

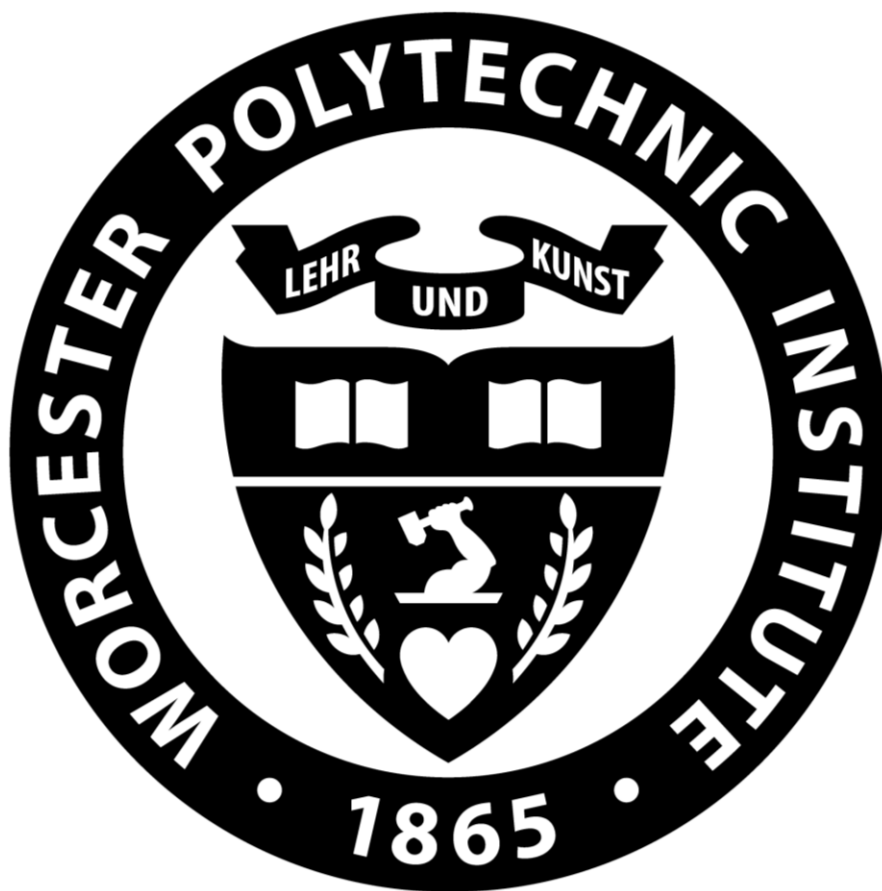
# Automated Tool Preparation

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

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# ABSTRACT

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Modern manufacturing methods employ the use of automated CNC machine tools. The use of this equipment, in conjunction with the wider adoption of “lights out” manufacturing, results in higher production output while also requiring more frequent tooling maintenance. The purpose of this project, as chartered by our sponsor, General Electric Aviation, is to develop an automated system for replacing cutting tools as they wear. The system is designed such that an operator will be able to load a cart of used cutting tools into a work cell and retrieve a cart of newly prepared tooling upon process completion. The team implemented the use of an industrial robot for material handling and designed custom fixtures to process each tool. This system eliminates the human error related with tool height setting, and can be universally adapted with alternate tooling in the future.

# ACKNOWLEDGMENTS

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Much of what was accomplished this year by the project team would not have been possible without the support of many groups and individuals, both on and off the campus of Worcester Polytechnic Institute. Without the funding provided by our sponsor, General Electric Aviation, this project would not have been possible. Our main contact at General Electric was John Graham, who provided feedback to the project team as the system was being developed.

Professor Craig Putnam and Professor Gregory advised the project. They both met with the project team on a weekly basis to provide input and ideas, especially when the project team was overcoming a challenge.

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# Contents

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Abstract.....	ii
Acknowledgments.....	iii
Figures.....	vi
Introduction.....	1
Background.....	5
Production Floor Tooling.....	5
Industrial Robotics.....	8
Programmable Logic Controllers.....	9
Peg in the Hole.....	11
Relevant Technologies.....	12
Gripping.....	12
Tool holders.....	14
Linear Actuators.....	17
Industrial vision systems.....	20
Safety systems.....	21
Methodology.....	25
End Effector.....	28
Tool Cart and Dock.....	43
Tooling Drawer.....	52
Tool Assembly System.....	58
Control System.....	66
Communication.....	66
The Existing Solution.....	67

Allen & Bradley.....	68
Automation Direct T1H PLC.....	69
DeviceNet & Modbus .....	70
Fanuc Robot Controller.....	71
Tooling Drawer.....	71
Tool Assembly System Control.....	73
Tool Height Setting.....	74
Chuck Dog Height Setting .....	77
Results.....	80
Discussion.....	85
Future Work .....	86
References.....	87

# FIGURES

---

Figure 1: A typical cutting tool used for milling .....	1
Figure 2: A CNC milling center.....	2
Figure 3: Milling chuck assembly exploded view .....	2
Figure 4: A blisk .....	3
Figure 5: Fanuc 6-axis robot.....	4
Figure 6: End mill labeled diagram (Wikimedia Commons, 2007).....	5
Figure 7: Tool wear influences (Marinov).....	6
Figure 8: GE's tool management flow chart .....	7
Figure 9: KUKA FAMULUS circa 1973 (KUKA Robot Group) .....	9
Figure 10: Allen-Bradley MicroLogix 1500 PLC controller with three expansion IO modules (Industrial Automation Control, 2011) .....	9
Figure 11: Ladder logic programming with instruction list (The Learning Pit) ...	10
Figure 12: Remote center of compliance (Nordmann, 2008) .....	11
Figure 13: ATI Industrial Automation's remote center of compliance .....	12
Figure 14: A SCHUNK pneumatically driven actuator .....	13
Figure 15: A SHUNK servo driven gripper module.....	14
Figure 16: Diagram of tool holder components (Techniks, Inc.) .....	14
Figure 17: Model of a milling chuck tool holder (Lyndex-Nikken).....	16
Figure 18: Graph of expected tool life based on tool runout (Techniks, Inc.).....	17
Figure 19: Screw type linear actuator (Ultra Motion) .....	18
Figure 20: Pneumatic piston cutaway (Design World Online).....	18
Figure 21: Ball screw (McMaster-Carr) .....	19
Figure 22: Acme screw (McMaster-Carr).....	20
Figure 23: Emergency stop button (Direct Industry) .....	22
Figure 24: SICK C4000 palletizer light curtain (SICK) .....	23
Figure 25: SICK roller contact safety limit switch (SICK) .....	23
Figure 26: SICK non-contact magnetic sensor (SICK) .....	24
Figure 27: SICK laser safety sensor (SICK).....	24

Figure 28: Top-down view of work cell and access areas .....	27
Figure 29: Process Flow Chart.....	28
Figure 30: Overhead end effector design.....	30
Figure 31: Side approach end effector design (cutting tool).....	30
Figure 32: Side approach end effector design (tool holder) .....	30
Figure 33: SCHUNK pneumatic actuator, model PGN 125/1 .....	31
Figure 34: SCHUNK pneumatic actuator, model PZN 80I .....	31
Figure 35: Actuator mounting plate, robot side .....	32
Figure 36: Actuator mounting plate, actuator side.....	32
Figure 37: Pointer .....	33
Figure 38: End effector mounting plate .....	34
Figure 39: Cutting tool end effector geometry test models .....	35
Figure 40: End effector test mating block.....	36
Figure 41: Cutting tool end effector geometry test fingers.....	36
Figure 42: End effector fingers, first iteration CAD model.....	38
Figure 43: End effector wooden prototype .....	39
Figure 44: Prototype finger lateral deflection.....	39
Figure 45: End effector fingers, iteration 1 .....	40
Figure 46: End effector fingers, iteration 2 CAD model .....	42
Figure 47: End effector fingers, final iteration .....	42
Figure 48: Tool cart ramp analysis, free body diagram .....	43
Figure 49: Tool cart ramp length vs. force graph .....	45
Figure 50: Picture of the tool cart docking area.....	46
Figure 51: Tool cart comparison chart.....	47
Figure 52: Tool cart with tab rings .....	48
Figure 53: Roller ball tool cart dock idea .....	49
Figure 54: Tool cart dock CAD model .....	49
Figure 55: Tooling drawer sketch.....	52
Figure 56: Tooling drawer prototype.....	53
Figure 57: Inductance proximity sensor .....	54
Figure 58: Tooling drawer CAD model.....	55

Figure 59: Interior tooling drawer CAD model .....	56
Figure 60: Drawer assembly process .....	57
Figure 61: Threaded insert press-fit test .....	57
Figure 62: Assembled tooling drawer, top view .....	58
Figure 63: Assembled tooling drawer, bottom view.....	58
Figure 64: Diagram of tool holder fixture plate.....	60
Figure 65: Cutaway view of nut locking dogs .....	62
Figure 66: Sliding assembly with height control .....	63
Figure 67: Cutaway view of height setting pin.....	64
Figure 68: Work Cell Communication Interfaces.....	67
Figure 69: Tool Drawer LED Indicator Light Wiring Diagram .....	73
Figure 70: Tolomatic Smart ICR RP .....	75
Figure 71: CME 2 Simple Programing Interface.....	75
Figure 72: CME2 Live Time Diagnostic Panel (Copley Motion, 2015) .....	76
Figure 73: Keyence LV-N11CN.....	77
Figure 74: Keyence LV-S72 .....	77
Figure 75: Firgelli LAC .....	78
Figure 76: Pololu Jrk 12v12.....	79
Figure 77: Rendered image of the finished work cell.....	83
Figure 78: Completed state of the work cell.....	83



# INTRODUCTION

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In today's consumer-based world, manufacturing holds a very important position. In order for there to continue to be products on the shelves of stores, factories must continue to produce products at fast rates. And more importantly, they must produce them at a price that the consumer can afford.

There are many different manufacturing processes used to produce all of the products that surround us. Machining is an example of one of these processes. Machining is a process where a machine is used to subtract material down to its final shape. A common machining process is milling, where a rotating cutting tool is used to remove selected material. An example of a cutting tool used for milling can be seen below in Figure 1.



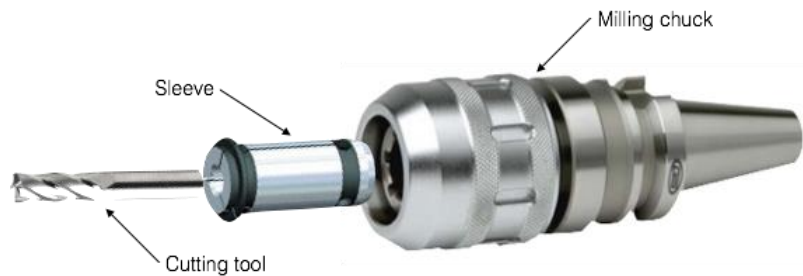
**Figure 1: A typical cutting tool used for milling**

Milling is a powerful process that allows for the manufacture of complexly shaped parts with tight tolerance requirements. Often in mass production settings, this process is computer-controlled in order to improve tolerance capabilities. This computer-controlled system is called a CNC milling center and an example of this system can be seen below in Figure 2.



**Figure 2: A CNC milling center**

If a cutting tool is used for an extended period of time, the cutting edge of the tool will begin to wear away. This will often have a negative effect on the quality of the part being produced. To address this problem, cutting tools must be replaced after a pre-defined amount of cutting time. Currently, this process requires an operator to manually replace the cutting tools. The time required to replace cutting tools is dependent on the method of tool holding used by the manufacturer. Tool holding systems are used to ensure that the cutting tool is securely fastened to the CNC milling center. There are many different types of tool holding systems, such as heat-shrink and hydraulic. For the purpose of this project, the project team will focus on the mechanical tool holding assembly known as a milling chuck assembly. This assembly consists of the milling chuck and a sleeve. Please see the exploded view below in Figure 3 to see how the assembly is arranged.



**Figure 3: Milling chuck assembly exploded view**

In this tooling assembly, a sleeve is inserted into the opening of the milling chuck. The internal diameter of the sleeve must match the shank diameter of the cutting tool that the tooling assembly is to hold. Next, the cutting tool is inserted into the sleeve. Finally, a wrench is used to rotate the milling chuck until it cannot be tightened further. This pulls the sleeve down into a slight taper within the milling chuck, causing the sleeve to compress. This compression is used to hold the cutting tool during milling. General Electric (GE) is a company that uses machining to produce many of its complexly shaped parts. GE is a technology company that participates in a variety of different industries. Machining is especially important to their aviation division. Some of the most complex parts in any aircraft engine are the bladed-disks that rotate to create thrust. These disks are referred to as blisks. An example of a blisk can be seen below in Figure 4. GE chooses to produce blisks using CNC milling due to geometric tolerances required of this component.



Figure 4: A blisk

Machining is a time-intensive process because all of the unneeded material must be removed. When milling a blisk, a large amount of the starting material has to be removed. Also, material properties often limit how fast material can be removed. Blisks are made of hard materials such as titanium and Inconel, which have low thermal conductivity and high coefficients of friction. This means that if machined too fast, a large amount of heat will be produced. This will cause deformation in the part and damage to the cutting tool. Thus, material must be removed slowly.

Milling accounts for a significant amount of the time dedicated to blisk production. And due to the limits of the milling process, it does not appear that an increase in productivity can come from that step in production. A large amount of time is spent on the preparation of tooling for the machining process, such as disassembling tooling assemblies, replacing the cutting tool, and then re-assembling the tooling assembly. Given the number of CNC milling centers and the number of tools in each of those machines, the overall time spent on tool preparation adds up to a significant amount of time (Graham, 2015).

If this process could be automated, the skilled operators that currently perform this operation could be tasked with more value-adding labor. To automate this process, GE has loaned a 6-axis Fanuc robot to the project team, shown in Figure 5. The goal of the project is to use the Fanuc robot work cell to receive worn tooling assemblies, disassemble the tool holding assembly, replace the worn cutting tool, and reassemble the tool holding assembly. The system must also collect worn tooling, and store them in a safe location until they are sent out for re-sharpening.



**Figure 5: Fanuc 6-axis robot**

# BACKGROUND

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## Production Floor Tooling

Many differently shaped and sized cutting tools are commonly used on production floors. For the purposes of this project, only the design of end mills will be discussed. The term “end mill” is used to describe a wide category of tooling. In general, there are three features on an end mill: flutes, teeth, and a shank. The shank is the feature that is inserted into the tool holder. The teeth are the sharp features used to cut material during machining. The flutes are the spaces between the teeth that are used as a path for material evacuation during machining. Please see the labeled diagram below.

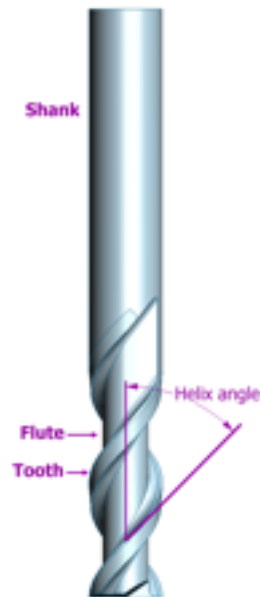


Figure 6: End mill labeled diagram (Wikimedia Commons, 2007)

There are many different characteristics used to describe an end mill. These include:

Tool diameter: Outermost diameter of the cutting teeth of the end mill

Shank diameter: Diameter of the shank of the end mill

Corner radius: The radius formed between the bottom of the end mill and the vertical cutting teeth. An end mill with a corner radius is called a bull nose end mill. An end mill with

no corner radius is called a flat nose end mill. An end mill with a corner radius that is equal to the tool radius is called a ball mill.

Tool length: Distance from the bottom of the end mill to the end of the cutting teeth

Shank length: Distance from the end of the cutting teeth to the end of the shank

Number of teeth: The number of teeth and flutes on an end mill

Cutting tools experience tool wear as they are used. Tool wear can be broken down into two different categories: gradual tool wear and abrupt tool failure (Marinov). Since it is possible to avoid abrupt tool failure in mass production, only gradual tool wear will be discussed. This gradual tool wear creates an unpredictable change in tool geometry that can have an effect on the dimensions and surface finish of the part being produced.

Many factors have an influence on the degradation of a tool during an operation. Excessive heat during the machining process is a large contributor to tool wear (Haddag & Nouari, 2013). Many measures can be taken to minimize heat. For example, the cutting speed can be slowed, tools can be coated in lubricated coatings, and coolants can be used. Please see the diagram for a more complete understanding of the influences that cause tool wear.

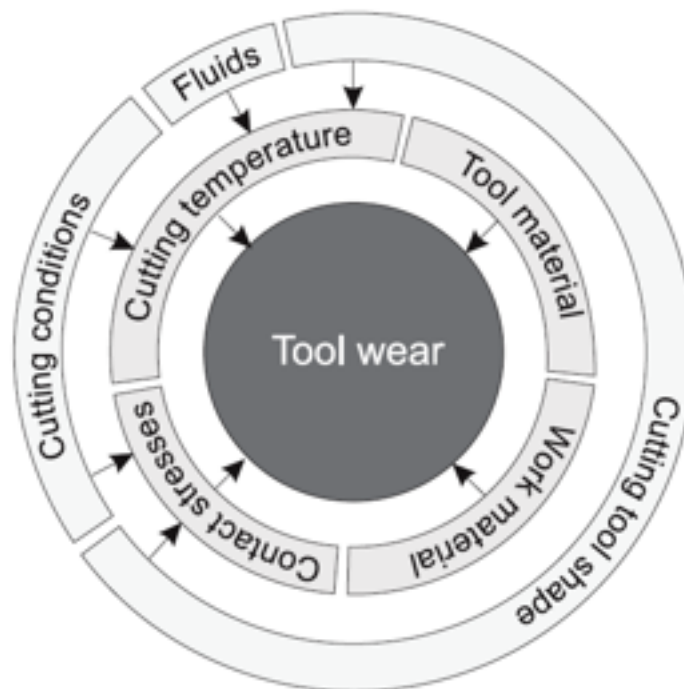


Figure 7: Tool wear influences (Marinov)

Unfortunately, most tools will eventually wear to the point where it is no longer functional, despite the machining conditions. One solution to this problem is to monitor how long a tool has been in operation and have it re-sharpened after it has reached a pre-defined tool life. If this is not properly monitored and excessive tool wear occurs during an operation, the tool could fail to the point where sharpening is not feasible (abrupt tool failure). Therefore, tool life management is an important aspect of effectively managing a production floor.

General Electric currently uses a tool management system to ensure that their blisk machining operations run efficiently. A flow chart of their system can be seen below.

