Project Title: Sensor System for Cranes
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Acknowledgment
Acknowledgement

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Abstract/Summary
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The Steel Dynamics, Inc. steel mills produce large coils of sheet metal, and they stock their inventory on the floors of storage warehouses. These large coils that weigh 22-ton on average are picked up and placed in an appropriate position by using overhead cranes, often referred to as bridge cranes. These cranes ride the entire length of the warehouse along two parallel rails. A trolley containing a hoist can slide to any point on the bridge, and the hoist then lowers a hook or mechanical claw to pick up or release the desired object. Operators control the crane’s movement via an overhead control cabin or by remote-control from the manufacturing floor. The fact that the cranes are being controlled by human operators allows room for accidents and miscalculations to happen.

The goal of this project is to develop a system to prevent cranes that are on the same rail from colliding. The system will also prevent the operator from causing the load to collide with any of the permanent stationary objects in the warehouse by erecting virtual “walls”, which create restricted areas that the crane cannot access unless manually overridden. A radio-frequency wireless system is desired to detect the location of the trolley of the crane. This system must have a connection to the crane’s drives in order to prevent collisions and to prevent the cranes’ loads from being lost when the cranes are stopped. The system must have a control that can be manually overridden for maintenance on the cranes for any specific operations that would normally be disallowed.
Problem Statement
Problem Statement

We propose to design and implement a control system which will be integrated with industrial cranes via onboard PLCs, with the purpose of monitoring the cranes’ position and motion to prevent collisions. This control system will utilize software, sensors, and RF wireless hardware to detect nearby cranes and stationary objects, and will then interact with the PLCs to preemptively stop collisions without causing the cranes to lose their payload.

For this system to be a success and to ensure the safety of the crane operators, it must meet the conditions below.

Requirements & Specifications

The control system is being developed first and foremost as a safety measure, to protect both the equipment and the human personnel inside the facility. As such, it must meet the following minimum criteria:

- The system needs to be expandable, so that multiple cranes can be set up to use the same system. At minimum, this system must work with four cranes.
- Sensors attached to each crane must detect other nearby cranes and stationary objects. The detection range must be great enough to allow the control system to safely slow and stop the cranes should they get too close to a detected object.
- Virtual ‘walls’ must be implemented in software to prevent cranes from crossing operator-determined boundaries. These walls must be able to be modified as needed by the crane operators.
- The control system needs to communicate with the Programmable Logic Controller (PLC) which is in each crane to control the motion of the cranes.
- Through the PLC, the system must be able to control the motion of the cranes in such a way that the cranes and their payloads can be slowed, stopped, or otherwise moved to prevent collisions.
- By collection information from sensors, the control system must be able to determine when a collision of one crane with another crane, a pilot station housing an operator, or another object in the industrial facility is imminent. The system must then be able to slow, stop, or move the crane to prevent the collision from occurring.
Design Variables
The design variables to be considered in the design of this sensor system are hardware, software, and the operating conditions. “Hardware” includes all the physical components which are part of the system being designed. The “software” refers to the computer programs which will in part govern the control of the operating equipment. “Operating Environment” is the variable aspects of the environment which this system will be used in.

Hardware
- Computer – The computer or microcontroller used for each crane in the system must be able to interface with all of the system’s sensors as well as with the PLCs on each crane.
- Sensors – The sensors which are used by the system for data acquisition must be capable of determining each crane’s position with relation to other cranes and objects in the operating facility.
- Control Interface – An interface and/or controller which allows the enabling and disabling of the system must be included, as well as a method through which virtual boundaries can be set and modified if necessary.
- Communication Channel – Each sensor in the system must be able to communicate fluidly with the proper computer, which must then be able to communicate with the crane it is controlling.

Software
- Data Acquisition – The data which is sent to the computer from the sensors must be gathered and stored for use.
- Data Analysis – Information gathered from the system’s sensors must be analyzed to determine the position and motion of each crane.
- Boundary Implementation – The software will be responsible for providing an interface through which the system operator can create virtual walls, as well as the implementation of these boundaries to restrict the cranes from going past them.
- Collision Prevention – After analyzing data gathered from sensors, the system software will determine if a collision is possible and will determine a way to avoid it.
• PLC Communication – Any communication to the PLC by the computer will be coordinated by the software to ensure that the proper controls are used to limit the motion of cranes in the system.

Operating Environment
• Electromagnetic Interference – The operating facilities make use of equipment which creates a large amount of EM radiation at many different frequencies. Any communication done or sensor detection done by the system cannot impede existing communications or be hindered by them.
• Surrounding equipment – Materials of many types are often moved and left stationary at various points in the facility. The system cannot be hampered by the arbitrary position of materials within the operating environment. These objects may also often be highly reflective, and therefore the sensors and communication done by the system cannot be impeded by the material types.

Project Limitations
The following additional restrictions must be observed in completing this project.
• Cost – the cost of the system cannot exceed the final cap set by Steel Dynamics, Inc.
• Time – A final design must be finalized by December, 2015, and the project must be completed by May, 2016.
Additional Considerations

- Safety – The primary purpose of the system is to ensure the safety of the operators, the cranes, and the materials within the operating environment. The safety of personnel inside the facility must be the absolute priority.

- Reliability – A failure of the system to protect personnel and to otherwise do its designed task could be highly destructive or even fatal. Fail-safes must be included to prevent system breakdown and to alert operators in case of emergency.

- Crane Limitations – Each crane is attached to a bridge which physically cannot pass through the bridges of other cranes. As such, the position of the crane bridges must be one of the main considerations when detecting possible collisions.

- Payload Movement – The improper alteration of a crane’s path could swing its payload into another object or lose it entirely. When the software is determining how to avoid collisions, the payload of each crane must be considered.
Concept Generation
**Concept Generation**

Using the specifications established in the problem statement for our Sensor System for Cranes, we began to generate possible concepts for our project. This began by researching multiple solutions we could implement to achieve our goal. The main focus of our research was to analyze what type of sensor would give us the best overall performance while being the most cost effective solution as well.

Before generating any concepts for our design, the team visited the facilities of Steel Dynamics Inc. to observe the operating environment and better understand the nature of the problems faced. The measurements for the warehouse length and width were also determined, since the scale of the facility would also affect the type of system that would need to be implemented. Furthermore, the types of systems which are already being used to control and monitor the cranes needed to be known so that the new system could take both take advantage of existing hardware and avoid conflicting with any radio frequencies or other communications equipment.
Concepts
Concepts

Concept 1: Symeo Sensors

The first design concept would implement the position detection of the cranes using Symeo sensors. We will start by designing the system for a single crane. For a second crane, a second antenna would attach to the warehouse wall unit and the second crane would have the same system installed as in the first crane. The design will be based around a central PLC at the access point on the wall. The PLC will communicate a digital output from the wall to the crane drive via radio communication in sensors. The access point provides the ability to override the system to be full manual. The system will have hardwired relays in the sensors to the drive inputs. The PLC will output information to the drive output via the multiplier block in the program to slow down or completely stop the bridge/trolley. By adding another antenna on the wall, we would be able to monitor a second crane. Once the programming is completed and tested for one crane, the program can be copied and modified slightly to incorporate a second crane. Finally, the structure can be made modular to accommodate up to four cranes, which would allow the entire system to be used in similar warehouses.

