Capstone Design Experience for a Self-Designed Major Engineering Student

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***Abstract*—A student came to the engineering program at York College of Pennsylvania to major in Mechanical Engineering. After his first cooperative (co-op) education assignment with Multi-dimensional Integration, he became interested in automated manufacturing. More specifically, he wanted to learn more about Programmable Logic Controllers (PLC) in a manufacturing environment. He really wanted to combine parts of a traditional mechanical engineering degree and parts of an electrical engineering degree. This paper briefly describes the curriculum of this students self-designed major in "Electro-Mechanical Engineering", and then more specifically concentrates on the capstone design experience. The capstone project was a PLC-based box sorting conveyor, and the student was tasked with designing the system from scratch. This paper provides the details on project planning, design, and implementation.**

***Keywords*—programmable logic controllers, CLICK programming software, self-designed major, capstone project**

I. Introduction

A self-designed major requires highly motivated students due to its unique requirements. A recent study showed that self-designed major students' motivation is focused on personal development compared to non-self-designed major students, who are mostly career oriented [1]. Self-designed major students are inclined to learn through experiential learning along with self-designed learning strategy. The engineering departments at York College wanted to provide an opportunity for a self-designed major for a student who was motivated by his exposure to automated manufacturing through the cooperative education program [2]. The student initially enrolled in the mechanical engineering degree program, but his work in automation made him interested in electrical engineering. A combined degree with electrical and mechanical engineering made perfect sense for him. The problem was that such a degree program did not exist at the College. After learning about the interest and motivation of the student, two faculty members (one from each degree program) worked together with the student to develop a combined engineering major for the student—Electro-Mechanical Engineering.

II. Literature Review

The main objective of an engineering degree program is to produce graduates who are ready to contribute in engineering fields by applying their knowledge to analyze and evaluate a problem to create a better product. To achieve this, an engineering curriculum needs to scaffold the learning carefully. Each course and project need to be placed carefully to develop knowledge and skills necessary for the current industry. Customizing a technical degree program is not new. In 1965, a jointly sponsored program funded by both the Federal Government and industry, a Consortium of schools was formed to create a curriculum to produce specialized workforce [3]. Many institutions offer specialized degree programs in engineering and most of them are inter-disciplinary [4–7]. Some institutions offer specialized design projects to provide students with multi-disciplinary experiences [8–10]. A custom designed curriculum along with the project-based learning was implemented to provide the student with skills and experiences needed for the industry [11]. The curriculum and project prepared the student to conduct independent research, solve problems, create prototype, and evaluate the design process.

III. Electro-mechanical Curriculum

When preparing the electro-mechanical curriculum, the faculty advisors involved decided the best approach would be to have the student complete the fundamental elements required from each of the two programs as they related to manufacturing design with PLCs. Then, to satisfy the student's interest and intrinsic motivation, the curriculum would culminate in project-based Capstone course.

To satisfy the mechanical requirements of a manufacturing environment, courses were chosen in introduction to mechanical engineering (a mechanical drawing and machining class), statics, and strength of materials. To satisfy the energy transport aspects of a

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manufacturing environment, courses were chosen in thermodynamics, fluid mechanics, and power electronics. To complete the building blocks of a manufacturing design environment, courses were needed for the student to get the required background in sensors, actuators, circuit design, and programming. To achieve this goal, courses were chosen in the fundamentals of computer science, the fundamentals of electrical engineering, the design of digital and analog circuits, signal processing, and instrumentation. Finally, to complete the systems integration design necessary for a manufacturing environment, courses were chosen including mechatronics, system modeling, and automatic controls. The required courses are listed below in Table I. In addition to the traditional coursework, the student was also required to complete three co-op semesters. It was determined that he could stay with Multi-dimensional Integration for all three of these terms to continue to develop the hands-on skills required to work with PLCs in a manufacturing environment. Of course, an engineering degree would also need to include math, science, and general education requirements, but these requirements were the same for all students at the college.

TABLE I. ENGINEERING COURSE CURRICULUM

Courses	Courses' Names
Electrical Engineering Courses	Fundamental of Computer Science
	Design and Analysis of Digital Circuits
	Fundamental of Electrical Engineering
	Design and Analysis of Analog Circuits
	Introduction to Signal Processing
	Power Electronics
	Capstone Project
Mechanical Engineering Courses	Introduction to Mechanical Engineering
	Statics
	Strength of Materials
	Fluid Mechanics
	Thermodynamics
	Instrumentation Lab
	Capstone Project
General Engineering Courses	Mechatronics
	System Modeling and Analysis
	Automatic Controls
	Three semesters of Co-operative education

With the rest of the course work laid out, the capstone design project would require the student to apply the knowledge and skills he picked up during these courses to solve a complex, real-world problems. Due to the student's interest and motivation, it was decided that he would design, build, and test an automated conveyor belt sorting system to enhance his experience in automation. The following sections document each step of this capstone design project.

