIG(1010,-1011,-1012) AND (greenquantity > 0) THEN
        SIGNAL (-4)
        APPRO #greenpickup, 75
        MOVES #greenpickup
        CLOSEI
        APPRO #greenpickup, 75
        MOVE #center
        MOVE #boxdropoff
        OPENI
        greenquantity = (greenquantity-1)
        GOTO 3
END

IF SIG(1010,-1011,-1012) AND (bluequantity > 0) THEN
        SIGNAL (-4)
        APPRO #bluepickup, 75
        MOVES #bluepickup
        CLOSEI
        APPRO #bluepickup, 75
        MOVE #center
        MOVE #boxdropoff
```

```
        OPENI

        bluequantity = (bluequantity-1)

        GOTO 3

END

GOTO 3
```

Appendix C

The laboratory manual for this class was developed from various resources. Experiments One through Four were primarily developed by Trey Shirley, with some assistance from Mike Baraky. Graduate assistants in the Mechanical Engineering department of Clemson University created experiments Five and Six, with some modifications by Trey Shirley. Students originally designed exercises Seven and Eight, however changes were constructed by Mike Baraky and Trey Shirley [23].

Exercise 1 - Introduction to PLCs: Home Security System

Programmable Logic Controllers (PLC) will be introduced and a “home security system” will be created that will show the basics of how to use a PLC. Every major industry uses some form of PLC to control various processes; therefore the understanding of how a PLC operates is critical for engineers. In this task, the goal will be to wire the inputs and outputs of the system to the PLC and program the PLC to create a security system.

Background

A programmable logic controller is a special form of microprocessor-based controller that uses a programmable memory to store instructions and to implement functions such as logic, sequencing, timing, counting and arithmetic in order to control machines and processes. One PLC can replace the need for thousands of individual relays, cam timers, and drum sequencers that were previously used for control schemes.

The greatest advantage for using a PLC is that it can be reprogrammed relatively easily by simply changing the program in its memory, as opposed to having to rewire an entire control panel. A PLC is very similar to a computer; however PLCs are rugged and designed to withstand the harsh environment inside a factory and they are also built with multiple input and output points for easy interface between devices.

The PLC that will be used in this experiment is an Allen Bradley MicroLogix 1000. It can be seen in Figure C-1.

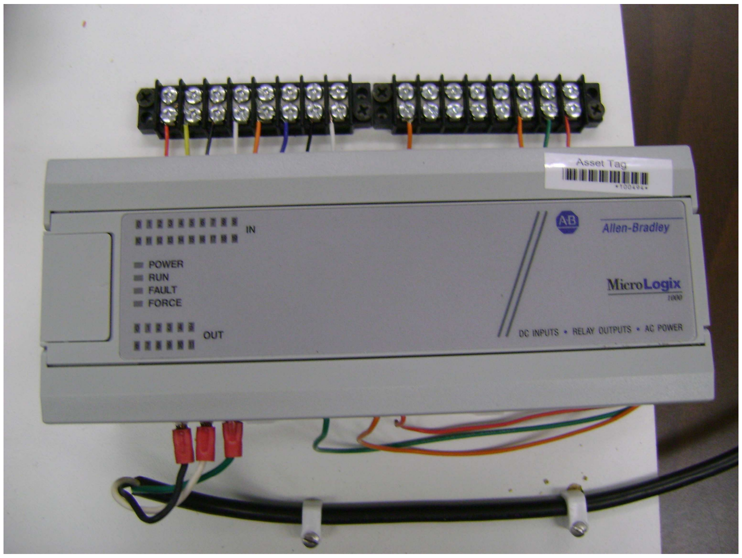


Figure C-1: Allen Bradley MicroLogix 1000 PLC [23]

There are 24 inputs and 12 outputs that can be used. Wire from the equipment is simply wired into the input and output terminals on the PLC. Each terminal is numbered and that number will be used when programming the PLC.

Allen-Bradley PLCs [and most PLCs] function in this sequence: read the inputs, execute the program, and update the outputs. When the inputs are read, the values are stored in an internal file. If the program stored on the PLC is dependent on an input value, it goes to this internal file, not the physical input. Due to the cycle time for a PLC being extremely fast, there would rarely be a time when the physical input and the internal file did not match. The program in the PLC is written in a format called Ladder Logic. Ladder Logic operates by linking inputs with outputs by a series of rungs. When the input condition is true, the output on the rung will be energized. An example of ladder logic is shown in Figure C-2.

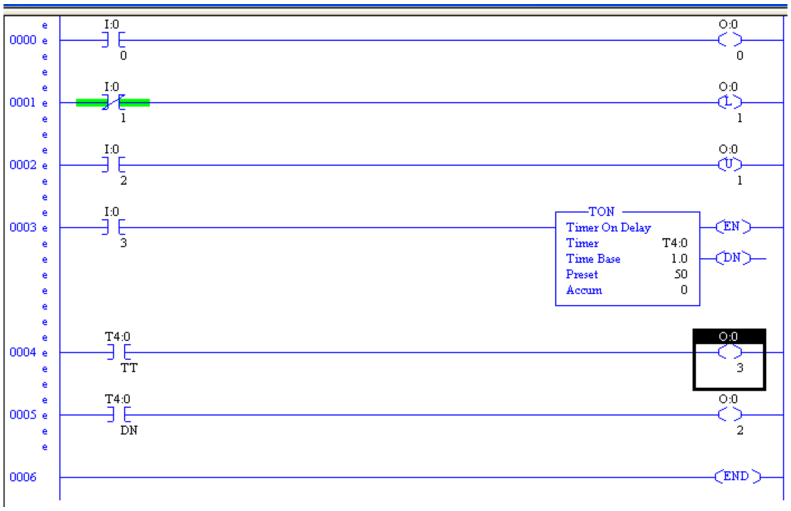


Figure C-2: Ladder logic example [23]

Figure C-2 shows the inputs and outputs that will be required to complete this task. Two different inputs are shown. They are Examine if Closed (XIC) and Examine if Open (XIO). Lines 0, 2, and 3 are XIC inputs. If the operation is true, the input will be energized. Line 1 shows an XIO input. It is energized when the operation is false. If it was desired to turn a light **on** when a button was held down, then an **XIC** input would be used. If it was desired that the light only turn **off** when a button was pushed down then an **XIO** input would be used. Three outputs are shown on lines 0, 1, and 2. The first is an Output Energize (OTE). When it is energized by the inputs on the rung, it turns the output on. As soon as the inputs are no longer energized the OTE will turn off. The second output is an Output Latch (OTL). When it is energized, it will hold the output on permanently. The third Output is an Output Unlatch (OTU). When it is energized, it will deactivate which ever output it is associated with. In this example, it will unlatch the output that can be latched in line 1.

A timer is also shown in Figure C-2. This timer has three outputs that can be used to activate different things. They are Enable (EN), Timer Timing (TT), and Done (DN). When the timer is energized by the inputs on that rung, EN will be active. ‘TT’ is active when the timer is timing and ‘DN’ is activated as soon as the timer is done. Only two can be activated at the same time, as ‘Timer Timing’ and ‘Done’ cannot be on at the same time. ‘EN’ can be on in conjunction with either as long as the input on the rung with the timer is energized. Lines 4 and 5 show an example of how the timer can be used. In line 4, if the timer is timing, that input will be energized and output 3 would be activated. When the timer is done, the input on line 5 will activate and turn on output 2. There are many ways to use the timer.

The final step in the PLC cycle is to update the physical outputs to match the electronic output file. As the program scans the entire ladder it updates an electronic table that corresponds to each output. Once the entire program has been executed, the physical outputs will be energized or de-energized to match the final electronic output table. If two rungs have conflicting output states, an output would not activate and then quickly deactivate, it would never activate originally. If two inputs giving directions for one output are both energized the directions from the input that is on a rung lower in the program will win out. This phenomenon is known as the ‘Last Rung Wins’ principle. Lines 1 and 2 of Figure C-2 are an example of this. If inputs 1 and 2 are both energized, output 1 will not be activated. This is because the OTU command is below the OTL command so the output would stay unlatched. This is important to keep in mind when programming a PLC.

Inputs

There will be four inputs to the PLC all shown in Figure C-3. The first is an infrared motion detector. The motion detector is a normally closed circuit. This means that if the detector does not see any motion the circuit will be closed, allowing energy to flow through. When something moves in its field of vision the circuit will open. The second input is a contact switch, which for a house would be installed on a window. It is set up so that when the window is closed the two sides of the switch are in contact with each other. This switch is normally closed as well. When the window is opened the sides would no longer be in contact. This opens the circuit and can be used to signify that the window has been opened. The next input is a vibration detector. This piece detects a vibration and sends the signal back to the security device. An example of a use for the detector would be a broken window. If a burglar attempted to enter a house through a broken window, the action of breaking the window would cause a vibration which would trip the detector. This detector is also normally closed. A normally closed mushroom-head pushbutton will be used as a ‘panic switch’.

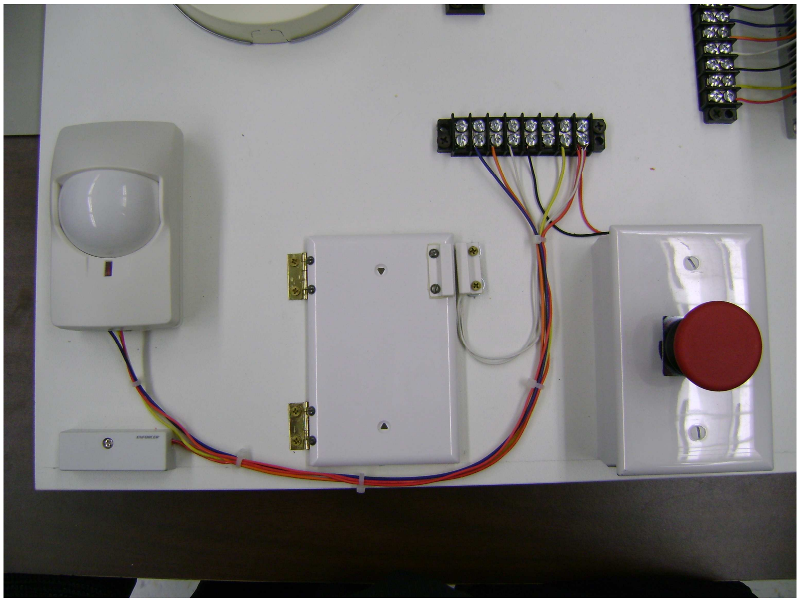


Figure C-3: Inputs to PLC [23]

Four On/Off switches will be used in the set-up. These switches will either be open or closed depending on the switch position. Below is a picture of the switches.

Figure C-4: Toggle switches [23]

Outputs

The output for the system is a 3 color light stack with an alarm. This stack has four separate outputs as each light and the alarm can independently be used. A picture is shown in Figure C-5.

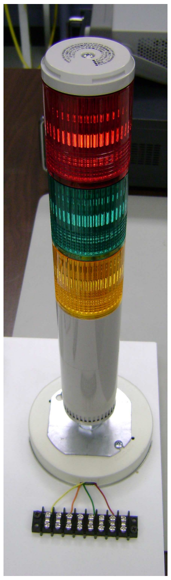


Figure C-5: Three color light stack with alarm [23]

Procedure

1. Wire inputs and outputs to PLC
2. Create program using RSLogix500 to accomplish task:
    a. The system should be set to ready when the inputs switches read '0000' and the green light should turn on
    b. When a device detects an "intrusion" the green light should turn off and the yellow light should turn on

c. After 5 seconds, if the proper code has not been switched, the yellow light should turn off, the red light should turn on, and the alarm should sound for 2 seconds

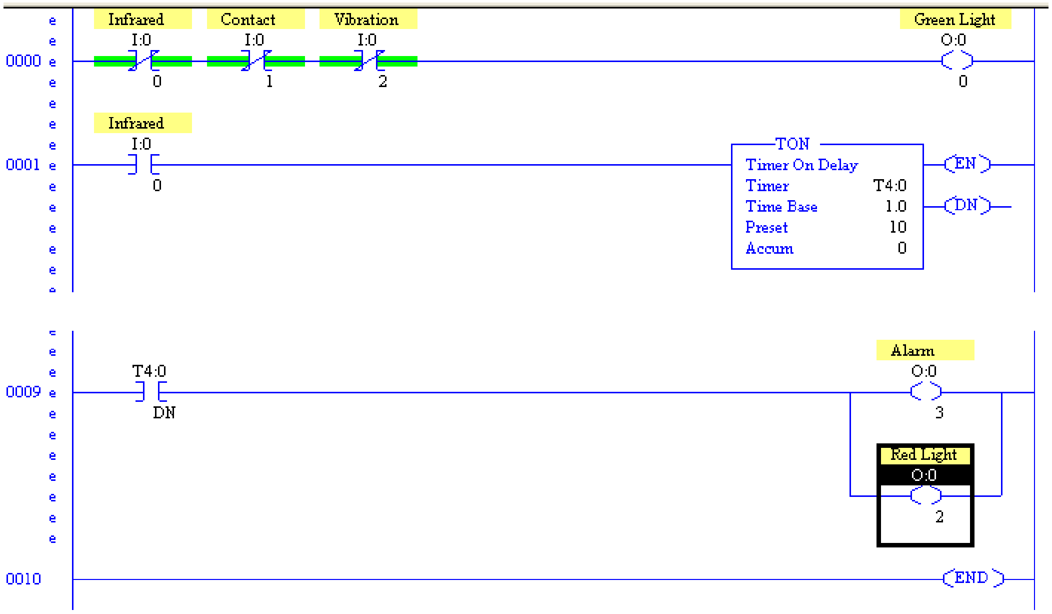


Figure C-6: Partial example of home security ladder logic [23]

Miscellaneous

When opening a new file in RS Logix 500 the processor that should be selected is Bul.1761 MicroLogix 1000. The PLC must be switched on. To download the file to the PLC, the file must be saved. Then go to the Download option under the Command Menu. Push Ok through the pop ups (Put PLC into program mode, put PLC back to run mode, Go Online). After this is completed the program will run.

Exercise 2 - Networking PLCs: Basic Conveyor System

On the factory floor, networks allow communication between multiple PLCs. Although there are different types of network protocols (DH-485, DeviceNet, EtherNet, etc.), students that understand the basics of one protocol should be able to extrapolate their knowledge to many others. This laboratory module creates a network to operate a conveyor system. One PLC will be connected to the switches that will control the conveyor system, while another PLC will actually power the conveyor rollers.

Background

When two PLCs are networked together, they can communicate during real-time with one another and convey useful information using the MSG command provided by RSLogix. The MSG instruction is available with a read and write feature and is useful across a variety of applications. In this particular setup, we will utilize the Robot Cage in Cook Laboratory. The network has already been configured for the two PLCs employed in this lab experiment. PLC1 has the capability of controlling a portion of the conveyor system, while PLC2 is connected to two pushbuttons for control purposes and two lights.

System Description

The PLC network is created by the use of ENI Modules. An ENI module will communicate with an individual PLC, and with other ENI modules. A PLC and ENI Module are connected through a dedicated RS-232 cable. The ENI Modules are connected through a Cat-5 Ethernet cable, which has been plugged into a switch. These cables are no different from the cables plugged into a typical computer, however in an industrial factory, they typically have added shielding. The ENI Modules communicate with themselves by sending data in the form of integer files. Integer files are stored internally using bits (same as your computer on a microscopic level). As can be observed in the diagram below, a pushbutton would control a bit in an integer file in PLC 1. PLC1 would then communicate with its own ENI Module. This ENI Module would send the data from the integer file specifically to the other ENI Module. If there were multiple ENI Modules connected to the network, only the ENI Module specified would keep the data, the rest would ignore the transmission. PLC2 decodes the information from its respective ENI module. PLC2 then places the information into its own integer file. The code in PLC2 will use the individual bits from the integer file to control the conveyor motors.

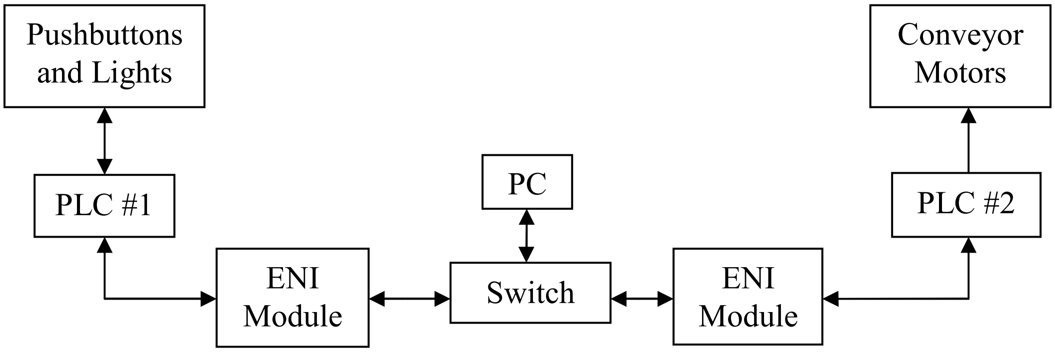
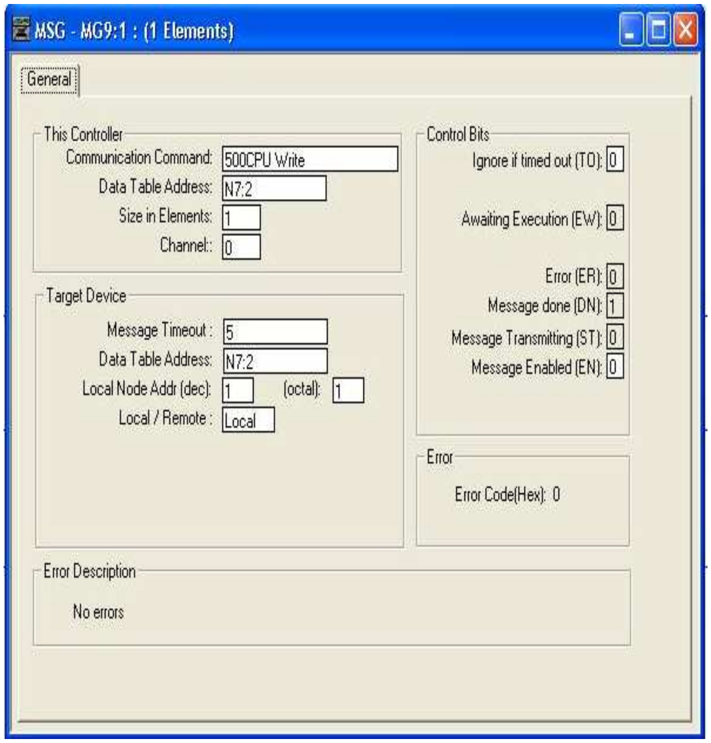


Figure C-7: Network diagram [23]

MSG Setup Screen

The message instruction (MSG) is a powerful tool when using multiple PLCs. It allows for the easy transfer of information. The MSG instruction can only send Integer files from a destination PLC to a target PLC, so any data must be stored in these files. For the purpose of this lab, the integer file will contain data on the status of the pushbuttons and output lights connected to PLC2. To use the MSG instruction, first place it in a rung. The instruction will only send a message on a ‘false to true’ transition. After inserting the instruction, declare the MSG File. This will be the address the PLC uses to control the instruction. Typically, the register MG9 is used. Next, double-click on the word ‘Setup Screen’ in the instruction box. This will bring up the following dialog box shown in Figure C-8.



This Controller
Communication Command: 500CPU Write
Data Table Address: N7:2
Size in Elements: 1
Channel: 0

Target Device
Message Timeout : 5
Data Table Address: N7:2
Local Node Addr (dec): 1 (octal): 1
Local / Remote : Local

Control Bits
Ignore if timed out (TO): 0
Awaiting Execution (EW): 0
Error (ER): 0
Message done (DN): 1
Message Transmitting (ST): 0
Message Enabled (EN): 0

Error
Error Code(Hex): 0

Error Description
No errors

Figure C-8: MSG setup screen [23]

For the MSG instruction to function properly the following fields must be correctly filled. The communication command should be either ‘500CPU Write’ or ‘500CPU Read’, depending on the desired function. If a Write command is used, the

MSG instruction will take the Integer file specified, and place it in the target device's Integer file. If a Read command is used, the MSG instruction will get the Integer file at the target node, and place it in the Integer file specified. The Data Table Address is where the data will come from – it must be an integer file. The 'Size in Elements' box lets the PLC know how many integer files to send in the message. 'Message Timeout' is generally set to 5 seconds. The 'Local Node' is the node that the Target Device is set up as in the ENI modules. For PLC1 it is node 1, for PLC2 it is node 2. Notice these are different nodes numbers than the ones used for programming the PLCs. The 'Local/Remote' box should say 'Local'.

Procedure

1. Place a pallet at the Start point
2. When a pushbutton connected to PLC2 is pressed, the conveyor system will move the pallet to the stop point
3. Once the pallet is at the stop point, an output light connected to PLC2 will energize
4. After a second pushbutton is activated, the conveyor system will reverse direction and send the pallet back to the Start point
5. A different output light connected to PLC2 will then energize
6. Communication between PLC1 and PLC2 must take place via MSG commands.

Exercise 3 - Introduction to the Stäubli RX130 Industrial Robot

Programming and operation of industrial robots, such as the Stäubli Robot, are essential tools for any engineer tasked with the creation or support of a mechatronics system. In this task, the robotic arm will be programmed to assemble one piston and place it in a pallet located on the conveyor. This will be accomplished by defining points, programming commands, and executing a program stored in the robot's memory. Once completed, the student should have a good understanding of the robot's basic commands and the implementation of these commands. Due to the complexity of the exercise, students must be sure to operate in a safe and intelligent manner to protect the robot and conveyor along with themselves.

Background

Industrial robots are an effective and efficient way of accomplishing a given task in manufacturing. The ability to precisely repeat an action is critical for assembly line processes. Industrial robots are being used now more than ever due to lower costs, more reliable machines, and easier programming. A six degree of freedom machine, like the Staubli RX-130, can perform a multitude of tasks. The Staubli has a pneumatic actuator which can be fitted with different end effectors. This allows for part pick-and-place operations.

Using the Teaching Pendent

In order to control the Stäubli robot, a teaching pendent is provided to define the points needed to control the movement in the programs. Shown in Figure C-9, the controller allows the user to move the specific joints of the robotic arm. Once familiar with the locations of the buttons on the teaching pendent, you should get familiar with how it moves. Before you begin moving the robot, make sure to set the speed between 10 and 15 percent of the machine's speed. This will allow you enough time to press the E-stop button if the robot doesn't perform as expected. Enable the arm power to begin moving the robot. To do this, press the "Comp/Power" button. Once the power is supplied, you must set the robot to manual mode. Use the "Man/Halt" key to accomplish this and continue to press this button until the light appears below "Joint". The Joint mode allows the user to move the joints individually with the "+" and "-" buttons on the travel speed bar.

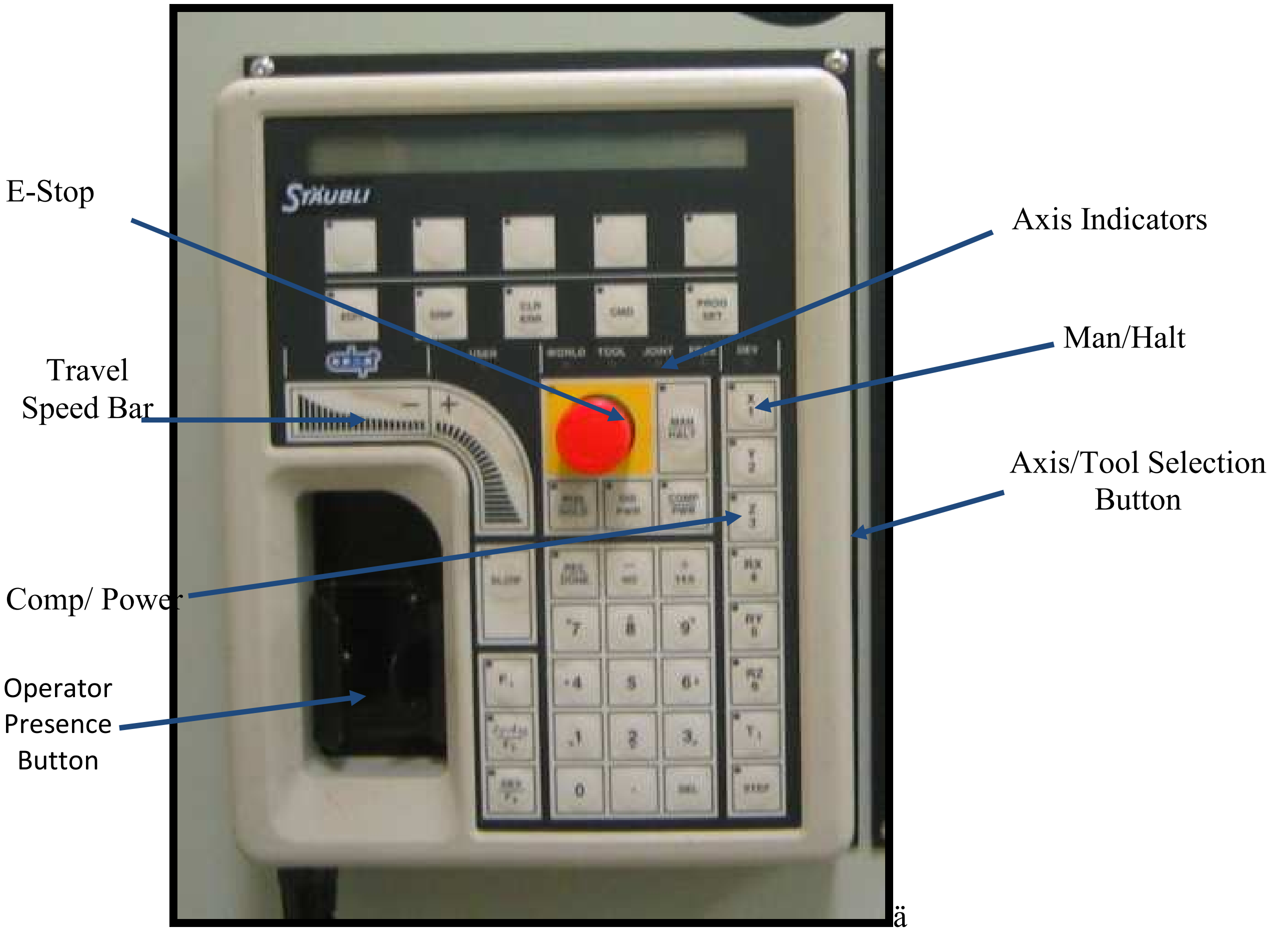


Figure C-9: Teaching pendent [23]

The Axis selection buttons specify the individual joints for this mode. The “World” mode defines the coordinates of the system in reference to the cage. The “Tool” mode defines the coordinates in reference to the gripper. These different modes are helpful when the maximum range of one joint is reached. Switching to another mode can allow the range to become larger and have more movement available. The presence button is the safety feature of the teaching pendent. This button should be pressed at all times in order for the robot to move. Once this button is released, the operator must turn on the power to the arm again, select the mode and select the joint to be moved.

Programming Commands

The Stäubli robot has a few basic commands that are necessary for its operation. There are other commands available for more advanced operations. The commands provided in Table C-1 will allow the completion of this lab and most other basic tasks.

Commands	**Actions**
READY	Moves the arm to vertical position
OPENI	Opens the gripper
CLOSEI	Closes the gripper
MOVE #a	Moves the robot to point #a along any trajectory
MOVES #a	Moves the robot to point #a along a straight trajectory
APPRO #a, distance	Allows robot to approach point #a by a distance(in mm) along the z-axis
DEPARTS distance	Moves the robot back from a point along the z-axis
DELAY time	Specifies a time interval between commands

Table C-1: Commands list [23]

In order to execute these commands, they have to be saved into a file on the terminal. This is done by using the SEE editor. For example, to create a file for this lab you must type **see box.** The editor will notice if there isn't a file created and will ask you if you would like to create one.

Defining Points

The ability to define points is one of the Stäubli robots more important features. It allows the programmer to create a very exact trajectory that is essential to maneuvering the robotic arm around objects. Defining the points is one of slower processes during the programming of the robot. They must be manually defined using the teaching pendent.

The robot must be moved carefully to one of its desired spots along a trajectory. Once the robot is in the correct position, the user must type **HERE #a** and press enter. When the display asks if you would like to change the point, press enter. The point #a is now defined in the program ready to be used. This lab will require you to define multiple points.

Sample Program

Considering the complexity of this exercise, a rough program has been written to facilitate students through the activity. This is a simple program but does show how the commands are interrelated. The program needed for the successful completion of this lab will involve these same commands.