As this concept was decided upon as the final design based on the design matrix found in Table 1, a more thorough explanation can be found in the Final Design section.
Concept 2: Long Distance Laser Sensors

The second concept is developed around the idea of using long range laser sensors. Typical data outputs for laser sensors are serial RS232, RS422 and current loop 4-20 mA signals. This type of device must be connected to either a PLC or a PC for calculations and control, a configuration for all the concepts being developed in the project. Laser triangulations sensors can be divided into two categories based upon their performance and intended use. High resolution lasers are usually used in position and displacement monitoring applications. This applications require sensors with high accuracy, high stability and low temperature drift. Proximity type laser triangulation sensors are much less expensive and are typically used to detect the presence of a part. Laser triangulation sensors contain a laser light source and a position sensitive detector (PSD) or a complementary metal-oxide-semiconductor (CMOS). The laser beam is projected on the target being measured and a portion of the beam is reflected through focusing optics into a detector. Laser triangulation sensors can be used on highly reflective surfaces. This surfaces are commonly referred to as specular. Reflection off of smooth surfaces such as mirrors or a calm body of water leads to a type of reflection known as specular reflection. Reflection off of rough surfaces such as clothing, paper, and the asphalt roadway leads to a type of reflection known as diffuse reflection. With specular surfaces, a typical triangulation sensor can’t be used because the laser light would bounce directly back to itself. For this particular cases it is necessary to direct the beam towards the reflecting target at an angle.

Laser sensors are non-contact by design. This means they have the ability to precisely measure the position or displacement from the sensor to an object without affecting the objects physical properties in any way.

When utilizing a laser sensor, it is first necessary to determine the surface reflectivity. A consistent matte finish is desirable for best performance when using diffuse heads. If a highly polished or mirror finish would be used it is recommended to use a specular laser head.

Because laser triangulation systems are optical type sensors it is important to keep the optical path clean and free from obstructions or foreign materials. Dirt, dust and smoke can affect the measurement results or even render sensors completely useless. Care should be taken to eliminate such contamination and clean air purge systems should be used when required. If this type of system is not possible it is important to regularly clean the outer lenses to avoid project. Care should also be taken to ensure the laser return light is not blocked by some previously established feature on the target being measured. The most common environmental problem that can affect the accuracy of a laser sensor is temperature. Not only do electronics exhibit temperature drift, but the expansion and contraction of mechanical components and fixtures can physically change the sensor gap. It is also essential that the fixture holding a laser sensor is stable. As mentioned above, temperature changes can cause expansion and contraction,
resulting in a distance change to the target. The signal received at the detector is used to determine the relative distance to the target.

The laser concept would consist of placing three laser sensors on each bridge of the crane, and therefore three reflective targets or receiver sensors for each bridge. A common configuration for a single crane positioning system is shown in Figure 1. The first laser sensor labeled (D1) would be determining the x-axis position of the bridge. The second sensor (D2) would be in charge of determining the y-axis position of the bridge, and the third sensor (D3) would determine the z-axis position of the load. In case of collision avoidance between two bridges, two extra sensors and receivers would be needed to control collision avoidance between two bridges.

Figure 1 - Example of setup for laser sensors to determine X and Y position of crane
Concept 3: Radio Based Systems

Concept 3 serves as an umbrella for two sub-concepts, both of which rely on an RFID approach and signal power to determine the position of a radio receiver relative to corresponding transmitters. Both of these systems are similar in concept and in implementation, and so were grouped together.

Concept 3a: Passive RFID

A passive RFID solution was explored for the third concept. This strategy would be based around a set of radio-frequency identification radio transceivers and passive tags operating in the 900 MHz range. One transceiver would be placed on each crane, and a grid of passive RFID tags would be placed in the operating facility a meter above the height of the cranes.

The grid that is created will space the passive RFID tags at a distance close to twice their operating range in all directions to take maximum advantage of their capabilities, and the position of each tag as well as the tag’s code will be both static and known to the PLC base station. As the cranes move, the RFID receivers on them will constantly output a signal which will be reflected off of the RFID tags along with their unique embedded codes. The receivers will find the strength of each coded signal it reads, and then transmit this information over the existing Wi-Fi network to the PLC base station. This PLC will then be able to determine the position of each crane based on the RFID tags in the grid which responded to the transceiver. These position measurements can then be compared to recent position calculations to calculate the current velocity and acceleration of each crane in the system.

The illustration in Figure 2 demonstrates a small section of the potential grid that would be established within the operating facility that the system would be installed in. Depending on the specific RFID tags which would be used, the maximum tag read and transmit range would vary. Based on preliminary

Figure 2 - Diagram showing a portion of the passive RFID grid system and its interaction with the crane transmitter
research, the best range would be approximately 3 meters. This would indicate that the tags would need to be spaced less than 6 meters apart from one another for the RFID transmitter to always be readable by at least one tag. In a building that is 560 ft. by 220 ft., the result is that over 670 tags would be required just to insure that a single tag could find the position of the crane. In practice, a reading from a single tag could indicate that the crane is anywhere within the broad reading range of that tag. The distance between tags would then need to be shortened to under the 3 meter tag reading distance to allow multiple tags to find the transmitter for each crane, thereby facilitating the triangulation of the crane’s position no matter where in the warehouse it’s located.

The sheer number of tags that would be required as well as the difficulty of both initially setting this grid up in the facility and then maintaining it were the major factors in this concept’s low score in the design matrix.

A Passive RFID system has a few main benefits that were taken into account when it was considered as one of the two possible schemes under Concept 3’s radio-frequency based umbrella. This RFID system would be cheap to implement, costing under $8,000 to implement even when using high-durability RFID tags. It would also reduce the need for powered components in the system, since the passive tags would require no source of power to operate and respond to the RFID transceivers. While this makes the system look feasible on paper, there are three main disadvantages to this system. First, creating and maintaining the grid of RFID tags is impractical in the dynamic environment that this system is being designed for. Second, the accuracy of the positional measurements is over 12 inches, making Concepts 1 and 2 far superior in precision. Finally, it operates in the same range as existing communications within the facility which could potentially lead to data collision and noise while operating.
Concept 3b: Wi-Fi Positioning

The second design grouped under concept 3 is a high frequency radio position detection system. This Wi-Fi system would operate between 2.405 – 2.480 GHz, with this frequency being adjustable in this range as needed to avoid the communication frequencies of devices already in use within the operating environment.

The hardware of the system would include the same Human-Machine Interface and PLC base station as would be used in any of the previously mentioned concepts. In addition, this scheme would use four radio receivers and a transmitter for each crane in the operating warehouse. This setup could then be duplicated for each new warehouse which required a similar collision avoidance system to be implemented.

