

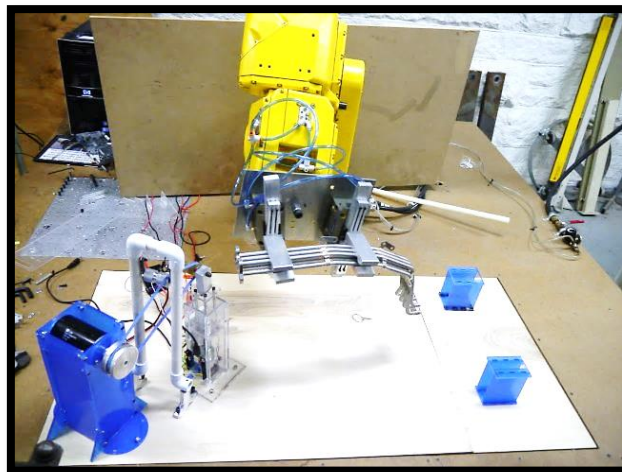
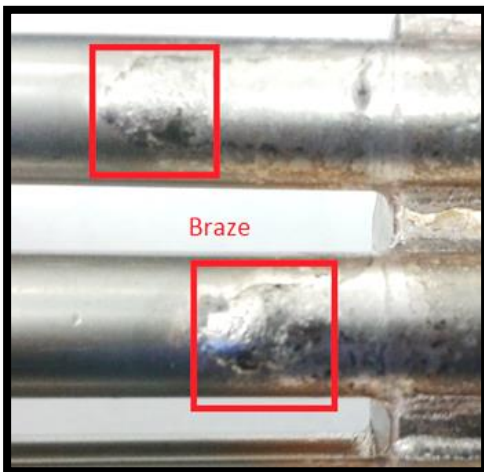
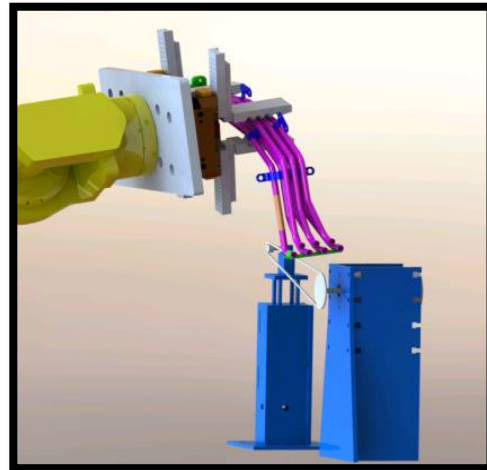


WPI

GE Tube Polishing System



GE Aviation



Keywords:

Robot, Polishing, Automation,
Industrial Robot, Cleaning, Braze,
Weld, Tube, Pipe.

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GE Tube Polishing System

A Major Qualifying Project Report
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WORCESTER POLYTECHNIC INSTITUTE
in partial fulfillment of the requirements for the
Degree of Bachelor of Science
by
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Submitted to:

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Professor Stephen S. Nestinger, Advisor, WPI

This report represents the work of four WPI undergraduate students submitted to the faculty as evidence of completion of a degree requirement. WPI routinely publishes these reports on its website without editorial or peer review.

Abstract

The goal of this project is to automate the polishing process of brazed or welded areas on a tube assembly supplied by GE Aviation. An end-of-arm-tooling for a Fanuc 200iB was designed and fabricated to manipulate the tube. A work cell layout was determined and part fixtures were developed. A force controlled polishing system was implemented and interfaced with the Fanuc 200iB. Analytical and experimental analyses were conducted to determine the necessary polishing forces. Design considerations were made for future enhancements to the automated tube polishing system.

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1. Introduction

Industrial robotics was founded on the principals that any dull, dirty, or dangerous job repeated in large quantities should be done by a machine. For a human to repeat a substantial amount of work would not only bring down efficiency of the production, but also lower the expected quality of the outcome. Industrial robots are widely used in the manufacturing sector, especially with batch production. Since the introduction of robotic labor into the manufacturing industry, development of robotic technologies has grown exponentially due to fast growing needs. GE Aviation, one of General Electric's divisions, manufactures a variety of jet engines. Currently, GE Aviation utilizes a mix of manual and automated manufacturing methods to produce components for aircraft engines. Some of these components are comprised of a large variety of tube assemblies of varying dimensions.

During tube manufacturing, the tubes are joined through welding or brazing. The welded or brazed unions on these tube assemblies affect the performance of the engines. During welding or brazing processes, discolorations and various types of discontinuities are formed on the surface of the tubes. Cumulative discontinuities inevitably increase the mass of the tubes and potentially increase the rate of corrosion. Aside from performance degradation, discoloration decreases the aesthetics of the tubes, which leaves a bad impression for the customers. GE Aviation invests a significant amount of manual labor on polishing these brazed or welded parts to meet the quality specifications of these tubes.

Currently, a manual polishing process is being used at the GE Aviation Hooksett site. The tube is held by the worker using two hands so that the brazed or welded unions to be polished are in between where the tube is gripped. The worker then rotates the tube and polishes the brazed or

welded areas by using a spinning polishing wheel. After the brazed or welded areas are polished, the worker manually examines the polished part and decides if further polishing is needed. This process is time consuming, tedious and potentially unsafe for the workers. Since a large quantity of tubes needs to be polished each day, GE Aviation decided to investigate the viability of a robotic system that could polish these tubes automatically.

The goal of this project was to create a robotic process capable of polishing the brazed or welded areas on the tube supplied by GE Aviation. The project included two key areas of development: an end-of-arm-tooling for manipulating tubes, and a method for polishing.

Once the entire project is fully developed and implemented, it will bring benefits to the GE Aviation plant in Hooksett, New Hampshire. This automated system will add a higher level of precision and consistency to the polishing process and allow the workers who are currently manually polishing the tubes to be assigned to more important tasks that cannot be automated.

2. Background

This chapter provides background regarding the GE Aviation and their current tube polishing methods, industrial robotics and end-of-the-arm tooling, tube welding and brazing techniques, and methods for inspecting tube welds and brazes.

2.1. GE Aviation

GE Aviation was founded during World War I and has been an aviation powerhouse ever since. They have a reputation for introducing innovative parts and assembly processes to the world of aviation. Currently, GE is leading the world in producing large and small jet engines for commercial and military aircraft. GE currently has five different types of facilities: Manufacturing, Overhaul, Accessories, On-Wing Support, and Component Repair. Each facility is in charge of a different process in the construction of the engine [1].

2.2. Manufacturing Materials Processes: Brazing and Welding

The joining of two metals is a fundamental concern of the manufacturing and materials processing found in many industrial applications. Two common methods of joining materials are through the processes of brazing and welding.

Brazing is a metal-joining process [2]. This process consists of heating a filler metal until the point of melting, whereby it is introduced between two main metal pieces to be joined. The melted filler metal then, through the ability of capillary action, is drawn up a narrow channel between the two main pieces of metal. This brazing process often leaves left over residue in the form of solidified filler material.

In typical aircraft applications of industrial welding, a part, usually made from aluminum, is subjected to welding to either produce a desired assembly or for repair. Methods for welding aluminum vary, but one method of one of the more common methods is the Gas Tungsten Arc Welding method (GTAW) also referred to as the TIG (Tungsten Inert Gas) welding process.

2.2.1. Brazing Process

When considering the brazing process, one must consider the selection of materials before any procedure is implemented. The importance of material selection is weighed based on the filler material as well as the Base-metal characteristics. In the case of the filler material it has to have certain attributes that make it appropriate for its intended usage.

Filler metal characteristics include:

1. Limited Reaction with the base metal:

- The Material should not produce a chemical reaction with the base-metal. Chemical reactions usually include a precursor for discontinuities in the workpiece or areas of contamination.

2. Workable Temperature Ranges:

- Capable of melting at temperatures comparably lower than the base-metal to prevent undesired change to the base-metal,
- Capable of flowing in its molten state, and
- Able to cool evenly and rapidly without cracks or distortions.

Base metal characteristics include:

1. The Stronger, the Better:

- The base-metal is ultimately what the joining process attempts to make into one continuous piece; this selection quality usually is common or widespread in practice.
- If the base-metal is not inherently a strong metal, but a hardenable metal, it might form fairly unpredictable stress cracks or discontinuities during the brazing process with the filler metal throughout the heating and cooling sub-processes.

2. Brazing Occurs Last:

- It is recommended that the base-metal not be cold-worked.
- Annealing is a by-product of the brazing process, and it is again recommended not to provide any further working to the metal to prevent discontinuities from forming.
- Metal selection is limited to oil-quenched, hardenable air-quenched, and precipitation-quenched metals, so long as the solution treatment occurs at the same time as the brazing.

2.2.2. GTAW Process

The GTAW process is a very difficult welding process first developed in the late 1950s as a variant on popular inert gas methods using argon and helium as a gas medium but with a non-consumable tungsten electrode to produce the weld. Operation of a proper TIG welder requires an electrical arc hot enough to melt the affected area of a work metal with the option of inserting a filler material or combining two heated pieces of a material. This electrical arc is created by a high frequency generator that provides the electric spark and is shielded in an inert gas to prevent oxidation of the material. The GTAW process, shown in Figure 1, for welding aluminum consists of a proper workspace, proper welding controls, and an experienced and patient welder.

A proper GTAW workspace requires:

1. **Proper Current Selection and Generation:** It is suggested that for every 0.001 inch of thickness of aluminum being melted, an ampere of current is required. A 1/8 inch thick piece of aluminum being melted can require up to 125 A of current.
2. **Gas Selection and Flow Rate:** Typically argon is the selected inert gas, but combinations of argon and helium can be chosen for thicker work pieces. Typically a gas feed rate of about 15-20•ft³/hr is chosen, with additional increments of 5•ft³/hr if needed.
3. **Tungsten Type and Diameter:** Normal aluminum applications call for pure tungsten electrodes, however, on welds thinner than 0.09 inch modifications of the electrode can be made implementing a composite electrode. The diameter is chosen based off Tungsten's current-carrying capacities. The typical Diameter to Ampere ratio is 0.093 inches to 200 Amps.
4. **Proper Filler Material:** Filler material should have matching qualities to the work material.
5. **Frequency Control:** High Frequency AC is required in order to create a constant bridge between the workpiece and the electrode. Because high frequency emissions interfere with modern electronics, it is important to place the grounding clamp as close to the weld as possible.

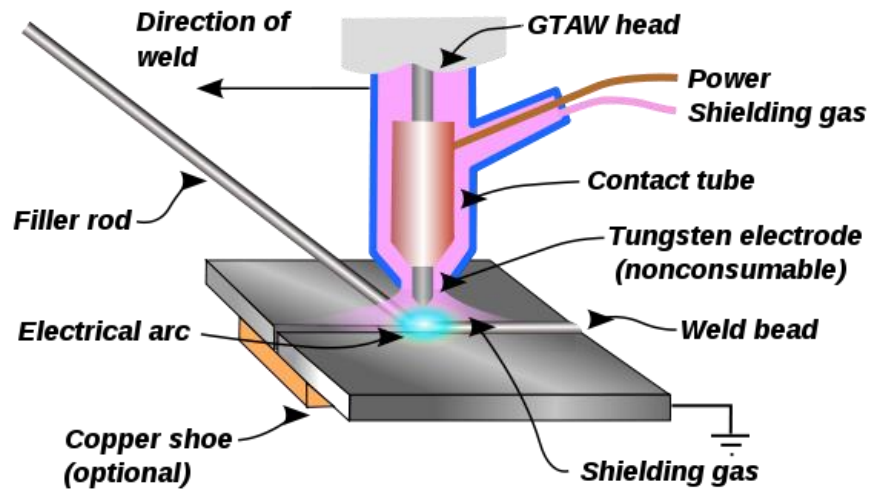


Figure 1. Image of a Gas Tungsten Arc Weld (GTAW) setup.

The GTAW (TIG) process is notably used in the aerospace industry for thin, nonferrous materials such as lightweight aluminum because of its ability to require minimal filler material, and the resulting welds are resistant to corrosion and cracking over long periods.

2.3. Brazing & Weld Analysis and Problems with Brazes and Welds

During the welding process, weld discontinuities and discolorations may occur [3]. The following provide the causes, issues, and removal process for weld discontinuities and discolorations.

1. Discontinuities

- **Cause:** The welding process, poor weld joint design, improper welding technique or application, and inferior quality base metal or filler metal can all contribute to discontinuities of the tube welds.
- **Issues:** Discontinuities add additional weight to the tube, and may lead to faster corrosion.

- **Removal process:** Discontinuities are mechanically removed first then chemically treated with a passivation treatment to ensure all corrosion has been removed.

2. Discolorations

- **Cause:** If the tube is not properly shielded or purged with inert gas or flux during welding process, discoloration will occur. Typical welding-grade argon is 99.985% pure. Figure 2 shows the results from different amounts of oxygen in the argon purging gas. The more oxygen that is contained in the inert gas, the more discoloration will occur on the tube [4].

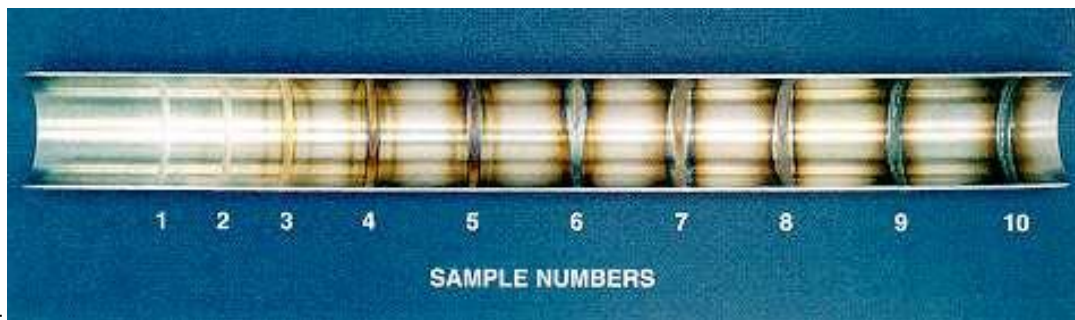


Figure 2. Discolorations on a welded tube

Weld 1 was made with 0.001% oxygen, weld 4 was made with 0.01% oxygen, and weld 7 was made with 0.1% oxygen.

- **Issues:** Discolorations will cause the surface to be less corrosion resistant. From a customer's standard, the more discolorations the tube has, the less desirable the product is.
- **Removal process:** Mechanical or chemical cleaning followed by a passivation treatment.

2.4. Computer Vision

Computer vision systems can be used to detect the brazed locations on a tube due to the discoloration caused by the braze filler material and the discontinuous surface characteristics. The typical discoloration of a tube from GE Aviation is shown in Figure 3.

