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Team 519: PLC Control Lab

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Abstract

The abstract is a concise statement of the significant contents of your project. The abstract should be one paragraph of between 150 and 500 words. The abstract is not indents.

Keywords: *Programmable Logic Computers, Mechatronics, Higher Education*

Disclaimer

Your sponsor may require a disclaimer on the report. Especially if it is a government sponsored project or confidential project. If a disclaimer is not required delete this section.

Acknowledgement

These remarks thanks those that helped you complete your senior design project. Especially those who have sponsored the project, provided mentorship advice, and materials. 4

- Paragraph 1 thank sponsor!
- Paragraph 2 thank advisors.
- Paragraph 3 thank those that provided you materials and resources.
- Paragraph 4 thank anyone else who helped you.

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Notation

ASCII	American Standard Code for Information Interchange
CPU	Computer processing unit
E-stop	Emergency stop
EEPROM	Electronic erasable programmable read only memory
LCD	Liquid crystal display
OSHA	Occupational Safety and Health Administration
PLC	Programmable logic computer
PPE	Personal protective equipment
RAM	Random access memory

Chapter One: EML 4551C

1.1 Project Scope

1.1.1 Project Description

The objective of this project is to develop curriculum for Mechanical Engineering students at the FAMU-FSU College of Engineering to address the current lack of Programmable Logic Controller (PLC) training. This curriculum will be integrated into Dr. C. Ordonez's Introduction to Mechatronics course. PLCs are computers that are widely used to control industrial equipment. They facilitate manufacturing and production lines by analyzing inputs via sensors or timers and controlling outputs. Through custom programming, PLCs reduce costs, saves time, and yields little to no manual labor. The current market value of PLCs is roughly $11.6 billion and is expected to continue to grow by 4.7% in the next eight years (Transparency Market Research, 2023). Therefore, training students with PLCs will allow them to keep up with the market trends, making them more likely to find a relevant career.

1.1.2 Key Goals

Key goals are necessary in creating a project or design because it serves as motivation and relays to the customer's needs. Project team 519's aspiration is to expose students to PLCs for future opportunities by creating curriculum.

The first key goal is to design and produce three labs while providing lab stations for all student groups as per the sponsor's requirements, including their lab manuals and documentation for the Introduction to Mechatronics course. These labs will teach students how to program PLCs to control functional hardware within an industrial environment. The labs will introduce the fundamentals of PLCs and their physical hardware, programming methods, and troubleshooting techniques.

The second key goal is to create curriculum on the importance and opportunities associated with PLCs. PLCs are widely used in a variety of different industries: aerospace & defense, automotive, chemical, food & beverage, manufacturing, oil & gas, transportation, and more (Global Market Insights, 2024). Annually, there is an increase in demand for PLCs due to their ability to withstand harsh conditions and operate quickly. Because many companies utilize these devices, it is important to introduce students to PLCs so that they can grow their perspectives in different career paths.

The third key goal is to ensure students can apply logic principles to various PLC models and applications, expanding the range of systems they can work with. This approach enhances the students' versatility and broadens their skill sets for future employment opportunities. The programming language Team 519 will utilize in the learning system is ladder logic, the most common within the industry, with structured text being a stretch goal.

Lastly, the fourth key goal is to prove to the Mechatronics staff, the professor and teaching assistants, that the instructional methods developed for the labs are effective. Team 519 will measure the effectiveness of the curriculum by implementing post-lab assessments for the students and/or surveys to see how much of the material stuck with them. The surveys will also gather information on whether the students enjoyed the material and if they see themselves entering a career path involving PLCs.

1.1.3 Markets

One of the primary markets for this project is Dr. Camilo Ordonez, the Introduction to Mechatronics professor at the FAMU-FSU College of Engineering. The teaching assistants (TAs) for this course will also be included in the primary markets, as they are the ones facilitating the labs for the course. Additionally, another primary market is the students enrolled in the course. The concepts of PLC controls and automation will be taught, and students are expected to complete these labs within their Mechatronics groups.

A secondary market for the project is other universities, as they may take the content that this project creates as inspiration or a guide to implement their own version of the content. Other secondary markets are automation companies which use PLCs regularly and who would benefit from hiring individuals with PLC experience. They can also use the lab manuals created by Team 519 for training purposes.

1.1.4 Assumptions

This project will require several assumptions in order to successfully build curriculum that engages students in PLC content. These assumptions will be fundamental in maintaining our project within its timeline, budget, and ultimately satisfying the customer.

The team assumes that there will be access to shop facilities, tools, materials, university personnel, and communication with sponsors during regular business hours, given that the university is not closed due to weather, holidays, or other inconveniences. Proper training techniques, such as LinkedIn Learning courses, are provided for each team member to overcome the learning curve of PLCs and ladder logic. Furthermore, it is assumed that the College of Engineering will be providing and funding the hardware, PLC materials, a Prusa 3D printer, and other peripherals, so students enrolled in the course are not expected to be financially responsible for the necessary equipment. It is expected for Team 519 to utilize the entire budget by senior design day. This will be done by supplying materials to each individual lab station with extra equipment that will last for a few years. The budget also will be used to purchase a 3D printer, which allows for proper lab hardware to be printed efficiently while teaching students how to 3D print materials.

Another assumption is that students will have a basic understanding of circuits, programming, and logic from currently being enrolled in the Introduction to Mechatronics course and their prerequisites. This will allow for a smooth transition into the fundamentals of PLCs and how they operate. Moreover, another assumption is that the professor and teaching assistants of the course will be competent to supervise and teach the material. They are expected to be able to assist students during the labs and monitor the operations to ensure safety within the classroom. The labs are assumed to take place in the Mechatronics I Lab at the College of Engineering, located in room 356 on the B side of the campus.

As for safety purposes, the assumption is all personnel that are monitoring the labs will follow legal and safety protocols. This will include the proper training and reviewing of policies and procedures prior to implementing this content within the classroom. The team assumes that electrical safety equipment will be included in the classroom in preparation for operating PLCs. Additionally, it is assumed that the students are forbidden to bring any liquids or food into the lab, as that can potentially cause an accident which will ruin equipment and be expensive to replace.

1.1.5 Stakeholders

	Investors	**Decision Maker**	**Advisors**	**Receivers**
Sponsors	Dr. McConomy Dr. Ordonez	Dr. Ordonez	Dr. McConomy Dr. Ordonez	Dr. McConomy Dr. Ordonez
Managers	Dr. McConomy Dr. Ordonez	Dr. McConomy Dr. Ordonez	Dr. McConomy Dr. Ordonez	Dr. McConomy Dr. Ordonez
Operators	N/A	Dr. Ordonez	Dr. Ordonez	Dr. Ordonez Students, TA’s
General Readers	N/A	Dr. Ordonez	Dr. McConomy Dr. Ordonez	Dr. McConomy Dr. Ordonez Students, TA’s

				General Public

Table 1: Stakeholders Matrix

Dr. Camilo Ordonez: Dr. Camilo Ordonez has a vested interest in this project as our advisor and sponsor, and he will provide advice and guidance for the team. He will also familiarize himself with the materials provided by Team 519 to ensure comprehensive support for the students. He is the end user that will operate the labs and integrate them into his current curriculum.

Dr. Shayne McConomy: Dr. Shayne McConomy has a vested interest in this project by giving team 519 valuable time, via insight and guidance, and fostering his relationship with Rockwell Automation.

1.1.6 Conclusion

Team 519 will work cohesively with the stakeholders to fulfill the key goals of creating curriculum for Mechatronics I that involves PLC controls and automation concepts. The assumptions will be held for the duration of this project, and any concerns will be communicated to our advisor. This project will serve as the foundation for a potential Industrial Mechatronics course that the sponsor aspires to include in the Mechanical Engineering curriculum map.

1.2 Customer Needs

1.2.1 Customer Definition

The customer, Dr. Camilo Ordonez, wants new Programmable Logic Controller (PLC) curriculum for the Mechatronics I course he teaches at the FAMU-FSU College of Engineering. The needs were determined by a meeting attended by representatives from Rockwell

Automation, Dr. Ordonez, Dr. McConomy, and the 519 project team. The questions listed below were asked during this meeting.

Rockwell Automation is not officially registered as a customer for the project however their representatives have offered to mentor the team. Rockwell specializes in the design, manufacturing, and implementation of PLC systems for their customers. Since Rockwell is willing to offer advice, potential training, and insight, Team 519 and our advisor/customer, Dr. Ordonez, consulted with them when determining the project needs. Their insight and expertise on PLCs and PLC curriculum provided our team and our customer (Dr. Ordonez) with crucial knowledge on what a successful curriculum model includes. Therefore, we will consider Rockwell as a customer, in addition to Dr. Ordonez, because they will be able to articulate their needs more concisely due to their expertise. The questions shown in (Table 1) represent answers from both Rockwell representatives and Dr. Ordonez.

1.2.2 Questions, Statements, and Needs

The table below, table 2, shows the questions asked in the first column, the answers recorded in the second column, and the interpreted need from the perspective of the customer in the third column. Question 1 was directed at Dr. Ordonez, and all subsequent questions were answered by the Rockwell representatives.

	Question	Customer Statement	Interpreted Need
1	What do you envision the curriculum to look like?	Three labs that take 3 hours each, with each lab building off the last.	We want enough content to provide the students with an introductory understanding of PLCs by building on the current curriculum of Mechatronics I.

