Team #7: Crane Cats

Final Report

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1.0 Abstract

The purpose of our project is to build an electronic system to aid and support crane operators in the appropriate placement of coiled aluminum sheet metal in cradles on storage racks. This project is being developed for use by Logan Aluminum, who has recently observed issues of efficiency from improper placement of coils on the storage racks. The system will communicate with the crane operator information regarding the front-to-back position of the coil during placement. By utilizing this system, the crane operators of Logan Aluminum will become more efficient, and the system will create a safer work environment. Our project requirements discussed below were developed for our final design iteration, which involves a set of sensors to detect the position of the coil verses the position of the coil cradle to provide visual feedback via light emitting diodes to the crane operator. This report provides the speculations and requirements of our project to direct our team in finalizing the described system to ensure that it meets the system and marketing requirements previously defined.

2. Problem Statement

2.1 Need

Logan Aluminum's daily operations require the constant movement of large coils of aluminum sheet metal to different locations in the facility. They carry out these movements with an overhead forklift type of crane by sliding the crane's arm into the cylindrical sleeve of the aluminum coil and lifting it up. Once the coil reaches its desired destination, the operator is to drop off the coil on a rack. Here is where the problem takes place. The issue that is being observed by Logan Aluminum is that crane operators execute different approaches to the lifting and lowering of the coils. Due to the orientation of the crane, the operators do not have a 100% visual of the rack when they are to lower the coils. This sometimes causes the coil to be placed too far inside, bumping with the coil on the other side of the rack, or too far out of the rack, where the coils then don't allow the free movement of other cranes going through the aisle. This leads to inefficiency because it slows down the operation by having to send a crane operator to pull out and restock certain coils of aluminum. Logan Aluminum needs a way to standardize the depth the coils of aluminum that are laid on the rack so they are properly positioned on the first attempt. Figure 1 below is a visual of a crane storing a coil of aluminum. Figure 2 shows the back of the rack with a possible coil collision we will work to prevent.

2.2 Objective

The objective of this project is to design and test a sensor system that will assist in standardizing the placement of the aluminum coils on storage racks at Logan Aluminum. The system will give visual feedback to the operator to provide insight on the proper positioning of where to lower the coil onto the storage rack. This will allow us to solve the inefficiency problem Logan is dealing with when storing the coils.

2.3 Background

Sensing devices and automation have become indispensable for all kinds of industrial settings. Their wide variety of uses ranges from tracking distances to controlling automated processes. One type of sensor that is of great use are proximity sensors. [1] These sensors measure distance, but use different embedded technologies to do so. More specifically, ultrasonic proximity sensors and laser sensors have a range that is more desirable when measuring larger distances.

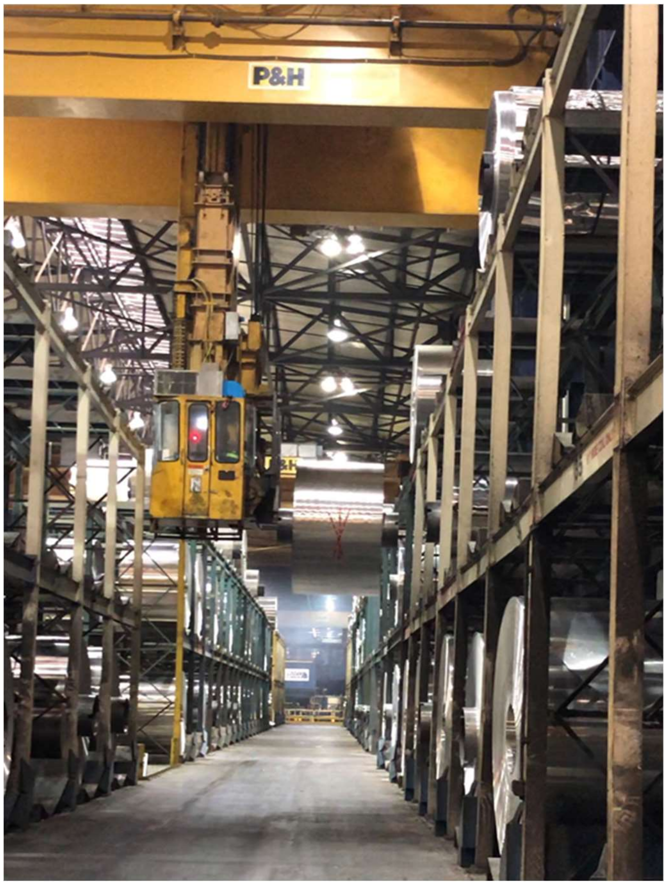


Figure 1: The picture displayed provides a visual representation of a crane storing a coil of aluminum on the storage racks

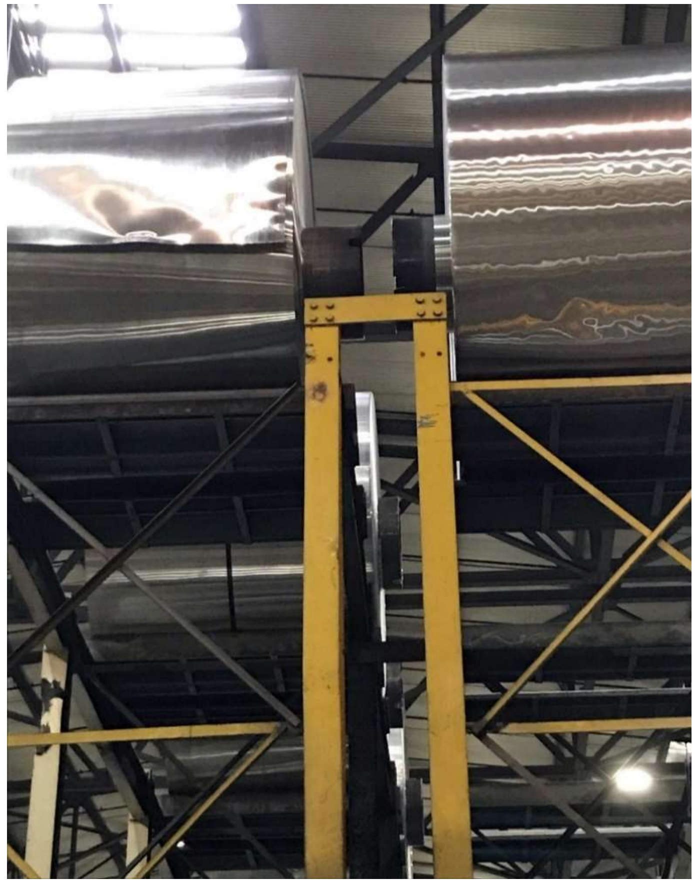


Figure 2: The picture shown above brings insight on the tight tolerances seen between steel sleeves at the posterior regions of the storage racks

Most industrial settings employ some kind of crane or forklift to carry out their daily operations. This type of machinery can produce dangers in industrial environments, so the development of crane proximity systems have taken place. [2] These systems are mostly implemented for safety reasons to make sure cranes does not collide with other objects or people present in the area. These systems employ proximity sensors which are very common for automated systems in industrial settings.

While there is a significant amount of documentation for crane safety systems, there is little public documentation on the use of proximity sensing systems to aid crane operation due to the main use being within an industrial setting.

Logan Aluminum uses an overhead ceiling crane to transport aluminum coils throughout the factory. This crane is designed to move in 3 dimensions throughout the plant space. For our design we have defined the 3 dimensions as X, Y, and Z, these are represented in Figure 3. The Y dimension is defined where the crane moves horizontally and in parallel along the rows of the rack storage space. The Z dimension is defined where the crane moves in and out of the rack perpendicular to the rows of rack storage. The X dimension, which is pointing out of the page in Figure 3, is defined where the crane moves vertically up and down from the ceiling to place coils on different levels of the rack storage. The crane cab is attached to the crane and this is defined as the area where the crane operator sits and controls the movement of the crane. The crane has an arm that sticks out to lift the aluminum coil and transport it. The operator controls the arm and inserts it into the steel sleeve to lift the aluminum coil and transport it throughout the factory and storage space in the 3 dimensions defined. The storage space is displayed in Figure 3 as well, defined as the “Coil Storage Rack.” The rack consists of three dimensions of bars, which lay in the three defined dimensions. The vertical bars of the rack, meaning the bars that extend in the X-Dimension, are labelled in the drawing.

3.0 Design Requirements

The design requirements for our project are identified through multiple layers. The requirements begin with the high-level marketing requirements, which represent specific characteristics and qualities of our

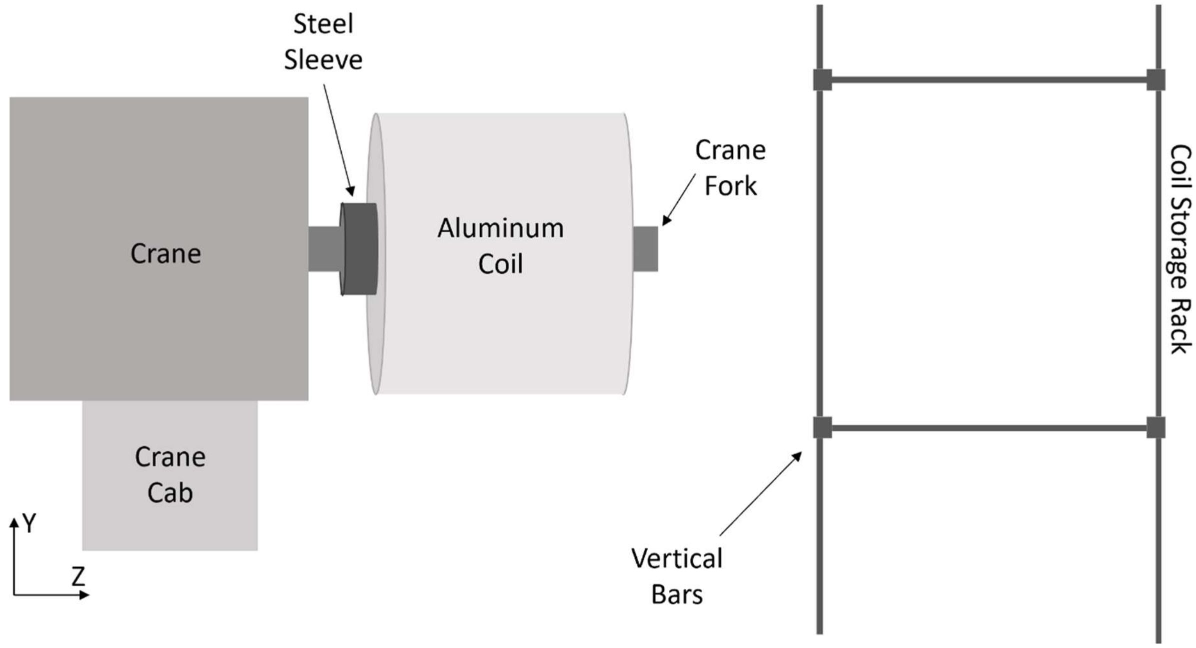


Figure 3: Display of the Crane System movement and operation from the viewpoint of the ceiling.

project that are needed for it to be successful. Beneath the marketing requirements are the engineering requirements, which represent the technical features necessary to meet each marketing requirement. A set of test methods are included to verify all engineering requirements are met by the system.

3.1 Marketing Requirements

1. System shall reliably detect distance measurements of coil storage racks and coil sleeve on crane

2. System shall be able to withstand factory conditions

3. System shall be small enough to fit on crane

4. System shall provide feedback to crane operator

5. System shall interface with a programmable controller

6. System should be low cost

7. System shall be versatile with all types of racks and coils

8. Visual Feedback given to crane operator shall be intuitive

9. System shall accurately sense the current location of the coil

3.2 Engineering Requirements

Below is a table containing the engineering requirements of our project. Each engineering requirement is accompanied by a justification of why the requirement is needed for the system and the marketing requirement that the engineering requirement applies to.

Table 1: A table listing the Engineering Requirement for our project along with justifications of the requirements and the associated marketing requirements met by each engineering requirement.

Number	Marketing Requirement	Engineering Requirement	Justification
1	2, 3	Sensors shall be placed in a protected position on the crane.	The sensor must be in a spot that will not affect crane operation and in addition a spot that will protect the sensor and allow it to work as intended.
2	1, 2	Electronics shall be able to withstand high temperatures (130°)	The sensor and associated wiring must be able function properly while handling max temperatures of 120° F that were detected in the factory
3	1, 2	Electronics shall be able to withstand high amounts of vibration	There are high torque motors and machines that cause vibrations throughout the factory. Electronics must function properly while handling these vibrations
4	3	Sensor electronics shall fall within 6 cubic inches	The electronics must be small enough to fit on the crane and within an encasing.
5	2, 3	Electronics shall be mounted solidly on crane	The electronics must be stable and remain in the same location so calibration and measurements are consistent.
6	4, 5, 8	There shall be visual feedback for the operator detailing coil location	The sensor should interface with the programmable controller and provide a simple user interface for the crane operator to see coil location in reference to the rack.
7	1, 4	System shall not interfere with operation of crane	The system is meant to be used as an aid for the crane operator but should not interrupt the operator from operating the crane properly
8	5	Sensors shall integrate into programmable controller through wired connection.	The programmable controller will be the basis of the system, enabling analysis of the inputs to provide proper signaled communication with the Light Emitting Diode (LED) LightBar
9	6	Project total cost shall be less than $1000	The sponsor funding is $1000 and our design will ensure that total cost including all electronics, prototyping, and testing is within the budget

10	6	Sensor assembly shall be less than $600	The sensor assembly including the encasing and mounting shall be less than $600 to allow for additional budget to be used for testing and interfacing
11	1, 7, 9	Sensor shall measure distance between cab and steel sleeve within .8” (2cm) tolerance	The first sensor used for detecting where the steel sleeve is in reference to the crane must have the ability to measure distances precisely.
12	1, 7, 9	Sensor shall detect distance between edge of coil cradle and crane cab within .8” (2cm) of true edge	The sleeves are placed closely together on the racks within a few inches. The sensor must be able to measure precisely to prevent collision or inaccurate display of sleeve position
13	8	System shall be accompanied by infographic	For ease of use we will provide an infographic for the crane operators with information on how the system works and how distance measurements are presented in the User Interface (UI)
14	8, 9	Visual feedback shall be easily interpreted and updated in less than 50ms	The position of the crane and sleeve are constantly changing so our sensor must constantly update and provide real time feedback to the operator
15	4, 8	Visual feedback system shall operate in a range of +/- 5.6 inches	The visual feedback presented to the operator must be almost exact to what the sensor is seeing to ensure the sleeve is being placed correctly according to sensor measurements
16	1, 5	System shall be powered by the Programmable Logic Controller (PLC) power output	The sensor will interface with the PLC through a wired connection. That will give the system reliable power and allow for constant updating from the sensor to the plc.

3.3 Verification of Engineering Requirements

Each engineering requirement found in section 3.2 can be validated through a selected testing process. One method of verification for each of the engineering requirements is listed in the table below.