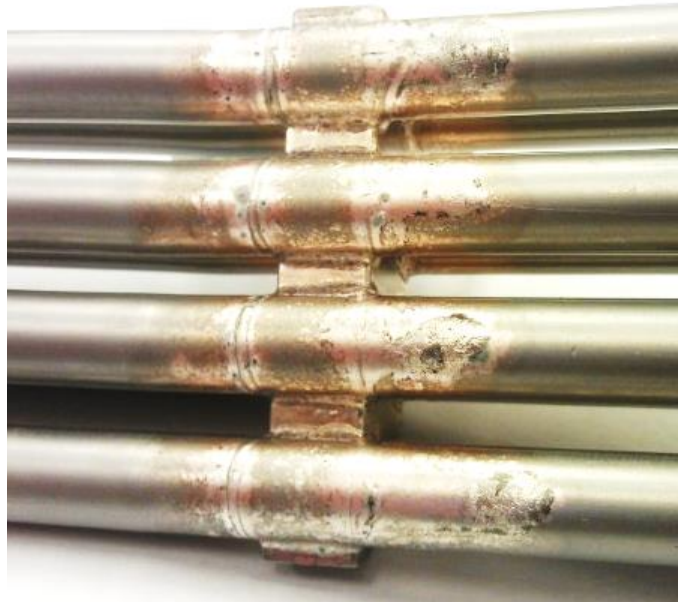


Figure 3. Discoloration on the tube supplied by GE

2.4.1. Computer Vision Software

There are several existing software packages that can be used to detect changes in color, changes in the surface texture, and obvious discontinuities in the shape of the tubes: Open Source Computer Vision Library (OpenCV), CMVision and Matlab Image Processing Toolbox.

OpenCV is an open source computer vision software library. The library has more than 2500 algorithms that can be used to detect and recognize faces, identify objects, classify human actions in videos, track movements, and track objects. For color recognition, OpenCV provides the ability to process real time images collected from the camera. When the image is loaded, a

2D array of the image can be generated with RGB values representing the colors of each pixel. Users can manipulate and extract color-based data from the image [5].

CMVision is open source software developed by Carnegie Mellon University. It can create simple, robust vision systems suitable for real time robotics applications. The system aims to perform global low level color vision at video rates without the use of special purpose hardware. Images can be processed using color-based threshold classification [6].

Matlab is a high-level language and interactive environment for numerical computation, visualization, and programming. Users can analyze data, develop algorithms, and create models and applications using Matlab [7]. Matlab provides an Image Processing Toolbox that contains a comprehensive set of reference-standard algorithms and graphical tools for image processing, analysis, visualization, and algorithm development. Users can perform color-based manipulations using Matlab Image Processing Toolbox [8].

2.4.2. Computer Vision Implementation – Manipulator Control

Manipulator control for robot arms is often assisted by a computer vision system. The camera can be used to determine the position and orientation of a given object. The camera used for the computer vision can either be placed so that it overlooks the work cell from a fixed location or the camera can be placed on the end of the robot arm, or a combination of the two cameras. An end-effector mounted camera can either be placed so that it can see the tooling and the object or so that the camera only sees the object. The way the camera is mounted depends on the requirements of the task of the tooling and the way vision sensing and force sensing interact to control the system.

Integrated force sensing and vision for control can come in several forms: traded, hybrid, and shared control. Traded control is when the direction of the manipulator is only being controlled by one method, either vision or force sensing, at a time. Hybrid control is when vision and force sensing control different directions of motion at the same time. Shared control is when vision and force sensing control a single manipulator direction simultaneously.

2.5. Robots in Manufacturing

Modern robots can be used to perform many tasks. For example, most industrial robots can be programmed to polish, mill, deburr, drill or cut material. Robots are chosen to complete these tasks over conventional machining tools because they have higher precision and flexibility than conventional machines. The reason why modern robots are much more advanced in automation is due to the utilization of sensors and software control. The sensors and software give the robot information about its surroundings and a better understanding of its tasks. Modern robots allow the operators to dictate how much force the robot will use and also control how fast the robot will maneuver. This gives them the ability to complete production more accurately and at a faster rate than if there were no sensors deployed to allow for feedback from the environment.

These qualities have propelled modern robots over the conventional machines that were previously used in manufacturing. Robotics can also potentially make the workspace a safer place. They eliminate some of the tedious and harmful work that human beings were once responsible for.

2.5.1. Polishing Robots

Polishing is the process of removing a small amount of material to achieve a smooth finish, enhance the visual appearance of an item, remove and prevent oxidation, and prevent corrosion

of the material. The importance of polishing tubes is to ensure that the airplane meets the customer's desired specifications and that each tube is lighter. The polishing process serves also to eliminate oxidation, discoloration, and other defects that may damage the tubes, thus shortening its lifetime.

Industrial robots are often utilized to perform the polishing tasks because of their precision, speed, and repeatability. These robots are arm-shaped and have multiple degrees of freedom, therefore qualifying achieving high quality of polishing results.

2.5.2. The End-of-Arm-Tooling

The End-of-Arm-Tooling (EOAT), also known as the robot end effector, is the part of a robot that interacts with the work environment. It is the last link of a serial robotic manipulator and can be a gripper for picking up and manipulating parts or it could be a specialized tool such as a welding gun, glue dispenser, or polisher [9].

There are a variety of EOAT's and the EOAT selection is dependent on the overall system design and application. Pneumatic grippers are ideal for grabbing an object that is always the same size because the gripper only needs an open and closed setting. Standard grippers often have a two-finger or three-finger design and may include force-sensing to provide feedback.

2.5.3. Force Sensing

Force sensing can be accomplished with resistive, capacitive, piezoelectric, or optical sensors [10].

- Resistive sensors measure a change in resistance over the area of a material as it is deformed. Resistive sensors are small and highly sensitive; however they can be fragile and costly.

- Capacitive sensors can detect normal and shear forces by measuring change in capacitance due to deformation. The sensing capabilities are dependent on the arrangement of the capacitors and can be very sensitive.
- Piezoelectric sensors turn received pressure into an electric voltage and do not require a power supply in order to function. They are robust and have wide applications, but can lose voltage output over time.
- Optical sensors detect a change in light. The idea behind optical sensors is that an applied force will change the intensity of light passing through a membrane.

2.6. Polishing Alternative: Sand Blasting/Glass Bead Blasting

GE has provided an assembly that is composed of tubes that have been brazed together. Brazing is a process used to join metals using a filler metal, typically copper mixed with silver or nickel. The process of brazing is done with temperatures below the melting point of the base material, stainless steel.

Due to the complex angles that the tube assembly (shown in Figure 4) contains, certain areas of the tubes will be complicated to polish. These difficult to polish areas are located in the center of the brazed unions and would require complex programming that would allow the robot to maneuver with accuracy within a very small area.



Figure 4. Complex-angled tube assembly received from GE Aviation

Due to the brazed portions being so small, there is the potential to utilize sand blasting. Sand blasting consists of blowing sand particles at a fast rate through a nozzle using water, air, or steam pressure [10]. This method has been used to polish and cut/carve material, and is a suitable alternative to a polishing wheel. It allows polishing and cleaning areas that a polishing wheel could not fit into and has a wider range of flexibility. Sand blasting does present some risks though, one of which is that it leaves harmful particles in the air [11].

Sand blasting is done in confined and insulated places due to the generation of dangerous silica particles. These particles can be inhaled and can cause lung problems. Aware of the dangers, employees should take all necessary precautions by wearing goggles to protect their eyes and face masks to prevent inhaling the particles. Also wearing protective clothing is necessary to protect the skin from the particles deflecting backward and hitting the employee [12]. There is a less risky alternative, though, which is bead blasting with glass beads.

Bead blasting is a more environmentally friendly approach and involves fewer chemicals. The glass beads used in bead blasting are lead-free and do not contain silica. These glass beads can be recycled up to 30 times, which is a financial benefit.

In terms of performance, bead blasting produces a smoother and brighter finish than sand blasting. Also glass bead blasting leaves no embedded residue and does not change the surface's dimension. Glass bead blasting can also improve corrosion resistance. Glass bead blasting is used on a wide range of materials including brass, stainless steel, copper, steel, aluminum, etc. [13]. Because glass beads do not contain silica, the health concern of silica particles in the air is no longer a safety factor. Therefore glass bead blasting will be easier to implement because there will not be many extra safety precautions needed.

In terms of cost, glass bead blasting is also a lower cost process than sand blasting. During the process of sand blasting, the sand is fragile and breaks apart easily. This causes dust particles to float in the air and causes the health issues for employees. The sand isn't recyclable due to breakage, so there will be constant replacement. This constant replacement will add up and be more expensive than reusable glass beads. Also sand blasting cause changes in the work dynamic because employees would have to change their clothing and conceal certain areas of their work stations.

3. Methodology

The goal of this project is to automate the polishing process of brazed or welded areas on a tube assembly supplied by GE Aviation. A statement of work was developed and supplied to GE Aviation for approval guaranteeing that the concept behind the project was understood: a first year prototype deliverable to GE capable of polishing braze locations on a specific tube assembly supplied by GE Aviation. The project included two key areas of development: an end-of-arm-tooling for manipulating tubes, and a method for polishing.

Background research was accompanied to determine if prior work relevant to the project was conducted. Topics covering the two key components were researched.

The initial prototype design procedure included brainstorming different methods of manipulating the tubes, and polishing the tubes. After all the potential methods and EOAT designs were listed, a design metric capable of narrowing down the selection was created. Selection of which of the polishing processes, methods, and EOAT design implementations would be relevant to the scope of the project was made. Though sand blasting, particularly glass bead blasting, was the most appealing of the polishing methods, it was cost prohibitive and ultimately eliminated in favor of traditional belt polishing. For all other aspects of the project, time cost, system precision, functionalities, and complexities were considered in their own individual metric. The top two or three methods were selected as the final designs. CAD models and hand drawn sketches were used to create visual representations, and simulations were conducted to test if the system would meet the project goal. By comparing the final two or three designs, the most feasible one was chosen as the final decision.

The initial components for the gripper design were purchased and an initial prototype of the grippers was fabricated and further tested. Force calculations were determined using a simple scale and a square inch of sandpaper of useable grit that would resemble our polishing methods. The work cell provided by GE Aviation was not usable during the span of the MQP, but an alternative existing Fanuc robotic arm was used. The pneumatic grippers were purchased from Schunk. The fingers attached to the grippers of the prototype system were manufactured using the CNC machines located at WPI. The parts were assembled for testing. Results were collected as the project progressed.

4. System Requirements and Specifications

In this chapter, the following requirements are analyzed:

1. Economic Considerations
2. Safety Considerations
3. Social Impact
4. Use and Importance of Standards

4.1. Economic Considerations

There were two major components in this project that needed economic consideration: the robot to perform the polishing process and the polisher to perform the polishing and force sensing. The system was a new design that would be relatively economical to implement as well as completely modular.

4.2. Safety Considerations

Safety considerations for the tube polishing process are related to the work cell of the robot. The danger of the polishing process comes from the potential for personnel working near the robot to be struck by the arm as it moves about its work cell as well as the moving polishing belt/wheel. This means that personnel must stay outside of the work cell of the robot while it is in operation. This is accomplished by establishing a safe perimeter around the robot during operation. A protective box should surround the robot in order to establish a safe work cell perimeter. Safety locks should be connected to the control system. When doors are open or not locked, the system should automatically stop operating. The robot should always be powered down when

performing maintenance on either the robot or the polishing wheel and personnel should not enter the protective box around the robot while it is in operation. The aforementioned precautions will help maintain a safe work environment near the work cell of the robot as it performs its polishing task.

4.3. Social Impact

As robots become more advanced, more tedious and less desirable jobs will be able to be accomplished by robots instead of human employees. This will increase efficiency in the workplace and release the employees from undesirable working conditions. In this case, human employees will be able to focus more on managerial tasks and some tasks that a robot cannot achieve.

There are other concerns when considering the removal of a laborer's position. The ethical consideration for removal of a laborer's position based on the company's desire for more profitability or reduction in risks and training might be considered by some to be self-serving. It has a legitimate founding in previous iterations of technology and industry. In just 2009, Foxconn, the Taiwanese multinational electronics manufacturing company, headquarters was set to replace millions of workers with more than 1 million robotic stations over the span of 3 years [15]. There was a concern if the replacing of all these jobs was ethical or even advisable, since the profits and savings could be overshadowed by the negative image the public would perceive this replacement to be. Some other concerns included the possibility of hostile work environments, sabotage being one of those issues.

4.4. Use and Importance of Standards

All tube properties must fall within the purview of the American Society for Testing Materials (ASTM) standards shown in Appendix A. The standards utilized is for Aerospace Material Specification (AMS) 5557 – 321 Seamless or Welded Stainless Tubes. Where applicable, SAE (Society of Automotive Engineers) standards are also followed to ensure the highest quality of material being produced. Finally, GE Internal specifications are also applied to the tubes.

5. System Design and Analysis

This chapter provides the design and analysis of the subsystems of the End-of-Arm-Tooling, the polishing methods, the polishing routine and programming, the polisher design and force sensing, the electronics and interface, and the software.

5.1. End-of-Arm Tooling (EOAT)

The robot must be able to pick up the tube to perform the polishing process, thus a robotic gripper EOAT is required to achieve this task. This EOAT was designed to attach to the Fanuc M-710iC/50 Industrial Robot. Since the M-710iC/50 Industrial Robot was not fully setup during the first year of the project, the EOAT was then customized for the Fanuc LR Mate 200iB robot that WPI already had running.

There are two major requirements for the EOAT:

1. The EOAT must be able to adapt to various shapes of tubes up to a size that a manual process can achieve
2. The EOAT must not damage the tubes by changing the shapes or over-polishing the tubes.

Two candidate solutions were brainstormed, analyzed and discussed: the Gripper Base and the Tube Follower.

5.1.1. Gripper Base

The gripper base is a universal design that can change the gripping positions and orientations to adapt to different shapes of tubes as shown in Figure 5 and Figure 6.