2	How have other universities structured their PLC labs?	There are a few universities that have developed great programs, including Ohio, University of Wisconsin in Milwaukee, and Cleveland State.	We want the curriculum to match the quality of what is produced at some of our current partner universities.
3	What kind of logic should the students learn for introducing them to PLCs?	Students should focus on learning ladder logic, with structured text being a stretch goal.	Ladder logic is the foundation for our training curriculum, so we want the project to match this.
4	What programming software do you guys use to train new employees for PLCs?	There is a toolkit that combines a number of products, including Encourse, Studio 5000, Learning Plus, and Logix Echo.	The curriculum should match the content covered in our training toolkit to reduce the learning curve for new employees.
5	What kind of hardware is mostly used in industry and manufacturing processes?	It depends on the application. We offer solutions for large, small, and micro applications	We want Team 519 to determine the best PLC size to use by considering budget and application.
6	Do you think that just learning the software is enough for students, or should they learn the hardware interface?	A combination of both would be good. Physically making connections helps with mental mapping and creates troubleshooting opportunities.	Students will be best prepared if they're given conditions that best match industry, which includes software and hardware troubleshooting.
7	Are there any topics other than physical connections and ladder logic we could focus on?	It is important to know communication networks and industrial safety when working with PLCs.	Creating communication networks is an advanced skill that is important for our PLC engineers to know
8	Can you think of any examples that might be good to use for the classroom?	During engineer in training (EIT) training, we developed a stoplight system. This training is a good way to build on concepts and is more challenging than it seems.	EITs who have prior experience simulating an automated system with PLCs will be well equipped to handle their responsibilities as a new employee
9	How important is it to know how to display screens with PLCs?	Human Machine Interfaces (HMI) like these are more complicated and would probably need to be something that you program for the students.	HMI development is an important and advanced skill that could boost the value of our employees.

10	Will you be able to give any guidance regarding curriculum?	We will be able to aid in developing the curriculum.	We want the curriculum to support our training material.

Table 2: Customer Questions, Statements, and Interpreted Needs

1.2.3 Explanation of Results

In conclusion, the customer wants teaching material that focuses on the fundamentals of PLCs and their applications. The customer also emphasized the importance of having the lab tasks and hardware simulate conditions that match the automated manufacturing process. In addition, the customer noted that students will ideally build upon the knowledge gained from previous weeks of Mechatronics I material to complete these labs. Overall, the customer needs the curriculum to deliver an understanding of ladder logic such that it can be applied to PLCs and its hardware. As a stretch goal, the customer suggests students being introduced communication networks and their application with PLCs.

1.3 Functional Decomposition

1.3.1 Introduction

To fully understand how the PLC learning system will work, a functional decomposition chart has been created (see Figure 1 below). Functional decomposition is utilized when analyzing a system and breaking it down into individual elements to further understand its operations. This hierarchical chart breaks the system into subsystems, functions, and subfunctions. By organizing each of these components into tiers, one can better understand how they support each other. Additionally, a functional decomposition cross reference chart is used to further understand how each function supports each system (see Figure 2 below).

1.3.2 Data Generation

Team 519 gathered the necessary data to generate this functional decomposition from meeting with the customers, sponsor, and Dr. S. McConomy. This meeting occurred on 9/24/24 at the FAMU-FSU College of Engineering. During this meeting, Team 519 asked numerous questions about how the PLC learning system would best support novice students and what topics should be covered to ensure a strong foundation. This allowed the team to determine which functions were critical to the success of the project and how these functions relate to each other.

1.3.3 Hierarchy Chart and Cross-Reference Table

Once the team understood and interpreted the customer’s needs, the subsystems and their functions were formed into a hierarchy chart. The hierarchical flow chart displayed in Figure 1 shows the system’s main subsystems before diving into the lower-level functions and sub-functions that display the operations of the learning system. The three subsystems were determined to be crucial to create the learning system: “facilitate”, “plant”, and “control”. These subsystems are then branched into the lower-level functions and sub-functions to achieve the project’s key goals while maintaining the assumptions found in the project scope.

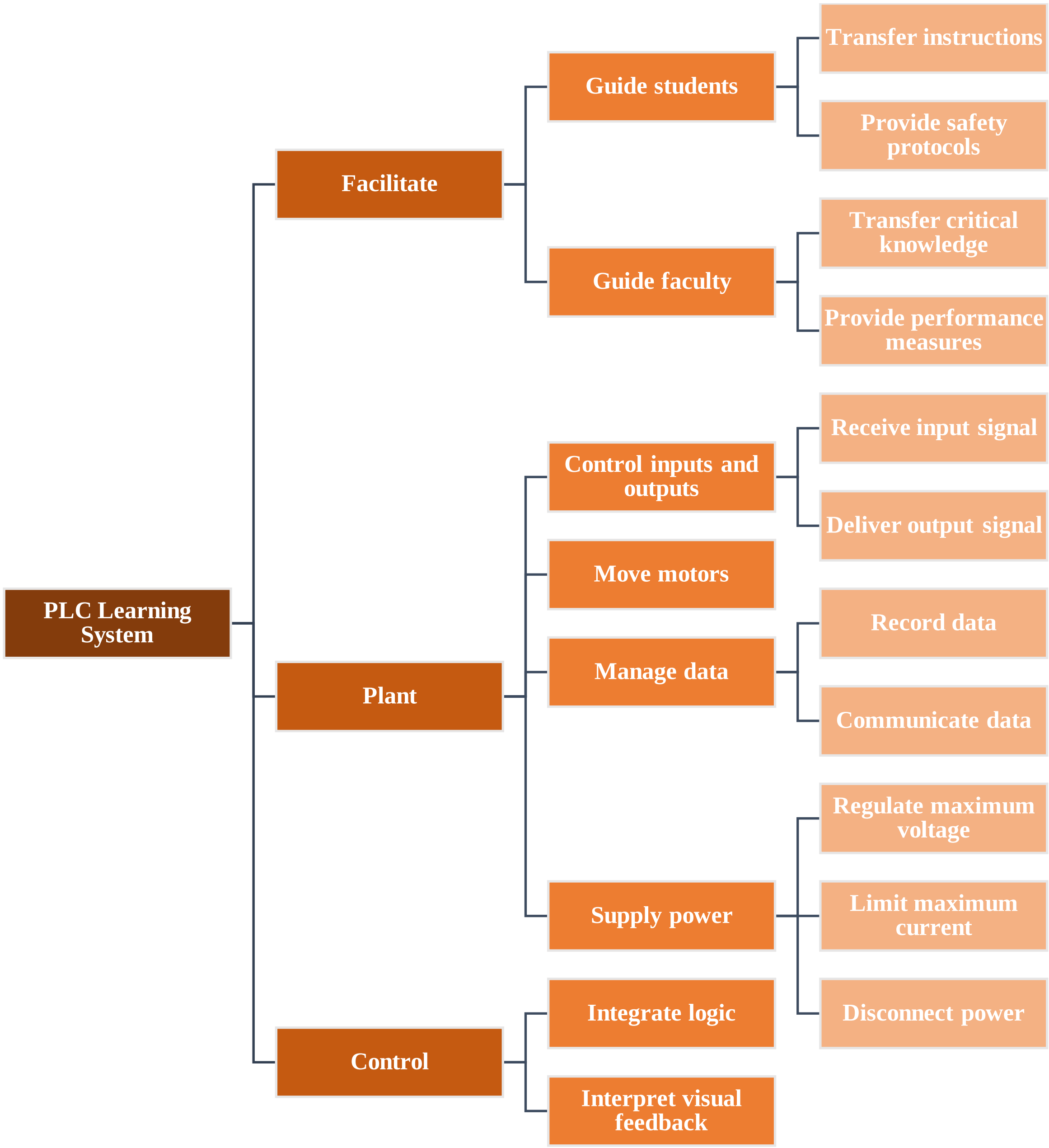

Figure 1: Team 519's Hierarchy Chart

After the hierarchy chart was formed, a cross-reference table was then created to display the functions that the PLC learning system will operate and the systems that each function falls into. The correlation between the functions and what system it falls into is denoted by an 'X', which can be seen below.

Functions	Systems		
	Facilitate	Plant	Control
Integrate logic.	**X**		**X**
Interpret visual feedback.	**X**	**X**	**X**
Communicate data.	**X**	**X**	**X**
Record data			
Transfer critical knowledge.	**X**		
Move motors.		**X**	**X**
Disconnect power.		**X**	**X**
Deliver output signal.	**X**	**X**	**X**
Regulate maximum voltage.	**X**	**X**	
Receive input signal.		**X**	**X**
Limit maximum current.	**X**	**X**	
Specify safety protocols.	**X**		
Transfer instructions.	**X**		
Provide performance milestones.	**X**		

Table 3: Team 519's Cross-Reference Table

Number of Functions per System	
Facilitate	11
Plant	8
Control	7

Table 4: Quantitative Data of Functions per System

1.3.4 Connection to Systems

The Cross-Reference Table (Table 3) and Quantitative Data of Functions per System Table (Table 4) show the connection of the base functions with each system. It was determined that the "facilitate" subsystem has the most functions connected to it followed by "plant" then "control". This ties into the over-arching objective of our project: to implement a new PLC learning system to guide students. Table 4 helps quantify the relationships associated between the systems.

The “facilitate” system deals with the transfer of information required to complete the learning system. Eleven of the fourteen functions are connected to the “facilitate” section because of the required information needed for those functions to perform. For example, the ‘Integrate logic’ function is connected to “facilitate” and “control” because the student’s learning will need to be facilitated prior to implementing the logic onto the PLC. Due to the PLC learning module being an interactive system between students and equipment, it is necessary for the facilitation of knowledge to the parties involved in order to operate the system.

The “plant” system solely deals with the hardware that will be operated within this learning system. The students will not be able to utilize PLCs without the device itself, making the plant a crucial component to this project. Eight out of the fourteen functions are connected to “plant”, yet none fall under it alone. This shows that the other two systems work closely together with “plant”, allowing for successful operation. Some functions are enabling the end-users to operate the plant through guidance provided by the team, which allows for the functions to fall under “facilitate” in addition to “plant”. Other more advanced functions such as ‘Integrate logic’, ‘Move motors’, and ‘Receive input signal’, allow for the functions to be connected to “control” and “plant”.

The “control” subsystem in the table above (Table 3) references the software applications in the learning system. This promotes the use of code and logic to control desired inputs or outputs. Functions including ‘Integrate logic’ and ‘Communicate data’ fall into this section by requiring the user to specifically create or manipulate logic. Furthermore, applications that involve the “plant” system like ‘Move Motors’ tie into “control” as well because the user is required to complete certain code to complete the task. “Control” is a necessary system for desired outputs which is why it's closely related to “plant”; however, it also heavily links to “facilitate” because this logic will be a part of the learning system objective.