Figure 3 - Diagram of Wi-Fi position detection setup

This system would operate very similarly to Concept 3a, and an example of how this concept would be implemented can be seen in Figure 3. The transmitters on each crane would continuously send out a steady signal at their maximum power. The receivers on each wall would each individually obtain the signal put out from each transmitter, calculating the distance to each transmitter based on the strength of the Wi-Fi signal. These receivers would send this information back to the base PLC, which will use the two of the four different measurements to triangulate the position of each crane in the facility. This position calculation will happen several times, using a different pair of Wi-Fi receivers each time. The determined positions can then be averaged together to reduce error, and this position can be compared to the last calculated position to find the velocity and acceleration of each crane. All of this data will then be used in coordination with the information stored on the PLC regarding the virtual walls which dictate where the cranes are allowed to move, as well as to limit their speeds when near other cranes.
This Wi-Fi range system was considered as a design concept for a few key reasons. First, the communication between the PLC base station and the crane sensors would be entirely wireless. While wireless communication is not a requirement for the project, the real world application of any solution to this problem would be incredibly inconvenient to implement if a wired network had to be added to the existing infrastructure. Second, operating at a high frequency would allow fast communication between the transceivers on the cranes and on the walls. This fast transmit speed would allow for quick position determination, and would also mean that the position of other cranes and the full data map for the virtual walls which will be implemented in the system could be kept on board the PLC of each crane, granting each crane a backup to at least avoid the virtual walls in its environment in case of a temporary breakdown in the system communication chain, even if it could not avoid other cranes until the system reestablished a transmission link. Third, this option is significantly cheaper than the passive RFID concept, and cheaper by far than the laser or Symeo radar sensor concepts. Excluding the HMI and master PLC that will be used in every concept, this system would cost around $2,000.

While this concept is more feasible to implement than Concept 3a, it shares a low positional accuracy which makes it less desirable than either Concept 1 or 2. Being a Wi-Fi based system, it also operates in the same range as the 2.4 GHz Wi-Fi band which is already in use within the operating environment and could result in data collision.
Final Concept Selection
Final Concept Selection

The team generated a decision matrix in order to determine which concept to implement. The matrix contains six areas where the project would be examined. They include the frequency used, positional accuracy, low maintenance, repeatability/expandability, ease of implementation, and cost. The decision matrix is shown in Table 1 below.

Table 1 - Decision Matrix

<table>
<thead>
<tr>
<th></th>
<th>Concept 1 (Symeo)</th>
<th>Concept 2 (Laser)</th>
<th>Concept 3a (Passive RFID)</th>
<th>Concept 3b (Wi-Fi Position)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weight</td>
<td>Rating</td>
<td>Weighted Rating</td>
<td>Rating</td>
<td>Weighted Rating</td>
</tr>
<tr>
<td>Frequency Used</td>
<td>25.00%</td>
<td>4</td>
<td>1</td>
<td>5</td>
</tr>
<tr>
<td>Positional accuracy</td>
<td>30.00%</td>
<td>5</td>
<td>1.5</td>
<td>5</td>
</tr>
<tr>
<td>Low Maintenance</td>
<td>15.00%</td>
<td>4</td>
<td>0.6</td>
<td>4</td>
</tr>
<tr>
<td>Repeatability/Expandability</td>
<td>15.00%</td>
<td>4</td>
<td>0.6</td>
<td>2</td>
</tr>
<tr>
<td>Ease of Implementation</td>
<td>10.00%</td>
<td>4</td>
<td>0.4</td>
<td>2</td>
</tr>
<tr>
<td>Cost</td>
<td>5.00%</td>
<td>3</td>
<td>0.15</td>
<td>1</td>
</tr>
<tr>
<td>Totals</td>
<td>100.00%</td>
<td>4.25</td>
<td>3.9</td>
<td>1.95</td>
</tr>
</tbody>
</table>

Each one of the six areas was assigned a weight factor based on what the team determined to be most crucial to the project. Positional accuracy received the highest weight factor with a 30%, while the cost of the system received the lowest weight with a 5%. An explanation of each area follows below.

- **Frequency Used**: There are a lot of different systems that already operate in different frequency ranges, and any additional sensors should conflict as little as possible with any of the frequency ranges already being used. The remote control for the crane drives operates at a frequency of around 9 MHz, while the Wi-Fi frequency range is 2.4 GHz.

- **Positional Accuracy**: The objective of the project is to create a system that will prevent cranes from colliding with other cranes and stationary objects in the facilities, so the accuracy of the sensor is crucial to the system. A sensor with higher accuracy will provide better results for the system and allow more precise positions to be known, allowing for a safer and more reliable system overall.
- **Low Maintenance:** The sensors will be installed on the crane bridges, so the system should have low maintenance requirements to offset the difficulty of accessing the system. The cranes in the factory usually operate on a continuous basis, and if they have to be stopped to access this system, the delay could result in a loss of production for the company.

- **Repeatability/Expandability:** The design of the system should be simple enough that it can be repeated at different locations without major issues. The design of the system should be modular, so that it can adapt if an additional crane is placed in the warehouse.

- **Ease of Implementation:** The design should allow for sensors to be easily mounted to the cranes, and minimal initial alignment and calibration should be required.

- **Cost:** Steel Dynamics Inc. set out a budget of $50,000 for the project. While the main priority of the system is performance, the total cost of the project needs to remain under budget. For the concepts discussed above, the majority of the design cost would come from the sensors. Other costs to consider would be the PLC act as the controller and provide communication and calculation support, as well as any necessary materials to create a communication channel between the sensors and the main controller.

The design matrix was used to determine the optimum design to be implemented in this project, according to the listed criteria. Concept number one will be implemented as the primary design. This concept provides several advantages when compared to the rest of the designs. These advantages include positional accuracy (with ±5cm maximum uncertainty in measurements), low maintenance requirements (a centralized access point will be used at ground level, and the hardware is robust and shouldn’t require frequent replacement), its cost efficiency (being at least $10,000 under budget), and low frequency interference with existing hardware (5.8 GHz signal frequency band is unused).

Concept 2 will be the backup design based on the score of the decision matrix. Concept 2 will be a similar system to concept 1, but will instead use long range laser sensors. This design might result in a less cost efficient solution, while also providing less accuracy. Another major concern with the laser sensor concept is that these sensors may not operate well in foggy or dusty conditions. Since this system will be installed in a steel factory, the laser sensor might not operate at its highest capacity due to these factors.
Final Design
Final Design

The final concept is created around the idea of using Symeo sensors to detect the position of the cranes. Symeo is a Germany based company that produces HF radio sensor technology components. The Symeo sensor would then send this information to a central PLC that process the position of each crane from the sensors for processing. The PLC that will be utilized is an Allen-Bradley MicroLogix 1100. An example of the expandability of the system is shown in Figure 4.

Figure 4 – An example topology of the proposed system
Hardware

The Symeo sensors chosen have a range of up to 1800m with the longest bay in the plant ranging up to 820 feet which translates to 250m. The sensors also maintain high accuracy with an uncertainty in position of ±5cm which correlates to the wavelength of the signal used. A signal at 5.8 GHz corresponds to a wavelength of 5cm. This is achieved through highly accurate time synchronized actuated identifiers which can achieve accuracy in the picosecond range. A configuration for the Symeo LPR-1D and the attached antenna is shown in Figure 5.

The antennas connected to the sensors are 23dBi planar antennas with a 9 degree from apex conical propagation to -3dB signal attenuation providing flexibility in placement for line of sight illustrated in Figure 6. Maximum transmitted power from the sensor is 0.025 W EIRP which will have no interference with other electronics or present danger to the human body.

The LPR-1D sensors and antennas consume up to a maximum of 8W at any given time. With a 24V power supply, current draw limits to a maximum of .33A of Direct Current allowing for readily available 14 or 16 AWG wire to be used.