Table 2: A table displaying the methods of testing and verifying that our project meets each engineering requirement

Engineering Requirement	Engineering Requirement	Method for Validating Engineering Requirement
1	Sensors shall be placed in a protected position on the crane.	Consult with Crane operators (experts) to verify placement of sensors is on a rarely contacted surface
2	Electronics shall be able to withstand high temperatures (130°)	Electronics assembly will be designed with maximum temperature and humidity conditions in mind. Since we don't have access to this environment, we will verify through data sheets of the electronics we decide upon
3	Electronics shall be able to withstand high amounts of vibration	Compare functionality and accuracy of system outputs before and after a shake test. A shake test can be defined by manual vigorous shaking of the sensor system for more than 1 minute
4	Sensor electronics shall fall within 6 cubic inches	Measure the dimensions of the sensor module and verify that sensor will fit within a maximum of a 6 cubic inches container
5	Electronics shall be mounted solidly on crane.	Comparing positioning of sensor before and after movement test on crane to ensure mounting is not altered
6	There shall be visual feedback for the operator detailing coil location	Verify that feedback system is included in system by optical inspection of system and requirement confirmed by operator
7	System shall not interfere with operation of crane	Verify that there are no connections to crane control software of PLC and our system is external to crane controls
8	Sensors shall integrate into programmable controller through wired connection	Verify that wired connections to microcontroller are present and offer reliable channels of communication to the microcontroller
9	Project total cost shall be less than $1000	Compare overall cost of project through budget sheets to the projected project budget of $1000
10	Sensor assembly shall be less than $600	Compare overall cost of sensors assembly from Assembly Bill of Materials to projected budget of $600

11	Sensor shall measure distance between cab and steel sleeve within .1” tolerance	Compare data collected by programmable controller with data collected by physical measurements to verify the requirement
12	Sensor shall detect distance between edge of coil cradle and crane cab within .2” of true edge	Comparing data collected by programmable controller with data collected by physical measurements to verify the requirement
13	System shall be accompanied by infographic	Verified via visual inspection of assembly
14	Visual feedback shall be easily interpreted and updated in less than 50ms	Verified through controller datasheet (Clock cycle and program length) and through measuring program cycle times
15	Visual feedback system shall operate in a range of +/- 1.4 inches	Confirmed by comparing measurements displayed by visual output with measurements computed by controller (Engineering Requirements 11 & 12 must be verified before doing this procedure)
16	System shall be powered by the PLC power output	Conduct an analysis of power sourced through PLC and power consumed by sub-systems (Sensors and Light-Bar)

3.4 Objective Tree

The objective tree shown in Figure 4 below identifies the primary aims of the project, and the marketing requirements needed to achieve them. Each of the marketing requirements has been assigned a relative weight using the analytic hierarchy process (AHP), in order to discern the most important requirements. The calculations behind these weights are detailed in the Appendix.

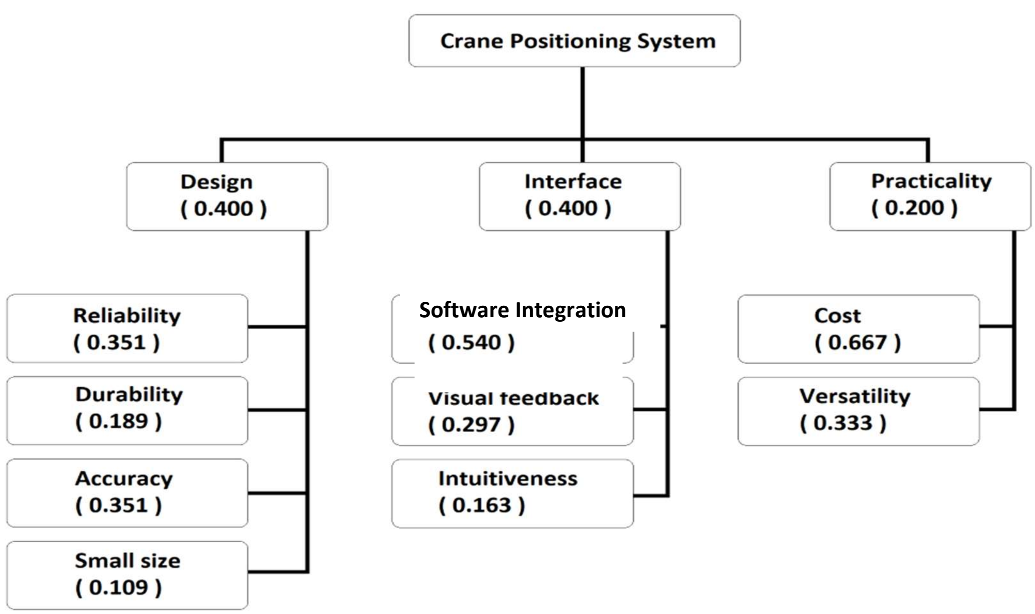


Figure 4: A display of our project’s requirements shown in hierarchy according to levels of requirements throughout the project

4.0 Design Impact

4.1 Health and Safety

The Health and Safety impact is one that was not explicitly expressed as a need from Logan Aluminum themselves, but it is evident that our design will be impactful to the safety of Logan Aluminum. Our products main purpose is to keep isle ways clear of any obstruction, this being the aluminum coils, and having them all placed properly on the racks. These coils could be a hazard for operators on the floor or to crane operators themselves. If a crane were to bump into a coil that was not placed properly there is a change to endanger the safety of someone below or even damage the crane, both of which would cost the company extra money. [3] In 2018, there was a reported average of 3.5 injuries relating to aluminum rolling and storage. This is a number that we believe our product could effectively bring down if our product were in use.

4.2 Economic

Our Economic impact is the driving force behind this project. Our purpose is to correct the improper placement of aluminum coils which is costing the company and workers extra money and time. The impact our product would have in operation of Logan Aluminum would be completely correcting the error in misplacement by using the sensors to detect the cranes distance from the rack to itself and communicating this to the crane operator. Instead of taking extra time to correct these errors during peak work creating extra stress on the operators and putting the company's work behind, they will be able to save that time to operate in a timely manner. Also, as mentioned above in Health and Safety, there would be an economic impact to save the company money for any possible injury to a worker or doing any damage to the crane by hitting a coil.

4.3 Social

The Social impact is something we had to keep in mind while working on our product as we did not want it to interfere with the crane operator's regular work. We wanted it to be used as a very intuitive tool for the crane operator instead of something that would just make his work more complex. We believe it will have a good social impact on the crane operators as it would make their work less stressful as they would not have to worry about any coil misplaced causing them extra work in the future. We also believe that it will have a positive social impact on the owners and the company. Our design will not cause any work to be halted in peak hours and they will be able to meet any deadlines they without worry of prior human error from improper storage of an aluminum coil.

4.4 Manufacturability

Our products manufacturability is something we had to keep in mind while designing our product as we wanted it to be small enough to fit properly on the crane and not interfere with the crane operator in any way. We were also given a $1,000 budget and we believe we can design our product with significantly less than the budget without hindering its effectiveness. Our product also does not require massive integration within the company as they will only need 1 of our systems per crane and it operates as a stand-alone system besides being powered by the Allen Bradly PLC on board the crane.

4.5 Environmental

Our product is designed to be very low energy consuming. It is powered by the on-board Allen Bradley PLC. It consists of the system that is mounted outside of the cab of the crane which consists of sensors to measure the distance from the rack and then transmits that data to LED lights that are inside the crane to communicate with the crane operator. This system will not require much power to run and will effectively lower energy usage within the company, as the crane, is much more energy demanding, and our product will be eliminating any times that the crane will need to be used to correct a misplaced aluminum coil.

5.0 Design

The overall purpose of this project is to assist crane operators at Logan Aluminum in correctly placing aluminum coils on a three-level rack. The crane places these aluminum coils front ways, like placing them on a shelf, on to these racks. The crane operators have trouble on occasion on judging the distance in the rack these coils are being placed, and they have only about a 2-inch margin of room to work with before the coil may go too far into the rack, displacing area for an aluminum coil on the rack behind. Also, the aluminum coil may not go in far enough making it a hazard for the crane and the operators when moving the crane throughout the aisles. Our system will assist the crane operators with may systems of sensors and feedback methods. One sensor system will measure the distance the aluminum coil is away from the crane once loaded onto the fork of the crane. Next, a separate system of sensors will measure the distance the crane is from the rack. With these two measurements, we will know how far the center of the coil is from the center spot of the rack, going into the rack itself. We will then crunch the numbers given from our systems and send them to the operator through a feedback system of a vertical line of 15 LED lights. The middle light, the 8th one, will be our ‘sweet spot’ for out coil. As the crane operator approaches the sweet spot the line of LEDs will light up starting at the bottom LED giving the operator a sense of how close they are to the ‘sweet-spot’. If they go past the ‘sweet-spot’, the remaining 7 LED lights above the middle light will begin to light up as the operator passes over the middle of the rack, letting the operator know they need to bring the coil backwards. This systems purpose is meant to be a tool for the operator, not do the work for the operator, by eliminating any issues of misplaced aluminum coils at the storage facility of Logan Aluminum.

5.1 Design Overview – Functional Decomposition

5.1.1 Level 0

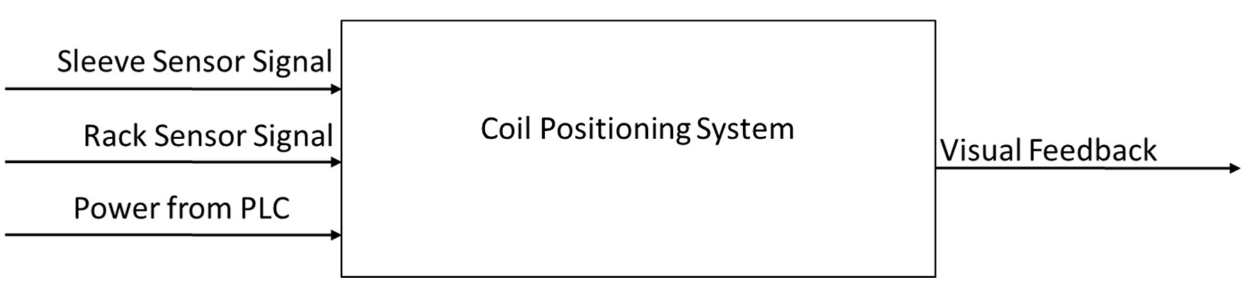


Figure 5: Level 0 Design of Coil Positioning System

Table 3: Level 0 Coil Positioning System

Module	**Coil Positioning System**
Inputs	• Sleeve Sensor Signal • Rack Sensor Signal • Power
Outputs	• Visual Feedback
Functionality	Takes sensor signal inputs and gives visual feedback on coil offset distance

The coil positioning system block seen above in Figure 5 represents the system that we are designing, omitting the sensors that are supplying the system with distance measurements. The block receives these two measurements and outputs visual feedback to the crane operator. The system is powered from the PLC power outputs, and the block can be studied in more detail below through the higher-level functional decompositions.

5.1.2 Level 1

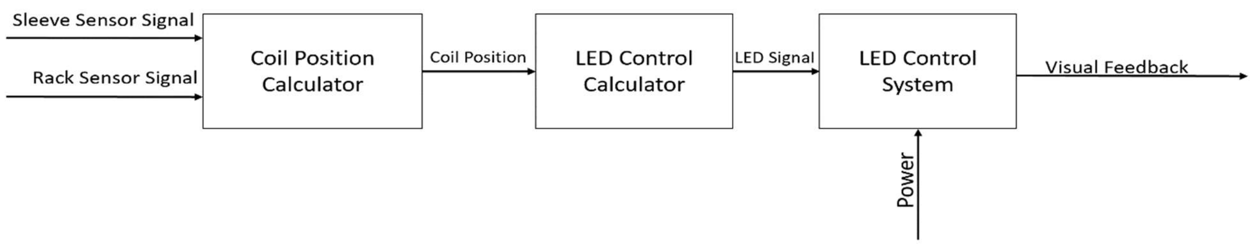


Figure 6: Level 1 Design of Coil Positioning System

Table 4: Level 1 Coil Positioning System

Module	**Coil Positioning System**
Inputs	• Sleeve Sensor Signal • Rack Sensor Signal • Power
Outputs	• Visual Feedback
Functionality	Takes sensor signal inputs then goes through programmable controller software to give LED visual feedback

The level 1 functional decomposition, seen in Figure 6, displays the three main functions of the system. Acting as a more in-depth block diagram of what is seen in Figure 5, the system translates the distance measurements received as voltage inputs into visual feedback to the operator through three sets of high level functions. These functions can be listed as the coil position calculator, LED control calculator, and the LED control system, each of which are studied more in depth in the following Figures.

5.1.3 Level 2

5.1.3.1 Level 2 – Coil Position Calculator

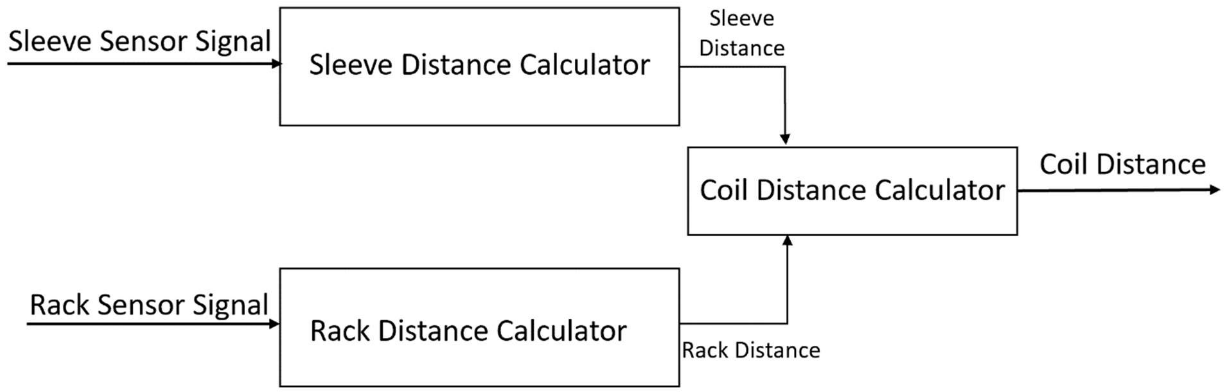


Figure 7: Level 2 Design of Coil Position Calculator

Table 5: Level 2 Coil Position Calculator

Module	**Coil Positioning System**
Inputs	• Sleeve Sensor Signal • Rack Sensor Signal
Outputs	• Coil Distance
Functionality	Takes sensor signal inputs then calculates coil position using distance calculators designed in the programmable controller software

The coil position calculator block functions as a calculator to receive the voltage signals from the rack and sleeve sensors and translate them into a meaningful coil distance. This is done by transforming the voltage signal inputs into distance values through equations characteristic of the individual sensors. The sleeve distance is the subtracted from the rack distance to calculate the distance from the edge of the rack to the edge of the sleeve. Additional calculations may be necessary to account for differences in mounting positions of the two sensor subsystems.