1.3.5 Smart Integration

The ‘Regulate Maximum Voltage,’ ‘Limit Maximum Current,’ and ‘Disconnect Power’ functions could all be integrated easily. By having a circuit which measures the input voltage and current to the PLC, one can automate an emergency-stop function. Also, this function could be activated externally via a physical input, such as a button.

The ‘Specify Safety Protocols,’ ‘Provide Performance Milestones,’ and ‘Transfer Instructions’ can be integrated as they will all be ‘soft’ deliverables for the project. This means that there can be one large document that is provided to the faculty. This way, the faculty can parse out the information that they see fit to provide to the students.

1.3.6 Action and Outcome

The learning system will be given to students in Dr. Ordonez’s Introduction to Mechatronics to enable them to learn how to use PLCs. To enable this to happen, the learning system must “Facilitate” this process, have a functioning “Plant,” and provide means to “Control” the hardware.

First, the goal of the “Facilitate” subsystem is to create support documents for the faculty and students. This means that the teacher will be able to pick up the material and begin teaching the content with minimal lead time. Part of this teaching also includes evaluating the students, which this learning system will provide metrics for. Furthermore, the students will need the same support as the professor. This will include lab manuals.

Second, the “Plant” system will include all of the physical components of the system. For this function to be considered successful, the learning system must provide the customer with all the required components to execute the learning activities. This includes the PLC, wires, and any other components deemed necessary to teach students control, such as motors. This will also incorporate any safety hardware that must occur within the plant, such as an e-stop.

Third, students having the opportunity to control different components and interpret data will mark success for the "Control" system. This system represents all the programmatic tasks that students will be expected to know after using this learning system. This includes interpreting inputs, controlling outputs, and receiving and communicating data.

1.3.7 Function Resolution

While this project has diverse goals, there are a number of fundamental tasks that the learning system must be capable of. First, the learning system must contain the required software and hardware to complete the learning activities. Without these, it will not be impossible for the students to get hands-on experience, defeating the purpose of this project. Next, proper support must be provided to the faculty and students. If this is not included, there will not be a functional learning system that the customer is able to use.

1.4 Target Summary

1.4.1 Introduction

After team 519 created the functional decomposition to determine the operations that our learning system will contain, each function must be analyzed to find their specific targets and metrics. Targets are numerical values that represent desired outcomes for the system. They will serve as benchmarks for the system's performance, and the design of this specific learning system will be based around this quantitative data. On the other hand, metrics are how to validate a function. They assess whether the targets have been met and evaluate the system's performance by being measurable and observable, allowing validation throughout the design of the PLC learning system.

1.4.2 Derivation of Targets and Metrics

A variety of methods were used to derive the targets and metrics listed below. For some, there are regulatory requirements from governing bodies like the Occupational Safety and Health Administration (OSHA) that can be referenced, and for others there are competitors to benchmark against.

For the 'Supply Power' function, the metrics were derived from an understanding of electrical safety and electrical risk management. As for the target for 'Limit Maximum Current,' competitive benchmarking was used to find the typical values allowed for current in PLCs. As for the 'Regulate Maximum Voltage' target, simplified electrical calculations were done to determine the minimum voltage across the human body which might result in discomfort. Next, the 'Disconnect Power' metric was determined by considering the regulations set for by OSHA and estimating a reasonable amount of time that one could spend activating an emergency stop (e-stop) if their system complied with the regulations.

1.4.3 Targets and Metrics

_Plan_t System

Under "Plant" there is a subfunction "move motors" which means the learning system will need to move a motor in some form to compliment the learning system. In manufacturing applications, motors are widely used to move conveyor belts at either fixed or variable speeds depending on the system. Most motors are chosen based on a variety of performance specifications dependent on size, power, and cost constraints. Due to the goal of the learning system to simulate a manufacturing environment it was determined that the metric is to set the conveyor belt at various speeds. Due to the size constraints of the conveyor belt and safety concerns it was determined for the speed to be within 3-5 inches per second (Oketola, 2021). This metric can be tested by placing various loads onto a conveyor belt and calibrating a motor to achieve the necessary speed of the conveyor belt.

Also under the plant umbrella there is the function “control inputs and outputs” there are two sub functions “receive input signal” and “deliver output signal”. The two sub functions are closely related and are both considered critical metrics for the project to be successful. The control of inputs and outputs enables the PLC learning system to functions probably if the metrics are met. The metric used is called PLC scan time, this is the time it takes for a PLC to complete a full cycle of operations including reading inputs, executing the logic, and updating the outputs accordingly. The standard scan time for PLC’s in industry is 1/1000 to 5/1000 of a second which is equivalent to 1 to 5 millisecond AutomationDirect). To make the PLC learning system closely related to manufacturing applications it was determined for our scan time target to be less than 5 milliseconds.

Under the “Manage Data” function, “Recording Data” and “Communicating Data” will be utilized in the learning system as these functions are essential in the manufacturing industry. In the “Communicating Data” sub function, information about the process is crucial for debugging and improving processes. Required ports for communication will be RS232, RS422, or RS485. Also, an electronic device such as a computer will be required for data sharing. For shorter distance computer communication, which will be utilized in this learning system, must be withing 30 meters for accurate transfer. For “Record Data”, there are three main types of methods including Bit memory, numeric memory, and the American Standard Code for Information Interchange (ASCII) memory. The two that will be utilized will be the first two listed. For bit memory, this is a type of method used in manufacturing facilities that track what stage the process the machine is in so steps can be executed in the correct order. This is important for multistep processes and will be implemented in the learning system. The PLC must have a storage location that will be used to hold binary values. Students will integrate internal relays or "tags" within the logic to track the process. The next type, numeric memory, must have internal memory where numerical values, such as integers and decimals, are stored. The learning system will utilize a SCADA (Supervisory Control and Data Acquisition) which will take data from the RAM (Random Access Memory), which is short term memory. This data must transfer in 10 MB per second to ensure accuracy of information.

Under the 'Supply Power' function, there are three subfunctions: 'Regulate Maximum Voltage,' 'Limit Maximum Current,' and 'Disconnect Power.' The targets for the first two subfunctions will be measurements of the voltage and current from the output pins of the PLC. It is important to regulate the maximum voltage coming out of an output pin because every piece of hardware will have a specific range of voltage that it can operate under. If this voltage gets too high, the components can be damaged, creating an unsafe learning environment due to the possibility of smoke and/or sparks being generated. Furthermore, it is important to limit the maximum current that comes out of the pins for a similar reason. If a component is plugged into a source that allows too much current to flow, there can be damage as a result. Moreover, the PLC would likely be damaged by the process of outputting too much current as it also has its own range of normal operating current. The need to limit current is further exaggerated when one considers that current peaks tend to happen when shorts are created in a circuit. This is common for inexperienced learners, who might connect/disconnect components without disconnecting power. As for the 'Disconnect Power' subfunction, it is important to allow for rapid, simple, and decentralized disconnection of power as a safety measure. In emergency situations, such as an electrical fire, the first step is always to disconnect the power source. Without this action being taken, firefighting measures will not be nearly as effective. Therefore, we must be able to disconnect power to the PLC to ensure safety.

Each of these targets has been assigned a metric. As for 'Limit Maximum Current,' it is difficult to select a specific value as each PLC and component that connects to it will have different current tolerances. To give an example, though, the Rockwell ControlLogix 5580 Controllers have a rated output current of 1.20 amps at 5.1 Volts (Rockwell Automation, 2023). This voltage range is relevant as higher voltages, such as 120 VAC, are not appropriate for novices as they have the potential to harm themselves or equipment. Similarly, selecting a maximum output voltage is dependent on the equipment used. To ensure safety, though, an absolute maximum output voltage would be 125 V. Assuming a resistance of 2500 Ohms across the human body and a maximum tolerable current of 5 mA, the maximum voltage a person could tolerate is 125 V (ISATUR, 2010) (OSHA). Therefore, our target for maximum voltage will be 125V. Finally, as for 'Disconnect Power,' the target will be the speed at which an operator is able to react to an emergency, locate the power disconnection, and deactivate power. Because there is not official guidance about how quickly this must occur, we will select a value of two seconds. Furthermore, to meet OSHA standards, another metric is that the power disconnects latches mechanically and has only one action required to operate it (Townshend, 2023).

Control System

Under the “Control” function regarding software behind the learning system, the two sub-functions are “Integrate Logic” and “Interpret Visual Feedback”. The target for “Integrate Logic” will be the PLC’s central processing unit (CPU) ability to read ladder logic from input, determine if true, and output based on sequence of logic (top left to bottom right). The CPU stores data by the random access memory (RAM) and the Electronic Erasable Programmable Read Only Memory (EEPROM) will be required. The RAM stores data that is needed short term and will be lost when power to the PLC is lost, the EEPROM is required for more important memory that will be saved when the PLC loses power. Within both storage locations, depending on the PLC, 5-20MB of data is typical for the amount of data stored. With this being said, our target for the learning system is 10MB of active stored data. Applications that will be used for this type of data storage will be sensors and temperature values.

Ladder logic is created and read from “rungs” or horizontal lines; these act like a separate line of code. The second subfunction is “Interpret Visual Feedback”, this subfunction ties into integrating logic as the learning system will require desired visual outputs on devices such as a liquid crystal display (LCD) screen. The target for this sub-function will be to involve command in ladder logic to control message on an LCD screen within one second.. This will involve showing alarms for real experience with PLC equipment and logic.

Facilitate System

Under the “Facilitate” system, there are two functions: “Guide Students” and “Guide Faculty”. Focusing on “Guide Students” the two subfunctions are ‘Transfer Instructions’ and ‘Provide Safety Protocols’.

The ‘Transfer Instructions’ subfunction has a target and metric of 3 lab manuals. This was specified and requested by our customer, Dr. Ordonez. These lab manuals will contain a problem statement in which students will read some background information before configuring the issue that needs to be solved. They will also include some checkpoints to ensure the students are on the right track. Some code may be provided as well to guide the students in the right direction.