```
.program pistonball()
ENABLE POWER
SPEED 40
DO READY
MOVE #PARTSAPPO1        ; approach point for picking up parts from platform
MOVE #CONRODAPPO1    ; approach point for picking up conrod
CLOSEI
SPEED 10
MOVE #CONRODAPPO2    ; insert the closed jaws in conrod hole
OPENI
END
```

Procedure

For this exercise, students will use the robot and piston components to perform an assembly process. Before any programming is started, students should check if the proper assembly platforms are mounted above the conveyors, and they contain all necessary components (1 piston, 1 connecting rod, 1 wrist pin, and 1 piston tray). Additionally, students should make sure the straight gripper fingers are mounted on the robotic arm. Otherwise, assembly will be quite difficult.

The piston assembly process will involve 4 programming procedures:

1. The robotic arm will be programmed to retrieve a connecting rod from the part storage platform and place it on the assembly jig
2. The robotic arm will be programmed to retrieve a piston from the part storage platform and place it on the assembly jig, with the wrist pin holes aligned properly
3. The robotic arm will be programmed to retrieve a wrist pin from the part storage platform and insert it into the piston and connecting rod
4. The robotic arm will be programmed to pick and place the assembled piston into the empty pallet located on the conveyor

Exercise 4 - Integrating Inputs/Outputs with the Stäubli Robot Arm

To understand some of the feedback capabilities of the Staubli robot in Cook Hall, students will use the robot and conveyor to create an integrated material handling system.

This activity has been designed so that students will learn how to integrate both the Staubli robot and the conveyor segments together to form one cohesive industrial process. In addition to learning the industrial applications of the material handling system, students will also learn how photoelectric sensors operate, and how they communicate with the robot to ensure proper assembly. Students will have to apply robot programming and operation knowledge gained in previous mechatronic lab activities to be successful and expedient with the operation. Additionally, programs for both the PLC and the robot completed in earlier labs will be used. Due to the complexity of the exercise, students must be sure to operate in a safe and intelligent manner to protect the robot and conveyor along with themselves.

Background

The Staubli robot is capable of input and output operations through terminal blocks located in its control cabinet. In the most basic sense, a pushbutton can be connected to the input terminal block of the robot to start an operation. Similarly, a light can be connected to the output terminal block of the robot to signal an operation is completed. In this lab, a photoelectric sensor will be used. The sensor operates by emitting a beam of light, and measuring how much light returns. If an object is close, enough light will be reflected back to the sensor to overcome some predefined threshold and the sensor will activate an output signal. When this signal is connected to the robot, a process can be instituted that will ensure proper part placement.

Programming the Photoelectric Sensor

To program the photoelectric sensor, first turn on power to the robot so that the sensor is energized. It will emit a red light beam from the LED. To program the sensor's "off" setting (return of "false" to the robot), clear objects from the beam or place the desired object at a distance where a return of "false" would still be desired. Push the "set" button on the sensor controller. Now position the object where a "true" return is desired, and press the set button again. The sensor will set the true/false threshold to be the average of the two reflectivities. It is important to note that if the sensor returns a reflectivity of 9999 while the first point is being set, the calibration will not work. The settings will still be recorded, but likely will not work. The syntax for implementing the sensor into V+ code is as follows:

```
1 if SIG (10xx) < 0 then (operation)
```

where xx is the sensor number, ranging from 1 to 12.

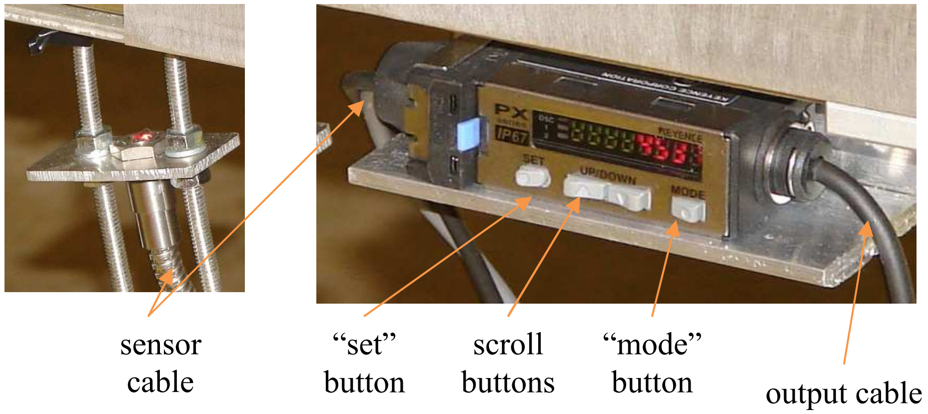


Figure C-10: Sensor assembly/ sensor controller [23]

System Integration

The Staubli robot will be integrated with the conveyor system to create a automotive piston assembly system. In this system, two pistons will be assembled and placed on a tool pallet that will travel along a conveyor system. To accomplish this goal, the conveyor system from Task 2 will be utilized. Two outputs from the Staubli will be connected to two inputs of PLC2, and two inputs from the Staubli will be connected to two outputs of PLC2 as shown below.

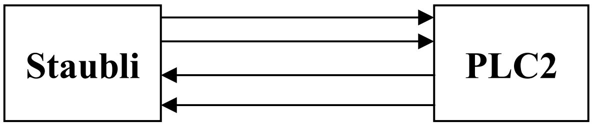


Figure C-11: Interconnection diagram between Staubli robot and PLC2 [23]

The program that controls the Staubli will send signals to PLC2 to control the operation of the conveyor system. It will utilize the inputs from the conveyor system to ensure the tool pallet is in its proper location. The program to assemble the pistons will be the same as in Task 3, with some slight modifications. The program to control the PLCs will be the same as in Task 2, with some slight modifications. Before any programming is started, students should check if the proper assembly platforms are mounted above the conveyors, and they contain all necessary components (2 pistons, 2 connecting rods, 2 wrist pins, and 1 piston tray). Additionally, students should make sure the straight gripper fingers are mounted on the robotic arm. Otherwise, assembly will be quite difficult.

Procedure

1. The photoelectric sensor located underneath the piston assembly jig will be programmed to detect the alignment of the aluminum wrist pin
2. The Staubli will send a signal to PLC2 to start moving the tray down the conveyor
3. The robotic arm will be programmed to retrieve a connecting rod from the part storage platform and place it on the assembly jig
4. The robotic arm will be programmed to retrieve a piston from the part storage platform and place it on the assembly jig, with the wrist pin holes aligned properly
5. The robotic arm will be programmed to retrieve a wrist pin from the part storage platform and insert it into the piston and connecting rod
6. The program will check to ensure the photoelectric sensor detects the wrist pin
7. The robotic arm will be programmed to pick and place the assembled piston into the empty pallet located on the conveyor
8. Once two completed pistons have been loaded onto the pallet, the Staubli will send another signal to PLC2 to move the pallet down the conveyor to the original starting location.

Exercise 5 - Coulomb's Torsional Pendulum and a Swinging Pendulum – Similarities and Differences

The behavior of two different types of pendulum will be observed and oscillatory motion of both the torsional and swinging pendulum laboratory fixtures will be characterized. Quantification of the torsional pendulum's motion is accomplished through the implementation of a Hall Effect sensor while swinging pendulum's motion is characterized by an accelerometer.

Background

Fundamentally, the function of a clock is to transform a predictable signal into some standard unit of time. In pendulum clocks, the position signal of the pendulum is converted into seconds, hours and minutes. A typical pendulum clock is shown in Figure C-12. Pendulum motion is predicable and consistent for long periods of time when the effects of friction are minimized. The second, minute and hour signals are extracted from the pendulum motion through a series of gears.

The swinging pendulum is the typical pendulum that is present in grandfather and wall clocks. In contrast, a torsional pendulum is used in anniversary clocks. It represents a mass hung by a short chord and rotates along the vertical axis. The period of the torsional pendulum is much longer than that of a swinging pendulum; therefore, the anniversary clocks will sometimes be called 400 day clocks because some of those clocks can last 400 days without needing to be wound. In this experiment, the student will study the governing equations of motion by using different laboratory data acquisition equipment. For the swinging pendulum, the acceleration of the bob will be measured by an accelerometer; the position and velocity of the bob will be obtained through mathematical manipulation of the acceleration signal. The torsional pendulum utilizes a Hall-Effect sensor to determine the rotational position of suspended mass. For this case, the student shall manipulate the position data to obtain the corresponding acceleration and velocity. Figure C-12 shows a general assembly for each pendulum.

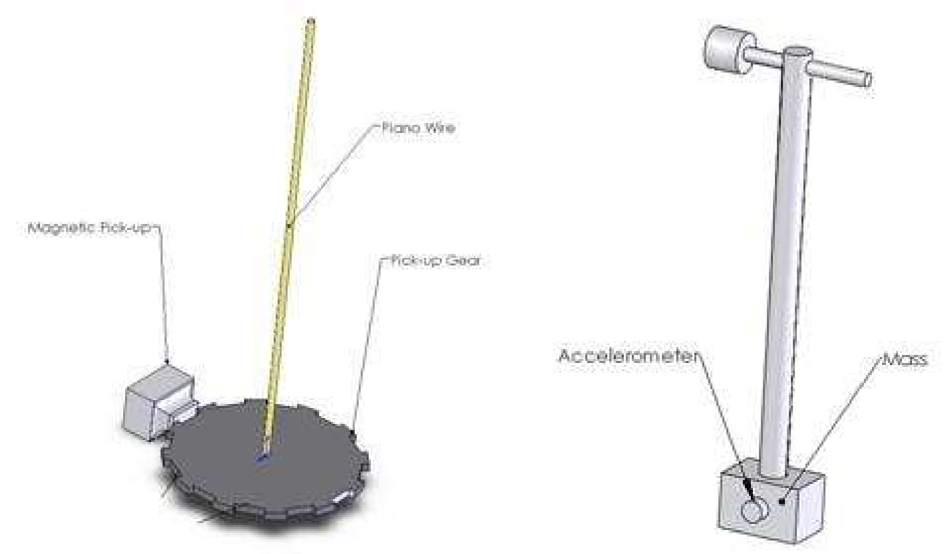


Figure C-12: Torsional and swinging pendulum [23]

Theoretical Background

Second Order Mechanical Systems

The following analysis of a pendulum first requires an understanding of some characteristics of second order mechanical systems. Second order systems are systems that described by a second order differential equation. The standard form for second order differential equations is:

$$\ddot{x} + 2\zeta\omega_n\dot{x} + \omega_n^2 x = u(t) \tag{5.1}$$

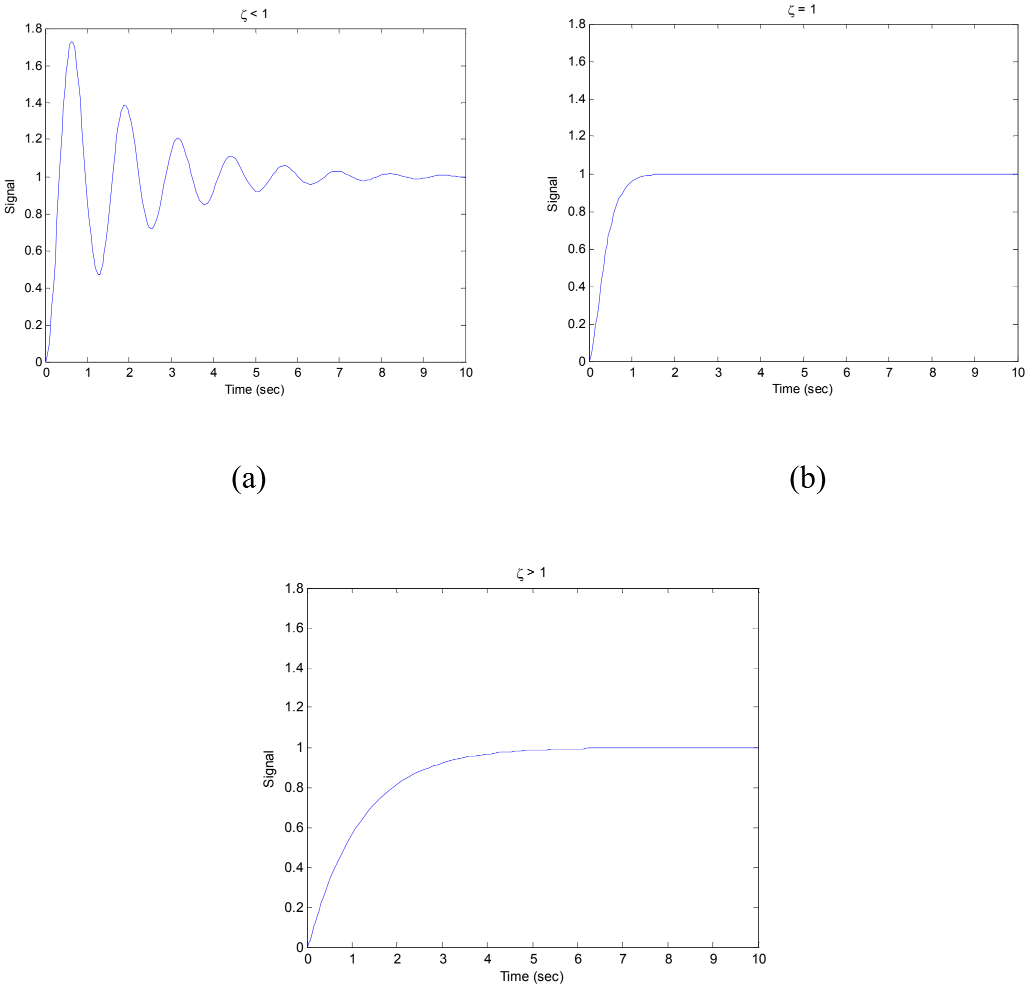
Where: ζ = dampening ratio,

w_n = natural frequency of the system, and

$u(t)$ = system input

The time response of a second order system is dictated by two parameters: the natural frequency and the dampening ratio. The natural frequency is the frequency the system operates at when a non-harmonic input is applied to the system. The dampening ratio is a ratio that characterizes the time required for the system to reach steady state.

Second order systems are classified into three categories: over damped systems, critically damped systems, and under damped systems. Oscillations are characteristic of under damped second order systems. A second order system is defined to be under damped if $\zeta < 1$, critically damped if $\zeta = 1$, and over damped if $\zeta > 1$. Figure C-13 shows the response of all three types of second order systems.



(a)

(b)

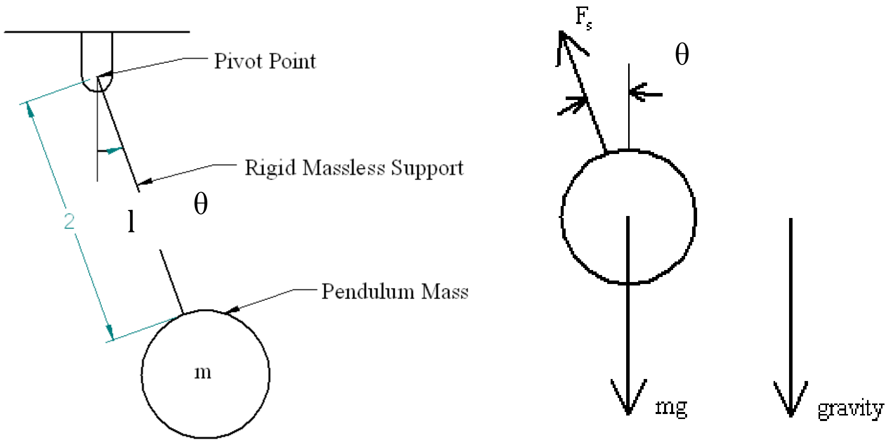
(c)

Figure C-13: Second order systems: (a) underdamped, (b) critically damped, (c) overdamped systems vary in behavior due to varying values of ζ [23]

Point Mass Pendulum Analysis

The characteristics of pendulum motion are affected by pendulum geometry. A simple pendulum is a concentrated point mass connected by a rigid mass less support to a pivot point, as shown in Figure C-14. When the pendulum is assumed to be a simple pendulum, only the pendulum mass affects the characteristics of the harmonic motion.

This type of analysis is called point mass pendulum analysis and though it does not precisely describe the motion of a real pendulum, it does give a good approximation of pendulum motion.



(a) (b)

Figure C-14: Simple pendulum (a) parameters and (b) free body diagram [23]

The pendulum’s motion is constrained to only degree of freedom, and therefore is described as a first order system. Given the inputs into the system, the pendulums motion can be completely defined by an ordinary differential equation of the form

$$\ddot{x} + \omega_n x = 0 \qquad (5.2)$$

The free body diagram of this motion is shown in Figure C-14. From this figure, the equation of motion is obtained by summing forces in the tangential direction:

$$\sum F_t = ma_t - mg \sin\theta = ma_t \qquad (5.3)$$

Where $a_t = l\ddot{\theta}$.

Equation 4.3 simplifies to:

$$\ddot{\theta} + \frac{g}{l}\sin\theta = 0 \tag{5.4}$$

Comparing Equation 5.1 with Equation 5.4, it can be seen that the frequency of oscillation of the pendulum is $\omega_n = \sqrt{\frac{g}{l}}$, and is independent of the mass of the pendulum.

The torque of the pendulum is given as:

$$\tau = \ddot{\theta}I, \tag{5.5}$$

Here $\ddot{\theta}$ is the angular acceleration, and I is the mass moment of inertia. The mass moment of inertia of the pendulum is calculated as:

$$I = ml^2 \tag{5.6}$$

Experimental setup

This experiment contains two different experimental setups for which properties will be determined. Each setup has a unique pendulum with either a 8 inch (20.3 cm) or 10 inch (25.4 cm) pendulum arm and a .5 pound (0.23 kg) or 1.5 pound (0.68 kg) pendulum weight. Figure C-15 shows the experimental setup of both the torsional and swinging pendulum apparatus.