IV. PROJECT TIMELINE AND CONSTRAINTS

The student had an introduction to PLCs at the co-op positions where he worked throughout his college career. Prior to the start of his senior year, the student prepared for two upcoming capstone design projects (capstone-I and capstone-II) that would include the use of a PLC. Capstone-I was focused on research, design, and development of PLC hardware and software. During the capstone-I, the student determined that the project would be an automated box sorting conveyor system. The scope of the project was developed by the student and approved by the advisors and Department Chair.

The student had thirteen weeks to complete the project during capstone-II. The project was broken up into four main goals. First was the design phase. This included the design and operation of the conveyor system. The next phase was the project construction phase. This phase is where all of the materials were collected/purchased and the conveyor design was put together. The third phase was to develop the control code for the PLC. Any code that needed to be designed was developed in this phase. The final phase was putting the whole project together, calibrating, and troubleshooting any issues. Weekly meetings occurred between the advisor and student to make sure that the project was staying on track.

Once the phases of the project were complete, the project was reviewed by the instructor. The final two weeks of the project were dedicated to drafting a final report. This report included the scope of the project, as well as the design developed. Minor changes and improvements to the project also occurred during this time.

One limitation put on the project was size. The project needed to fit in a corner of a room to keep the constraints of being a model and not a full-size design. The cost of the project required to be under the price of $1,000 for all materials used. Parts of the project were allowed to be purchased, however, materials found within the department must be used first. 3-D printed materials were used in this project for a quick production of the materials needed. A general construction conveyor was used for the project; the design was built around the use of this conveyor. This allowed the project to be more aesthetically pleasing, as the construction of a conveyor in 12 weeks would not be as robust. The primary controller for the project was a CLICK PLC. This PLC was chosen based on the affordability and functionality. It was also chosen by the ability to purchase expansion I/O cards to allow for more I/O. Since the goal of the project was a 12-week process, the construction needed to occur in a short timespan to ensure that all tasks could be completed. Lastly, a 120 VAC single-phase electrical connection was the only voltage source available so all products needed to be able to be powered off of this supply, or have a voltage conversion device to produce different voltages.

V. ELECTRO-MECHANICAL DESIGN

The following materials were used in the construction of the conveyor project. These materials were selected based on their availability, cost, and functionality. One goal of the project was to operate all equipment with digital inputs and outputs, all of which would run on 24 VDC input and output cards on the CLICK PLC.

A pre-constructed conveyor from BestEquip was purchased for the project that operated on 120 VAC. This conveyor could be operated in two directions with a varying speed. The conveyor was 48 inches long, which would allow for modifications to complete the project.

Three drop boxes with swing arms and a runoff box were designed for the conveyer project as shown in Fig. 1. The swing arms were a crucial piece in ensuring that packages diverted to the correct drop box. A 12 VDC motor with H-bridges were used to swing the arm to divert the packages. Swing arms and motor mounts were designed and constructed using a 3-D printer. Fig. 2 shows the motor mount and swing arm.

A combination of proximity sensors and a barcode scanner were used to detect packages. A Taiss 24 VDC, NPN proximity sensor, Photo Eye (PE) was selected for its reliability and cost. NPN switching is best suited with CLICK PLC Models due to the configuration of the input card. The input card detects when the pin reaches 24 VDC or 0 VDC. NPN switches will supply 24 VDC when the photosensor is blocked. This allows for the code to be written efficiently. The device is shown in Fig. 3 and is located at the start of the conveyor. This is also referred to as an induct eye, and it tells the PLC when a package has been placed on the conveyor. Each drop box is also equipped with a photo sensor. A MAIKRT Arduino-based barcode scanner was selected based off of its cost, and ability to communicate with RS232 of the CLICK PLC. To notify the user when a drop box is full, blue LEDs light up based on the box. These lights are installed into a pushbutton box with a start/stop pushbuttons that are used to turn on and off the conveyor system. Fig. 4 shows the pushbuttons and LEDs.