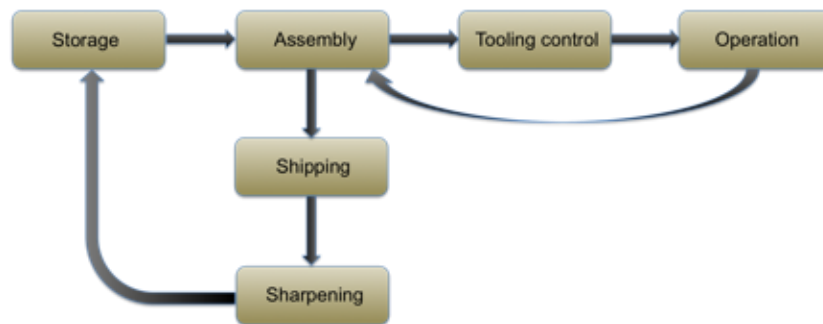


Figure 8: GE's tool management flow chart

Cutting tools begin their life when geometry is then ground onto the end of a long carbide rod by an external tooling vendor, as dictated by General Electric. These cutting tools are placed in storage until they are needed to replace worn tooling that is currently in use on the production floor. At that point, the operator takes a new cutting tool from storage and manually assembles a tooling assembly with the new cutting tool. The tooling assembly is then placed in tooling control, where it will be stored until it is needed in a CNC milling center. When a tool is needed for an operation, an operator goes to a tooling control kiosk, and removes the tooling assembly that he or she needs. He or she then installs the tooling assembly in the CNC milling center in preparation for a machining operation.

Once the tool has reached the end of its life, an operator removes the tooling assembly from the CNC milling center and returns it to tooling control. Once enough worn tooling assemblies have been collected, an operator will disassemble the tooling

assemblies. The worn tooling is then stored in another location until enough tools are collected to be shipped out for sharpening. During the sharpening process, an external vendor re-grinds the tooling geometry into the carbide rod, making the rod shorter every time it is sharpened. After sharpening, the tool is returned to tooling storage and awaits a request from tooling control. Eventually, the carbide rod is too short for operation, and must be discarded or recycled.

Only a limited amount of time in this process is actually spent in operation. General Electric sees value in maximizing the percentage of time a tool is in operation and removing the manual labor associated with this tool-changing process. The focus of this project will be on making improvements to the assembly and disassembly steps through the use of a 6-axis industrial robot.

### **Industrial Robotics**

The first industrial robot was named Unimate and developed by General Motors in then 1950's. There have been many technological leaps since then, most significantly with the introduction of the microprocessor. Ever since its inception, industrial robots have found successful implementations that have increased productivity within facilities (Christian, 1981). Due to increasing labor costs, the decreased cost of robotic systems, and increased performance of these systems, more and more companies are looking to robots to perform production task in low to medium volume production (Edmondson, 2005). Although GE does high volume production with some of its product lines, the tool changing process occurs at a rate that is similar to low to medium volume production. Therefore, the tool changing process is a great application for a 6-axis industrial robot.



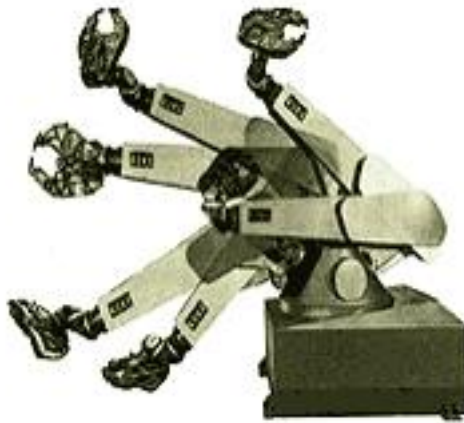


Figure 9: KUKA FAMULUS circa 1973 (KUKA Robot Group)

## Programmable Logic Controllers

A programmable logic controllers (PLC) is a common device used throughout many industries to provide a controlled output based on inputs to a programmatic sequence. PLC's are generally optimized to serve in an industrial setting where there are often harsh environmental conditions present. PLC's can be found in assembly lines, amusement park attractions, and outdoor exhibits, for example.



Figure 10: Allen-Bradley MicroLogix 1500 PLC controller with three expansion IO modules (Industrial Automation Control, 2011)

PLC's were initially designed to replace extensive relay logic networks. These networks used a series of relays that would be triggered by a set of inputs and/or sensors to switch the available outputs. The program language they interpret, called ladder logic, resembles what a schematic of a relay logic system might look like.

Ladder	Instruction List (IL)
	LD A ST X
	LDN A ST X
	LD A     LD A LD B     AND B ANB     ST X ST X
	LD A     LD A LDN B    ANDN B ANB     ST X ST X
	LD A     LD A LD B     OR B ORB     AND C LD C     ST X ANB     ST X ST X
	LD A     LD A LD B     LD B LD C     OR C ORB     ANB ANB     ST X ST X
	LD A     LD A LD B     OR B ORB     LD C LD C     OR D LD D     ANB ORB     ST X ANB     ST X ST X

Figure 11: Ladder logic programming with instruction list (The Learning Pit)

Ladder logic processes commands in a serial format, and often has an integrated development environment (IDE) that provides a flowchart-like feel to the programming language. This allows for simple programs to be developed quickly without extensive experience. To some, the simplicity of ladder logic programming can sometimes feel archaic because it lacks the advantages of modern day software packages.

The PLC is responsible for controlling the operation of the larger system and supporting numerous devices through a variety of inputs and outputs. These inputs and outputs (IO) allow users to connect sensors and actuators to the system. Each PLC has a limited number of input and outputs (IO), and is generally based upon the package size. However, remote IO units can be purchased to expand the capabilities of a single PLC. If additional processing power or IO ports are needed, additional PLC's can be purchased and configured to work together to accomplish the desired operation.

Popular PLC manufacturers include Allen & Bradley, Siemens, Automation Direct and countless others. The work cell that GE provided currently is equipped with an Allen & Bradley PLC controller that was previously configured to perform polishing operations.

## Peg in the Hole

One of the largest challenges that assembly robots face is the insertion of one component into the other, especially when there is limited clearance between the two components (Sanji, Nakamura, Suzuki, & Aoyagi). This is because of how critical proper alignment between the two components is. If there is even a slight angle between the two central axes, a large amount of force can be created and the parts can jam (Haskiya, Qiao, & Knight, 1997). This is of high importance to the project because of the required insertion of new tooling into tool holding assemblies. There is minimal clearance between the tool holder and the tool in order to meet the tool holding stability required for proper machining operation.

There are a few different strategies for overcoming this challenge. The first is the usage of a remote center of compliance. Although not recognized at first, compliance plays a key role in manually assembling systems (Rebman, 1979). A remote center of compliance is a device that is used to add compliance to a system and allow for some variance between the central axes of the two mating components. There are different types, but their purposes are all the same. Unfortunately, these systems are often costly due to the complexity of their design, and do add a reduction in position accuracy. Please see the diagrams below for a graphical description of how one might work, and an example of a system currently on the market.

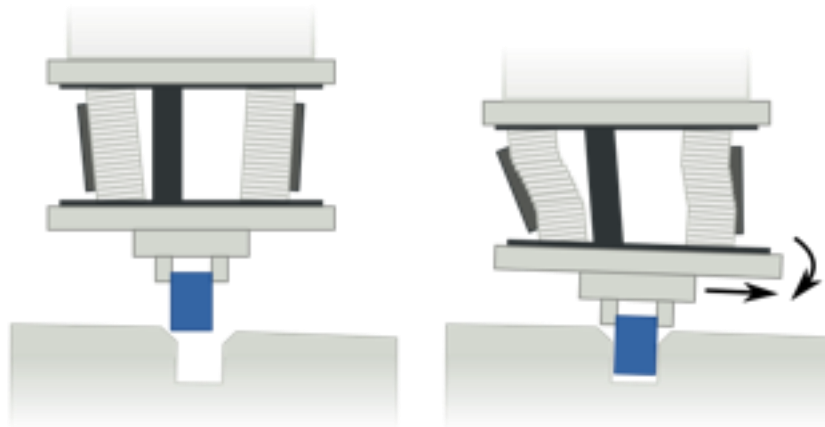


Figure 12: Remote center of compliance (Nordmann, 2008)



**Figure 13: ATI Industrial Automation's remote center of compliance**

Another method is using force sensing to alter the two central axes of the mating components until they are properly aligned with each other. This usually involves complicated logic in order to relate the force being detected to the required motion (Sanji, Nakamura, Suzuki, & Aoyagi). There are techniques that aim to simplify this logic through the use of different initial entry conditions (Haskiya, Qiao, & Knight, 1997), but at this point, the force sensing approach still appears complicated.

### **Relevant Technologies**

Before the project team could begin to develop a system to meet the expectations of GE, a number of technologies would need to be investigated. Although the high level design of the system has not been laid out at this point, some technologies may eventually be incorporated into the design of the system. The project team created a list of these relevant technologies, and they will be more thoroughly explained in this section of the document.

### **Gripping**

In this project, the robot will have to transport cutting tools and tooling assemblies around the work cell. This will require the robot to have some system of picking and placing these components in specific locations. It is critical that this system be strong enough to ensure nothing will fall to the ground, and sturdy enough to ensure that there is no variance in performance based on the size of the item it is carrying.

Two of the most common technologies used for pick-and-place style actuators are pneumatics and servos. A pneumatic system uses the power of compressed air to move a linear actuator between an open and closed position. A pneumatic actuator has some compliance built into it due to the natural compressibility of the air applying the force. Also, once a signal has been sent to the solenoid that controls the actuator, no power must continue to be applied in order to hold the actuator in that position. Unfortunately, this system can only be used in facilities with access to pressurized air. An example of a pneumatically driven gripping end effector can be seen below.



**Figure 14: A SCHUNK pneumatically driven actuator**

A servo-driven actuator utilizes a motor with location, force, and/or velocity based control to open and close an end effector. These systems must have some method of transforming the rotational motion of the motor into a gripping force. The design of these actuators are often times more complicated than pneumatic actuators. There is much better control and feedback on the position of the gripper fingers at any given moment with a servo-driven actuators. An example of a servo-driven actuator can be seen below.



Figure 15: A SHUNK servo driven gripper module

### Tool holders

A CNC tool holder is comprised of a number of components either designed to interact with the machine spindle or the cutting tool. Beginning with the machine tool components, one of the major features of a specific tool holder is the mating geometry found on the top of the holder. It has been observed by the project team that in industry the most common mating area found on tool holders used in milling centers is an 8-degree conical taper that is formed from the body of the holder. This taper is inserted into the machine spindle where an opposite mating taper is used to locate and position the tool holder. The machine tapers come in different shapes and sizes determined by the machine standard including: CAT, BT, NMTB, and HSK.

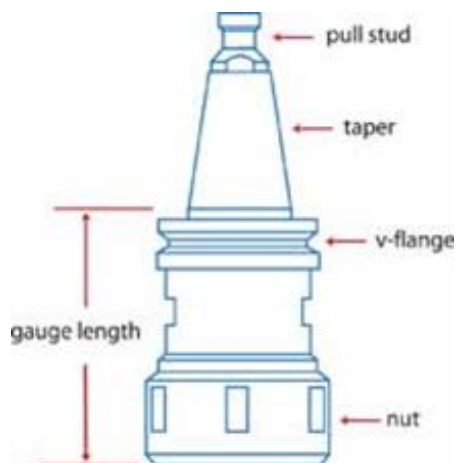


Figure 16: Diagram of tool holder components (Techniks, Inc.)

The component used to hold the tool holder up into the spindle is known as the pull stud or retention knob. It is threaded into a hole at the top of the taper of the tool holder. This rounded boss is pulled into the previously mentioned taper of the spindle by a spring loaded draw-bar. These pull studs also come in different shapes and sizes depending on the machine spindle with some allowing for coolant flow through the tool holder. The last component that interacts with the machine spindle is the flange which sits square up against the bottom of the spindle just below the end of the holder taper. The flange is designed with two machined slots that line up with exposed tabs on the spindle to keep the holder from spinning in the spindle and transfer rotational energy. The rest of the components below the flange of the holder are designed to fix the tool (Techniks, Inc.).

There are many different tool-holding methods used in CNC tool holders, the three most common types are end mill holder, collet chuck, and milling chuck. The end mill holder is by far the simplest solution with a single size bored hole to which the cutting tool shank is inserted and fixed by using a side locking set screw. Simplicity comes at a cost as the end mill holder is the poorest performer due to its lack of precision and versatility. The holder is both unbalanced and suffers from tool indicated runout (TIR which is defined as axial deflection of the cutting tool from the rotating axis. This makes end mill holders an economical choice for non-precision machining (Parlec, Inc.).

The next type, and arguably the most common, is the collet chuck tool holding system consisting of a universal holder with interchangeable collets. Although there are more specific types of collet chuck holders such as double angle, single angle, and ER, they have similar construction. To fix a tool, the collet nut is removed from the end of the holder and a collet is inserted into the body of the holder. The collets used in the collet chuck have tapered geometry that squeezes the collet when pressed into the body of the holder. The collet nut is threaded back onto the end of the holder and the shank of the cutting tool is inserted into the opening of the collet. Once in place, the collet nut is tightened down to fix the tool in place. This method of tool holding is more precise than end mill holders and adds versatility with the interchangeable collets (Parlec, Inc.).



**Figure 17: Model of a milling chuck tool holder (Lyndex-Nikken)**

The last type of tool holding is the milling chuck, shown in Figure 17 above, which has a similar construction to a collet chuck, but holds much higher tolerances. The milling chuck consists of an interchangeable straight collet, or sleeve, which is placed into the open bore of the holder and a roller bearing nut, or collar used to tighten the tool. With the nut loosened the shank of the cutting tool is placed into the straight collet and once in place the nut is tightened to fix the tool. What makes the milling chuck unique is the tighter tolerance of the holder itself along with use of the roller bearing nut that applies uniform pressure on the tool (Lyndex-Nikken). This even holding pressure prevents TIR and contributes to the performance of the milling chuck during heavy milling operations. The project will focus on the use of the milling chuck when completing the project goals, as this is the tool holder that is commonplace on GE's production floor.

The performance characteristics of a tool holder directly affect many aspects of the machining process. Low precision in tool holding will be reflected in the finished product in the form of wider machine tolerances, machine finish, and general machining imperfections. These issues are not limited to the workpiece, but can affect the tooling itself in the form of reduced tool life as shown in the Figure 18 below. The graph shows the average tool life percentage according to cutting time as a function of tool indicated runout measure in ten-thousandths of an inch. This tool runout can be caused by a number of reasons including imperfections in the spindle taper, and tool holding components such as collets and other contact surfaces.



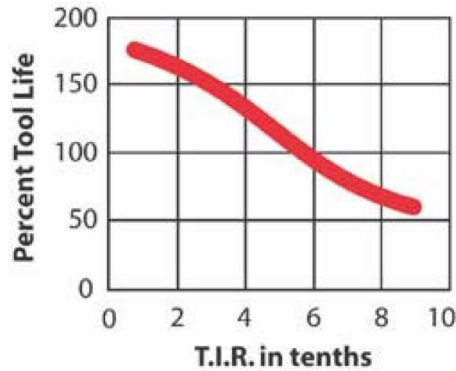


Figure 18: Graph of expected tool life based on tool runout (Techniks, Inc.)

In addition to the precision of the tool holder, it is important to select the correct tool holder for the job based on the properties of the tool holder and the specific machining application. For example, although the milling chuck may have better precision and uniform clamping force on the tool, it is not suitable for high speed cutting due to the weight of the roller bearing nut that would throw the holder out of balance at high speeds. In this case, an ER collet chuck, although having lower overall precision for high speed cutting operations, will perform better than a milling chuck. Therefore tool holding selection is never a black and white decision but determined by the individual application of the tooling (Parlec, Inc.).

### Linear Actuators

Linear actuators are actuators that provide linear motion to a system. This motion can be pneumatically, hydraulically, or electrically driven. Linear actuators can be found in a wide variety of machines such as cranes, printers, and automobiles. Sensors can be added to the system to provide feedback on the location and speed of the mechanism. Some manufacturers provide the actuator and sensors in one complete package. Omega, Parker, Festo, and Tolomatic are some well-known manufacturers of linear actuators.

The traditional design of a linear actuator consists of a screw with a nut that is restricted from rotating. The nut moves up and down the screw as the motor rotates the screw. This can more clearly be seen below in Figure 19. Given a small thread pitch and a large screw diameter, this design has the capability of providing a large amount of linear force to a system.

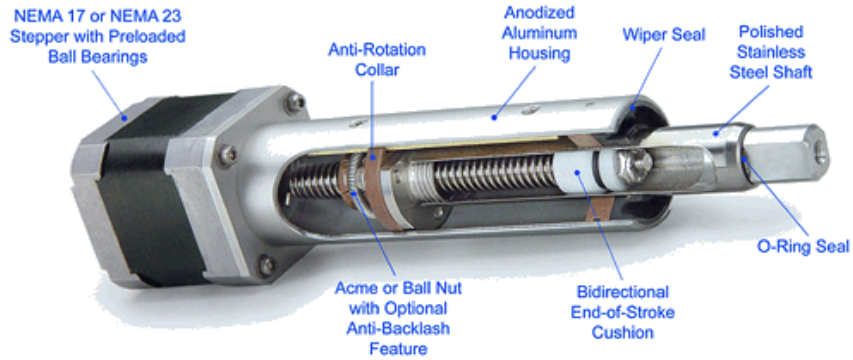


Figure 19: Screw type linear actuator (Ultra Motion)

Both pneumatic and hydraulic pistons can be considered linear actuators. The rod of a piston is driven by a pressure differential between the two reservoirs of the cylinder. The rod will move from the high pressure reservoir to the low pressure reservoir in an attempt to equalize the pressure. Since the position of the rod in the piston is controlled by the pressure differential position control can be a challenge due to compression of the air or hydraulic fluid (Goel, 2011).



Figure 20: Pneumatic piston cutaway (Design World Online)

Pneumatic systems are far more susceptible to position error because air is far more compressible than hydraulic fluid and therefore can be acted upon by outside forces much more readily than its hydraulic counterpart. Pneumatic systems tend to be used when two positions are desired in the stroke displacement, fully extended or fully retracted. Hydraulics, through the use of high speed switching valves, can be used to allow for the piston to be stopped along its stroke, much like a linear actuator might allow.

The more traditional linear actuator, utilizing a nut and screw, generally provided a much high degree of control because the nut's position on the screw can be calculated based on the number of rotations of the screw. Certain assumptions can be made allowing for this ideal position of the linear actuator to be calculated. Some assumptions include that the motor lacks back drive, there is no rotational shaft movement on the part of the motor, and there is no "compression" or slip on the part of the nut.

The direct correlation between screw rotations and the movement of the nut on that screw allows for a linear actuator to be controlled with an extreme amount of precision. Traditionally an encoder will be connected to the linear actuator as part of the drive mechanism. The encoder provides a digital pulse to the controller every time the encoder has been driven a pre-determined number of degrees. It is important to note that depending on the precision of encoder pulses could be provided numerous times per degree.

The type of screw being used by a linear actuator can also have a vast impact on its weight capacity without the addition of any external devices and without making any modifications to any part of the system. Primarily the angular pitch of the screw itself drives this static force. An acme screw for example would have the ability to support a large static load where as a ball screw would not. Ball screws are meant to allow the nut to glide more smoothly up and down the screw, but as a result have a much lower static load capacity.



