Robotic Automation PPFS Report

Team 07
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Calvin College
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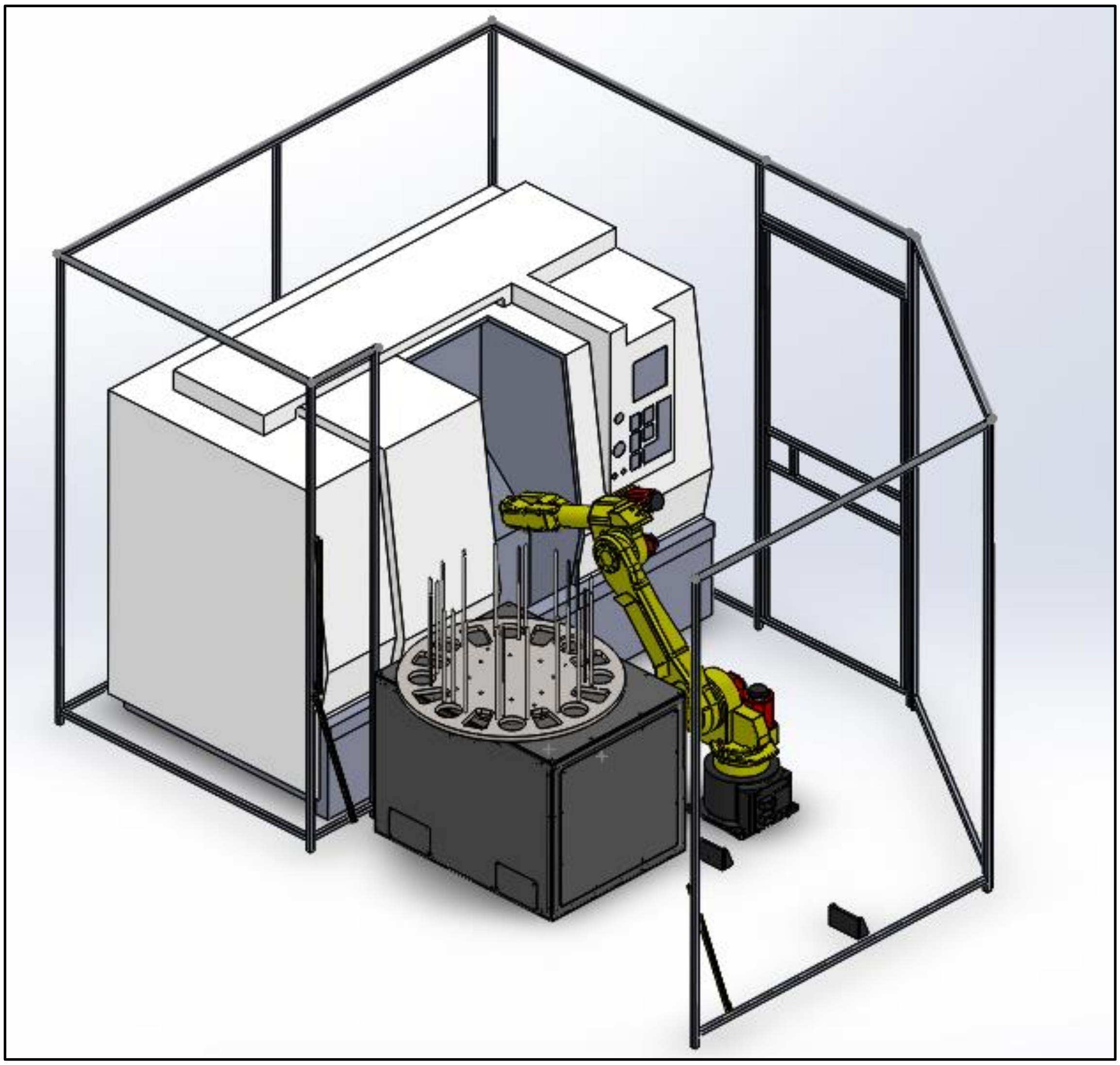

Project Abstract

At the beginning of the 2017 fall semester, the team was tasked with constructing a system which will properly load, re-orientate, and unload a cylindrical part for CNC lathe machining for Preferred Quality Services (PQS). The system will comply with workplace safety standards, perform reliably and robustly in the placing and orienting of parts, and will have the capability to track dimensionals, and compute process control capability during production. The system will be operable at a minimum rate of 120 parts per hour, and will be capable of functioning without supervision during that time. The system will be approved by the customer and will be ready for implementation immediately following the conclusion of the 2017-2018 academic year. On November 16, the customer notified the team that the old project was no longer applicable as the part was going to be canceled in the first quarter of 2018.

Due to the product cancellation, PQS assigned a new project to the team. This new project was to automate the loading and machining of a triangular shaped part. This system will also comply with workplace safety standards, produce consistent parts, and operate dependably. The machining of the new part is more complex; for this reason, the new system will operate at a rate of 75 parts per hour minimum. The new system will be approved by the customer and will be ready for operation by May 18, 2018.

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1 Overview of Project

1.1 Project Description

The objective of the project was to automate a task that was currently being done by a worker. The part being manufactured was a steel ring approximately two inches in diameter. It was made from a larger solid piece of stamped metal using two CNC lathes. The height of the part needed to be machined to a tight tolerance. However, near the end of the design process, the OEM notified PQS that the project will be canceled by the first quarter of 2018. Due to this, the team's project was scrapped.

PQS assigned the team a new automation project for a different part. The part is approximately an equilateral triangle with six inch sides. One side has a small notch cut in it for locating. The part has a thru hole in the center. This hole must be machined further to a specific profile by a single CNC lathe.

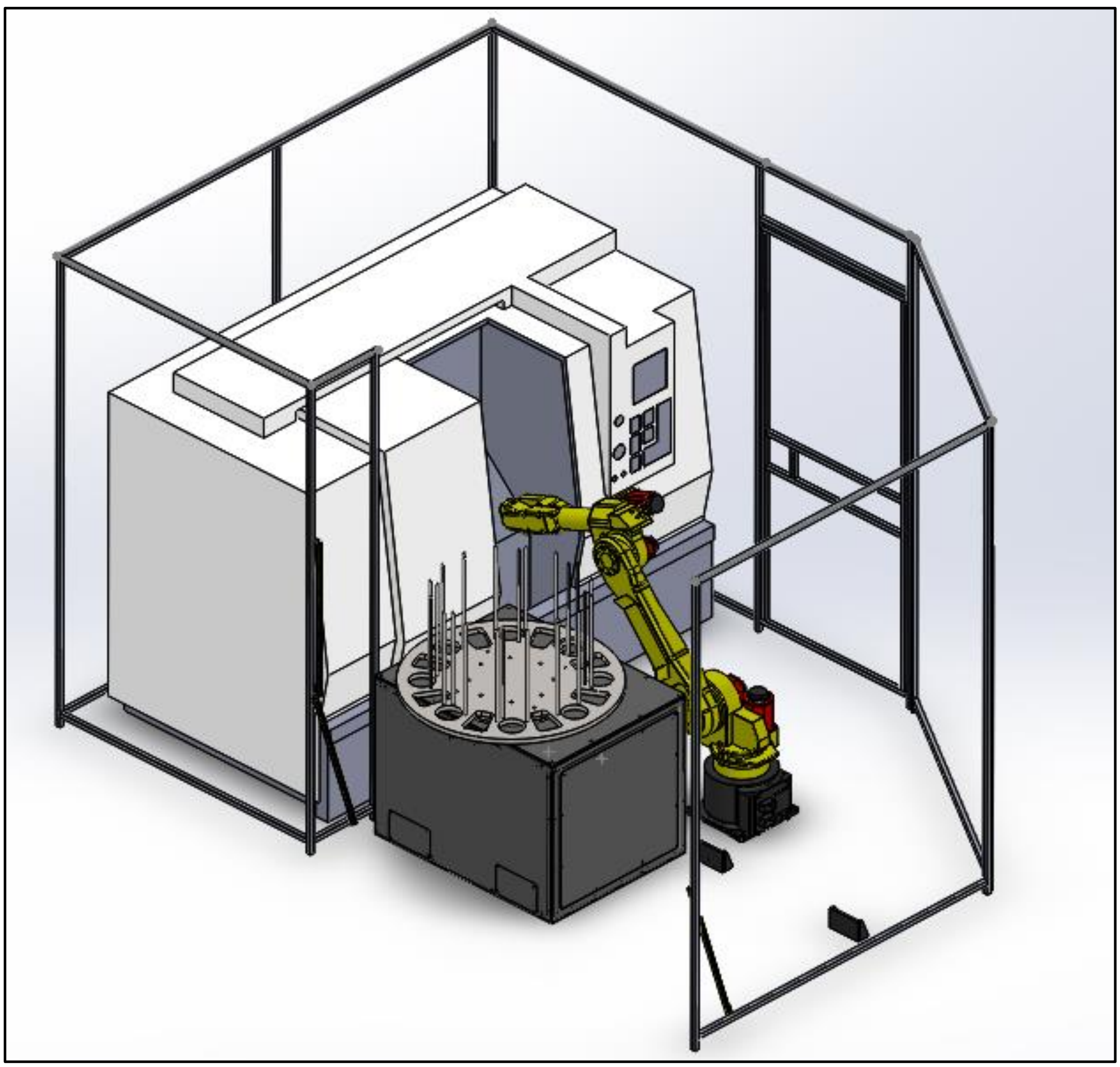


Figure 1: Project Cell with Robot Loading New Part.

1.2 Project Design

The overall design the team decided on for the initial project involved a robotic arm as the primary manipulator. The team designed a part loading system which would hold a large number of metal slugs, or the raw or un-machined metal, and dispense them one by one. The arm would grab this slug and load it into a lathe. Once the first lathe finished machining the first cut, the arm would grab the part again and place it into a second lathe where the machining would be finished. Then the arm would move the part into a measuring system. If the dimensions were deemed acceptable the part would be placed in a bin with other finished parts. If the final product was deemed unacceptable, it would be placed into a rejected bin. A Programmable Logic Controller, or PLC, would control the process, and caging would have been placed around the machines to prevent any potential injuries while individuals operate or monitor the system.

In the new project design, the part loader is a rotary system holding multiple stacks of raw parts. This system will orientate the raw parts in a consistent location for the robot to pick it up. A robot arm will then place the parts into a lathe and unload it when machining is completed. The final parts are placed in the correct bin. Similar safety requirements apply to the new project and will be implemented as the team begins to build and optimize the system.

1.2.1 Design Criteria

Since both the projects were for part manufacturing operations for the same company, most of the design criteria remained the same between the two projects.

The most important criterion for the customer is cost; cost is the ultimate driver for the project. If the cost of automating the process is greater than the cost of the employee's wages over the course the contract (two years) it is not worth pursuing.

The second most important criteria for the customer is scalability. The customer wants to use this project as a test run for future automation at the plant. This means standard industry practices should be used and the expensive equipment purchased should be applicable to different applications.

Other important and obvious considerations are reliability, safety, and reparability. The customer expects a robust system that will complete its task as dependably as possible. The customer assumes that the system will be built with all industry standard safety precautions, including OSHA requirements. The customer also wants the system to be built so that outside repairmen could quickly assess and correct any issues. This means that the system will need to be logically constructed and well documented. Implicit, less important criteria include minimizing shop footprint, minimizing noise, and appearance.

1.2.2 Design Norms

Since both the projects were for part manufacturing operations for the same company, the design norms remained mostly the same between the two projects.

The three design norms that are most pertinent to this project are humility, caring, and trust. The team should be humble when working with the technicians and engineers at PQS. They have been there longer and have valuable knowledge and skills that the team would want to utilize. The team should be sure to keep close communication with the workers at PQS to benefit from their knowledge.

The design should also be caring with respect to all those who work with it. Special care should be taken to ensure that no one could become injured using the system. The system should also avoid putting workers into non-ergonomic positions or requiring them to lift heavy loads.

Throughout the project, the team should also aim to establish trust with the customer. Clear and frequent communication is essential. Our customer should be aware of what the team is doing at all times. The team also need to ensure that the build is done logically, and the work is well documented so others can work on the system without the presence of the team.

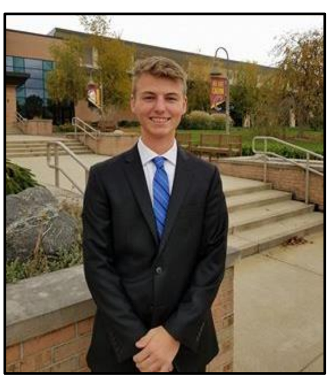
1.2.3 Design Alternatives

One alternative that would have significantly changed both projects was a custom-built arm. The team would be required to build a new robotic arm using steel and servo motors instead of purchasing one from a manufacturer. As discussed below in section 1.2.4, this alternative to a robotic arm was not recommended.

1.2.4 Design Decisions

Ultimately, the team decided that a custom arm did not align well with the customer's priorities. A custom arm would be difficult for outsiders to maintain and repair because it is inherently non-standard. It would also be less reliable than a purchased arm because the team’s troubleshooting and knowledge could not compare to the years of experience manufactures have. And finally, it would be difficult for the customer to re-program the arm for different applications because the team would be the only individuals knowledgeable of how to program it.

1.3 Team Members



Alex Keizer
Mechanical Engineer

Alex is a senior Mechanical Engineering student with minors in Business and Mathematics with an anticipated graduation date of May 2018. Alex previously held an internship with Best Metal Products where he designed and revised hydraulic cylinders. Currently, he is working as an engineering intern with Progressive Surface where he troubleshoots machine production problems. Upon graduation, Alex will continue working for Progressive Surface as a Mechanical Engineer. While doing this, he hopes to begin taking graduate school courses part-time for a Master’s in Business.

Josh Tempelman
Mechanical Engineer

Josh is a senior mechanical engineering student with a minor in math set to graduate in May of 2018. He has completed two internships with Yanfeng Automotive and works part-time during the school year with the Calvin College Engineering Department. After graduation, Josh hopes to either attend graduate school to study vibrations or obtain a job in automation or automotive.

Michael Bissetta
Electrical and Computer Engineer

Michael is a senior Electrical and Computer Engineering student with minors in Mathematics and Business. He is from Northeast Ohio and is set to graduate in May of 2018. He has worked for several different companies as an engineering technician, program manager, and consultant. His previous employment was through Eaton Corporation – Vehicle Business as a Program Management Intern over summer 2017. He hopes to work for a company as a Controls Engineer or Electrical Engineer and pursue an MBA to eventually grow in the company.

Nathan Casey
Electrical and Computer Engineer

Nathan is a senior electrical engineering student from Massachusetts who is set to graduate in May of 2018. He has worked for three summers in different departments of Abbvie Bioresearch. He has a strong background in robotics and controls and hopes to work for a company where he could expand his experience in these fields.

1.4 Team Organization

The team identified two forms of organization to utilize. Currently, the team utilizes Google Drive and the available Shared Drive through Calvin College to record and document progress. Each member of the team has their own file to record research, quotes, system designs, manuals, and more. The team started a "Parts-List" document to identify each design made with cost estimates and the equipment necessary to build the design. This has assisted in documenting the mechanical designs and will assist when the electrical panel is designed.

1.5 Schedule

The full schedule can be found in Appendix A.

1.6 Budget

The ultimate driver of the budget is labor cost. The customer, PQS, anticipated the project cost for the old project to be significantly cheaper than labor cost. Similarly, the new project is believed to be cheaper than the labor cost of labor currently being expended. Given that there are currently two shifts working on the project 6 days per week for both of the products, the justifiable cost is rather large. Since the nature of PQS's projects is rather volatile (hence the destruction of the initial project) our customer would like the system to have paid itself off within one year. The old project was scheduled to last another three years. The new project is anticipated to run for four more years. The budget then, based off of the wages and benefits of the employees is approximately $48,000. However, given the cost of the parts and how extremely important company budget is, the team is holding to an internal budget of $40,000.

1.7 Method of Approach

The team began the project by meeting with the customer to identify the overall project, its purpose, and any requirements set by them. After speaking with several individuals at the customer's facility, the team identified a few methods to complete the task. Each member of the team understood the basics of the project and the equipment necessary to successfully accomplish the project's goal, but research was required. The team assigned different areas of research to each member as the semester progressed until they were prepared to design each component. Once the team had final designs, they presented it to the customer and received approval. Unfortunately, the following day, the project was canceled, and the team was tasked with a new project. They once again began by identifying the project and began to research new methods. The team will continue to perform research and design a new system with the hope of finalizing the design in late January. When a new design is approved, they will begin to purchase equipment, to code the system, test it, and debug any issues.

2 Customer

2.1 About PQS

Preferred Quality Services (PQS) was founded in 1982. The company is located in Walker, MI. PQS operates within a 30,000 square foot facility and has approximately 200 employees. The company is ISO 9001:2008 certified. The company pursues excellence within their industry through attention to detail, commitment to quality, responsiveness, and customer satisfaction. The company has experience serving a wide variety of industries: automotive, furniture, aerospace, medical.

Preferred
Quality Services

Figure 2. Preferred Quality Services Logo.

PQS offers inspection, machining, and assembly services. Inspection is performed using visual, microscope, dimensional and gauge, machine vision, and CMM methods to confirm parts are to print. The company offers production machining as well as rework, CAD and CAM design, and prototyping with large part and 4^{th} axis machining capabilities. Assembly, kitting, and packaging services are also offered to serve customer's inventory, space, and time constraints.