The Symeo sensors operate at a frequency from 5.725 to 5.875 GHz which occupy the upper bandwidths of the 5 GHz Wi-Fi operational frequencies. To avoid interference, the IT department at Steel Dynamics will be switching to the lower bandwidths since there is no opportunity for interference with other routers in the area since the plant is located on a one square mile location that is fenced off from other businesses and homes.

Symeo also provides a user data transfer rate of 8 bytes/cycle up to 800 bytes/s. This provides the capabilities for the proposed centralized access point and PLC easing access to the system as a whole.

![Figure 5 – Symeo LPR-1D sensor and 23dBi antennas](image-url)
To verify the distance at which an accurate signal can be detected, a known energy must be propagated from the antenna. In using the known power, along with implementing the free space loss (FSL) equation given in (1), the loss of the signal can be converted to a very precise position. By rearranging the equation, a formulation for relative attenuation of the originally propagated signal is achieved.

\[
FSPL(dB) = 20 \log_{10} \left( \frac{4\pi}{c} df \right) \tag{1}
\]

Equation (1) can also be represented as,

\[
FSPL(dB) = 20 \log_{10} (d) + 20 \log_{10} (f) + 92.45 \tag{2}
\]

which leads to the distance relation as

\[
\frac{c}{4\pi f} \sqrt{\frac{10}{10}^{FSPL(dB)}} = d \tag{3}
\]

Where “d” is measured in kilometers and “f” is measured in gigahertz.

Using MATLAB, a plot showing the relation of the propagation loss to the distance between the two antennas is calculated and the relation between distance and power loss is illustrated in Figure 7.

The MicroLogix1100 Programmable Logic Controller will be used in conjunction with RSLogix Micro for system control. The controller can operate at a 10 Mbps/100 Mbps transfer rate providing ample communication and program refresh speed for operation in the environment.

The drives to be interfaced with are Magnatek G+ series 2 *variable frequency drives*. All cranes travel at a maximum of 350 feet per second with a maximum linear deceleration to stop time of 7 seconds from top speed.
Figure 7 - Distance versus power loss curve
System Topology

The communication between the sensor and the PLC will be via a TCP/IP configuration through a network switch. The PLC will draw the position data from the sensor across this connection and compare the relative positions within the program. If determined limits of proximity to either another crane or “exclusion zones” the PLC will transmit an enable/disable bit across the wireless radio connection between the specified sensors to the drive of the crane bridge and/or trolley. Upon receiving the signal, the drive will limit the acceleration and deceleration times of the bridge and/or trolley to avoid collision or equipment damage. A system topology diagram is shown in Figure 8.

The PLC will process the relative position of the cranes in the system to determine potential collision using comparator blocks in the ladder logic program. With a centralized PLC, custom “exclusion zones” can also be implemented and changed by supervisors. These are areas in which the trolley of the crane cannot travel. This will be achieved using an absolute coordinate system that will be programmed into the PLC and synchronized with the sensors. This will allow for zones (such as operator stations or stationary equipment) to not be accessed during normal operation protecting equipment and personnel in the area.

By centralizing the PLC, an access point for the system can be implemented. With a ground level access point, supervisors and operators can manually disable the system in the event of a malfunction or failure.
Figure 8 - System Topology
The sensors provide X and Y coordinates to the PLC which can compare the values to the other sensors or the pre-determined exclusion zones in the PLC. The PLC will provide an output to the respective crane to slow down or disable the drive. A flow chart for the program logic can be seen in Figure 9. The program will be written using RSLogix Micro Starter Lite which is a free download from Rockwell Automation and will allow for much more cost efficient implementation. An example program illustrating the layout is shown by Figure 10.
Figure 10 – RSLogix Micro Starter Lite
Hardware Location

A key component will be mounting the antennas in locations to avoid attenuation of the signal due to obstacles. The area of the first Fresnel Zone must be observed and accounted for in the placement. The first Fresnel Zone is the location in which most of the power of the signal is concentrated. This zone must be kept 80% clear by radio frequency communication standards for minimal signal attenuation. The zone for the planar antennas chosen is shown in Figure 11 along with a quick reference table for clearance distance. The zone is shown to be of an elliptical path with the thickest area of clearance needed in the center of the path. The precise distance can be calculated using (4) where \( \lambda \) is the wave length and the distance between the two antennas. For a frequency of 5.8 GHz a wave length \( \lambda \) of approx. 0.05 m is calculated. The maximum radius between the two antennas is indicated by \( b \).

For a single crane, a simple L-shaped arrangement will be utilized. This is shown in Figure 12. The sensors must be spaced far enough apart to avoid this interference as well. An example system layout is illustrated in Figure 13.

\[
b = 0.5 \times \sqrt{\lambda \times d}
\]  

(4)
Figure 12 - LPR-1D L-Shaped arrangement
Figure 13 - System hardware layout
Test Bench
Test Bench

Overview
Steel Dynamics Inc. will be able to provide a smaller crane system that could be used on specific dates so the system functionality and reliability can be tested. Before testing on a real size crane, a scaled testing fixture using 80/20 extruded aluminum that will simulate motion of a pair of crane bridges and the collision avoidance system would be created. This test fixture will utilize high-performance laser distance sensors to measure the distance from one end of the test stand and supply the PLC with an analog voltage between 0 and 10 volts. The PLC will convert the analog values to distances which will then be used to calculate the distance between crane bridges and/or virtual bridge walls.

The simulated bridges will be moved by a ½”-10 threaded rods indirectly driven by stepper motors with an integrated driver/controller. The integrated motor controller can be programmed with two speed profiles, then the motors can be controlled with four discreet outputs from the PLC.

The operator will use either physical control box or HMI move the bridges. In both input options there will be displays on the HMI to show the location of both bridges and the distance between them, as well as warning indicators.

- Test frame: 80/20 aluminum, sliders, and connection hardware
- Drive system: (2) ½”-10 Threaded rod driven indirectly by stepper motors
- Sensors: (2) OPT2011 High precision laser measurement between 50 and 3050mm for a total measurable distance of 3 meters.

The OPT2011 Laser measurement sensors were selected based on required measurement distance of the test stand, less than 3 meters, and most other sensors had much larger maximum measured distance with minimum distances outside the test stand dimensions.

The stepper motors were chosen since they integrated the driver and controller this allows for fewer wires and discrete components. The controller on the drives can be programmed with two speed profiles. The controllers have 4 discrete inputs that will allow for selection of speed profile, direction and enabling drive motion.