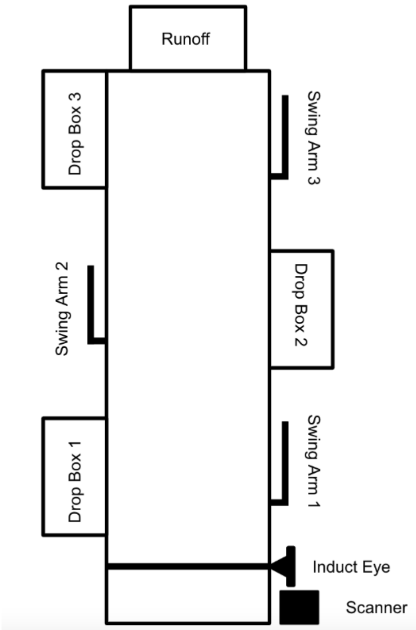

Fig. 1. Conveyer belt layout.

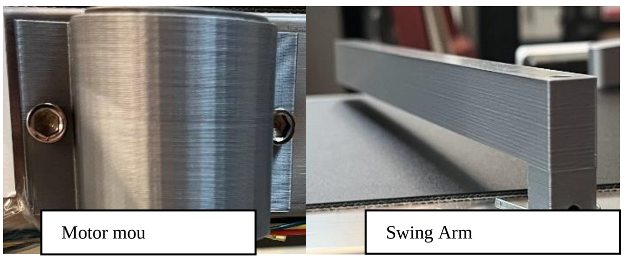

Fig. 2. Motor mount and swing arm.

Fig. 3. Photo sensor.

Fig. 4. Start/Stop pushbuttons and LED indicators.

VI. Control System Design

The project required 11 digital outputs and 8 digital inputs. The PLC processor had three outputs. To meet the overall I/O requirements, one 8 pt output card and one 8 pt input card were added to the expansion of the PLC. Fig. 5 shows the PLC with expansion I/O. DPDT ice cube relays and socket from Schneider Electric were used to operate the swing arms and control the conveyor primary motor. The PLC controlled these relays.

The control panel with PLC, I/O expansions, relays, circuit breakers, terminal strips, and power supply was completed to test with Photo Eye (PE), barcode scanner, and swing arm. The CLICK programming environment has the ability to check for all the connectivity. The completed conveyer belt system is shown in Fig. 6. A flow chart of the system operation is shown in Fig. 7. Table II shows the detailed control system connections.

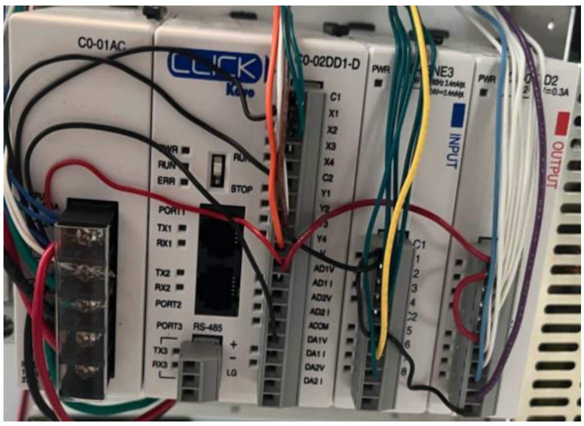

Fig. 5. PLC expansion with I/O.

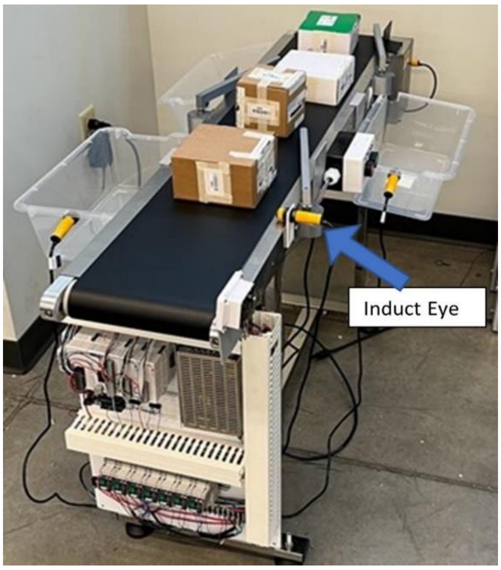

Fig. 6. Fully assembled conveyer belt system.