As for the ‘Provide Safety Protocols’ subfunction, this will include a target of maintaining the PLCs at a voltage well below 24 volts (Cope, 2018). 24V is the maximum voltage that a PLC can operate safely, therefore this will be mandated in the Mechatronics Lab by the professor and teaching assistants. The metric will be a safety inspection checklist provided by the team. This will be used prior to usage of the PLCs and other equipment to confirm that the students are not at any dangers or risks while using these devices. This checklist will include the proper personal protective equipment (PPE) that needs to be worn, confirmation on lockout and tagout, etcetera.

Transitioning to “Guide Faculty”, the two subfunctions are ‘Transfer Critical Knowledge’ and ‘Provide Performance Measures’.

‘Transfer Critical Knowledge’ is crucial for this project since we are providing the faculty with information and labs on how to properly conduct the PLCs within the classroom. The team needs to provide supporting documentation that includes solutions to the lab, any pseudocode or annotated code, troubleshooting guidelines, diagrams, and learning objectives that prove the students are understanding the content. The team wants to focus on frequently asked questions for our metric, since the concept of PLCs are a learning curve for the Mechatronics I faculty. The target is to contain 20 or more questions and tips on debugging, troubleshooting, or any other common misconceptions. This critical function will be further discussed below in section 1.4.5.

As for 'Provide Performance Measures', it is important that the team does so, so that the Mechatronics I faculty team knows if the learning system was effective or not. The team will not give guidance on how to grade, because that is up to the professor's interpretation, however we will include milestones in the lab manuals and notify the professor what key concepts the students should understand after working with the PLCs. With that being said, the target for this function is that most students should score a 70% or higher in order to prove that they learned the fundamentals of PLCs and confirmed how to deal with troubleshooting. These targets will be found through surveys and post-lab assessments that are created by the professor. Surveys will be useful before the students start these labs so the staff knows how much prior knowledge there is regarding PLCs. There will also be surveys at the end of the semester, to take record on how many students felt as though they learned how to use the devices, how they enjoyed the material, any changes that could be made, and if they foresee themselves entering the automation field post graduation. Then, post-lab assessments such as quizzes and the final exam will include PLC material to test the students on how much they learned.

Function	Target	Metrics
Integrate logic	10 MB	CPU (Volatile & Non-Volatile)
Interpret visual feedback	<1 sec	LCD (Alarm)
Communicate data	< 30m	Short Distance Computer Communication

Record data	10 MB/sec	Ethernet to SCADA Data Recording
Transfer critical knowledge	20+ Questions	Frequently Asked Questions
Move motors	3-5 in/s	Conveyor belt speed
Disconnect power	2 Sec	Disconnect Time
Deliver output signal	< 25 milliseconds	Scan time
Regulate maximum voltage	125 V	Maximum Output Voltage
Receive input signal	< 25 milliseconds	Scan time
Limit maximum current	1.20 A	Maximum Output Current
Provide safety protocols	< 24 V	Safety inspection checklist
Transfer instructions	3	Lab manuals
Provide performance milestones	70% or higher	Surveys/Post-lab assessments
Individual components	<30 lbs	Maximum weight
Storage ability of PLC, Sensors, and Motors	3 ft^3	Maximum Volume
Time of lab assembly	15 min	Maximum assembly time

Table 5: Summary Table of Critical Functions, Targets, and Metrics

1.4.4 Other Needs Addressed

Additional targets for the system include a maximum weight, volume, and time of lab assembly. The maximum weight of each component cannot exceed 50 pounds per OSHA standards for lifting. Team 519 determined that components weighing less than 30 pounds will help with the ease of assembling and disassembling the labs. Along with maximum weight of the components it was determined that the lab setup components will need to be able to fit within 3 foot cubic space due to storage restrictions within the Mechatronics lab room. Additionally, it was determined the maximum assembly time of the lab setup cannot exceed 15 minutes. This was determined by the time in between class sessions so the TA's would be able to assemble in the appropriate amount of time.

1.4.5 Critical Targets and Metrics

The critical targets and metrics were determined by addressing the key functions that need to operate for the system to work. The critical targets are related to the 'Disconnect Power,' 'Integrate Logic,' 'Deliver Output Signal,' 'Receive Input Signal,' and 'Transfer Critical Knowledge' functions. Each of these were selected as critical because they are foundational to the project and the higher-level functions rely on their success.

The target and metric for 'Disconnect Power,' a 2 second disconnect time, was selected as critical because it is required for the safe operation of the learning system. If there is not a way to disconnect power in emergency situations, the system may cause damage to property via fire, or to people via shock.

The 'integrate logic' target is crucial for the learning system because if the CPU does not read, store, and execute logic then the system will not function. The learning system addresses various components of a PLC and its functions, and the CPU's ability to perform determines all outputs.

As for the 25-millisecond output signal speed, this target was selected as critical because reliable outputs are the foundation of the learning system. One of the most basic functions of any microcontroller is to produce output signals. If this function does not work properly, and reliably, the learning system cannot be considered successful.

Furthermore, the same time target was selected for the 'Receive Input Signal' function for similar reasons. Being able to interpret data from the outside world, even in rudimentary forms like pushbuttons, is one of the most basic functions of operating a microcontroller. Not being able to demonstrate this function would be detrimental to the students' learning.

Finally, regarding the 'Transfer Critical Knowledge' function, the ability to address at least 20 FAQs is critical to the success of the learning system. This is because the instructor will need guidance on how to instruct the material, and without this guidance, the learning system will be rendered ineffective.

1.4.6 Testing Methods and Validation

To measure the 'Disconnect Power' metric, a set of trials will be run to determine the speed at which users can disconnect the power. This will be setup in such a way that the user is 'distracted' before being prompted to disconnect the power to simulate the reaction time that will occur in real scenarios. The measurement tool used will be a stopwatch.

To measure delivering output signals and receiving input signals the scan time will need to be tested. A method of testing the scan time includes using a test logic software that incorporates a high speed timer for the PLC to complete a cycle. Another method is to use diagnostic tools that come with several software packages dependent on the vendor that will display timestamps of the cycle. The tools necessary to complete this test include PLC software, a input, and an output.

Determining if the PLC is reading logic can be done by checking the program software to see if inputs are being read correctly and shown in the logic. Another way is the I/O module on the PLC, this has an LED that indicates whether the PLC is reading the input signal. Also, the program will display error messages if there are issues within the logic or if the PLC cannot read the inputs.

1.4.7 Summary

After determining each target and metric for our sub-functions of the learning system, Team 519 deemed five critical targets and metrics that are crucial for the success of the system.

First under “Control”, the system must integrate logic effectively to read logic and output operations in a certain sequence. The CPU must be able to hold 10 MB to reference real industry data storage circumstances.

Next for “Plant”, the systems hardware must be able to connect and operate based on the logic being integrated into the CPU. The PLC must first have a disconnect time of two seconds to ensure the safety of users. Next, it is critical for the PLC to receive input signals for the learning system to be modified and debugged. As for output signals, 25 milli seconds is the target to ensure responsiveness of the system.

Lastly, students comprehending and retaining information from the learning system is an integral part. Team 519 will be transferring critical knowledge to the instructor to proficiently conduct the learning system and help answer questions.

These targets and metrics will be attainable by implementing reliable hardware and software in the learning system. For the hands-on experience that will be achieved by this, the equipment being used must be up to specific standards. The instructor must also be knowledgeable about equipment in the learning system from resources given in order to achieve a learning environment that is interactive and beneficial.

1.5 Concept Generation

Team 519 used multiple concept generation techniques to come up with solutions to achieve the key goals and fulfil the customer's needs. The team came up with 100 different concepts using different techniques such as a morphological chart and brainstorming. Out of the one hundred concepts produced, the team picked five medium fidelity and three high fidelity concepts. The medium fidelity concepts are ideas that accomplish most if not all of the key goals of the project but have certain constraints such as time, feasibility of material, and constructability. The high-fidelity concepts are ideas that accomplish all the key goals and can be attainable within the project's scope constraints considering time, budget, and assembly feasibility.

1.5.1 Concept Generation Methods

The first method used for generating concepts was a morphological chart. The table was created with the columns being the critical base functions the learning system will need to accomplish in a lab. The remaining columns are possible solutions for each sub function. The table then creates a matrix where all different combinations are used to generate concepts. Team 519 determined that the learning system PLC lab could include a combination of components such as inputs, motors, transportation system, visual feedback, and a PLC to control all of them to create a complete final lab.

The second method used for concepts was brainstorming. Brainstorming was utilized to think of possible labs that did not involve all the components listed in the morphological chart. The team utilized brainstorming to think of unconventional lab setups that included various aspects to make the labs appeal more towards a student's interest. The brainstorming was also geared toward ideas that offer a smooth transition from the current Mechatronics I labs to PLC labs.

Morphological Chart

Lab Componets	Physical Solutions				
	1	2	3	4	5
PLC	Controllogix	MicroLogix	Arduino PLC	CompactLogix	Siemens PLC
Input	Limit switch	Push button	Sonar sensor	Pressure sensor	Photo sensor
Motors	Stepper Motor	Servo Motor	DC Motor	AC Motor	Geared DC motor
Transportation	Chain drive conveyor	Rack and pinion	Powered roller conveyor	CAM mechanism	belt conveyor
Visual feedback	LED	LCD Display	stoplight	HMI	Alarm

Table 6: Morphological Chart

1. A Lab simulating a manufacturing environment using a ControlLogix, Push button, Servo Motor, Chain drive conveyor, Alarm
2. A Lab simulating a manufacturing environment using a ControlLogix, Push button, Servo Motor, Rack and pinion, Stoplight
3. A Lab simulating a manufacturing environment using a ControlLogix, Push button, Servo Motor, Powered roller conveyor, LCD Display
4. ControlLogix, Push button, Servo Motor, CAM mechanism, HMI
5. ControlLogix, Push button, Servo Motor, Belt conveyor, LED
6. ControlLogix, Limit switch, Stepper Motor, Powered roller conveyor, Stoplight
7. ControlLogix, Limit switch, Stepper Motor, CAM mechanism, LCD Display
8. ControlLogix, Limit switch, Stepper Motor, Belt conveyor, HMI
9. ControlLogix, Limit switch, Stepper Motor, Chain drive conveyor, LED
10. MicroLogix, Sonar sensor, DC Motor, Chain drive conveyor, Alarm
11. MicroLogix, Sonar sensor, DC Motor, Rack and Pinion, Stoplight
12. MicroLogix, Sonar sensor, DC Motor, Powered roller conveyor, LCD Display
13. MicroLogix, Sonar sensor, DC Motor, CAM mechanism, HMI