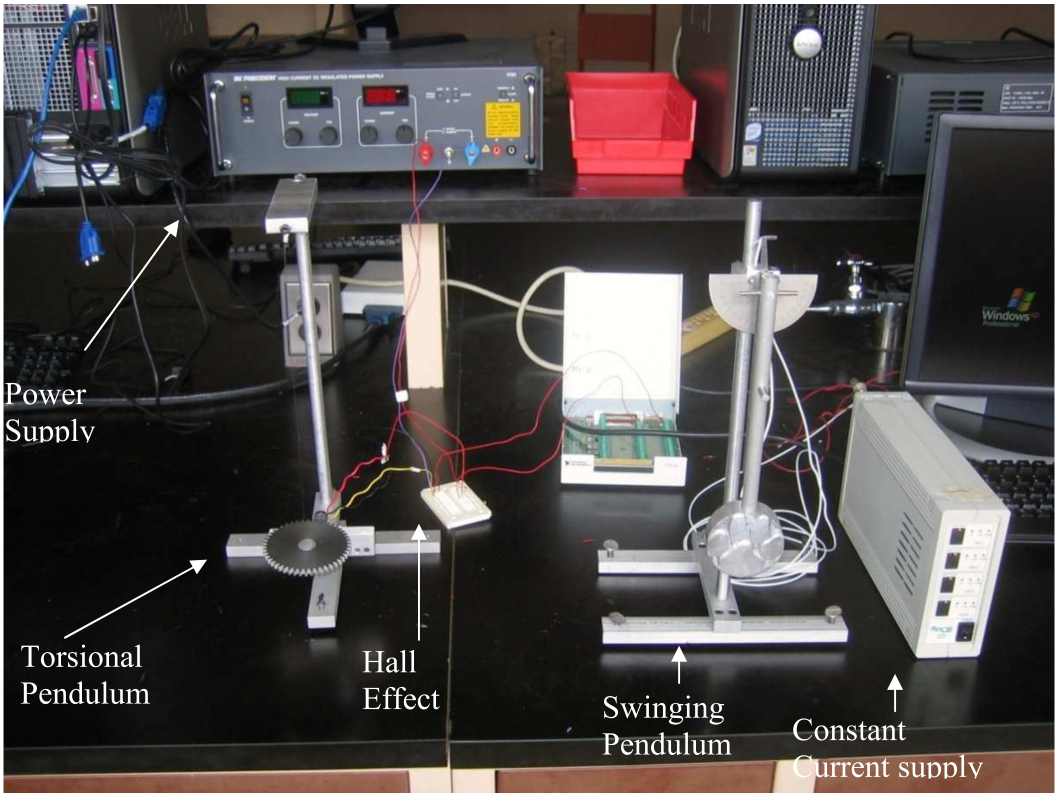


Figure C-15: Overall experimental set up [23]

Figures C-16 and C-17 detail the location of the accelerometer for the swinging pendulum and the location of the Hall Effect sensor for the torsional pendulum.

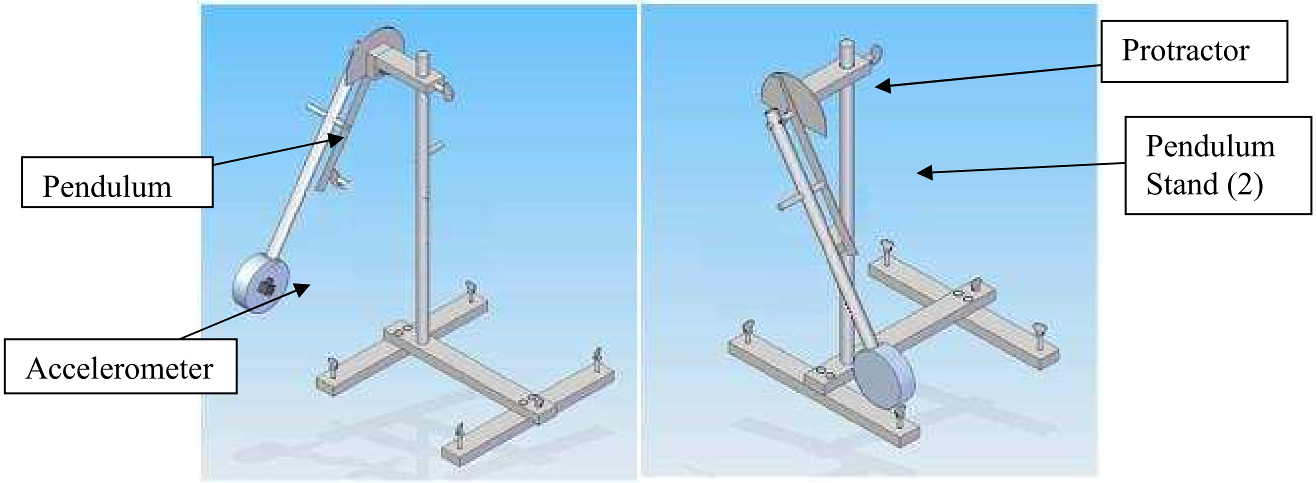


Figure C-16: Detail of swinging pendulum accelerometer placement [23]

The swinging pendulum experimental setup consists of a pendulum (1) supported by a pendulum stand (2), a protractor (3), and an accelerometer (4). In this configuration, the accelerometer is used to measure the tangential acceleration of the free swinging pendulum. The protractor is used to determine the angle of the pendulum.

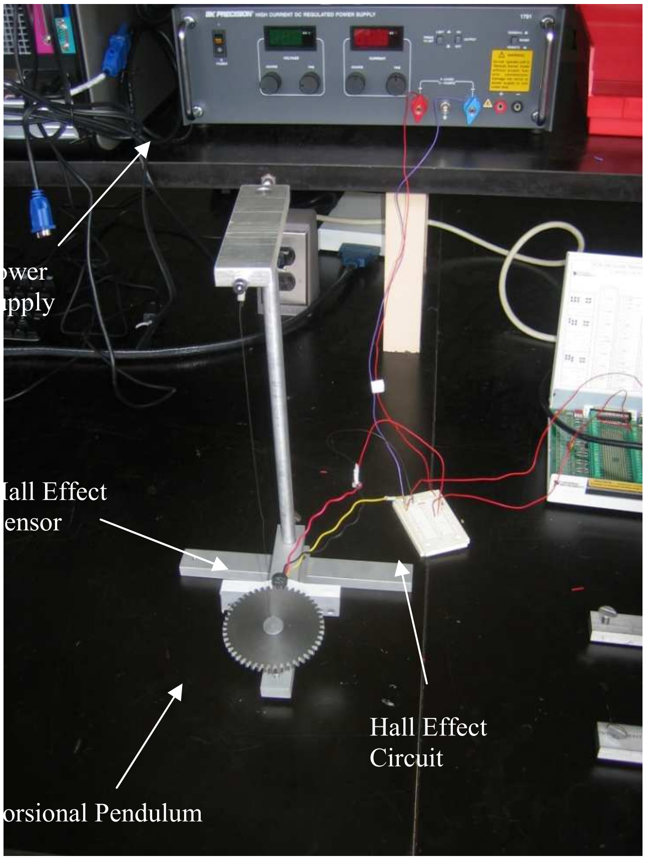


Figure C-17: Torsional pendulum in proximity of Hall Effect sensor [23]

The torsional pendulum setup consists of a stand which serves to support the bob and allow for mounting of the Hall Effect sensor. The Hall Effect sensor is utilized in conjunction with a 3 V power supply and a specific Hall Effect circuit. (Diagram provided in section D)

Sensors

Accelerometer Details

The accelerometers used in this lab will be the PCB Piezotronics shear accelerometer model number 333B30. The internal components of the shear accelerometer with the piezo-electric crystal are shown in Figure C-18. A shear accelerometer works by having a mass attached to a piezo-electric crystal and when the accelerometer is accelerated, the mass puts a shear strain on the crystal. This shear strain is what the accelerometer is actually measuring.

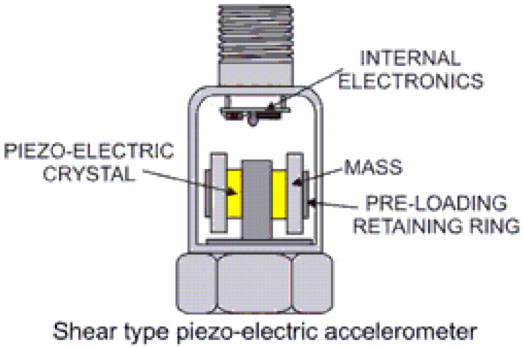


Figure C-18: Internal Components of a shear type piezo-electric accelerometer [23]

This particular accelerometer has an arrow indicating the direction the accelerometer measures acceleration. In the case of the torsional pendulum, the radius of rotation is needed to convert linear acceleration to rotational acceleration.

Hall-Effect Sensor Details

Hall-Effect sensors are commonly used in automobiles to time ignition or used to measure the engine speed which is displayed on a tachometer. A Hall-Effect sensor is a proximity sensor that uses the change in the magnetic flux to alter the output signal. A magnet is placed on the back side of the sensor which provides the magnetic flux that the sensor detects. If the north side of the magnet is facing the sensor, the output will be high at steady state and low when there is a change in the magnetic flux due to the proximity of a ferrous material. Therefore, it is typical for the south end of the magnet to be facing the sensor so that at steady state, the output will be low, and when a ferrous material changes the magnetic flux, the output will be high. The Hall-Effect sensor's pins are schematically presented in Figure C-19. When the writing on the sensor can be seen, the pin layout matches the one above.

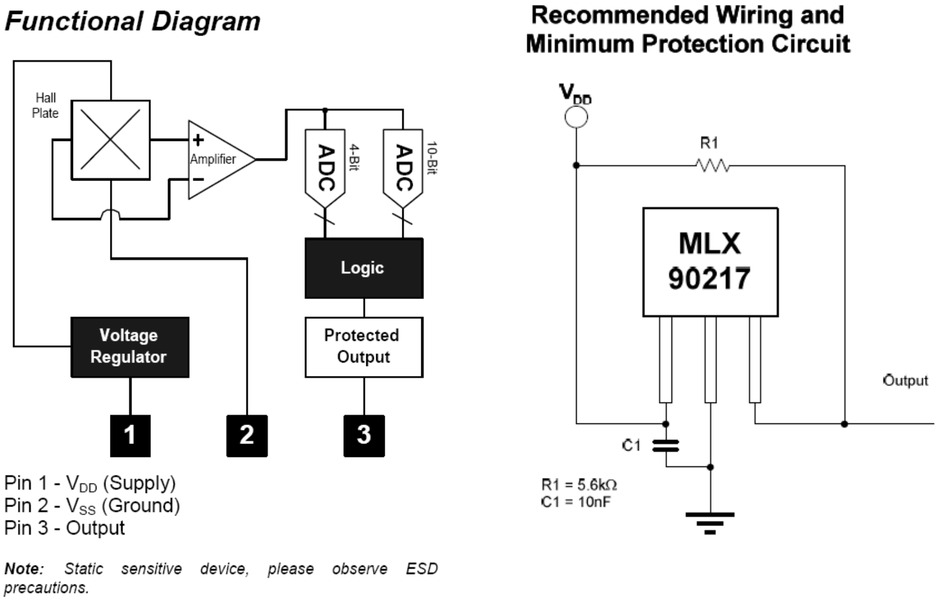


Figure C-19: Hall-Effect sensor internal schematic and wiring schematic [23]

The Hall Effect sensor signal should resemble the data presented in Figure C-20 below.

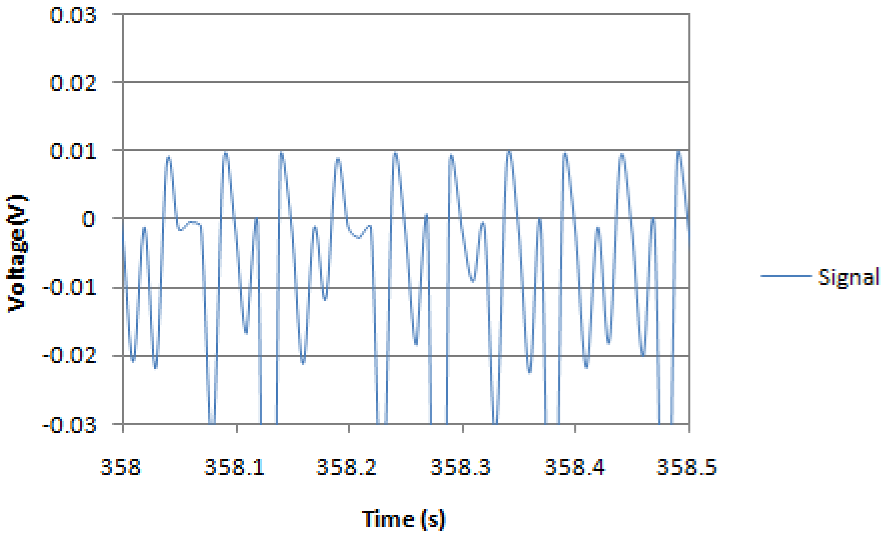


Figure C-20: Sample Hall Effect sensor signal over a time period of 0.5 seconds [23]

Each distinct peak nearing the 0.01 volt mark represents a tooth passing through the sensor's magnetic field. The rotations per minute of the gear can then be extracted from the peak/second value if the number of teeth on the gear is known.

Procedure

The procedure consists of mounting the pendulums to the stand and putting the sensors in place. The circuitry for the Hall-Effect sensor will need to be constructed per the provided diagram and positioned in a manner in which the gap between the torsional pendulum and the Hall Effect sensor is small enough for the sensor to output the data correctly. All parts needed for this experiment are listed in Table C-2.

Parts List	
2	Accelerometer
1	Swinging pendulum
1	Torsional pendulum
1	5.6kΩ resistor
1	10nF capacitor
1	Hall Effect sensor

Table C-2: Parts list [23]

Experimental Procedure for Torsional Pendulum Analysis

1. Connect the torsional pendulum to the test stand. Assure that the pendulum is secured and the Hall Effect sensor is in an adequate position to measure data.
2. Ensure that the Hall Effect circuit is set up and connected correctly to both the power supply and the sensor.
3. Turn the power supply on and set it to 3 volts.
4. Wind the pendulum 3-5 full rotations in either direction. Release the pendulum and, using the DAQ, record at least one full oscillation.
5. Calculate the angle per tooth on the gear to which will be used to determine the angular displacement.
6. Transfer data to Excel. Integrate the data from the accelerometer to go from acceleration to velocity to displacement. Then differentiate the data from the magnetic variable reluctance sensor to go from displacement to velocity to acceleration. Compare the two results.

Experimental Procedure for Swinging Pendulum Analysis

1. Connect the swinging pendulum to the test stand and mount the rotational potentiometer to the swinging joint.
2. Turn on the constant current PCB amplifier.
3. Rotate the pendulum to about 45° and release. Using the DAQ, record a minimum of five full oscillations.
4. Transfer data to Excel. Integrate the data from the accelerometer to obtain velocity and displacement. Compare the two results with those of the torsional pendulum.

Exercise 6 - Vibration Modes of a Chime Rod

The vibration behavior of a mechanical clock chime rod will be measured using an impact hammer with accelerometers. To supplement this study, the acoustics of the chime rod will also be recorded using a microphone attached to a computer workstation. The recorded data will be analyzed with Fast Fourier Transform (FFT) to identify the operating frequencies. The chime rod will be tested in a small semi-anechoic chamber.

Background

Chime rods, see Figure C-21, are used in time keeping mechanisms and offer a precise musical note which can be used to sound a melody. The striking hammer hits the chime rod to produce vibrations with frequencies that are dependent on the diameter and length of the rod.

Figure C-21: Wind chime configuration [23]

System Instrumentation

An impact hammer (Figure C-22) is a hand held device used to strike the chime rod in this experiment. Impact hammers are used to determine system response to impacts of varying amplitude and duration. A hammer with a force transducer in its head is paired with an accelerometer on the chime rod. It is used to compare impact and response. Some key components of the impact hammer are the force and pulse duration. Different tips can be used to vary the force and response times. The hard tips are used to measure response at the highest frequencies. Additional masses can attach to the back of the hammer head to increase the excitation force.

Figure C-22: Impact hammer [23]

Accelerometers (Figure C-23) are sensors used to measure, display, and analyze vibration in conjunction with a data acquisition system. Three main factors must be considered when selecting accelerometers: amplitude range, frequency range and ambient conditions. To minimize frequency response errors, the cables attached to the accelerometer must be securely attached to the chime rod to relive cable strain. This helps keep the accuracy of the readings as high as possible.

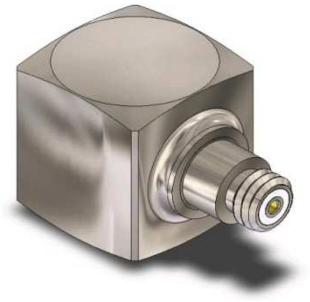


Figure C-23: Accelerometer [23]

A microphone, refer to Figure C-24, is a device made to capture waves and convert them into an electrical signal. The most common microphone uses a thin membrane that vibrates in response to sound pressure. These vibrations are turned into an electrical signal, which can be recorded to determine the frequency.

Figure C-24 Microphone used in experiment [23]

Fast Fourier Transform (FFT)

FFT is a method used to calculate the discrete Fourier Transform (DFT). It is an efficient method that uses algorithms in digital signal processing applications. Using this function in conjunction with MATLAB allows spectrum analysis to be conducted on the sound wave recorded using the microphone. The frequency can also be determined using this function.

MATLAB Code