5.1.3.2 Level 2 – LED Control Calculator

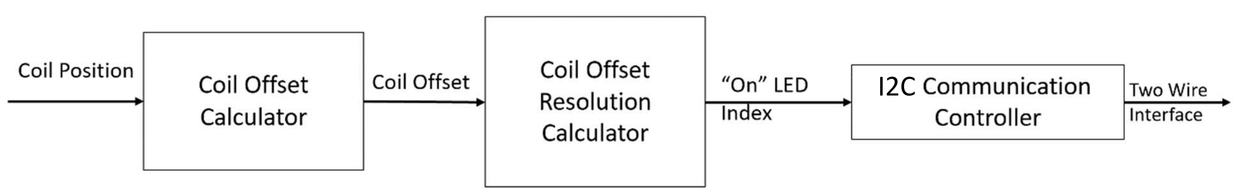


Figure 8: Level 2 functional decomposition focusing on the LED Control Calculation System within the programmable controller

Table 6: Level 2 LED Control Calculator

Module	**Coil Positioning System**
Inputs	• Coil Position in Inches
Outputs	• LED Control over a Two-Wire Interface (TWI) using Inter-Integrated Circuit (I2C) communication protocol
Functionality	Receives the current position of the coil and calculates the distance the coil is away from the ideal storage position (Offset), sending this distance to the LED system to display to the operator. Within the system, the offset is translated into a digital value that represents what LED should be turned "on".

The LED Control Calculator block receives the coil position, which is being passed from the Coil Position Calculator block. The block's purpose is to identify the index of the LED that is supposed to turn "On" according to the current coil position value. The Coil Offset is calculated within this block diagram by performing computations on the coil position value to result in the distance away from the current position to the ideal storage position. This coil offset value is then passed to the Coil Offset Resolution calculator which outputs the proper index of the LED to be turned "on." The Coil Offset Resolution calculator can be further studied in its own level 3 functional decomposition below. The LED index is then to be communicated to the LED Control System through a Two Wire Interface (TWI).

5.1.3.3 Level 2 – LED Control System

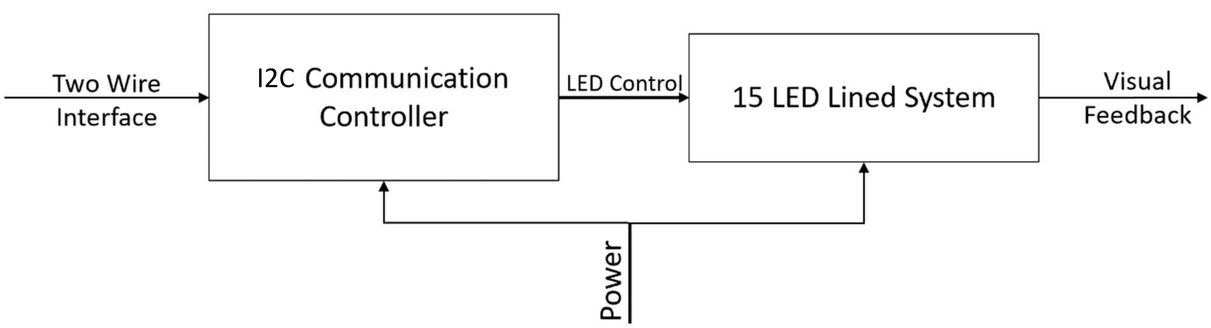


Figure 9: Level 2 functional decomposition focusing on the LED control system that provides the visual feedback to the operator

Table 7: Level 2 LED Control System

Module	**Coil Positioning System**
Inputs	• Power • TWI using I2C for LED Control
Outputs	• Visual Feedback
Functionality	Receives information from the TWI that represent the value of LED that should be turned "On." The system interprets this input and enables the power to the specified LED to provide appropriate visual feedback.

The level 2 functional decomposition for the LED control system in Figure 9 represents the hardware connections and communications between the lightbar and microcontroller. The communication controller receives and interprets information gathered from the sensor measurements through the 2-wire interface that determines the LED that should be on. This information is then sent to the 15 LED Lined System through the LED control line which controls the power and data of the individual LEDs. The individual LED is then turned on or off based on the data received, which results in the proper LED visual feedback for the crane operator.

5.1.4 Level 3 – Coil Offset Resolution Calculator

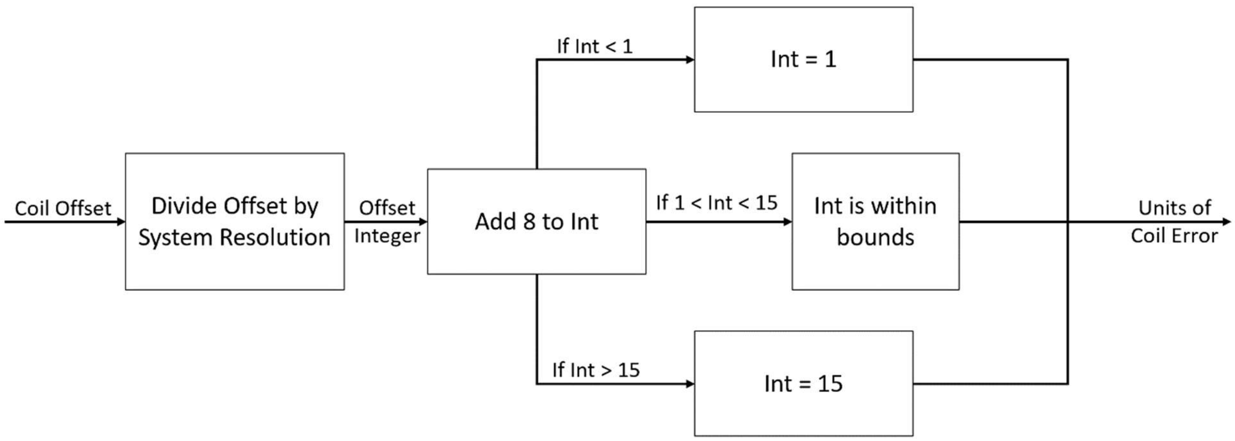


Figure 10: Level 3 functional decomposition focusing directly on the software that calculates the coil offset digital value that is sent to the LED control system

Table 8: Level 3 Coil Offset Resolution Calculator

Module	**Coil Positioning System**
Inputs	• Coil Offset
Outputs	• Digital value of LED to turn on
Functionality	The system receives the offset value and divides it by the resolution of the system, resulting in an integer value. This value has the integer 8 added to it, since LED 8 will be the center of the visual feedback system when using 15 LEDs. The bounds of the output are set to 1 and 15 using logic on the value of Int, which is then sent to the 4-bit encoder.

The level 3 functional decomposition seen in Figure 10 represents the software that will determine the index of the LED to turn on within the LED LightBar. The block will divide the current offset value by the resolution of the LED LightBar (Distance represented by each LED) and add the integer 8 to the resulting integer. Since the LED LightBar will be able to display both positive and negative offset values, the center LED (index 8) will represent zero offset distance, hence why the integer 8 is added to the offset integer. An LED will always be on, and therefore bounds must be placed on the index values. If the offset integer plus 8 is greater than 15, then the index of 15 is passed to the LED LightBar. Respectively, if the integer plus 8 is less than 1, then the index of 1 is passed to the LED LightBar. If the index is between the bounds of 1 and 15, then the index is passed freely.

5.2 System Design

5.2.1 Simulation Design

While the system is intended to be applied to the industrial cranes at Logan Aluminum, our team does not have direct access to those cranes throughout the semester, and therefore a workaround must be created for testing purposes. Our team has designed and constructed a simulation system such that we can test a scaled model of our design before finalizing and suggesting implementation on the industrial crane at Logan Aluminum. Our simulation consists of coil storage racks made out of a shoe rack with thicken bezzles, a wooden rail system to act as the crane support system which also keeps the crane in proper orientation to the racks, and a constructed crane cab. A diagram of the simulation can be further studied below in Figure 11. In term of electronics, the simulation will function the same way as if implemented on the real crane system, which will allow us to test the electronics and verify their usage before implementing on the Logan Aluminum crane system.

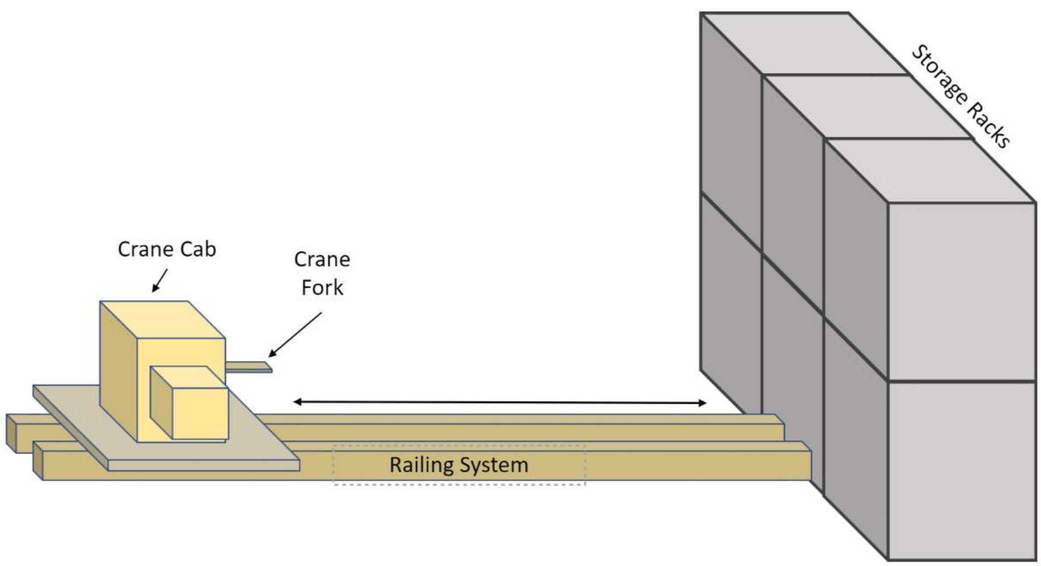


Figure 11: The Figure above shows a diagram of our constructed simulation design. The simulation is constructed of three basic components: The Crane cab which simulates the crane and portion that holds the coil, the storage racks where the coil is to be placed, and the railing system which simulates the ceiling supports of the crane that keeps it in orientation. A cab platform was also constructed to allow for access to the second level of storage racks.

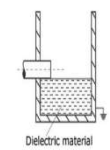
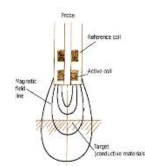
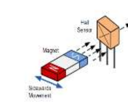
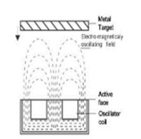
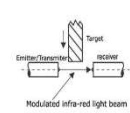
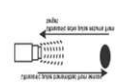
5.2.2 Sleeve Position Sensor System

5.2.2.1 LiDAR Sensor for Distance Detection

Detecting the distance between the crane and the leading edge of the steel sleeve of the aluminum coil is necessary for a successful system design. The sensors need to be able to measure the distance from the sleeve to then compare it to the distance of the rack and calculate the distance between the current coil position and ideal storage position on the rack. A proximity sensor will be used to measure this distance. Researching all the different technologies available for proximity sensors is crucial since different technologies have different ranges.

Proximity sensors detect objects up to a certain range depending on their technology. Once the object enters the sensor's maximum range, and is on the line of detection, the sensor will start sending a signal with the distance of the object. It is important to note that different proximity sensors can detect different types of targets depending on the technology of the sensor. These targets can vary in material, size, surface, and rate of speed, so a look at all these variables when choosing our sensor for the sleeve is imperative. Below, Table 9 shows the different technologies available for proximity sensors.

Table 9: Sensor Technologies for Distance Detection [4]

Type	Description	Range	Target	Speed	Applications	Image
Capacitive	Constructed with two parallel plates as an open capacitor; targets induce changes in capacitance.	3-60 mm	Non-ferrous materials	Relatively slow	Close-range, non-ferrous sensing; tank liquid level detection, sight glass monitoring.	
Eddy Current	Similar to inductive sensors; could be considered high-end inductive types.	Relatively short	Ferrous and non-ferrous materials	Average	Precision, high-resolution sensing in contaminated environments.	
Hall Effect/Magnetic	Measures the presence or absence of object based on an external magnetic field.	4-40 mm	Ferromagnetic	High	Measurement of fast rotational velocity.	
Inductive	Involve a wound iron core; coil inductance changes with presence of object within sensing range.	4-40 mm	Ferrous materials	Average	Close-range detection of ferrous materials; hazardous environments.	
Photoelectric	Use laser emitters and reflectors or receivers; targets cut off or reflect emissions.	Multiple Meters	Many types including metals	Average	Long-range detection of small or large objects; automatic faucets, color-dependent sensing.	
Ultrasonic	Similar to photoelectric types but use sound waves instead of visible emissions.	Multiple Meters	Many types including metals	Relatively high	Long-range detection of multi-colored objects	
LiDAR	Illuminates the target with laser and records the time it takes for the reflection to return to the sensor.	Multiple Meters	Many types including metals	Average	Long-range detection of multi-colored objects with varying surface properties.	

There are a few constraints imposed by the project that are considered when searching for the optimal sensor. The sensor must detect the closer edge of the sleeve from the crane which is about 1.5inches thick. The material of the sleeves is metal, so the sensor must work with this material. Also, a minimum sensing range of 6 inches (152.4mm) is needed.

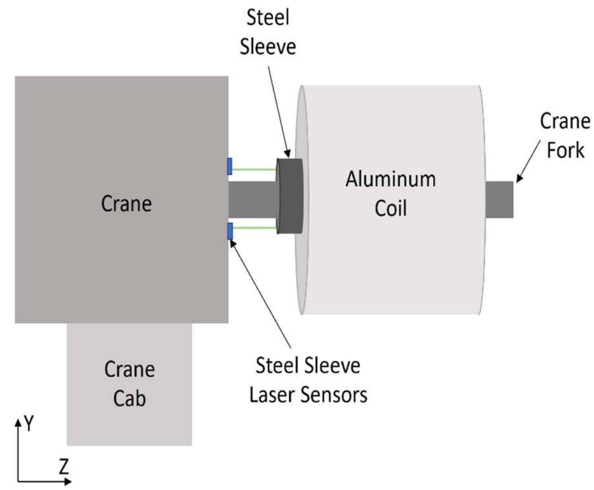


Figure 12: Sensor Positioning on the Crane

Considering most of the sensing technologies have a relatively short range, it has been concluded that ultrasonic, photoelectric, and Light Detection and Ranging (LiDAR) sensor technologies are the best choice for this portion of the project. These sensors have a higher range giving confidence that the sensor will always be able to reach the sleeve at any point during the picking up and lowering of the sleeve. All the other sensors have a maximum range of 40mm which is not sufficient to sense the sleeve, even if the operators slide the sleeve all the way onto the arm. Furthermore, these sensors need to work with metals, which is the material of the sleeve.