3. Project Requirements

3.1 Interface Requirements

A multitude of interfaces must work in harmony to ensure the successful implementation of the first project. There is an interface between the PLC, the robotic arm the team will be using (subsequently referred to by its manufacturer: Fanuc), the loading system, the lathe (subsequently referred to by its manufacturer: Haas), and the measurement system. The PLC controls all other parts and ensures harmonious interaction. The part loading system must consistently place pucks in a predefined orientation, which the Fanuc will be programmed to recognize as the pick-up location for a new puck. The Fanuc then interfaces with the Haas, as the two subsystems must then coordinate the door-opening and part loading/unloading. Once this is complete, the Fanuc moves to part measurement, at which point the automated arm must interface with a part measurement system to evaluate the quality of the finished product. Once this evaluation is complete, the part moves to binning, where the Fanuc must interface with the part measurement system to determine whether the part should be placed with the completed parts or the rejected parts.

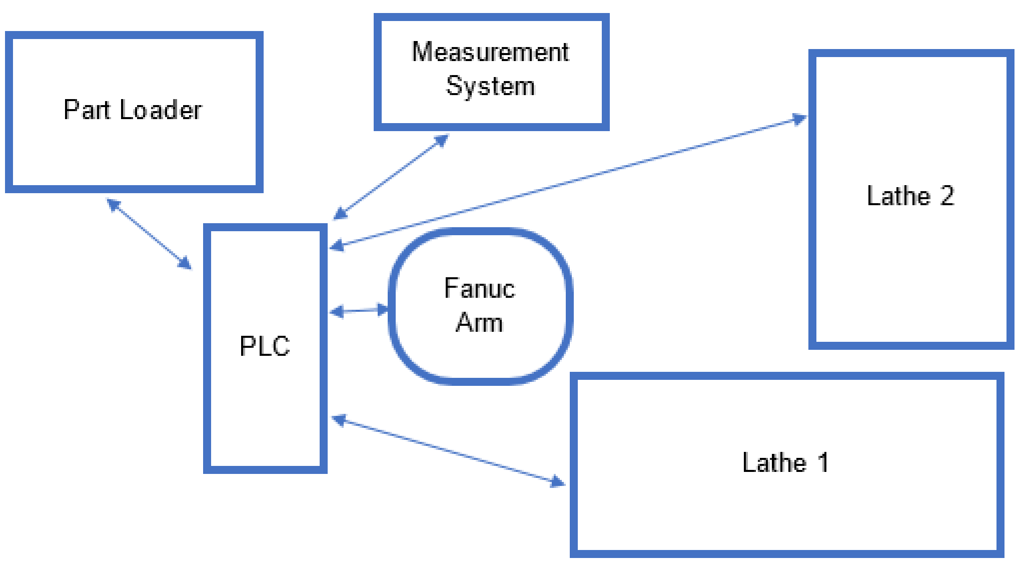


Figure 3: Block Diagram of PLC Interfacing of Original Project.

Expanding on the human interfaces of the system, it should be stated that the purpose of this project is to automate the machining and measuring process as much as possible. As a corollary, the human interface should be minimized. The interface requirements, to this date, can be broken into three components: coding, stacking, and maintenance. While the PLC script created for the design will meet customer requirements, there is still the possibility that PQS employees will seek to modify the process in the future, resulting in a modified script. For the physical interface, PQS employees will be tasked with the stacking of parts in the part loader in the specified orientation. As far as routine interface requirements are concerned, the goal for the team, as defined by PQS, is to eliminate the human interface as much as possible. The customers only interaction with the process should be to load in new unfinished parts and package the box of finished parts.

In the second project, the number of interface requirements is decreased. Since there is no measurement system and one less lathe, the communications can be summed up in the figure below. Since the manufactures for the lathe, robotic arm, and PLC did not change, the communication requirements are very similar between the projects.

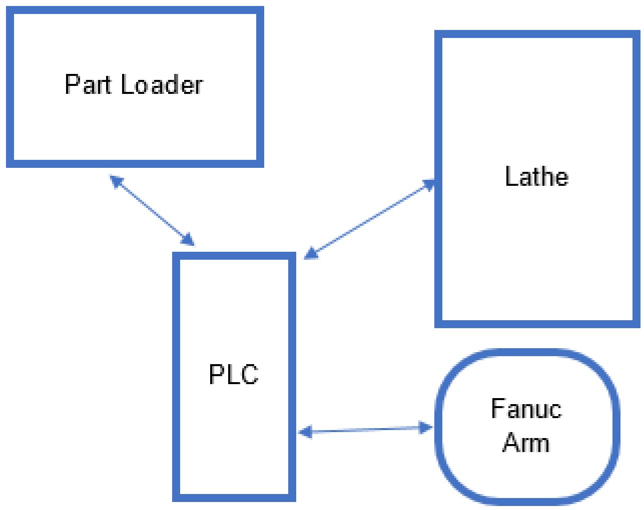


Figure 4: Block Diagram of PLC Interfacing of New Project.

3.2 Functional Requirements

The first project needed to correctly load, unload, measure, and bin a minimum of 120 parts per hour. Furthermore, the system should have been able to operate autonomously for periods of at least two hours. This means that for the span of 120 uninterrupted minutes, there has been no auxiliary aid required for the system to meet production requirements. This requirement precluded the prospect of any human assistance in part-placing, measuring, or binning.

Expanding on the pick-and-place requirements, the system must also have part-measurement and analysis capability. The system must have performed a minimum of four height-check measurements per part. Furthermore, the system should have then discerned if the measured part meets customer requirements, and delegated the binning of the part to a good or bad part bin accordingly. The measurement and binning process should have conformed to the aforementioned requirements of full autonomy for 120 minutes.

The new project has slightly different requirements. The machine needs to process 75 parts per hour. The machine should be able to operate for as long as possible without human interference. The team decided that 4 hours of autonomous operation was a realistic design goal.

3.3 Performance Requirements

The implemented system for the first project needed to meet functional requirements stated above with zero tolerance for malfunction or process deviation. For the part-loading requirements, the previously stated part-flow rate of 120 pucks per hour needed to be achieved while maintaining proper loading orientation. This meant that the puck must be placed for arm pick up in the orientation suitable for first face machining. Deviation from this desired orientation may result in a bad part or possible damage to the Haas CNC, so there is zero tolerance for incorrect orientation. As for part pick-and-place, the Fanuc was required to load the part into the CNC properly every time, ensuring the part is fully secured in the jaws of the lathe.

For the measurement of parts, the Fanuc arm should have interacted with a laser measurement system to evaluate the thickness of the finished product at 4 different locations for each part exiting the second lathe. This made the minimum measurement requirement to be 480 per hour, and the precision of the measurement system should consistently and repeatedly measure for a tolerance band of ±0.005 inches. Fanuc robots and laser measurement systems are notoriously reliable and can perform within an extremely tight tolerance band of 0.05mm, so the performance requirements are deemed attainable.

All requirements that applied to the first project also apply to the second project. The arm must still grab from the same place every time. One change is that the lathe of the new machine has an adjustable chuck that can account for many irregularities in the placement of the part. This gives the team greater margin for error and is part of what makes measuring the part unnecessary.

3.4 Environmental Requirements

The environmental requirements are the same for both projects.

3.4.1 Customer Defined Requirements

For direct customer-defined environment requirements, the principal point of concern conveyed to the team is that of spatial constraints. Being as the system is to be implemented into an industrial high-volume manufacturing environment, it is beneficial for PQS to have a system which is a compact as possible. Although there is not yet a determinate spatial requirement, the system should not inhibit the maneuverability of workers within the vicinity of the system.

Safety is a priority of PQS, so further environmental constraints are that the worker safety must not be jeopardized by the implemented system. To combat this, requirements of the system specify that there must be an automatic shut-off of the Fanuc and CNC when the safety cage is breached. Furthermore, there must not be the necessity for human workers to carry or lift over 50 pounds of material, and there must be no hazards on the part loading system which could lead to serious hand injuries.

3.4.2 OSHA Defined Requirements

Expounding on safety requirements, the Occupational Safety and Health Administration (OSHA) offers literature on safety standards and hazard assessment for automated manufacturing systems. The common sources of accidents for a robotic arm, as defined by OSHA, are impact, crushing and trapping, and mechanical part accidents. It is required that these incidents are prevented, so safety equipment (safety cage, auto-locks, etc.) must be evaluated and implemented. Worth noting is the OSHA acclaimed statement that a majority of accidents with automated systems occur during teaching, so it is strongly suggested that experienced controls engineers be present, or at least be able to provide input, for the teaching stages of implementation.

3.5 Project Deliverables

The deliverables of the projects can belong to one of two categories: Engineering 339/340 deliverables and PQS deliverables.

The end deliverables for Engineering 339/340 to fulfill the team's obligations in the course are to produce a document fully explaining the final design (PPFS report) as well as prepare a presentation to display the work which the team has performed at the senior design expo.

Since the project changed midway throughout the year, the PPFS will detail work done on both projects. But the final presentation will focus mostly on the second/final project.

The deliverable presented to PQS will be the successful implementation of the final system. This includes the correct installment and programming of the final system and all auxiliary sub-systems. Furthermore, the deliverable to PQS entails full troubleshooting and refinement of the implemented system, documentation of how the system was designed, and information manuals for the sub-systems (safety-cage, pneumatic cylinders, laser-measurer, etc.) with suggestions of future applicable usage.

4 Initial Project Design

4.1 Fanuc 6-Axis Robotic Arm

During our research and design phase for the first project, the team identified a 6-axis robotic arm to be the most essential and expensive equipment necessary to successfully automate this process. The robotic arm functions as a transferring device, moving raw and completed parts to and from different components of the system. The arm must operate successfully by smoothly maneuvering between CNC lathes, the loading system, and any additional systems necessary to successfully automate this system. The arm would have been programmed to pick up the raw part at the destination point in the loading system, maneuver into the CNC’s without collision, and drop the part off at the measurement system, where the machined part is measured and pushed different directions based on if it is faulty or not. A 6-axis arm allows movement in six directions. This is displayed in the following figure.

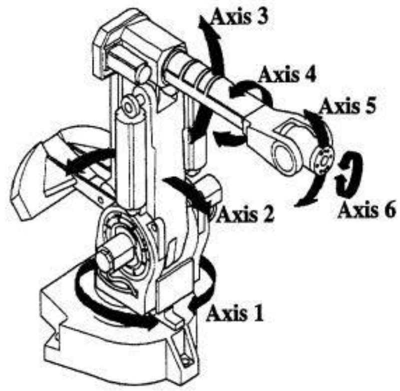


Figure 5: 6-Axis Robotic Arm Movement.

http://www.leadsingh.com/wp-content/uploads/2016/09/robot.jpg

These axes allow the arm to easily maneuver into the CNC lathe chamber and locate the gripper, where raw parts are placed. As the number of axes increases, the more complicated the maneuverability is. With that said, most robotic arms are built with six axes.

Robotic arms are powered by the controller, which typically contains the power management systems, safety circuits, PLC's, relays, and any other electrical component used to power or automate this system. Some controllers are smaller, and will require an additional control panel to hold the necessary equipment. The first-project would most likely require an additional control panel to scale this project in the future. Additionally, the robots require a teach pendant to operate or move the arm. All programming is done through the teach pendant in Karel form. Without this piece of equipment, the arm cannot operate.

While operators can program Fanuc robotic arms through the teach pendant, a large majority of industrial manufacturers use PLC's, or programmable logic controllers, to manage all functions, or programs, that the arm can perform. PLC's are required when the I/O communication count exceeds the number of which the arm can control alone. Typically, when an automated system is complex and has several processes utilizing different systems, such as a conveyor belt or CNC machines, it requires PLC's. PLC programming is similar to Fanuc robotic arm programming, but they have their differences. PLC's have continued to improve and have become the industry standard for automating manufacturing.

PLC's can be programmed in five languages or types of programming. The most common and best programming type for controlling several files is ladder diagram logic. This is used in industry today because the user can easily control what files, subroutines, or small sections of code to perform. Sequential function charts can withstand more advanced programs when comparing ladder logic. This type of programming is commonly used sequential programming - where programs are run back-to-back. Function block diagram programs are described in terms of graphical blocks. It is a graphical language that depicts signals and data flow through blocks or reusable software elements. Structured text programming resembles the languages using "If-Then-Else," "While," or "Repeat" statements. And the final type of programming is instruction list programming, where it uses mnemonic instructions from ladder logic programming and sends the instructions to the PLC via a programming terminal. During this project, the team will utilize ladder diagram logic to call functions.

Prior to identifying the make and model of a 6-axis robotic arm, the team performed some primary research and found some additional research - secondary research - on different makes and models. Each arm operates similarly but has its differences. During this research, the team identified two different manufacturers - Fanuc and ABB. The customer initially stated they would prefer a Fanuc robot over another manufacturer, but they wanted Team 07 to perform additional research to identify which manufactured arm is best for the team's design solution. Fanuc arms are well known for their performance and efficiency. Fanuc arms are robust systems, commonly used in industry.

4.1.1 Product Manuals

The team received several quotes to this date for a refurbished 6-axis robotic arm – three quotes for a Fanuc 6-axis robotic arm and two for an ABB robotic arm. Fanuc manuals can be found at the end of this report.

4.1.2 Communication with PLC

The Fanuc arm will be connected to the PLC with an ethernet cable. The communications through this cable will be similar to digital inputs and outputs on the PLC's I/O blocks. The Fanuc's controller, operated with the pennant, will determine which inputs and outputs to use and how they will appear to the PLC. This allows the PLC to interact with the Fanuc as it would a much simpler device. The "digital outputs" from the PLC will indicate to the Fanuc what subroutines should be activated and the Fanuc will send digital signals to the PLC's "inputs" to indicate the machines state and its progress through the subroutines. The end of arm will be operated entirely through the Fanuc's controller, the PLC will not be aware of their existence.

4.2 End-of-Arm

The end-of-arm system is attached to the end of the Fanuc robotic arm and is responsible for securing the interface between the robot and the part. The end-of-arm is a vital component of the system, as it is the means by which parts are maneuvered throughout the machining, measuring, and binning processes. The arm itself has several points of I/O near the end of arm that can be used instead of PLC I/O to simplify the difficulty of running cables up a moving arm.

4.2.1 Product Manuals

Product manuals produced by Magma, Adams, and End Of Arm Tooling Inc. allow Team 07 to learn more about the options available. The review of the literature revealed that traditional end-of-arm designs operate utilizing claw-like mechanisms or suction. While the literature regarding these design options is informative, design constraints which are elaborated on in section 3.2 revealed electromagnets to be a favorable solution. Review of design catalogs reveals that the electromagnets of the dimensions desired for this project were not readily available, though many manufacturers offer custom-built electromagnet solutions.

4.2.2 Electromagnetic Testing

Electromagnetic testing was projected to begin in the early months of 2018. The tests were designed to determine capability of variable-force features as well as test for communication interference.

4.2.3 Design Progression

Traditional end-of-arms, also known as end effectors, typically utilize a claw configuration suction to attach parts to the manipulator. Initially, the claw configuration appeared most attractive. The team envisioned a three-prong clamp which would entrap the parts in a similar fashion that the HAAS lathe grips the part for lathing. This designed is intuitive, but would be very difficult to execute as the exposed side profile of the finished part is very narrow when gripped in the secondary CNC lathe, meaning near perfect precision is needed to grip the part. Furthermore, the lubrication applied to the part will cause low friction between the end effector and finished product, which would further inhibit the performance of a claw system.

When it was discovered that the pucks are magnetic, the team began developing ideas for and end-of-arm system utilizing the magnetic properties of the material. The use of circular electromagnets was seen as the superior to claw systems, since the full front face of the part may be used for contact and the attachment is not dependent on friction. The electromagnetic end-effector can operate by a DC power supply and will be controlled by a relay. For the sake of ability to activate and deactivate the end effector as needed, high-low power input electromagnets were pursued for the applications in this project. Possible electromagnet solutions were provided by McMaster Carr, Magma, and Magnetic Sensor Systems.

In order to reduce the length of travel that the Fanuc must execute, it is beneficial to design an end-of-arm system which allows for the carry of multiple parts at the same time. This allows the end of arm to bring an un-machined part to a CNC, unload the machined part with the free effector, and place the un-machined part into the CNC jaw within the same visit to the CNC machining housing. End of arms utilizing two electromagnets at 90-degree and 180-orientations were evaluated. While the 90-degree separation is not uncommon for end-of-arm systems gripping multiple parts, the 180-degree separation allows for a slimmer profile which would be less congestive inside of the machining house of the CNC lathe.

It should be noted that the aforementioned industry practice of utilizing suction as a gripping mechanism was easily ruled out for the production process originally presented to Team 07. This is because the center of the part is completely bored through on the second CNC lathe, leaving no surface for suction to take effect. Electromagnets, however, can still attach to the part with ease regardless of the presence of a gap in the center of the part.

4.2.4 Final Design

Ultimately, the team elected to pursue electromagnetic end effectors for the first project. This choice was deemed optimal because it is easy to activate/deactivate to grip and release parts. Although the electromagnets were not purchased, the team is narrowed down manufacturers to supply the desired end-of-arm. The desired specifications for the electromagnet would entail an electromagnet to be roughly 2.25 inches in diameter to reconcile the dimensions of the finished part. A visual for a typical cylindrical electromagnet is provided by Magma and displayed below.