```
%This code is used to perform a spectral analysis on a wav file that is recorded in Sound Recorded using a microphone.

clc
clear all

[x Fs nbits]=wavread('chime.wav');  %Insert WAV file
time=length(x)/Fs;                  %2 steps to create time vector
t=linspace(0,time,length(x));

%THIS PIECE OF CODE IS FROM MATHWORKS.  IT CAN BE FOUND AT: http://www.mathworks.com/support/tech-notes/1700/1702.html

% Use next highest power of 2 greater than or equal to length(x) to calculate FFT.
nfft= 2^(nextpow2(length(x)));
% Take fft, padding with zeros so that length(fftx) is equal to nfft
fftx = fft(x,nfft);
% Calculate the number of unique points
NumUniquePts = ceil((nfft+1)/2);
% FFT is symmetric, throw away second half
fftx = fftx(1:NumUniquePts);
```

```
% Take the magnitude of fft of x and scale the fft so that it is not a function of
%the length of x
mx = abs(fftx)/length(x);
% Take the square of the magnitude of fft of x.
mx = mx.^2;

% Since we dropped half the FFT, we multiply mx by 2 to keep the same energy.
% The DC component and Nyquist component, if it exists, are unique and should not be multiplied by 2.
if rem(nfft, 2) % odd nfft excludes Nyquist point
  mx(2:end) = mx(2:end)*2;
else
  mx(2:end -1) = mx(2:end -1)*2;
end
% This is an evenly spaced frequency vector with NumUniquePts points.
f = (0:NumUniquePts-1)*Fs/nfft;

% Generate the plot, title and labels.
figure(1)
subplot(4,1,1)
    plot(t,x)
    title('Recorded Wave File')
```