Ultrasonic sensors send out waves to pick up the target's distance. These waves go in multiple directions causing the sensor to pick up multiple targets at a time. That could cause a problem considering the only intended target for this portion of the project is the edge of the steel sleeve. It would be difficult to pinpoint only the steel sleeve using this type of technology. On the other hand, the photoelectric and LiDAR sensors send out a laser that pinpoints a specific point making them the more reliable choice for this part of the project. The facts presented here have led to the conclusion that the optimal sensing technologies that must be used are LiDAR or photoelectric (laser) sensors.

Figure 13: Adafruit VL53L0X Distance Sensor

LiDAR technology measures distances using infrared light or lasers then measures the amount of reflection to determine the distance. LiDAR has many distinct advantages over traditional sensors which is why we gave it serious thought as a potential design. LiDAR technology can measure distances at high accuracy in a variety of ranges, with more advanced LiDAR being able to detect distances at a range of up to 570 meters with millimeter precision[6]. LiDAR has a fast-updating rate meaning it can obtain measurements in close to real time. This was an important feature as the crane sways slightly as it moves the coil onto the rack so real time updating of measurements would be useful. LIDAR also remains accurate in environments with non-extreme levels of ambient light, as it does use lasers or infrared light to detect distances. this was also useful in our consideration as parts of the factory are dimmer than others and no areas of the factory are overly light.

After reviewing the constraints of the project and the different proximity sensor technologies, we chosen Adafruit VL54L0X Distance Sensor. This sensor fits the needs of the project because it can detect metals in a range from 60mm up to 5m. This sensor also provides reliable tolerances for accurate measurements to use in the coil positioning computation.

5.2.2.2 Sleeve Sensor Validation Test

The purpose of this test is to verify engineering requirement number 1, 3, 5, and 11. These requirements consists of making sure the sensor is safely and properly placed on the crane and making sure it withstands high amounts of vibration. This test will also ensure that the sensor accurately measures the distance from the cab to the steel sleeve edge with a maximum tolerance of 0.1 inches.

<u>Test Materials:</u>

1.) Adafruit VL53L0X Time of Flight Distance Sensor
2.) Arduino Leonardo
3.) Arduino code
4.) Computer with Arduino IDE and USB communication capabilities
5.) USB-A to USB-B Micro cable
6.) Crane cab simulator box

<u>Test Methods:</u>

1.) Measure and mark distances of 24’’, 12’’, and 6’’ away from a flat surface
2.) Wire the sensor to the Arduino as shown in Figure 14
3.) Place sensor on the crane cab simulator box on a smooth surface at the marked distance of 24” from the reference surface
4.) Record ten sensor measurements
5.) Add vibration to the sensor and record distance measured by the sensor again
6.) Move sensor to a distance of 12” from the reference surface
7.) Repeat steps 4 and 5
8.) Move sensor to a distance of 6” from the reference surface
9.) Repeat steps 4 and 5.
10.) Perform statistical analysis on the 10 measured values for each distance to verify the tolerances and guarantee a quality product. Find the average of the 10 values at each distance and subtract from the actual physical distance to find error.

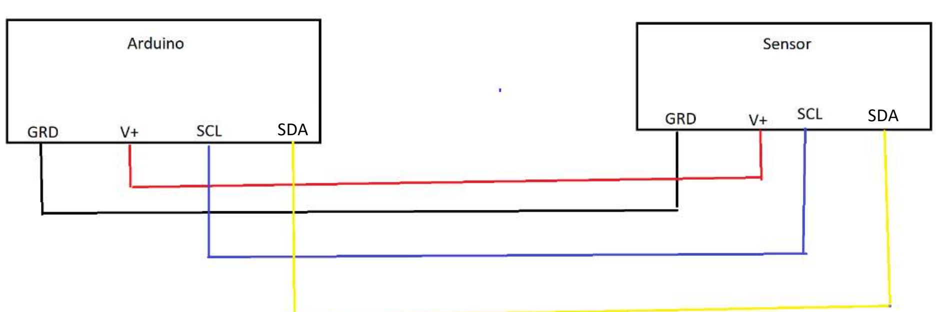


Figure 14: Test Wiring Diagram

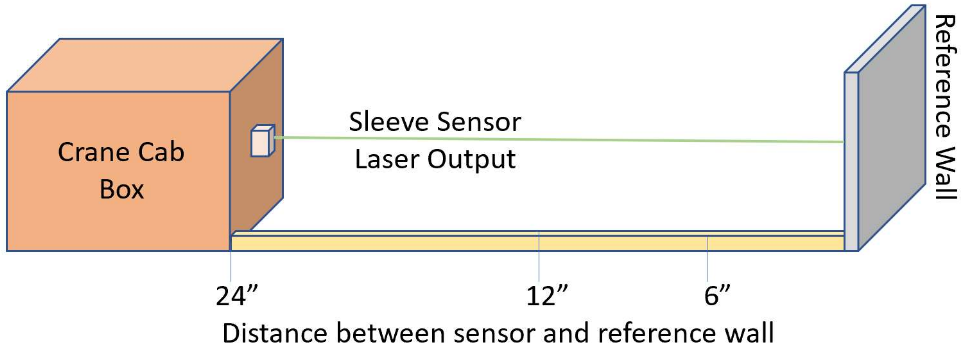


Figure 15: Sleeve Sensor Test Setup

Results:

Table 10: Results from Sleeve Sensor Testing at 5.8” Distance

Trial #	Recorded distance	Recorded distance with vibration
1	5.64	5.68
2	5.84	5.72
3	5.72	5.76
4	5.68	5.68
5	5.72	5.76
6	5.68	5.72
7	5.72	5.72
8	5.72	5.64
9	5.64	5.76
10	5.72	5.76

Statistics – Without Vibration

Average = 5.71''

Range = 0.2''

Error = 5.71-.5.8 = 0.09’’

With Vibration

Average = 5.72''

Range = 0.08

Error= 5.72-5.8 = 0.08’’

Table 11: Results from Sleeve Sensor Testing at 12” Distance

Trial #	Recorded distance	Recorded distance with vibration
1	11.84	12.04
2	11.96	11.96
3	11.96	11.88

4	11.92	11.84
5	12.08	11.96
6	12.00	11.92
7	11.92	11.92
8	11.92	11.88
9	11.92	11.92
10	11.88	12.00

<u>Statistics – Without Vibration</u>
Average = 11.95''
Range = 0.2''
Error = 0.05’’
<u>With Vibration</u>
Average = 11.932''
Range = 0.2
Error = 0.068’’

Table 12: Results from Sleeve Sensor Testing at 24” Distance

Trial #	Recorded distance	Recorded distance with vibration
1	22.80	22.80
2	22.80	22.96
3	22.72	22.52
4	22.68	22.64
5	22.68	22.88
6	22.48	22.88
7	22.72	22.6
8	23.12	22.64
9	22.76	22.80
10	22.8	22.60

<u>Statistics – Without Vibration</u>
Average = 22.75''
Range = 0.64''
Error = 1.25’’

<u>With Vibration</u>
Average = 22.732''
Range = 0.36”
Error = 1.268”

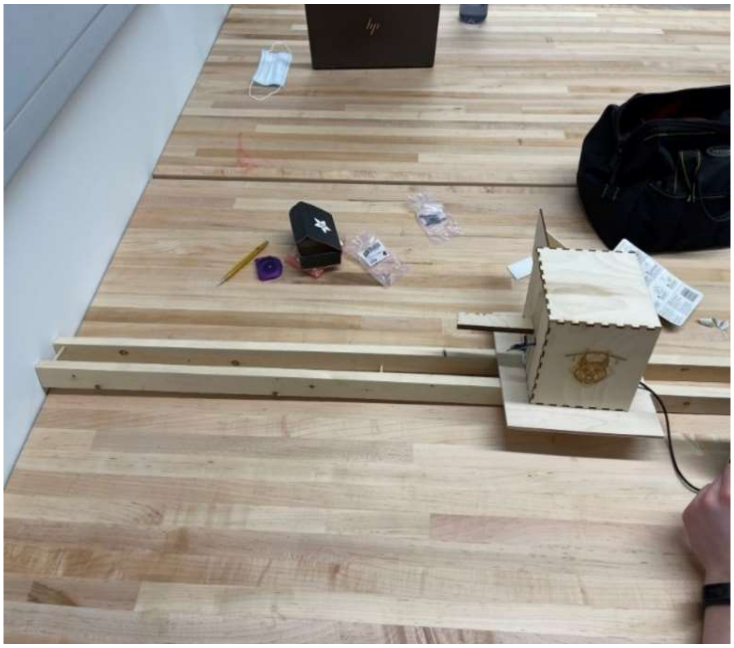


Figure 16: Sensor Test Set up

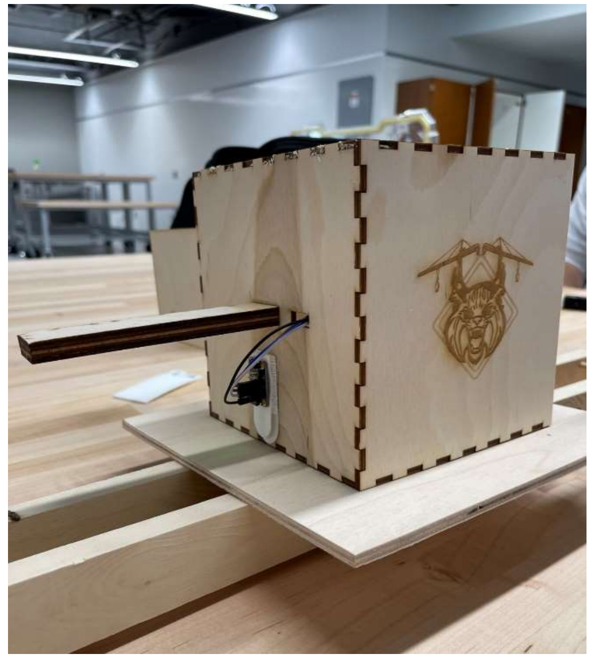


Figure 17: Sensor Test Cab

The test results reveal that the chosen sensor is reliable at a closer ranger with an error of 0.1 inches. It has also been concluded through the test that vibrations will not drastically affect the accuracy of the sensor since there is minimal difference between the vibration and no vibration test results. The ranges tested confirm that this sensor will work efficiently on our simulation, however, if we were to implement our system with actual cranes at Logan Aluminum, we would use the Garmin LIDAR sensor used for the rack sensing system. This sensor is the same technology with similar specs, but it has higher accuracy for longer distances.

5.2.3 Rack Position Sensor System

5.2.3.1 Photoelectric Sensor for Rack Position

The rack position sensor plays a crucial part of our goal of placing the coil with precise measurement in its correct location. To do this we will require sensors to measure the distance between a point from the crane to a point of the rack. This distance will be an ever-changing distance as the crane moves the coil closer which will require a loop of measuring until the placement is complete. The distance of the coil on the fork has been found and is now a fixed distance. We can then calculate the where the center of the coil is because the coil sleeve (which is an edge we are detecting is the sleeve measurement) is a set length of 7’ 2”. Finally, with the distance from the edge of the sleeve to the sleeve sensor, added with half the length of the coil we can subtract that off the distance the sensor is away from the rack bars, added with the fixed distance that each outer facing of the rack bars are away from our center point, sweet spot is on the inside of the rack.

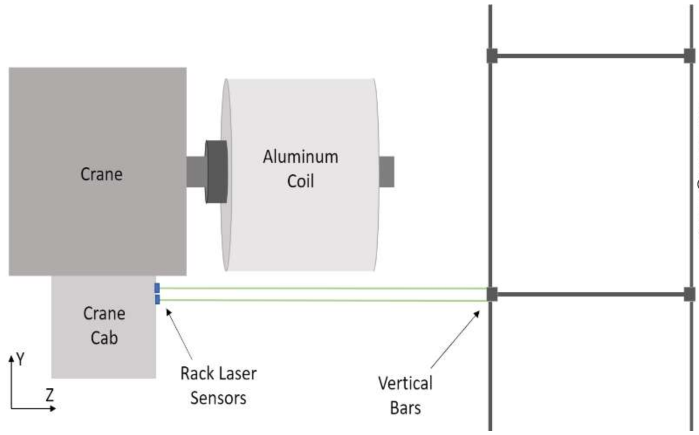


Figure 18: A diagram showing the functional design of the rack sensor in terms of our entire system design.

When it came to choosing the sensor for this portion of the project, we started our search on Allen-Bradley's website Rockwell Automation. After looking through multiple sensors we realized the multitude of sensors with varying specific uses making it difficult to pinpoint a sensor that would fill the need to detect the bars of the rack at such a long distance with accuracy. We came to ultrasonic sensors because they had a maximum distance of at least a meter, where the other sensors had distances of just a few millimeters. When discussing our project with Rockwell Tech specialist he suggested that an ultrasonic sensor would create more problems when it came to sensing the racks as the ultrasonic sensor would be emitting a wave that would be detecting much more things than the rack, possibly even the current coil on the fork. He noted that ultrasonic sensors were mainly used for tanks with liquid instead of what we were planning to use it for. This took ultrasonic sensors out of the question. He then recommended three other sensors of the same type which were photoelectric sensors. These sensors relied on a laser light that would detect the distance of whatever they are specifically pointing. The prices of these Rockwell sensors were a bit out of our budget range, but now that we had an idea of what type of sensor we needed, we found the Garmin LiDAR-Lite Optical Distance LED Sensor - V4 which had a maximum sensing range of 10 meters. In high accuracy mode, the distance is decreased to 1 meter, but we would get more accurate readings of +/- 1 cm. Though the sensor has LiDAR in the name, it is still a photoelectric sensor as it does not use a laser for measuring distance.

Placement of these sensors required some work around as we know the crane is constantly moving 3-dimensionally and we would like our rack detecting sensor to always be looking at a bar of the rack no matter how high or low, or offset to the right or left the crane is from the rack when placing the coil. We also need the sensor to be lined up with a bar of the rack no matter how close it gets to the rack to not worry about any angles being involved in the measurement. We decided that we could mount the sensors on the left side of the crane with an offset of 2 inches from each other horizontally. The reason for this decision is the bars of the rack being about 3 inches in width and we see that the crane operators can get the center of the coil lined up horizontally centered with the rack ±2 inches. This would allow us to gain to sensor measurements of the rack, where one of the sensors will be used in the case that the operators are not completely centered and off by a small margin. Both sensor measurements will be taken, and we will use the smaller value out of the two sensors because in the usual case that one of the sensors is off the bar off the rack it would be sensing something behind the bars giving a longer distance measurement which can be not used. We also will be using background suppression on these sensors which will allow us to adjust the maximum distance that these sensors will detect.