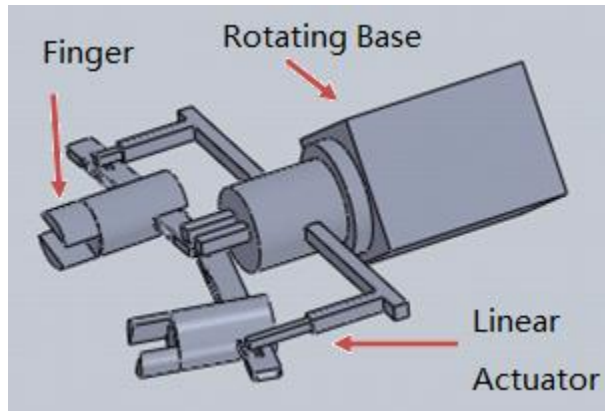


Figure 5. Gripper Base used to grab planar, angled, and non-planar tubes

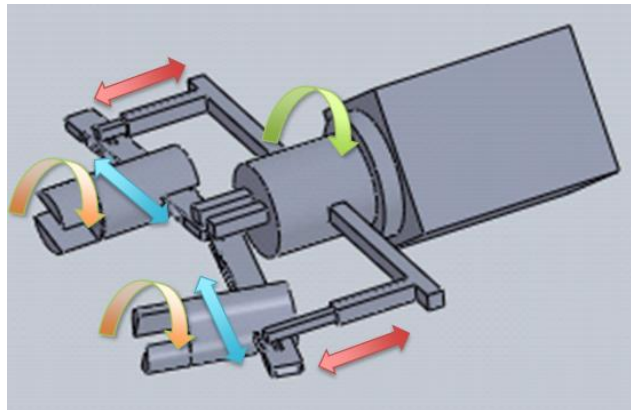


Figure 6. Gripper Base showing multiple degrees of freedom

The Gripper Base has multiple degrees of freedom as each of the joints can rotate or slide to adapt to the shape of the tube.

Gripper Base Components

The Gripper Base consists of three parts: fingers, linear actuator, and rotating base.

Fingers

The fingers as shown in Figure 7 are attached to a sliding bar. They can rotate to different angles, and open and close while sliding on a rail from the linear actuator part.

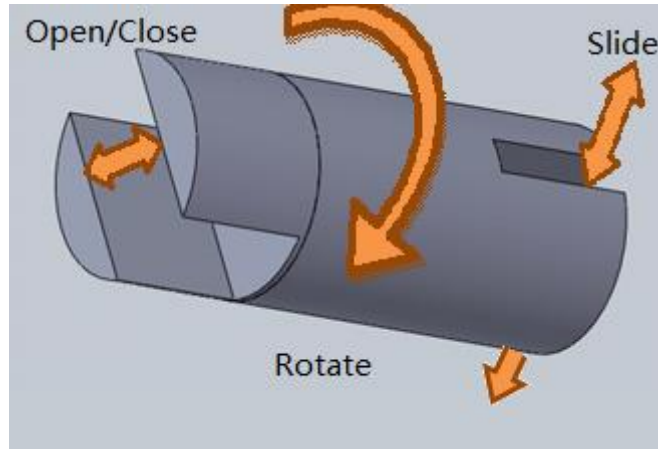


Figure 7. Universal fingers for the Gripper Base design meant to clamp and rotate

The fingertips are interchangeable so that customized fingers can be made to adapt to specific tubes that are not standard sized or shaped.

Linear Actuator

The linear actuator of the Gripper Base is a set of rails allowing the fingers to slide and move up and down. The two rails are designed to have rack gears so that the attached fingers can move along them. The rails have linear motions on the both axis. Figure 8 shows the movement of the linear actuator of the Gripper Base.

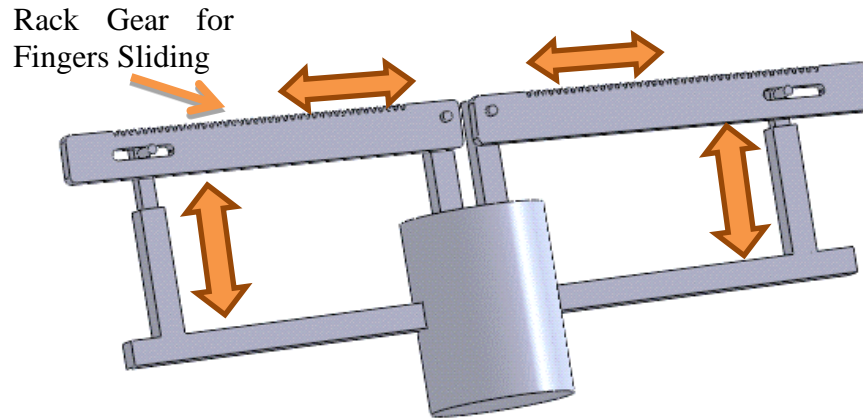


Figure 8. Gripper Base linear actuator is meant to be capable of a large range of motion

Rotating Base

The rotating base is the final part of the Gripper Base. The rotating base might not be necessary if there is already an existing degree of freedom of the robot arm that generates the same rotational motion. The rotating base is shown in Figure 9.

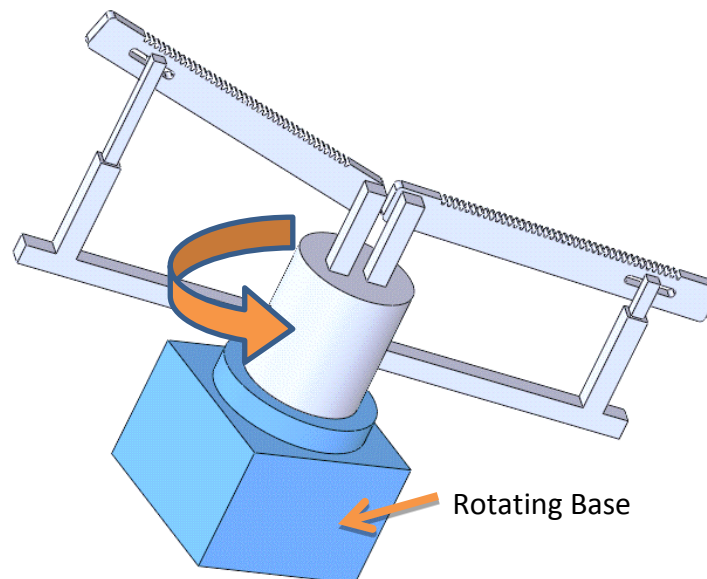


Figure 9. Rotating Base adds a DOF for the gripper for rotational manipulation

Feature Analysis

The Gripper Base is designed to intend for handling all regular-sized single-branched tubes of various shapes within a motion range. The fingers are able to slide to the left and right to grip a linear tube; the linear actuator is able to move up and down to grip a planar tube in addition to the finger sliding; the fingers are able to rotate to grip a non-planar tube. Different gripping poses are as shown in Figure 10.

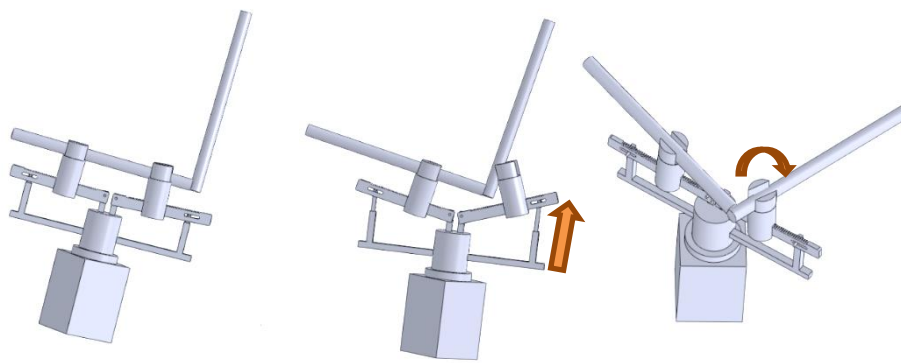


Figure 10. Depiction of Gripper Base design interacting with a planar tube at different angles

5.1.2. Tube Follower

The second proposed design is the Tube Follower. The Tube Follower is intended to be an apparatus that encloses the tube. It is intended to move along the tube path and follows the shape of the tube while using machine vision to identify a weld/braze then polishes it using a built-in belt.

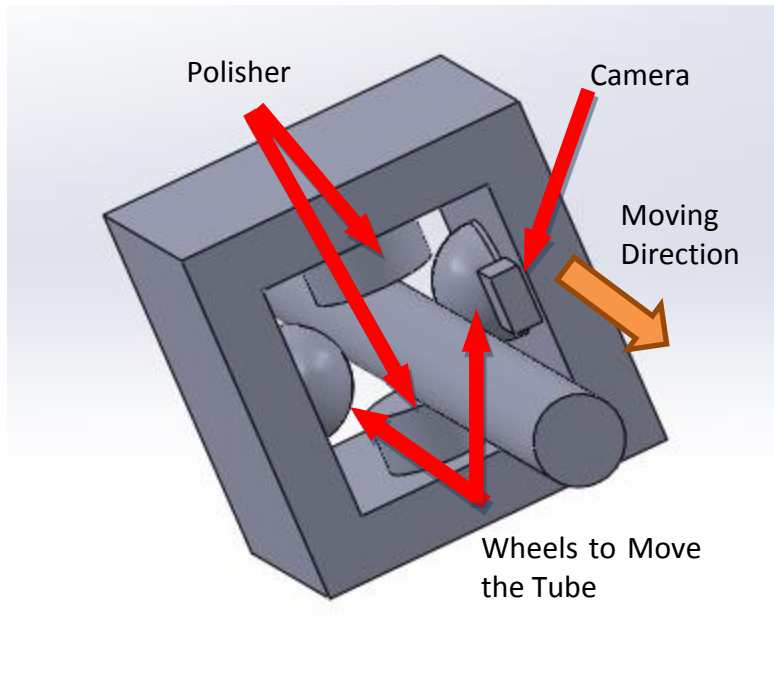


Figure 11. Tube Follower polishes brazes as it crawls along the length singular tubes

Tube Follower Component

The Tube Follower would consist of three parts: the Moving Wheel, the Camera, and the Polisher. They would all be built on the inside-edge of the Tube Follower.

Moving Wheel

The moving wheel is inside the Tube Follower. The main function of this moving wheel is to enable the Tube Follower to move along the tube following its shape. When the Moving Wheel hit a turning point on the tube, it can detect the force on one side thus change the orientation of the Tube Follower to move along the tube.

Camera

A computer vision camera could be embedded inside the Tube Follower to identify the locations of the welds or brazes.

Polisher

A polisher could be used to perform the polishing process. The tube could be in contact with the polisher during the polishing process.

Feature Analysis

The Tube Follower is a unique design that is different from traditional industrial robot arm. It could follow a tube's shape thus making it easier to perform the polishing process regardless of the tube shape. The tube follower would be able to handle various shapes and sizes, but its down side is that it would not be able to handle branches.

5.1.3. Design Comparison

The pros and cons for each EOAT design are listed below:

Pros and Cons of the Gripper Base:

Pros:

- Multi-purpose design. Can be either mounted on the robot arm or on the table as a tube fixture
- Flexible joints that can adapt to different tubes
- Interchangeable fingers

Cons:

- Complex design with multiple DOF

Design Difficulty

Programming complexity

Need to adapt to different shapes of tubes

Mechanical design complexity

Needs numerous actuators to fully control it

Resources

Cost (Budget)

Motors, raw materials, manufacturing and pneumatic grippers

Time cost (for GE)

Robot needs to move the tube to different positions for full polishing.

Performance

Precision

Hard to determine and locate the areas that need to be polished

Desired functions absence

No distinct disadvantage

Pros and Cons of the Tube Follower:

Pros:

- Different tube shapes become trivial
- Using a belt to polish, less potential for damage
- A robot arm may not be required

Cons:

- Only operates on one branch at a time
- Limited Diameter range

Design Difficulty

Programming complexity

Very easy programming by following the path of the tube.

Mechanical design complexity

Customized EOAT to perform tube following

EOAT

A circular shape tool with polishing belt, vision system inside.

Resources

Cost (Budget)

Necessary components: Customized EOAT, robotic arm

Time cost (for GE)

Tasks that consume time: picking up the tube, tube following while polishing.

Performance

Precision

With proper control and spot polishing, the system potentially has a very low risk of damaging the tubes. The system will use polishing belt instead of polisher.

Desired functions absence

Cannot polish branches.

Based on multiple design requirements, the team made a rubric for accessing these two EOATs. A scale from 1 to 5 was used, where 5 meant the highest penalty. See Table 1 for the complete design metrics. Based on the penalty score, the Gripper Base design was selected as the final design prototype.

EOAT	Gripper Base	Tube Follower
Metrics		
Design Difficulty		
Programming complexity	4 Need to adapt to different tubes	2
Mechanical design complexity	3	5 Highly customized design
Resources		
Cost (Budget)	3	4 Highly customized design
Time cost (for GE)	4 May change gripping locations	3
Performance		
Precision	4 Harder to determine polish area	3
Desired functions absence	2	5 Cannot polish branches
Total	20	22

Table 1. Design metrics for EOAT

5.1.4. Final Design

A final design was implemented based on the seven-tube assembly shown in Figure 12 supplied by GE Aviation.

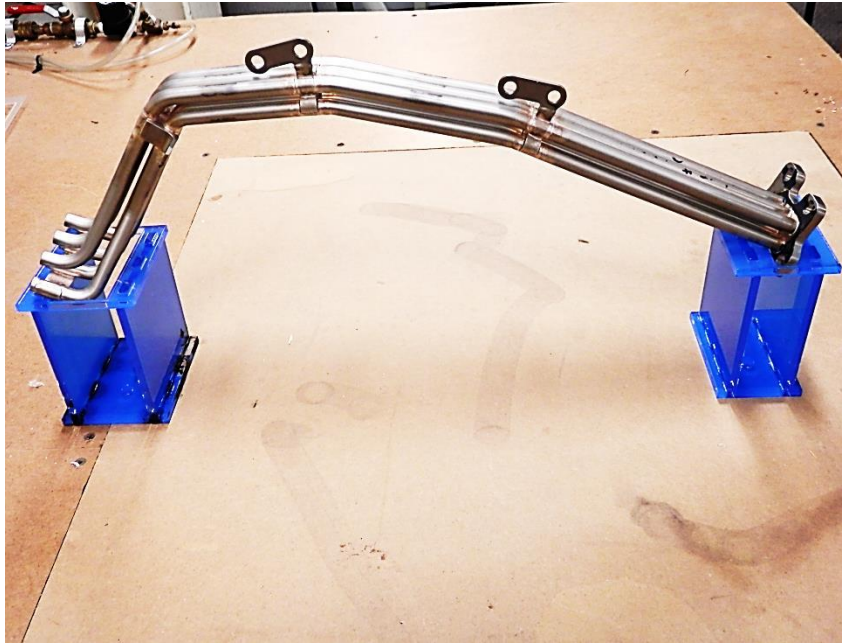


Figure 12. Seven-tube assembly supplied by GE Aviation

Based on the unique shape of this tube assembly, a customized fingertip was designed to adapt to the specific shape of the tube assembly. The second-phase Gripper Base design is shown in Figure 13. The fingers have 4 concaved slots to match the side of the tube assembly.