```
    xlabel('Time (s)')
    ylabel('Amplitude')
subplot(4,1,2)
    plot(f,mx)
    ylabel('Spectral Analysis')
    xlabel('Frequency (Hz)')
subplot(2,1,2)
    plot(f,mx)
    axis([10000 11500 0 .00000000000001])
    ylabel('Spectral Analysis')
    xlabel('Frequency (Hz)')
```

Chime Rods

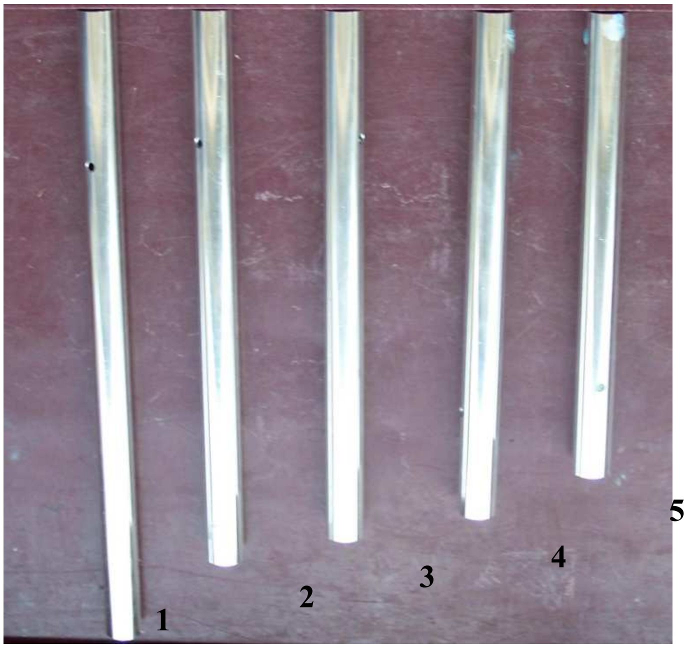


Figure C-25: Chime rods [23]

Dimensions of these rods are given in the Table C-3:

	L	***D***	***d***
Rod 1	15.1	0.963	0.865
Rod 2	13.0	0.978	0.872
Rod 3	12.3	0.972	0.873
Rod 4	11.6	0.973	0.878
Rod 5	10.5	0.966	0.870

Table C-3: dimensions in inches for the chime rods [23]

where is L is the length, D and d are the external and internal diameter respectively.

Vibrations

Vibration refers to mechanical oscillations about an equilibrium point. In this experiment, free vibration is studied. Free vibration is a type of vibration that occurs when an object is impacted with an initial force and then allowed to vibrate freely. The object will produce vibrations until it damps to zero. Objects usually vibrate at their natural frequency. See Figure C-25 for an example of the free vibration of a chime rod; the peak is the natural frequency of the system.

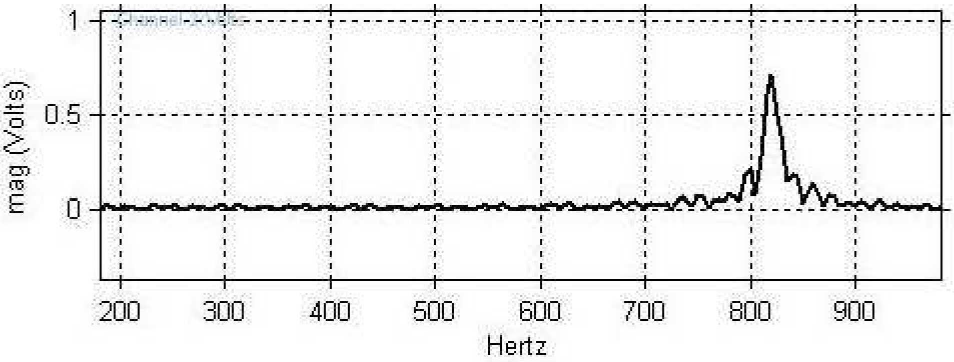


Figure C-26: Frequency response of a chime rod in free vibration [23]

Procedure—Acoustics Experiment

1. Hang chime rod on the rear hook inside semi-anechoic chamber.
2. Place the microphone on the stand.
3. Connect the microphone to input 1 on Audio Buddy pre-amp box.

Figure C-27: Audio amplifier [23]

4. Connect the red cord from output 1 on Audio Buddy to the computer (microphone input).
5. Set microphone inside semi-anechoic chamber as close to the chime rod as possible without touching it.
6. Open Sound Recorder from Windows start menu.
7. Press Record and strike the chime rod.

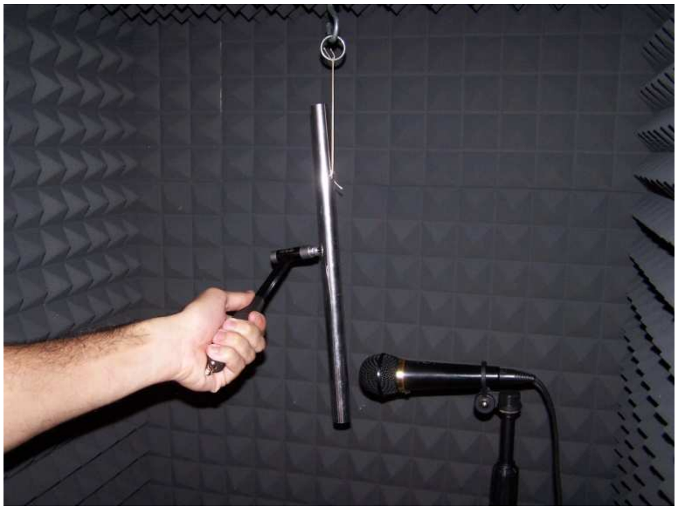


Figure C-28: set up for acoustic experiment [23]

8. Press Stop after collecting sound data.
9. Save Sound Recorder file as chime.wav in the MATLAB folder.
10. Open wavanal.m file in MATLAB.
11. Run the program and observe the resulting graphs of the spectrum analysis and frequency of the chime rod.
12. Repeat experiment using a different chime rod. Observe any differences in the spectrum analysis and frequency graphs.

Procedure—Vibration Experiment

1. Install accelerometer (100mV/g) on chime rod. Hang chime rod on the rear hook inside semi-anechoic chamber.

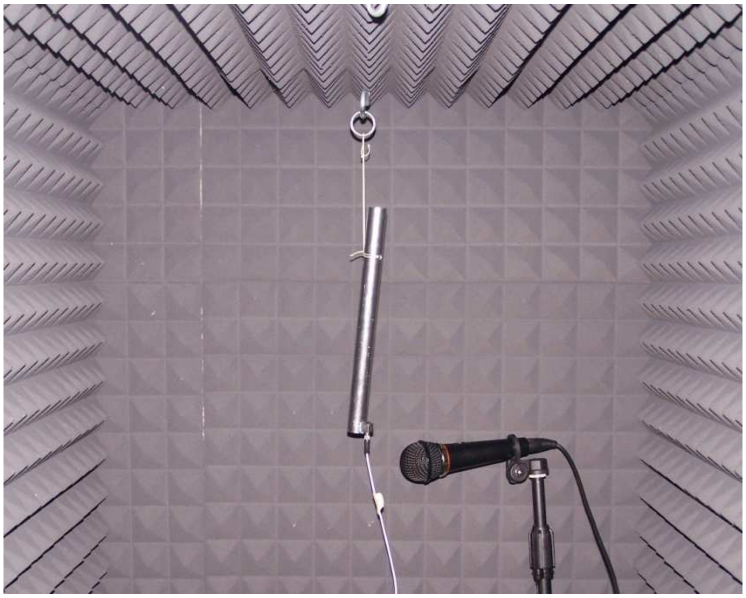


Figure C-29: Rod with accelerometer in the chamber [23]

2. Connect the accelerometer cable to channel 2 on SigLab.

3. Connect the impact hammer cable to channel 1 on SigLab.

Figure C-30: Connections at Siglab [23]

4. Type “sigdemo” on the command window of MatLab.
5. Press VNA (Virtual Network Analyzer) button in Siglab.
6. Open MechatronicsLab.vna file in SigLab (parameters for this experiment are saved in this file).
7. Hit “AVG” and strike chime rod using impact hammer. Observe for changes in the graphs.
8. Hit “STOP”.
9. Copy the plots (impulse response from the hammer and FFT response from the accelerometer) or export data to be analyzed later.
10. Detach the accelerometer from the chime rod and install it on the next rod to be tested. Repeat procedures 7-9 until all the 5 rods have been tested.

Figure C-31: Set up for vibration experiment [23]

Exercise 7 - Electronic Dice Circuit

Light emitting diodes (LED's) will be used to create an electronic dice. The LED's will be powered by a 4017 decade counter with a clock pulse coming from a 555 timer in astable mode. A toggle switch will control when the dice is effectively "rolling" and freeze the output state. This circuit uses a high frequency clock pulse so that the output of the decade counter can not be controlled, creating a random number generator. This random number lights up the LED's in the appropriate configuration to simulate a dice.

Background

As electronic designs get bigger and more complex, it becomes difficult to build the complete circuit. An Integrated Circuit (IC) has many transistors inside it that are connected together to form a circuit. Metal pins are connected to the circuit and the circuit is inserted into a piece of plastic or ceramic so that the metal pins are sticking out the side. These pins allow you to connect other devices to the circuit inside.

When working with a stable circuit, the voltage remains the same. A change in input voltage results in a change in output voltage, and again the voltage remains constant until the input is changed. A 555 IC is designed so that when the input changes, the output goes from 0 to Vcc (Vcc is the voltage of the power supply). The voltage will stay at Vcc for an amount of time before returning to 0 volts. A graph illustrating this phenomenon is given in Figure C-32.

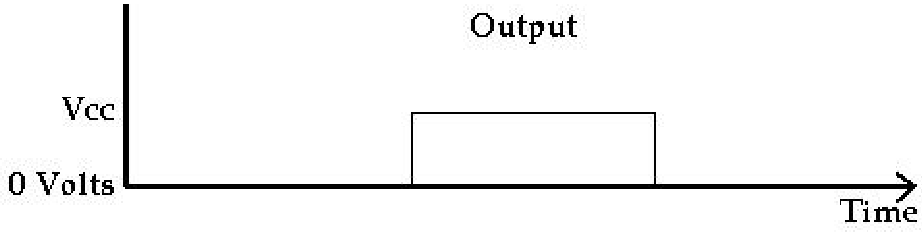


Figure C-32: A voltage “pulse” [23]

A circuit that varies voltage in this manner continuously is called an oscillator. An oscillator produces a series of pulses. The output continuously oscillates between 0 to Vcc. This output is called a clock. You can count the number of pulses to tell how much time has gone by. A 555 timer can be used to generate continuously varying output shown in Figure C-33.

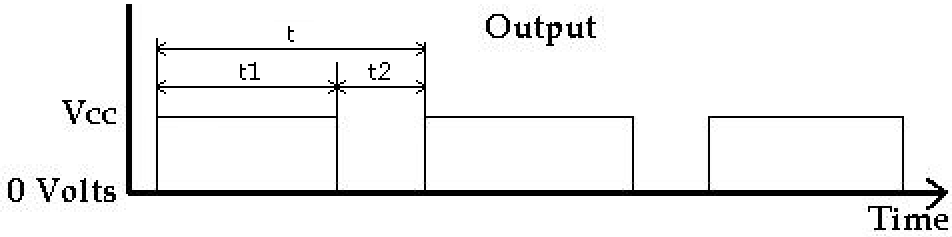


Figure C-33: Timer Output or Clock [23]

Capacitor Details

For example, one type of capacitor is a ceramic disk capacitor, and is shown below in Figure C-34.

Figure C-34: Capacitor Picture [23]

Capacitors are comprised of two metallic plates separated by a dielectric material. This creates an electric field which produces certain properties. Certain capacitors may have markings indicated the polarity of the capacitor. For safety reasons, always insert the capacitor in the correct orientation if polarity markings are present.

A capacitor can charge and discharge similar to a rechargeable battery. If a 12 volt supply is used to charge a capacitor, it will start with 0 volts and go from 0 volts to 12 volts. A representation a capacitor being charged is shown below in Figure C-35.

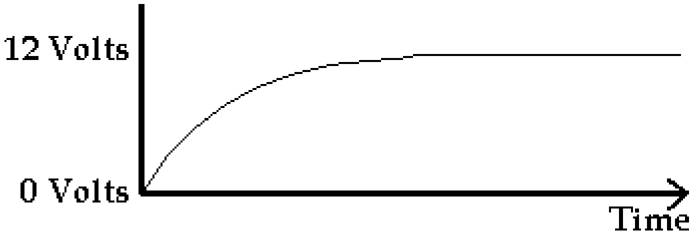


Figure C-35: Capacitor Charging [23]

The capacitor discharges in a similar manner as it charges. If the capacitor has been charged to 12 volts and is then shorted thru a resistor, the capacitor will discharge as shown in Figure C-36. The rate of a capacitor's charging and discharging can be controlled using resistors.

Figure C-36: Capacitor Discharging [23]

555 Timer Details

To create a pulse using a 555 timer it is necessary to connect the timer with resistors and capacitors into a circuit. The resistor is used to control how fast the capacitor charges. The bigger the resistance, the longer it takes to charge the capacitor. The voltage in the capacitor can then be used as an input to another switch. Since the voltage starts at 0, nothing happens to the second switch. But eventually the capacitor will charge up to some point where the second switch comes on. The pin-out diagram for the 555 timer is shown in Figure C-37.

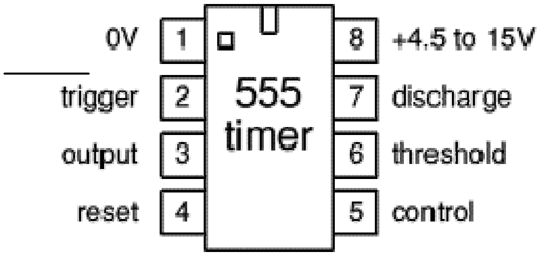


Figure C-37: 555 Timer Pinout [23]

The 555 timer operates so that when the voltage supply is connected, the Output pin goes to Vcc (the positive power supply voltage) and starts charging the capacitor. When the capacitor voltage gets to 2/3 Vcc (that is Vcc * 2/3) the second switch turns on which makes the output go to 0 volts.

Pin 2 (Trigger) is the 'on' switch for the pulse. The line over the word Trigger is representative of the fact that voltage levels are the opposite of what you would normally expect. To turn the switch on you apply 0 volts to pin 2. Pin 6 is the off switch for the pulse. We connect the positive side of the capacitor to this pin and the negative side of the capacitor to ground. When Pin 2 (Trigger) is at Vcc, the 555 holds Pin 7 at 0 volts (note the inverted voltage). When Pin 2 goes to 0 volts, the 555 stops holding Pin 7 at 0 volts and the capacitor starts charging. The capacitor is charged through a resistor connected to Vcc. The current starts flowing into the capacitor, and the voltage in the capacitor starts to increase. Pin 3 is the output (where the actual pulse comes out). The voltage on this pin starts at 0 volts. When 0 volts is applied to the trigger (Pin 2), the 555 timer puts out Vcc on Pin 3 and holds it at Vcc until Pin 6 reaches 2/3 of Vcc. The 555 pulls the voltage at Pin 3 to ground creating a pulse. The voltage on Pin 7 is also pulled to ground, connecting the capacitor to ground and discharging it. A diagram can be seen in Figure C-38.