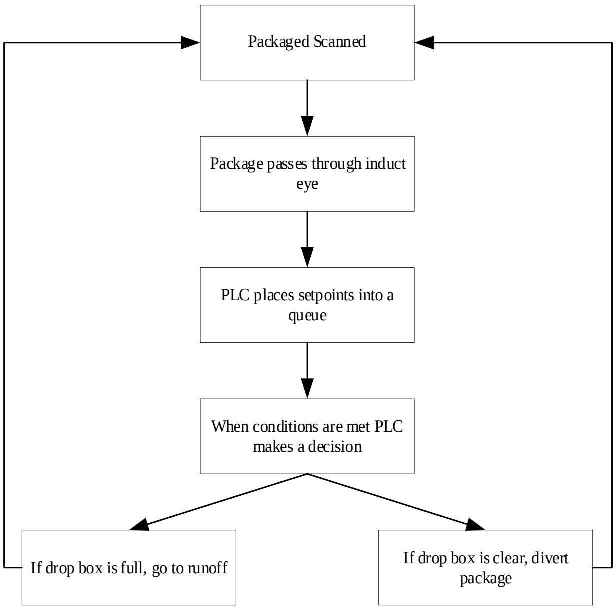

Fig. 7. Flow chart.

Two sets of code were developed to complete the conveyor project. The first code was to calibrate the diverts for the drop boxes. This code documented the timing of when a package leaves the induct eye until it reaches the correct divert. The timing of the swing arm extending and retracting needed to be documented as well. This code provided timing information for the final version of the code. An example of how a swing arm retracts is shown in Fig. 8.

The second set of code has the following sub-routines: Arduino Scanner, Divert Control, Lights Alarms, Motor Control, and Start Stop.

The Arduino Scanner Routine diverts the package to the intended box. This will be based of off two inputs X001 and X002 which will be discussed further in Design Challenges.

The Lights and Alarms Routine monitors conditions in the Divert Control sub-routine. This code is to operate the Blue LEDs which will inform the user of when a divert is full and unavailable for diverting.

TABLE II. DETAILED CONTROL SYSTEM CONNECTIONS

Device Type	Device Name	Device Type	PLC Pin	PLC Data Point	Data Register Nickname
Motor	DVT1_Extend	Output	Slot 2:1	Y201	DVT1 Arm Extend
Motor	DVT1_Retract	Output	Slot 2:2	Y202	DVT1 Arm Retract
Motor	DVT2_Extend	Output	Slot 2:3	Y203	DVT2 Arm Extend
Motor	DVT2_Retract	Output	Slot 2:4	Y204	DVT2 Arm Retract
Motor	DVT3_Extend	Output	Slot 2:5	Y205	DVT3 Arm Extend
Motor	DVT3_Retract	Output	Slot 2:6	Y206	DVT3 Arm Retract
Blue LED	BC_FULL_1	Output	Slot 2:7	Y207	DVT1 Full Beacon
Blue LED	BC_FULL_2	Output	Slot 2:8	Y208	DVT2 Full Beacon
Motor	CONVEYOR_MOTOR	Output	Slot 0:Y2	Y002	Conveyor Motor Control
Blue LED	BC_FULL_3	Output	Slot 0:Y3	Y003	DVT3 Full Beacon
Blue LED	BC_FULL_RUNOFF	Output	Slot 0:Y4	Y004	Runoff Full Beacon
Proximity Sensor	DVT1_PE_FULL	Input	Slot 1:1	X101	DVT 1 Full PE
Proximity Sensor	DVT2_PE_FULL	Input	Slot 1:2	X102	DVT 2 Full PE
Proximity Sensor	DVT3_PE_FULL	Input	Slot 1:3	X103	DVT 3 Full PE
Proximity Sensor	RUNOFF_PE_FULL	Input	Slot 1:4	X104	Runoff Full PE
Start PB	START_PB	Input	Slot 1:5	X105	Start PB
Stop PB	STOP_PB	Input	Slot 1:6	X106	Stop PB
Proximity Sensor	INDUCT_PE	Input	Slot 1:7	X107	Induct PE

The Motor Control routine has a setup similar to the calibration code as shown in Fig. 8. This sequence ties into the Divert Control sub-routine and has condition bits to ensure that the swing arms only operate when the conveyor is on and the drop boxes are available.

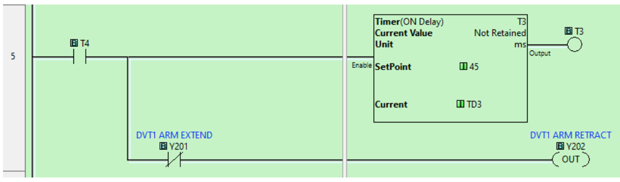

Fig. 8. Swing arm retracts calibration code.