To actuate the fingers, a variety of actuators were considered. Since the fingers only need two states: open and close, and the force required to keep the tube in the fingers should be large enough to hold the tube, pneumatic grippers were considered as the best choice. After choosing the Schunk PGN-125/1 Pneumatic Gripper as the actuator, further redesigning was conducted to integrate the Schunk gripper and the fingers. A silicone pad was used to prevent potential

damage to the tube. One half of the customized finger is shown in Figure 14. Figure 15 shows how the silicone padding protects the tubes while gripping them securely. An integrated finger with Schunk gripper is shown in Figure 16.

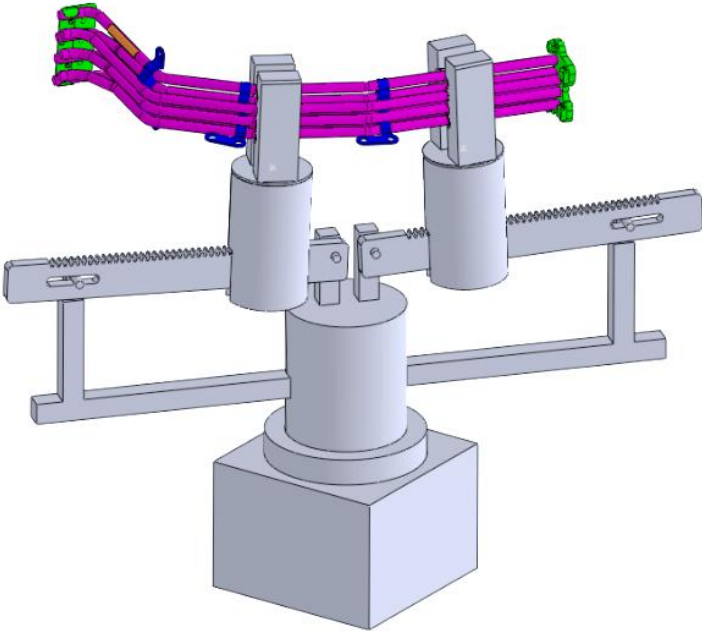


Figure 13. Second-phase finger design shown gripping the GE tube assembly

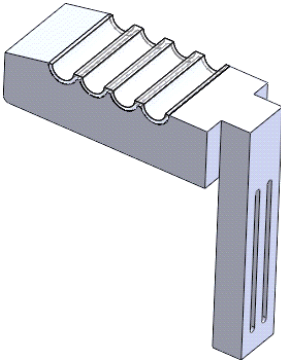


Figure 14. Final design of a single unit of the customized finger

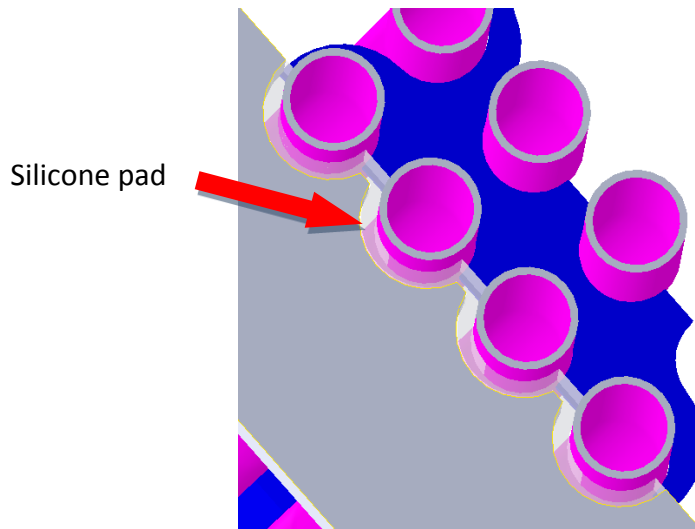


Figure 15. Implementation of the silicone pad on the finger to disperse contact forces

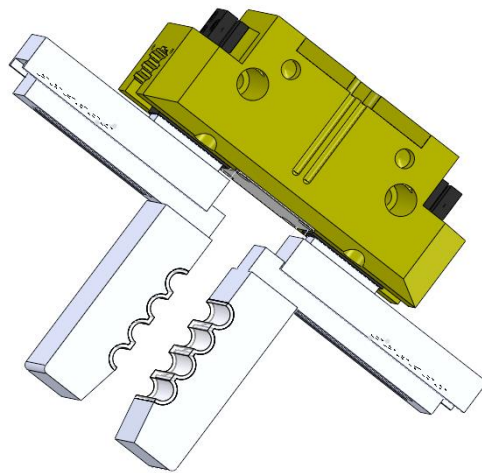


Figure 16. Pneumatic gripper assembled with redesigned fingers attached

Two half-fingers were combined together as one set on a Schunk PGN 125/1 parallel gripper to perform the gripping. Two sets of fingers were used to mimic the two hands of a worker and to secure the orientation of the tube while polishing.

To simplify the Gripper Base as a first-year design, a non-rotational plate with customized fingers is implemented as shown in Figure 17. The plate is fixed between the robot and the two Schunk grippers. The linear actuator and rotation base are not implemented. Given the angle of rotation between the two sets of fingers and the fixed distance between them, there is only one way to grab the tube assembly.

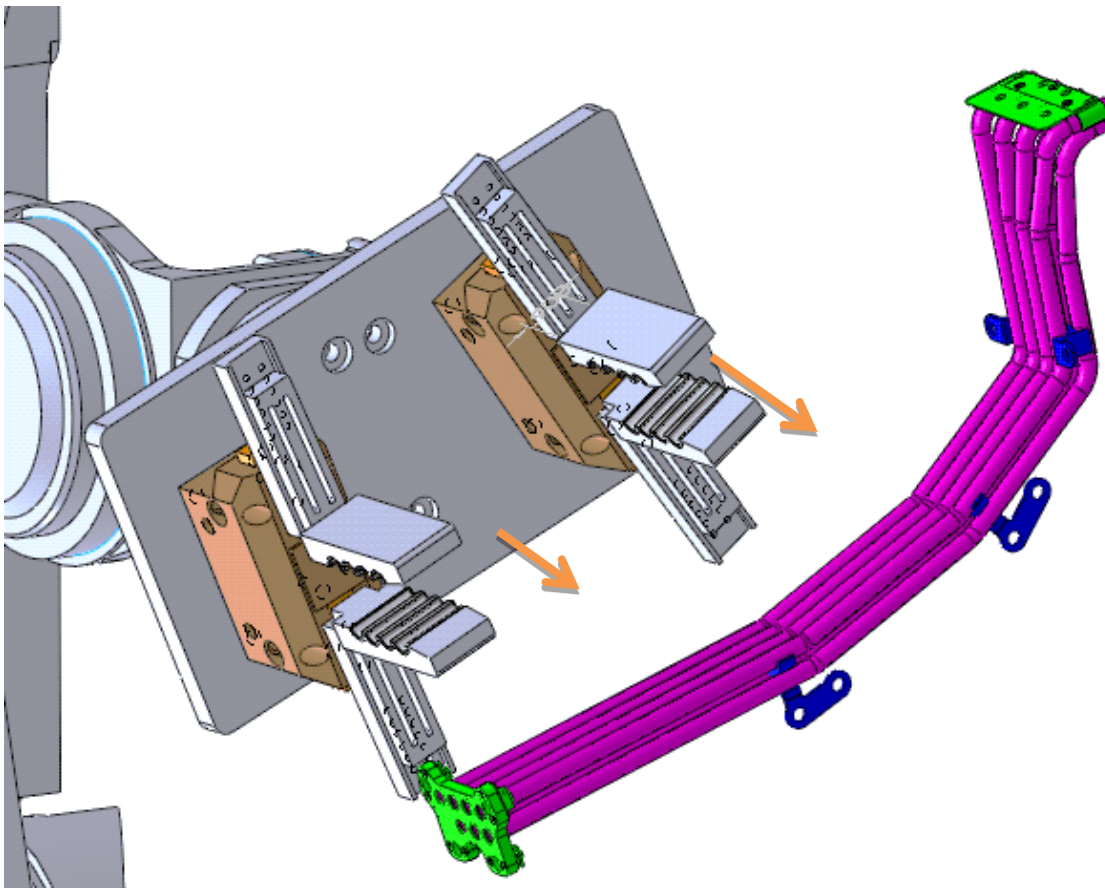


Figure 17. Complete gripper design with pneumatic gripper, fingers and tube assembly

5.2. Polishing Method

A polishing method is needed to mimic the current manual polishing process used at the GE Aviation Hooksett site. A polisher design is then needed to perform the polishing process.

There were two major requirements for the polishing method and the polisher:

1. The polishing method and polisher must be able fully polish the tube from various angles.
2. The polishing method and polisher must not damage the tube or the robot.

Both the polishing wheel and sand/beads blasting were considered as potential polishing methods. However, due to the limited work space and testing equipment, neither the sand blasting nor the glass beads blasting method was further considered, therefore they were not tested or implemented in this project.

Three final candidate solutions were analyzed and discussed: the Moving Tube Fixed Polisher, the Moving Polisher Fixed Tube, and the Moving Tube Moving Polisher.

5.2.1. Moving Tube, Fixed Polisher

The Moving Tube, Fixed Polisher means that the robot grabs the tube, holds the tube onto a fixed polishing wheel, changes polishing angles of the tube until it is polished. The Moving Tube, Fixed Polisher is as shown in Figure 18.

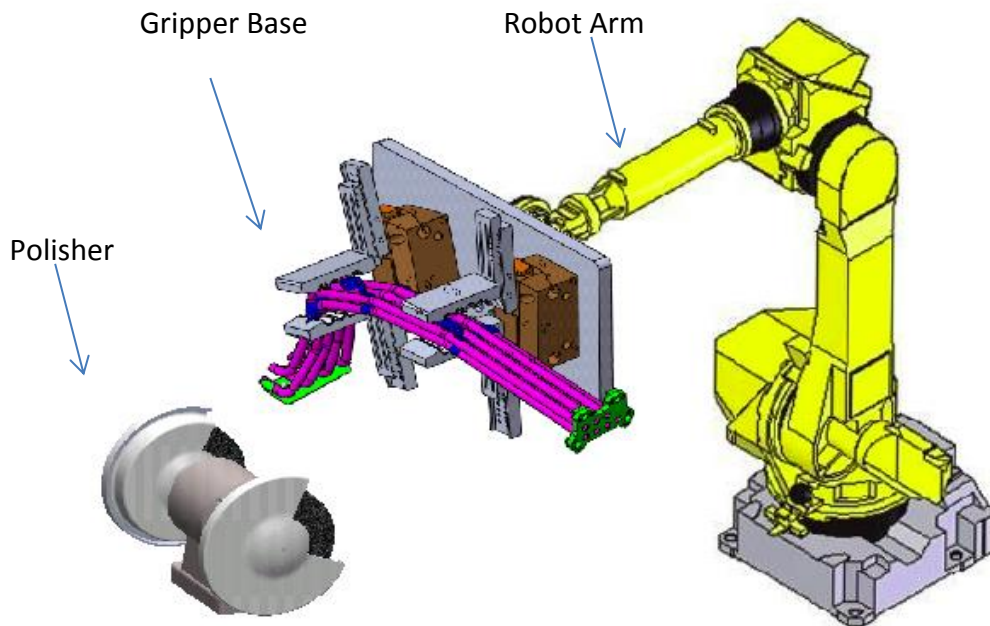


Figure 18. Moving Tube, Fixed Polisher with tube being brought to the polishing station

Feature Analysis

The Moving Tube, Fixed Polisher polishing method features a flexible Gripper Base mounted on the robot arm, and a stationary polishing wheel fixture on the ground which can sense the force on the tube while polishing. The robot only needs to pick up the tube from a specified location, holds it tight, moves to the polisher then starts to polish while moving or rotating the tube as necessary to polish different areas. After the polishing is completed, the robot will drop off the tube at another specified location. The next iteration then starts again.

5.2.2. Moving Polisher, Fixed Tube

The second design is the Moving Polisher, Fixed Tube. This polishing method is the opposite of the Moving Tube, Fixed Polisher. The robot arm grabs the tube, passes it to the Gripper Base fixture, changes the tool from grippers to polishing wheel then starts to polish. The design is shown in Figure 19.

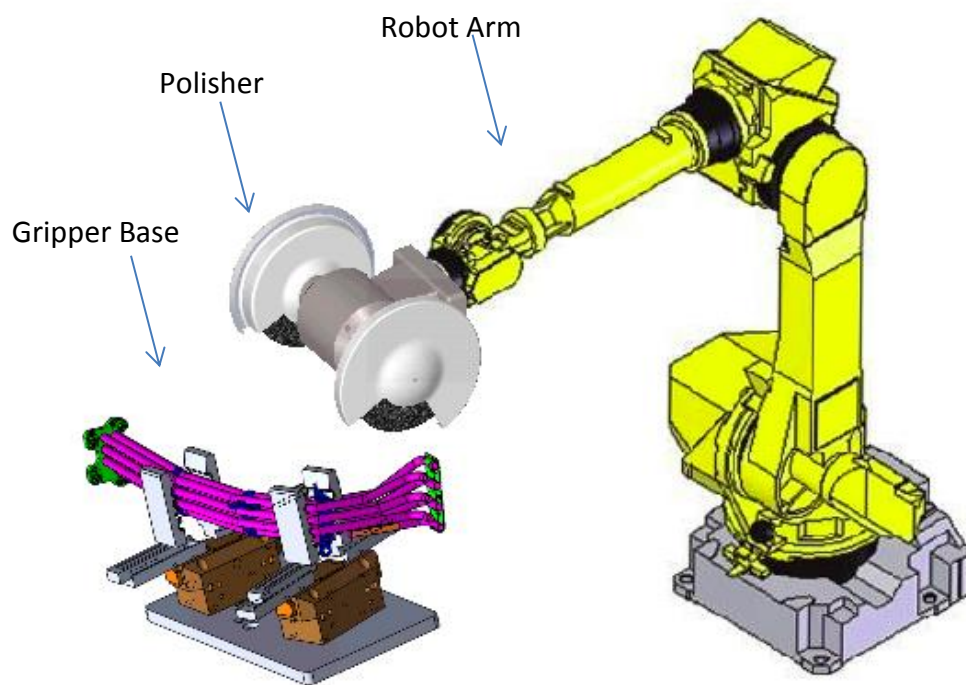


Figure 19. Moving Polisher, Fixed Tube with tube being fixed on the polishing station

Feature Analysis

The Moving Polisher, Fixed Tube polishing method features a Gripper Base mounted on the ground or table as a fixture, and a polishing wheel mounted directed on the robot as an EOAT which can sense the force while polishing. The robot needs to pick up the tube from a specified

location, pass it to the Gripper Base, change the tool to a polishing wheel, then start to polish the tube on the fixture. After the polishing being completed, the robot will change the tool back to the gripper, pick up the tube from the fixture, drop off the tube at another specified location, then change the tool back to grippers. The next iteration then starts again.