Figure 21: Ball screw (McMaster-Carr)



Figure 22: Acme screw (McMaster-Carr)

### Industrial vision systems

An industrial vision system, or machine vision, involves the technology used to automate specific processes with the use of cameras and other imaging devices. Vision systems are capable of a variety of functions that allow them to be utilized to assist in the automation of tasks. Depending on the intended use, vision systems are fitted with either a conventional 2D imaging device, for example a camera, or a type of 3D imaging device, for example a laser array,, scans an area to produce an image. The functionality of the vision system stems from the imaging processing performed once the device has captured an image. Image processing methods include edge detection, pattern recognition, color analysis, barcode, and character recognition. Most modern vision systems process the image instantly without the need of external processing by a computer – meaning the system will generally output a pass/fail signal meaning the system can be integrated similarly to a sensor (Golnabi & Asadpour, 2007).

Using the capabilities of an industrial vision system, the primary applications can be divided into two major types. The first, and most common use of vision systems, is its role in automated visual inspection (AVI). This task involves automating the inspection process, predominantly performed during manufacturing, which would otherwise need to be done by hand. The functions of modern vision systems allow them to identify geometry to make measurements or simply identify a part both quickly and reliably. The second application of industrial vision systems is the use in robotic guidance and control when performing automated processes (Golnabi & Asadpour, 2007). In this application the imaging device is used to identify the space in which the robot operates. In this case, the vision system is used as a smart sensor to identify both position and orientation when performing different operations that require constant feedback.

## Safety systems

Safety systems are a critical component to any manual, autonomous, or semi-autonomous system. In 2013, 4405 workers were killed on the job (United States Department of Labor, OSHA). This is an average of 12 deaths every day. Although a large portion of those deaths comes from construction, industrial accidents frequently happen and installing the appropriate safety systems around machinery can help mitigate many risks.

An emergency stop function must be able to be controlled by a single human interaction that must remain functional at all times and bring the machine to a stop.

Safety systems can be implemented in both an active or passive manner and can even involve direct operator interaction. Some devices such as a dead man switch must be held or depressed in order for machine operation to progress. Other safety systems including light curtains, safety cameras, or safety lasers that can detect when an object crosses the threshold into a protected area and will trigger an emergency stop of the machine. Additional lower tech solutions such as mechanical guarding in the form of a chain link fence or safety bar aim to physically prevent an operator or part of an operators extremities to enter an area of danger.

Choosing the appropriate sensor for the application is also important. Certain safety sensors, such as a light curtain, form a perimeter around the system but would not detect a foreign object in the safety zone if the object started inside the zone. These sensors are susceptible to foreign objects not breaking the safety plane during machine operation because they have already previously broken the safety plane prior to the activation of the safety systems.

Safety systems should be designed such that if any component in the safety chain were to break or lose communication the system would treat the incident as a trigger and bring the system to an immediate stop. This type of behavior, also known as “fail safe”, ensures that no portion of the safety system could fail and go unnoticed. This system architecture also ensures in the event of an extreme catastrophic failure, where the safety system or the components that form the safety system are damaged as part of the failure the system comes to an immediate stop.

It is important to note that no safety system is perfect. A combination of the appropriate safety sensors and established protocols can help maintain a safe working environment; however, caution should be used at all times when working with industrial machinery.

Numerous components that can make up and/or be part of a safety system are detailed below. The Occupational Safety and Health Administration, commonly referred to as OSHA, has extensive regulations that govern the suggested implementation of many of these safety items. The project team had included a brief overview of some of the common components for the reader's awareness, but the following sections do not provide a comprehensive review of each technology.

### *E-stop Buttons*

Emergency stop buttons often found in the form of a “mushroom” button must be red in color with a yellow backing or background. An emergency stop switch must require additional manual intervention to reset the switch such as a twisting motion or a key switch. Emergency stop buttons that simply require the operator pulling the switch back “out” to re-engage the safety contacts are generally not desired as they can be inadvertently reset. The resetting of an emergency stop shall not under any circumstance restart the machine or process but simply allow the machine to be restarted, as it would be normally.



Figure 23: Emergency stop button (Direct Industry)

### *Light Fences*

Light fences consist of two primary devices: a transmitter and receiver that form a “curtain” of light around a designated area. Mirrors can be used to bounce the curtain at an angle allowing one set of light fences to be used to establish a curtain around a curved area if it is desired. Light fences can be purchased with varying range and resolution

abilities. Typical resolutions are between 14mm and 40mm with a range of anywhere from .5m to 6m.



Figure 24: SICK C4000 palletizer light curtain (SICK)

### *Limit Switches*

Safety limit switches are specialized designed limit switches that operate in the same basic manner as a traditional limit switch but carry a higher rating and undergo further testing as they are considered part of a safety system. Limit switches come in many forms that can be broken up into two main groups: electro-mechanical and non-contact.

Electro-mechanical switches have a wide variety of actuators whether it is a lever with a wheel, a push button, hinge, or an extending rod. Additionally electro-mechanical switches include those that are used to monitor the status of a door and offer the ability to lock with either a spring or electromagnet.



Figure 25: SICK roller contact safety limit switch (SICK)

Non-contact sensors include those that can be triggered passively via magnetic force or inductive force. These sensors can come in handy when physical contact between two mechanisms is not desired or practical.



**Figure 26: SICK non-contact magnetic sensor (SICK)**

One advanced safety sensor is a laser scanner that can monitor a “field” and trigger either “stops” or “warning’s” to a machines controller. One major advantage of this sensor is that it provides active monitoring of the work area and, unlike a light curtain, is not susceptible to a foreign object located in a protective zone before the safety system is brought online.

Presence sensors are aware of what the monitored area should look like while empty and ensures the laser scan of the area matched that expected mapping.



**Figure 27: SICK laser safety sensor (SICK)**



# METHODOLOGY

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Before beginning to develop the system, there must be an understanding of the specifications that the final system must meet. In order to determine what the results of the system should be, the project team met with our sponsor, General Electric Aviation, to discuss the details of the system they would like us to develop. From this discussion, a list of project specifications was developed. The specifications are:

- The system can autonomously remove and replace the supplied tools into the supplied tool holders
- The system operates at a minimum rate of two tools per hour
- The process is repeatable
- The system can accept a single shank size
- The system can accept two different types of cutting tools
- The system can disassemble worn tooling assemblies
- The system can assemble tooling assemblies with new cutting tools
- The tool height is properly set to a known height within a tolerance of  $\pm 0.025$  in.
- The tooling assembly is assembled according to GE process specifications
- The system operates within a closed space
- The system must include safety measures for human interaction with the cell
- The system does not damage cutting tools or tool holders during operations

After agreeing to these minimum specifications, the project team decided to target higher standards in a few areas. For example, it is expected that the system will be able to accept two different shank sizes,  $\frac{1}{2}$ " and  $\frac{3}{4}$ " rather than a single shank size. It is also expected that we will be able to do a minimum of six tools per hour, and we will be able to properly set the tool height to a known height within  $\pm 0.025$ ".

Now that the goals for the project had been established, the project team could work towards planning a system that would meet or exceed them. A strong technique for

organizing a large project is to break the project down into smaller parts. Inherent in these design specifications are individual subsystems that must perform specialized tasks.

These systems are: tooling assembly intake, tooling assembly output, new cutting tool storage, worn cutting tool storage, method for disassembling tooling assemblies, method for assembling tooling assemblies, and a method for cutting tool and tool holder manipulation.

The system needs a method of inputting the worn tooling assemblies. The project team developed two designs that could address this need: drawer-fed and tool cart-fed. In the drawer-fed design, the operator would place worn tooling assemblies in a drawer on the side of the work cell. Once the operator placed all the worn tooling assemblies in the drawer, the operator would slide the drawer into the work cell, and the robot would begin processing. With the tool cart design, the operator would roll a tool cart into the work cell and the robot would process the tooling assemblies directly off the tool cart. Currently, the worn tooling assemblies are already placed on a tool cart as they are removed from CNC milling centers. A tool cart is a standard cart except that it has special cups that are designed to hold the taper of a tool holder. This system would require some docking system that would ensure that pick and place locations of the tool cart are in the same position each time the operator loads the work cell. Both of these designs would allow for the processed tooling assemblies to be output in the same location that they were loaded into the work cell.

The drawer-fed design would mean that the operator would have an extra step before the work cell could process the worn tooling assemblies. The operator would have to pull the worn tooling assemblies from the tool cart and place them in the drawer. Likewise, the operator would have to pull the process tooling assemblies from the drawer and place them on the tool cart after the work cell is finished processing them. The tool cart-fed design eliminates this step. For this reason, the project team decided to move forward with the tool cart-fed design.

It is also important that the system have a method for storing new and worn cutting tools. The new cutting tools will be used to replace the worn cutting tools in the tooling assemblies that are loaded into the work cell. The worn cutting tools will be retrieved by the operator after processing so that they can be shipped to an external

vendor for re-sharpening. A simple drawer could be used to store both new and worn cutting tools. This would allow the operator to have access to the system from outside the work cell. It also would provide a constant pick and place location for the robot.

The system must also have some mechanism for assembling and disassembling tooling assemblies. It is expected that this will be one system that can be run one way to disassemble tooling assemblies and reversed to assemble tooling assemblies. The robot will be used to remove and insert cutting tools into loosened tooling assemblies. As mentioned in the background section of this document, a remote center of compliance may be necessary.

As previously mentioned, a Fanuc 6-axis robot will be used for material handling within this system. In our case, this means that the robot will be manipulating tooling assemblies and cutting tools between the tool cart, the tooling assembly mechanism, and the tooling drawer. Therefore, an end effector must be developed that can successfully accomplish this task.

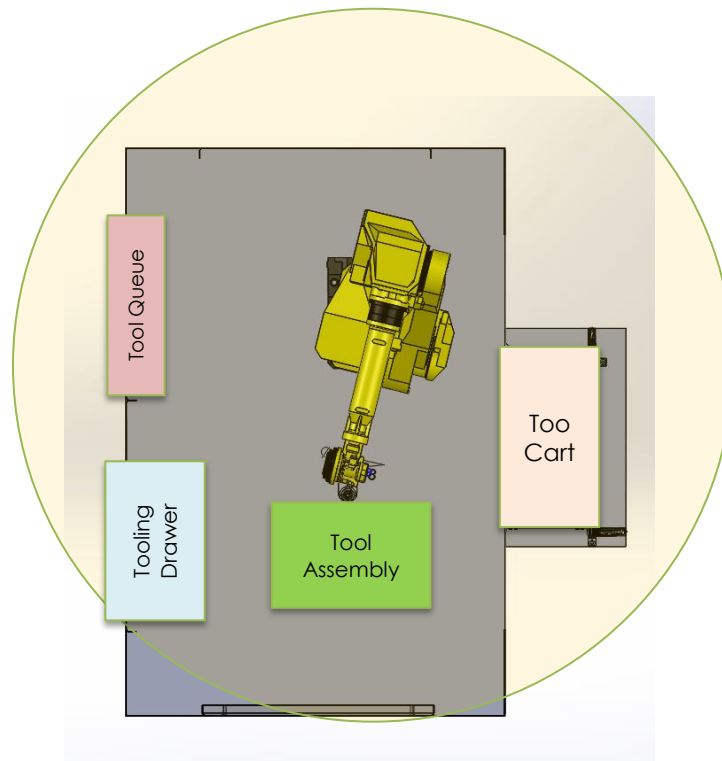


Figure 28: Top-down view of work cell and access areas

Now that the system has been broken down into different subsystems as shown in Figure 28 above, it is appropriate to lay out the framework of how the robot would process tooling assemblies. To begin, the robot will pick a worn tooling assembly off of the tool cart using the specially-designed end effector. The robot will then transport the tooling assembly to the tooling assembly mechanism. That system will then loosen the nut on the tool holder, and the robot will pull the cutting tool out of the tooling assembly. After that, the robot will safely deposit the worn cutting tool in the tooling drawer, and pick a new cutting tool from the tooling drawer. Next, the robot will insert the new cutting tool into the tooling assembly. The tooling assembly system will set the height of the tool, and then tighten the nut on the tool holder to GE's process specifications. Finally, the tooling assembly will be returned to the tool cart. The robot will then begin to process the next tooling assembly on the cart.

In order to better visualize this process, a flow chart was developed. It can be seen below in Figure 29.

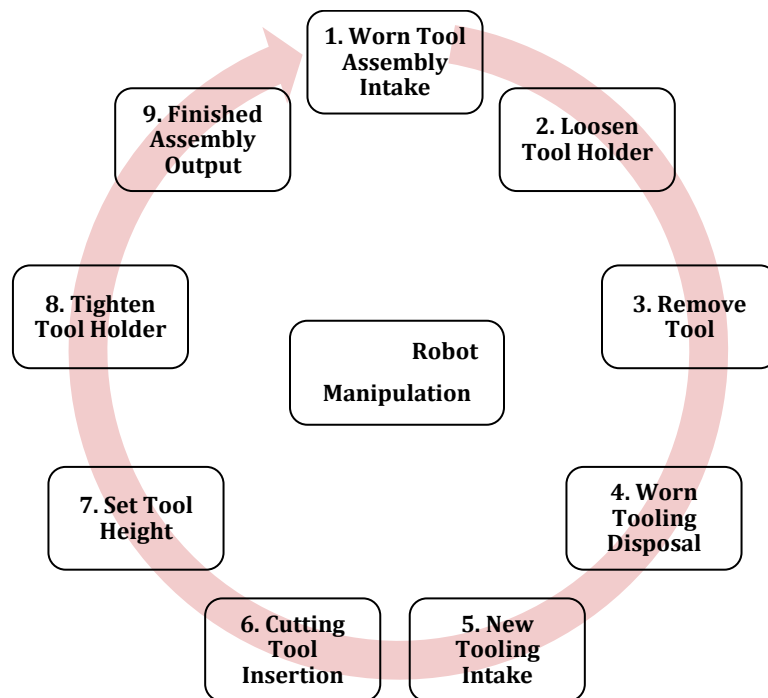


Figure 29: Process Flow Chart

## End Effector

The end effector is required to work with all the sub-systems within the work cell, so it makes sense to design this component first. Before designing, the project team

established a set of criteria that the design must adhere to. The end effector must be able to manipulate cutting tools with ½” and ¾” shank diameters and the tool holders provided to us by GE. This must be done in a safe manner to ensure no damage is done to any cutting tools or tool holders. The end effector must also be able to accurately insert and remove cutting tools from tooling assemblies during the assembly step of the process. The mating geometries of the end effector must be accurate to ensure that the assembly process is highly repeatable. If this were not the case, the pick and place locations would need to be adjusted every time the end effector was disassembled. Finally, the end effector must rigidly mount to the end of the Fanuc industrial robot.

The project team discussed many different options when designing this subsystem. The idea of having two end effectors was brought up in discussion. This would allow for end effectors that were more specifically designed for manipulating either cutting tools or tool holders. The work cell donation included a set of plates that would allow for the end effector to be changed mid-operation. The plates included connections for electricity and compressed air however adding an end effector change to the process would not only increase cycle time but also create an additional location for error to be introduced into the system. Implementing an interchangeable plate system would also added a level of complexity associated with an end effector change that was not necessary based on the design criteria. Based upon a needs assessment the project team decided to design a single end effector that would serve to manipulate both cutting tools and tool holders.

One design that would allow for manipulation of both end effectors and tool holders, could utilize side pickup of cutting tools and tool holders. This means that the weight of the tooling assemblies would not be directly below the actuator, which could result in deflection of the fingers of the end effector. This was a lesson learned by the previous project associated with this work cell. Another option was to develop a tall end effector that would pick up the tooling assemblies from directly overhead. Figure 30 shows the sketches that were drawn for this idea. Unfortunately, all of these designs did not seem feasible after some further investigation. So it was decided that a properly designed end effector would deflect minimally if a tooling assembly were picked up from the side. Sketches of this design can be seen below in Figure 31 and Figure 32.

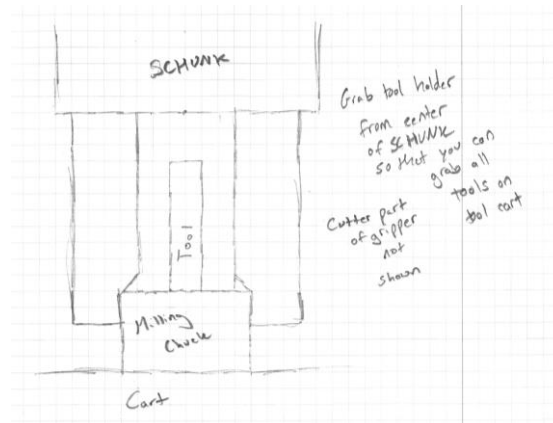


Figure 30: Overhead end effector design

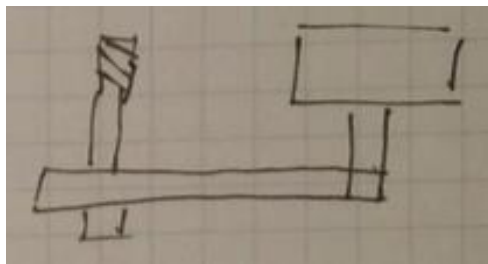


Figure 31: Side approach end effector design (cutting tool)

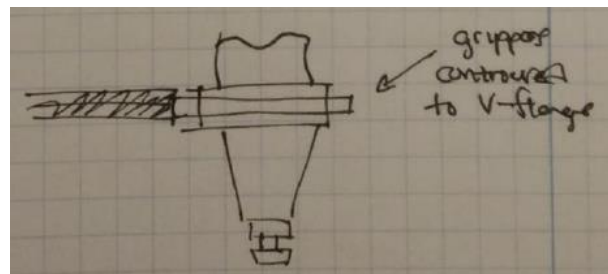


Figure 32: Side approach end effector design (tool holder)

Two different pneumatic actuators came with the work cell. Both actuators are produced by SCHUNK. One is a two-finger system (Model PGN 125/1), and the other is a three-finger system (Model PZN 80I). Pictures of these actuators can be seen in Figure 33 and Figure 34 respectively. The two-finger system would be easier to implement with the side pickup design that was previously decided on, so it was chosen for use.