Figure 14 shows the shows a 3D rendering of the structural components of the test bench in an exploded, piecewise view. Figure 15 shows a possible Human Machine Interface with controls for the movement of the bridges, which would also allow the controller to view the current position of each bridge in the test bed. Figure 16 shows the initial 3D rendering of the test stand, which shows a conceptual view including the laser sensor, PLC, and motor drive system.
Figure 14: Rendering of structural Components of test bench

Figure 15: Sample of HMI interface with motion controls
Figure 16: Test stand concept with sensor 3D render
Cost Analysis
Cost Analysis

In Table 2 the individual and combined cost of the components used for the testing stand. Table 3 shows the cost of the entire system to be implemented on the cranes. The PLC used in the testing stand is a Micrologix 1100 donated by SDI. The total cost of the materials for the testing stand comes to $1,709.75, this is $290 under the budgeted $2000 for it. The total cost of the sensors and the testing fixture comes to $39,602.87 well under the $50,000 budget set by SDI. Some incidental cost maybe added to both the test fixture and the crane system if the PLC needs to be upgraded beyond the ones being supplied by the sponsor.
<table>
<thead>
<tr>
<th>Part Name</th>
<th>Qty</th>
<th>Price/Unit</th>
<th>Total Cost</th>
</tr>
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<td>1.5&quot; x 1.5&quot; Lite 80/20 (145&quot; Clear Anodized)</td>
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<td>$131.95</td>
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<td>$295.00</td>
<td>$590.00</td>
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<td>OPT2011 Mounting Bracket</td>
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<td>$5.50</td>
<td>$11.00</td>
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<td>OPT2011 Connection Cable</td>
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<td>$8.25</td>
<td>$16.50</td>
</tr>
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<td>17MDSI Stepper Motor with Integrated Driver and Controller</td>
<td>2</td>
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<td>1/2 - 10 Threaded Rod (6 ft.) (Keystone)</td>
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<tr>
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<td>0</td>
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<tr>
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<td>0</td>
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<td></td>
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<tr>
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<tr>
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<td>2</td>
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<td>$3,058.00</td>
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<td>23dBi planar antenna</td>
<td>8</td>
<td>$297.01</td>
<td>$2,376.08</td>
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<td>adjustable mounting device</td>
<td>8</td>
<td>$86.38</td>
<td>$691.04</td>
</tr>
<tr>
<td>HF-antenna cable 4m</td>
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<td>$271.25</td>
<td>$1,627.50</td>
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<tr>
<td>HF-antenna cable 6m</td>
<td>2</td>
<td>$368.23</td>
<td>$736.46</td>
</tr>
<tr>
<td>Connector RJ45</td>
<td>2</td>
<td>$65.16</td>
<td>$130.32</td>
</tr>
<tr>
<td>NBX 490 Gateway</td>
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<td>$715.00</td>
<td>$715.00</td>
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<td>HMI (Various Parts)</td>
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<td>$221.97</td>
<td>$221.97</td>
</tr>
<tr>
<td>Power Supplies</td>
<td>5</td>
<td>$353.37</td>
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<td>PLC</td>
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</tr>
<tr>
<td></td>
<td>USD</td>
<td></td>
<td>$37,893.12</td>
</tr>
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</table>
Design Modifications
Gateway

Upon further discovery, the MicroLogix 1100 PLC is incapable of communicating by TCP/IP protocol. The processors are only capable of communicating with other Allen Bradley processors by CIP (Common Industrial Protocol) to transmit data to other processors. To avoid this roadblock and allow the processor to obtain data from the Symeo sensors, a Real Time Automation 490NBX gateway was purchased and implemented. This module allows for translation from ASCII to a protocol that can be understood by the MicroLogix processor.

Web Browser Configuration

The NBX gateway is configurable through a web server connection that can allow for testing incoming data for register allocation within the PLC. The web interface is shown in Figure 17.

![Figure 17 - Home webpage interface for the RTA interface](image)

The IP address of the module must be configured to the same network as is being used. From here, the gateway needs to have the PLC address and configuration defined to send
information to the PLC. In Figure 18, the controller type must be selected along with the IP address of the controller which must also be on the same network. Since the Ethernet port is integrated with the MicroLogix 1100, the controller slot is 0. The controller is connected so it uses Class 3 Explicit communication mode with the gateway. A heartbeat is useful to troubleshoot if data ceases to come in from the sensors and determine if the gateway is not connected or if the sensors have failed. A heartbeat is configured to an integer register within the PLC. The gateway sends this information directly to this location.

![PLC configuration through the RTA interface](image)

Figure 18 - PLC configuration through the RTA interface

The TCP/IP network must be configured as well. In Figure 19, a screen to communicate with a complete set of sensors is shown. The sensor that is directly connected to the network switch at the wall must be addressed with the data port on the sensor configured as the TCP port. An inactivity timeout and reconnect delay are chosen in case communication is lost with the sensor.
46

Figure 19 - Setup for the communication addresses of clients connected to the gateway

Default message configuration with the gateway uses ASCII text. Communication must be enabled from ASCII to MicroLogix and a data type and File Name must be defined, as shown below in Figure 20. In this case, an INT[array] was chosen to easily access Null characters and all bytes of incoming data. To define the end case of the message, the character count was set to 25 characters which was chosen by the data length of the fixed frame coming from the sensors which will be explained later. Similarly, if variable frame protocol was used, start and end delimiters could be used to define the start and end of the incoming message. This will start and cut off any messages coming in whenever the gateway sees these characters in any byte coming from the sensors. The message que size must be set to at least 10 characters since the sensor is sending 6 messages per cycle which is roughly 70ms. By leaving the Data Conversion NULL Character Handling to None, the gateway will not discard any NULL characters that come in. This is critical, as the sensors will later fill in these previously empty bytes as new data is retrieved and sent along the communication chain.
The last page used for this configuration is the Diagnostics page which is depicted in Figure 21. This page will show a very slowly refreshing stream of the data coming from the sensors. When no sensors are connected, a test message can be sent to the MicroLogix to test connection and show data conversion from ASCII to binary or hexadecimal.
Figure 21 - RTA status and diagnostics page for setup and troubleshooting
Sensor Configuration

When using the Symeo LPR 1D Wizard desktop app provided with the sensors, they must be configured to their precise application. In this case, application 3 under the LPR 1D configuration is selected. This allows for X/Y position of a crane trolley to be transmitted. A group ID is selected as well to give specific addresses to each unit and ensure no frequency interference. The region is chosen to comply with frequency regulations of the region of application. The measurement cycle must be 70ms at minimum and can be configured up to 100ms to ensure accuracy of the antennas and transmission of data across the link. Figure 22 depicts the first step of the configuration setup.

Figure 22 - Configuration utility for the Symeo sensors

Figure 23 illustrates the setup of the group master settings. Interface, antenna type, and cable type must be chosen for antenna ports 1 and 2. This ensures accurate measurements when the antennas are calibrated.
The same configuration is used for the Slave 1 and 2 setups. Slave 1 will be using a 6m cable to allow for easier placement of the antenna and sensor. When the configuration is set up, it is saved and noted as its group configuration so it may be accessed at a later date. Up to 30 groups can be configured in this manner.
Data Flow

The incoming data from the LPR sensors comes in as an array to the specified data location shown in Figure 24. From this string, the data type, source sensor, distance, velocity, error codes, and other data can be extracted.