14. MicroLogix, Sonar sensor, DC Motor, Belt conveyor, LED
15. MicroLogix, Pressure sensor, AC Motor, Chain drive conveyor, Alarm
16. MicroLogix, Pressure sensor, AC Motor, Rack and pinion, Stoplight
17. MicroLogix, Pressure sensor, AC Motor, Powered roller conveyor, LCD Display
18. MicroLogix, Pressure sensor, AC Motor, CAM mechanism, HMI
19. MicroLogix, Pressure sensor, AC Motor, Belt conveyor, LED
20. MicroLogix, Photo sensor, Geared DC Motor, Rack and pinion, Stoplight
21. MicroLogix, Photo sensor, Geared DC Motor, Powered roller conveyor, LCD Display
22. MicroLogix, Photo sensor, Geared DC Motor, CAM mechanism, HMI
23. MicroLogix, Photo sensor, Geared DC Motor, Belt conveyor, LED
24. Arduino PLC, Limit switch, Stepper Motor, Rack and pinion, Stoplight
25. Arduino PLC, Limit switch, Stepper Motor, Powered roller conveyor, LCD Display
26. Arduino PLC, Limit switch, Stepper Motor, CAM mechanism, HMI
27. Arduino PLC, Limit switch, Stepper Motor, Belt conveyor, LED
28. Arduino PLC, Pressure sensor, AC Motor, Rack and pinion, Stoplight
29. Arduino PLC, Pressure sensor, AC Motor, Powered roller conveyor, LCD Display
30. Arduino PLC, Pressure sensor, AC Motor, CAM mechanism, HMI
31. Arduino PLC, Pressure sensor, AC Motor, Belt conveyor, LED
32. Arduino PLC, Photo sensor, Geared DC Motor, Rack and pinion, Stoplight
33. Arduino PLC, Photo sensor, Geared DC Motor, Powered roller conveyor, LCD Display
34. Arduino PLC, Photo sensor, Geared DC Motor, CAM mechanism, HMI

35. Arduino PLC, Photo sensor, Geared DC Motor, Belt conveyor, LED
36. Compact Logix, Limit switch, Stepper Motor, Chain drive conveyor, Alarm
37. Compact Logix, Limit switch, Stepper Motor, Rack and pinion, Stoplight
38. Compact Logix, Limit switch, Stepper Motor, Powered roller conveyor, LCD Display
39. Compact Logix, Limit switch, Stepper Motor, CAM mechanism, HMI
40. Compact Logix, Limit switch, Stepper Motor, Belt conveyor, LED
41. Compact Logix, Sonar sensor, DC Motor, Chain drive conveyor, Alarm
42. Compact Logix, Sonar sensor, DC Motor, Rack and pinion, Stoplight
43. Compact Logix, Sonar sensor, DC Motor, Powered roller conveyor, LCD Display
44. Compact Logix, Sonar sensor, DC Motor, CAM mechanism, HMI
45. Compact Logix, Sonar sensor, DC Motor, Belt conveyor, LED
46. Compact Logix, Photo sensor, Geared DC Motor, Chain drive conveyor, Alarm
47. Compact Logix, Photo sensor, Geared DC Motor, Rack and pinion, Stoplight
48. Compact Logix, Photo sensor, Geared DC Motor, Powered roller conveyor, LCD Display
49. Compact Logix, Photo sensor, Geared DC Motor, CAM mechanism, HMI
50. Compact Logix, Photo sensor, Geared DC Motor, Belt conveyor, LED

Brainstorming

The following concepts were determined using brainstorming:

51. A system that simulates an intersection, including pedestrian and vehicle traffic control methods

52. Create a system that simulates a sorting system of different-sized blocks into separate bins utilizing a LCD to display the size of each box that is measured by height using a sonar sensor. A robotic arm trigged by a limit switch will rotate and place the boxes.

53. A system that uses a belt conveyor belt at different speeds depending on the load of the object on it by utilizing a stoplight and a series of push buttons.

54. A system that utilizes servo motors and sensors to detect height to play a game of tic-tac-toe and display instructions on a LCD screen.

55. A software lab that simulates a timer associated with cars at an intersection to dictate a stoplight to keep the flow of traffic.

56. A system that controls several servo motors to create a robotic arm to move in certain directions based on a variety of sensor inputs.

57. A lab that uses a motor to push a hydraulic arm to a certain force dependent on user inputs and display the force on a LCD display.

58. A system that moves a temperature sensor on a controlled robotic arm to different objects and records the temperatures measured on a display.

59. A lab that uses proximity sensors to control a stoplight at the entrance of the mechatronics lab with sensors being located in the hallway of the classroom and in the doorway of the lab.

60. A lab uses a potentiometer to control a hydraulic arm that pushes a pressure sensor that can measure force and set off an alarm once a certain threshold is met.

61. A lab that uses a pulley system controlled by motors to simulate an elevator utilizing push buttons and force sensors to control speed.

62. A lab that controls the brightness of an LED based on various temperatures of objects using a robotic arm to move around a temperature sensor.

63. A system that uses a belt conveyor with a series of different motors and sensors to sort different shaped blocks via mechanical mechanism into certain blocks while using a LCD display the steps along the way.

64. A system that uses a color sensor and a mechanical arm made from a series of servo motors to automate a game of “connect 4” with the user being able to control the puck placement with a series of push buttons.

Robotic Arm Applications

65. A system that simulates an assembly line by applying a repetitive motion to a ‘part,’ sensing if the part is present and sending a signal to move the part once the applied motion is complete.

66. A system that allows a user to select a preset arm configuration using an HMI like an LCD and push buttons.

67. A system that uses a robotic arm to mirror the movement of a hand. This would be done by using an ultrasonic sensor to detect the height of the per son’s hand from some datum. In response, the arm would be articulated such that its end effector changed its height by the same amount.

Labs involving Two PLC’s

68. A system that uses two PLC’s that will communicate with one another simulating real industry. Data will be transferred, and the output of one PLC will be the input of the other.

69. System that uses two PLC’s, IR emitter on one PLC will count objects and send data to the other, the other PLC will take that data and stop the motor after a certain count.

70. System that uses two PLC’s, both moving motors, controller two will have to match motor speed of controller one.

71. System that uses two PLC’s, traffic light simulation where each PLC controls an intersection and improves traffic flow.

72. System that uses two PLC’s, tank level control system. One PLC controls the inflow of one tank while the other PLC controls the other tank outflow, need to balance level in each tank.

73. System that uses two PLC’s, security gate system. One PLC controls the entry gate after security conditions are met, the second PLC controls exit gate, ensuring both gates are not open at the same time.

74. System that uses two PLC’s, elevator system. Each PLC controls one elevator can work simultaneously based on user inputs.

75. System that uses two PLC’s, parking management system. One PLC controls vehicle entry and gives parking spots, the other controls exit and communicated with first PLC to update availability.

76. System that uses two PLC’s, dual conveyer belt system. One PLC controls main conveyer, the second PLC controls secondary conveyer having different tasks.

77. System that uses two PLC's, railroad system. One PLC monitors train approach and warning signal, the other PLC controls safety gate.

78. System that uses two PLC's, bottling system. One PLC fills bottles to a certain level and the other PLC ensures the fill level is constant.

79. System that uses two PLC's, painting system. One PLC applies to the first layer, the second PLC receives data and waits for drying time to apply to the final layer.

80. System that uses two PLC's, library system. One PLC scans book and sorts them by category, the other PLC arranges them in storage.

Intro to Mechatronics 'Copies'

81. Two push buttons, a DC motor, and a motor driver, allow the user to change tthe speed of DC motor by finite increments. One button will increase the speed of the motor in one direction, and the other will do the opposite.
82. Using a stepper motor, simulate a car-gate system. The car's presence will be detected with an HMI, like a touchscreen. When the car is present, the gate will open. Once the car leaves, the gate will close after five seconds. The gate will immediately go to the 'opening' state in the presence of a car.
83. Using two DIP switches and multiple LEDs, allow for different sequences of lighting to be created based on user input via the dip switches. The lights should be able to be in one of four states: all on, all off, sequencing one by one to the left, and sequencing one by one to the right.
84. Create a steer-by-wire simulation using a stepper motor and a potentiometer, and print values about the system on an LCD. When the potentiometer is turn, the stepper

motor should turn by the same amount, 'following' the motion of the potentiometer. The LCD will print the angle of the stepper motor.

85. Create a hardware interrupt that increases a value every time the user presses a button.
86. Create a timer interrupt to count .1 msec intervals. Provide a PWM voltage to an LED to increase and decrease it's intensity. The sequence will start once a user flips a dip switch. The sequence will be: increasing in intensity for five seconds to maximum intensity, maintaining this intensity for five seconds, then decrease this intensity for five seconds back to zero intensity. This cycle will only repeat once the switch has been flipped back, then flipped again.
87. Using a push-button, create a RC circuit that will debounce the button's output. Increase a variable each time the button is pressed.
88. Create a motor driver for a DC motor by creating an h-bridge circuit, complete with fly-back diode and four BJT transistors.

Manufacturing Labs

89. A lab that simulates an automated assembly line with a conveyer belt that perform repetitive tasks (i.e., push a button X amount of times or a blinking LED lightbulb)
90. A lab that utilizes a PLC to identify objects via sensors and sort them by their weight
91. A lab that simulates a bottling station where the bottles are filled, capped, and labeled
92. A lab that simulates a drill press or machining station that requires precise positioning
93. A lab that simulates buttons being painted/printed

94. A lab that uses the PLC and multiple conveyer belts to move objects from station to station, including merging and diverting lanes
95. A lab that automates a process for packaging items in boxes, filling them with packing peanuts, and sealing them
96. A lab that simulates quality inspections on a production line through sensors, trigger cameras, alarms, and rejecting products that don't meet the standards
97. A lab that simulates a palletizing operation and organization, where products are stacked on pallets in a specific pattern
98. A lab that simulates a painting booth where objects are sprayed as they pass through via conveyer belt
99. A lab that automates a heating and cooling process, allowing for students to be able to adjust the temperatures through the software
100. A lab that simulates an automated coating booth where objects are sprayed with protective coating as they pass through via conveyer belt

1.5.2 High Fidelity Concepts

One high-fidelity concept chosen by Team 519 is concept number 51, which would be a simulation of an intersection. Students would incorporate pedestrian and vehicle traffic control methods, making it a real-life application, allowing for students to engage. This is high fidelity because it meets the customer's needs and the team's key goals while keeping it applicable to the real world. This lab would include a conveyer belt, colored LED lights for the traffic signals, an LCD screen to initiate pedestrians to walk, buttons to initiate the crosswalk, and a variety of timers and sensors.