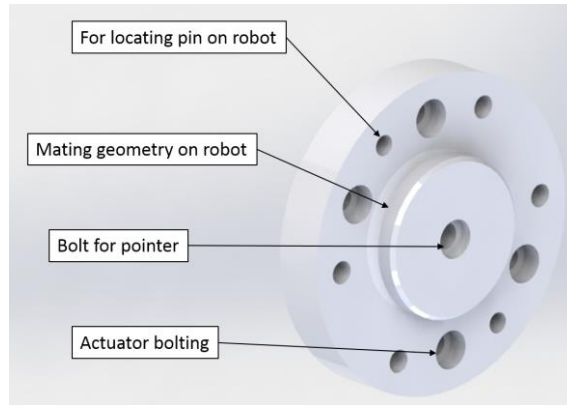


Figure 33: SCHUNK pneumatic actuator, model PGN 125/1

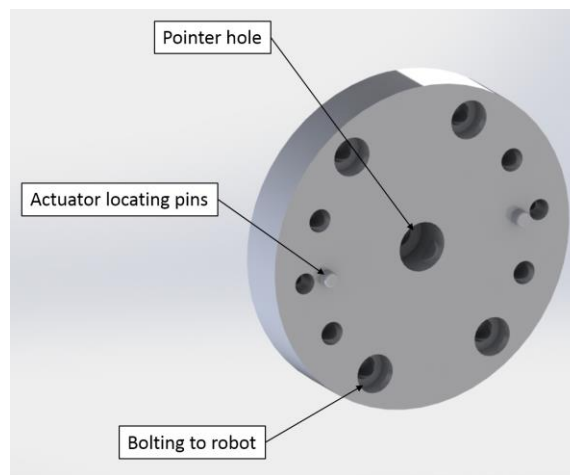


Figure 34: SCHUNK pneumatic actuator, model PZN 80I

Once the actuator was determined, a method for mounting the actuator to the end of the Fanuc robot had to be developed. A plate was designed that would bolt to both the robot and the actuator. This plate is made out of 6061-T651 aluminum because it is easily sourced, economical, and easily machined. The plate contains a large circular boss on one side that acts as a locating geometry for the end of the Fanuc robot, along with two clearance holes that accept the 8mm locating pin on the robot. On that same side are counter sunk holes that will serve as bolting locations for the actuator. On the other side of the plate are countersunk holes that serve as bolting locations for the end of the Fanuc robot, along with the pins that serve as locating features for the actuator. A CAD model was developed, and can be seen in Figure 35 and Figure 36.



**Figure 35: Actuator mounting plate, robot side**



**Figure 36: Actuator mounting plate, actuator side**

This mounting plate was also designed to serve as a mounting plate for a pointer. A pointer is a common device used to locate features and geometry relative to the robot coordinate frame. It is simply a rod that has one side turned down to a sharp point. The project team will need this when the robot begins to be programmed. A picture of the assembled mounting plate and pointer can be seen below in Figure 37.



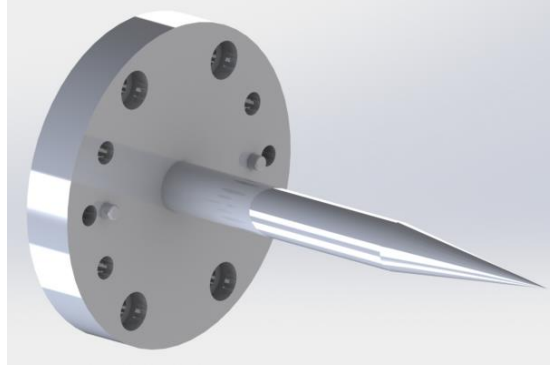


Figure 37: Pointer

The mounting plate was CNC machined on the Haas VM2 in Washburn Shops. In order to ensure that the robot mating geometry would fit properly, cutter compensation was used on the operation that cut the circular boss feature of the mounting plate. Cutter compensation is a machining technique that allows the machine operator to easily modify the operation on the CNC controller. With this flexibility, the project team was able to trim the diameter of the circular boss down until it fit perfectly on the end of the Fanuc robot. This technique will be used for many operations throughout the project.

This was the first time the project team was using this technique, and made a small mistake on the offset of the first pass. The circular boss now has an indentation on one side of the circle where the cutting tool came in too far. It was caught before the entire circle was machined, meaning this mistake did not ruin the part. The error was corrected, and the part was completed. The part, along with the indentation, can be seen below in Figure 38.



Figure 38: End effector mounting plate

The actuator must be bolted to the mounting plate before the mounting plate is bolted to the robot. When first mounting the actuator to the robot, it was realized that the pneumatic fittings on the side of the actuator were not accounted for. They did not prevent assembly, but made it more difficult as they blocked direct access to two of the bolts needed to mount the plate to the robot. An Allen key with a ball-tip is necessary to tighten those bolts.

Once the chosen actuator had been mounted to the end of the robot, the geometry of the fingers that would be mounted to the actuator could be developed. This end effector would be responsible for manipulating both tool holders and cutting tools. The end effector would grab the tool holders by the v-flange, as this is the most consistent geometry on all of the tool holders. The end effector will grab cutting tools via the shank in order to prevent damage to the flutes of the cutting tool.

The project team aims to manipulate cutting tools with two different diameters:  $\frac{1}{2}$ " and  $\frac{3}{4}$ ". Through the brainstorming process, four different geometries were developed to hold the cutting tools. The cutting tool could be held using two, three, four, or infinite contact points. Two flat plates would provide two contact points, a flat plate and a groove would provide three contact points, and two grooves would provide four contact points. An infinite-contact point system would require the plates to have the shank geometry of

the cutting tool cut into them. Each design has varying degrees of compliance and control. In order to determine which design produces an acceptable compromise between compliance and control, a test was conducted using each of these geometries. The test fingers for the four geometries can be seen below in Figure 39. The holes for the actuator and an extra hole for proper work holding during machining are seen in these models.

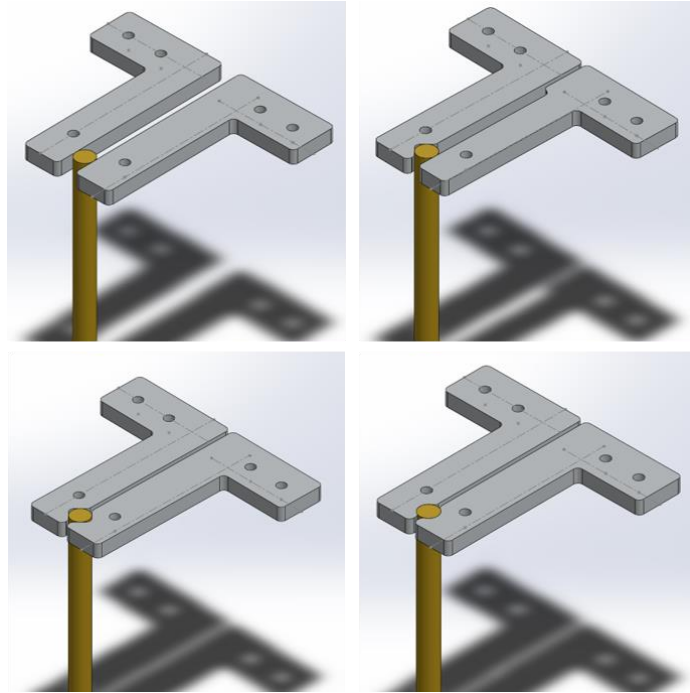


Figure 39: Cutting tool end effector geometry test models

The actuator chosen has a very unique mating geometry. The mating geometry required to be on the fingers is a rectangular block with two smaller rectangular pins on the top of it. In order to mount the flat fingers on this actuator, a block was developed that converted this proprietary mating geometry into a simple two pin design. It was machined out of 6061-T651 aluminum, and cutter compensation was used on all of the mating geometry, similar to the mating geometry of the mounting plate. A picture of this block can be seen below in Figure 40.

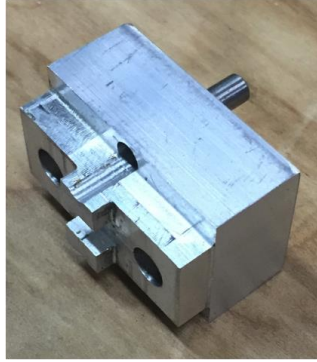


Figure 40: End effector test mating block

These fingers were designed to be made of 6061-T651 aluminum, similar to the mounting plate and mating block. They were CNC machined on the Haas VM2 in Washburn Shops. There were no major complications during this process. The four sets of machined fingers can be seen below in Figure 41.

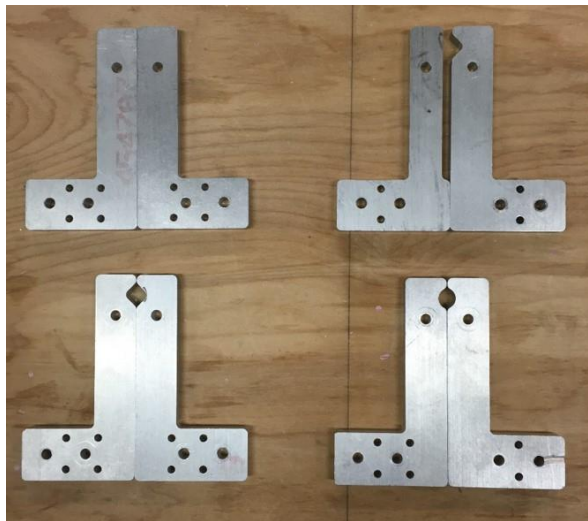


Figure 41: Cutting tool end effector geometry test fingers

All of these fingers were mounted to the actuator and tested in the work cell with cutting tools provided by GE. A tool holder was placed in a fixture that was clamped to a table within the work cell. Using manual controls, the project team attempted to insert and remove cutting tools from the tool holder. Insertion was the first task attempted. This was not expected to be easy due to the difficulty of perfectly aligning the cutting tool and tool holder. When they are not perfectly aligned, the system will be susceptible to jamming. The two pieces were aligned by eye, and insertion was attempted. Full insertion

could not be completed. As the tool was inserted into the tool holder, either the tool holder, fixture, or table would move to account for the misalignment.

A remote center of compliance is the common solution to this problem. But the purchase of one would represent a large portion of our budget. If an alternate solution could be developed, then this money could be used to purchase higher quality equipment for the remainder of the system.

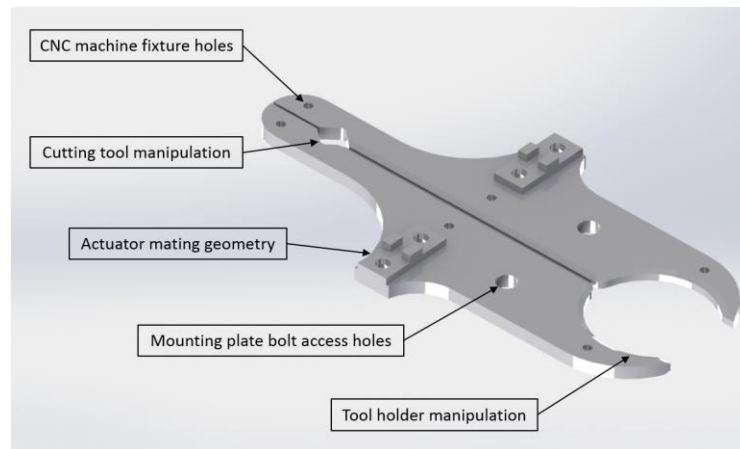
During the testing, the project team was able to develop a technique that would not require this purchase. A cutting tool was inserted about 1mm into the tool holder and then the end effector released it. This method of partial insertion aligned the cutting tool in the tool holder and ensured it would not fall to the ground when the end effector released it. The cutting tool would simply fall to the bottom of the tool holder. This method was tested for repeatability, and showed promising results. Therefore, the project team decided to forego purchasing a remote center of compliance and would move forward with this technique for insertion.

A series of tool handling tests to find an appropriate balance between compliance and control ability were conducted by the team. The team specifically tested the four proposed geometries shown in Figure 41 by inserting cutters of both diameters into the tool drawer test fixture shown in Figure 56 as well as the tolling assembly. In part due to the flexibility in implementation that this technique allows, the 4 contact point geometry was chosen to be the most effective. The end effector does not need to have compliance in order to successfully insert a cutting tool, which was determined by the geometry testing outlined above. This means that control of the tool can be prioritized allowing for better location repeatability of the cutting tool. With a properly designed groove, one geometry can manipulate both the ½” and ¾” cutting tools.

Cutting tool removal is another required task of this end effector. This task proved to be easier than insertion. All of the finger geometries were able to accomplish this task. Therefore, the four contact point geometry would be used for removal so that the end effector would only have one geometry responsible for cutting tool manipulation.

Upon the conclusion of testing, the final end effector geometry could begin to be developed. It was designed to effectively manipulate cutting tools and tool holders from the side. One end of the fingers would have the geometry required to manipulate tool

holders and the other end would have the geometry to manipulate cutting tools. From the testing, the double groove four contact point geometry would be used for the cutting tool end. On the tool holder end, the fingers would be properly chamfered to fit in the v-groove of the tool holder. A finger thickness of  $\frac{1}{4}$ " would most easily work with the necessary chamfers. The mating geometry for the actuator will be built directly into the fingers, meaning no mating block would be necessary. This helps better ensure assembly accuracy and reduces the number of components within the system. A CAD model of the first iteration can be seen below in Figure 42.



**Figure 42: End effector fingers, first iteration CAD model**

Before these fingers were produced, a prototype was produced in wood using the last cutter in Washburn shops. This machine provides the project team with a great method of quickly prototyping a design before producing in more suitable materials. Unfortunately, only 2D shapes can be produced, so the 2D geometry of the CAD model was imported. This meant that the mating geometry block used in the cutting tool end effector geometry test would have to be used, and two pinholes were included in the design. A picture of the wooden prototype can be seen below in Figure 43.



**Figure 43: End effector wooden prototype**

Some testing was done before producing the final fingers. They were mounted to the actuator using the mating blocks. The geometry fit both the cutting tools and the tool holder well. The only concern came when it grabbed a  $\frac{3}{4}$ " cutting tool, the fingers deflected laterally. This was assumed to be due to mechanical properties of the wood. Although it may not be a concern when this is produced with more robust materials, this something that the project team must look for when testing the final design. The air pressure supplied to the actuator can also be decreased to minimize this deflection. A picture of this issue can be seen below in Figure 44.



**Figure 44: Prototype finger lateral deflection**

The final iteration of the team's end effector was CNC machined using the Haas VM2 in Washburn Shops. 6061-T651 aluminum was chosen for this component due to its low cost and ease of machining. The stock material for this part was  $\frac{3}{4}$ " thick due to the

actuator mating geometry. Cutter compensation was used on all mating geometries to ensure they fit properly. They can be seen below in Figure 45.



Figure 45: End effector fingers, iteration 1

A number of issues were associated with the fingers produced. To begin, the fingers could not properly be bolted to the actuator without removing the dust cover on the bottom of the actuator (See Figure 33). This was taken into account in the design, but a machining error eliminated the clearance that was left for the dust cover. The dust cover is used for maintenance access to the linkage inside the actuator. This cover is not necessary, but definitely provides some protection to the inner mechanism of the actuator. This dust cover was removed, and the fingers could be mounted to the actuator.

Once the fingers were mounted on the actuator, a tooling assembly was placed in the fingers. The chamfers held it very rigidly, with no concern that the end effector would drop it accidentally. Unfortunately, interference was detected during this testing. A tool holder with a long enough tool could not fully rotate around the end of the robot. Clearance was given for the end of the robot, but not for the box that is mounted on the side of the end of the robot. When designing the end effector, the distance from the pick location of both the tool holder was made as short as possible in an effort to minimize deflection of the fingers when holding a tool holder. The same was done for the cutting tool geometry pick location on the other side of the end effector. The project team could move forward with these fingers, but would need to be careful of the joint 6 position of the robot.



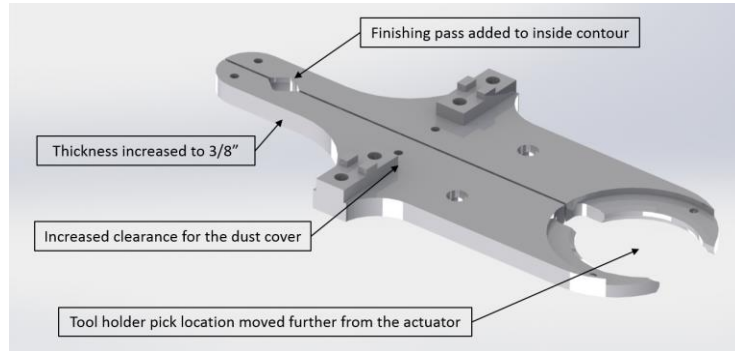
It was also realized that the end effector could not grab a tooling assembly off of a fixture that had tabs on it. There are slots on tool holders for tabs. Tabs are used to spin the tooling assembly when it has been placed in a spindle. In our project, tabs would be used in the disassembly and assembly of the tooling assembly. The fingers were brought back to the CNC machine, and an operation was written to remove material to provide clearance.

The largest issue with these fingers came when testing was done with holding cutting tools. When the end effector grabbed cutting tools, the cutting tools would still be able to wobble inside the fingers. It was not holding it firmly like the test fingers did. The edges of the finger geometry were lightly filed down in an attempt to repair it. Unfortunately, this was not effective. The cutting tool was still only being grabbed on two points within the grabbing geometry.

A couple theories were discussed in an effort to determine what happened. The flatness of the part could be the reason for this. If one finger is slightly straighter than the other one, the cutting tool would experience this wobble. There was a work holding issue during the facing operation of the fingers, which could have resulted in flatness issues. Another factor could have been the material removal patterns of the cutting tool as it was machining that specific geometry. On one of the fingers, the cutting tool was under full-engagement conditions, and on the other finger it experienced standard climb milling conditions. The climb milling conditions would lead to more tool deflection on that pass. This means that finger could have a side face not perfectly perpendicular to the top and bottom faces of the fingers. One final idea was that the feed rate on the contouring operation was too fast without a finishing pass. This would result in a terrible surface finish that could impact that way the fingers grabbed the cutting tool. Upon visual inspection, the surface finish on the profile of the fingers was relatively rough.

The fingers were redesigned to address these issues. To begin, the general thickness of the fingers was increased from  $\frac{1}{4}$ " to  $\frac{3}{8}$ ". This was the thickness of the test fingers and was done to improve the flatness of the final part. In order to maintain the geometry required to hold the tool holders, the area surrounding that geometry was reduced in thickness to  $\frac{1}{4}$ ". The location where tooling assemblies are held was pulled farther away from the actuator to eliminate the clearance issue found in the first iteration.

The clearance between the bottom of the actuator and the top of the fingers was increased to provide clearance for the dust cover. Lastly, a finishing operation was added to the machining process to improve the surface finish quality of the side face of the fingers. A picture of the CAD model and the machined fingers can be seen below in Figure 46 and Figure 47 respectfully.



**Figure 46: End effector fingers, iteration 2 CAD model**



**Figure 47: End effector fingers, final iteration**

This set of fingers was able to solve all of the issues associated with the first iteration. The dust cover could now fit below the actuator. The project team would not have to worry about a collision between tooling assemblies and the box on the side of the end of the robot. Most importantly, the end effector could now rigidly hold cutting tools. When holding both the cutting tools and the tool holder, there was minimal deflection

due to gravity or due to the pressure of the actuator. This design was deemed effective and the development of the end effector was concluded.