Figure 24 - An example of the incoming data retrieved from the Symeo units
Figure 25, taken from the LPR 1D manual, explicitly defines each data location:

### 7.2.1 Type 0x00 – Distance Data

Direction: LPR® 1D → User

<table>
<thead>
<tr>
<th>Content</th>
<th>Length</th>
<th>Data type</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>START</td>
<td>1</td>
<td>unsigned integer</td>
<td>0x7E</td>
</tr>
<tr>
<td>TYPE</td>
<td>1</td>
<td>unsigned integer</td>
<td>0x00</td>
</tr>
<tr>
<td>Source¹ (LPR® address)</td>
<td>2</td>
<td>see chapter 7.4.1</td>
<td>0x####</td>
</tr>
<tr>
<td>Destination² (LPR® address)</td>
<td>2</td>
<td>see chapter 7.4.1</td>
<td>0x####</td>
</tr>
<tr>
<td>Antenna number²</td>
<td>1</td>
<td>unsigned integer</td>
<td>0x##</td>
</tr>
<tr>
<td>Distance [mm]</td>
<td>4</td>
<td>signed integer</td>
<td>0x##### ######</td>
</tr>
<tr>
<td>Velocity [mm/s]</td>
<td>4</td>
<td>signed integer</td>
<td>0x##### ######</td>
</tr>
<tr>
<td>Level [dB]</td>
<td>1</td>
<td>signed integer</td>
<td>0x##</td>
</tr>
<tr>
<td>Distance Error</td>
<td>1</td>
<td>see chapter 7.4.2</td>
<td>0x##</td>
</tr>
<tr>
<td>Status³</td>
<td>1</td>
<td>unsigned integer</td>
<td>0x00</td>
</tr>
<tr>
<td>CRC</td>
<td>2</td>
<td>unsigned integer</td>
<td>0x####</td>
</tr>
<tr>
<td>END</td>
<td>1</td>
<td>unsigned integer</td>
<td>0x7F</td>
</tr>
</tbody>
</table>

Total length without byte stuffing: 21 byte

¹) Any measurement is always executed by a LPR® 1D Slave Unit, this means, the Slave Unit measures its distance etc. towards a Group Master Unit. The source field always contains the address of the LPR® 1D Slave Unit. The destination field contains the address of the measured Group Master Unit. Even if the data set is transferred further on to another unit (e.g. another Group Master Unit), the value of the source and destination field is maintained.

²) The field antenna contains the antenna number of the Slave Unit as well as the antenna number of the measured Group Master Unit. The 4 lower bits represent the antenna number of the Slave Unit (values 1...4) and the higher ones the antenna number of the Group Master Unit (values 1...4).

³) reserved for future application. Currently set to 0.

**Example of Distance Data**

```
7E 02 C1 81 7F
7E 00 10 03 08 02 11 00 00 10 02 00 00 00 7A E6 00 00 AF C4 7F
```

*Figure 59 - Protocol for a single 1D measurement: request data and following distance data*

This protocol shows a simple example for 1D measurement. A distance data set (or also 2 distance data sets) alternate with a send request. The Send Request indicates that the LPR® unit is listening to a data set from the user (for example relays external commands). The Distance Data sends the data to the user (i.e. to a PLC or to a PC/software).

*Figure 25 - Precise list of available data in the Symeo communication packet sent over TCP/IP*
The extracted data can then be organized through data manipulation in the ladder logic of the PLC subroutine to get the absolute position. Since the distance is measured in millimeters from the LPR, there must be a conversion to feet within the program to allow for ease of implementation in an American setting. In the provided code for data file “U:5” in the ladder logic, the program will copy the data bit for bit to a new register if new data has been transmitted. Then using the known locations of the addresses and codes for each sensor, an internal bit is toggled depending on whether the data is from the sensor measuring the X location or the Y location of the trolley. Based on this information, the data will then be moved to a new register for manipulation. In rungs 3 through 5, the data locations of the X position data are moved and masked for manipulation provided that the incoming data is length data from the sensor providing the X position. In rungs 6 through 12, math operations are used to combine all incoming data and convert to feet at the end of the routine. This same logic was used when manipulating data for the Y position of this sensor group.

To repeat this for another crane is to create more data registers for organization and filter out the address based on the group number of the sensor.
HMI

The Human Machine Interface (HMI) has both hardware and software components, enabling the visualization of all of the information involved with the monitoring of the crane system.

Software

The centralized PLC allows for a central Human Machine Interface (HMI) to monitor the system status, bridge and trolley position, and their relative distances. By using a free software package called AdvancedHMI, the network can be enabled, disabled, and customized to provide any system data from each of the sensors. The program is written using Visual Basic and is fully customizable. Figure 26 below shows a sample HMI with selection buttons. A basic HMI was created and tested for the test bench, and was expanded upon for further use and development as wanted by Steel Dynamics.

Figure 26 - Example of the HMI software developed for viewing crane information
At the same constructed HMI, a version of RSLogixMicro will be installed which will enable maintenance personnel to directly access the program to easily install new exclusion zones or to modify the program. This is run on a full Windows platform that can be configured to have specific users and passwords, which (for example) could give SDI the option to allow access to only supervisors and safety personnel, ensuring that an operator cannot turn off the system without the proper permission.

**Hardware**

In order to run a full Windows environment along with the software discussed in the above section, an Intel NUC computer was chosen to run the interface which allows supervisors and other personnel to view the system information. The NUC is small, portable, and can be easily expanded with additional storage or memory if required. It requires minimal power, has no fan, and can be safely left running continuously. These features allow it to be easily attached to a wall or the back of its connected monitor, keeping it useable but out of the way of everyday operations. For system storage, an SSD was chosen to provide fast boot and program load times, which could potentially decrease the time it takes for an operator to reboot the system or to respond to an event in the crane bay.

Using separate hardware for the HMI keeps it entirely separate from the PLC and the Symeo sensors. Since the Windows operating system does not operate in real-time, this is a critical feature: it means that should the computer encounter a fatal error and require a reboot, the safety system which is established by the rest of this system will continue to function without a negative impact, leaving time for system administrators to reboot the HMI without requiring the cranes to be disabled. The HMI, while offering a useful and convenient purpose, is not a critical part of the system as a whole.
Testing
Overview

After the complete sensor system was finalized, the system was taken into the Steel Dynamics facilities to be tested. The test consisted of taking two sensors to the plant: one sensor would simulate the sensor to be placed at the wall, and the second would emulate the sensor that is going to be placed on the bridge. Once the system was programmed and calibrated, the system was attached to a full-sized crane drive that was available for system and could fully replicate the system that would be used to operate the cranes in the future. The motor for this test operated in three profiles. The first profile consisted of full speed operation, operating at a rotational speed of 60 Hz. The second profile is a slow-down operation where the motor spins at a maximum of 6 Hz, with the ability to rotate between 0 Hz and 6 Hz. The last profile is when the motor is completely stopped.

These different profiles allowed the replication of the various speeds which would be allowed within the set buffer distances for the anti-collision and virtual wall avoidance parts of the overall system; the slowdown profile creates an area in which the crane drive can still move towards the boundary but must be within a reasonable speed. The stopping profile completely disallows movement of the crane motor if it’s moving towards the boundary, preventing collision and possibly injury.

To test the system, the sensors were aligned with each other and placed strategically in moving chairs. Three zones were created for the system depending on the distance between the sensors. The normal mode of operation is when the distance between the sensors is greater than any of the set buffer distances. The second mode is a slowdown mode, entered when the sensors start getting close to each other and are within the first set buffer. Finally, the stop zone is entered when the sensors come within a very short distance of each other. One sensor was placed in a moving chair to simulate the sensor that will be placed in the moving crane, and the second sensor was left stationary. The initial setup can be seen in Figure 27.
For testing, all speed profiles of the crane drive were tested in conjunction with the developed PLC anti-collision system. Each profile was tested multiple times and in multiple directions, to ensure that the crane drive would operate in the correct mode regardless of the direction of movement of the sensors or the current state of the drive. In Figure 28 and Figure 29, the manual movement of the Symeo sensors can be seen, which was done to test that the crane drive worked as expected.