The Start-Stop Routine determines whether the conveyor should be running. This is based on the conditions of the Start/Stop pushbuttons as well as monitoring to view if the runoff drop box is full. The timeout for the drop box is 5000 ms.

The most comprehensive sub-routine is the Divert Control routine. This is where all of the queuing and divert logic is stored. This logic is created with the ability to have up to three packages on the conveyor at once. This is through a process of having setpoints saved for all of the timing. These parameters are then copied into a skeleton design of the divert control when passing by the induct eye. Once a skeleton design is in use, the next one in line is utilized so on and so forth. Once a successful divert has happened (or a failed divert depending on if the drop box is full) that skeleton design is available again for use. This design was implemented to send multiple packages to the same divert, all at the same time. A part of the Divert Control sub-routine is shown in Fig. 9.

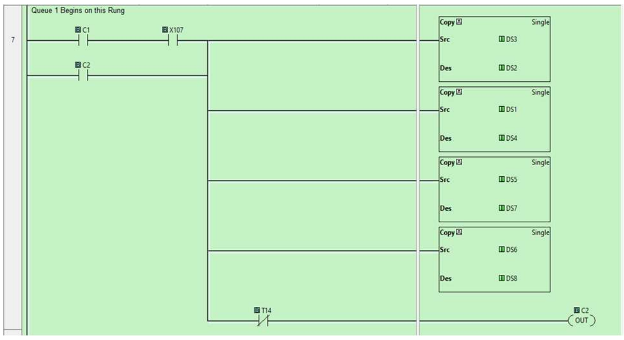

Fig. 9. Example of divert control sub-routine.

VII. Design Challenges

At first, the scanner and PLC were not communicating as intended. After many failed attempts, a hardware solution was implemented. The circuit, as shown in Fig. 10, utilizes two input pins on the PLC that were available that will be used in a binary fashion to determine where the package is supposed to go. This allowed for packages to be diverted to the intended destination.

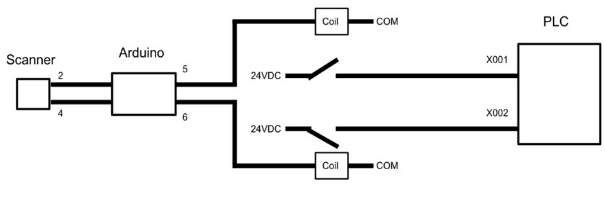

Fig. 10. Arduino-PLC relay design.

VIII. Outcome and Learning Experiences

Overall, the project was completed with a functional design. Hardware and software development worked as intended with some modifications. The final version of the code has 406 steps, or, 406 different decisions to make with each scan. The conveyor project is successfully able to divert packages to three different diverts or a runoff area based off of a barcode that is scanned. The final conveyer belt product is shown in Fig. 6.

This project allowed for growth in the design and implementation of a complete project. Being able to design a project from scratch allowed for research into what materials to use, and how to make those materials work for the intended result. Code troubleshooting experience greatly improved throughout the duration of the project, as well as keeping the coding style consistent throughout the project. Another learning experience was the importance of communication throughout the duration of the project. Working with advisors and other faculty, throughout the project required effective communication of the desired result and what was needed. The student summarized the experience as "My journey was rocky, but I think at the end of the day, every engineer questions whether they are going to make it through or not. I can finally say that I made it through."

IX. Conclusion

The goal of this project was to create a functional prototype for package sorting. The student successfully incorporated PLC, barcode scanner, sensors, and electro-mechanical devices to design and implement the system. This project allowed for student growth over the duration of the project. Many challenges were faced and every challenge resulted in a solution. This complete end-to-end design, test, and troubleshoot experience helped the student to prepare for the real-world engineering product development and testing. Student learned that no design is perfect. Every engineer needs to work with what they have and need to have the ability acquire new knowledge and use that knowledge to solve the problem.

Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

Kala Meah and Scott Kiefer are the faculty supervisors of the project. Meah and Kiefer worked with Lorenzen for two semesters on research, design, build, and test of the project; During that time Meah and Kiefer advised Michael on programing architecture, equipment selection, and overall operation of the system; Michael Lorenzen worked under the guidance of Meah and Kiefer to complete the project; Michael also wrote the first draft of the paper and Meah and Kiefer helped with editing; all authors had approved the final version.

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