## Tool Cart and Dock

Tooling assemblies are transported around the production floor using tool carts. Tool carts are capable of carrying a large number of tooling assemblies. For this system, the operator will be expected to roll the tool cart into the work envelope of the robot. The robot will pick one of the tooling assemblies and begin to process it. The tooling assembly will be returned to the tool cart upon process completion.

Before developing this system, the design criteria were laid out. This system must provide the operator with a convenient method of providing worn tooling assemblies to the system. This system must provide repeatable tooling assembly pick and place locations. This all must be done in a fashion that does not put the operator or the tooling assemblies in danger.

The floor of the work cell is located ten inches off the ground. This would mean that if the tool cart were to be rolled into the work cell itself, a ramp would need to be built to allow the operator to do that. Unfortunately there is limited space on the production floor and the shorter that you make that ramp, the more force the operator must apply to roll the tool cart up the ramp. In order to analyze the feasibility of this design, a basic force analysis was performed to establish how long the ramp would need to be.

To begin, a free body diagram of the system was drawn. In order to simplify this analysis, the friction in the wheels of the tool cart was ignored, and the force applied by the operator was assumed to be constant in the direction of the ramp. This free body diagram can be seen below in

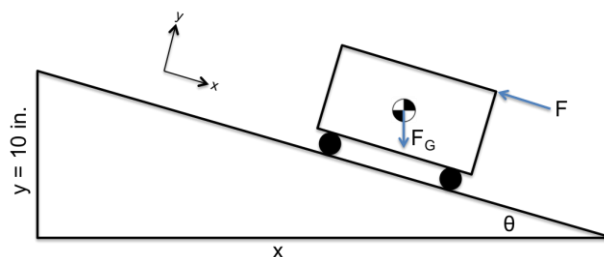


Figure 48: Tool cart ramp analysis, free body diagram

The weight of the tool cart is approximated at 170lbs. This approximation is based on a fifty pound tool cart holding twenty-four tooling assemblies, which each weigh about five pounds. The calculations were done given static conditions. With this information, the following equation can be stated based on Newton's first law of motion:

$$\begin{aligned}\sum F_x &= 0 \\ F - F_g * \sin(\theta) &= 0 \\ F &= F_g * \sin(\theta) \\ \sin(\theta) &= \frac{F}{F_g}\end{aligned}$$

Using the Pythagorean Theorem, the length of the ramp (hypotenuse of the triangle) can be calculated.

$$l = \sqrt{x^2 + y^2}$$

These equations were then substituted into the trigonometric definition of sine in order to develop an equation that relates the length of the ramp to the force applied by the operator.

$$\begin{aligned}\sin(\theta) &= \frac{y}{\sqrt{x^2 + y^2}} \\ \frac{F}{F_g} &= \frac{y}{\sqrt{x^2 + y^2}} \\ F &= \frac{F_g * y}{\sqrt{x^2 + y^2}} \\ F &= \frac{(170lbs.) * (10in.)}{\sqrt{x^2 + (10in.)^2}} \\ F &= \frac{1700}{\sqrt{x^2 + 100}}\end{aligned}$$

According to OSHA, the average worker is expected to be able to exert a minimum of 13lbs and a maximum of 57.5lbs of force. These limits, along with the curve of the equation derived above, are graphed in Figure 49.

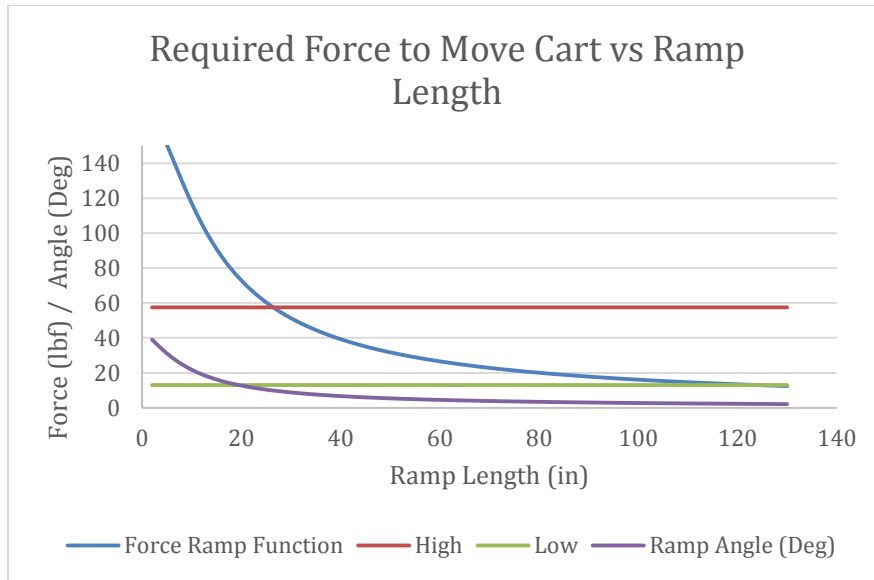


Figure 49: Tool cart ramp length vs. force graph

According to this graph, the minimum length is 28 inches and the maximum length is 124 inches. Given the mathematical assumptions that were stated at the beginning of this analysis, in reality the ramp would need to be closer to the 124 inches length. This would be extremely obtrusive to the work place, so an alternative to the ramp design is needed.

The project team began to consider the feasibility of keeping the tool cart outside of the work cell rather than elevating it and having it inside. The robot has a large enough envelope to reach outside of the cell, assuming one of the walls of the cell was removed. A light fence could be installed around the area where the cart would dock to ensure the process does not start while the operator is within the work envelope of the robot.



Figure 50: Picture of the tool cart docking area

One of the walls was removed from the cell, and the initial soft-stops established to protect the robot from crashing into the walls of the cell were edited accordingly. This solution eliminated the need to include a ramp in our final solution shown in Figure 50 above.

There are a wide variety of tool cart styles on the market. In order for the project team to identify which tool cart is most appropriate for the system, the important characteristics of a tool cart were identified. The tool capacity, tool alignment, top orientation, size, weight, and cost of the tool cart were the characteristics most important to this project. Tool capacity describes the number of tooling assemblies that a tool cart can hold. The operator should be able to process an acceptable amount of tooling assemblies at one time. The tool alignment describes how the tooling assemblies are held on the tool cart. A tool cart with straight alignment would be the easiest to program the robot to pick from. Sometimes, the tops of tool carts are angled to make it easier for operators to insert tooling assemblies into. Top orientation dictates whether the top is angled or flat. A flat top would make programming the robot slightly easier. The size of the tool cart is important because the work cell is spaced about two feet away from a wall, on the side where the tool cart would need to be docked. Weight is important to ensure that

the operator doesn't have a difficult time maneuvering the tool cart. Finally, cost is important because there is a limited budget for this project.

Research was done, and some of the common tool cart manufacturers were contacted. Using all of the data collected, a comparison chart was developed to determine which cart would best fit the needs of the system. This chart can be seen below in Figure 51.






Picture	Manufacturer	Product	Tool alignment	Top Orientation	Tool count	Max load (lbs)	Weight (lbs)	Width (in)	Length (in)	Height (in)	Cost
	Huot	ToolScoot 40 Taper	Straight	Flat	24	1000	79	18	35.25	35	\$469
	Huot	SuperScoot 40 Taper	Straight	Angled	45	1600	125	17.5	45.25	40	\$625
	Huot	SpeedyScoot 40 Taper	Staggered	Flat	24	1000	52	15	35.35	35	\$349
	Stanley Vidmar	VTT20040V/6	Straight	Flat	20		92.1	23	33	39.25	\$1,336
	Lista	Transporter Unit B220 (B220-A-40)	Straight	Flat	15		178.25	20	27	36.5	\$1,262

Figure 51: Tool cart comparison chart

Based on this information, the Huot SpeedyScoot was chosen. It held an acceptable amount of tooling assemblies, had a flat top orientation, fit between the work cell and the wall, and was priced within the budget. The staggered alignment may make it slightly more difficult to program the robot, since a simple grid algorithm cannot be used. But this was a trade-off that the team felt comfortable making.

Some modifications were made to the tool cart. Acrylic tabs were added to each of the tooling assembly pockets. These tabs would allow the tooling assemblies to only sit properly in one rotational orientation. This was done to ensure that the system knew exactly where the tab locations on the tooling assembly were when they were placed in a tool cart. This would be important when it came to the tool assembly system. Four different colors of acrylic were used to provide the operator with a clear differentiation

between the different tooling assemblies that would be processed by the system. A picture of the tool cart with the tab rings can be seen below in Figure 52.



Figure 52: Tool cart with tab rings

A docking system is necessary for our design. This dock would ensure that the pockets on the tool cart were in the same location each time the robot began to process tooling assemblies. The basic design of this system consisted of rails that the operator would roll the tool cart into. Many different design features were discussed before coming to the final solution. One of the more complicated ideas consisted of roller balls lifting the tool cart off of the floor when it was docked. This would be done to ensure that the wheels of the tool cart did not impede lateral movement if the tool cart was not perfectly aligned with the dock. A sketch of this idea can be seen below in Figure 53. This idea was considered too complicated for an issue that may not be a real problem. If this became an issue during testing, then it could be retrofitted to another docking solution.



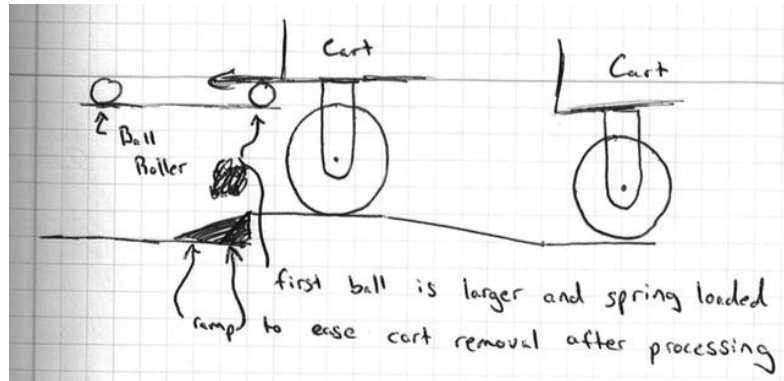


Figure 53: Roller ball tool cart dock idea

Another idea discussed was adding springs to the rails that would align the tool cart. This would better help ensure repeatable tooling assembly pick locations for the robot. At the same time, this could make it more difficult for the operator to roll the tool cart into. There is also a level of complexity inherent in this idea. This idea would be reconsidered if there were issues with the tool cart dock in testing.

This left the project team with a very rudimentary system for tool cart docking. 80/20 components would be used for the construction of the cart dock to make manufacturing even easier. Series 15 extrusions were chosen for added strength. A 3D CAD model of the system was drafted and sent to a vendor for fabrication. The CAD model can be seen below in Figure 54

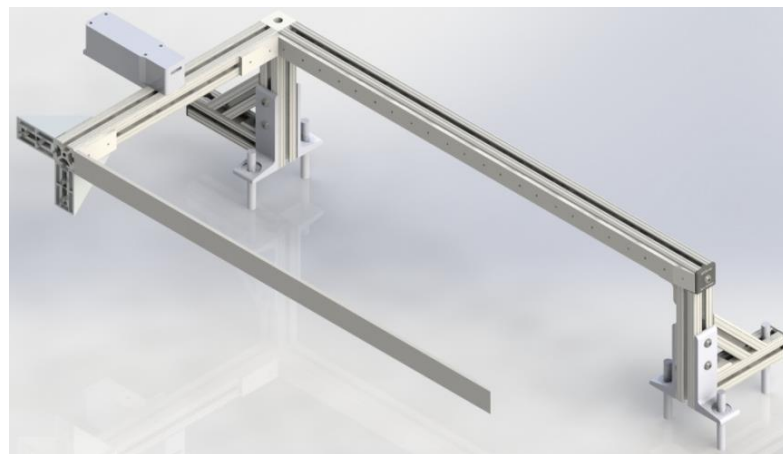


Figure 54: Tool cart dock CAD model

It was decided that rails were only needed toward the bottom of the tool cart. Rails toward the top would be better since it would be closer to the part of the tool cart that actually needed to have location repeatability. But, there would need to be a support

structure to ensure that the dock was rigid and robust at that height. So this was removed from the final design. Ultra-high molecular weight (UHMW) plastic slides were added to every contact point between the dock and the tool cart. This was done to reduce the friction between the tool cart and the rails as the operator docked the tool cart. The width of the dock was initially designed to match the nominal width of the tool cart with no additional clearance. A tight fit is required if the dock is to ensure location repeatability. The team allowed for the width of the as-build dock to be increased by up to 1” based upon how it was assembled if additional compliance was required. The team also expects the plastic slides to wear-in providing a fit that is tight but lacks interference. The entire system was bolted to the floor in two locations with a total of six floor anchors to ensure that it would not move during operation. Finally, a solenoid locking switch was added to the back of the dock to tell the system when the cart was properly docked and to lock the tool cart in place to prevent movement during operation. This required that the key for the switch be mounted to the tool cart.

The tooling assemblies will need to be processed from the front of the tooling cart to the back, given the design of the end effector. The project team decided to go with a side pickup strategy. This meant that there would need to be proper consideration for potential collisions. With the arrangement of the tool cart, the back tooling assemblies cannot be removed if there are tooling assemblies in front of them.

This also means that tooling assemblies cannot be returned directly to the pocket that they were originally pulled from. Otherwise that tooling assembly would be blocking access to other tooling assemblies that the system would need to process. In order to work around this issue, a tooling queue was added to the system. This queue consists of shelves containing pockets to store completed tooling assemblies. Tooling assemblies will be placed on these shelves as they are processed. Upon completion of the entire cycle, the Fanuc robot will return all of the tooling assemblies to the tool cart as a separate operation. It will place the tooling assemblies in the back row of the tool cart first and move towards the front in an effort to avoid collision issues.

The project team wanted to add a system that would identify which pockets of the tool cart are populated once the tool cart had been docked. This would prevent the system from wasting time processing pockets that don’t actually have tooling assemblies in

them. Two different designs were identified. The first design called for the installation of sensors in each pocket of the tool cart. The tool cart would communicate with the work cell through a wireless communication protocol, such as Bluetooth in order to not have to plug the cart into the work cell after docking. This would be expensive and would require a large amount of labor to install, but it used technologies that the project team had experience with. The second design called for the implementation of a vision system. A Cognex Insight smart camera was part of the long-term loan of the work cell by GE. This system would be inexpensive, not require as much physical labor, but the project team had no experience with vision systems.

The project team decided to learn how to use the Cognex Insight Explorer software and implement the vision system in order to add this feature to the system. Using some extra 80/20 components, the camera was mounted to an appropriate location above the tool cart dock.

The firmware on the camera was out-of-date, meaning that the project team would not have access to Cognex's Easybuilder software package. This software package is geared for new users who do not have much experience with vision systems. Since we were not looking to develop a sophisticated program, this software would work well. Normally there is a cost associated with firmware upgrades, but after explaining our project to Cognex, they donated the firmware upgrade to the project team.

Using the software, the Cognex camera was configured to recognize occupied and vacant pockets on the tool cart when the cart was docked. The program, or job, was set up using the built-in image processing tools included in the Easybuilder package. The specific tool used for our application detected the number of 'bright' pixels within a defined area of the image. An area was designated around each slot on the cart and a threshold was set that would trigger if a tool holder was present. When no tool holder was present the black insert on the cart would return few bright pixels; however when a holder was inserted the metallic finish and lighting would produce a significant change in bright pixels. The output of each tool task was then mapped to a discrete output to be passed to the PLC to provide feedback for tool cart population.

## Tooling Drawer

In order for the system to operate properly, it would need some method of taking in new cutting tools and disposing of worn cutting tools. Building off of the design of the previous project team, a drawer would be developed to accomplish this. In order to simplify the design, a single drawer would be designed that could handle both new and worn cutting tools. The tool cart that was chosen for this project holds twenty-four tooling assemblies. This drawer will be designed to hold enough tooling to support the assembly of these twenty-four tooling assemblies. A sketch of the drawer can be seen below in Figure 55.

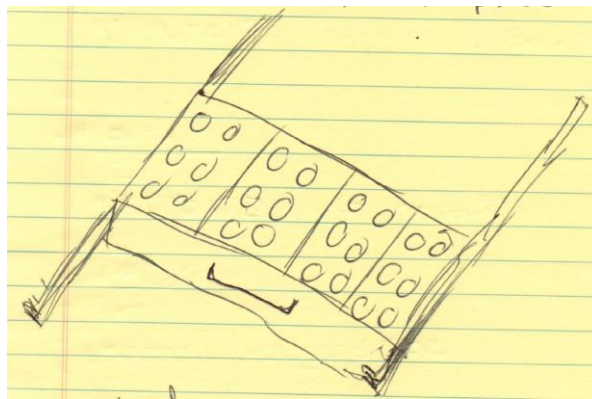


Figure 55: Tooling drawer sketch

This drawer must provide the operator with a safe method of loading new cutting tools into the work cell. This system must also provide the work cell with a safe place to deposit worn cutting tools as they are processed. The operator must have access to these worn cutting tools at the end of the cycle. And this must be done in a fashion that does not put the operator in danger.

Two designs were proposed in regards to the construction of the tooling drawer. The first design was mostly made of aluminum sheet metal. It would involve cutting, bending, and welding sheet metal to form the shape of the drawer. The other design involved an aluminum frame with acrylic sheets that formed the body of the drawer. Acrylic was chosen because it can easily be cut on the laser cutter in Washburn shops.

The sheet metal design is definitely more robust than the acrylic design. Acrylic is known to be a brittle material. This means that the acrylic plates could be susceptible to cracking over the life of the tooling drawer. At the same time, the project team has

limited experience working with the development of sheet metal components, and something like this would need to be sent to an outside vendor for fabrication. Acrylic can easily be cut here on campus. The use of acrylic also allows for the re-design of components if there was an error in the design. If an issue were discovered after fabrication, it would be more difficult for the project team to address it with the sheet metal design.

It was decided that the drawer would be constructed using the acrylic design. The pockets of the tooling drawer would be made from closed-cell foam. This would add compliance to the system, correcting for any minor misalignments in the robot pick and place locations. An inductance proximity sensor would be installed below each of the new cutting tool pockets, and LED's would be installed alongside the same pockets. Inductance proximity sensors would be effective here because the cutting tools are made of tungsten carbide, and because these sensors come in small packaging options. This would provide feedback to the operator, telling him or her that the cutting tool has been properly placed in the tooling drawer. The data collected from the proximity sensor could also be used to tell the system which pockets were populated with cutting tools. This would help improve the efficiency of the system.

Before the final design of the system was developed, a prototype was built to better understand the system that needed to be developed. A rudimentary system consisting of two acrylic plates separated by wood was built. The pockets were lined with pipe insulation to mimic the foam pockets of the final design. A picture of this prototype can be seen below in Figure 56.



**Figure 56: Tooling drawer prototype**

Given the electronics required of this system, the interior of the tooling drawer had to be carefully designed. Architectural 6061-T651 aluminum C-channel would be used for the frame. The acrylic plates would slide into the C-channel. Three different chambers would be needed within the inside of the tooling drawer. The top chamber would hold the foam and LED's. The top plate would consist of holes for the pockets and the LED's. Each tooling pocket will have a label engraved below it to assist the operator in loading the tooling drawer.