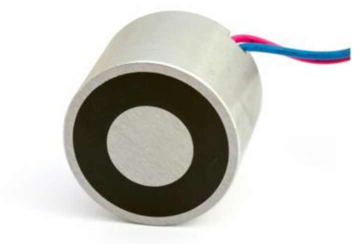
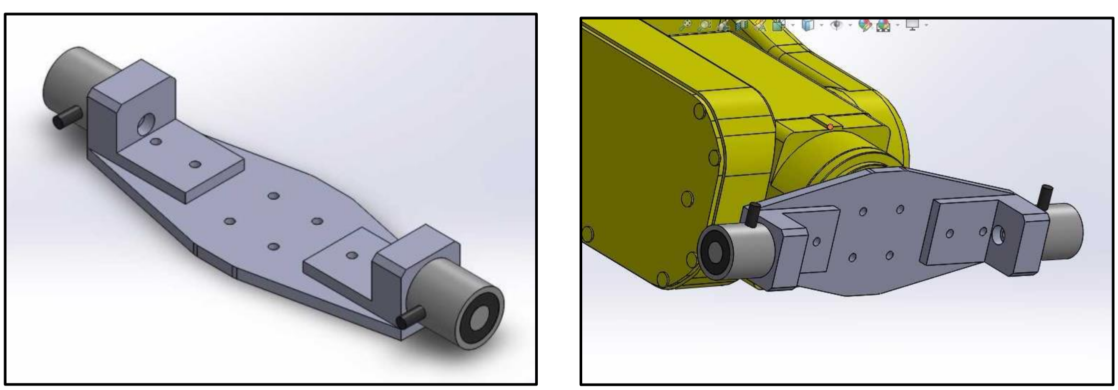


Figure 6: Electromagnet with High-Low Input.

http://www.magmamagnets.com/electromagnets-solenoids/round-electromagnets/

The end-of-arm design called for electromagnets to attach to the end-effector at a 180-degree angle. This would allow for the carrying of two parts simultaneously. The end-of-arm design is compatible with the Fanuc robot, and would have been securely attached to the arm via bolts. The end-of-arm will be machined from non-magnetic material. A preliminary CAD model of the first-project end-of-arm provides a visual of the intended system which is shown below.



(a) (b)

Figure 7: (a) CAD Model of End-of-Arm Design. (b) CAD Model of End-of-Arm Design with Installed on Fanuc Arm.

4.3 Loading System

4.3.2 Design Solutions

The design of the loading system was largely driven by the customer requirements. For the first project process, the customer produces one part every 30 seconds. Due to the two-hour autonomous operation requirement, the team was required to design a system capable of holding a minimum of 240 raw parts.

The raw part for the first project is a steel cylindrical, slug-shaped component. The raw part is a punch out from another process. Because of this process, the raw parts vary slightly in mass and diameter. The part weighs approximately 8 ounces and measures roughly 2.5” in diameter and 0.5” in height.

The customer specified that the machine cell be capable of operating for two hours autonomously. The process time for the first project for the CNC lathes is 30 seconds for CNC #1 and 28 seconds for CNC #2; the two CNC machines operate simultaneously. Hence the limiting factor was the 30 seconds of machining on CNC #1. Therefore, the part loader had to be capable of containing a minimum of 240 parts.

PQS notified the team that the raw part must be loaded into the CNC with specific orientation. The process utilized to manufacture the raw part results in one face being flatter than the other. When loading the part into the CNC, this flatter face must be placed flush with the chuck as it produces a better part. For this reason, the part loader of the first project was required to ensure that the part orientation properly to be consistent with the current manual loading method.

Additionally, the part loader must be capable of dispensing the part into a consistent location. Dispensing the part into a consistent location allows for the robot to not require machine vision. This will significantly reduce cost as well as the time required for testing and programming.

The team decided on a gravity-fed part loading design. The system consisted of five part stacks with approximately 50 parts per stack for a total of 250 parts. Under the first-project design, an employee of PQS would load the part loader paying careful attention to the orientation of the part. Then, the employee will signal to the PLC that a stack is properly loaded. The part loader would then actuate a pneumatic cylinder connected to the part loader causing one raw part to be dispensed on to the ramp where the robot will pick the part.

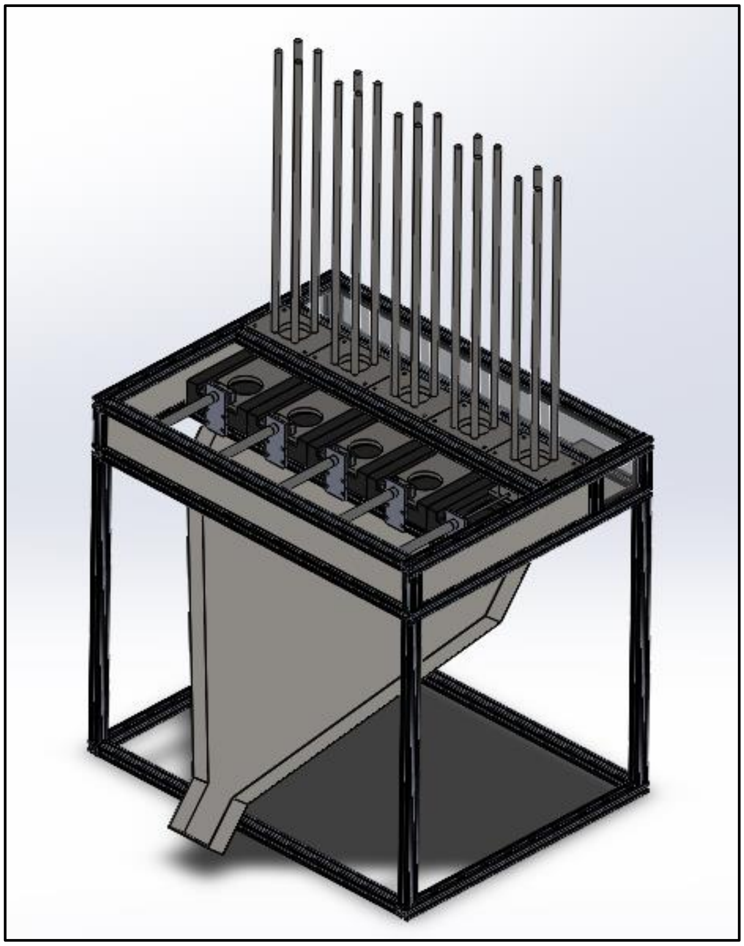


Figure 8: Part Loader System with Top Cover Removed.

There are many sub-components included in the first-project system. The frame of the part loader was specified to be constructed using aluminum extrusion bar (80/20) held together with T-nuts. This would minimize the amount of welding required, and would allow for the design to be modular due to the slotted design of the 80/20. The pneumatic cylinders are a purchased component and would be connected to the shop air at the customer facility. The part loading slide block is connected to the pneumatic cylinder and was planned to be manufactured by the team out of 1020 steel. This block rides in a groove cut in the dispenser block. The dispenser block was to be machined out of Delrin. This would allow the raw part and the dispenser block to slide with relative ease. Additionally, Delrin is highly machinable which would have aided the team in its manufacturing. The part stacker component is the only component of the part loader that requires welding. However, the welding required is minimal. The part ramp was specified to be constructed out of 14-gauge steel. This would allow for the ramp to be manufactured within the machine shop at Calvin College. The ramp required a plexiglass or steel cover to ensure the part for not rebound off the ramp after dispensing.

4.4 Haas CNC Lathes

The current system in place is operated by a worker and uses two Haas CNC's to do all of the machining. For the first-project automated system, the customer preferred to continue using Haas CNC's for the sake of consistency.

4.4.1 Model and Design

The customer will be providing two new CNC's for this project. These CNC's are the 2008 Haas SL20. Due to its age, official CAD models are not available for this particular model of CNC, so measurements will need to be taken in the field. The manual for the particular model of Haas CNC being used is attached in the appendix.

4.4.2 Communication with PLC

The Haas controller communicates with outside devices through ASCII codes sent through an RS-232 protocol with a selectable baud rate. Entire machining operations can be sent to the CNC in the form of M-code or G-code. However, this is only for writing new programs to the list of Haas programs, it is not possible to select a program from the list of available programs using. Once a program is selected, a single button press executes the entire program, including grabbing the part and opening and closing the guard doors. RS-232 can also be used for direct numeric control (DNC). This bypasses the machine controller and will execute a program line by line as provided by the PLC.

Similar to how there are two ways of writing to the Hass, writing new programs and DNC, there are two ways to learn the status of the CNC. The first way is again using RS-232. The status of the controller and several datum from the CNC can be accessed with machine data collection through Q commands. The most meaningful data that can be gathered is cycle time, tool in use, power-on time, mode, and most importantly status. This would allow the PLC to know whether the CNC was active, ready, or in error. The alternative to this form of data collection is the installation of an 8 Spare M-Code relay board. This optional hardware adds eight digital relays which indicate the status of the CNC. This would allow the PLC to know if the CNC is running, stopped, stopped due to an error, or in a different state.

4.4.2 Communication Options

Given the different ways the team can read and write to the Hass, there are two ways the team could approach PLC to CNC communication, with RS-232 and without RS-232. If the team decides to use RS-232 they would use direct numeric control to drive each individual action of the CNC. The status of the CNC could be determined using Q commands through the same RS-232 port. This option allows maximum control over the machining and slightly better data collection.

The other option bypasses RS-232. The active program would be set at the beginning of the day by the operator and the PLC would only control the starting of the program. It would start the program by using a relay in the place of the usual operator start button. Then the PLC would collect data from the relays to determine when the process was finished and whether there were any errors. This option could be implemented much faster but it does involve the purchase of an additional part and less control over the machining process.

4.5 Safety Cell

4.5.1 Interlocker Design

The team planned to purchase an interlocking device to lock the cell when the system was running. This locking device would only allow someone to enter the cell when the system was shut off. If the door was forced open, the system would automatically shut down, preventing any injury or worse. The CNC would continue to operate if the lathe door was closed, and the lathe was in the process of machining a part. The overall purpose of this interlocking device was to stop robot and part loader movement when an operator enters the cell. The device would contain a variety of buttons and switches, including an E-Stop button and key switch. Following a set procedure to enter the cell will be required. A request-to-enter button may be included in this design.

4.5.2 Cage Design

The team recognized the system would require a safety cage to prevent any injury while the system is operating. There are very few areas where someone could get hurt, but the cage system would prevent any potential injury. A cage system is required to eliminate any risk to employees, while complying with OSHA and any other set standards. PQS requested a safety cell within the team's system design, and the team designed a system to meet this request.

The team has received one quote from Industrial Controls, based out of Zeeland, MI. Their caging is slightly more expensive than a typical caging system, but it is also more durable and long-lasting. The caging is made by Velox Machine Guarding and may be cut to the customers liking. The Velox caging system is lightweight, yet it is made from strong 8-gauge wiring. Each panel has a reinforcing ridge, adding extra stability without adding weight. Additionally, the posts provide additional support, strength, and stability to the panels.

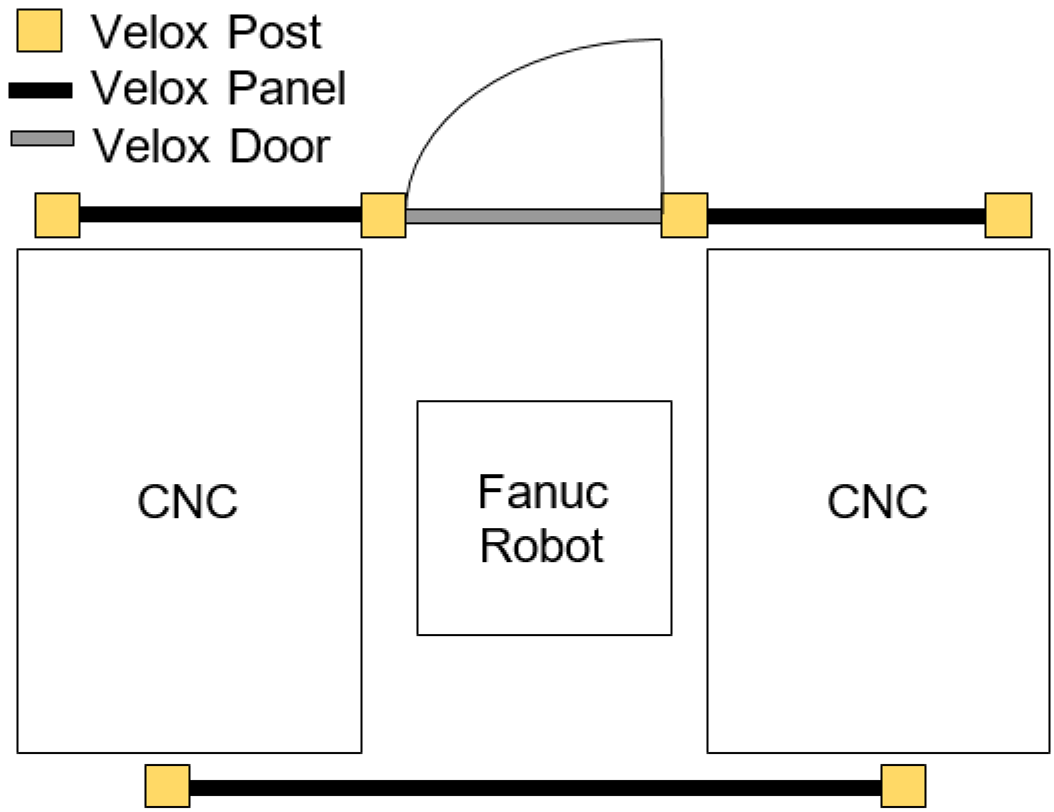


Figure 9: Velox Cage Layout.

4.5.3 Additional Solutions

The Velox cage design in the figure above displays the team's unofficial final design for the first-project system. As the team progressed the project, they were going to determine whether this design would fit well with the requirements. Additionally, the customer was going to approve this design prior to purchasing any equipment.

The design did not have caging surrounding the entire system to reduce cost. The panels were to be attached to the CNC to reduce the cost of the system. If this doesn't comply with OSHA or PQS standards, this design was going to be changed.

4.5.4 OSHA Requirements

OSHA requires that the system complies with ANSI/RIA R15.06 standards. Relevant restrictions to this project require that the system include safeguard devices. The safeguard device shall inhibit any interaction between a worker and an operating robot. This may be in the form of a cage of a fixed barrier. Furthermore, there should be presence-sensing or open-cage-identification systems in place to detect any breach of the operating vicinity, resulting in a shut-down.

4.6 Storage System

When an individual part is finished it needs to be placed somewhere. Ultimately, all finished parts must be stored in such a way that they can be shipped to the customer with minimal jostling or damage to the part.

4.6.1 Design Solutions

There are several methods which can accomplish this task. The simplest way is to have the Fanuc arm drop the parts into a bin. There would be a passed bin of parts that met the measuring specification and a failed bin of parts that did not. Special care would be taken to ensure that the parts were not dropped so far as to damage them. While this method would be the quickest to implement it would require an employee to rearrange the parts in a stacked, ordered fashion. This doesn't increase the amount of labor required for the system by much since the part loader would need to be refilled around the same time that the completed parts would need to be rearranged.

Another option would have been to have the robotic arm stack the parts neatly in the box. Although simple in theory, this idea comes with a host of problems. There would need to be a form of a vision system for the arm to know how high each stack was and where it should place the part. The system would also need to account for the magnetic pull of the end of arm on the already stacked parts.

The magnetism problem could be solved by an additional system that used a movable ramp. The arm would place the part at the top of the ramp and the ramp would move to ensure that the part fell in a stacked position in the box. This solution would still likely require a vision system and lots of testing because it is difficult to get parts that fall a short distance to an exact location.

4.7 Measurement System

When the team received the first project, they were tasked with designing a system to measure each completed product. As of now, the operator measures the height of each completed part at four places with a micrometer. The team researched a few forms of measurement, including vision, laser displacement, and a touch-based probe. Each of these pieces of equipment is commonly used in the industry today, proving they are reliable solutions. The team received quotes from Cognex Corporation for a vision and laser displacement system and a quote from Keyence for a touch-based probe. After performing more research and talking with mentors, the team opted to use the Keyence probe (GT2-H32). The GT2-H32 model can measure up to 32 mm, or 1.26" and is accurate up to 0.5µm, or 0.02 Mil. The final parts must be accurate to 1 Thou, so the resolution of the probe is within the requirements.

4.8 Floor Layout

The floor layout, displayed below, is very simple because of the required systems. The team designed the layout to allow the robot to easily access any other system. The Fanuc robot sits in the center of everything with two CNC's on opposite sides and the loading system across from the measurement system. The measurement system is not displayed in the photo below because that system was not designed.

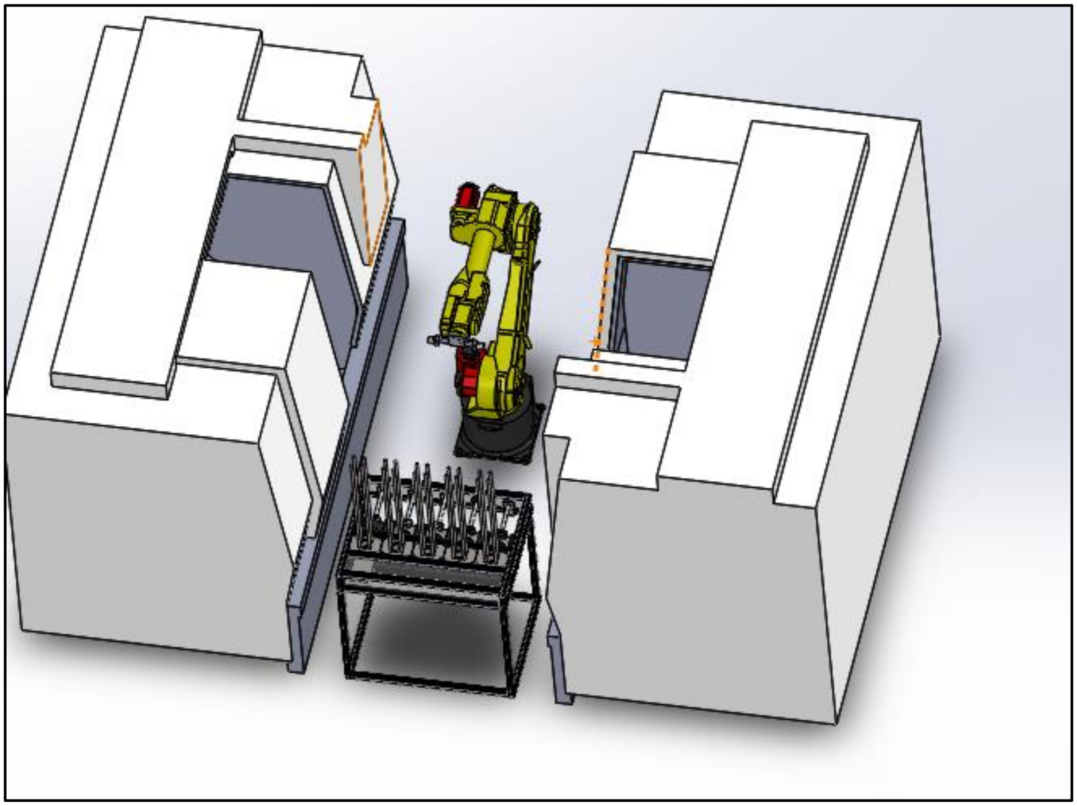


Figure 10: Preliminary Floor Layout.