Test Results

After testing all speed profiles and zones of operation, the software and hardware were demonstrated to be working correctly and consistently without error. This indicates that the system is working as intended, and can be safely recommended to SDI for future development and use.
Figure 28: Sensor system entering the slow down mode

Figure 29: Sensor system entering stop mode
Evaluation and Recommendations
Evaluation and Recommendations

The achieved results are compared against the requirements, specifications, limitations, and constraints. Recommendations for future improvements are given.

Evaluation

The proof of concept is achieved. Through test bench evaluation and testing in a Steel Dynamics Inc. shop setting while directly connected to a drive and motor, exclusion zones and anti-collision through absolute positioning are achieved.

A template for a local access point to enable, disable, and alter the system has been designed and built. This will completely enable modification for ease of maintenance.

An anti-collision program based on drawing data from the sensors has been achieved and can control a variable frequency drive with multiple frequency selection profiles based on position.

Through similar testing, a position detection for specific locations within a bay for a crane to be unable to access has been achieved with absolute positioning.

The system is expandable from one crane up to as many cranes as are present on a rail. Only limitation being the size of the network switch and the number of Ethernet ports.

Since the system was not implemented onto a physical crane due to time constraints of circumstances out of the group’s control, the ability to limit sway of the load could not be tested.
Recommendations

Using all data the sensors have to offer would provide a much smoother program. By including the velocity of the cranes, a variable stopping distance could be implemented taking into account the inertia of the crane which would also provide the ability to prevent loss of the load or excessive sway.

Purchasing 3 LPR 1D sensors with internal dry contact relays instead of using the STU for remote relay switching would make the communication much more intuitive and easier to program. Placing these sensors as the master of the two existing groups and moving the current master units to be slaves of a third group would allow for a third crane to be immediately implemented. The removed STU units could be used to employ encoders on the hoist motors and provide a third dimension for a more dynamic program that could implement a Z direction in the axis.

Another option could be to place a MicroLogix 1100 connected to a three port network switch with a Real Time Automation 490NBX for TCP/IP translation to read user data from the centralized PLC and switch inputs to the Magnatek drives. This option would remove the need to purchase more LPR sensors and could immediately employ the encoder option of the STU units.
Conclusion
Conclusion

Many different approaches to solving the problem at Steel Dynamics, Inc. were explored, and three different ideas were analyzed specifically. The four concepts (Symeo Sensors, Laser Sensors, Radio Sensors, and Wi-Fi sensors) that were developed based on these ideas were all expanded upon, researched, and finally compared in a decision matrix to find the best solution. The final of project design will incorporate Concept 1. This was determined by the decision matrix that compared every possible design concept against a list of requirements.

A test bed has been designed which is modeled loosely on the warehouse that the system will be implemented in, and is based off of Concepts 1 and 2 to provide a realistic foundation for testing both the hardware and the software that will be used in the final system. The test bed was developed using laser sensors due to cost constraints.

The Symeo sensors were used to develop the final design of the deliverable given to Steel Dynamics, as detailed previously in this report. Their fast and accurate communication abilities proved essential to developing the network between the RTA gateway, the PLC, and the sensors on each crane without sacrificing the safety components of the system.

Both an anti-collision system for the individual cranes as well as a virtual boundary avoidance system were implemented and tested using the Symeo sensors and a crane drive at the Steel Dynamics plant, proving that the system works as required and can be used and developed further by Steel Dynamics as required. The total cost of the project puts this solution well below equivalent commercially available products as well as maintaining the project well under the previously established budget, and produces the results that SDI required for the project.

Due to lack of documentation, the team was unable to take full advantage of the capabilities of the Symeo Sensor systems. The next stage of this project would consist of integrating the internal relay system that the Serial Transmission Unit system provides and blending it together with the already developed design to produce optimal performance while lowering complexity of both installation and operation.

The team again would like to thank Steel Dynamics, Inc. for sponsoring the project and for their assistance in the development process.
Appendix A
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<th>Bytes</th>
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<td>SYS</td>
<td>0</td>
<td>No</td>
<td>0</td>
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<td>0</td>
<td>No</td>
<td>0</td>
</tr>
<tr>
<td>GET POS 1</td>
<td>2</td>
<td>LADDER</td>
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<td>450</td>
</tr>
<tr>
<td></td>
<td>7</td>
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ALWAYS OFF
B3:0
14

STOP PROFILE
B3:0
2

WARN PROFILE
B3:0
3

JSR
Jump To Subroutine
SBR File Number
U:5

JSR
Jump To Subroutine
SBR File Number
U:6

JSR
Jump To Subroutine
SBR File Number
U:7
Only move data into the file if the length is greater than zero

```
0000
IN_L NEQ 
Not Equal
Source A N21:0
0<
Source B 0
0<
```

Copy File
Source #N21:0
Dest #N22:0
Length 1

save the length of the last data string

```
0000
#SAVED_LENGTH
```

length of incoming data

```
IN_L MOV 
Move Source 0
0<
Dest N21:0
0<
```

Mask off attenuation level of antennas to get just the lowest byte of the velocity data to be used later in the ladder

```
0001
MVM 
Masked Move
Source N21:8
17855<
Mask N20:5
FF00h<
Dest N21:8
17855<
```

This bit enables the data to pass to the crane 1 x registers

```
0002
X_DATA_IN
```

```
0003
Y_DATA_IN
```

This bit enables the data to pass to the crane 1 y registers

```
0004
HIGH_X
```

This bit enables the data to pass to the crane 1 x registers

```
0002
X_DATA_IN
```

```
0003
Y_DATA_IN
```

```
0004
HIGH_X
```

IN_L EQU 
Equal
Source A N21:1
32256<
Source B N24:0
32256<

IN_L EQU 
Equal
Source A N21:2
6147<
Source B N24:1
4099<

IN_L EQU 
Equal
Source A N21:3
2050<
Source B N24:2
2050<

IN_L EQU 
Equal
Source A N21:1
32256<
Source B N24:0
32256<

IN_L EQU 
Equal
Source A N21:2
6147<
Source B N24:1
4099<

IN_L EQU 
Equal
Source A N21:3
2050<
Source B N24:2
2050<

IN_L EQU 
Equal
Source A N21:1
32256<
Source B N24:0
32256<

IN_L EQU 
Equal
Source A N21:2
6147<
Source B N24:1
4099<

IN_L EQU 
Equal
Source A N21:3
2050<
Source B N24:2
2050<

IN_L EQU 
Equal
Source A N21:1
32256<
Source B N24:0
32256<

IN_L EQU 
Equal
Source A N21:2
6147<
Source B N24:1
4099<

IN_L EQU 
Equal
Source A N21:3
2050<
Source B N24:2
2050<

IN_L EQU 
Equal
Source A N21:1
32256<
Source B N24:0
32256<

IN_L EQU 
Equal
Source A N21:2
6147<
Source B N24:1
4099<

IN_L EQU 
Equal
Source A N21:3
2050<
Source B N24:2
2050<

IN_L GRT 
Greater Than (A>B)
Source A N22:0
21<
Source B 5
5<

IN_L GRT 
Greater Than (A>B)
Source A N22:0
21<
Source B 5
5<

IN_L GRT 
Greater Than (A>B)
Source A N22:0
21<
Source B 5
5<
This bit enables the data to pass to the crane 1 x registers