The second chamber would hold the proximity sensors. Through discussions with Automation Direct, the project team was able to finalize a donation of a certain proximity sensor. The only criteria was that the sensor needed to operate at 24V, have a small sensing distance, and have a slim profile in order to minimize the thickness of the tooling drawer. Automation Direct was able to provide us with sensors that met our requirements. A picture of the proximity sensor can be seen below in Figure 57.



**Figure 57: Inductance proximity sensor**

A thin sheet of acrylic would be used to separate the first and second chambers. This was done to prevent any coolant or oil from damaging the electronics within the tooling drawer. The sensing distance of the proximity sensor determined the thickness of this plate. The sensing distance of the proximity sensor provided to the project team was four millimeters. A guard plate thickness of 1/16" was chosen because it is less than four millimeters. A bench top test was done to ensure that a cutting tool could be detected through an acrylic plate of that thickness.

The second chamber of the tooling drawer held the proximity sensors. The thickness of this chamber would be equivalent to the height of the proximity sensors. The proximity sensors would be mounted to the plate forming the bottom of the second chamber. The sensors were mounted using the one locating geometry and a single M2 screw. In order to ensure that the threads would not be ruined if the screw were

accidentally over-tightened during assembly, threaded brass inserts were pressed into this acrylic plate.

The third and final chamber would hold all of the wiring for the tooling drawer. A good amount of space would be needed for wiring required of the twenty-four LED's and twenty-four proximity sensors. A DB-25 sub connector and Anderson PowerPole ports would be included in this chamber as well. These ports would provide an easy way manage communication and power between the system and the tooling drawer. Since all of the wiring would be done in this chamber, all of the plates above the wiring chamber needed to include holes for wire passage.

Given the space requirements of each of the chambers, 3-inch wide C-channel would be needed. Each of the chambers of the tooling drawer would be separated by standoffs. All of the standoffs would be different lengths depending on the needs of each chamber. The standoff that supports the foam chamber was designed to be shorter than the foam held in that chamber. This was to provide some compliance to the height of all of the contents of the drawer in an effort to ensure that the system could be assembled. A 3D CAD model of the system was developed to help manage the design of this system. This model can be seen in Figure 58 and Figure 59.

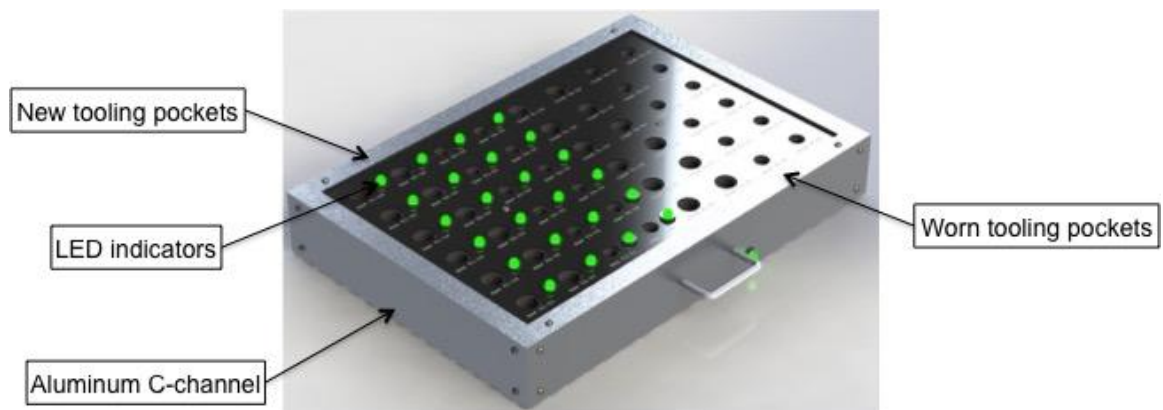


Figure 58: Tooling drawer CAD model

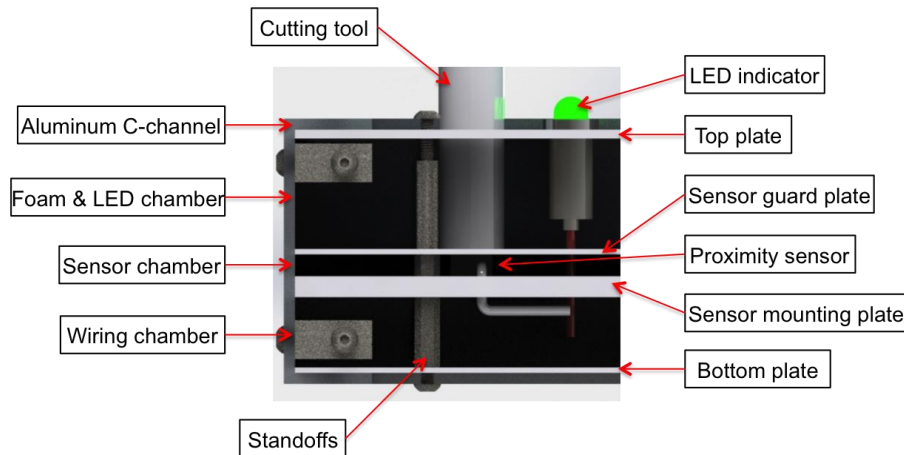
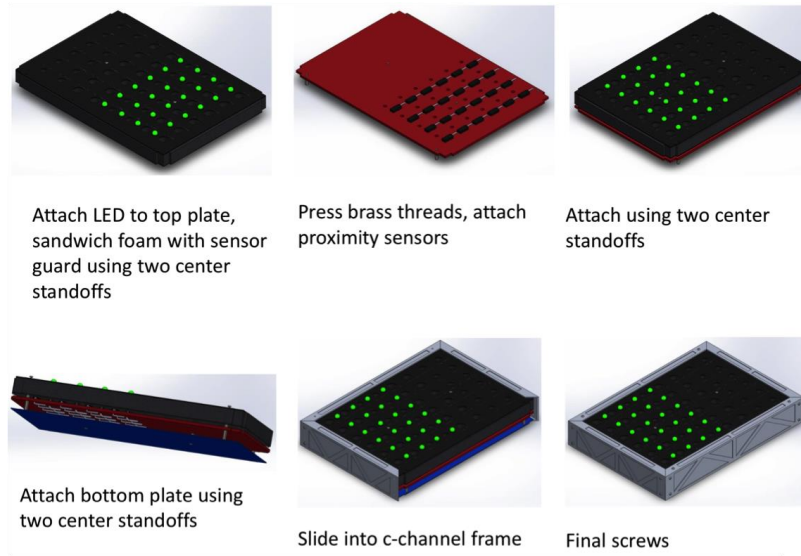


Figure 59: Interior tooling drawer CAD model

Similar to the tool cart dock, a solenoid-locking switch is to be mounted to the drawer support system. This is to prevent movement during operation and to provide feedback to the system. The drawer support system will be made out of 80/20 components.

Before the design of the drawer could be finalized, the project team needed to ensure that the system could be assembled. The assembly process would be as follows: the foam would be sandwiched between the sensor guard plate and the top plate using the standoffs located in the center of the assembly. Separately, the threaded inserts would be pressed into the sensor mounting plate and the proximity sensors would be mounted. These two components would then be assembled together using all six standoff locations. At this point, all of the wiring would be done for the system. After this, the bottom plate would be attached using the standoffs, and the entire system would be slid into the C-channel frame. Lastly, the fourth side of the frame would be attached using the corner brackets. This process was summed up in the diagram shown below in Figure 60.





**Figure 60: Drawer assembly process**

All of the materials needed for this design were ordered. Once the acrylic was obtained, the four plates needed (top plate, sensor guard plate, sensor mounting plate, and bottom plate) were cut on the laser cutter. In order to ensure the brass threaded inserts would not crack the acrylic when it was pressed into the acrylic, a quick test was conducted. In this test, twelve holes of varying diameters were cut into a 1/4” thick piece of acrylic. The threaded brass insert was pressed into each of the holes. No cracking occurred, but some of the diameters crushed the threaded insert significantly. The 0.158” diameter hole was chosen because it was easy to press, difficult to remove, and did not significantly crush the threaded insert. A picture of the test can be seen below in Figure 61.



**Figure 61: Threaded insert press-fit test**

The tooling drawer was successfully assembled according to the assembly plan that was previously mentioned. The rails were mounted onto the drawer, and the support system was fabricated. Pictures of the assembled system can be seen below in Figure 62 and Figure 63.



Figure 62: Assembled tooling drawer, top view

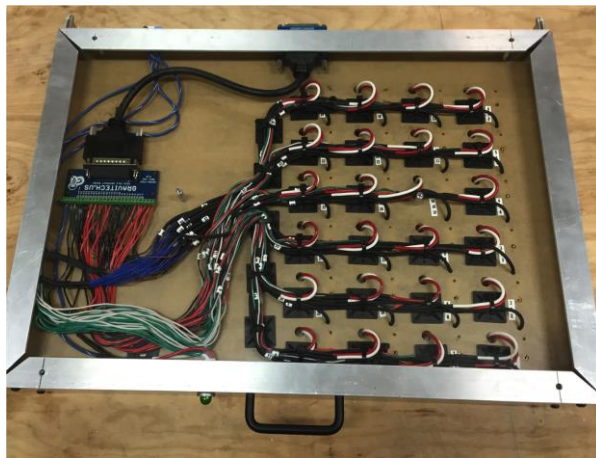


Figure 63: Assembled tooling drawer, bottom view

### Tool Assembly System

The tool assembly system is designed to receive a worn tooling assembly, delivered by the robot, and perform the steps required to output a finished tooling assembly. In order to complete this task there are a number of criteria this system needed to meet. First, the fixture was required to reliably and consistently receive a tool holder due to the amount of precision needed for pick and place insertion. The system needed the ability to rotate the tool holder nut continuously in both directions and apply a minimum of 75 ft-lbs of torque. The axial movement of the nut needed to be accounted for due to the motion of the nut during rotation as well as the different nut locations depending on holder gauge length. The system needed to incorporate a mechanism to control and accurately measure tool length within the  $\pm 0.025$  in specification outlined by

GE. And perhaps most importantly the system could not damage the tool holder in any way during processing.

The design component investigated by the project team was the mechanism responsible for rotating the tool holder. The project team understood that this component would act as the base of the fixture responsible for housing each individual tool holder during the assembly process. The previous project team had acquired an industrial rotary indexing table to use for the rotation of the tool holder. This particular unit produced by Camco was well suited for the application due to its large gear-down motor and rotary platform. The large gear reduction worm gear transmission paired with the powerful motor produced a controlled rotational speed with ample torque to disassemble and assemble tool holders. The housing and platform featured a hollow center disc rotating within a fixed outer casing. The indexing motion of the table was divided into 45 degree increments for every full revolution of the worm gear shaft of the table.

The configuration of the rotary table, with the center plate rotating within the housing, yielded an alternative method for tool holder assembly. Conventional manual methods required fixing the base or body of each tool holder then rotating the nut about the stationary body. The open rotating center plate allowed the project team to design around a different approach that involved fixing the tool holder nut stationary and rotating the body relative to the nut. The design for implementing this method includes a fixture that can mate with the tapered geometry of the tool holder as well as preventing the holder from rotating similar to a manual tool tightening fixture. This component was designed with an eight degree tapered bore that mated up with the CAT40 taper and two opposing alignment tabs that prevented the holder from rotating in the bore. The mating geometry of this plate was important because it directly controlled the position of each tool holder placed in the fixture affecting the insertion point of the cutting tool.

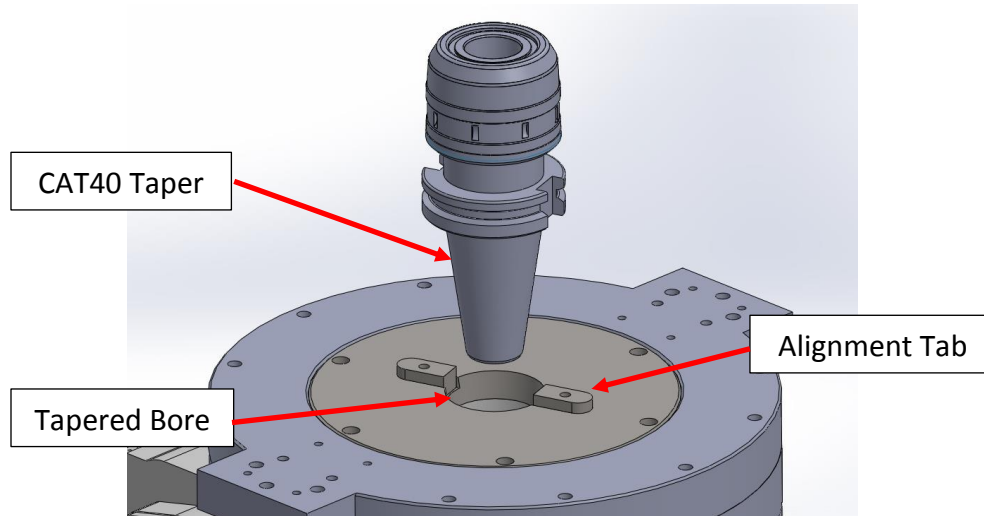


Figure 64: Diagram of tool holder fixture plate

With the tool holder located and seated into the center fixture plate the next component design focused on fixing the tool holder nut during rotation. This mechanism need to fulfill a number of requirements outlined by the identified design criteria including the nut locking and vertical movement. Beginning with the task of locking the nut in place, two different methods were explored. The first involved the uses of friction on the nut applied by two opposing contoured pads. The reasoning behind this design was by designing oversized pads this would eliminate the need for specialized setup to support different gauge length tool holders. The pads were driven up against the surface of the tool holder nut using pneumatic cylinders firing from opposite sides. The use of pneumatic cylinders meant the clamping force applied by the friction pads could be adjusted via a regulator. The surface of the pads were covered with a compliant friction material that when placed under pressure would conform to the shape of the opposing surface maximizing direct surface contact.

The second method explored for locking the holder nut used a pair of locking dogs designed to engage with the machined notches located on the side of the tool holder nut. The engagement of the dogs creates a mechanical connection that holds the nut stationary during rotation. The dog pins themselves were designed as a slip fit into the notches to prevent any binding that may occur from part interference. The dogs, like the pads, were positioned on opposite sides of the tool holder each driven by a pneumatic piston. The opposing pistons ensured that the tool holder was locked in an upright

position being supported on both sides. This upright orientation was important in maintaining insertion location and alignment of the collet bore during cutting tool removal and insertion. A regulator would act as a spring adjustment to provide the minimum amount of force required to lock and retract the dogs during operation.

Both of the methods were tested for effectiveness and repeatability using prototypes and the same dual piston setup. The friction pad method was tested by fabricating the contoured blocks out of wood and applying the friction material to both sides before fitting them to the pistons. The material used on the surface of the blocks was a high density foam measuring at an eighth of an inch thick coated with a tacky rubber like coating. Initial testing showed the pads were able to grip the nut and rotate both to loosen and tighten the holder with the regulator passing 30 psi of pressure to the pistons. However, after further cycle testing the nut began to slip from in between the pads requiring the pressure to be adjusted to as high as 80 psi. After, 15 cycles the friction material became ineffective due to the deterioration of the foam.

The dog pin method was tested using more robust materials as the interlocking of the geometry put a larger load on a smaller band of material. The dog pin consisted of a single square block of 6061 aluminum with a tapped hole at one end and a curved extrusion, which matched the contour of the notches of the nut, on the other. The shape of the pin on the dog meant that the dogs would need to be aligned with the height of notches on the nut before attempting to interlock the two. During testing the dogs would engage and lock into the notches with the regulator set to as little as 20 psi; however after the nut was tightened would require at least 65 psi to retract. This was caused by the binding of the dog pins in the slots after several rotations. Upon investigation, the project team discovered this was caused by the deflection of the dog and piston due to the shear applied to the dogs during rotation. This issue was addressed by adding side support to the dog blocks to prevent deflection. The final configuration can be seen below in Figure 65.

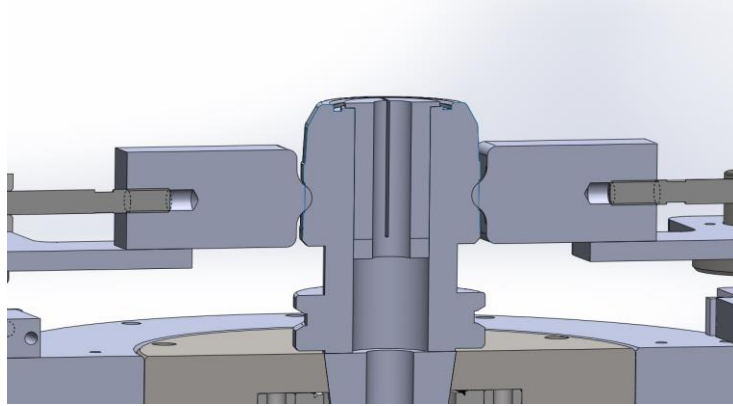


Figure 65: Cutaway view of nut locking dogs

After selecting a method to lock the tool holder nut in place, the design moved to address the vertical movement of the locking mechanism. Vertical movement of this mechanism was necessary to compensate for the movement of the nut during rotation and allow support for different tool holder gauge lengths. After testing the pin locking mechanism the group explored linear motion solutions in order to add the vertical motion to dog pins. The purpose of the linear motion was to fulfill two requirements: active control to align the dogs for each holder and allow passive control during rotation. Designs including both mechanical and pneumatic driving systems were explored but no single component could meet both requirements. Pneumatic slides lacked the control needed to move the dogs to a precise location while motor linear actuators cannot move passively.

The team decided to develop a mechanism that combined passive linear motion with the control of motion control of a linear actuator. Evaluating the two tool holder gauge lengths included in the project scope resulted in a required motion range of 1.5 inches. The design needed to include passive motion and provide rigid support to the nut locking dogs while rotating the tool holder. A number of linear slide systems were researched including slide rails and extruded bar rails. Given the load and the short motion required the team selected the Drylin Igus linear bearing system due to dry bearings that can handle light transverse loads while being relatively service free. The Drylin system also offered a number of different parts including different sized rods and rod anchors to meet our needs. The final design included two 12mm slide rods affixed to the platform of the rotary table spaced five inches apart. The sliding carriage holding the

piston and dog pins consisted of a plate with two slide bearings used to slide the 12mm slide rods shown in Figure 66.