5.2.3. Moving Tube, Moving Polisher

The last design combines the first and the second design together. Two robots are designed to be used to implement this polishing method. One robot holds the tube; the other robot uses a polisher to polish the tube.

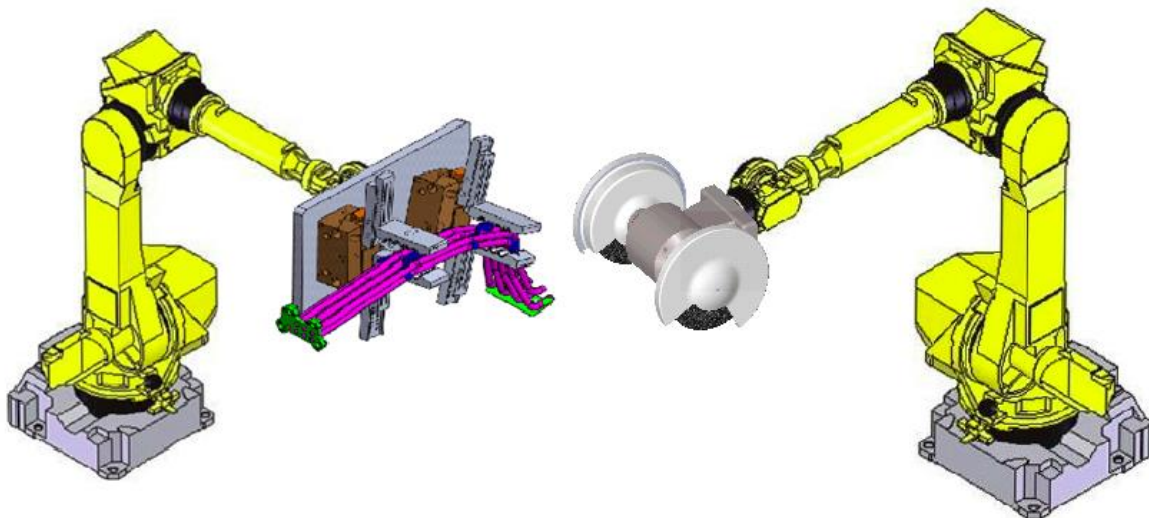


Figure 20. Moving Tube, Moving Polisher with tube and polisher moving at the same time

Feature Analysis

The Moving Tube, Moving Polisher polishing method features a Gripper Base mounted on one robot, and a polishing wheel mounted on the other robot as an EOAT which can sense the force while polishing. The robot with Gripper Base needs to pick up the tube from a specified location, and then the robot with Polisher will start to polish the tube. Both robots will move simultaneously to perform the polishing process. After the polishing is completed, the robot holding the tube will drop off the tube at another specified location. The next iteration then starts again.

5.2.4. Design Comparison

The pros and cons for each polishing method design are listed below:

Pros and Cons of the Moving Tube, Fixed Polisher:

Pros:

- No need for tool changing
- Can pick up the tube then starts to polish immediately

Cons:

- EOAT design requires two grippers that can adapt to the tube
- EOAT has harder force sensing implementation

Design Difficulty

Programming complexity

Force sensing on the EOAT or Polisher

Mechanical design complexity

Gripper mounted to robotic arm, polishing wheel fixed

EOAT

Two mechanical jaw grippers with a force sensor

Resources

Cost (Budget)

Necessary components: gripper base, polishing wheel, robotic arm

Time cost (for GE)

Tasks that consume time: picking up the tube, polishing.

Performance

Precision

Tubes are pressed up against a polisher; force is measured by EOAT (gripper base)
or Polisher

Desired functions absence

No distinct disadvantage

Pros and Cons of the Moving Polisher, Fixed Tube:

Pros:

- Fewer kinematics calculations

Cons:

- Need to change tools several times
- Need to precisely pass the tube to the Gripper Base (tube fixture)

Design Difficulty

Programming complexity

Force sensing on the EOAT, needs to pass the tube to gripper base

Mechanical design complexity

Needs tool changing during the process

EOAT

Only a polisher mounted on the robot arm

Resources

Cost (Budget)

Necessary components: gripper base, polishing wheel, robotic arm, tool changer

Time cost (for GE)

Tasks that consume time: picking up the tube, passing the tube to gripper base, tool changing, polishing.

Performance

Precision

Tubes are pressed up against a polisher; force is measured by EOAT (polisher)

Desired functions absence

No distinct disadvantage

Pros and Cons of the Moving Tube, Moving Polisher:

Pros:

- Fast, requires no tool change

Cons:

- Massive work cell
- Two robot arms
- Parallel Spatial Awareness sensing
- Complicated kinematics

Design Difficulty

Programming complexity

Force sensing for the polisher arm, two separate systems, the grippers and the polisher, interacting with each other.

Mechanical design complexity

Gripper base and one polisher

EOAT

Tooling requires two mechanical jaw grippers. Also requires one custom spot polisher with force sensing on the arm.

Resources

Cost (Budget)

Necessary components: gripper base, polishing wheel, two robotic arms

Time cost (for GE)

Tasks that consume time: picking up the tube, polishing.

Performance

Precision

Hard to control the forces on both arms.

Desired functions absence

No distinct disadvantage

Based on multiple design requirements, a metric for accessing these three polishing methods was made. A scale from 1 to 5 was used, where 5 meant the highest penalty. See Table 2 for complete design comparison metrics.

The Moving Tube Fixed Polisher design was selected as the final decision. This was affected by the fact that only one robot was available and the tool changing process would introduce more potential problems in the future.

Methods Metrics	Moving Tube, Fixed Polisher	Moving Polisher, Fixed Tube	Moving Tube, Moving Polisher
Design Difficulty			
Programming complexity	3	4 Need to pass the tube	5
Mechanical design complexity	2	3 Need to change tools	4
EOAT	3 A gripper base	2	4
Resources			
Cost (Budget)	2	3 Need tool changer	4
Time cost (for GE)	4	5 Need to pass the tube	3
Performance			
Precision	4 Force sensing on a more complex EOAT	3	5
Desired functions absence	2	2	2
Total	20	22	27

Table 2. Design metrics for polishing methods

5.2.5. Final Design

After deciding to use the Moving Tube, Fixed Polisher polishing method, a polisher was designed to implement the polishing task. The polisher design is further discussed in section 5.3.

5.3. Polisher Design and Force Sensing

In this section, the force calculations and the polishing station are introduced.

5.3.1. Polishing Wheel Analysis

The GE Aviation Tube Polishing System is a controllable system made to polish the surface of the tube assembly against a polishing wheel of a fixed radius. This means that the system is going to experience contact forces and that there is a possibility of applying too much or too little force to the tube assembly, either damaging it or reducing efficiency. The torque of the polishing wheel needs to be calculated in order to determine the force required to fully polish the tube.

Cylinder in Contact with a Fixed Point

When the cylinder-shaped tube contacts a fixed point, torque and force are generated.

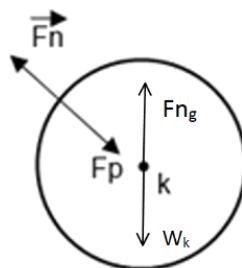
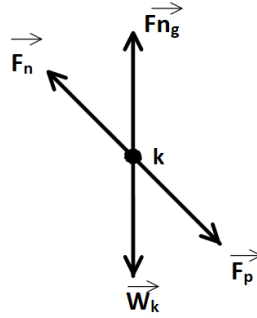


Figure 21. Stationary wheel contacting fixed point

In Figure 21, F_p is the force on the point, K is the axle load bearing, and F_N is the normal force. Forces F_p and F_N happened on the outer rim of the wheel. Because the wheel was uniform and had a load bearing axle, the forces can be represented as occurring off k.



In a static system, since system has no acceleration, the two forces will be equal and opposite.

$$\sum F = \vec{F}_p - \vec{F}_N = 0$$

Rotating Wheel in Contact with a Fixed Point

The moment of inertia for any cylinder is purely a function of the radius and the mass. Thus, when describing any polishing system where the force occurs at the outer surface a flat disk can be used to describe the torque of the system. Here we understand that the cylindrical body has characteristics length L, mass M, change in volume dV, and change in radius dr.

The equation for moment of inertia is determined as:

$$I = \int_0^M r^2$$

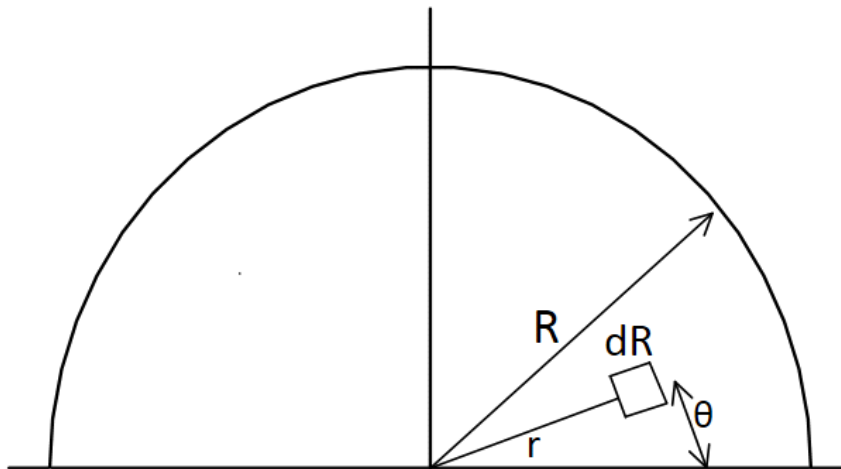
With the equation for the given density of any given volume as:

$$\rho =$$

The equation for area is given by:

$$A = \pi$$

The infinitesimal rate of change in radius is then described in the diagram below



Relating the previous equations back to the density, you solve for the change in mass.

$$\partial m = \rho \partial V = [\rho \cdot L \cdot 2$$

Substituting the change in mass back into the moment of inertia equation you get

$$I = 2\pi\rho \int_0^e r^3 dr = 2\pi\rho L \frac{R^4}{4} = MR^2$$

A rotating disk spinning with torque T and rotational velocity ω about k in contact with point p is shown in Figure 22.

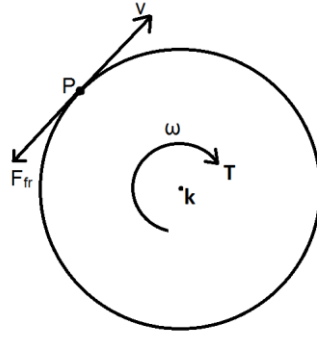


Figure 22. Rotating flattened cylinder

Given that the normal force for any system is, $\mu F_N = F_{fr}$ then the Frictional Force is Restorative for the system of a rotating disk as well. Assuming as well that the force is tangential, applied at 90° , then the equation

$$\tau = I \cdot \alpha = F \times r = rF \cdot \sin\theta,$$

Reduces to the equation

$$\tau = r \cdot F_{fr}$$

These series of equations show us that the torque is defined as the relation between the radius and the force of friction. This will later be used to derive the necessary force required for material removal.

Measuring Force by Change in Distance

Using $\tau = rF_{fr}$ it can be asserted that the radius is constant, or that any force causing the radius to compress produces a negligible amount of deflection, and therefore produces a constant force on the point. Measuring the forces knowing only the change in position is important for deriving how fast a system needs to go to produce the adequate force necessary.

The frictional forces on any system are as follows.

$$F_{fr} = \mu F_N$$

Knowing the frictional force, we can derive the force exerted by the point P as being opposite to the normal force F_N .

$$F_N = -F_P$$

Force of the point is defined then as, $F_P = m_p \cdot a$ where m_p is the mass of the pipe and a is acceleration.

Acceleration is understood to be the change in velocity over time, and the velocity is known to be the change in distance over time. This axiom is represented by the notion of the \dot{x} and \ddot{x} which represents the differentiation of the change of position or the double differentiation.

$$a = \ddot{x} \left(\vec{x} = (\vec{x}, \vec{y}), \ddot{x} = \frac{\partial^2 x}{\partial t^2} \right)$$

Since the mass of the system, M , is constant therefore the change in position, the difference of \vec{x} over time is all that is required to measure force at the point, P.

5.3.2. Calculation for Tangential Force on the Polishing Wheel and Tube

The surface polishing forces involved in a specific example related to the project will be calculated. The parameters are as follows:

- Material: Low carbon steel
- Wheel diameter (D): 6 inches

- Rotational speed (N): 3000 RPM
- Width of cut (w): 1 in
- Depth of cut (d): 0.02 in
- Feed rate of the work piece (v): 0.12 in/min

The goal is to calculate the cutting force (the force tangential to the wheel) F_c and the thrust force (the force normal to the work piece surface) F_n via calculating the Material-removal rate first.

The material-removal rate (MRR) is given by:

$$MRR = d * \omega * v = 0.02 * 1 * 0.12 = 0.0024 \text{ in}^3/\text{min}$$

The power consumed is given by

$$\text{Power} = u * MRR$$

where u is the specific energy. For Low-carbon steel, the specific energy is estimated to be $15 \text{ hp} * \text{min}/\text{in}^3$.

$$\text{Power} = 15 * 0.0024 = 0.036 \text{ hp}$$

$$1 \text{ hp} = 33,000 \text{ ft} * \text{lb}/\text{min} = 396,000 \text{ in} * \text{lb}/\text{min},$$

$$\text{Power} = 0.0036 * 396000 = 1425.6 \text{ in} * \text{lb}/\text{min}$$

Since power is defined as

$$\text{Power} = T\omega,$$

where the torque $T = F_c * D/2$ and ω is the rotational speed of the wheel in radians per minute ($\omega = 2 * \pi * N$).

It follows that

$$1425.6 = F_c * (6/2) * 2 * \pi * 3000$$

Therefore,

$$F_c = 0.02521 \text{ lb}$$

The thrust force, F_n , can be calculated directly; however, it also can be estimated by noting from experimental data that it is about 30% higher than the cutting force, F_c [16].

Consequently,

$$F_n = 1.3 * 0.02521 = 0.03277 \text{ lb}$$

Therefore the force required to remove the brazes or welds on the tube is not outside of our measuring range, which is the 25lb limit for a FlexiForce pressure sensor.