Another high-fidelity concept chosen was concept number 20: a system using a belt conveyor along with a series of motors, sensors, and a LCD display to sort different sized boxes. The concept was chosen to be high-fidelity due to the lab accomplishing all the key goals but also simulating a realistic manufacturing application used in industry. The lab would be geared toward the end of the class due to the complexity of all the components involved.

The last high-fidelity concept was concept number 53, which is a system that utilizes a conveyer belt, a stoplight, a series of push buttons. This apparatus would be used to control the conveyer belt at different speeds depending on the object's differing load applications. This is high-fidelity because it incorporates the students' previous knowledge of incorporating buttons through labs already completed in the course. This is also a lab that would focus more on the software aspect and allowing for students to understand how to utilize ladder logic to control the speed of the conveyer belt at the appropriate times.

1.5.3 Medium Fidelity Concepts

One medium-fidelity concept is concept number 17: A lab uses a potentiometer to control a hydraulic arm that pushes a pressure sensor that can measure force and set off an alarm once a certain threshold is met. The lab would be able to cover some of the key goals by giving students an example of a PLC system used in the world. The concept is also different from the typical lab setup with students being able to see and test different situations with their programming. One constraint that may limit this concept is the availability of space in the entrance of the Mechatronics classroom. The limited space next to the doorway gives certain design challenges that may limit what the lab could accomplish.

Two more medium fidelity concepts are inspired from the current Mechatronics I content. Both of these concepts were considered medium fidelity as they are already proven to be relevant and important to the Mechatronics I material. Furthermore, the instructor and TAs are already familiar with the process of the labs, and there are grading schema already in place. These two concepts are Mechatronic concept 8 and 2.

Another medium fidelity concept would be an idea chosen from the brainstorming section, using two PLCs to communicate with one another to match tank levels. Float and limit switches as well as pressure sensors would be used to ensure fill level as ethernet cable will allow PLC communication. This is a medium fidelity concept as it shows the application of communication among PLC's as well as hardware integration.

Another medium fidelity idea chosen from the brainstorming section is the painting system using two PLC's. The PLCs would use ethernet cable to communicate as one PLC would control servo motor used as the first layer of paint and the second PLC would control anther servo motor for the final layer of paint. This lab portrays communication of data between PLC's and integrates hardware.

1.6 Concept Selection

After generating over 100 different concepts, the team distinguished 5 medium fidelity and 3 high fidelity concepts that will potentially be used for the final selection. As the project moves forward, concept selection is the next step to determining which concept is most ideal for the PLC learning system. Concept selection is crucial because it helps put the qualitative aspects like customer requirements and metrics into quantitative data to narrow down the best final selection. This is done through evaluating a variety of charts that compare different aspects of each concept, and this process is shown below.

1.6.1 Binary Pairwise Comparison

The binary pairwise comparison is the initial table to be created in the concept selection process. This table analyzes the 14 customer needs and compares them to one other to determine which has a higher precedence. Something that is crucial for the binary pairwise comparison is to make sure the diagonal is marked off to ensure there is no comparison with the same customer need. This comparison is done by analyzing if the row is more important to the project than the column. If the row deems more important, it is labeled with a “1”, and if it deems not as important as the column, it is labeled with a “0”. It is important to set the opposite value for the transposed position. Now that the binary pairwise comparison is completed, this leads to distinguishing the weight factors for creating the House of Quality.

	Provide Students with Understanding of PLC Applications	Produce curriculum comprable to other universities	Teach students ladder logic	Base Curriculum off of Rockwell's training materials	Select appropriate PLC	Create software and hardware debugging challenges	Introduce networking basics	Have students apply knowledge to a real world example	Teach students how to use HMI	Create three laboratory assignments and select hardware	Provide supporting material for faculty	Provide performance metrics for student progress	Row Total
Provide Students with Understanding of PLC Applications		1	0	1	0	0	1	0	0	0	0	1	4
Produce curriculum comprable to other universities	0		0	1	0	0	1	0	0	0	0	0	2
Teach students ladder logic	1	1		1	1	1	1	1	1	1	1	1	11
Base Curriculum off of Rockwell's training materials	0	0	0		0	0	1	0	0	0	0	0	1
Select appropriate PLC	1	1	0	1		1	1	1	1	1	1	1	10
Create software and hardware debugging challenges	1	1	0	1	0		1	1	0	0	0	1	6
Introduce networking basics	0	0	0	0	0	0		0	0	0	1	1	2
Have students apply knowledge to a real world example	1	1	0	1	0	0	1		0	0	0	1	5
Teach students how to use HMI	1	1	0	1	0	1	1	1		0	1	1	8
Create three laboratory assignments and select hardware	1	1	0	1	0	1	1	1	1		1	1	9
Provide supporting material for faculty	1	1	0	1	0	1	0	1	0	0		1	6
Provide performance metrics for student progress	0	1	0	1	0	0	0	0	0	0	0		2
Column Total	7	9	0	10	1	5	9	6	3	2	5	9	
						Column Total to Row Total Ratio:							1

Figure 2: Binary Pairwise Comparison

1.6.2 House of Quality

The House of Quality (HoQ) is a table that compares the same 14 customer requirements to the engineering characteristics, which consist of the targets and metrics that were determined earlier in the project timeline. The engineering characteristics were derived from the functional decomposition and additionally was written with its appropriate units and arrows. There is an up arrow and a down arrow, which correlates to the desired outcome for each characteristic. For example, there is an up arrow for “Output speed”, since it is ideal for the output speed to be increased for faster results.

The HoQ is a system where the team ranks the importance of the customer requirement to the engineering characteristic with values “1”, “3”, “9”. If the two don’t align whatsoever, there is no value placed. On the contrary, if there is a large contribution, the value “9” would be written between the customer’s requirement and the engineering characteristic. Thus, the relevancy of the values increases, with “1” being the lowest and “9” being the highest. It is important to note that the binary pairwise comparison gave an importance weight factor for each customer need, which is then used for the House of Quality.

After values were placed for each customer requirement versus each engineering characteristic, raw scores, relative weight percentage, and rank order is provided. This allows the team to understand which engineering characteristics are most important, which in this case is ‘Frequently Asked Questions’. Now that the order of the characteristics are quantified, the Pugh Charts can be generated.

		Engineering Characteristics																
Improvement Direction		↑	↓	↑	↑		↑	↓	↑	↑	↑	↑				↓	↓	↓
Units		MB	sec	m	MB/se	N/a	in/s	sec	ms	V	ms	A	N/a	N/a	N/a	lb	ft^3	min
Customer Requirements	Importance Weight Factor	CPU Size	LCD	Short Distance Computer Communication	Ethernet to SCADA Data Recording	Frequently Asked Questions	Conveyor belt speed	Disconnect Time	Output speed	Maximum Output Voltage	Input speed	Maximum Output Current	Safety inspection checklist	Lab manuals	Surveys/Post-lab assessments	Maximum weight	Maximum Volume	Maximum assembly time
Provide Students with Understanding of PLC Applications	4	1				1	1		1	1	1	1		3	3			
Produce curriculum comprable to other universities	2		3	3	1	3	1							3				
Teach students ladder logic	11					9	3		3		3				9			
Base Curriculum off of Rockwell's training materials	1		3	3	1	3	3							3				
Select appropriate PLC	10	9	9	9	3	1	1		9	9	9	9				9	9	
Create software and hardware debugging challenges	6		9	3	3	9	9	9	3		3							
Introduce networking basics	2	1		9	9	1												
Have students apply knowledge to a real world example	5		9	9	3	3	9	9		1		1						
Teach students how to use HMI	8	3	9	3	1	3	3	9										
Create three laboratory assignments and select hardware	9		3			9	9								9	3	3	1
Provide supporting material for faculty	6					9	3	1		9		9	9	9	3			9
Provide performance metrics for student progress	2												9	9	9			3
Raw Score		120	297	204	92	352	274	177	145	153	145	153	72	93	228	117	117	69
Relative Weight %		0.043	0.106	0.073	0.033	0.125	0.098	0.063	0.052	0.054	0.052	0.054	0.026	0.033	0.081	0.042	0.042	0.025
Rank Order		11	2	5	15	1	3	6	9	7	9	7	16	14	4	12	12	17

Figure 3: House of Quality

1.6.3 Pugh Charts

Moving forward, Pugh Charts are useful when comparing the team's medium and high-fidelity concepts to designs or concepts that exist in the real world. These "datum" concepts can be found from benchmarking any concepts in the current market that is comparable to the concepts generated. From the House of Quality from above, it is shown that the top five engineering characteristics are: 'Frequently Asked Questions,' 'LCD', 'Conveyer Belt Speed', 'Surveys/Post-lab Assessments', and 'Short Distance Computer Communication'. These five characteristics will then be used to assess the Pugh Charts, which include the 3 high-fidelity and 5 medium-fidelity concepts. Each element is assigned an "S" for satisfactory, "+" for a concept that is better than the datum, and "-" for a concept that is not as ideal as the datum. This applies for each concept and each characteristic. The total number of "+" and "-" are summed at the bottom of the chart, which then will allow for the second Pugh Chart to be created.