5.2.3.2 Sensor Selection

Table 13: Rack Position Sensor Selection

Technology	Advantages	Disadvantages
Photo Electric Sensor	- Good maximum sensing distance. - Works with metal materials	- Requires accurate placements of the sensors for good reading.
Ultrasonic Sensor	- Good maximum sensing distance. -Works with metal materials.	- Sends out a wave that would pick up multiple objects.
Camera Optical Sensor	- Real-Time visual feedback -Accurate distance measurement	- Difficult to create controller software for camera - More expensive
LiDAR Sensor	- Most Accurate Distance Detection - Useful in any amount of lighting	- Most expensive option - Overkill for distance measurements we need

5.2.3.3 Camera Optical Sensor Design Alternative

As an alternative to the photoelectric sensor for determining rack position, we considered using a camera with a built-in optical sensor. A camera optical sensor uses transmission and reflection of light to detect distance. Using a camera had a few advantages over the photoelectric sensor that caused us to consider implementing it into our design. By using a camera our design would provide real time video feedback to the operator. With real time video feedback, the operator would not only get feedback from our LED feedback system but also confirmation through video that the coil was correctly placed onto the rack. The optical sensor is also very accurate when there is an appropriate amount of light and can precisely detect distances down to millimeters.

However, with the camera optical sensor we found some issues that led us to choose the photoelectric sensor. The camera optical sensor is more expensive than the photelectric sensor, the extra expense would cause us to reduce our budget for other parts of the design. As mentioned, the camera optical sensor also requires an appropriate amount of light to function properly, since the Logan Aluminum factory has inconsistent lighting it could present problems with measurement accuracy if we used a camera. Overall, we found that while the camera presented some unique features that would enhance our design, the risks associated with the accuracy and the extra cost led us to choose against the implementation of a camera.

5.2.3.4 Measuring Sensors Size Testing Procedure

This test procedure is to verify Engineering Requirement 4, which is that each of our sensor subsystems are to fit within a 6 cubic inch area. This includes associated wiring, the sensors, and mounting brackets.

Test Materials:

1. (2) Garmin LIDAR-Lite Optical Distance LED Sensor - V4
2. (2) Adafruit VL53L0X Time of Flight Distance Sensor
3. Sensor wiring
4. Rack Sensor Mounting Brackets
5. Sleeve Sensor Mounting Brackets
6. Measuring tape
7. Crane cab simulator box

Test Methods:

1. Obtain measurements of each of the sensors by either measuring by hand or using data sheets.
2. Place sensors, associated wires, and mounting brackets in different configurations on the Crane cab simulator box.
3. Make sure each sensor is not being obstructed by the configuration (i.e., wires or brackets blocking the sensor.)
4. Measure dimensions of each subsystem configuration.
5. If the configuration is <6 cubic inches, test procedure is complete, and ER 4 is verified.

Results:

All four sensors and mounting materials were able to be placed within the crane cab box, which is a 6" cube. We can then verify that the entire electronics subassembly consumes less than 6 cubic inches of space and satisfy engineering requirement 4.

Table 14: Results from measuring sensor sizes

All items in Subsystem	**Total Size(LxWxH)**	**ER 4 Satisfied?**
Arduino Leonardo, associated wires.	(68.6 x 53.3 x 10.2) mm	Yes
X2 Garmin LIDAR – Lite V4 LED Sensor, associated wires.	(52.2 x 48 x 21.2) mm	Yes
Adafruit VL53L0X Time of Flight Sensor, associated wires.	(26.1 x 20 x 5.3) mm	Yes

5.2.3.5 Rack Sensor Test Procedure

This test procedure is to verify Engineering Requirement 3, 5, and 12. Which are: Electronics shall be able to withstand high amounts of vibration, Electronics shall be mounted solidly on crane, and Sensor shall detect distance between rack edge and sensor within .2", respectively. The main objective of this test procedure is to get accurate readings from our rack sensors under regular conditions as well as adding vibration to mimic vibration of the crane.

Test Materials

1. Garmin LIDAR-Lite Optical Distance LED Sensor - V4
2. Arduino Leonardo
3. Arduino code

4. Computer with Arduino IDE and USB communication capabilities
5. USB-A to USB-B Micro cable
6. Crane cab simulator box

Test Methods:

1. Place crane cab simulator box on rail system facing a flat surface(wall).
2. Measure out a total distance parallel with rail system of 1 meter with marks at 750cm, 500cm, 250cm, 100cm, 75cm, 50cm, and 25cm.
3. Place Garmin LIDAR-Lite Optical Distance LED Sensor - V4 on the crane cab simulator box.
4. Wire Garmin LIDAR-Lite Optical Distance LED Sensor - V4 to Arduino.
5. Starting at any marked distance, take 10 measurements, record measurements.
6. Add vibration to crane cab simulator box and take another 10 measurements and record them.
7. Perform Step 5 and 6 at each marked distance.
8. Analyze all results, perform any necessary tweaks to the system, and rerun tests until all ER Requirements are verified.

Results:

We tested 25cm, 50cm, 75cm, and 100cm to get an idea of the accuracy and any offsets we might need to apply to our final code. Our results can be seen below in Table 14. Each distance produced a very precise frame of distances, most of which were at or around the true distance. At 50 cm, the sensor recorded distances that were slightly off, but this may also be attributed to human error when measuring out the true physical distance. The overall accuracy of the sensor is satisfactory and falls within our design constraints.

Table 15: The below data represents the resulting distance recorded by the Garmin Lidar Lite sensor throughout the sensor's testing procedure

Trial #	25cm	50cm	75cm	100cm
1	26cm	48cm	75cm	100cm
2	25cm	48cm	75cm	100cm
3	26cm	49cm	75cm	100cm
4	25cm	48cm	76cm	101cm
5	25cm	48cm	76cm	101cm
6	25cm	48cm	76cm	100cm
7	25cm	48cm	75cm	100cm
8	26cm	49cm	75cm	101cm
9	25cm	49cm	75cm	100cm
10	25cm	49cm	75cm	100cm

5.2.4 Operator Feedback System

5.2.4.1 Operator Feedback System

The design of the feedback system consists of an LED light strip and plastic encasing to encompass the LED lightbar. This lightbar will be mounted inside the crane cab for ease of use and to provide the best user experience for the crane operator. The LED light strip will be powered and programmed by an external Arduino microcontroller through Inter-Integrated Circuit (I2C) communication. This microcontroller will receive power from the Allen Bradley PLC in the crane cab. The entire feedback system will be located inside the crane cab but will receive communication from the sensors through the Arduino microcontroller. The initial design of the Lightbar feedback system is shown in Figure 19 below.

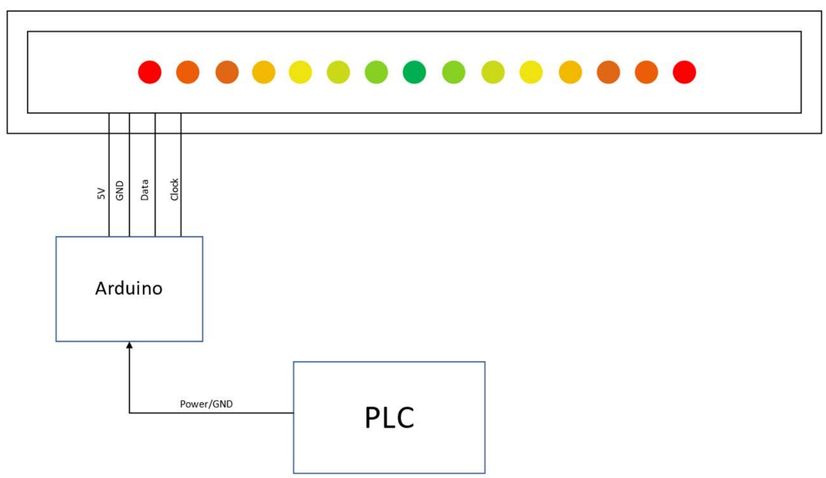


Figure 19: Design of LED Feedback system

The LED strip consists of 15 individually programmable RGB LEDs. The individual LEDs on the strip will turn on and off as the crane operator moves the steel sleeve into place. Which LED is on is determined by calculations from the sensors and then programmed by the Arduino microcontroller. The LEDs on the outside edges of the strip will be red to signal that the sleeve is not in the expected rack position. The LEDs will turn from red on the outside edges to yellow and green for the LEDs in the middle of the strip to show the crane operator how close the steel sleeve is to the ideal position. The green LED in the very middle of the strip will represent perfect positioning on the rack within our tolerance range. The total tolerance range for the lightbar is +/- 5.6 inches from the ideal position. The exact middle LED representing 0.0 inches while each subsequent LED will represent a range of 0.8 inches. The LED that is on will switch as the crane operator changes the position of the coil by more than 0.8 inches within the tolerance range The overall intent is for the operator to find the location where the middle LED is on so that the steel sleeve is placed in a good position on the rack.

The LED light strip chosen for the design was the Adafruit DotStar RGB LED Strip with 60 LEDs per meter. The layout of the light strip consists of LEDs that can be powered as a strip but are individually programmable, the layout is seen in Figure 20 referenced in the datasheet.

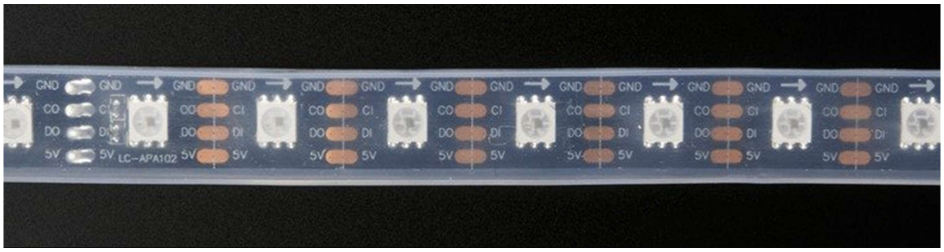


Figure 20: Layout of the Adafruit RGB LED strip consisting of a flexible strip with 60 LEDs per meter

The Adafruit DotStars were selected for the design due to distinct advantages it had over other programmable light strips. The first advantage is the Adafruit strip is easily programmable through an Arduino. There are pre-programmed Arduino libraries for the Adafruit DotStars making it easy to program the light strip to our design needs. The DotStars also have a fast-updating rate; according to the data specifications the strip has a frequency of 8 Mhz and a 20 kHz PWM rate making it useful for quickly updating the LEDs in the strip as the operator moves the coil into place on the rack. This fast clock rate will allow us to update the feedback system every 10ms which fulfills engineering requirement 14. Another advantage of the Adafruit DotStars light strip is each individual LED can handle 24-bit color data so we can easily customize colors to provide the best user experience for the crane operator.

The LED strip will be powered by the Arduino, with an output voltage of 5V. Based on the DotStar Data Sheet it is recommended to use no more than 2 dozen DotStars if you are powering it through a microcontroller. This is good for our case since our design is using 15 LEDs and only one will be on at a time. The maximum current draw for each LED at full brightness is 60 milliamps. For the 15 LED strip the max current draw would be 0.9 amps. Using 5 Volts to power the LED strip the maximum power output from the Arduino would be 4.5 Watts. However, the typical power output during operation would be for only one LED on, which would be 0.3 Watts. The maximum power consumption is within our design limits, and power consumption from the Feedback System will be tested and verified.

5.2.4.2 Feedback System Communication Test

This test is written to verify correct communication between the Arduino Leonardo and the Adafruit Lightbar. To verify communication a procedure is written involving a standard 4 wire interface and test code. Upon completion of the test correct communication can be verified or determination of incorrect communication can be concluded. This test satisfies engineering requirement 6.

<u>Test Materials</u>

1. Arduino Leonardo
2. Adafruit Lightbar
3. USB to micro-USB cable
4. USB device with Arduino IDE and power capability

<u>Test Procedure</u>

1. Connect Arduino to Adafruit Lightbar using 4 pin connection
    - 5V Power (Arduino) to Lightbar Power Pin
    - SCL (Arduino) to Lightbar Clock Pin
    - SDA (Arduino) to Lightbar Data Pin
    - GND (Arduino) to Lightbar Ground Pin

2. Initialize Arduino Test Code and Load to the lightbar. Setup lightbar communication and Define 15 LEDs using code shown below

```
#include <Adafruit_DotStar.h>
#include <SPI.h>

#define NUMPIXELS 15 // Number of LEDs in strip
#define DATAPIN 4
#define CLOCKPIN 5
Adafruit_DotStar strip(NUMPIXELS, DATAPIN, CLOCKPIN, DOTSTAR_BRG); //defines DotStar Strip

uint32_t ledColor;

void setup() {
 // put your setup code here, to run once:
 strip.Begin(); //Begins port communication with LED LightBar
 strip.show(); //Initializes all LEDs to "off"
 int coilOffset = 1;
}
```

3. Test communication between Arduino and Individual LEDs using test loop that turns on individual LEDs

```
void loop() {

delay(1000);

switch(count) { //Sets certain LEDs to certain colors
    case 1:
    case 2:
    case 14:
    case 15:
     ledColor = strip.color(255,0,0); //LEDs 1,2,14,15 are Red
     break;
    case 3:
    case 4:
    case 12:
    case 13:
     ledColor = strip.color(255,165,0); //LEDs 3,4,12,13 are Orange
     break;
    case 5:
    case 6:
    case 7:
    case 9:
    case 11:
    case 10:
     ledColor = strip.color(255,255,0); //LEDs 5,6,7,9,10,11 are Yellow
     break;
```

```
    case 8:
      ledColor = strip.color(0,255,0); //LED 8 is Green
      break;
  }

  strip.clear(); //Turns all LEDs "off"
  strip.setPixelColor(coilOffset, ledColor); //Sets LED[coilOffset] to the specified color
  strip.show(); //Pushes set colors onto LED strip

  count = count + 1; //counts through LEDs
  if(count > 15){ //If you reach the 15th LED cycle back to 1st LED
    count = 1;
  }
}
```

4. Verify communication is correct by physically verifying the LEDs cycle through a loop and are the correct color based on the case statements. If this is successful the test procedure for Lightbar Communication can be graded as PASS
    - LEDs 1,2,14,15 – RED
    - LEDs 2,4,12,13 – ORANGE
    - LEDs 5, 6, 7, 9, 10, 11 – YELLOW
    - LED 8 - GREEN

Results

By performing this test, we verified the successful communication between the Arduino Leonardo and the Adafruit Lightbar. We connected the Arduino and Lightbar hardware as described in step one and programmed the Arduino to run the test code provided in the procedure. We verified successful communication by physically examining the lightbar output at described in step four. By verifying successful communication at the subsystem level, the lightbar can be integrated into the main system.

5.2.4.3 Feedback System Integration Test

This test procedure is written to verify the integration of the LED Lightbar into the full system. This test will verify that the Lightbar correctly outputs visual feedback based on the sensor readings. This test involves physically moving the prototype crane cab system across 19 increments to determine if the Lightbar output is correct as the coil moves in and out of the rack system. This test satisfies engineering requirements 6, 14 and 15.