The overall floor design reduces the amount of space needed for the cage. One flaw with this design is the amount of room available for an operator to access the CNC's for a tool change or to address any maintenance issues.

5 Initial Project Cost Analysis

Since this project was canceled before budgeting was complete some items will be marked TBD. These prices were not locked in at the time of cancellation and the team decided that they were not relevant enough to quote any more.

5.1 Fanuc 6-Axis Robotic Arm

The team has received several quotes for the arm that will be used in the design. These quotes came from Antenen Robotics from West Chester, Ohio. This quote was initially requested at the beginning of this semester to identify a cost estimate for robotic arms. The cost breakdown can be found below.

5.1.1 Component Cost Breakdown

Table 1: Initial Robotic Arm Cost Breakdown.

ITEM DESCRIPTION	QTY	UNIT COST	TOTAL COST
Fanuc M-16iB/ArcMate120iB RJ3iB	1	$23,500.00	$23,500.00
Fanuc Collision Guard (OPTIONAL) - Recommended	1	$1,200.00	$1,200.00
Fanuc Hotline Phone Support (OPTIONAL)	1	$1,000.00	$1,000.00
EE Connector Upgrade (OPTIONAL)	1	$975.00	$975.00
Antenen Robotics Phone Support	1	$0.00	$0.00
Robot Mounting Base	1	TBD	TBD
Additional Control Panel	1	TBD	TBD
TOTAL COST	-----	---------------	$26,675.00

5.2 End-of-Arm

5.2.1 Component Cost Breakdown

Table 2: Initial End of Arm Cost Breakdown.

ITEM DESCRIPTION	QTY	UNIT COST	TOTAL COST
Electromagnets	2	$60.00	$120.00
Aluminum 6061 Bar Stock	24 in	$2.58/in	$62.00
TOTAL COST	-----	---------------	$182.00

5.3 Loading System

5.3.1 Component Cost Breakdown

Table 3: Initial Part Loading System Cost Breakdown.

ITEM DESCRIPTION	QTY	UNIT COST	TOTAL COST
Pneumatic Cylinders	5	TBD	TBD
Air Hose	TBD	TBD	TBD
Aluminum 6061 Bar Stock	TBD	TBD	TBD
Delrin Bar Stock	TBD	TBD	TBD
1-0” x 1-0” 80/20 Aluminum Extrusion Bar	950 in	$0.23/in	$218.50
Pneumatic Solenoids	5	$30	$150
Inductive Proximity Sensors	5	$20	$100
Indicator Lights	5	$20	$100
Miscellaneous Hardware	1	$50	$50
TOTAL COST	-----	--------------	TBD

5.4 Haas CNC Lathes

Preferred Quality Services is currently producing the part on two Haas SL-20 lathes. However, to reduce downtime during installation and testing, the customer plans to purchase two more lathes.

The customer would have overseen the purchase of the CNC lathe. Preferred Quality Service is taking responsibility for purchasing this equipment because they have the best contacts to find used CNC machines at a competitive price. Additionally, they have the best knowledge of what CNC can perform the quality of work required for this project and future projects. It is possible that the team will need to purchase a door opener depending on the type of CNC provided. Depending on the method of control used, additional relays may need to be purchased.

5.5 Safety Cell

5.5.1 Component Cost Breakdown

Table 4: Initial Safety Cell Cost Breakdown.

ITEM DESCRIPTION	QTY	UNIT COST	TOTAL COST
6ft High 94" Panel	1	$179.18	179.18
6ft High 46: Panel	2	$107.97	215.94
3ft Swing Door	1	$324.12	$324.12
Door Posts	2	$100.00	$200.00
Panel Posts	4	$72.70	$290.80
Safety Interlocker System	1	TBD	TBD
Additional Accessories	TBD	TBD	TBD
TOTAL COST	-----	--------------	$1,210.04

5.6 Measurement System

5.6.1 System Cost Breakdown

Table 5: Initial Part Measurement System Cost Breakdown.

ITEM DESCRIPTION	QTY	UNIT COST	TOTAL COST
Gocator 1380 Laser Measurement	1	$4,200.00	$4,200.00
Additional Cables (ft)	TBD	~$350.00	~$350.00
Measurement Platform Materials	TBD	TBD	TBD
TOTAL COST	-----	--------------	$4,550.00

5.7 System Control

5.7.1 System Cost Breakdown

Table 6: Initial System Control Cost Breakdown.

ITEM DESCRIPTION	QTY	UNIT COST	TOTAL COST

Allen Bradley Micro850 Controller	1	$650	$650
Human Machine Interface	1	$500	$500
Safety Circuit	1	TBD	TBD
Relays	12	$30	$180
Panel	1	$500	$500
Wiring	1	$300	$300
TOTAL COST	-----	--------------	$2,130

5.8 Total Project Cost

5.8.1 System Cost Breakdown

Table 7: Initial Complete System Cost Breakdown.

ITEM DESCRIPTION	QTY	UNIT COST	TOTAL COST
Robotic Arm	1	$26,675.00	$26,675.00
End-of-Arm Tooling	1	$182.00	$182.00
Safety Cage	1	$1,210.04	$1,210.04
Part Measurement System	1	$4,550.00	$4,550.00
Part Loading System	1	TBD	TBD
Control System	1	$2,130	$2,130
TOTAL COST	-----	--------------	$34,747

6 New Project Design

6.1 Fanuc 6-Axis Robotic Arm

6.1.1 Alternative Arm Options

During the team's discussions with PQS, the customer expressed interest in exploring less expensive options for the robotic arm. In particular, PQS was convinced that a gantry arm would be much cheaper than a 6-axis arm. Gantry arms are supported from the top on moving rails, so it can hold a large work envelope. However, when the team talked with suppliers of gantry arms, the team found that arms for our application started at $30,000. Since our application requires movement across multiple axes, the gantry system would also need to have an additional axis on the arm that hangs down. This extra weight requires extra support and the cost increases very quickly.

The team also investigated the possibilities of using a small six axis arm. M-6iB / ArcMate 100iB RJ3iB costs $2000 dollars less than the larger M-16iB/ArcMate120iB RJ3iB. However, this version had 1 foot 7 inches less of reach and nine pounds less of payload. Two factors caused the team to not pursue this design. First, for a 9% cost decrease, PQS would purchase a machine with significantly fewer capabilities. And while this may be acceptable for the current application the machines uses would be limited when the project was over, and it was time to be repurposed. Secondly, the smaller arm forces the team to make the work cell very tight on space. With the shorter reach of the arm, all components of the design would need to be placed in close proximity to each other. And while this may be efficient it would make maintenance in the cell difficult and cramped.

6.1.2 Product Manuals

See Appendix H

6.1.3 Communication

The communication between the Fanuc and PLC will be through ethernet. From the PLC's perspective, this is set up as a large number of digital inputs and digital outputs. The Fanuc has its own controller which will moderate the data transfer and interpret PLC data. The digital outputs of the PLC will signal the Fanuc to operate various subroutines. The PLC will have no awareness of the end of arm, all of its control will be handled by subroutines of the Fanuc. The emergency stop for the entire system will also be connected through the ethernet so that if any component in the system goes into E-stop, the Fanuc will also go into its own emergency protocol. The arm will be programmed independently with its included teaching pendant. This pendant allows the team to define the actions of subroutines, set controls for the end of arm, and dictate PLC communication. The pendant also allows the team to define for the Fanuc where obstacles in its workstation are so that it cannot crash into them.

6.1.4 Installation

The Fanuc arm will be delivered to PQS on a pallet. PQS has forklifts that can move the arm near the cell where it will be installed. A mounting base will be constructed out of thick steel bars and will be mounted to the concrete with lag bolts. An engine hoist or an equivalent provided by PQS will be used to center the arm over its base. Thick bolts will then mount the arm to its base. The arm will be provided 120 volts of three-phase power. This power will be run through fuses in the panels to protect the arm.

6.2 End-of-Arm

6.2.1 Product Manuals

Several product manuals have been read by both Vaccon Vacuum Products and FIPA Vacuum Technology. The product manuals have provided the team with a more refined understanding of how vacuum pick-and-place is practiced in industry. Furthermore, the product manuals have provided specifications for the various components of an end-of-arm system such as suction cups and vacuum pumps. See appendix for manuals used.

6.2.2 Decision to use suction cups

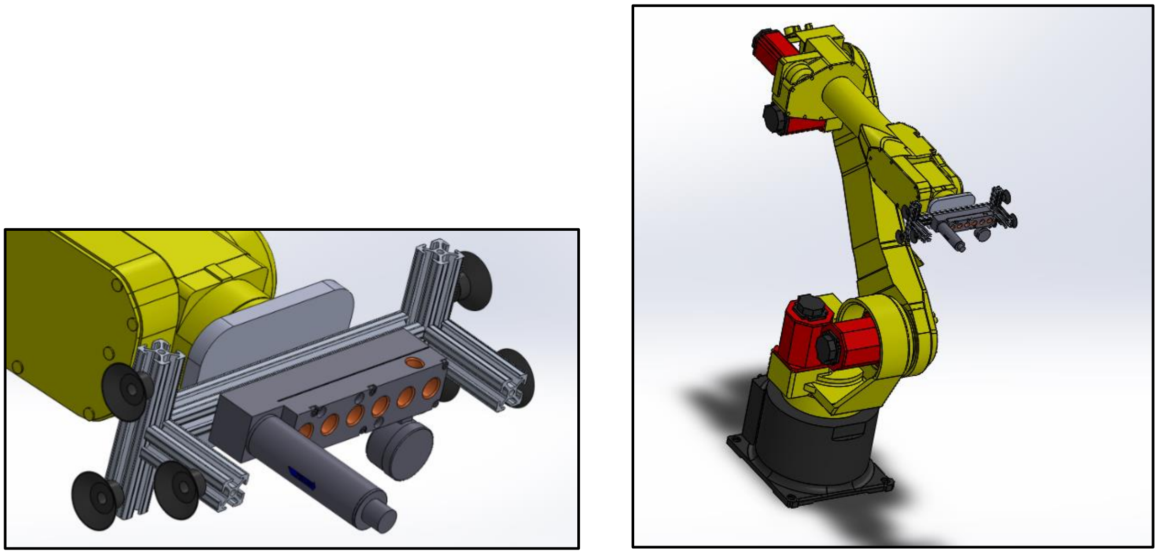
With the new process, the parts are much larger. This makes electromagnetism a less reliable end of arm effector because the magnetism would need to be much stronger to hold the part. More importantly, this new part has flat smooth surfaces, unlike the previous part. These surfaces allow the team to use suction cups to grab the part. Unlike magnets, suction cups will not interfere with any other sensors or hard drives. Suction cups are also more industry standard than magnets because of their reliability and predictable interactions with their environment.

6.2.3 Design Progression

Initially, end-of-arm concepts were explored which use shop-air pressure and suction to grab parts. Being that the requirements for carrying two parts at once still apply to the new design, initial designs resembled a similar form to the end-of-arm considered for the previous project which had two grab sites 180 degrees apart. This design was pursued and modeled. However, the new design which uses vacuum suction is larger. This is because the new part is larger and because the end-of-arm must now incorporate a valve bank. For this reason, the team was worried that an end-of-arm with 180-degree part separation may be too large given the new constraints. To ensure maneuverability of the end of arm, alternative solutions using a 90-degree separation between parts were investigated.

The specific material and valve actuators to employ on this end-of-arm were more difficult to determine. Many grades of suction cups are offered depending on the application. After review of the Vaccon catalog, the team has decided to pursue vinyl cups produced by Vaccon for their versatility and wide application base. Furthermore, the VP90 Multi-Port Venturi Vacuum Pump has been determined to be suitable for our applications due to its ability to control multiple cups at once. There is little debate as to what the best source of pressure is for the system as shop air is readily available at PQS.

For the configuration of the cups on the arm, it was quickly concluded that a three-point of contact configuration is best gripping the part. Literature provided by Vaccon Vacuum Products emphasizes the importance of gripping a part so that the center of gravity aligns with the center of the vacuum force. Hence, a three-point contact configuration is intuitive for the profile of the part in question. While originally a triangular plate was proposed to orientate the three-point configuration, previous experience in manufacturing led the team to pursue solutions which use 80/20.



(a) (b)

Figure 11: (a) Initial End of Arm Design (b) Initial End of Arm Design Mounted on Fanuc.

6.2.4 Final Design

The final end-of-arm design utilizes Vaccon VP90 vacuum pumps and vinyl cups. The team has reached out to Vaccon to request technical support in selecting specific part numbers from the product series already agreed upon by the team. While the investigation into vacuum end-of-arms was throughout, the team lacks valuable experience and expertise in this rather specialized field, so it will be beneficial to hear from industry experts prior to placing purchase orders.

Nevertheless, the team knows enough about the products to create the final end-of-arm design. The frame of the final design is made entirely of 80/20 extrusion. The use of 80/20 will cut out unnecessary machining cost and simplify the design. The frame is mounted to the Fanuc arm with a mounting plate. This plate will be made out of aluminum to ensure that the end-of-arm is not heavier than the payload of the Fanuc when fully loaded with parts. The frame of the end-of-arm parts from the bracket at 90 degree angles. At the end of these branches is the part-picking site.

The part is contacted at three locations by vacuum cups. With a two-pound part, the recommended safety factor of four is easily obtained. The pressure of the cups is high enough so that only a square inch of contact area is enough to securely grab the part. With vacuum cups of approximately one inch square grabbing at three points on the part, the resulting pressure creates a force of approximately 40 pounds which provides for a safety factor of ten.

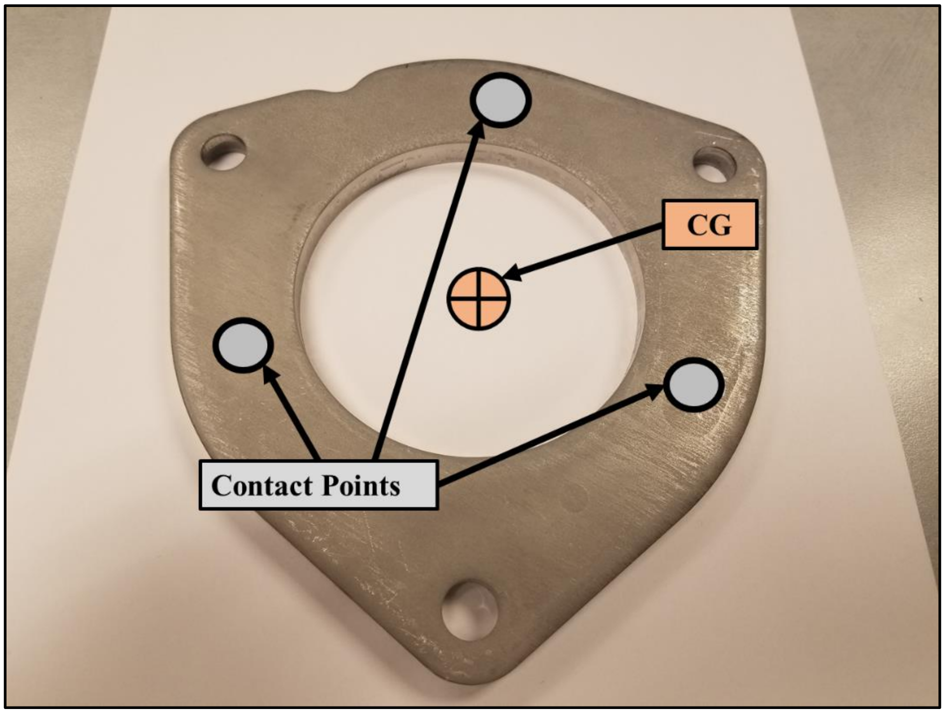
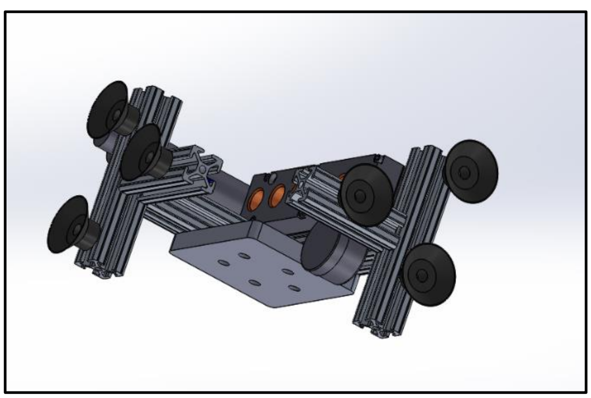
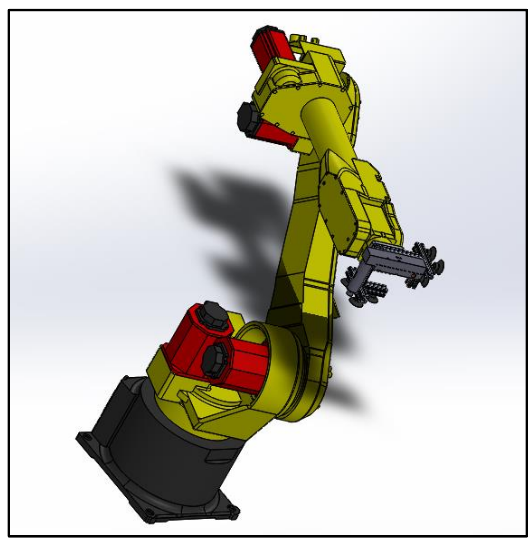


Figure 12: Contact Locations for End-of-Arm Suction.