Selection Criteria	Datum	MircroLogix, Pressure Sensor, AC Motor, Roller, LCD	Car-gate system	Motor Driver	Tank Controller	Painter	Traffic Simulation	Manufacturing Simulation	Draw bridge simulation
Frequently asked questions	Airport Luggage Automation	+	+	+	+	+	+	+	+
LCD		S	-	-	S	S	-	-	-
Conveyor belt speed		S	-	-	-	+	-	+	-
Surveys/Post-lab assessments		+	+	+	+	+	+	+	+
Short Distance Computer Communication		S	S	-	S	S	S	S	S
Total Pluses:		2	2	2	2	3	2	3	2
Total Minuses:		0	2	3	1	0	2	1	2

Figure 4: Pugh Chart for Market

Now, the second Pugh Chart utilizes the most mediocre concept for the datum. For this second chart, the concepts are narrowed down to analyze the best concepts. In other words, the concepts that have the most “+” and “S” are analyzed with the datum, and the other concepts are eliminated.

Selection Criteria	Datum	Motor Driver	Traffic Simulation	Manufacturing Simulation
Frequently asked questions	Draw bridge simulation	+	S	S
LCD		-	+	+
Conveyor belt speed		S	S	+
Surveys/Post-lab assessments		+	+	S
Short Distance Computer Communication		-	-	S
Total Pluses:		2	2	2
Total Minuses:		2	1	0

Figure 5: Pugh Chart for Concept

1.6.4 Analytical Hierarchy Process

An analytical hierarchy process (AHP) was used to check the consistency of the team’s decisions throughout the concept selection process. The value returned from the AHP is called the consistency ratio, which is a measure of how consistent the decisions were. The closer to 0 this number is, the better the consistency was. Following this, the higher the number is the less consistent, or more 'random,' the choices were.

Two separate AHPs were used. The first checked the consistency of decisions made about the relative importance of the selection criteria. These selection criteria were: 'Frequently asked questions,' 'LCD,' 'Conveyor belt speed,' 'Surveys/Post-lab assessments,' and 'Short Distance Computer Communication.' The consistency ratio for these decisions was found to be 0.185, above the normal tolerance of 0.10. The most likely reason for this inconsistency is the lack of any dependencies between these selection criteria. In other words, the selection criteria were of relatively equal importance. This made comparing any two selection criteria more 'random,' as it was difficult to decide on how to compare importance. Figures 6 and 7 below show the process used to determine the consistency ratio.

	Frequently asked questions	LCD	Conveyor belt speed	Surveys/Post-lab assessments	Short Distance Computer Communication
Frequently asked questions	0.626	0.429	0.333	0.775	0.458
LCD	0.089	0.061	0.143	0.031	0.017
Conveyor belt speed	0.089	0.020	0.048	0.022	0.017
Surveys/Post-lab assessments	0.125	0.306	0.333	0.155	0.458
Short Distance Computer Communication	0.070	0.184	0.143	0.017	0.051
Sum (Validation):	1.000	1	1	1.000	1.000

Ranked Values			Criteria Weights
Frequently asked questions	0.524	Frequently asked questions	0.524
Surveys/Post-lab assessments	0.275	LCD	0.068
Short Distance Computer Communication	0.093	Conveyor belt speed	0.039
LCD	0.068	Surveys/Post-lab assessments	0.275
Conveyor belt speed	0.039	Short Distance Computer Communica	0.093
Sum (Validation):	1.000	Sum (Validation):	1.000

Figure 6: Normalized Matrix for the first AHP

Consistency Check		
{Ws} = [C]{W}	{W}	Cons={Ws}./{W}
Weighted Sum Vector	Criteria Weights	Consistency Vector
3.490	0.524	6.659
0.347	0.068	5.083
0.207	0.039	5.271
1.832	0.275	6.653
0.505	0.093	5.434
	Consistency Check:	5.820

Figure 7: Consistency Check for the first AHP

The second AHP was used to compare the selection criteria for each of the top three design choices. These design choices were of the top three from the Pugh chart, and are as follows: ‘Motor Driver, “Traffic Simulation,’ and ‘Manufacturing Simulation.’ All of the consistency ratios from this process were below the threshold of 0.1, with all the values being zero except for one which was 0.0413. Because of these low values, the team can be confident that the decision-making process was consistent and that the results of this process can be trusted. The appendix contains Figures A1 and A2 which show each AHP done for the selection criteria.

1.6.5 Final Selection

After all concept selection steps were completed, the data revealed that “Motor Driver” was the best. This concept satisfied most criteria and was deemed most efficient. The steps taken to achieve this outcome were necessary and helpful to the team.

Ranked Concept	Alt. Value
Motor Driver	0.597
Manufacturing Simulation	0.481
Traffic Simulation	0.433

Figure 6: Ranked Concept

The motor driver learning system will help students understand PLC ladder logic as well as integrate hardware. The desired outcomes of "Motor Driver" will be; for students to understand the uses of an H-bridge circuit, learn to implement flyback diodes and understand the reason for using them, program the PLC to move the motor in a desired direction. These will give students experience in circuit diagrams and wiring, as well as PLC logic.

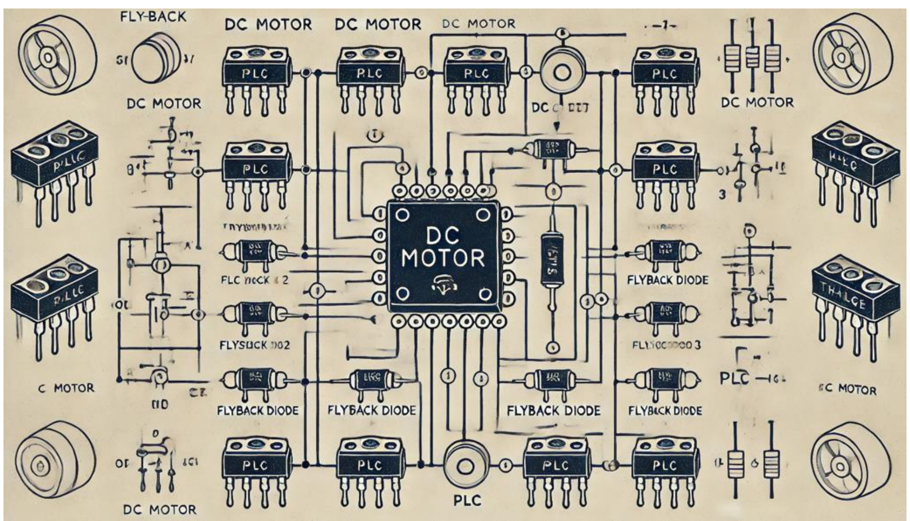

Figure 7: H-Bridge Schematic for Motor Driver Concept

[OpenAI. (2024). *H-Bridge Circuit Schematic for DC Motor Control using PLC* [Digital Image]. Generated by DALL-E, OpenAI.]

The figure above is an AI generated picture that represents the connection between the DC Motor, Transistor, Flyback Diode, and the PLC. These components will be used in the “Motor Driver” learning system and will play an integral role in learning not only PLC logic but constantly used electrical hardware.

1.8 Spring Project Plan

Chapter Two: EML 4552C

2.1 Spring Plan

Project Plan.

Build Plan.

Appendices

Appendix A: Code of Conduct

Mission Statement

Team 519's mission is to inspire the next generation of engineers by developing hands-on Mechatronics labs for students to gain experience in coding and programmable logic controllers. Through teamwork, collaboration, and mutual respect, the team will grow individually and collectively, utilizing skills to become successful engineers and leading innovation for those to come.

Outside Obligations

Team 519 utilized a website called When2Meet, which allows each member to input time frames available for every day of the week throughout the fall semester. Additionally, the team will use Outlook calendar weekly for any schedule adjustments/changes, which allows for the members to meet at different times when needed.

Grant Hoffmeyer currently works as a project engineer intern with the Whiting-Turner Contracting Company. His work includes the construction management of FSU's new Football facility building which takes up 15-20 hours per week.

Jack Vranicar currently works as a Teaching Assistant for Mechatronics 1 and as a Research Assistant for the CISCOR laboratory. Research demands 10 hours a week of work and being a TA requires 15, with both jobs operating on an inconsistent schedule.

Mason Walters works for a contracting and consulting company working on demands for varies government contracts, consuming about 10-15 hours per week.

Onyx Oh currently serves as a Learning Assistant in Dynamic Systems I, which takes 10 hours per week. She also partakes in undergraduate research for the RTHM Lab with Dr. Taylor

Higgins, which includes 2 weekly meetings and outside work. Additionally, she has a part-time job which can take up to 13 hours per week.

Team Roles

Systems and Test Engineer: Grant Hoffmeyer

The Systems and Test Engineer is responsible for the integration of the code and hardware to build and test working setups to be taught in the lab. The Systems and Test Engineer will work closely with the Design and Software Engineers to develop code and materials. The goals set by the Curriculum Engineer will lead the Systems Engineer in the design of the lab setup.

Software Engineer Jack Vranicar

The Software Engineer is responsible for developing code to produce desired outputs. These desired outputs will be dictated by the hardware provided by the Design Engineer, goals set by the Curriculum Coordinator, and feedback provided by the Systems and Test Engineer. The Software Engineer is also responsible for maintaining the code in an organized repository.

Design Engineer: Mason Walters

The Design Engineer is responsible for hardware production and material handling. This includes designing adequate material that is desired by the Software and Systems Engineers. This role also analyzes materials options for the project and compares financial aspects. This role is responsible for part production in CAD and 3D printing.

Project Engineer: Onyx Oh

The Project Engineer is responsible for translating the work achieved by the team throughout the duration of the project into material for the curriculum for the students. Prior research, benchmarking, and networking with other companies or universities is expected. This role includes creating and organizing documentation for the team, the professor, and teaching/learning assistants. This role is in charge of ensuring the clarity of the team's progression is easily translated to the students and sponsor. Additionally, all communication between the sponsors, advisors, and remaining points of contact is managed by the Project Engineer.