Based on the experiment conducted, the actual force needed is around 1 pound-force. The data collected are shown in Table 3. The testing was conducted in an attempt to find the best force applied to a part that would result in a material removal rate of $1\text{mm}^3/5\text{s}$. Each pass is to be considered a 1 second stroke during the testing.

P50 Grit A 0801 Polishing Wheel

Force #Passes	0.2-oz	0.4-oz	0.8-oz	1-lb	2-lb
5	min	min	med	med	complete
10	min	min	med	large	
15	min	min	med	complete	
20	min	min	complete		
25	min	min			
30	min	min			
Conclusion	Insufficient force	Insufficient force	Sufficient	Sufficient	Sufficient, damages tubes
min = minimal removal					
med = medium removal					
large = large removal					

Table 3. Actual polishing force and its removal results

In conclusion, when later designing the polishing wheel and force sensor components, a force of one pound-force was considered as the desired removal force.

5.3.3. Polishing Station

The prototype for the MQP required that the system be capable of providing feedback into the system to do two things. The first is to realize when the system is providing too much force. The second is to limit the range of forces on the system to be within acceptable polishing levels. To do this we had to create a motor mount station and feedback-controlled linear actuator to increase or decrease the force applied by the system.

Motor Mount Station

For the design specifications presented, the motor needs to be medium-sized and provide enough torque and RPM. The speed of the motor also needs to be controlled. Because of this, the CIM Motor, P/N: 217-2000CIM was selected along with a Victor 884 Controller [17]. The motor was

housed inside a motor mount (Figure 23) specifically designed to be 11 inches off the ground and 5 inches apart from the polishing station.



Figure 23. Motor mount fixture for holding the CIM motor

Polishing Linear Actuator Station

The linear polishing station is comprised of a housing that can be readily bolted to the floor. The polishing station is shown in Figure 24. The station makes use of a motor and a screw to linearly drive a platform, (Figure 25 and Figure 26), up and down to increase, or decrease, the contact force of any tube on the polishing belt. A FlexiForce pressure sensor is glued to the platform to measure the force in vertical direction.

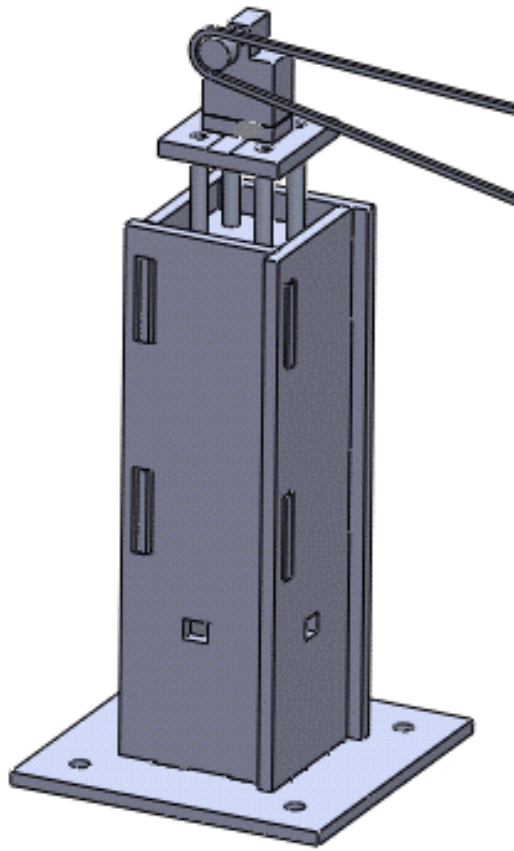


Figure 24. Linear actuator polishing station with polishing belt

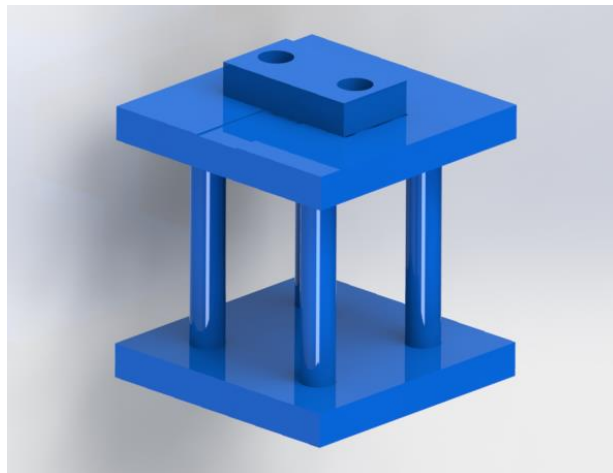


Figure 25. The carriage head housing holds the force sensor

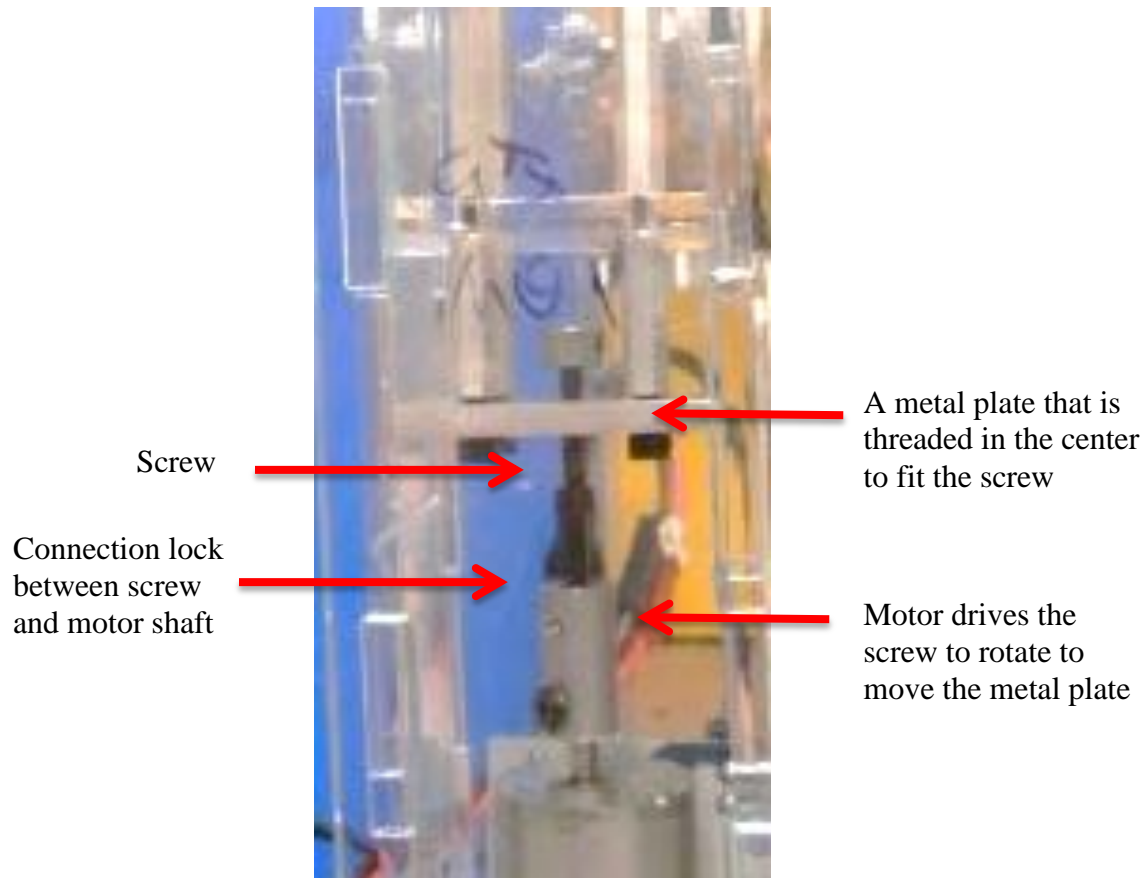


Figure 26. Linear driving mechanism

The combined polishing station utilizes both the motor mount housing and the linear station shown in Figure 27 and Figure 28, as well as an embedded microcontroller to fully interpret force changes and create a control signal to the polishing station. Since the linear actuator will move up and down, the tension on the belt is changing due to the movement. A belt tensioner is installed in between to keep the belt tensioned at all times. The polishing belt coming into contact with the tube is shown in Figure 29.

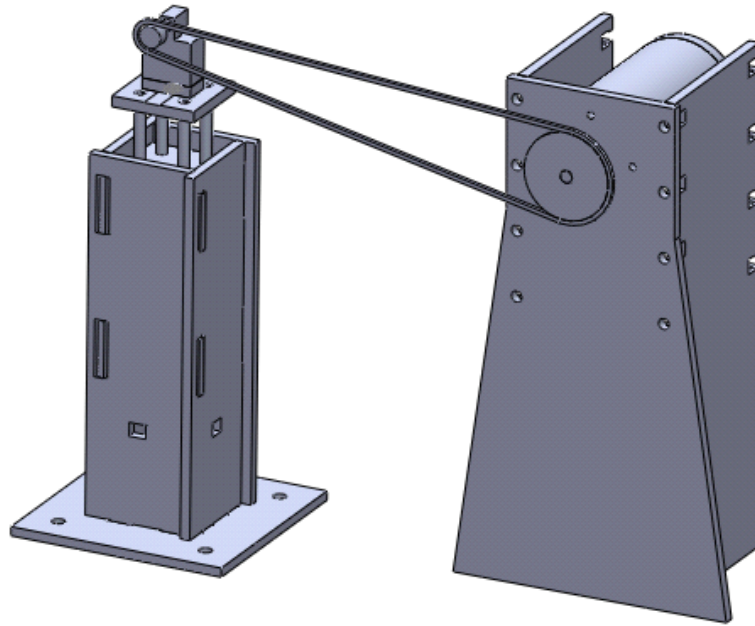


Figure 27. CAD drawing of the polishing station with motor mount and belt.

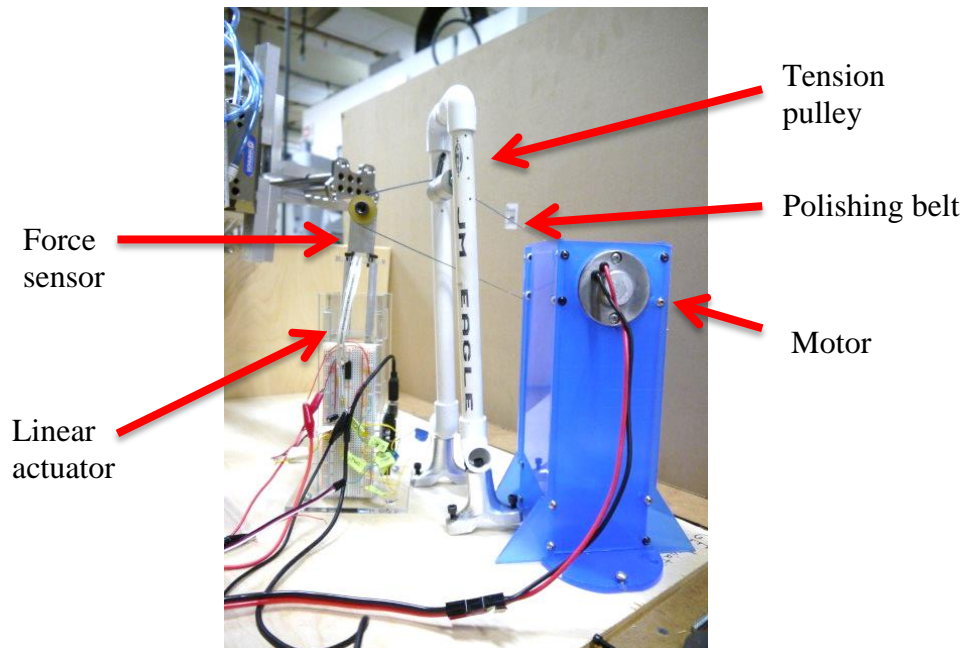


Figure 28. Actual polishing station



Figure 29. Polishing belt coming into contact with the tube

For the final testing result, however, the polishing belt was unable to fully to polish brazes/welds on the tube due to the limited current supplied to the CIM motor. One pound of force applying on the polishing belt would cause the motor to stall. Currently the power supply only provided 2.5 amps, however, the CIM motor needs 17 amps of current in order to achieve the torque required to fully polish the tube.

5.3.4. FlexiForce Force Sensor Data

An Arduino microcontroller was used to collect the force data from the polishing wheel using a FlexiForce sensor. The FlexiForce pressure sensor changes resistance when different force is applied to it. The correlation between the output reading from the Arduino and the force applied to the FlexiForce force sensor is shown in Figure 30. The vertical axis is the analog pressure sensor reading from Arduino. A value of 1023 is the largest force it can detect, and a value of 0 means there is no force applied.

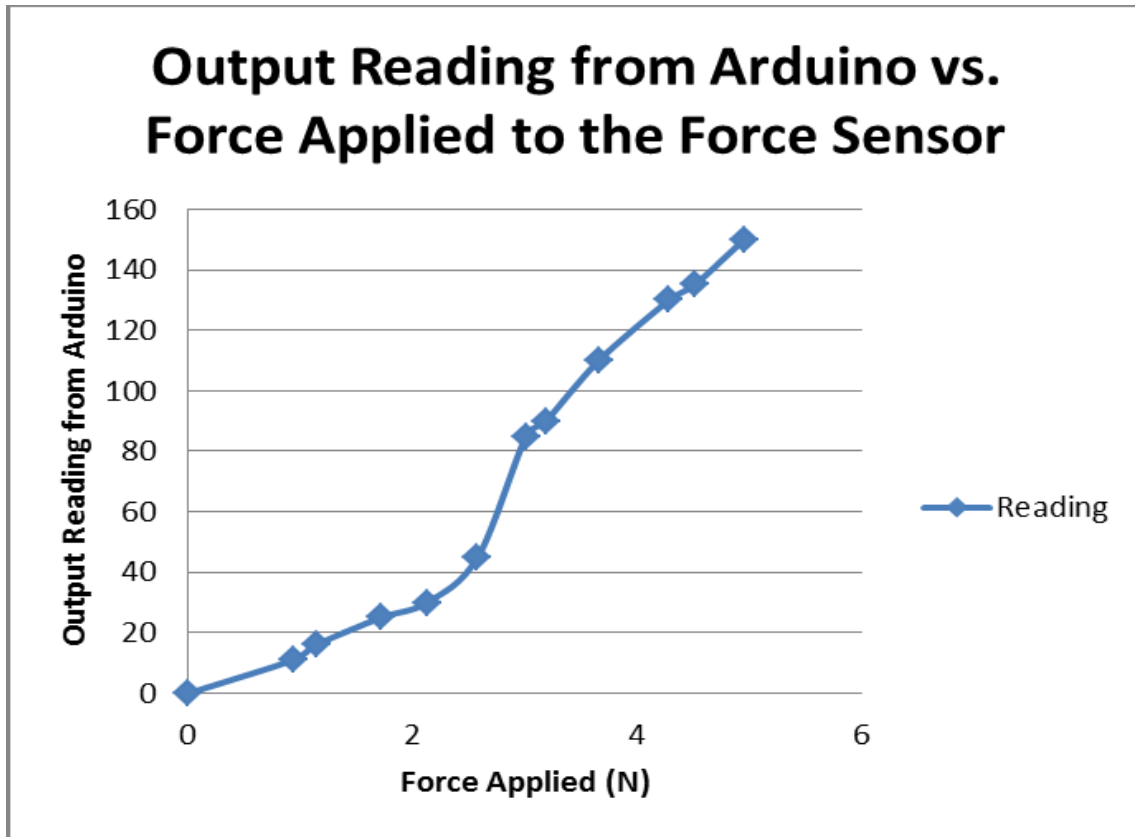


Figure 30. Output reading from Arduino vs. force applied to the force sensor

According to a 100lb force sensor resistance-force plot, which is similar to the 25lb force sensor being used in the project (Figure 31), the force versus resistance relationship is non-linear below approximately the first one-fifth of its range of measurement. In the plot, the pink line is the actual typical results and the black one is the theoretical conductance. This is why the data collected above were not linear. Therefore the force sensor is pre-loaded with an initial pressure in the Carriage Housing Head (Figure 25) in order to have a linear correlation to detect a 1 pound force change.