The 90-degree angle of the final design allows the end-of-arm to be far more compact than the 180 degree alternative. The cuts out two inches of length front the initial design. This reduction in size could prove pivotal in determining the maneuvers which the robot may perform. The images shown below provide a CAD representation of the intended final design of the end-of-arm.





(a) (b)

Figure 13: (a) Final End of Arm Design (b) Final End of Arm Design Mounted on Fanuc.

6.3 Loading System

6.3.2 Design Changes

Since the new parts are so much larger, the ramp design would no longer work because the adjusted system would be inconveniently large. Furthermore, the customer discussed that an important priority for them is the number of parts that the process could handle in between reloading. Therefore, a solution with a larger part capacity was pursued.

6.3.2 Design Solutions

The indexing loading system is a system that was designed by the team. This system must hold as many parts as possible to reduce the amount of operator interaction required. Additionally, the system must dispense parts into a single location to alleviate the need for robotic vision. The indexing loading table, as the name says, must be accurate enough to revolve precisely and accurately. This system will consist of a welded frame, a gearbox, servo motor, and pneumatic cylinder.

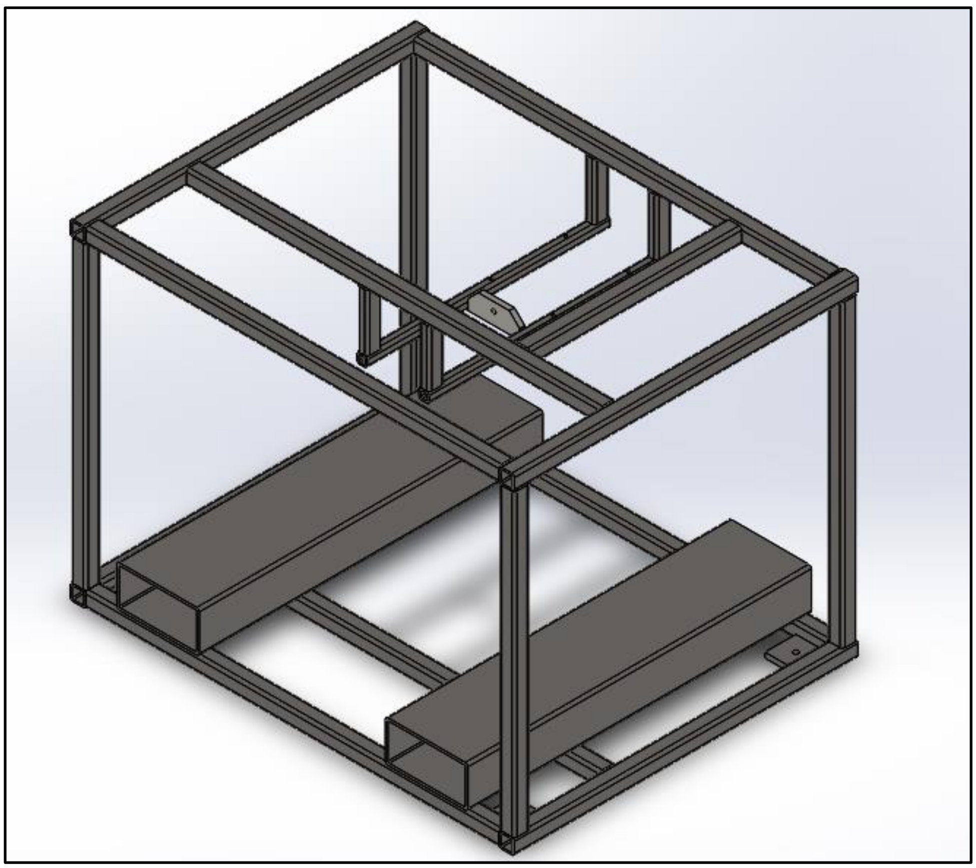


Figure 14: Indexing Loading System Frame.

The frame will be constructed of 1-1/2” x 1-1/2” steel tubing. The frame is 33-1/4” x 43-0” x 32-0” (Base x Width x Height). Weight is not a huge concern as the system will not be moved after it is in place. To aid in the placement of this system, forklift tubes are to be welded to the frame. Once the frame is in place, it will be anchored to the floor at each of the corners using Hilti or Powers anchors.

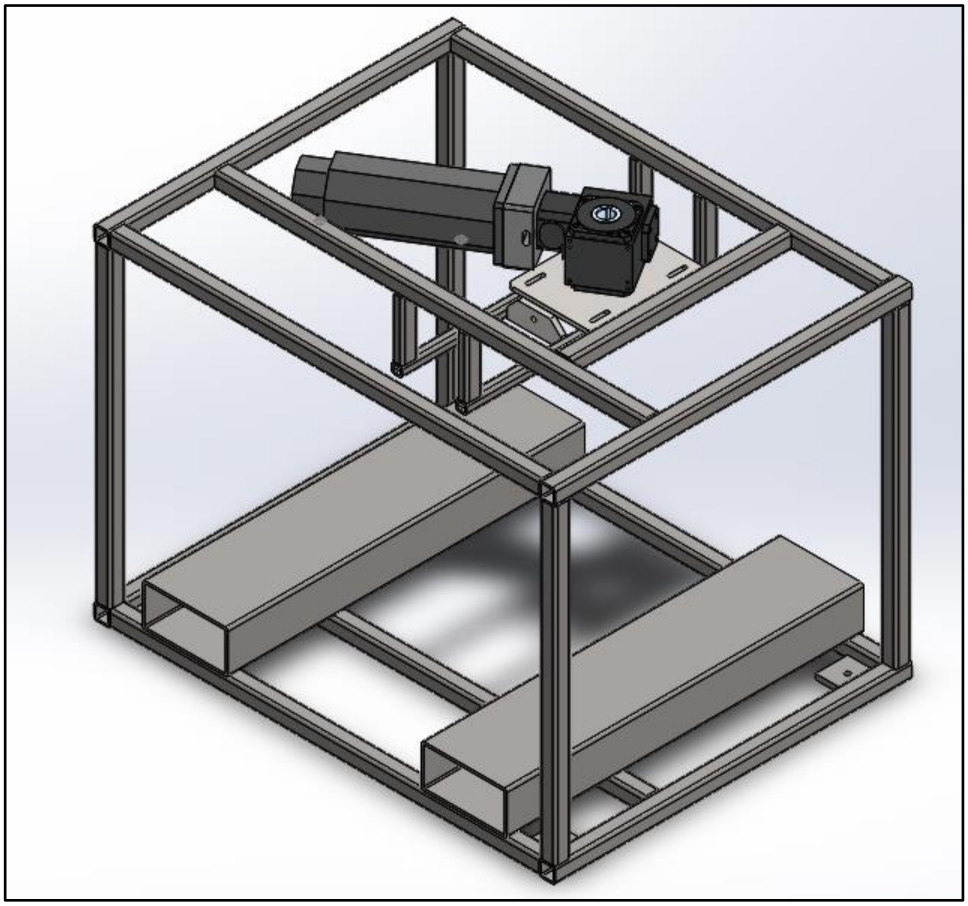


Figure 15: Indexing Loading System Motor and Gearbox.

The servo and gearbox were selected based on the part load and required indexing time. Refer to Appendix B for the calculations involving motor requirements. The servo motor selected was the Allen Bradley F-4050. This was selected to aid in combability with the PLC. The gearbox selected was the Cone Drive W051050LSAS03FJNDK. This gearbox has a 50:1 ratio and will handle the system and servo loads. A mounting plate will be made to mount this system to the frame. This plate is slotted to add some adjustability and account for machining tolerances. The motor is angled to allow it to fit within the allocated floor layout. To ensure proper meshing further up the drivetrain, a bolt will be added to push the mounting block into the proper location. This bolt threads into the chamfered block shown in the figure above.

A pneumatic cylinder will be used to lift parts to the desired pick location. The specific cylinder has yet to be determined due to the hastiness in the project change. Implementing a cylinder for lifting is feasible due to the addition of an induction sensor at the top of a part stack. If the sensor does not recognize a part at the top of the stack, air will be added to the cylinder. Similarly, if the sensor at the bottom of the stack notices that no parts are present, the cylinder will retract and the table will rotate.

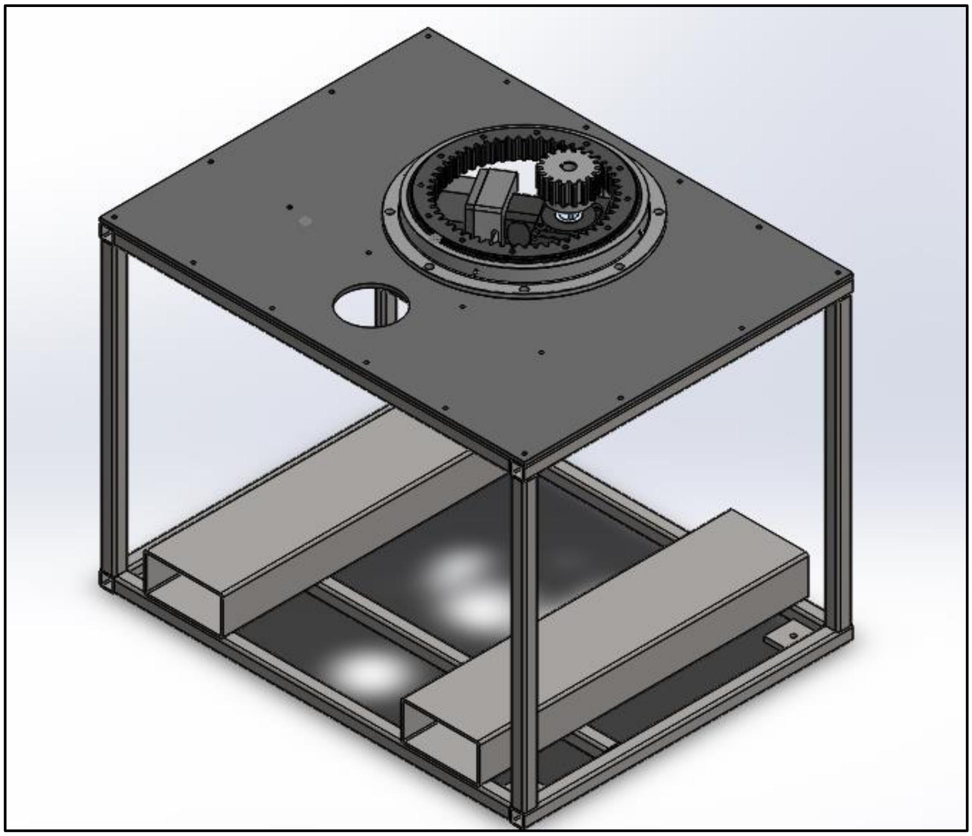


Figure 16: Indexing Loading System With Bearing and Pinion.

The table top on this system will be constructed of 3/8” thick steel to ensure proper mounting of further components. It will be secured to the frame with twenty 3/8” hex head bolts. This component will be purchased from an outside supplier of PQS’s choice.

The slewing ring bearing is the most essential component for feasibility in the design. The ring bearing functions just as any other bearing, but is much larger than typical bearings. It compensates for the axial and moment loads in the system. The bearing is approximately sixteen inches in diameter at the point of contact with the table. This significantly reduces the moment load caused by the weight of the parts. Additionally, the ring bearing has gear teeth cut on the inner diameter which allows for the rotation of the table. Progressive Surface has experience using Kaydon ring bearings, hence, the team chose to use this brand. The model number is RK6-16N1Z. Additionally, a Kaydon pinion will be purchased to ensure a good mesh is created between the ring bearing and pinion. The pinion is model number 39200002. Reference Appendix C for critical dimensions of the ring bearing.

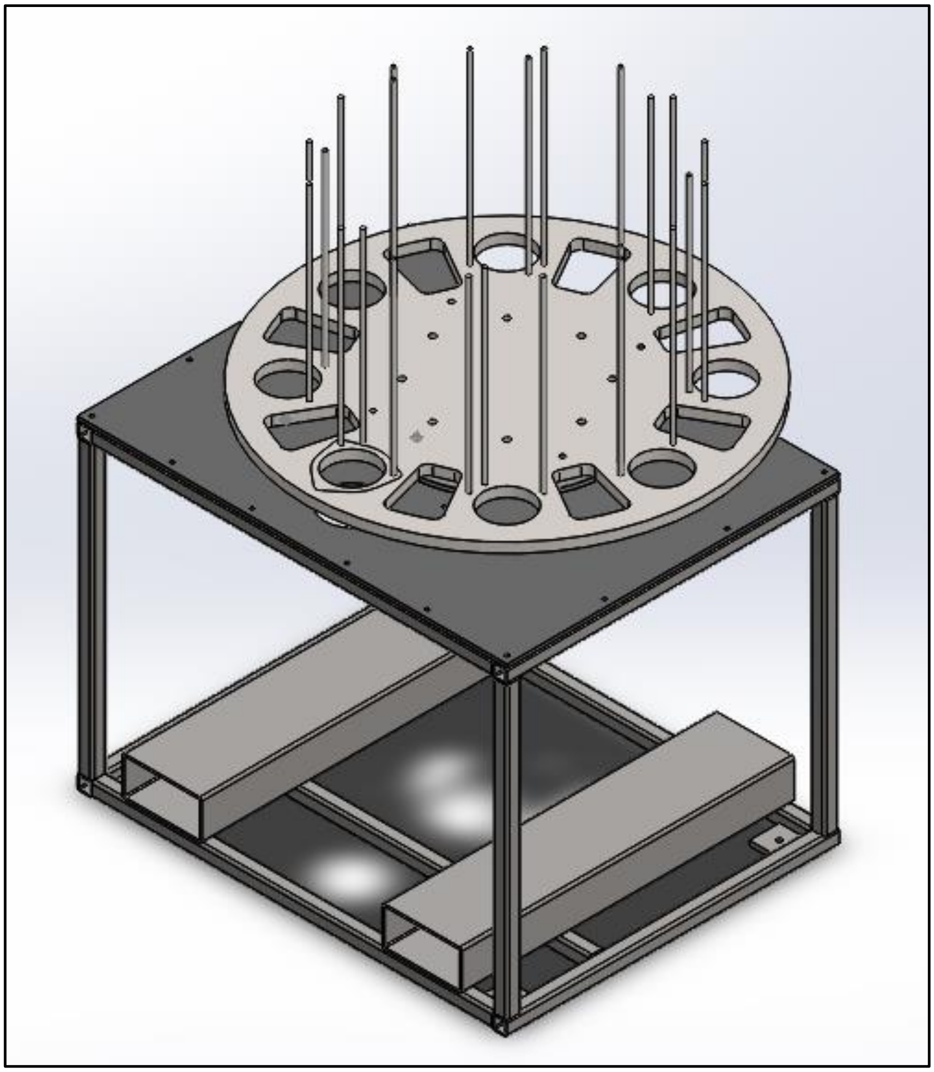


Figure 17: Indexing Loading System with Table.

The final major component of the part loader is the table. The table is to be constructed out of 1/2" thick steel. 4 eyebolts will be used to lower the table into a position where it will be secured to the ring bearing through 8 bolts. There are 2 different style cutouts on this table. The first cutout is circular, and allows for the pneumatic cylinder to push parts upwards. This hole is sized to ensure the part cannot fall through and includes clearance to ensure the flange mounted to the end of the cylinder does not contact the table. The other hole is included to reduce the mass of the table. Large fillets are added here to reduce stress concentrations that could lead to failure. Refer to Appendix D for FEA on the table. The overall weight of the table is 260 lbs. This component will also be purchased from an outside source.

Covers and side panels will be bolted to the frame to ensure the system is aesthetically pleasing. The covers are placed to allow adequate access to the pneumatic cylinder, servo, gearbox, and ring bearing since these components will require periodic maintenance.