Communication

Team 519 plans to utilize Microsoft Teams as the main form of communication in preparation for corporate life, where most offices utilize this software. This allows the team to use the chat function for any questions, discussions, or planning. Additionally, any files and assignments can be found in Microsoft Teams, and the team can work on assignments jointly. For scheduling purposes, Outlook Calendar is used. This allows team members to see each other's weekly availability to schedule last-minute meetings or plan for upcoming milestones accordingly. The team will resort to emails and text messages as a secondary form of communication, in case of urgent matters that need punctual responses. This form of communication will be used if the team has not heard from a team member. Any team member will have up to 24 hours to respond on Teams before they will be reached out to via email, text message, or phone calls. Team members are expected to check their Teams application and emails at least 3 times a day to ensure constant communication amongst one another and sponsors or advisors. Sponsors and advisors will be reached out to via email in a professional manner and will utilize Teams for meetings. With professional meetings, the camera is expected to be on, and each member must be in business casual attire. Ultimately, the team will express respect, trust, and reliability as they communicate amongst each other. There will be meeting minutes documented every time the team meets, with descriptions of what was done, any questions to ask the sponsors, and any upcoming goals.

Dress Code

The team will not be in any dress code or in uniform during class times and team meetings. During presentations, including the Virtual Design Reviews, and professional interactions, it is required for each member to dress in professional business attire.

Attendance Policy

Team members must attend all class sessions, in person and online group meetings, sponsor meetings, and advisor meetings and contribute reasonably. Occasions which a team member will be excused from meetings are as follows: meetings which are scheduled outside of the hours of 8am to 10pm; meetings which are scheduled with less than 24 hours' notice; meetings that the member has a legitimate excuse, including but not limited to doctor's appointments, holidays, illness, or prior commitments. As for unexcused absences, in cases where the member's absence is detrimental to interpersonal relationships, such as with the sponsor, efforts will be made to attend the meeting virtually. In other cases of unexcused absences, the member will be responsible for completing an amount of work commiserate with the work done during the meeting on their own time.

Each member will be allotted three unexcused absences per semester, with each subsequent absence requiring more intervention. The first will be a no-questions-asked pass that each member may use at their own discretion. The second will require electronic documentation stating that the member used one of their unexcused absences and will not come with serious intervention. Members are expected to self-report these absences, making note of them in the 'Absences' chat in Teams within 48 hours. Finally, a third unexcused absence will result in a meeting with at least two other group members to develop a plan to prevent future absences. Members may be forgiven for unexcused absences provided they bring adequate snacks to the subsequent meetings

How to Notify Group

Communication will be done primarily in Teams. Members are expected to respond to messages within 24 hours, barring previously communicated off times and emergencies. Emergencies include sickness, hospitalization, death, etc. The use of text messaging and calling will be reserved for instances where the member has not responded within 24 hours or there is an urgent situation, such as a short notice meeting with the sponsor, which cannot wait 24 hours.

How to Respond to People in Professional Meeting

Formality will be the default mode of communication for meetings and correspondence outside of team-only meetings. This will entail proper use of pronouns like Sir/Ma'am/Doctor/Professor etc. Adjustments will be made should a person indicate that they prefer another way of being addressed, such as by different pronouns or by first name.

What do we do before Dr. McConomy or TAs

Each member will have three strikes before communication with Dr. McConomy is initiated. A strike is further defined as an unexcused absence, lack of cooperation, or communication. The consequences of each strike are defined in attendance policy.

At what point do we contact Dr. McConomy

At the point at which group members cannot reach civil agreement past the 3 strikes or other impasse, the team members will contact Dr. McConomy.

What do you want Dr. McConomy to do when you come

Dr. McConomy would take the role of mediation during group dispute. Recommendations made during mediation will be enforced.

How to amend

In order to amend, all team members must vote and provide formal documentation stating their reasoning/purpose for their vote based on said proposal. A formal proposal in professional writing needs to be presented to the team before any voting may occur. A majority vote of 3 out 4 team members is required for any amendment to pass. If an amendment is passed, it is required for the team to add the said amendment as an additional supplement to the code of conduct and evidence book documentation.

Statement of Understanding

All four members of Team 519 have discussed and contributed to the Code of Conducts in full agreement. Each signature below represents the team's understanding of the information and requirements specified above. The team confirms that these statements will be followed unless amended.

Grant Hoffmeyer

X ____________________

Date

09/10/24

Jack Vranicar

X ____________________

Date

09/10/24

Mason Walters

X ____________________

Date

09/10/24

Onyx Oh

X ____________________

Date

09/10/24

Appendix B: Functional Decomposition

Appendix C: Target Catalog

Appendix A: APA Headings (delete)

Heading 1 is Centered, Boldface, Uppercase and Lowercase Heading

Heading 2 is Flush Left, Boldface, Uppercase and Lowercase Heading

Heading 3 is indented, boldface lowercase paragraph heading ending with a period.

Heading 4 is indented, boldface, italicized, lowercase paragraph heading ending with a period.

Heading 5 is indented, italicized, lowercase paragraph heading ending with a period.

See publication manual of the American Psychological Association page 62

Appendix B Figures and Tables

The following figures were used for concept selection. These are the AHP tables for each of the selection criteria.

C Matrix for:		Frequently asked questions		
	Motor Driver	Traffic Simulation	Manufacturing Simulation	Avg:
Motor Driver	1.00	5.00	5.00	3.67
Traffic Simulation	0.20	1.00	1.00	0.73
Manufacturing Simulation	0.20	1.00	1.00	0.73
Sum:	1.40	7.00	7.00	
Avg:	0.47	2.33	2.33	
SumTotal:	15.40			

C Matrix for:		LCD		
	Motor Driver	Traffic Simulation	Manufacturing Simulation	Avg:
Motor Driver	1.00	0.11	0.11	0.41
Traffic Simulation	9.00	1.00	1.00	3.67
Manufacturing Simulation	9.00	1.00	1.00	3.67
Sum:	19.00	2.11	2.11	
Avg:	6.33	0.70	0.70	
SumTotal:	23.22			

C Matrix for:		Conveyor belt speed		
	Motor Driver	Traffic Simulation	Manufacturing Simulation	Avg:
Motor Driver	1.00	1.00	0.11	0.70
Traffic Simulation	1.00	1.00	0.11	0.70
Manufacturing Simulation	9.00	9.00	1.00	6.33
Sum:	11.00	11.00	1.22	
Avg:	3.67	3.67	0.41	
SumTotal:	23.22			

C Matrix for:		Surveys/Post-lab assessments		
	Motor Driver	Traffic Simulation	Manufacturing Simulation	Avg:
Motor Driver	1.00	3.00	5.00	3.00
Traffic Simulation	0.33	1.00	3.00	1.44
Manufacturing Simulation	0.20	0.33	1.00	0.51
Sum:	1.53	4.33	9.00	
Avg:	0.51	1.44	3.00	
SumTotal:	14.87			

C Matrix for:		Short Distance Computer Communication		
	Motor Driver	Traffic Simulation	Manufacturing Simulation	Avg:
Motor Driver	1.00	0.20	0.20	0.47
Traffic Simulation	5.00	1.00	1.00	2.33
Manufacturing Simulation	5.00	1.00	1.00	2.33
Sum:	11.00	2.20	2.20	
Avg:	3.67	0.73	0.73	
SumTotal:	15.40			

Norm C Matrix For:		Frequently asked questions		{Pi}
	Motor Driver	Traffic Simulation	Manufacturing Simulation	
Motor Driver	0.71	0.71	0.71	0.714
Traffic Simulation	0.14	0.14	0.14	0.143
Manufacturing Simulation	0.14	0.14	0.14	0.143
Sum:	1	1	1	

Norm C Matrix For:		LCD		{Pi}
	Motor Driver	Traffic Simulation	Manufacturing Simulation	
Motor Driver	0.71	0.02	0.02	0.249
Traffic Simulation	6.43	0.14	0.14	2.238
Manufacturing Simulation	6.43	0.14	0.14	2.238
Sum:	13.57142857	0.301587302	0.301587302	

Norm C Matrix For:		Conveyor belt speed		{Pi}
	Motor Driver	Traffic Simulation	Manufacturing Simulation	
Motor Driver	0.71	0.14	0.02	0.291
Traffic Simulation	0.71	0.14	0.02	0.291
Manufacturing Simulation	6.43	1.29	0.14	2.619
Sum:	7.857142857	1.571428571	0.174603175	

Norm C Matrix For:		Surveys/Post-lab assessments		{Pi}
	Motor Driver	Traffic Simulation	Manufacturing Simulation	
Motor Driver	0.71	0.43	0.71	0.619
Traffic Simulation	0.24	0.14	0.43	0.270
Manufacturing Simulation	0.14	0.05	0.14	0.111
Sum:	1.095238095	0.619047619	1.285714286	

Norm C Matrix For:		Short Distance Computer Communication		{Pi}
	Motor Driver	Traffic Simulation	Manufacturing Simulation	
Motor Driver	0.71	0.03	0.03	0.257
Traffic Simulation	3.57	0.14	0.14	1.286
Manufacturing Simulation	3.57	0.14	0.14	1.286
Sum:	7.857142857	0.314285714	0.314285714	

Figure A1: Normalized Matrices for each selection criteria

{Ws} = [C]{Pi}	{Pi}	Cons = {Ws}./{Pi}
2.143	0.714	3.000
0.429	0.143	3.000
0.429	0.143	3.000

Lambda	CI	RI	CR
3.000	0.000	0.520	0.0000

{Ws} = [C]{Pi}	{Pi}	Cons = {Ws}./{Pi}
0.746	0.249	3.000
6.714	2.238	3.000
6.714	2.238	3.000

Lambda	CI	RI	CR
3.000	0.000	0.520	0.0000

{Ws} = [C]{Pi}	{Pi}	Cons = {Ws}./{Pi}
0.873	0.291	3.000
0.873	0.291	3.000
7.857	2.619	3.000

Lambda	CI	RI	CR
3.000	0.000	0.520	0.0000

{Ws} = [C]{Pi}	{Pi}	Cons = {Ws}./{Pi}
1.984	0.619	3.205
0.810	0.270	3.000
0.325	0.111	2.924

Lambda	CI	RI	CR
3.043	0.021	0.520	0.0413

{Ws} = [C]{Pi}	{Pi}	Cons = {Ws}./{Pi}
0.771	0.257	3.000
3.857	1.286	3.000
3.857	1.286	3.000

Lambda	CI	RI	CR
3.000	0.000	0.520	0.0000

Figure A2: Consistency Matrices and Ratios for each selection criteria

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