X_DATA_IN

B3:0

0

0005

save the length of the last data string

SAVED_LENGTH

GRT

Greater Than (A>B)

Source A N22:0

21<

Source B 5

5<

middle word of x data

#MID_X

COP

Copy File

Source #N21:5

Dest #N22:2

Length 1

This bit enables the data to pass to the crane 1 x registers

X_DATA_IN

B3:0

0

0006

save the length of the last data string

SAVED_LENGTH

GRT

Greater Than (A>B)

Source A N22:0

21<

Source B 5

5<

lower byte of x data

LD_X

MVM

Masked Move

Source N21:6

-11777<

Mask N20:1

7F00h<

Dest N22:3

17920<

Divide masked integer by 256 to move the information to the least significant byte of the word

This bit enables the data to pass to the crane 1 x registers

X_DATA_IN

B3:0

0

0007

DIV

Divide

Source A N22:3

17920<

Source B N20:2

256<

Dest N22:4

70<

Move the integer to a float for ease of addition and data manipulation

This bit enables the data to pass to the crane 1 x registers

X_DATA_IN

B3:0

0

0008

MOV

Move

Source N22:4

70<

Dest F25:0

72.0<

Since integer types are signed integers, if the MSB is a 1, it would switch to a negative integer. We masked this out and must add it in if this bit in the incoming data is 1 and was removed. By adding 128 if this bit was removed, we account for this removal.

This bit enables the data to pass to the crane 1 x registers

X_DATA_IN

B3:0

0

0009

ADD

Add

Source A F25:0

72.0<

Source B N20:3

128<

Dest F25:1

239.0<
Move the integer file to a float to be added to the least significant byte later.

```
0010
```

This bit enables the data to pass to the crane 1 x registers

| X_DATA_IN | B3:0 | 0 |

high word float pre multiplication to get correct value

```
0012
```

This bit enables the data to pass to the crane 1 x registers

| X_DATA_IN | B3:0 | N21:6 |

Multiply this word by 256 to account for the 8 bit shift to the right when coming in from the sensor. We do not need to account for the most significant byte since the constraints of all buildings being used do not go up to that length of the bays does not go up to 2147483647mm or 2147483.647m.

```
0011
```

This bit enables the data to pass to the crane 1 x registers

| X_DATA_IN | B3:0 | 0 |

distance data from middle word

```
0013
```

This bit enables the data to pass to the crane 1 x registers

| X_DATA_IN | B3:0 | 0 |

if sign bit was re-introduced, use this command

```
0014
```

This bit enables the data to pass to the crane 1 x registers

| X_DATA_IN | B3:0 | #N21:7 |

Copy velocity data to a long data type for a signed integer.

```
0015
```

This bit enables the data to pass to the crane 1 x registers

| X_DATA_IN | B3:0 | #L13:0 |

```
After lowest byte has been removed, divide by 256 to get correct value.

This bit enables the data to pass to the crane 1 x registers

**X_DATA_IN**

| B3:0 | 0 |

**DIV**

Divide

- **Source A**: L13:0 0<
- **Source B**: 256 256<
- **Dest**: L13:2 8388607<

**X_FINAL_X_VELO**

final velocity of x direction sensor

This bit enables the data to pass to the crane 1 y registers

**Y_DATA_IN**

| B3:0 | 1 |

**GRT**

Greater Than (A>B)

- **Source A**: N22:0 21<
- **Source B**: 5 5<

**HIGH_Y**

save the length of the last data string

**SAVED_LENGTH**

**COP**

Copy File

- **Source**: #N21:5
- **Dest**: #N23:2
- **Length**: 1

**MID_Y**

middle word of y data

**LO_Y**

low byte of y data

**MVM**

Masked Move

- **Source**: N21:6 -11777<
- **Mask**: N20:1 7F00h<
- **Dest**: N23:3 20736<

This bit enables the data to pass to the crane 1 y registers

**Y_DATA_IN**

| B3:0 | 1 |

**GRT**

Greater Than (A>B)

- **Source A**: N22:0 21<
- **Source B**: 5 5<

This bit enables the data to pass to the crane 1 y registers

| B3:0 | 1 |

**GRT**

Greater Than (A>B)

- **Source A**: N22:0 21<
- **Source B**: 5 5<

This bit enables the data to pass to the crane 1 y registers

| B3:0 | 1 |

**GRT**

Greater Than (A>B)

- **Source A**: N22:0 21<
- **Source B**: 5 5<
This bit enables the data to pass to the crane 1 y registers

Y_DATA_IN

B3:0

1

crane 1 Y position in millimeters

C_1_Y_MM

ADD

Add

Source A

F26:3

1024.0<

Source B

F26:0

81.0<

Dest

F26:4

1105.0<

Copy velocity data to a long data type for a signed integer.

This bit enables the data to pass to the crane 1 y registers

Y_DATA_IN

B3:0

1

Final velocity of y direction sensor

C_1_FINAL_Y_VELD

CPW

Copy Word

Source

#N21:7

Dest

#L15:0

Length

2

After lowest byte has been removed, divide by 256 to get correct value.

This bit enables the data to pass to the crane 1 y registers

Y_DATA_IN

B3:0

1

crane 1 final velocity of y direction sensor

C1_FINAL_Y_VELD

DIV

Divide

Source A

L15:0

0<

Source B

256

256<

Dest

L15:1

0<

Convert the X value to feet

crane 1 x value in feet

C_1_X_FT

DIV

Divide

Source A

F25:4

3912.0<

Source B

F27:0

304.8<

Dest

F25:5

47.24081<

Convert the Y value to feet

crane 1 Y value in feet

C_1_Y_FT

DIV

Divide

Source A

F26:4

1105.0<

Source B

F27:0

304.8<

Dest

F26:5

20.28872<
Stop distance between cranes

- **C_1_X_FT**
  - Grtr Than or Eql (A>=B)
  - Source A: F25:5, 47.24081<
  - Source B: F27:3, 7.0<
- **C_1_Y_FT**
  - Grtr Than or Eql (A>=B)
  - Source A: F26:5, 20.28872<
  - Source B: F27:5, 7.0<
- **C_1_X_FT**
  - Less Than or Eql (A<=B)
  - Source A: F25:5, 20.28872<
  - Source B: F27:6, 10.0<

**EX2_HI_X_W**
- ADD
- Source A: F27:8, 26.0<
- Source B: F27:2, 3.0<
- Dest: F27:16, 29.0<

**EX2_LO_Y_W**
- SUB
- Source A: F27:9, 34.0<
- Source B: F27:1, 3.0<
- Dest: F27:17, 31.0<
### Warning distance between cranes

<table>
<thead>
<tr>
<th>Relative Distance between Cranes</th>
<th>Source A</th>
<th>Source B</th>
<th>Dest</th>
</tr>
</thead>
<tbody>
<tr>
<td>Less Than (A&lt;B)</td>
<td>F28:2</td>
<td>F28:0</td>
<td>26.9521 &lt; 6.0</td>
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### Stop distance between cranes

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