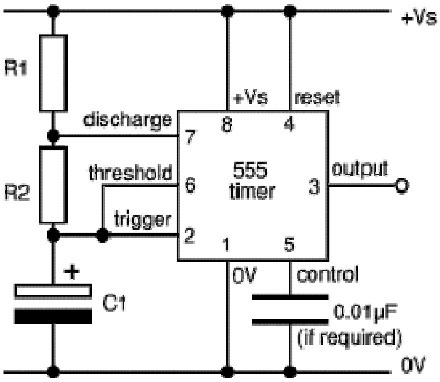


Figure C-38: A stable 555 Timer [23]

In order to make better use of the timer, the speed can be calculated with the following formulas. See Figure C-38 for descriptions of the variables.

$$t_1 = 0.693 * C * (R_1 + R_2) \quad (1)$$

$$t_2 = 0.693 * C * R_2 \quad (2)$$

Decade Counter details

A decade counter is an IC given the coded designation of CD4017. There are many manufacturers of this semiconductor, but they all follow the same pinout as seen in Figure C-39. The IC uses a clock pulse to cycle through 10 different pins. When a clock pulse is detected, the IC "counts up" 1 pin. The outputs are in order from Q0-Q9 with only one being high at the same time. The counter also has a pin that is low from 0 to 4 and high from 5 to 9. This is a decade pin which will create a clock pulse for another counter counting the 10's digit. Counters can be chained to count very high numbers. The Reset pin is used to reset the counter back to Q0. This is useful if the circuit does not require counting to a full ten, since the output of one pin can be used to trigger the Reset pin. The disable pin prevents any outputs from being on. This IC can handle between 5 and 15 volts.

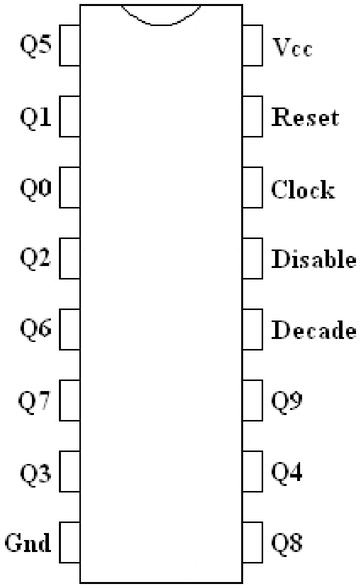


Figure C-39: 4017 Counter Pinout [23]

Procedure

The procedure for building this circuit will follow the diagram below, but will be built in sections so that each portion of the circuit can be tested for troubleshooting.

Qty	Part
3	330 Ohm Resistor
3	10K Ohm Resistor
1	470 Ohm Resistor
1	.01uF Capacitor
1	.1 uF Capacitor
1	555 Timer
1	4017 Decade Counter
1	Toggle Switch
7	LED's

Table C-4: Part list for electronic dice [23]

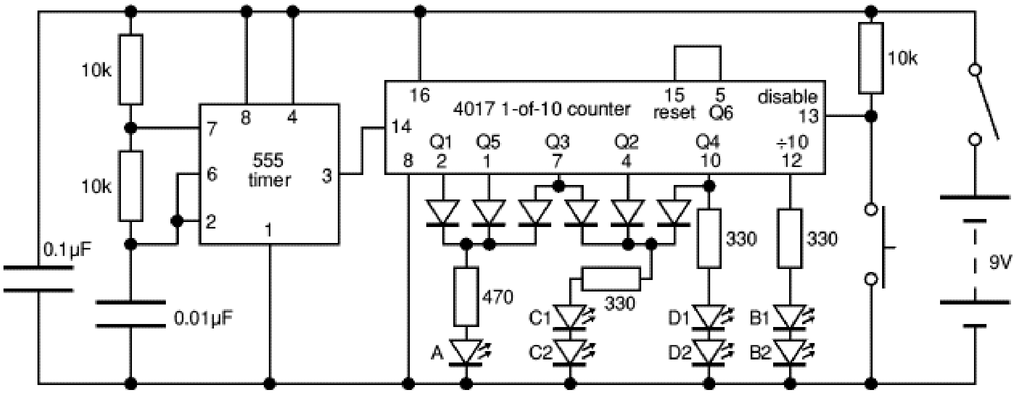


Figure C-40: Circuit Diagram [23]

555 Oscillator Circuit

1. First place the 555 timer into the breadboard with the number 1 pin in the top left.
2. Connect Pins 8 and 4 to +5V and connect pin 1 to ground.
3. Connect one side of a 10k Ohm resistor to +5V and the other side to Pin 7.
4. Take another 10k Ohm resistor and connect pin 7 to pin 6.
5. Use a piece of wire to connect pin 6 to pin 2.
6. Place a 0.01uF capacitor between pin 2 and ground.

7. The circuit is now complete for the oscillator. Check to see if the circuit is functioning by connecting the onboard speaker to pin 3 and ground. If you hear a ringing note, it is functioning.

LED Configuration

8. Take the 7 LED's and arrange them on the breadboard in a dice configuration. Make sure the cathode and anode are not on the same rail and that no LED shares the rail with another. There are three sets of LED's in series with the middle LED being alone. See the diagram below.
9. Connect a 330 Ohm resistors to A, B, and D in the diagram below.
10. Connect a 470 Ohm resistor to C.

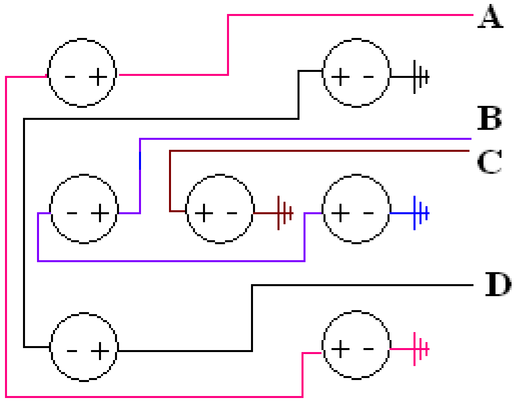


Figure: C-41: LED Diagram [23]

11. Apply +5V through the resistors to the LED's and verify that all 7 are lit. This section of the circuit is complete.

4017 Counter Circuit

12. Place the 4017 counter with pin 1 oriented in the top left corner.
13. Connect Pin 16 to +5V.
14. Connect Pin 8 to ground.
15. Connect the 1N4148 signal diodes to pins 1, 2, and 7. Bring the diodes together on one rail and connect this rail to C on the previous diagram using the 470 Ohm resistor.
16. Connect the 1N4148 signal diodes to pins 4, 7, and 10. Bring the diodes together on one rail and connect this rail to D on the previous diagram using the 330 Ohm resistor.
17. Connect pin 10 to B on the previous diagram using a 330 Ohm Resistor.
18. Connect pin 12 to A on the previous diagram using a 330 Ohm Resistor.
19. Use a 10K Ohm resistor to connect +5V to pin 13.
20. Wire the switch from pin 13 to ground.
21. Connect pin 14 of the 4017 counter to pin 3 of the 555 timer.
22. Connect a 0.1 uF capacitor to between +5V and ground to smooth the power supply.
23. The circuit is now complete. When powered on, the circuit should light all 7 LED's until the switch is pressed again. At that point, there should be a number displayed through the LED configuration.

Exercise 8 - Rotation Counter

A circuit that uses an opto-isolator approach will be created that is capable of counting revolutions. Once per revolution the opto-isolator circuit creates a signal that causes an integrated circuit to count and display the result on a seven segment display.

Background

This circuit uses four major components that will be covered in the following sections, light emitting diodes, light dependent resistors, 741 operational amplifiers, and the 4026 CMOS integrated circuit. The light emitting diode causes the resistance of the light dependent resistor to drop when the hole is between them. When the resistance drops, the 741 operational amplifier provides a +9V signal to the 4026 integrated circuit. This causes the 4026 to count up one and display the number on a seven segment driver. This effectively counts the number of revolutions.

Light Emitting Diodes

Light emitting diodes (LED) use the flow of electrons through a semiconductor material to generate a visible light output. The type of material used and the amount of current flowing determines the brightness of the light. There are two different purposes for LED’s in this circuit. The first purpose is to create enough light to drop the resistance of the light dependent resistor. The LED used for this purpose is a 10 mm white LED, similar to the one pictured in Figure C-42. LED’s require a particular voltage and current, or the LED will burn out. Generally a larger wavelength requires a smaller voltage drop.

Red LED’s require less voltage than Blue LED’s. The white LED used in this experiment requires roughly 4 volts and 50 mA.

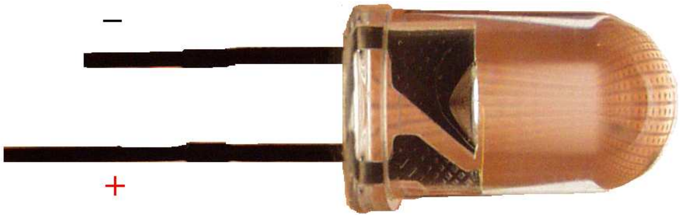


Figure C-42: Light Emitting Diode [23]

The second use of LED’s in this circuit is the seven segment display. Seven segment displays are an arrangement of seven LED’s that are capable of displaying a number from 0 to 9. These displays can be either common cathode or common anode. Common cathode means each LED shares a common ground, while common anode means they share a common power source. The displays used in this lab are common cathode and the pinout can be seen in Figure C-43. In Figure C-43, each letter corresponds to one of the segments, and “DP” refers to the decimal point.

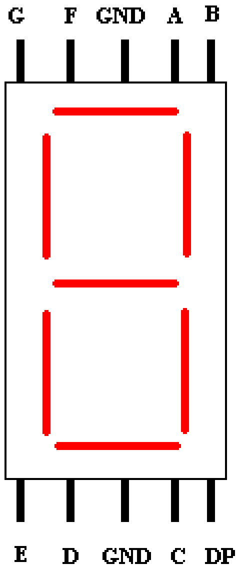


Figure C-43: Seven Segment Pinout [23]

Light Dependent Resistors

Light dependent resistors (LDR)'s are resistive elements that are influenced by the amount of light present. When a LDR is removed from light, its resistance is high. When a light source is aimed towards the photocell, the resistance drops significantly. The resistance value can vary. For this circuit, the LDR has a resistance of roughly 10,000 ohms in the dark and 900 ohms when placed into the light. LDR's are typically not polarized, so current direction does not matter. A typical light dependent resistor can be seen in Figure C-34.

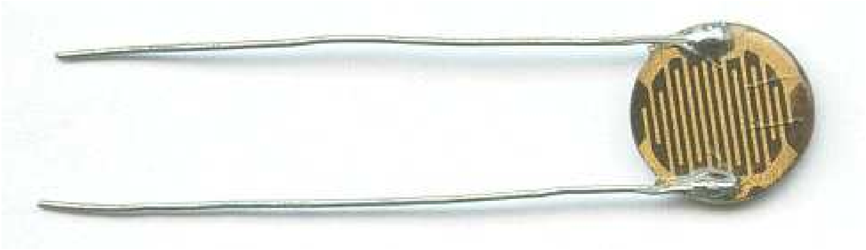


Figure C-44: Light Dependent Resistor [23]

741 Operational Amplifier

The operational amplifier is capable of taking an input voltage and amplifying it so that small voltage differences can be used for comparisons or logic circuits. The maximum voltage that an operational amplifier can reach is determined by its supply voltage. In this experiment, the 741 operational amplifier will only have +9 volts and ground, so the max it will produce is 9 volts. The amplifier in this circuit is used as a comparator. It provides a 9 volt or 0 volt signal based on the voltages present at pins 2 and 3. When pin 2 is higher, the output will be 0 volts. When pin 3 is higher, the output will be +9 volts. A pinout of the 741 operational amplifier can be seen in Figure C-45. A voltage output based on the resistance of the light dependent resistor (LDR) and resistor on pin 2 (R1) can be seen in Figure C-46.