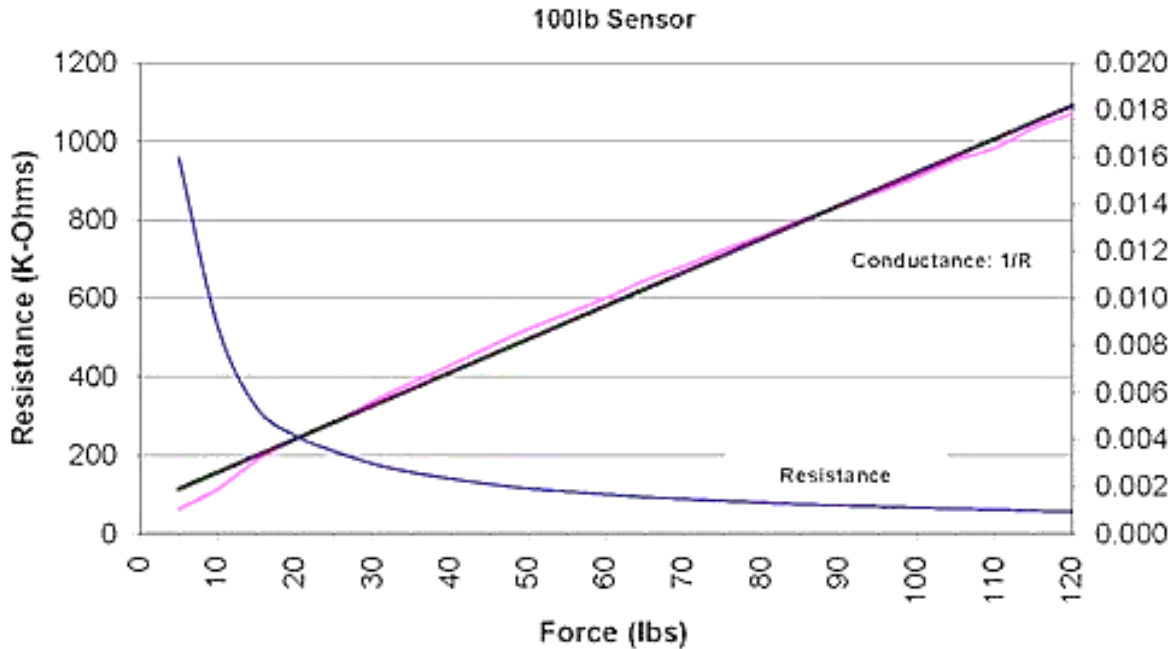


Figure 31. Resistance-force plot of FlexiForce sensor

5.3.5. Embedded System for Force Sensing

The Arduino Uno microcontroller board, as shown in Figure 32, was chosen as the embedded system for the force sensing platform. The Arduino Uno has 14 digital input/output pins which are handled by an ATmega328 microcontroller at a clock speed of 16MHz. The detailed Arduino specifications are listed in Appendix B.

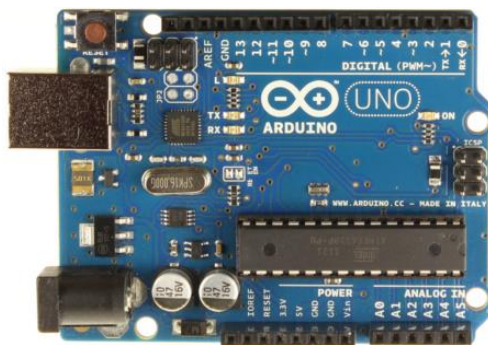


Figure 32. Arduino Uno microcontroller

The 16 MHz high-speed microcontroller is desired to sample the changes in analog voltage values and then calculate forces based on the change of those analog values. The digital input and output pins allow the Arduino system to communicate with the Fanuc robot. With a high-speed controller, data can be processed faster and communication signals between the force sensor and the robot will not be delayed.

Feedback Loop for Force Control

The feedback system designed is required to control the polishing wheel to prevent any damage to the tube assembly. This requires a certain control on the system depending on the sensor readings. Since the linear motor moves the polishing wheel up and down, the reaction force on the polishing wheel will become the feedback for the motor itself. When the polishing process starts, the polishing wheels moves upward until the tube and the polishing wheel are in contact. The force sensor collects the data and the Arduino compares the data with a threshold value in the program. Once the desired force is reached, the linear drive will stop moving upward.

5.4. Polishing Routine

The following is the sequence used to accomplish the polishing task:

1. Move to the tube pick up station
2. Extend arm towards the tube.
3. Open gripper.
4. Extend arm and grab tube.
5. Close gripper.
6. Move arm towards polishing wheel.
7. Polish one side.

8. Rotate.
9. Polish the other side.
10. Move tube back to the desired drop-off location.
11. Place the tube down
12. Open gripper.
13. Bring Arm back to its initial position.

5.5. Electrical and Hardware Interface

The Tube Polishing System encompasses the communication between the Fanuc robot, the force sensor, and the Arduino.

The overall interface is shown in Figure 33. The force sensor collects the data and outputs the sensor signal data through op-amps to the Arduino. The Arduino processes the force signal then generates PWM signals to control the linear actuator via the H-bridge. Once the desired force is reached and detected by the force sensor, the Arduino will send a signal to the Fanuc robot through the NI DAQ. The robot can also send signals back to the Arduino using the DAQ.

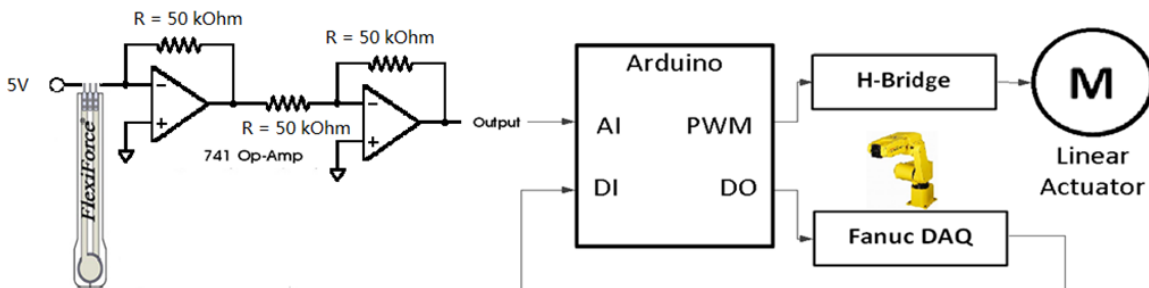


Figure 33. High level electrical connections schematic

5.5.1. Electronics

An Arduino microcontroller is used to gather sensor data from the force sensor below the polishing wheel. The force sensor and its signal conditioning circuit are shown in Figure 34. The gain of the first op-amp is $-\frac{50k\Omega}{R_{FlexiForce}}$; the second op-amp has a gain of -1. Therefore the overall gain becomes positive $\frac{50k\Omega}{R_{FlexiForce}}$. The FlexiForce force sensor is connected to a negative feedback loop to allow for easier linearization. The output from the op-amp circuit is directly connected to the analog input pin on the Arduino. The Arduino then interprets the signal from the sensor on a 10-bit scale and then compares the input signal to the previous output signal; which then determines which direction the motor will be controlled via PWM signal.

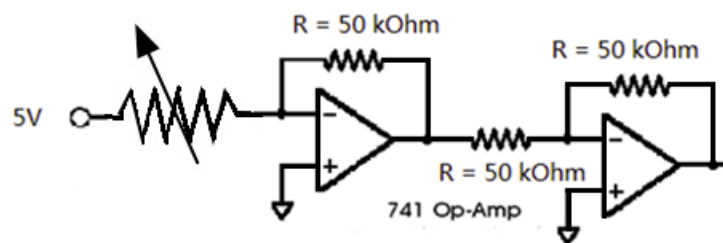


Figure 34. Force sensor circuit

After the Arduino takes the signal from the force sensor, it generates a PWM output signal that can control the linear driving motor. The signal goes through an H-Bridge shown in Figure 35. The H-Bridge takes 2 PWM signals from the Arduino to control the motor for forward and reverse movement.

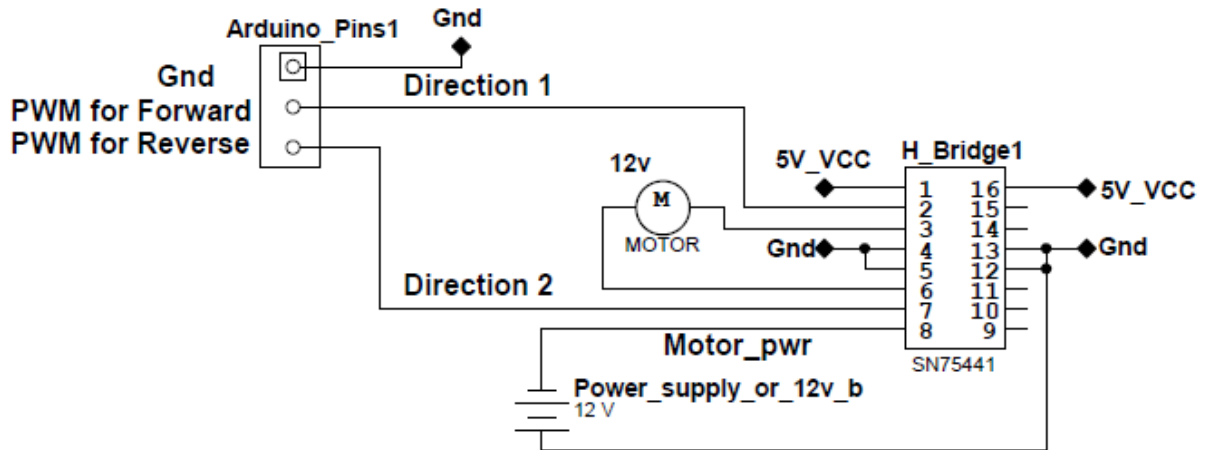


Figure 35. H-Bridge for controlling linear driving motor

5.5.2. Pneumatics

The Schunk PGN 125/1 pneumatic actuators connect to the end joint on the Fanuc. The pneumatic connections are located on the front of the J3 casting. Approximately 1341 mm of pneumatic tubing was required to reach from the EOAT to the connection spot. Two tubing splitters were used so that the two actuators would be synchronized to a single robot gripper movement command. The nominal pressure required for the PNG actuators was 6.0bar. The PGN actuators were controlled by Robot I/O PIN 1 and 2.



Figure 36. The pneumatic tubing.

5.6. Programming and Software

The programming involves two parts: the Fanuc robot programming and the Arduino controller programming. The Fanuc robot program controlled the positions of the EOAT for each movement during the whole process. The Arduino program controlled the feedback control from the force sensor. The Arduino interfaced with the Fanuc during the polishing process to accomplish the task.

Two pieces of software were required for running the polishing process: an Arduino program running on the Uno and a program written in Karel (the native language of the Fanuc)

to control the robot itself. The Karel program was used to control the movement of the robot arm as it went through the motions of manipulating and polishing the tube. The Arduino language (a derivative of C/C++) was used to program the Arduino Uno microcontroller for interpreting the data from the force sensor on the polishing wheel and control the communications from/to the robot. The complete Arduino program is documented in Appendix C, and the complete Fanuc program is documented in Appendix D.

5.7. Work Cell

The work cell consists of a 6400 square inches (80 inches by 80 inches) table with the Fanuc 200iB located in the center. Three additional structures within the work cell were the polishing station as well as a pick-up stand and drop-off stand for holding the tube. The tube pick-up stand and polishing station were set up on a removable 2x4 foot platform set within the top of the table. The drop-off stand was originally going to be set up in the 2x4 foot platform as well, but was placed on a smaller platform to the side of the robot to allow the arm more maneuverability between the pick-up stand and the polishing station. The distance from the robot to the main platform of the work cell is 8.5 inches. The robot can reach up to 30 inches in every direction. The robot can cover most of the work cell with ease as shown in Figure 37.

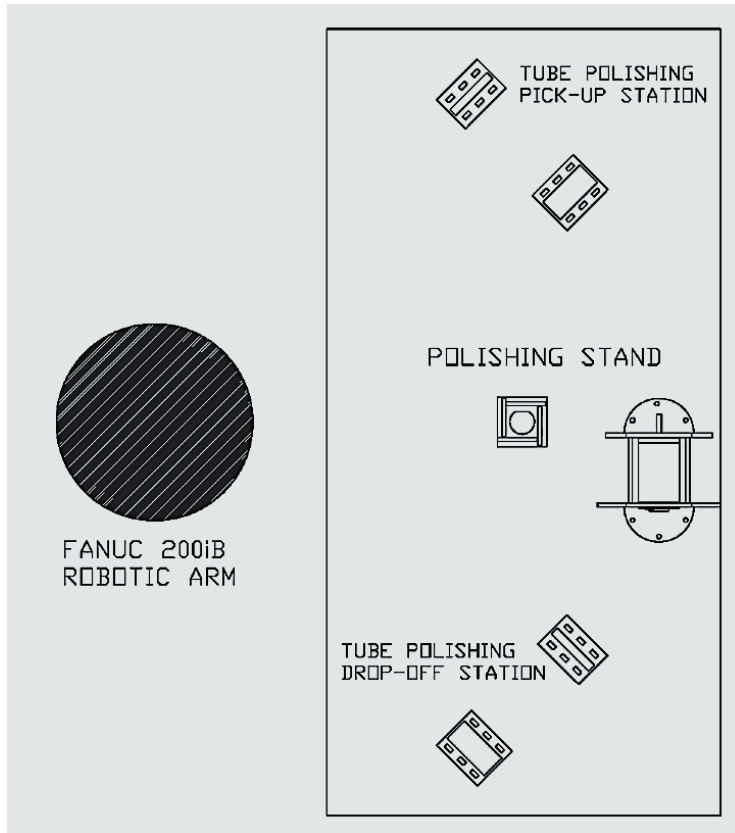


Figure 37. Top view of the work cell

In a real work environment, the work cell layout would be altered to better fit an automated environment where a conveyor system would either position the tube at the pick-up position and/or a receiver conveyor system at the drop off station. An alternative to this would be a hopper/lift system that would deposit the tubes right on the pickup station and another bay that would receive the tube assemblies. In this current implementation, the pickup would either have to be singular a person manually adding tube assemblies to the tube stand and removing the polished tube from the drop off location or further expanded with a multi-tiered pickup with locations referred to by indices in the code.