Test Materials

1. Fully Wired and Connected System (Sensor Systems, Power Systems, Lightbar System)
2. Arduino Leonardo
3. Adafruit Lightbar
4. Prototype Crane Cab for Testing
5. Prototype Rack System for Testing

Test Procedure

1. Wire the entire system including each subsystem based on the wiring diagram shown.

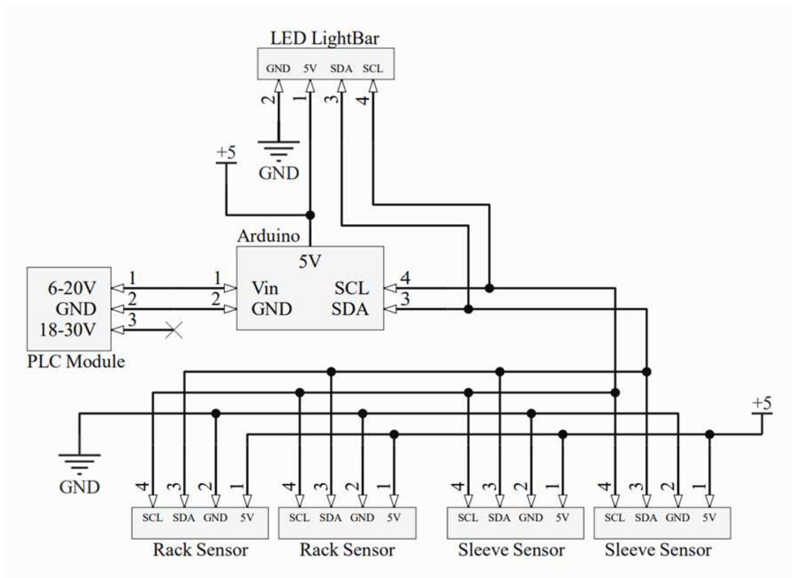


Figure 21: Full System Wiring Diagram

2. Physically set the prototype crane cab in a position where the sensors read approximately -7.2 inches away from the ideal coil location (7.2 inches not far enough into the rack). A tolerance of +/- 0.1 inches is suitable for this test.
3. Verify the sensor readings to the Arduino are accurate to ensure proper data is sent to the lightbar.
4. Move the prototype crane cab in increments of approximately 0.8 inches from -7.2 inches to 7.2 inches. Check the output of the lightbar at each increment as well as during the movement between the increments, there should be 19 total readings.
5. The expected reading at each increment is as follows:
   - Increment 1: **-7.2 inches = Only LED 1 ON (RED)**
   - Increment 2: **-6.4 inches = Only LED 1 ON (RED)**
   - Increment 3: **-5.6 inches = Only LED 1 ON (RED)**
   - Increment 4: **-4.8 inches = Only LED 2 ON (RED)**
   - Increment 5: **-4.0 inches = Only LED 3 ON (ORANGE)**
   - Increment 6: **-3.2 inches = Only LED 4 ON (ORANGE)**
   - Increment 7: **-2.4 inches = Only LED 5 ON (YELLOW)**
   - Increment 8: **-1.6 inches = Only LED 6 ON (YELLOW)**
   - Increment 9: **-0.8 inches = Only LED 7 ON (YELLOW)**
   - Increment 10: **+0.0 inches = Only LED 8 ON (GREEN)**
   - Increment 11: **+0.8 inches = Only LED 9 ON (YELLOW)**
   - Increment 12: **+1.6 inches = Only LED 10 ON (YELLOW)**
   - Increment 13: **+2.4 inches = Only LED 11 ON (YELLOW)**
   - Increment 14: **+3.2 inches = Only LED 12 ON (ORANGE)**
   - Increment 15: **+4.0 inches = Only LED 13 ON (ORANGE)**
   - Increment 16: **+4.8 inches = Only LED 14 ON (RED)**
   - Increment 17: **+5.6 inches = Only LED 15 ON (RED)**
   - Increment 18: **+6.4 inches = Only LED 15 ON (RED)**

- Increment 19: **+7.2 inches = Only LED 15 ON (RED)**

6. If the readings at each increment are correct the Lightbar Integration can be considered successful.

This test will be performed when the full system assembly is complete. Successful completion of this test will verify that the feedback system is accurate and useful to the crane operator. It ensures that the integration of the lightbar into the full system is successful and verifies that the lightbar exhibits the same properties within the full system as it did in the individual subsystem.

<u>Results</u>

Table 16: Feedback System Integration Test Results

Recorded Distance From Target (Inches)	Expected LED Index	Recorded LED Index
-7.2	1	1
-6.4	1	1
-5.6	1	1
-4.8	2	2
-4.0	3	3
-3.2	4	4
-2.4	5	5
-1.6	6	6
-0.8	7	7
0	8	8
0.8	9	9
1.6	10	10
2.4	11	11
3.2	12	12
4.0	13	13
4.8	14	14
5.6	15	15
6.4	15	15
7.2	15	15

Based on our results it is evident that the Feedback System Integration Test was successful. All recorded indexes matched the expected indexes as described in the test procedure. These results verify that the LED Lightbar works as intended when integrated into the full system. These results verify engineering requirement 6 stating there shall be visual feedback for the operator detailing coil location, engineering requirement 14 stating visual feedback shall be easily interpreted and updated in less than 50ms, and engineering requirement 15 stating visual feedback system shall operate in a range of +/- 5.6 inches.

5.2.5 System Hardware Interface

For the positioning system to function, the appropriate hardware connections must exist to provide power to the separate components as well as allowing them to communicate with each other to transmit information to the crane operator. This involves utilizing a controller to process input signals from the sensors, determine the position of the steel sleeve, and communicate this to the LED feedback system. To accomplish this, two primary options were investigated, namely the Allen-Bradley PLC module on board the crane and an Arduino Uno microcontroller. A diagram of the Allen-Bradley PLC output is shown in Figure 22 below.

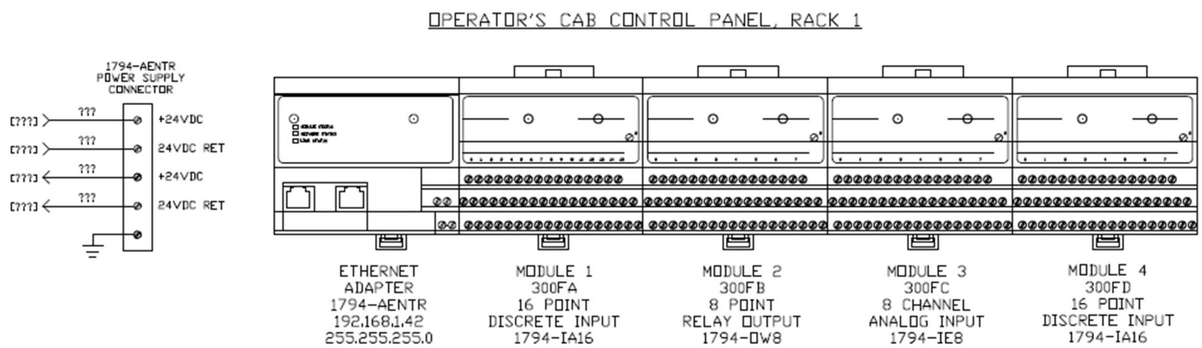


Figure 22: Allen-Bradley PLC Wiring Output

Due to its simpler hardware and more familiar software design, we opted to use an Arduino Leonardo for our controller and communication interface. A diagram of the Arduino Leonardo pinout is shown in Figure 23.

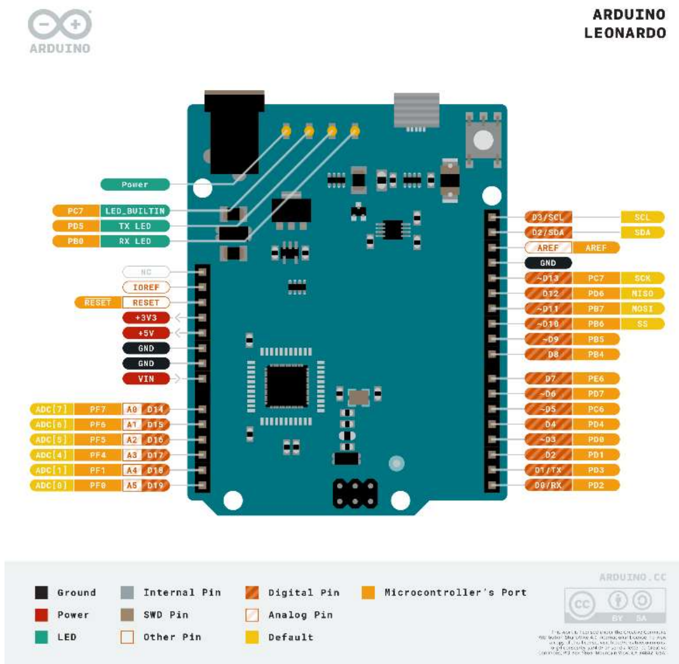


Figure 23: Arduino Leonardo Pinout [7]

We will still use the Allen-Bradley PLC to provide DC voltage to the Arduino and the sensor subsystems. The PLC has 2 channels providing up to 30V of DC output. The Arduino requires 7-12V of DC input and both sensors require 5V of input voltage. The schematic for the overall system is shown in Figure 21.

5.2.5.1 Hardware Connection and Stability Testing

This test procedure is written to verify the crane PLC can provide sufficient power for the system. The Crane PLC can provide a range of DC Voltage from 6V to 20V. This test procedure will verify that the PLC can provide stable power to all sub systems. The maximum voltage input we will test is 9 volts as that is the maximum recommended voltage input to the Arduino Leonardo according to the specification sheet. The procedure will also find the minimum voltage needed to provide stable power to the system, in the case that an alternate power supply to the PLC is used. This test satisfies engineering requirement 16.

<u>Test Materials</u>

1. DC Power Supply
2. Oscilloscope
3. Arduino Leonardo
4. Adafruit Lightbar
5. Rack Sensors
6. Sleeve Sensors

<u>Test Procedure</u>

1. Wire the power and ground pins of each individual component (arduino, lightbar, sensors) in parallel connected to a single channel of the DC Power Supply
2. Initially set the output voltage of the power supply to 4V

3. Use the oscilloscope to verify if all device power connections (voltage and current) are correct and stable according to each individual specification sheet
4. Adjust the voltage between a range of 4 – 9 volts in steps of 1 volt
5. Repeat step 3 until a minimum voltage that provides sufficient power is found
6. Verify that the minimum voltage found has repeatable results by performing step 3 multiple times
7. If the minimum voltage has repeatable results then that is concluded as the minimum DC voltage needed to power the entire system. If there are not repeatable results then continue performing steps 4 and 5 until a minimum voltage is found.

This test will be performed once the main system assembly is completed. By verifying the system power stability through an external DC Voltage source we can successfully wire and integrate our system with the Allen Bradley PLC located inside the crane cab.

Results

Table 17: Power Testing Results

Voltage (V)	Current (A)	Max Power Consumption
4.0	0.14	0.56 W
5.0	0.17	0.85 W
6.0	0.2	1.2 W
7.0	0.2	1.4 W
8.0	0.2	1.6 W
9.0	0.2	1.8 W

The goal of this test was to find the minimum voltage that could provide stable power to the system. Based on Table 17 we found the minimum voltage required was 6 Volts. This was determined through physical inspection of our system, all devices powered on and behaved as specified in our design once the threshold of 6 Volts was reached. Below 6 Volts the system did not behave as intended and the current output was not sufficient to correctly power the system. The current needed to run our full system was determined to be 0.2 Amps. Once this current input is reached the Arduino automatically limits the current input to prevent over current from occurring. Based on the results we can successfully power our system with a minimum of 6 Volts and maximum of 9 Volts. This verifies that the Allen Bradley PLC can power our system and verifies that we can implement a 9 Volt battery to power our prototype and simulation. This test successfully verified engineering requirement 16 which states system shall be powered by the PLC power output.

5.2.6 System Software and Data Flow

5.2.6.1 Software Solution

The software included in our system design is essential to the functionality of the system, encompassing the analysis and utilization of the sensors' readings as well as providing a corresponding output signal to the operator feedback system. The software is responsible for receiving information from our sensors and supplying a signal to the LED Feedback system according to the current position of the coil with respect to the ideal storage position on the storage rack. As seen in many of the functional decomposition diagrams, systems of calculations embody a significant portion of the system's purpose. Table 18 below displays all the calculations necessary of the software along with their purpose and preceding calculations. The calculations are labeled in the order of operations. Figure 24 below displays a visual of the calculations seen in Table 18.

Table 18: A collection and description of each calculation required by the software system

Calculation	Purpose	Preceding
1- Sleeve Measurement Calculation	Receives signal input from Rack sensors and calculates the corresponding distance measured- Calculation will be characteristic to the sensors we use	-
2- Rack Measurement Calculation	Receives signal input from Sleeve sensors and calculates the corresponding distance measured - Calculation will be characteristic to the sensors we use	-
3- Coil Distance Calculation	Receives Sleeve and Rack distance measurements and calculates the distance from the outside edge of the steel sleeve to the outside edge of the rack	1,2
4- Coil Offset Calculation	Receives the Coil Distance and calculates the distance away from the ideal coil placement position - Calculation will be dependent on mounting of sensors	3
5- Coil Offset Resolution Calculation	Receives Coil Offset and divides this by the resolution of our feedback system - This calculates the number of standard units that the coil is away from the ideal position	4
6- Encoding of Coil Offset	Receives the Coil Offset resolution calculation and encodes the measurement into a TWI to transmit to the LED Feedback system	5

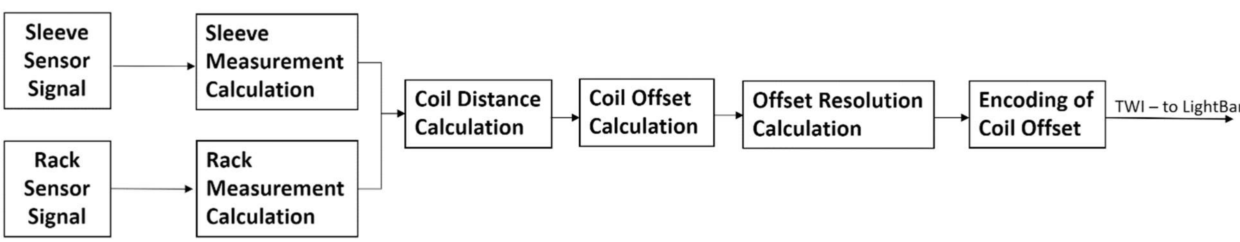


Figure 24: Data Flow Diagram for Software

The first two calculations depend on the sensor selected, as the mathematics required to convert the signal from the sensor to a usable value will be characteristic of the sensor selected. In calculating the coil offset distance, many factors will be involved total offset calculated. These factors include the mount positioning of both sensor systems and the ideal positioning of the coil on the rack. Currently, the ideal placement of the coil is when the outside edge of the steel sleeve is 2 inches in front of the outside edge of the rack, therefor the simplest form of the calculation is the distance from the rack minus the distance of the sleeve. The Coil Offset Resolution calculation also is dependent on the number of LEDs used in the operator feedback and the amount of distance that each LED represents. The calculation will include limits on the offset calculated based on the resolution value and the number of LEDS so that at least a single LED will always be activated.