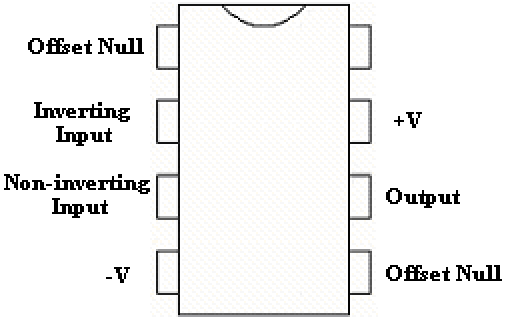


Figure C-45: 741 Pin Configuration [23]

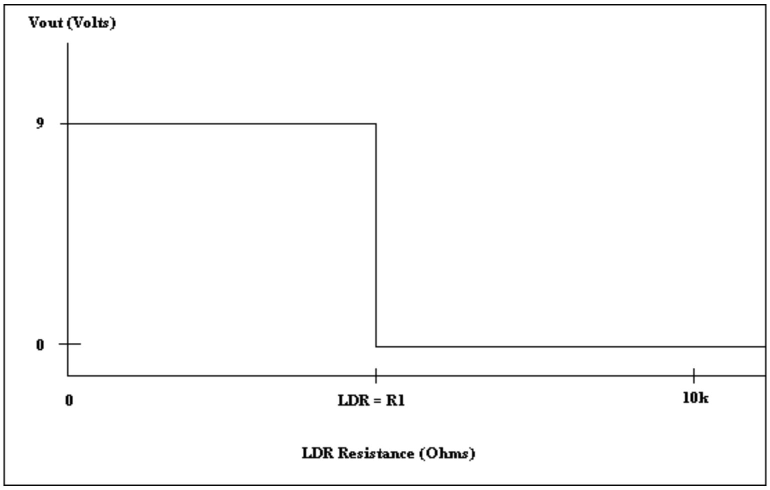


Figure C-46: Comparator Output [23]

4026 CMOS Integrated Circuit

The 4026 CMOS integrated circuit provides two functions in one chip. It provides a decade counter with the ability to count from 0 to 9. The 4026 also simplifies wiring by converting this number to a format that can be displayed on a seven segment display. A pinout can be seen in Figure C-47 and the output based on count is shown in Figure C-48.

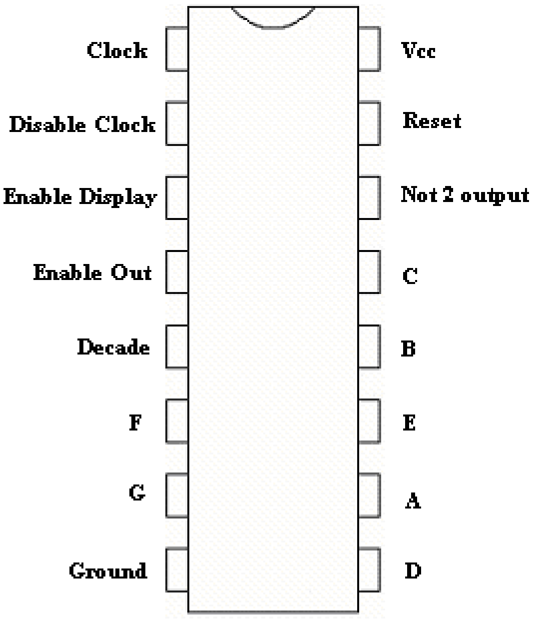
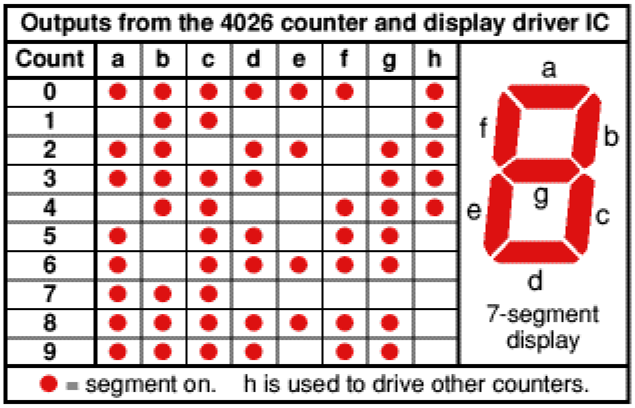


Figure C-47: 4026 Integrated Circuit [23]

The clock input on the 4026 is used for counting. If the disable clock pin is high, the 4026 pauses counting. The enable display pin must be high or the display will be blank. Enable out follows the input with a brief delay. The decade pin provides a low output from 0 to 4 and a high output from 5 to 9. Reset allows the count to be returned to zero. The not 2 output is high unless the count is 2. Outputs A through F represent the seven segments of the display.



Outputs from the 4026 counter and display driver IC

Count	a	b	c	d	e	f	g	h
0	●	●	●	●	●	●		●
1		●	●					●
2	●	●		●	●		●	●
3	●	●	●	●			●	●
4		●	●			●	●	●
5	●		●	●		●	●	
6	●		●	●	●	●	●	
7	●	●	●					
8	●	●	●	●	●	●	●	
9	●	●	●	●		●	●	

● = segment on. h is used to drive other counters.

Figure C-48: 4026 Output [23]

Procedure

The procedure for building this circuit will follow the diagrams in Figure C-49 and Figure C-50, but will be built in sections so that each portion of the circuit can be tested for troubleshooting.

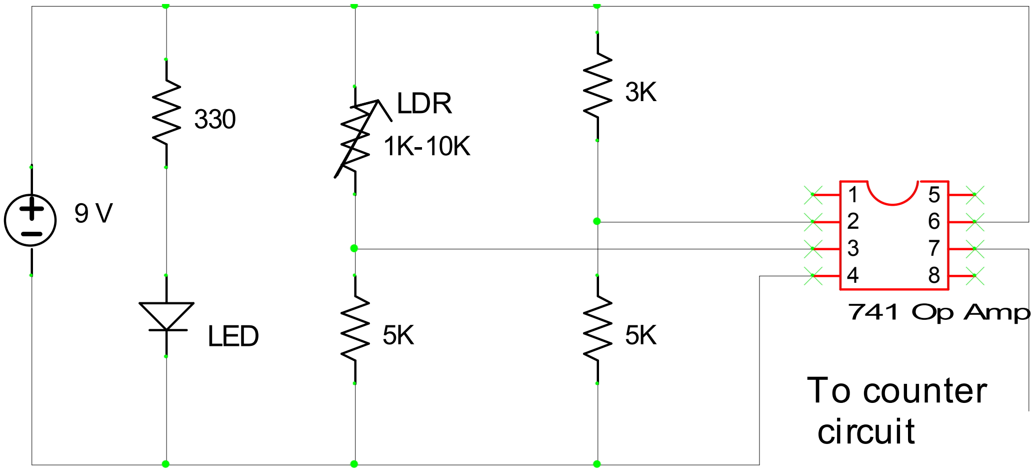


Figure C-49: Sensor Circuit

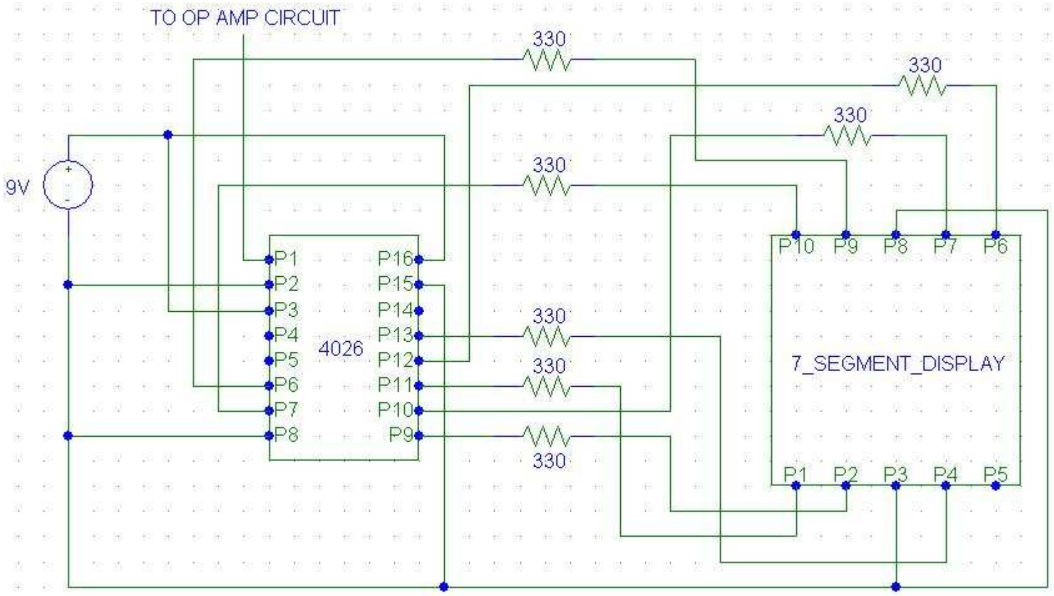


Figure C-50 Display Circuit [23]

Table C-5: Part list for rotation counter [23]

Sensing Circuit

1. First place the 741 amplifier into the breadboard with the number 1 pin in the top left.
2. Connect Pin 7 to +9V and connect pin 4 to ground.

3. Take the leads coming from the LDR and connect one to +9V and connect the other to pin 3 of the 741 amplifier. The leads should be black.

4. Take a 3k ohm resistor and connect one side to +9V and the other side to pin 2 of the 741 amplifier.
5. Connect a 330 Ohm resistor to +9V and connect the other end to the positive lead for the LED. The color of this wire should be red.
6. Connect the ground of the LED to ground. The color of this wire should be yellow.
7. Time to test the circuit. Place a LED with 330 ohm resistor to pin 6 of the 741 amplifier. Spin the wheel and check to ensure the LED is flashing when appropriate. If the LED fails to light, increase the resistor to pin 2. If the LED is always on, decrease the resistor to pin 2. Once the circuit is verified working, remove the LED and resistor.

Display Circuit

8. First place the 4026 IC into the breadboard with the number 1 pin in the top left.
9. Connect pins 3 and 16 to +9V. Connect pins 2,8, and 15 to ground.
10. Place the seven segment display onto the breadboard. Follow the diagram and connect pins as described in Table C-6. Include 330 Ohm resistors in each connection.

4026 Pin	Display Pin
6	10
7	9
9	2
10	7
11	1
12	6
13	4

Table C-6: Pin Connections [23]

11. Connect Pin 1 of the 4026 IC to +9V and make sure it counts up one. If the circuit counts up one, connect pin 1 of the 4026 IC to pin 6 of the 741 op amp.
12. Connect the positive lead for the motor to a 47 Ohm resistor, and the other side to +5 V. Connect the ground for the motor to ground.
13. The circuit is finished. Give the wheel a spin and watch the counter count up the total number of spins.

REFERENCES

1. Material Handling Institute of America, www.mhia.org/learning/marketresearch, 2009
2. Khan, O., “Current Technological Development and Mechatronics”, proceedings of the IEEE International Multi-Topic Conference, pp. 111-117, Lahorse University, Pakistan, December 2001.
3. Merkel, C., and Fisher, D., “A Quick and Easy PLC Learning Experience for Mechatronics”, Proceedings of the ASEE Annual Conference, pp. 895 – 906, Chicago, IL, June 2006.
4. Chiou, R., Kwon, Y., Rauniar, S., and Sosa, H., “Internet-based Robotics and Mechatronics Experiments for Remote Laboratory Development”, Proceedings of the ASEE Annual Conference, pp. 1363-1379, Honolulu, HI, June 2007.
5. Lee, C., and Park, S., “Sensor-Based Robot Control Laboratory”, Proceedings of the ASEE Annual Conference, New Orleans, LA, June 1991.
6. Marsico, S., “Incorporating a Flexible Manufacturing System into a Design Course”, Proceedings of the ASEE Annual Conference, Montreal, Quebec, Canada, June 2002.
7. Erickson, K., “Innovative Experiments for Undergraduate Factory Automation”, proceedings of the 13th World Congress, International Federation of Automatic Control, San Francisco, CA, June 1996.

8. Stormont, D., and Chen, Y., “Using Mobile Robots for Controls and Mechatronics Education”, International Journal of Engineering Education, vol. 21, no. 6, pp. 1039-1042, 2005.
9. Ghone, M., and Wagner, J., “A Multi-Disciplinary Mechatronics Laboratory”, Proceedings of the ASEE Annual Conference, Nashville, TN, pp. 1607-1614, June 2003.
10. Vermaak, H., and Jordaan, G., “Automated Component-Handling System for Education and Research in Mechatronics”, Proceedings of IEEE AFRICON Conference, pp. 4401627, Windhoek, South Africa, September 2007.
11. Bassily, H., Sekhon, R., Butts, D., and Wagner, J., “A Mechatronics Educational Laboratory – Programmable Logic Controllers and Material Handling Experiments”, Journal of Mechatronics, vol. 17, no. 9, pp. 480-488, November 2007.
12. Material Handling Institute of America (MHIA), www.mhia.org, 2008.
13. Wagner, J., "Evolving Industry Expectations for Engineers - The Impact of Global Manufacturing", Proceedings of the ASEE Conference, Charlotte, NC, June 1999.
14. Acar, M., and Parkin, R., “Engineering Education for Mechatronics”, IEEE Transactions on Industrial Electronics, vol. 43, no. 1, pp. 106-112, February 1996.
15. Krotkov, E., “Robotics Laboratory Exercises”, IEEE Transactions on Education, vol. 39, no. 1, pp. 94-97, February 1996.
16. Ghone, M., Schubert, M., and Wagner, J., “Development of a Mechatronics Laboratory-Eliminating Barriers to Manufacturing and Control”, IEEE Transactions on Industrial Electronics, vol. 50, no. 2, pp. 394-397, April 2003.

17. Shirley, J., Wagner, J., Collins, R., and Gramopadhye, A., “A Mechatronics (and Material Handling Systems) Course – Classroom Topics, Laboratory Experiments, and Project”, Proceedings of the ASEE Annual Conference, Austin, TX, June 2009.
18. Murray, W., and Garbini, J., “Mechatronics Capstone Design Projects at the University of Washington”, Proceedings of the IEEE/ASME International Conference on Advanced Intelligent Mechatronics, pp. 598-604, Atlanta, GA, September 1999.
19. Ebert-Uphoff, I., Gardner, J., Murray, W., and Perez, R., “Preparing for the Next Century: the State of Mechatronics Education”, IEEE/ASME Transactions on Mechatronics, vol. 5, no. 2, pp. 226-227, June 2000.
20. Du, W., “On Improvement of Graduate Mechatronics Course”, Innovations in Engineering Education 2005: Mechanical Engineering Education, Mechanical Engineering Technology Department Heads, vol. 2005, pp. 191-196, Orlando, FL, November 2005.
21. Thrambouldis, K., “Model-Integrated Mechatronics – Toward a New Paradigm in the Development of Manufacturing Systems”, IEEE Transactions on Industrial Informatics, vol. 1, no. 1, pp. 54-61, February 2005.
22. Jammes, F., and Smit, H., “Service-oriented Paradigms in Industrial Automation”, IEEE Transactions on Industrial Informatics, vol. 1,no. 1, pp. 62-70, February 2005.
23. Wagner, J., “ME 493/693 Laboratory Manual”, V2.0, Department of Mechanical Engineering, Clemson University, Clemson, SC, August 2009.