6. Conclusion

As a result of the project, EOAT designed specifically for the seven-tube assembly was manufactured and mounted on the Fanuc LR Mate 200iB robot. This EOAT could grip the tube assembly without damaging it. The tube could be held tight between the fingers in order to perform polishing process. The Fanuc robot was able to maneuver the tube from pick up station to polishing station then to the drop off station. A polishing system with force sensor capability was created. The polishing system was able to detect the force acting on the polishing belt. The polishing belt was unable to fully to polish brazes/welds on the tube due to the limited current supplied to the CIM motor. Slight polishing results could be achieved through the polishing system.

7. Future Work

One of the intended future steps for this project is to implement a computer vision system to detect the shape of a tube so that the robot knows how and where to grasp the tube with the manipulator, to identify the brazed locations on the tube, and to determine whether the brazes/welds have been sufficiently polished. Computer vision software can be used to recognize the features of the tube shape therefore determine the grasp positions. Detecting the discolorations on the tube would therefore determine the locations of brazes/welds and determine whether further polishing is needed.

Another possible augmentation to incorporate into the design of the robot would be touch sensing in the fingers of the EOAT. Touch functionality would assist in the ability to handle various tube shapes and would work in conjunction with the vision system. Once the robot has identified where to grasp a section of tubing and moved the EOAT into place then the touch sensing will control how tight of a grip to use.

The polishing station can be revised to a more stable system. Inside the Fanuc work cell sits an existing polishing belt with the force sensor built into the gripper can be implemented.

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Appendix A. Standards

1. ASTM Standards

- 1.1. ASTM A 262 - This specification covers the standard practices for detecting susceptibility to intergranular attack in austenitic stainless steels. These practices include five intergranular corrosion tests.
- 1.2. ASTM A 370 – Provides testing methods for the specified mechanical properties of steel, stainless steel, and related alloys. This is a legally binding contract of regulation for the quality of product that must exist before transfer of product is allowable. Properties tested include: Tension, Bend, Hardness (Brinell and Rockwell scales), Portability, and Impact Resistance.
- 1.3. ASTM E 122 – This practice is intended for use in determining the sample size required to estimate, with specified precision, a measure of quality of a lot or process.
- 1.4. ASTM E 353 – These test methods for the chemical analysis of metals and alloys are primarily intended as referee methods to test such materials for compliance with compositional specifications, particularly those under the jurisdiction of ASTM Committee A1 on Steel, Stainless Steel, and Related Alloys.
- 1.5. ASTM E 426 – Eddy-current testing is a nondestructive method of locating discontinuities in a product. Changes in electromagnetic response caused by the presence of discontinuities are detected by the sensor, amplified and modified in order to actuate audio or visual indicating devices, or both, or a mechanical marker.
- 1.6. ASTM E 1417 - Establishes the basic parameters for controlling the application of the liquid penetrant method in ASTM E 426.

2. SAE Standards

- 2.1. AMS 2243 – Specification that covers corrosion and heat-resistant steel in the form of seamless or welded drawn tubing.
- 2.2. MAM 2243 – Same AMS 2243
- 2.3. AMS 2248 - Chemical Check Analysis Limits, Corrosion and Heat-Resistant Steels and Alloys, Maraging and Other Highly-Alloyed Steels, and Iron Alloys
- 2.4. AMS 2371 - Quality Assurance Sampling and Testing, Corrosion and Heat-Resistant Steels and Alloys, Wrought Products and Forging Stock
- 2.5. AMS 2634 - Ultrasonic Inspection, Thin Wall Metal Tubing
- 2.6. AMS 2807 - Identification, Carbon and Low-Alloy Steels, Corrosion and Heat-Resistant Steels and Alloys, Sheet, Strip, Plate, and Aircraft Tubing

Appendix B. Arduino Specifications

Summary

Microcontroller	ATmega328
Operating Voltage	5V
Input Voltage (recommended)	7-12V
Input Voltage (limits)	6-20V
Digital I/O Pins	14 (of which 6 provide PWM output)
Analog Input Pins	6
DC Current per I/O Pin	40 mA
DC Current for 3.3V Pin	50 mA
Flash Memory	32 KB (ATmega328) of which 0.5 KB used by bootloader
SRAM	2 KB (ATmega328)
EEPROM	1 KB (ATmega328)
Clock Speed	16 MHz

Appendix C. Program for Arduino

```
#define REVERSE_PIN 6
#define FORWARD_PIN 5
#define MOTORPIN 8

#include <Servo.h>
Servo myservo;

//the pin for informing the robot during polishing process
int informPin1 = 13;
// select the input pin for the first force sensor
int sensorPin1 = A0;
// select the input pin for the first force sensor
int flagPin1 = 2;
// variable to store the value coming from the sensor
int sensorValue1 = 0;
int sensorValue = 0; //senfor value
// the input value responding to 1 lbf to polish
int grindingForce = 5;
int offset = 590; //offset for 0 force
int initVal = 0; //initial value for each time of starting
//flag received from robot: 0 waiting, 1 starting to polish
int flag = 0;
//informs robot: 0 means polishing, 1 means stop
int inform = 0;
int currentForce = 0; //stores current force (difference
between current sensor data and init data

void setup(){
  Serial.begin(9600);
  pinMode(REVERSE_PIN, OUTPUT);
  pinMode(FORWARD_PIN, OUTPUT);
  pinMode(sensorPin1, INPUT);
  pinMode(flagPin1, INPUT);
  pinMode(informPin1, OUTPUT);
  myservo.attach(MOTORPIN, 1000, 2000);
}

void loop() {
  myservo.write(108);
  sensorValue = analogRead(sensorPin1);
  flag = digitalRead(flagPin1);
  delay(10);
  currentForce = sensorValue - offset;
  Serial.print(sensorValue);
  Serial.print("\t");
  Serial.println(currentForce);
  //waiting

  if(flag == 0)
  {
    if (currentForce > 20) //some errors margins for zero
    force
    {
      //down
      analogWrite(FORWARD_PIN, 255);
      analogWrite(REVERSE_PIN, 0);
    }
    else
    {
      //stop
      analogWrite(FORWARD_PIN, 0);
      analogWrite(REVERSE_PIN, 0);
    }
    inform = 0; //polish not done
  }
  //polishing
  else{
    if (currentForce > grindingForce)
    {
      //stop if force reached to desired level
      analogWrite(FORWARD_PIN, 0);
      analogWrite(REVERSE_PIN, 0);
      delay(500); //right now using timing for polishing
      inform = 1; //informs robot polishing completed
    }
    else
    {
      //move up
      analogWrite(FORWARD_PIN, 0);
      analogWrite(REVERSE_PIN, 255);
      inform = 0;
    }
  }
  digitalWrite(informPin1, inform);
}
```

Appendix D. Program for Fanuc Robot

```

/PROG TPSDEMOP
/ATTR
/MN
1:J P[1] 100% FINE ;
2:J P[2] 100% FINE ;
3:J P[14] 100% FINE ;
4: RO[1]=ON ;
5: WAIT 2.00(sec) ;
6:J P[10] 100% FINE ;
7: RO[2]=ON ;
8: WAIT 2.00(sec) ;
9:J P[11] 100% FINE ;
10:J P[4] 100% FINE ;
11:J P[12] 100% FINE ;
12:J P[9] 100% FINE ;
13:J P[18] 100% FINE ;
14: DO[101]=ON ;
15: LBL[1];
16: IF DO[101]=ON,JMP LBL[1];
17:J P[3] 100% FINE ;
18:J P[19] 100% FINE ;
19:J P[20] 100% FINE ;
20: DO[101]=ON ;
21: LBL[2];
22: IF DO[101]=ON,JMP LBL[2];
23:J P[21] 100% FINE ;
24:J P[16] 100% FINE ;
25:J P[7] 100% FINE ;
26:J P[6] 100% FINE ;
27:J P[5] 100% FINE ;
28: RO[1]=ON ;
29: WAIT 2.00(sec) ;
30:J P[8] 100% FINE ;
31:J P[17] 100% FINE ;
32:J P[13] 100% FINE ;

/POS
P[1]{
GP1:
UF: 0,
UT: 2,
CONFIG: 'N U T, , 0, 0',

X = 39.449 mm,
Y = 506.402 mm,
Z = 101.224 mm,
W = 1.078 deg,
P = -86.808 deg,
R = -95.479 deg
};

P[2]{
GP1:
UF: 0,
UT: 2,
CONFIG: 'N U T, , 0, 0',

X = -139.977 mm,
Y = 510.634 mm,
Z = 104.465 mm,
W = 5.450 deg,
P = -86.072 deg,
R = -77.704 deg
};

P[14]{
GP1:
UF: 0,
UT: 2,
CONFIG: 'N U T, , 0, 0',

X = -117.897 mm,
Y = 568.715 mm,
Z = -41.775 mm,
W = 7.420 deg,
P = -86.333 deg,
R = -8.503 deg
};

P[10]{
GP1:
UF: 0,
UT: 2,
CONFIG: 'N U T, , 0, 0',

X = -160.328 mm,
Y = 568.713 mm,
Z = -41.783 mm,
W = 7.391 deg,
P = -86.334 deg,
R = -8.474 deg
};

P[11]{
GP1:
UF: 0,
UT: 2,
CONFIG: 'N U T, , 0, 0',

X = -117.897 mm,

```

Y = 586.715 mm,
Z = -41.775 mm,
W = 7.420 deg,
P = -86.333 deg,
R = -8.503 deg
};

P[4]{
GP1:
UF: 0,
UT: 2,
CONFIG: 'N U T, , 0, 0',

X = -117.896 mm,
Y = 441.995 mm,
Z = -39.375.000 mm,
W = 7.420 deg,
P = -86.333.000 deg,
R = -89.310 deg
};

P[12]{
GP1:
UF: 0,
UT: 2,
CONFIG: 'N U T, , 0, 0',

X = 9.704 mm,
Y = 430.555 mm,
Z = 85.585 mm,
W = -3.648 deg,
P = -86.327 deg,
R = -89.669 deg
};

P[9]{
GP1:
UF: 0,
UT: 2,
CONFIG: 'N U T, , 0, 0',

X = 22.904 mm,
Y = 491.275 mm,
Z = 85.585 mm,
W = -3.648 deg,
P = -86.327 deg,
R = -89.669 deg
};

P[18]{
GP1:
UF: 0,
UT: 2,
CONFIG: 'N U T, , 0, 0',

X = 9.704 mm,
Y = 430.555 mm,
Z = 85.585 mm,
W = -3.648 deg,
P = -86.327 deg,
R = -89.669 deg

};
P[3]{
GP1:
UF: 0,
UT: 2,
CONFIG: 'N U T, , 0, 0',

X = 449.588 mm,
Y = 7.600 mm,
Z = 49.505 mm,
W = -3.648 deg,
P = -86.327 deg,
R = -166.954 deg
};

P[19]{
GP1:
UF: 0,
UT: 2,
CONFIG: 'N U T, , 0, 0',

X = 595.347 mm,
Y = 8.400 mm,
Z = -150.575 mm,
W = -3.648 deg,
P = -86.327 deg,
R = -166.954 deg
};

P[21]{
GP1:
UF: 0,
UT: 2,
CONFIG: 'N U T, , 0, 0',

X = 458.707 mm,
Y = 8.400 mm,
Z = -150.575 mm,
W = -3.648 deg,
P = -86.327 deg,
R = -166.954 deg
};

P[16]{
GP1:
UF: 0,
UT: 2,
CONFIG: 'N U T, , 0, 0',

```

X = 458.707 mm,
Y = 8.400 mm,
Z = -150.575 mm
W = -3.648 deg,
P = -86.327 deg,
R = -166.954 deg
};

P[7]{
  GP1:
    UF: 0,
    UT: 2,
    CONFIG: 'N U T, , 0, 0',

    X = 458.707 mm,
    Y = 8.400 mm,
    Z = -150.575 mm
    W = -3.648 deg,
    P = -86.327 deg,
    R = -166.954 deg
};

P[6]{
  GP1:
    UF: 0,
    UT: 2,
    CONFIG: 'N U T, , 0, 0',

    X = 458.707 mm,
    Y = 8.400 mm,
    Z = -150.575 mm
    W = -3.648 deg,
    P = -86.327 deg,
    R = -166.954 deg
};

P[5]{
  GP1:
    UF: 0,
    UT: 2,
    CONFIG: 'N U T, , 0, 0',

    X = 458.707 mm,
    Y = 8.400 mm,
    Z = -150.575 mm
    W = -3.648 deg,
    P = -86.327 deg,
    R = -166.954 deg
};

P[8]{
  GP1:
    UF: 0,
    UT: 2,
    CONFIG: 'N U T, , 0, 0',

    X = 458.707 mm,
    Y = 8.400 mm,
    Z = -150.575 mm
    W = -3.648 deg,
    P = -86.327 deg,
    R = -166.954 deg
};

P[17]{
  GP1:
    UF: 0,
    UT: 2,
    CONFIG: 'N U T, , 0, 0',

    X = 458.707 mm,
    Y = 8.400 mm,
    Z = -150.575 mm
    W = -3.648 deg,
    P = -86.327 deg,
    R = -166.954 deg
};

P[13]{
  GP1:
    UF: 0,
    UT: 2,
    CONFIG: 'N U T, , 0, 0',

    X = 134.836 mm,
    Y = 440.266 mm,
    Z = 40.354 mm,
    W = -7.357 deg,
    P = -87.090 deg,
    R = -91.459 deg
};

```