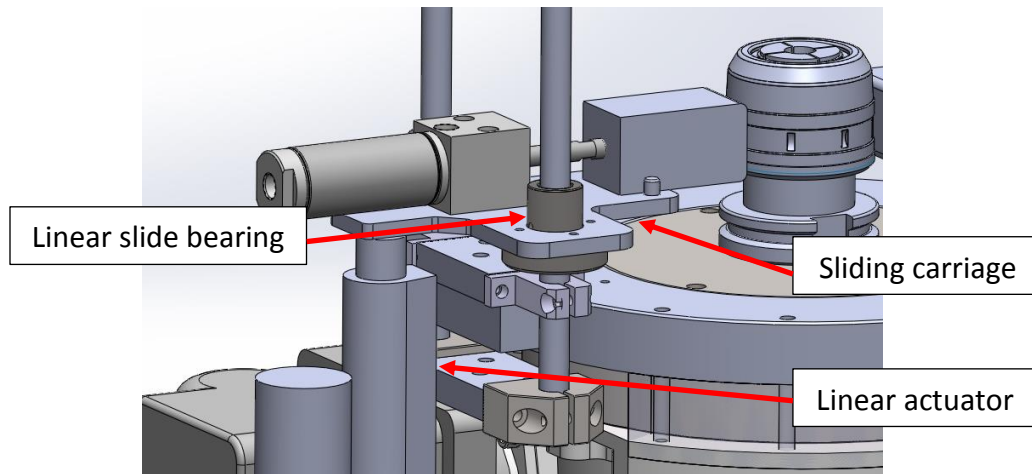


Figure 66: Sliding assembly with height control

The height of the dog pins are controlled using a small linear actuator that upon extension would support the slide carriage moving it upward on the slide rods. The specific linear actuator used was a Feedback Actuator from Firgelli Automation which includes an internal potentiometer to track stroke location. This linear actuator paired with a feedback motor controller would allow the carriage to be moved to precise height along the 2 inch travel of the actuator. However, since the actuator merely supports the carriage from underneath passively rather being fixed, passive motion can be achieved by retracting the actuators once the nut has been locked by the dogs.

The final task the assembly station was responsible for was the setting of tool height or tool extension. The process of setting the tool height is divided into two aspects: height control and height measurement. The height control is responsible for the movement of each cutting tool, raising or lowering it until the correct height is reached. Height measurement is the system that is able to accurately measure the tool height in order to determine the difference from the target height. The only criteria dictating the design of the height setting mechanism was the  $\pm 0.025$  inches outlined by the scope. The team first focused on height control developing two different methods. The first method utilized the robot end effector for height control by grasping the cutting tool, while loose in the tool holder, and moving axially to raise or lower it. The robot, according to the listed specifications, was able to operate within the tolerance limits of the height setting

given both accuracy and repeatability factors. During testing however, the same issues encountered with tool insertion occurred again as any misalignment between the tool and the end effector would result in binding.

The second method for height control took a different approach to height control by supporting the cutting tool from the bottom. The team developed this solution by using the specific configuration of the tool holders used by GE. The thru coolant pull studs affixed at the end of the taper includes a port, approximately 0.25 inch in diameter, designed to direct the flow of coolant. This port leads into the hollow body of the tool holder which aligns with the collet bore where the cutting tool is inserted. The mechanism uses this access by driving a 0.125 inch diameter pin up through the pull stud and into the body where it can support the bottom of the cutting tool.

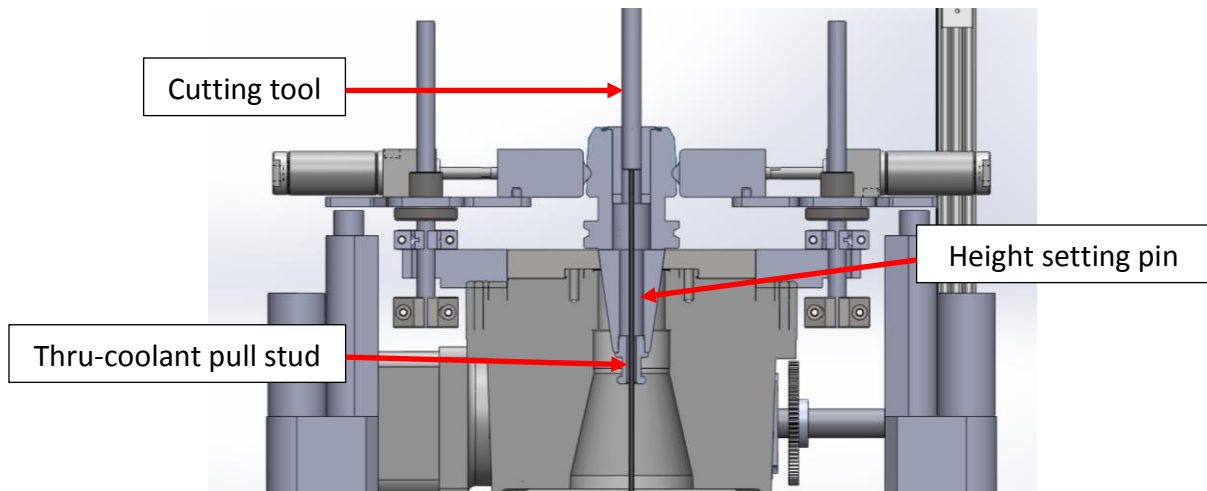


Figure 67: Cutaway view of height setting pin

At this point it was understood that the control of the support pin directly corresponded to the accuracy of the tool height. Linear actuator systems were sourced as they provided both the accuracy and control needed to fulfill the height tolerance. However, it became difficult to find a component that could maintain such high accuracy over the necessary 8 inch stroke required to drive the pin from the pull stud to the end of the collet. The unit produced by Tolomatic, known as the Smart ICR, was able to meet both requirements due to its custom construction and onboard controller with precision encoder used to track position. This specific component was able to perform with motion accuracy within 0.002 inches and a repeatability of 0.001 inches over a 12 inch stroke, based upon testing



conducted using the included diagnostics suite, well within the desired tolerance. The project team was able to obtain a demo unit to perform capability testing for this specific application. The actuator itself was designed to be mounted underneath the rotary table, and with the help of guide bushings, drive the pin directly from the end of the actuator.

The last component required for setting the correct tool height was height measurement. Several methods were researched by the project team including the use of mechanical switches, vision system, and optical trigger switches. The mechanical switch involved mounting a physical limit switch at a known height and driving the tool up until the switch was triggered. Concerns regarding the accuracy and repeatable performance of a mechanical switch swayed the team from pursuing this solution. The team also considered incorporated the use of a second vision system such as a Cognex machine vision camera to track the profile of the cutting tool and measure tool extension. The image processing of the vision system could theoretically determine, in real time, the length of the tool by identifying the cutting tool profile and collet surface. This proved to be difficult as the small resolution of the vision system could not reliably locate the tip of each cutting tool in the image therefore affecting measurement values.

The design for height measurement executed by the project team integrated the use of an optical break sensor in the form of a laser. The laser would be mounted to a fixed location on the tool assembly system and the beam would be aimed across the center of the rotary table fixture. The purpose of the laser was to act a switch that would be triggered when an object, in this case the cutting tool, broke the beam between the emitter and the receiver. For this application, the choice of a laser over an ordinary optical break sensor was chosen due to the fine column of light generated by a laser as well as the power needed to bridge a large gap. The specific laser sensor used in the system was sourced from Keyence. This unit was capable of achieving 0.001 inch trigger accuracy over a sensing distance of 15 inches allowing a great deal of flexibility in fixture placement while maintaining performance. The purpose of the fixed laser was to be used as a locating tool to determine a known tool height before moving to a target. The cutting tool would be raised until the laser was triggered; then with the current height known, moved to the target height using the control from the linear actuator.

## **Control System**

The team developed numerous mechanical systems and solutions in order to overcome the hurdles presented by the tool changing challenge. At an early stage the team began to identify each sub-system and independent action that would together comprise the final solution. It became apparent that significant integration would be required between these sub-systems in order to intelligently and accurately complete the project.

General Electric charged the team to develop an industrial system that autonomously performed the tool changing operation. The team took many steps to develop an industrial grade system mechanically and as a result the team wanted to ensure that the control system was also of industrial grade and reliability. With this in mind the team chose to pursue a control solution that centered on Programmable Ladder Logic Controllers (PLC's) as opposed to more common and sometimes flexible microcontrollers that are often leveraged within the field of developmental robotics.

This decision to fully embody General Electric's desire to develop an industrial and hardened solution played into many of the decisions that occurred when examining different parts of the control system. Every decision was made with this directive in mind, from the selection of hardware components to the manner in which cables were terminated, to the wiring and color code standards that were established to ensure constancy throughout the system.

## **Communication**

The designed solution requires the control system to integrate into each individual sub system including the tool cart and vision system, the tool assembly system, the tooling drawer, and the robot itself. There is no single communication protocol that each of these systems support or can channel their control needs through. In the final implementation of the system a mix of TCP/IP, Modbus TCP/IP, and remote I/O devices were used to fulfill the needs of the system.

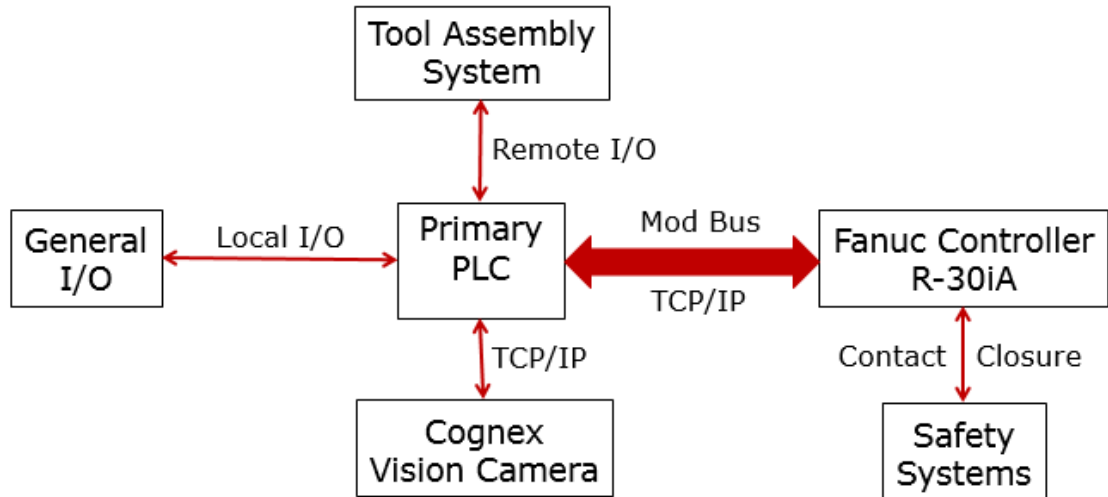


Figure 68: Work Cell Communication Interfaces

Figure 68 above, provides insight into how each subsystem that is part of the complete solution communicates with one another. It can be seen that the PLC is at the center on the diagram acting as the “master” controller within the system.

### The Existing Solution

As provided, the work cell was equipped with an Allen & Bradley Micrologix 1500 PLC controller which interfaced with the FANUC robot controller using DeviceNet and the Cognex high speed camera using raw TCP/IP. The PLC was programmed to support a grinding and polishing task which was what the work cell was originally built to accomplish but no supporting documentation was provided to the team.

Upon further investigation the team was unable to locate support documentation covering the PLC programming or electrical schematics for the cell. The team even reached out to ATC – the original integrator that designed and built the cell for GE Aviation before it was given to WPI on long term loan. ATC was unable to produce any documentation or schematics for the cell which they had built. The team continued to work through significant hurdles as they attempted to dive into the existing control system from password protected programs, old firmware versions, and expensive licensing that the team did not have.

## Allen & Bradley

The Allen & Bradley PLC was equipped with 3 additional local I/O modules including a Device Net scanner card and two analog output modules. In addition to the three additional local modules there were two an extended I/O modules, one input and one output respectively.

The software to read and program the Allen & Bradley is called RS Logix 500 and was not provided to the team. After the team launched numerous solicitations to Allen & Bradley they were redirected to a local distributor who was able to provide the team with a trial license for the software. Unfortunately even though the team was able to eventually acquire the software and start to explore the programming of the MicroLogix 1500 they were quickly faced with more hurdles. ATC has used no comments, “labels” or anything that resembled any internal documentation in the programming leading to ladder logic programming such as, “Register 5C8 = JumpTo Line 302”. What controls register 5C8 or what is on line 302 had to be manually checked and documented by the team as they started to explore the programming. Facing the required use of software that the team did not have a license to and the severe lack of documentation in addition to communication challenges presented by the use of DeviceNet (which will be discussed below) the team decided to seek an alternative solution.

The Allen & Brady as configured simply passed the state of the available I/O over the DeviceNet bus. At that, only half of this I/O was operational; the robot could see the state of the PLC’s inputs but the robot was unable to toggle any of the outputs. Additionally the PLC’s programming was a “black box” and, as configured, integral to the robot’s operation. Between the PLC’s heartbeat signal and a IMSTP flag controlled by the PLC, basically a software based emergency stop, the team became very concerned over leaving the Allen & Bradley in place, hoping it just doesn’t break.

This became an unacceptable option for the team and alternative PLC controllers were reviewed to replace the Allen & Bradley. The team worked closely with Automation Direct and replaced the MicroLogix 1500 with an Automation Direct T1H Stackable PLC.

## Automation Direct T1H PLC

The team reached out to Automation Direct soliciting advice when selecting the appropriate PLC for our desired application. Upon reviewing the projects needs which included Ethernet control, Modbus, an expandable interface, remote I/O, a mix of discrete I/O and analog I/O and finally the ability to read an encoder, often referred to as a high speed counter in the industrial automation industry, the team settled on the Automation Direct Do-more T1H stackable PLC.

The T1H is both cost effective and provides the team with all of its desired functionality including the ability to integrate a high speed counter. The T1H had its full documentation and programming software suite available online which was a completely different experience than the weeks of trouble the team went through to simply obtain a trial software license key for the Allen & Bradley software.

With a CPU unit that was capable of storing 192k words and had an Ethernet, USB, and RS232 interface available natively along with a wide variety of hot swappable modules available for the team to select from, it became the perfect platform for the team to develop on knowing that as the project expanded the selected control platform could expand along with it.

One unexpected side effect of choosing the Do-more T1H PLC was the ease of set-up and configuration. The team simply snapped the modules together both on the local I/O backplane and the remote I/O backplane utilizing the Ethernet slave. The T1H booted right up, automatically detecting the connected modules, including those that were available over the remote Ethernet I/O. The Do-more designer software that was used to both program and configure the T1H was both intuitive and well documented. It included an extensive amount of inline help in addition to substantial dedicated documentation covering the system.

The local I/O modules that were housed in the work cell control cabinet are as follows:

Module	Part Number	Type
1	T1K-01AC	Power Supply
2	T1H-DME	CPU w/ Ethernet
3	T1K-08ND3	8 In
4	T1K-08TRS	8 out Relay ISO
	T1K-10CBL-1	1m Local Jump Cable
5	T1K-16ND3	16 In
6	T1K-16ND3	16 In
7	T1K-16TD2-1	16 Out +24VDC

This “local” I/O was chosen to primarily fulfill the needs of signals that were entering the control cabinet. It is the teams full intention to leverage the remote I/O capability of the T1H with a remote Ethernet I/O bus which will be described further when the controls for the tool assembly system are discussed below.

This local I/O focused around the discrete I/O required for the tooling drawer, safety systems, operational indicators such as status lights and stack lights, and finally provided a small amount of additional I/O to be used if additional I/O requirements were identified during the final integration stages.

### DeviceNet & Modbus

The work cell was provided with DeviceNet as the provided communications protocol between the Allen & Bradley and the robot controller. DeviceNet is an antiquated protocol that although is still fairly prevalent today in existing installations is rarely used in any new installations. The team decided to move away from DeviceNet due to its lack of native compatibility with most modern PLC’s and the requirement of a special DeviceNet “scanner card” to program or manipulate the DeviceNet bus. The team looked into purchasing a DeviceNet scanner card for a PC to use such that the team could manipulate the bus and received quotes in excess of \$3,000.

The team looked for a more readily available and easier to interface with protocol and quickly found Modbus TCP/IP. Modbus is an open source serial based protocol that

can be carried via standard 4 wire copper cable over Ethernet using TCP/IP. Modbus is natively supported by the PLC that the team decided to replace the Allen & Bradley with and can be monitored by a standard PC. It quickly became the communication protocol of choice as the team looked for something that could be utilized by the robot controller, the PLC, and other systems that might be integrated in the future.

### **Fanuc Robot Controller**

The 6 axis Fanuc robot is driven by a standalone controller provided by Fanuc. The R30ia is the full size open air robot controller that provides the processing power and subsequent motor driver commands that actually allow the robot to be manipulated. The controller as configured, has limited I/O and it meant to control the robot alone with few if any ties to external systems. At this time the team uses the robot I/O for the sole purpose of the actuation of the end of arm tooling.

Although the robot controller has a limited amount of locally available I/O the controller is currently licensed to run both Modbus TCP/IP and DeviceNet. Modbus TCP/IP and DeviceNet are both communication protocols that are available for use to interface with the controller and allows the controller to access remote I/O devices such as a PLC.

It is worth mentioning that Fanuc has an extensive package of add-ons available that provide the robot controller with additional I/O and communications functionality that allows the robot controller to act in a manner that more closely resembles a primary controller but the robot the team has at its disposal is not equipped with these options.

### **Tooling Drawer**

The team faced a unique controls challenge with the tooling drawer as they wanted to ensure that they were able to detect how many new tools were actually loaded into the work cell for use by the system. Due to the fact that the system was designed to process up to 24 tools at one this meant that whatever system was developed had to be replicated 24 times. The team discussed also monitoring the worn tooling but decide it

did not provide sufficient value to the project to warrant the additional sensing capability as well as I/O on the PLC.

The team decided to use a set of Automation Direct APS4-12S-E2-D proximity sensors, featuring a rectangular top sensing area with a 4mm sensing distance for use in the bottom of the tooling drawer. This proximity sensor is a PNP or sourcing device meaning that its signal, when tripped, is a positive voltage. This allowed the team to solve another problem they faced in an elegant manner.

The team desired to provide an operator who might be loading tools into the tooling drawer with a visual indicator that the tool was properly loaded and detected by the system. At first the team contemplated using the PLC I/O to trigger a LED that would be matched with every tool slot. Although technically simple this presented the team with the need to utilize 48 I/O lines for a system that was relatively simple and straightforward, and a small component of the overall system. I/O was also generally a premium throughout the system design due to the limitations imposed on the team by the Allen & Bradley PLC controller. It was determined that by utilizing a 24VDC LED in line with each proximity sensor's signal line the team could provide the desired visual indication to the operator without taxing the PLC as seen in Figure 69. This unfortunately would allow for a situation where the operator might receive a false positive regarding the tool detection if something was wrong with the PLC. In such a case the operator would still be instructed by the system in the form of the LED indicator that the tool was detected, but the PLC might not actually be receiving and/or processing the input signal. This was determined to be an acceptable risk by the team as the correct and full insertion of the tool, such that it was detected by the proximity sensor, was more of the primary concern of the team than indicating if the PLC was functioning appropriately.