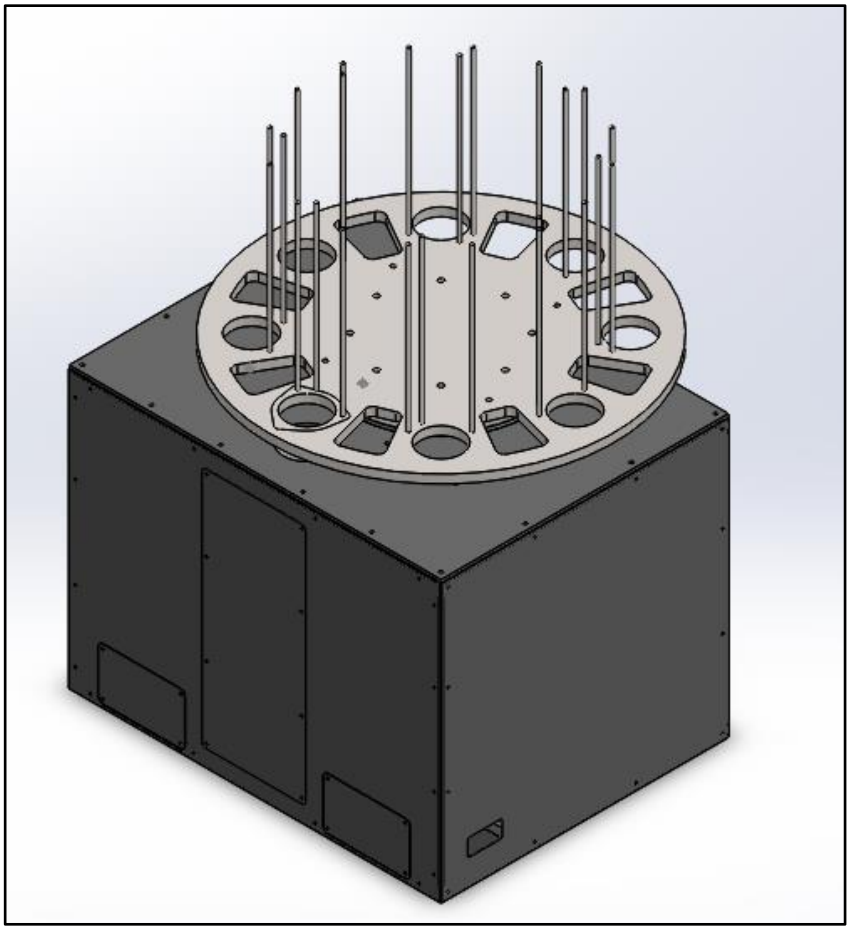


Figure 18: Complete Indexing Loading System.

6.4 Haas CNC Lathes

6.4.1 Changes for new design

The new project still uses a Haas brand lathe, but the new project only requires one CNC. The start button will be wired in parallel to the PLC, so it can be started manually or automatically. The emergency stop will be wired similarly into the safety circuit, so if any emergency stop in the system is activated, all devices will activate their own emergency protocols. Additional hardware will be purchased from Haas which will send the current state of the Haas out in a series of digital outputs. These outputs will be read from the PLC to control sequencing.

6.5 Safety Cell

6.5.1 Interlocker and Light Curtain Design

With the team’s design, an operator is required to access the system for maintenance purposes and load the system with raw parts. This requires an area for the operators to easily access each system.

To access the area, a door is required. The team performed some research and identified a few systems that would assist in the team's safety cell design. The team is looking into purchasing and interlocking device to lock the cell when the system is running. This locks all doors and shuts down all movement within the system when opened with or without force. Interlocking devices are commonly used in manufacturing facilities today. A company by the name of Fortress Interlocks manufactures many interlocking devices. The team is looking to purchase the TGard, which can be optimized to any design specifications the team requires. This device is simple to install, because it only requires two bolts to mount. It can contain ten devices to control opening the door, including push buttons, lamps, selector switches, key switches, three position illuminated switches, and E-Stop buttons. This device is easily customizable and will prevent any dangers from occurring within the cage.

The team is also looking at purchasing two light curtains to monitor any movement into the cage. Industrial light curtains are commonly-used devices in manufacture facilities, because it easily monitors into a cage. When its sensors recognize movement, the system will shut down. The CNC will continue to operate, but the robotic arm and indexing loading system will not move. This will prevent any injury when the operator reaches into the cage to reload the indexing table with raw parts.

6.5.2 Cage Design

The cage design for the new project is very different than the old system, but follows the same concept. A cage system is required by OSHA regulations, and the customer requested a design. This cage system will contain two areas of entry - an open area guarded by light curtains and a door locked with an interlocking device. An operator can enter the opened area at any moment, because the light curtain will send a signal to stop all movement. The door can be entered when the correct precautions are taken - the system must be set into "Pause" mode to open the door. When in "Pause" mode, no machine movement within the cell is allowed. The CNC can continue to operate only if the CNC door is closed. The system is in "Emergency" mode when an E-Stop button is pressed or a system malfunctions, creating a dangerous environment. All systems will immediately shut down to prevent any injury. The figure below displays the cage system. The team designed the cell out of 80/20 construction framing and caging panels. This design is preferred over the Velox caging, because of the simplicity and cost. A system designed with 80/20 is significantly cheaper than Velox caging, but will require additional work.

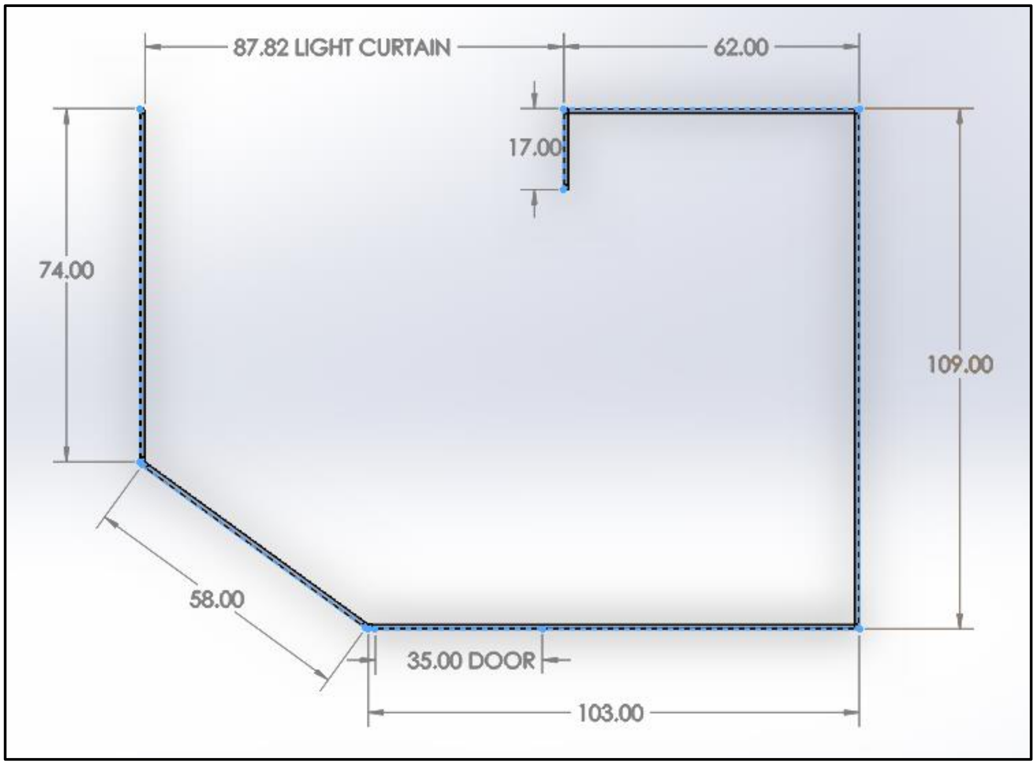


Figure 19: Cage Design for New Project.

6.5.3 Additional Solutions

The team is continuing to research more cost-effective and efficient designs for the caging system. Due to the high cost of an interlocking device from Fortress Interlocks, the team may decide to go with a basic magnetic sensor system within the door system. This system will identify whether the door is opened with a basic safety circuit, connected to the cage. The team is still looking into purchasing a similar system or building one. Currently, the team does not have a design for this system, because of lack of time from the project change.

6.5.4 OSHA Requirements

As stated in section 5.5.2, the team is required to follow OSHA regulations when designing a safety cell system for the overall project. The design must comply with ANSI/RIA R15.06 standards. Refer to section 4.5.4 for more information.

6.6 Storage System

6.6.1 Design Changes

After the raw parts are machined, the robotic arm will dump the final product into a large metal bin. When the bin is full (roughly 550 parts), an operator can remove the bin with a forklift. They can then place an empty bin in the same position to continue production. A system will be set to pause production while movement within the cell occurs. This bin will be stationed next to the opened entrance, so it can easily be accessed. The bin will sit on a wooden pallet for easy forklift access.

6.7 Measurement System

The newly assigned project does not require any measurement system. No measurements will be required for the production of this part, unless the bit used to machine the part becomes damaged. An LED will light up when the bit should be replaced. As of now the team has not identified how many parts should be machined before a tool change is required. PQS may shed some light on this in the future.

6.8 Floor Layout

The floor layout changed due to the project change. The overall floor design is similar but simplified because of the equipment required. The new design includes one Haas CNC Lathe, a final product bin, a Fanuc 6-axis robotic arm, and the indexing table. The team's floor design can be found below.

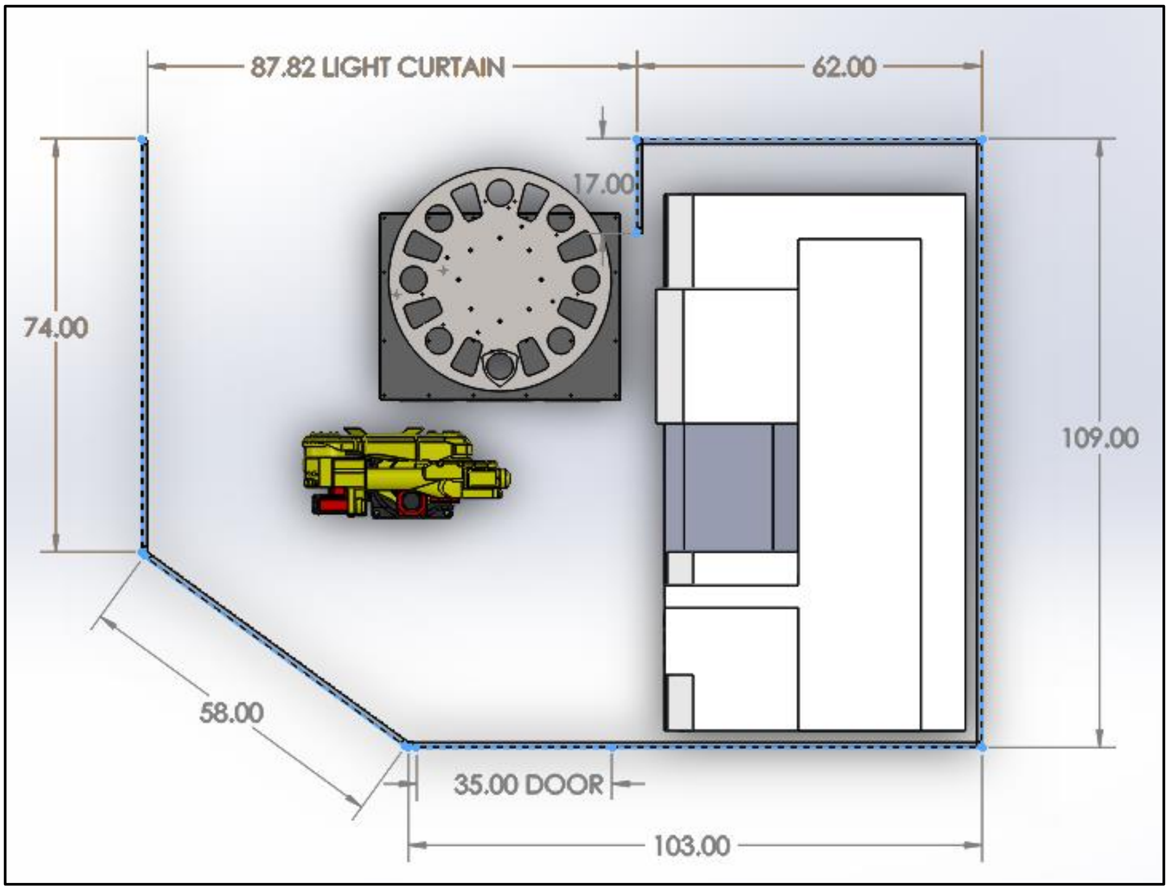


Figure 20: Floor Layout Design of New Project.

The overall floor design reduces the amount of space needed for the cage. The team decided to leave a larger space within the cage to allow operators to enter the cell for maintenance purposes.

7 New Project Cost Analysis

7.1 Fanuc 6-Axis Robotic Arm

7.1.1 Component Cost Breakdown

Table 8: New Robotic Arm Cost Breakdown.

ITEM DESCRIPTION	QTY	UNIT COST	TOTAL COST
Fanuc M-16iB/ArcMate120iB RJ3iB	1	$21,500.00	$21,500.00
Fanuc Collision Guard (OPTIONAL) - Recommended	1	$1,200.00	$1,200.00
Fanuc Hotline Phone Support (OPTIONAL)	1	$1,000.00	$1,000.00
EE Connector Upgrade (OPTIONAL)	1	$975.00	$975.00
Antenen Robotics Phone Support	1	$0.00	$0.00
TOTAL COST	-----	---------------	$26,675.00

7.2 End-of-Arm

7.2.1 Component Cost Breakdown

Table 9: New End of Arm Cost Breakdown.

ITEM DESCRIPTION	QTY	UNIT COST	TOTAL COST
Cups	6	$12.00	$72.00
Aluminum 6061 Bar Stock	12 in	$2.58/in	$31.00
Valve Bank	1	$400	$400
Air Hose	24 in	$1.00/in	$24
Contingency (+20% of Current Cost Estimate)	N/A	N/A	$100
TOTAL COST	-----	---------------	$627

7.3 Indexing Loading System

7.3.1 Component Cost Breakdown

Table 10: New Indexing Loading System Cost Breakdown

ITEM DESCRIPTION	QTY	UNIT COST	TOTAL COST
Pneumatic Cylinder	1	TBD	TBD
Air Hose	TBD	TBD	TBD
AB F-4050 Servo Motor	1	$1,500	$1,500
Cone Drive Gearbox	1	$1,500	$1,500
Rotary Table	1	TBD	TBD
Tabletop Machining	1	TBD	TBD
Access Cover A	1	TBD	TBD
Access Cover B	1	TBD	TBD
Fork Tube Cover	4	TBD	TBD
Side Panel A	1	TBD	TBD
Side Panel B	1	TBD	TBD
Side Panel C	1	TBD	TBD
Side Panel D	1	TBD	TBD
Kaydon Ring Bearing	1	$4,000	$4,000
Kaydon Pinion Gear	1	$500	$500
1-1/2” x 1-1/2” Steel Tubing	394 in	TBD	TBD
1-0” x 1-1/2” Steel Tubing	22 in	TBD	TBD
1-0” x 1-0” Steel Tubing	47 in	TBD	TBD
1/2" x 2-0” Steel Bar Stock	5	TBD	TBD
4-0” x 10-0” Steel Tubing	67 in	TBD	TBD
1/2” x 3-0” Steel Bar Stock	12 in	TBD	TBD
Inductive Proximity Sensors	1	$50	$100
Indicator Stacklight	1	$100	$100
Miscellaneous Hardware	TBD	TBD	TBD
Contingency (+50% of Current Cost Estimate)	N/A	N/A	$3,850
TOTAL COST	-----	--------------	$11,550

The contingency cost for the part loading system is primarily driven by the purchased, laser-cut components. The team has not quoted these yet, so the cost is completely unknown. Despite this, 50% contingency seems quite high since material costs for all components (neglecting the rotary table and tabletop) will be relatively inexpensive.

7.4 Haas CNC Lathes

Preferred Quality Services is currently producing the part on two Haas SL-20 lathes. However, to reduce downtime during installation and testing, the customer plans to purchase two more lathes.

The customer will be in charge of the purchase of another CNC lathe. This responsibility is Preferred Quality Service's because they have the best contacts to find used CNC machines at a competitive price and because they have the best knowledge of what CNC can perform the quality of work required for this project and future projects. It is possible that the team will need to purchase a door opener depending on the type of CNC provided. Depending on the method of control used, additional relays may need to be purchased as well.

7.5 Safety Cell

7.5.1 Component Cost Breakdown

Table 11: New Safety Cell Cost Breakdown.

ITEM DESCRIPTION	QTY	UNIT COST	TOTAL COST
1-0" x 1-0" 8020 Aluminum Extrusion Bar	2232 in	0.23/in	$514
Mesh Paneling	TBD	TBD	TBD
Magnetized Safety Switch	1	TBD	TBD
32" Light Panel (Receiver)	2	$415	$815
32" Light Curtain (Transmitter)	2	$430	$860
Contingency (+50% of Current Cost Estimate)	N/A	N/A	$1,100
TOTAL COST	-----	--------------	$3,290

7.6 Storage System

7.6.1 Component Cost Breakdown

Table 12: New Part Measurement System Cost Breakdown.

ITEM DESCRIPTION	QTY	UNIT COST	TOTAL COST
Large Metal Bin (Provided)	N/A	N/A	N/A
TOTAL COST	-----	---------------	$0.00

7.7 System Control

7.7.1 System Cost Breakdown

Table 13: New System Control Cost Breakdown.

ITEM DESCRIPTION	QTY	UNIT COST	TOTAL COST
Allen Bradley Micro850 Controller	1	$650	$650
Human Machine Interface	1	$500	$500
Safety Circuit	1	TBD	TBD
Relays	12	$30	$180
Panel	1	$500	$500
Wiring	1	$300	$300
Contingency (+20% of Current Cost Estimate)	N/A	N/A	$425
TOTAL COST	-----	---------------	$2,555

7.8 Total Project Cost

7.8.1 System Cost Breakdown

Table 14: New Complete System Cost Breakdown.

ITEM DESCRIPTION	QTY	UNIT COST	TOTAL COST
Robotic Arm	1	$26,675	$26,675
End-of-Arm Tooling	1	$627	$627
Part Loading System	1	$11,550	$11,550
Safety Cell	1	$3,290	$3,290
Storage System	1	$0.00	$0.00
System Control	1	$2,555	$2,555
TOTAL COST	-----	--------------	$44,697

8 Integration, Testing, and Debugging

Information on integration, testing, and debugging will be included in this section once the system is constructed during interim and spring semester.