5.2.6.2 Software Implementation Options

Two options of software implementations were discussed for use on this project: a microcontroller (Arduino) or a programmable logic controller (Allen-Bradley PLC). While both implementations offered ample functionality to our system, both brought specific benefits and challenges to the project which can be seen in Table 19 below. Our decision ultimately weighted on the ability to integrate well with the currently selected LED LightBar design, and therefore, the use of the microcontroller matched the needs of our project more due to its current software tools created for use with the LED LightBar. The software design will be moving forward with the implementation of an Arduino Leonardo Microcontroller which can be seen in Figure 25.

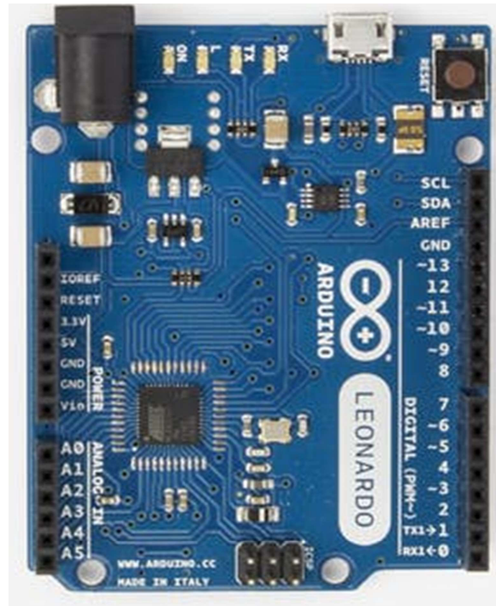


Figure 25: An Arduino Leonardo, the microcontroller selected to perform calculations and control our system in our design.

Table 19: Deciding factors for implementation of Software tools

Implementation Options		
	PLC	Microcontroller
Benefits	• Already installed on all cranes (Cheaper for multiple installations) • Recommended by Logan Aluminum	• Experienced with microcontroller programming • Easier access for testing and software development • Easy integration of I2C communication for integration of multiple sensors
Challenges	• Difficult to access programming Software • Little to no access to PLC for testing • Limited prior experience with PLC • Possible inability for fast communicate with multiple sensors over I2C	• More difficult to install on cranes • Need to design around Factory Conditions

5.2.6.3 System Communication Testing

To verify that all slave devices have a stable channel of communication with the host device through the TWI which communicates via I2C protocol, the measurements from the sensors will be taken while varying a target for individual sensors. If a varying distance is seen in relation to the varying distance of the physical target through only the proper sensor while all other sensor measurements remain stable,

stable channels of communication between the slaves and hosts have been established. No results for this testing procedure have been collected to date. This test verifies Engineering Requirements: 8

Test Materials:

1. Complete Electronics System of the Crane Positioning System

   Includes:

   i. 2 Sleeve Sensors
   ii. 2 Rack Sensors
   iii. LED LightBar
   iv. Arduino Leonardo
   v. Proper Electrical Connections$_1$
2. Crane Cab Encasement
3. Variable Physical Target (A hand will be sufficient)
4. Computer with Arduino IDE
5. Modified System Arduino Code
   a. Modifications to the code are shown at the end of the testing protocol
6. USB-A to USB-B micro cable
7. Flat Surfaced Wall
8. Imperial Measuring Tool of 2 foot minimum

Test Methods:

1. Load Modified Arduino Code [5] into Arduino IDE on Computer [4]
2. Connect the USB-A male connecter [6] into the appropriate computer port [4]
3. Connect the USB-B Micro head [6] into the appropriate port of the Arduino within the Crane System [1]
4. Ensure that the Electronics System [1] is properly attached and/or encased within the Crane Cab Encasement [2]
5. Verify the Program within the Arduino IDE by pressing the Check Mark button at the top left of the Arduino Window
6. Within the Arduino IDE, upload the Modified Arduino Code [5] onto the Crane System Arduino by pressing the Arrow button at the top left of the Arduino Window
7. Open the Serial Monitor within the Arduino IDE
   a. Tools -> Serial Monitor
   b. From here you will see a continuous printing in the serial monitor of the 4 sensor readings and the LED Lightbar output signal. You can see an example below:

```
------------------------------
Sleeve Sensor 1: 34.43"
Sleeve Sensor 2: 34.43"
Rack Sensor 1: 34.43"
Rack Sensor 2: 34.43"
```

Lightbar Index Output: 5
----

8. Use the Imperial Measuring tool [8] to mark 2' away from the flat surfaced wall [7]
9. Place the Crane Cab Encasement [2] with the laser edge flush on the 2' marking
10. Record an output reading for each of the slave devices
11. Use the Imperial Measuring tool [8] to mark 1' away from the flat surfaced wall [7]
12. Place the Variable Physical Target [3] on the 1' marking in front of Sleeve Sensor 1
13. Repeat Step 10
14. Repeat Steps 12 and 13 varying the sensor that the Variable Physical Target is in front of by the following order:
    a. Sleeve Sensor 2
    b. Rack Sensor 1
    c. Rack Sensor 2
15. Move the entire Crane Cab Encasement [2] to the 1' mark, ensuring to keep the sensor side flush towards the wall [7]
16. Repeat Step 10

<u>Arduino Code Modifications:</u>

Added to the Setup():
Serial.begin(9600);

Added to the bottom of the loop() function:
Serial.print("----------------------------\n ");
Serial.println("Sleeve Sensor 1: " + sleeveSensor_1_distance + " inches");
Serial.println("Sleeve Sensor 2: " + sleeveSensor_2_distance + " inches");
Serial.println("Rack Sensor 1: " + rackSensor_1_distance + " inches");
Serial.println("Rack Sensor 1: " + rackSensor_2_distance + " inches");
Serial.println("Lightbar Index Output: " + lightbar_Output);

<u>Results:</u>

The appropriate sensors record movement in the output while the other sensors remain a stable output. This shows that each sensor has a proper channel of communication with the master device and our system meets the engineering requirement. The recorded results can be seen below in Table 20, which lead us to our verification of our system meeting engineering requirement 8.

Table 20: The results from the system communication testing protocol

Moving Sleeve Sensor		
Before:	1st	2nd
Sleeve	4	4.1
Rack	72	72
After		
Sleeve	11.3	11.2
Rack	71	72

Moving Rack Sensors		
Before:	1st	2nd
Sleeve	11.3	11.2
Rack	71	72
After		
Sleeve	11.4	11.3
Rack	43	43

5.2.6.4 System Update Time

To verify the 50ms maximum update timing requirement of the system, a test to measure and compute an average update time must be conducted. The following methods will be followed to complete the testing and verify that we meet or do not meet the requirement of a maximum of 50ms system update time. This testing procedure verifies Engineering Requirements: 14

Test Materials:

1) Completed and Up-to-date Crane Sensing system[1]
2) Modified Arduino Code
    (a) Modifications to code are described below the test methods
3) Computer with Arduino IDE and USB communication capabilities
4) USB-A to USB-B Micro cable

Test Methods:
Items from above list will be referenced in the test methods through brackets. (Example: Item 1 will be references by the following [1])

1. Load Modified Arduino Code [2] into Arduino IDE on Computer [3]
2. Connect the USB-A male connecter [4] into the appropriate computer port [3]
3. Connect the USB-B Micro head [4] into the appropriate port of the Arduino within the Crane System [1]
4. Verify the Program within the Arduino IDE by pressing the Check Mark button at the top left of the Arduino Window
5. Within the Arduino IDE, upload the Modified Arduino Code [2] onto the Crane System Arduino by pressing the Arrow button at the top left of the Arduino Window
6. Open the Serial Monitor within the Arduino IDE
    a. Tools -> Serial Monitor
7. Record 100 measurements from the Serial Monitor into an excel document
8. Calculate the average of the 100 measurements

Arduino Code Modifications:

Added to the Setup():
Serial.begin(9600);

Added to the top of the loop() function:
initTime = millis();

Added to the bottom of the loop() function:
endTime = millis();
Serial.print("Measured Time: ");
Serial.println(endTime - initTime);

Results:

Table 21: The results from the loop time testing protocol above showing the loop time per run for 10 separate measured loops

Trial	Time (ms)
1	45
2	46
3	48
4	43
5	44
6	45
7	47
8	46
9	46
10	44

The data points received from the above testing procedure are displayed in Table 21 above. All of the recorded timings were below the required maximum time of 50 ms, and the average loop time was 45.4 ms. The software to record this time also included sending and receiving information through serial communication to the computer, which added significant delay to the loop timing. With the average falling comfortably below the maximum time listed in the engineering requirement, even with a delay for serial communication added on, we are confident in verifying that our system meets engineering requirement 14.

6.0 Project Plan

6.1 Implementation Plan and Reflection

While our project has been completed and proved successful, we still have challenges that lay in the future implementation. While our sleeve sensor was substantial for our model design, it h proved that it does not have the specifications needed to create a functioning and reliable system within a factory setting. This was confirmed through the sleeve sensor testing results at longer distances. Through this, we are able to suggest moving forward with implementation of the system using the rack sensors for both the sleeve and rack sensors. The rack sensor was able to prove itself as substantial for the rack sensing, and therefore will also work for the sleeve sensing. The remaining system presented itself as a reliable and functioning system worth implementing in a factory setting to meet the marketing requirements set by us and Logan Aluminum.

Along with the system, we have also created an infographic to supply to Logan Aluminum to display the proper use of the system. This will allow for easy understanding of the visible feedback to the operator to help eliminate the confusion associated with implementing new systems within industry. This infographic can be seen below in Figure 26.

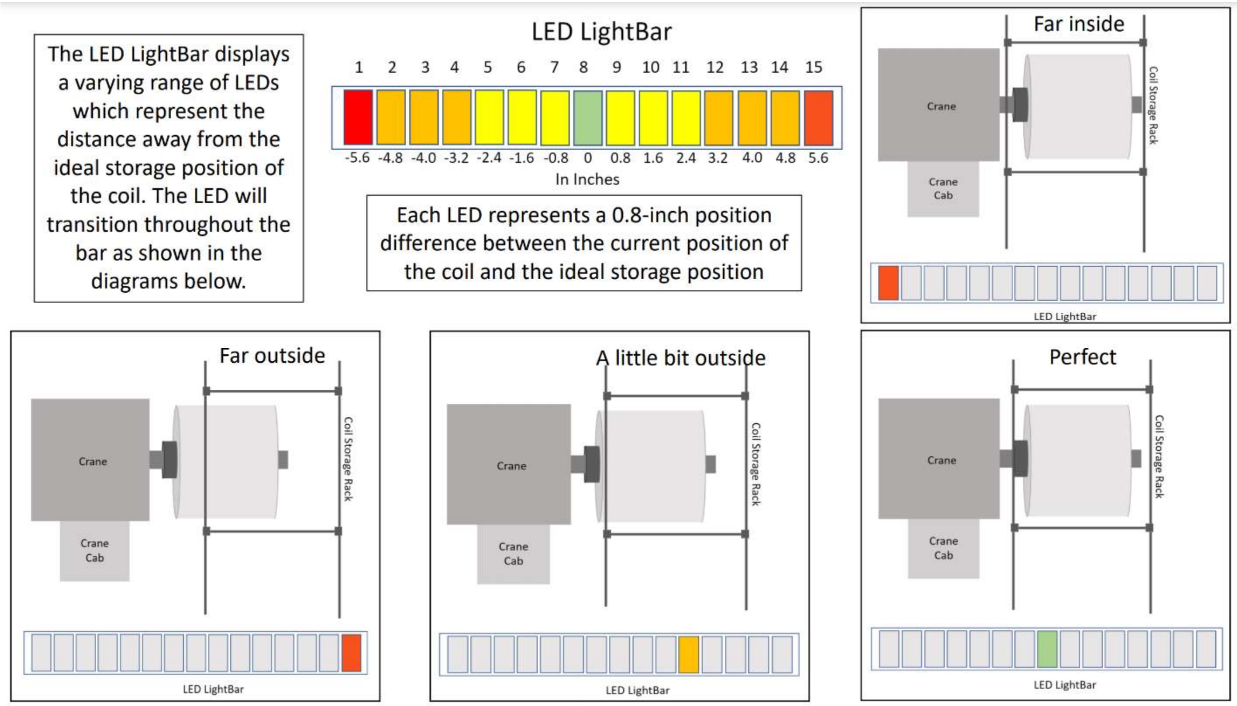


Figure 26: An infographic associated with our system. This may be distributed with our system to the crane operators for easier understanding of the visual feedback that our system produces.

The project has taught us a lot throughout the past two semesters. Reflecting on the past will often show you where you could have done better, and therefore, where your weaknesses lie. In our outcome, we saw that we had a short coming with one of our sensors, something we believe could have been easily avoided with earlier testing of the sensors. Thinking back, we delayed the ordering and testing of the sensors way too far, and are very lucky that one of the two sensors were substantial for our system. If we were to do the project again, we would jump on the sensors as fast as possible to ensure that the sensors were able to provide good measurements for out system.

6.2 Work Breakdown Structure (WBS)

The team has worked together to create a work breakdown structure of the remainder of the project. The WBS displays each measurable task in order, or milestone, that needs to be completed for the overall project to be successful. Each task is listed along with a description of the task, what needs to be completed/delivered by the task, the approximated time to complete the task, and resources assigned to each task including both team members and physical supplies. Not every category is assigned for each task since not every task has a deliverable or specific resources. Preceding tasks are also displayed to both help with the critical timeline displayed in the Gantt Chart and also ensure we are only beginning tasks that we are ready to. The estimated duration of each task was decided upon by the team by averaging an optimistic timeframe and a pessimistic timeframe for each task.