9 Conclusion

The team was forced to rapidly adapt when the previous project was canceled. Although quite a lot changed we learned that most of our work was still applicable and only the part loader needed to be completely redesigned. Although our customer pushed us to find a cheaper alternative for a Fanuc arm, the team learned that the cost of large, overhead gantry systems cannot be purchased cheaper than the Fanuc without heavily sacrificing quality. The team also learned that designs can be very quickly improved by sharing them with experienced outsiders. Major design alterations were ultimately driven by advice from experienced individuals referenced below. Similarly, we learned the importance of frequent customer communication. Near the end of the first project, we learned that the orientation of the puck was optional but we had thought orientation was a strict constraint. Better communication would have saved us time and energy spend devising a system that controlled orientation. Going forward we expect to spend a lot of time debugging onsite, to allow time for this we plan to have the design finalized and all equipment in-house by the end of January.

9.1 Acknowledgments

The team would like to thank a few individuals for their support through this design phase - Mr. Eric Walstra, Mr. Ben Greve, Mr. Bobby Lanser, Mr. Marc Keizer, and Professor Mark Michmerhuizen. The team met with their industrial consultant, Eric Walstra, to talk about the project and design. The team is grateful for the equipment recommendations that Mr. Waltra provided. The team has been in constant communication with Ben Greve, a Sales Applications Engineer at Industrial Controls out of Zeeland, MI. He has designed very similar systems and is very knowledgeable about equipment. Bobbly Lanser currently works at JR Automation in Holland, MI as a Controls Engineer and has assisted the team is design, equipment, and overall project recommendations. Additionally, he has assisted the team by reading through the PPFS to ensure the information is accurate. Mr. Marc Keizer, the owner of PQS, has been incredibly supportive through this project change. He has provided the team with the necessary project information and has also provided the necessary feedback. Finally, Professor Mark Michmerhuizen at Calvin College has assisted the team in many forms. The team holds weekly meetings with him to review designs and provide updates. The team is very grateful for the time that these individuals have spent to support the project. The team hopes to build these relationships as time progresses.

Appendices

Appendix A – Schedule:

The two images below display the team’s WBS, or Work Breakdown Structure.

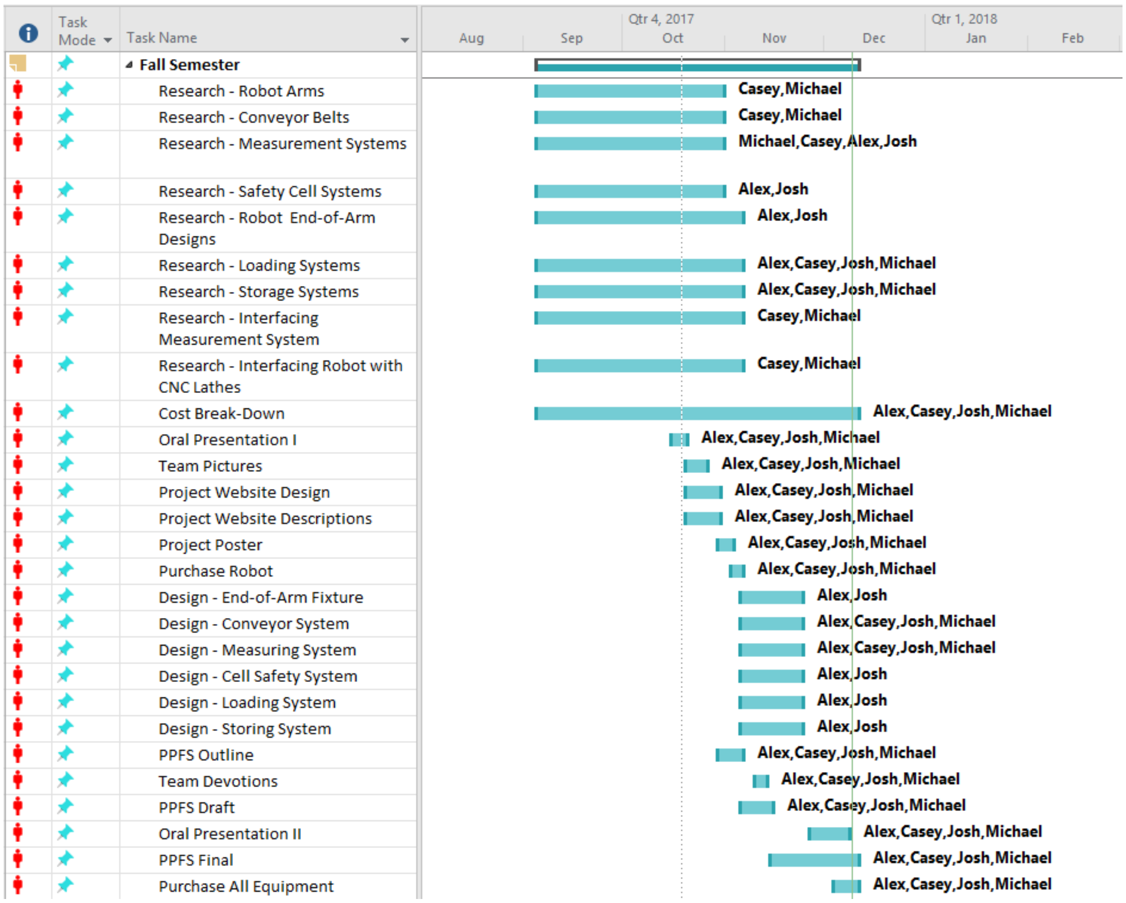


Figure 21: Fall Semester Schedule and Deliverables

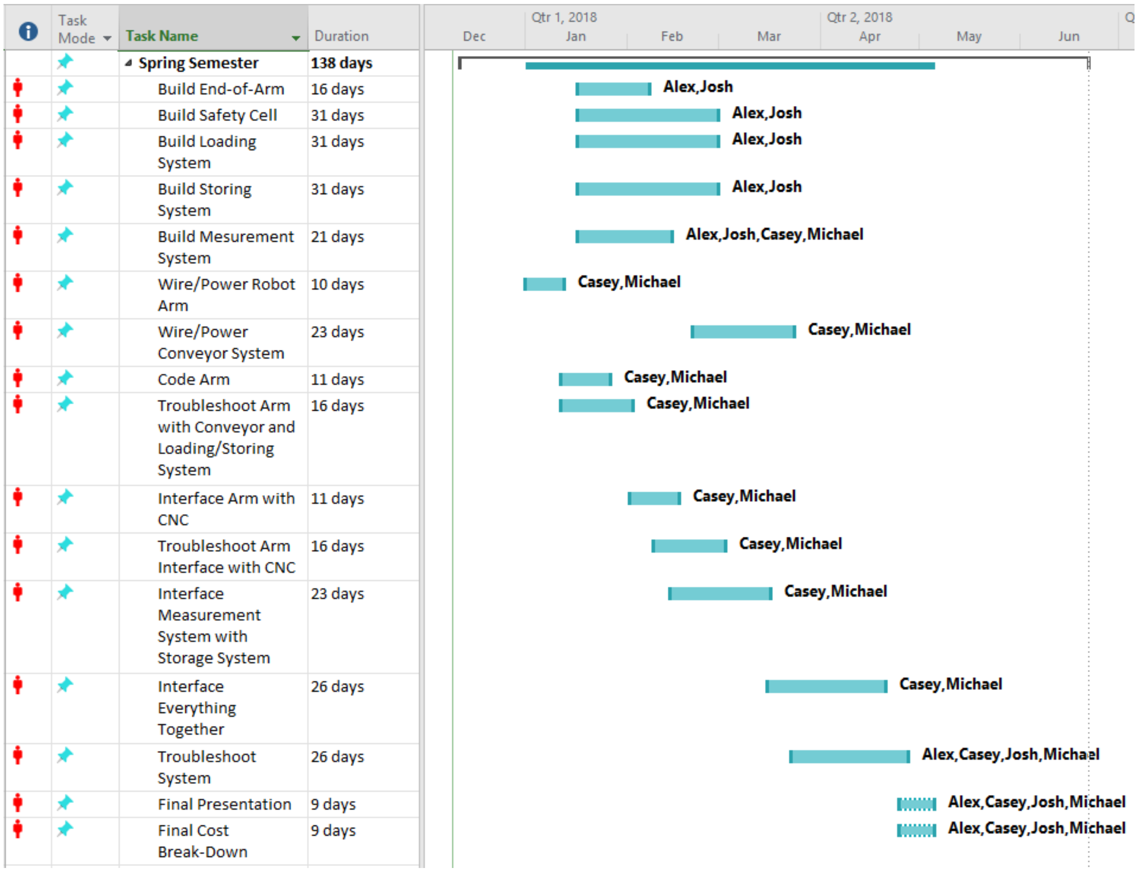


Figure 22: Spring Semester Schedule and Deliverables.

Appendix B – Calculations for New Part Loader:

The design of the new part loading system raised concern amongst the team regarding the forces and stresses at play. To combat this, predictive models are formed to analyze the rotational power, rotational acceleration, applied moments, and motion of the table. Of particular interest is the rotational velocity and torque required from the systems motor and the forces induced on the placement rods from the tangential acceleration of the parts.

Harmonic functions are chosen for the equations of motion which will define the movement of the turn table. Harmonic functions are ideal for this application because a gear box is implemented. With any gear system, it is important to ensure that jerk (ζ) begins and ends at zero. This ensures that there is no situation which will apply an infinite force on the gear box thereby shortening the effective life of the system. Harmonic functions are commonly used on cams as well to attenuate alternating stress deterioration. The harmonic equations assume the form of the following.

$$\theta(t) = \frac{h}{2}\left[1 - \cos\left(\frac{\pi t}{t_{end}}\right)\right] \qquad (B1)$$

$$\dot{\theta}(t) = \omega(t) = \frac{\pi h}{2t_{end}}\sin\left(\frac{\pi t}{t_{end}}\right) \qquad (B2)$$

$$\ddot{\theta}(t) = \alpha(t) = \frac{\pi^2 h}{2t_{end}^2}\sin\left(\frac{\pi t}{t_{end}}\right) \qquad (B3)$$

$$\dddot{\theta}(t) = \zeta(t) = \frac{-\pi^3 h}{2t_{end}^3}\cos\left(\frac{\pi t}{t_{end}}\right) \qquad (B4)$$

Where the variable h is defined as the end rotational distance (rads), t refers to time (seconds), and t_{end} refers to the total time required to complete the partial rotation. The equations used to describe force, torque, and momentum for the turn table employ classic Newtonian physics. The key features which are employed to discover angular velocity of gears and motors (ω), rotational power of systems (P), and moment enacted on stacks (m).

$$\frac{\omega_1}{\omega_2} = \frac{D_2}{D_1} = \frac{t_2}{t_1} \qquad (B5)$$

$$P = \tau\omega \qquad (B6)$$

The equation for finding the moment applied to the guide rods works by breaking the force required to accelerate the parts on a part-by-part summation. By this method, every part at is evaluated based on the respective distance from the base of the guide rods.

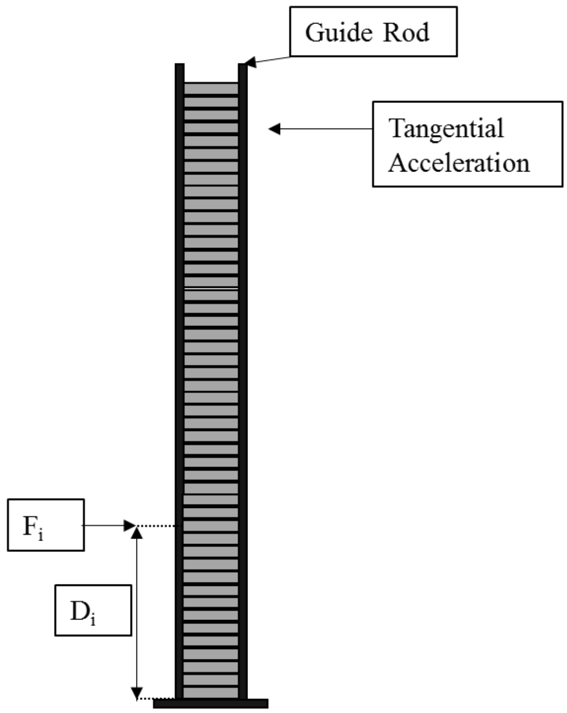


Figure 23: Part Stack Schematic.

$$m = \sum_{i=1}^{N} F_i D_i \qquad (B7)$$

The time allotted to complete the partial rotation of the table is set to 6 seconds. This acceleration time is found to require a peak torque of 0.0224 N-m and a peak velocity of about 980 rpm. These peak values are within the specifications of the selected motor. Furthermore, the peak moment applied to the guide rods is determined to be 0.416 N-m, which is low enough to alleviate concern of the rods failing.

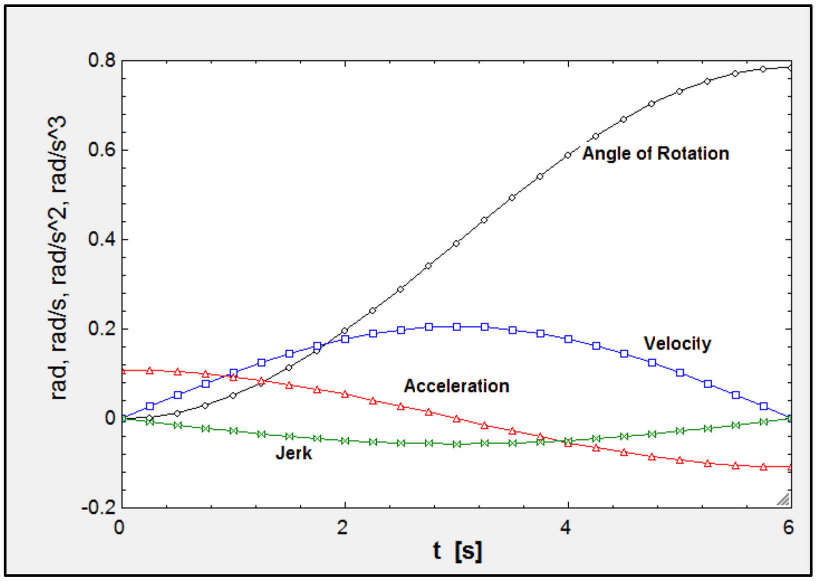


Figure 24: Plot of Angle of Rotation (black), Angular Velocity (blue), Angular Acceleration (red), and Angular Jerk (green) as a Function of Time.

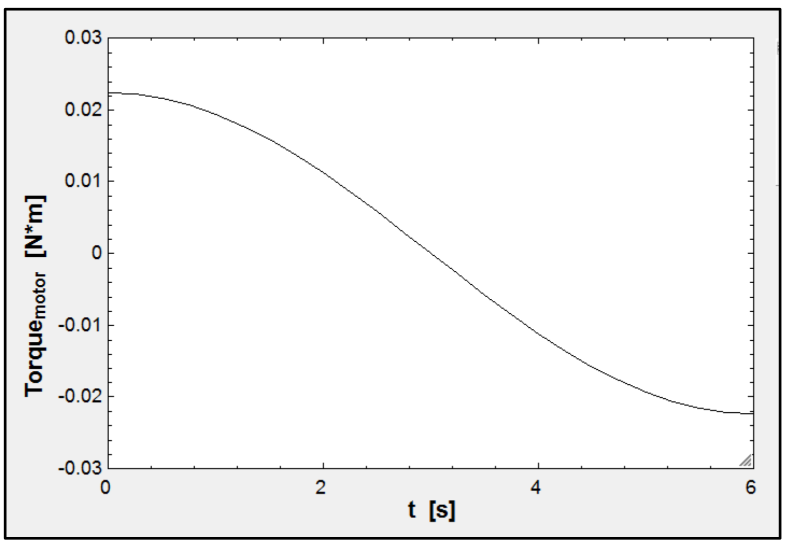


Figure 25: Plot of Torque Required of Motor as Function of Time.

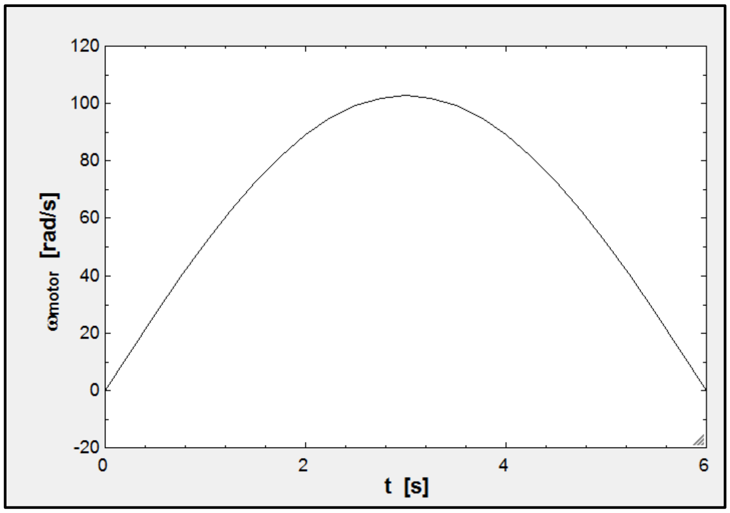


Figure 26: Plot of Rotational Velocity of Motor (rad/s) as Function of Time.

Note that the torque required of the motor is negative during deceleration. This is expected since the force will need to be applied in the opposite direction following peak velocity. For more information pertaining the equations of motion, please refer to the files added in the following appendix. MATLAB was utilized to determine the moment of the accelerating stacks, and EES was used to compute all other values.

Appendix C – EES File and Solutions for Equations of Motion:

```
"-------------------------------------------------------------------------------------

    Calculations for Forces and Motion of Turn Table

    Team 07; Calvin College Senior Design

----------------------------------------------------------------
Nomenclature and statements
-------------------
   -!DV --> A variable which Can be changed
   -Units are converted to metric for ease of calculation
   -Results are converted back to English standard units
-------------------------------------------------------------------------------------"


h=2*pi/N_racks
time=6[s]                                   {!DV}
t=0.5 [s]


"-----------------Harmonic EOM's---------------"
s=h/2*(1-cos(pi*t/time))
v=(pi*h)/(time*2)*sin(pi*t/time)
a=(pi^2*h)/(time^2*2)*cos(pi*t/time)
j=(-pi^3*h)/(time^3*2)*sin(pi*t/time)
"-------------------------------------------------------"



"----------Table and part parameters---------"
t_part=0.4 [in]
h_rod=18 [in]                               {!DV}
N_stack=h_rod/t_part
N_racks=8                                   {!DV}
N_total=N_racks*N_stack                     {!DV}
Mass_part=2.1/2.2
Mass_table=273.88/2.2                       {!DV}
Mass_stack=N_stack*Mass_part
 "-------------------------------------------------------"



"-----------Diameters----------------------"
D_bearing=16 *convert(in, m)
D_table=40 *convert(in, m)
D_load=31*convert(in, m)
"-------------------------------------------------------"
r_parts=D_load/2
```

```
r_table=D_table/2
r_bearing=D_bearing/2
"--------------------------------------------------------"


"----------Inertias-----------------------"
m_parts=Mass_part*N_total
I_parts=r_parts^2*m_parts
I_table=0.5*Mass_table*r_table^2
I=I_parts+I_table
 "--------------------------------------------------------"


"-------------Torques--------------------"
Torque_table=I*a
Torque_table_english=Torque_table*convert(N*M, in*lbf)
Power=Torque_table*v
 "--------------------------------------------------------"


"-------------Ratios to Motor-------------"
t_pinion=17                                   {!DV}
t_bearing=53                                  {!DV}
D_pinion=4*convert(in, m)
"--------------------------------------------------------"
Force_gear=Torque_table/r_bearing
Omega_gear= v*D_table/D_pinion
"--------------------------------------------------------"
BoxRatio=50                                   {!DV}
FullRatio=BoxRatio*(t_bearing/t_pinion)
  "--------------------------------------------------------"
{To account for energy dissation}
Power_motor=Power*1.5                         {!DV}
 "--------------------------------------------------------"
Omega_motor=Omega_gear*BoxRatio
Power_motor=Omega_motor*Torque_motor
 "--------------------------------------------------------"


"-----------Linear Equation of motions for Parts-----------"
v=V_part/r_parts
a_parts=(((v^2*r_parts)^2+(a*r_parts)^2)^0.5)
F_rack_base=a_parts*Mass_stack
 "--------------------------------------------------------"
```

Figure 27: EES Solutions Window.

Appendix D – MATLAB Script for Indexing Part Loader Torque:

```
%////////////////////////////////////////////////////////////////////
%
%                       Moment Calcs for Base of Stack
%                       Team 07; Calvin College Senior Design
%
%Pull EES from S:\Engineering\Teams\Team07\Calculations and Documents
%
%Refer to EES file: Equations of motion.EES
%
%////////////////////////////////////////////////////////////////////


%---------------------------------------------------------
clear all
close all
%---------------------------------------------------------
mass_part=0.9545;    %[kg]
a_part=0.04239;      %[m/s^2]
N_parts=45;
t=0.01016;           %[m]
%---------------------------------------------------------
h=t/2;               %[m]
row=1;
col=1;
%---------------------------------------------------------

for part=1:1:N_parts

    moment(col, 1)= a_part*mass_part*h;

    h=h+t;
    col=col+1;

end

%---------------------------------------------------------
Totalmoment=sum(moment(:))   %[N-m]
%--------------------------------------------
```

Appendix E – Slewing Ring Bearing Data:

Critical dimensions on the slewing ring bearing are shown below. As noted above, the bearing is Kaydon model number RK6-16N1Z. This component is critical to the design as it allows for rotation and indexing of the table. The slewing ring bearing will be driven by a pinion gear connected to the gearbox and servo motor by a driveshaft.

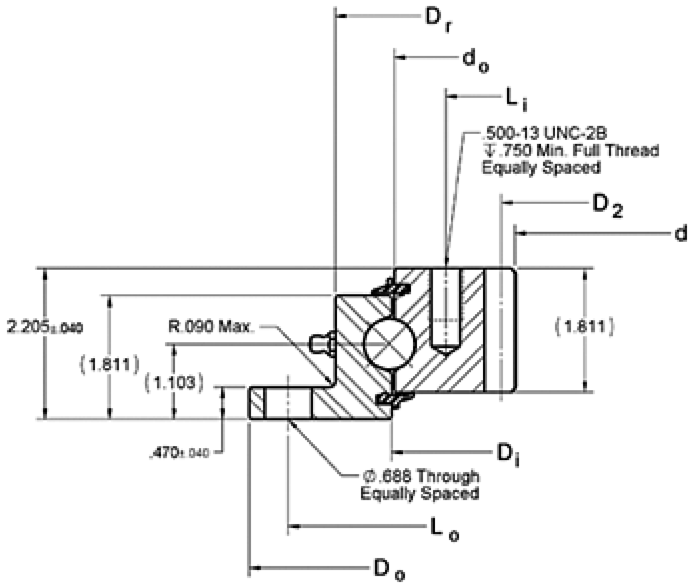


Figure 28: Kaydon Slewing Ring Bearing Dimensions.

Table 15: Slewing Ring Bearing Outline Dimensions and Weight.

D_o (in)	d_i (in)	D_r (in)	D_i (in)	d_o (in)	G (lbs)
20.390	12.850	17.870	16.220	16.140	65

Table 16: Slewing Ring Bearing Mounting Hole Dimensions.

L_o (in)	n_o	L_i (in)	n_i
19.250	8	14.880	12

Table 17: Slewing Ring Bearing Gear Data

α	D_2 (in)	P_d	z_2	Max Tooth Load (lbs)	Moment Rating (ft-lbs)
20°	13.250	4	53	6,800	22,700

Thrust loads are irrelevant in this situation due to them being very minimal in our usage. Despite this, the team computed the thrust load capable of being handled. The maximum moment load on the ring bearing is shown below in Equation C1.

$$Max\ Moment = \left[45\ \frac{parts}{stack}\right]\ [8\ stacks]\left[2.10\frac{lb}{part}\right][2\ ft] \qquad (C1)$$

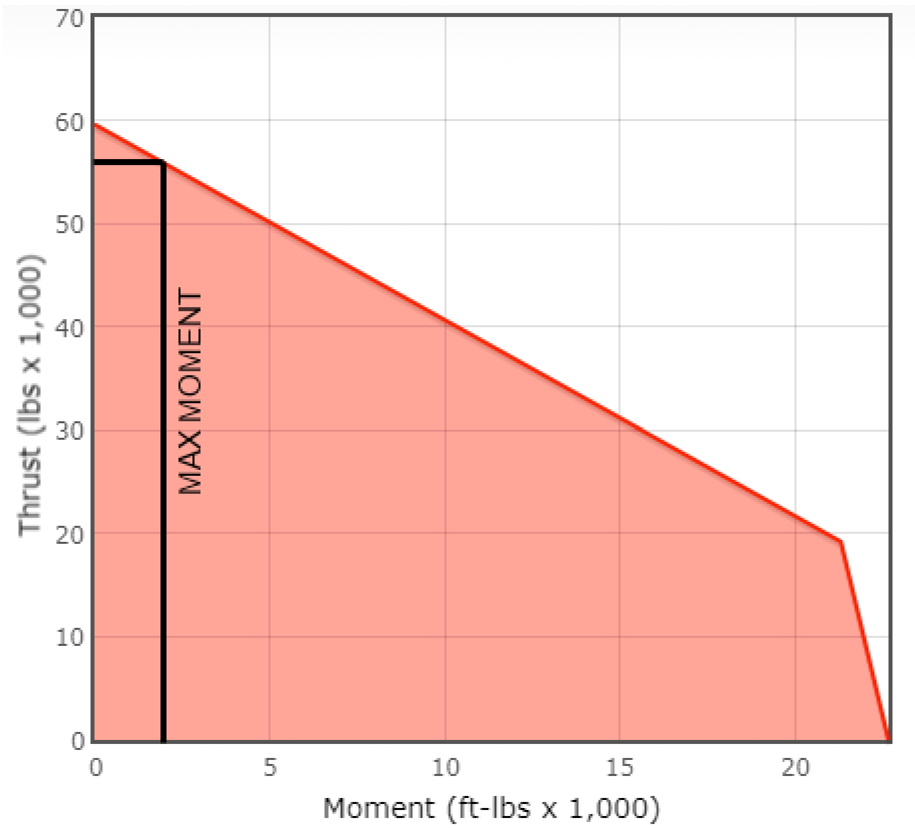
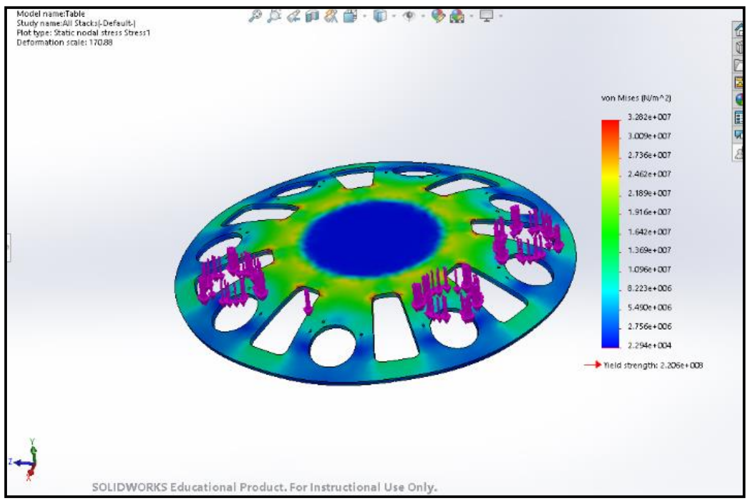


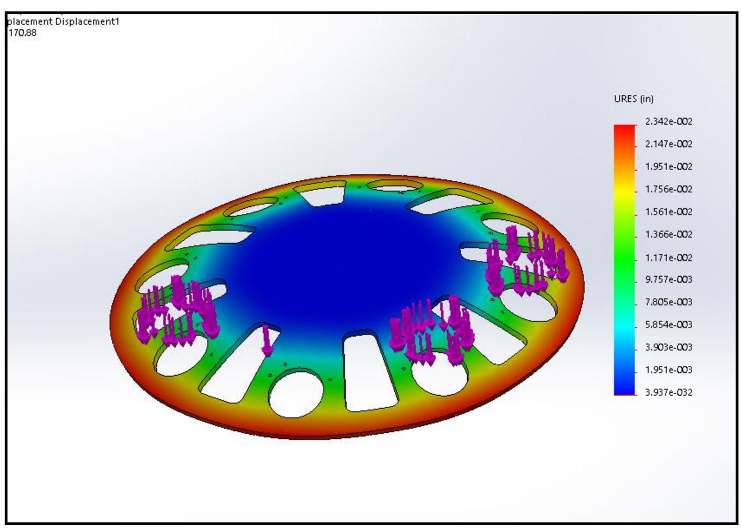
Figure 29: Thrust Load as a Function of Moment Load on Ring Bearing.

Appendix F – FEA Simulation on Indexing Part Loader Table:

FEA simulations were performed on the disk-shaped table which will be used to hold the raw parts. The deflection of the table is a point of concern for the project, since edge deflections on the table may circumvent accurate predictions for the location of parts atop the stack. Variability in part location may prove problematic for the Fanuc arms ability to accurately secure parts in when loading. Furthermore, stress induced on the table is also of interest since the project is long-term, and stress close to the yield point for steel may result in creep or failure. FEA simulations to evaluate the Von Mises stress and displacement induced on a one-half inch thick and three-quarter inch table were conducted to investigate these issues. The results of the FEA simulations are shown in the following figures.

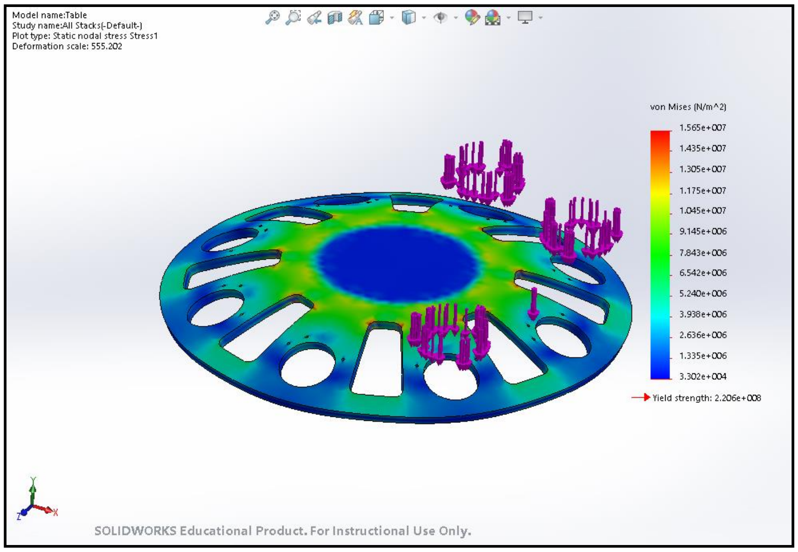


(a)

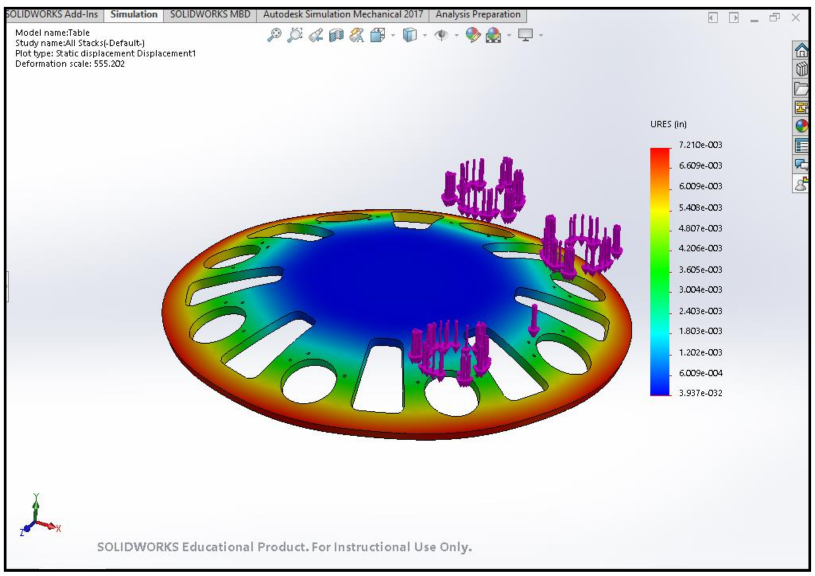


(b)

Figure 30: (a) Von Mises Stresses for a Fully Loaded Half-inch Thick Plate (b) Displacement to a Fully Loaded Half-inch Thick Plate.



(a)



(b)

Figure 31: (a) Von Mises Stresses for a Fully Loaded Three-quarter-inch Thick Plate (b) Displacement to a Fully Loaded Three-quarter-inch Thick Plate.

The results of the FEA analysis show the maximum displacement energy (Von Mises) stress to be 3.28 MPa for a half-inch plate and 1.56 MPa for a three-quarter inch plate. Furthermore, the maximum deflection is found to be 0.024 inches for the half-inch plate and 0.00721 inches for the three-quarter-inch plate. These results prove that a half-inch thick plate is fully capable of performing reliably for the duration of the project life-span. The displacement of 0.024 inches is small enough to vacate concern of part location variability, and the Von Mises stress of 3.28 MPa is far below the yield strength of steel which is 350 MPa.

Appendix G – OSHA Guidelines:

Information quoted from https://www.osha.gov/dts/osta/otm/otm_iv/otm_iv_4.html. Refer to this site for further information.

- R15.06-1999, Industrial Robots and Robot Systems - Safety Requirements. Provides requirements for industrial robot manufacture, remanufacture and rebuild; robot system integration/installation; and methods of safeguarding to enhance the safety of personnel associated with the use of robots and robot systems. This second review further limits the potential requirements for any retrofit of existing systems, revises the description of control reliable circuitry, and reorganizes several clauses to enhance understanding.
- TR R15.106-2006, Technical Report on Teaching Multiple Robots. Robotics Industries Association (RIA). Provides additional safety information relative to teaching (programming) multiple industrial robots in a common safeguarded space in an industrial setting. It supplements the ANSI/RIA R15.06-1999 robot safety standard.
- B11.TR3-2000, Risk Assessment and Risk Reduction - A Guide to Estimate, Evaluate and Reduce Risks Associated with Machine Tools. Provides a means to identify hazards associated with a particular machine or system when used as intended, and provides a procedure to estimate, evaluate, and reduce the risks of harm to individuals associated with these hazards under the various conditions of use of that machine or system.

Appendix H – Product Manuals:

Haas:

https://diy.haascnc.com/sites/default/files/Locked/Manuals/Operator/2008/Lathe/Lathe_Operators_Manual_96-8700U_9_Rev_U_English_June_2008.pdf

Note: This manual was not printed due to page count

Fanuc Arms:

See printed manuals at end of document.

Servo Motor:

See printed manual at end of document.

End-of-Arm

See printed manual at end of document.

Gearbox:

See printed manual at end of document.