Table 22: A table displaying the tasks associated with the successful completion of the project

WBS	Task Name	Duration	Predecessors	Start	Finish
1	**Agree on Selected Electronics**	**20 days**		**Tue 10/13/20**	**Mon 11/9/20**
1.1	Select Sleeve Sensors	2 days		Tue 10/13/20	Wed 10/14/20
1.2	Select Rack Sensors	2 days		Tue 10/13/20	Wed 10/14/20
1.3	Select LEDs for Lightbar	2 days		Tue 10/13/20	Wed 10/14/20
1.4	Select Decoder for Lightbar	2 days	4	Thu 10/15/20	Fri 10/16/20
1.5	PDR Draft and Presentation	2 days		Tue 10/13/20	Wed 10/14/20
1.6	PDR Final Report	4 days	6	Wed 11/4/20	Mon 11/9/20
2.0	**Integrate Sensors into Design**	**28 days**		**Thu 10/15/20**	**Mon 11/23/20**
2.1	**Design Rack Sensor Positioning**	**10 days**		**Tue 11/10/20**	**Mon 11/23/20**
2.1.1	Design Rack Sensor positioning for Inside Rack	5 days	3,7	Tue 11/10/20	Mon 11/16/20
2.1.2	Design Rack Sensor positioning for Outside Rack	5 days	3,10	Tue 11/17/20	Mon 11/23/20

2.2	Design Sleeve Sensor Positioning	5 days	2	Thu 10/15/20	Wed 10/21/20
3.0	**Software Integration**	**130 days**		**Tue 10/13/20**	**Mon 4/12/21**
3.1	**Design Program for PLC**	**26 days**		**Mon 10/19/20**	**Mon 11/23/20**
3.1.1	Create program to receive and intepret Sensor Signal	10 days	2,3,7	Tue 11/10/20	Mon 11/23/20
3.1.2	Create program to transmit signal to Lightbar	5 days	5	Mon 10/19/20	Fri 10/23/20
3.2	**Design LED Lightbar System**	**130 days**		**Tue 10/13/20**	**Mon 4/12/21**
3.2.1	Design LED lightbar Mounting	5 days	4,5,7	Tue 11/10/20	Mon 11/16/20
3.2.2	Design system to control LED On/Off according to Signal	5 days	5,15,16	Tue 11/24/20	Mon 11/30/20
3.3	Individual Design Report	10 days	7	Tue 11/10/20	Mon 11/23/20
3.4	Design Poster	2 days	20	Tue 11/24/20	Wed 11/25/20
0.0	Winter Break	70 days		Tue 10/13/20	Mon 1/18/21
4.0	**Contruct Simulation**	**22 days**	22	**Tue 1/19/21**	**Wed 2/17/21**
4.1	Order Parts for Simulation	3 days	22	Tue 1/19/21	Thu 1/21/21
4.2	**Construct Crane System**	**8 days**		**Fri 1/22/21**	**Tue 2/2/21**
4.2.1	Construct the rail system	8 days	24	**Fri 1/22/21**	**Tue 2/2/21**
4.2.2	Construct Crane Cab Platform	1 day	24	Fri 1/22/21	Fri 1/22/21
4.2.3	Design Crane Cab Encasement	1 day		Fri 1/22/21	Fri 1/22/21

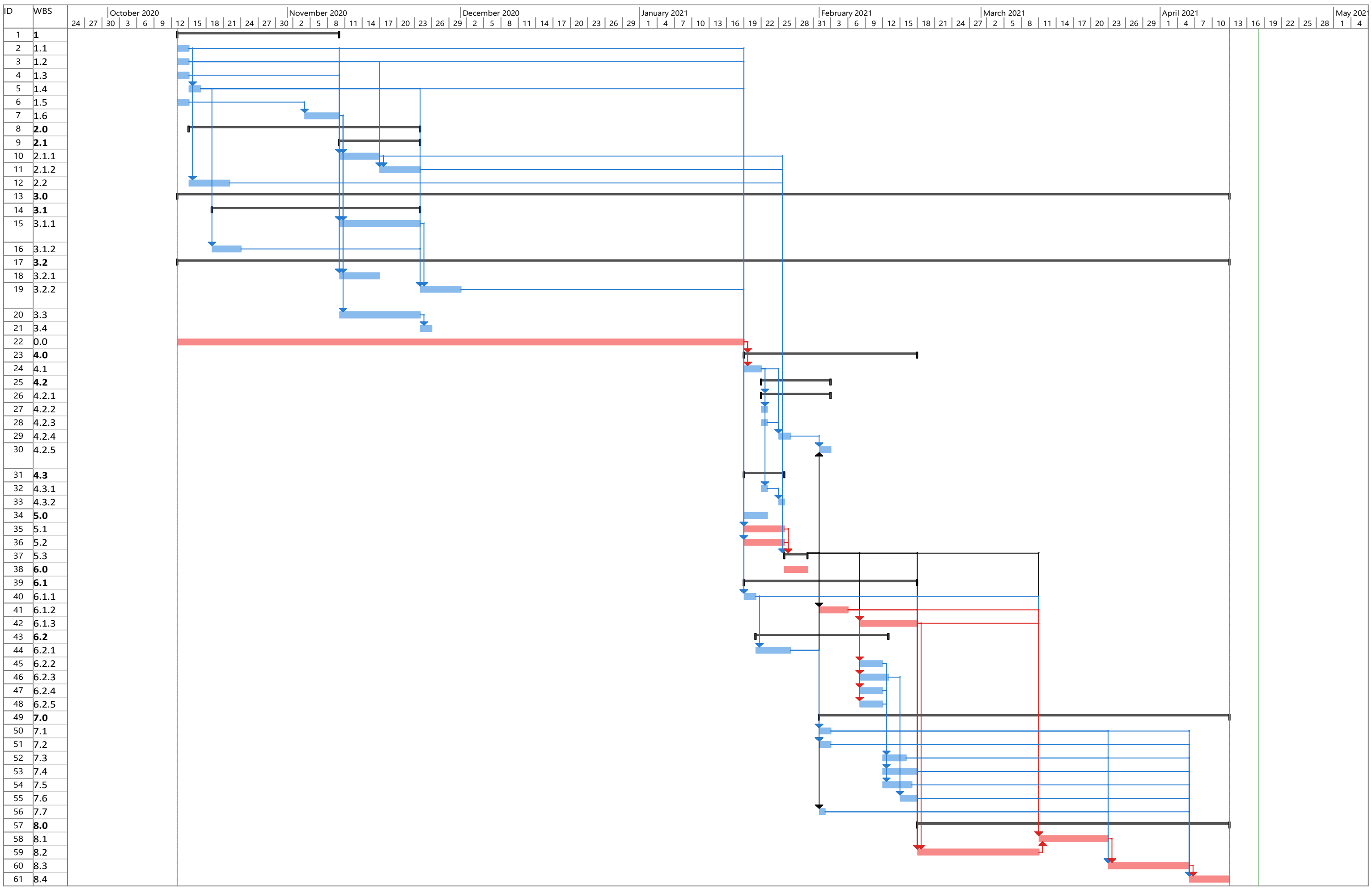
4.2.4	Assembly Crane Cab Encasement	2 days	24,28	Mon 1/25/21	Tue 1/26/21
4.2.5	Mount Electronic Assembly to Crane System	2 days	29,37	Mon 2/1/21	Tue 2/2/21
4.3	**Construct Rack System**	**5 days**		**Tue 1/19/21**	**Mon 1/25/21**
4.3.1	Cut Foamboard to dimension	1 day	24	Fri 1/22/21	Fri 1/22/21
4.3.2	Adhere Foambaord to Shoe Shelf	1 day	32	Mon 1/25/21	Mon 1/25/21
5.0	**Assemble Electronic System**	**4 days**		Tue 1/19/21	Fri 1/22/21
5.1	Order Sleeve Sensors	5 days	2	Tue 1/19/21	Mon 1/25/21
5.2	Order Rack Sensors	5 days	3	Tue 1/19/21	Mon 1/25/21
5.3	Establish electronic connections	4 days	10,11,12,35,36	**Tue 1/26/21**	**Fri 1/29/21**
6.0	**Complete Software Designs**	**4 days**		Tue 1/26/21	Fri 1/29/21
6.1	**Complete System Software**	**22 days**		**Tue 1/19/21**	**Wed 2/17/21**
6.1.1	Create Software for LightBar	2 days	5,19	Tue 1/19/21	Wed 1/20/21
6.1.2	Software for Sleeve Sensors	5 days	37	Mon 2/1/21	Fri 2/5/21
6.1.3	Software for Rack Sensor	8 days	37,41	Mon 2/8/21	Wed 2/17/21
6.2	**Software for Testing Protocols**	**17 days**		**Thu 1/21/21**	**Fri 2/12/21**
6.2.1	Software for LightBar testing	4 days	40	Thu 1/21/21	Tue 1/26/21
6.2.2	Software for Sensor accuracy testing	4 days	41	Mon 2/8/21	Thu 2/11/21

6.2.3	Software for sensor accuracy testing	5 days	41	Mon 2/8/21	Fri 2/12/21
6.2.4	Software for System Communication	4 days	41	Mon 2/8/21	Thu 2/11/21
6.2.5	Software for System Speed	4 days	41	Mon 2/8/21	Thu 2/11/21
7.0	**Testing**	**51 days**		**Mon 2/1/21**	**Mon 4/12/21**
7.1	LightBar Functionality	2 days	44,37	Mon 2/1/21	Tue 2/2/21
7.2	LightBar Distance	2 days	44,37	Mon 2/1/21	Tue 2/2/21
7.3	System Speed	2 days	48	Fri 2/12/21	Mon 2/15/21
7.4	System Communication	4 days	47	Fri 2/12/21	Wed 2/17/21
7.5	Sleeve Sensor Accuracy	3 days	45	Fri 2/12/21	Tue 2/16/21
7.6	Rack Sensor Accuracy	3 days	46	Mon 2/15/21	Wed 2/17/21
7.7	Sensor Size	1 day	37	Mon 2/1/21	Mon 2/1/21
8.0	**Present Project**	38 days		**Thu 2/18/21**	**Mon 4/12/21**
8.1	Raw Video Draft of Project	8 days	37,40,41,42,59	Thu 3/11/21	Mon 3/22/21
8.2	Final Prototype	15 days	37,40,41,42	Thu 2/18/21	Wed 3/10/21
8.3	Final Presentation	10 days	58,50,51,52,53,54,55,56	Tue 3/23/21	Mon 4/5/21
8.4	Final Report	5 days	60,50,51,52,53,54,55,56	Tue 4/6/21	Mon 4/12/21

6.3 Gantt Chart

The Gantt Chart seen below in Figure 27 represents the timeline we are expecting on our project broken up into the individual tasks displayed in the WBS shown in Table 22. The tasks displayed in a red are deemed as the critical path, and therefore these tasks should be a priority to complete on time in order to complete the project in the timeframe that we have planned. (The Gantt Chart would not fit in a single photo so it is separated into three sections. The section's calendars do not line up)

Figure 27: Gantt Chart representing the timeframe of tasks required for the timely success of our project



6.4 Cost Analysis

Table 23: A complete overview of the incorporated cost within each component of our project

Device	Manufacturer	Number	Cost per Piece	Total Cost of Items
Adafruit VL53L0X (Sleeve)	Adafruit	2	$ 14.95	$ 29.90
Garmin LIDAR-Lite	Garmin	2	$ 59.95	$ 119.90
Sleeve Sensor Mounting Bracket	Granger	2	$ 22.02	$ 44.04
Programmable Lightbar	Adafruit	1	$ 29.95	$ 29.95
Wires	Adafruit	1	$ 29.99	$ 29.99
Steel Conduit	AFC Cable Systems	1	$ 29.95	$ 29.95
Steel Epoxy	JB Weld	1	$ 6.95	$ 6.95
Arduino Leonardo	Ardiuno	1	$ 19.95	$ 19.95
Cost of System Assembly				$ 310.63
1"x 2"x 8' Pine Plank	Home Depot	2	$ 3.28	$ 6.56
3/16" x 2' Wooden Dowel	Home Depot	1	$ 0.76	$ 0.76
Elmer's Wood Glue (16 oz)	Elmer's	1	$ 6.89	$ 6.89
1lb of 3" Wood Screws	Home Depot	1	$ 4.59	$ 4.59
48" x 36" Foam Board	Staples	1	$ 12.89	$ 12.89
4 sq. Feet 1/4" Plywood	UK Innocation Center	1	$ 4.00	$ 4.00
Cost of Simulation Assembly				$ 35.69
			Total Cost	$ 346.32
			W/Tax	$ 367.10

7.0 References

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8.0 Appendix

To generate the objective tree presented earlier, three broader project goals were identified, namely Design, Interface, and Practicality. The goal of Design refers to the primary functioning of the device; Interface to the need for the device to properly communicate with the crane and its operator; and Practicality to the need for an affordable, flexible and realistic solution. Each goal was compared with the others individually and assigned a weight specifying the relative importance of the goal, with numbers less than, equal, and greater than 1 representing lesser, equal and greater importance, respectively. This is shown below in Table A.1. It was determined that Design and Interface were equally important, and slightly more so than Practicality, as the first priority for the project must be conceiving a system that can functionally solve the problem by obtaining correct information and relaying it to a crane operator. Only then can the system be realized in an accessible and practical way.

Table 1: AHP of Project Goals

Crane Positioning System	Design	Interface	Practicality	Geometric Mean	Weight
Design	1	1	2	1.260	0.400
Interface	1	1	2	1.260	0.400
Practicality	1/2	1/2	1	0.630	0.200

To further analyze the components of the project, the nine marketing requirements were sorted between the project goals above. The weighting process was repeated for each to obtain a more substantial hierarchical analysis. For Design, the associated marketing requirements were identified as Reliability (requirement 1), Durability (requirement 2), Small Size (requirement 3), and Accuracy (requirement 9). Table A.2 shows the AHP determined for these. Reliability and Accuracy were chosen as the most important, as the device will be useless if it is unable to provide correct data on a consistent basis. Durability was weighted as the next most important, as a device with poor survivability would present a major inconvenience to crane operators. Small size was weighted least important.

Table A.2: AHP of Design

Design	Reliability	Durability	Accuracy	Small size	Geometric Mean	Weight
Reliability	1	2	1	3	1.565	0.351
Durability	1/2	1	1/2	2	0.841	0.189
Accuracy	1	2	1	3	1.565	0.351
Small size	1/3	1/2	1/3	1	0.485	0.109

Next, for Interface, the necessary marketing requirements were selected as Visual Feedback (requirement 4), Software Integration (requirement 5), and Intuitiveness (requirement 8). Table A.3 previews the weights for these objectives. Software integration was chosen as the most important requirement, as this was a specific preference identified by Logan Aluminum and successful integration will make for a significantly more efficient solution. Visual feedback was selected as the next important, as the device must have some method of communicating with the crane operator to ensure coils are loaded properly. Intuitiveness was weighted least important, as ease-of-use is secondary to producing a functioning device.

Table A.3: AHP of Interface

Interface	Intuitiveness	Visual feedback	Software integration	Geometric Mean	Weights
Intuitiveness	1	1/2	1/3	0.550	0.163
Visual feedback	2	1	1/2	1.000	0.297
Software integration	3	2	1	1.817	0.540

For Practicality, the relevant marketing requirements were Cost (requirement 6) and Versatility (requirement 7). Table A.4 shows the AHP for Practicality. Cost was weighted more important, as a specific budget was provided to fund the project to which the device must adhere.

Table A.4: AHP of Practicality

Practicality	Cost	Versatility	Geometric Mean	Weights
Cost	1	2	1.414	0.667
Versatility	1/2	1	0.707	0.333