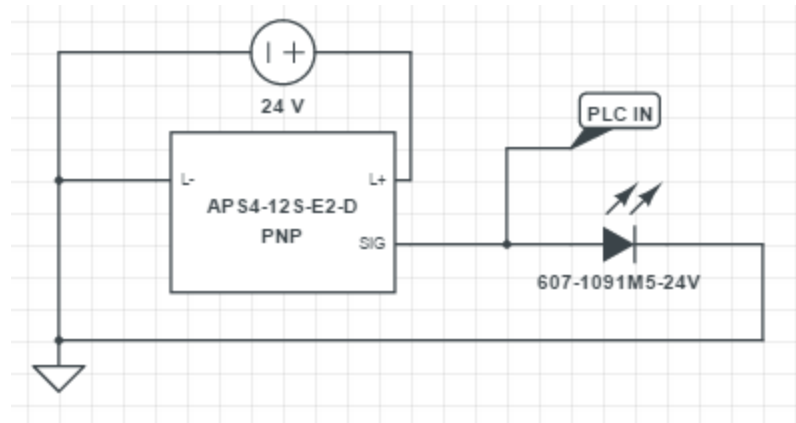


Figure 69: Tool Drawer LED Indicator Light Wiring Diagram

### Tool Assembly System Control

The tool assembly system became the home of numerous sub systems and required the integration of an extensive controls package to ensure that all devices on the tool assembly system could function appropriately. The team went through numerous design iterations with the tool assembly system, but there was a constant desire to keep this a relatively self-contained system.

As originally configured the cell housed all logic control in the control cabinet mounted atop the robot controller exterior to the work. This meant that all of the data and I/O lines were routed back to that cabinet from various locations within the cell. Although centralizing the processing for the cell simplified service this meant that a substantial amount of data would have to leave the tool assembly system to trigger other devices that were already on the tool assembly system. The team felt that this was unnecessarily complicated and wanted to centralize the necessary I/O and processing on the tool assembly system itself.

At first the team perused the idea of using an Arduino microcontroller to independently control the tool assembly system. This would allow the tool assembly system to receive simple “go” commands over a single digital input line or even possibly communicate with the main robot controller over serial but reduced the overall need for a substantial amount of I/O being sent off the tool assembly system. This also helped solve some of the issue presented by the limited I/O availability all together. This was a

concession to the team's goal of implementing an industrial solution end to end, but one the team felt was necessary for a successful implementation.

Once the team had officially decided to move away from the Allen & Bradley PLC in favor of the Automation Direct Do-more T1H series of controllers they were able to leverage the feature set of the T1H series in order to establish a remote I/O bank that was communicated with via Ethernet. This was a game changing development that allowed the tool assembly system to be fully controlled by the PLC while at the same time keeping all the necessary I/O lines local to the tool assembly system.

The tool assembly system is equipped with the following Automation Direct T1H PLC modules.

Module	Part Number	Type
1	T1K-01AC	Power Supply
2	T1H-EBC100	Ethernet Slave
3	T1H-CTRIO	High Speed Counter
4	T1F-08DA-2	8Ch Analog Output
5	T1K-08TRS	8 Output ISO Relay
6	T1K-16TR	16 Output Relay

The modules on the assembly station worked together to provide all of the local I/O required by the systems present. The high speed counter was used in conjunction with the encoder used to monitor table rotation, while the analog output module provides the control voltage for the Firgelli linear actuators used to set the height of the chuck dogs. The combination of the ISO relays and the general use 16 out relays are used to send control signals to the other systems on the assembly station such as the Tolomatic, the solenoid, the motor controller, and power the indicator lights on the assembly station.

### **Tool Height Setting**

Tool height setting was accomplished through the use of two systems, the use of a Tolomatic ICR SmartActuator and a Keyence laser system. The Tolomatic SmartAcuator was chosen for its on board control system and high precision that allowed for it to run independently of any outside control system.

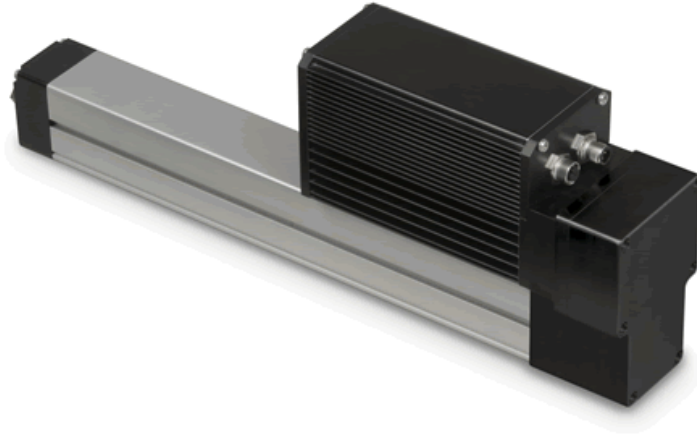


Figure 70: Tolomatic Smart ICR RP

The Tolomatic has eight digital inputs and two digital outputs that can be programmed in combination with internal software, allowing the team to offload the linear actuator drive control to its internal controller and simply command the linear actuator to the desired position via its available communication protocols. The Tolomatic supports CAN, serial, and direct I/O control. At this time the team has chosen to utilize the integrated I/O of the Tolomatic to receive a signal from the PLC indicating when it should start its programmed operation and what tool type it should be running the operation for.

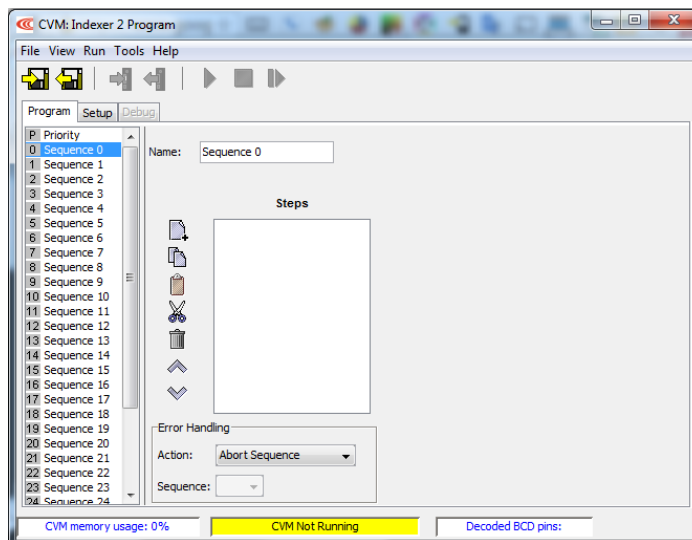


Figure 71: CME 2 Simple Programming Interface

The Copley Motion software, CM2 that the Tolomatic runs onboard is a very straightforward tool that not only provides the ability to program the internal controller with a basic motion sequence and command the Tolomatic to response to external inputs but it also allows for the tuning and calibration of the ICR SmartAcuator. CM2 also provides an interface for debugging and real time monitoring of the driver to ensure the desired operation is being achieved as seen in Figure 72.

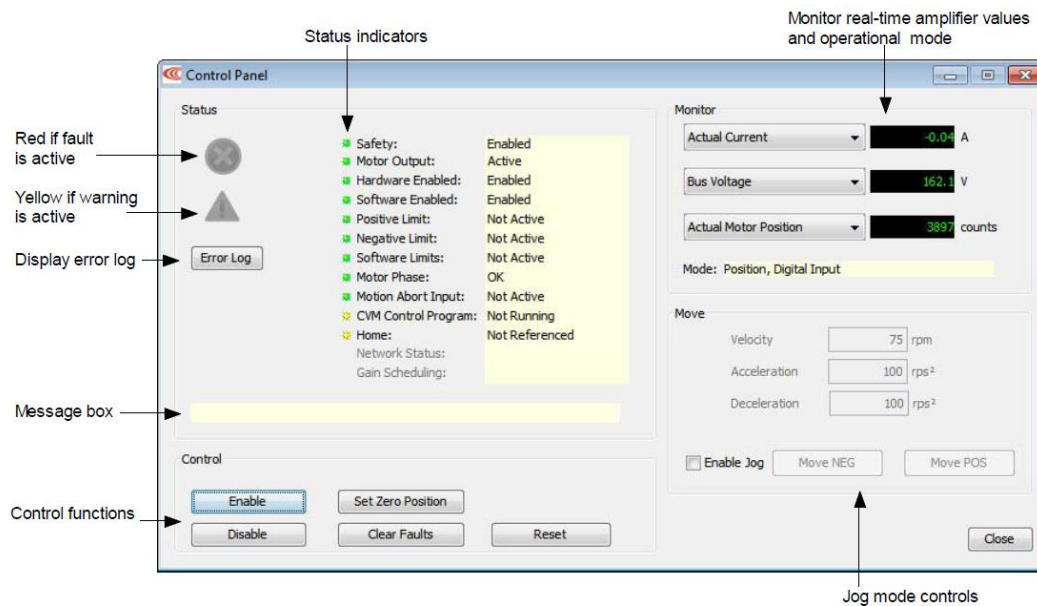


Figure 72: CME2 Live Time Diagnostic Panel (Copley Motion, 2015)

The Keyence LV-N11CN and LV-S72, the laser driver and head respectively, is a 100% self-contained and commercially available system that triggered an output when the laser beam is broken. The team has placed the laser at a pre-determined height to identify a known offset location in space. Once the laser beam is broken a signal is sent to the Tolomatic, bring the tool motion to a stop. The desired tool height can then be commanded from the stopped location in the form of a positive or negative offset. The laser driver is connected directly to one of the Tolomatic inputs in an effort to reduce any delay caused by system response if the laser driver were to be hooked up to an external controller such as a PLC and then the PLC would have to trigger the Tolomatic.



Figure 73: Keyence LV-N11CN

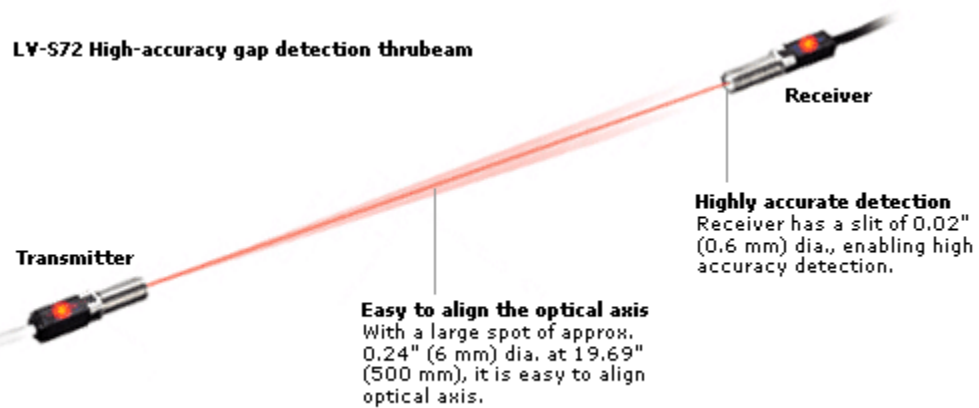


Figure 74: Keyence LV-S72

## Chuck Dog Height Setting

The chuck dogs ride on two sets of passive linear slide bearings, which allow them to move freely up and down with the system as required by the tightening or loosening operation. A set of two inch stroke Firgelli linear actuators are used to raise the dogs to the appropriate height for their initial engagement to each tool holder. These linear actuators are driven by an integral 12 VDC motor and lead screw assembly. The actuator has a ten-turn potentiometer built into the housing that is mechanically linked to the lead screw and provides control feedback to the system.

Firgelli manufactures a Linear Actuator Control Board, or as they call it a “LAC”, however the controller is largely undocumented, is poorly constructed, and clearly made for primarily consumer based-applications. The team attempted to integrate Firgelli’s LAC into the system but had numerous issues with the board failing to respond to control input, erratically controlling the linear actuator, and about every other time the system was powered the board would fail to turn on.



Figure 75: Firgelli LAC

After running into numerous issues with the Firgelli LAC and it clearly becoming a weak point in the system the team started to look for alternate motor drivers that would fulfill the needs of the application. Very quickly the Pololu Jrk 12v12 Motor Controller with Feedback was identified as a brushed DC motor controller that would be able to drive the linear actuators, and account for the feedback potentiometer, all while being controlled over USB, logic level serial, or analog voltage.

Pololu is a trusted brand in motor controllers and has been used by the team numerous times in the past. The thorough documentation and explanation of operation that accompanied the Pololu left the Firgelli’s one page quick reference guide in the dust. Once the team replaced the LAC with the Jrk 12v12 the team’s control irregularities went away and a dependable system was finally in place to drive the chuck dogs as desired.

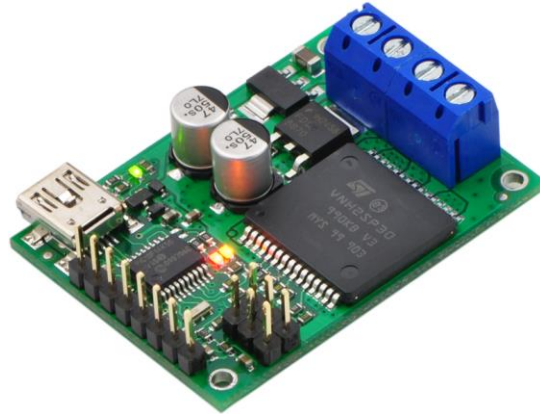


Figure 76: Pololu Jrk 12v12

Both the Pololu and the LAC were driven by a 0 to 5VDC analog voltage from the PLC. An analog voltage interface was chosen originally due to the limited type of control interfaces available on the LAC. The team decided to stay with an analog voltage control method over a more involved protocol such as serial due to its simplicity both in programming and troubleshooting and the team had already procured PLC hardware to command the motor drivers via an analog voltage.

Upon receiving the Pololu's the team was able to calibrate each controller to match the available travel in each linear actuator. Calibration was an important feature of the Pololu as the Firgelli's do not appear to be designed for precise control and have significantly larger tolerances than the Tolomatic. One issue the project team faced was that the travel of each Firgelli linear actuator did not match each other exactly. The Pololu motor controllers were able to account for the mismatch and scale the input to match the output shaft extension between the two actuators.

# RESULTS

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After many months of hard work, the project team was able to accomplish many of the goals that were established at the beginning of the project. In this section of the document, the system results will be compared back to the design criteria and specification set out in the methodology section.

From the beginning, the system was expected to be capable of manipulating cutting tools with a single shank diameter. The system that was developed surpassed this expectation. The system is capable of manipulating two different shank diameters:  $\frac{1}{2}$ " and  $\frac{3}{4}$ ". This meant that the end effector had to be capable of transporting both sizes, and that the tooling drawer had pockets for both sizes. These features were included in the design of these sub-systems, meaning this specification established by GE was met.

Another system specification stated that the system must accept two different types of cutting tools. Given the design of our system, this was easy to implement as long as the end effector could properly manipulate the cutting tools. In our design, there are separate pockets on the tool cart and on the tooling drawer for the two different types of cutting tools of each shank diameter. This is another design specification that was met.

A critical part of the entire system is its ability to assemble and disassemble cutting tools. The tool assembly system was developed to do exactly that. The project team fully implemented the tool assembly system, and tested its performance. This design specification was properly addressed.

GE has requested that when processing the tooling assemblies that the tool height be set to a target within  $\pm 0.025$ ". The tolerance is this large because the length of the tooling assembly will be measured and properly accounted for when installed in a CNC milling center on the production floor. The tolerance of the tool height setting mechanism is based on the tolerance of two components: the Tolomatic linear actuator and the Keyence laser sensor. The actuator has a tolerance of  $0.002$ ", and the laser sensor has a tolerance of  $0.003$ ". The worst error possible would be the combination of these values, or  $0.005$ ". This far exceeds the specification laid out by GE, but would still require proper measuring before the CNC milling process could begin.



GE's specification for tightening tooling assemblies is as follows: the nut on the tooling assembly must be rotated until the operator cannot rotate it any further. At that point, the operator loosens the nut  $\frac{1}{4}$  turn. This same specification must be matched by our tool assembly system. An encoder was added to the rotator table to identify when the nut stopped spinning. At this point, the rotator table will reverse  $\frac{1}{4}$  turn to meet this standard.

Inherent in this assembly process is the ability to insert and remove cutting tools from tooling assemblies. The insertion aspect of the project was expected to be a difficult challenge to overcome. This issue was addressed with the drop insertion technique discussed earlier in this document.

Throughout the entire process, damage to tool holders and cutting tools must be avoided. The end effector provides a rigid method of manipulating these items without concern for dropping them.

Safety is an important aspect of this project. GE would like to see this system operate within a closed space. Although one wall of the work cell was removed to allow the Fanuc robot to interact with the tool cart, a light fence was installed to protect the system from operating when an operator entered the exposed area. At the same time, E-stops were added to allow the operator to stop the operation at any time. Solenoid locking switches were added to the tooling drawer and tool cart dock to ensure that the operator could not gain access to these areas while the system was in operation. Finally, an interlocking switch was installed on the door of the work cell to allow operator access to the inside of the work cell only when the system was not in operation.

Further testing is required to identify how well the system met some of the initial design specifications. The design specifications call for a system that processes tooling assemblies at a rate of two per hour. Even though each of the individual sub-systems have been successfully implemented, the integration of the entire system is still under development. An analysis on the repeatability of this system is needed before a conclusion could be made in regards to that specific design specification.

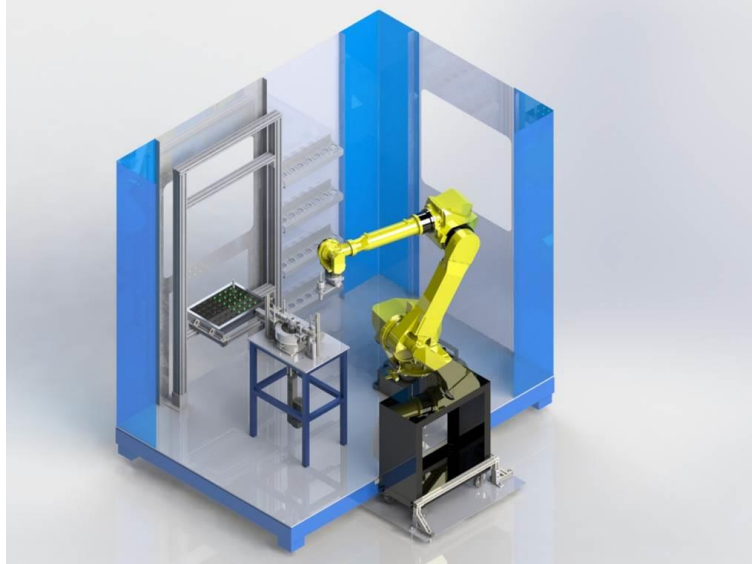
The end effector met all of the design requirements initially established for it. It successfully was able to safely manipulate cutting tools with both  $\frac{1}{2}$ " and  $\frac{3}{4}$ " shank diameters, along with tooling assemblies. The final implementation does not have any of

the interference or collision concerns as some of the previous designs had. The fingers deflect an insignificant amount under the weight of tooling assemblies and the force from the actuator.

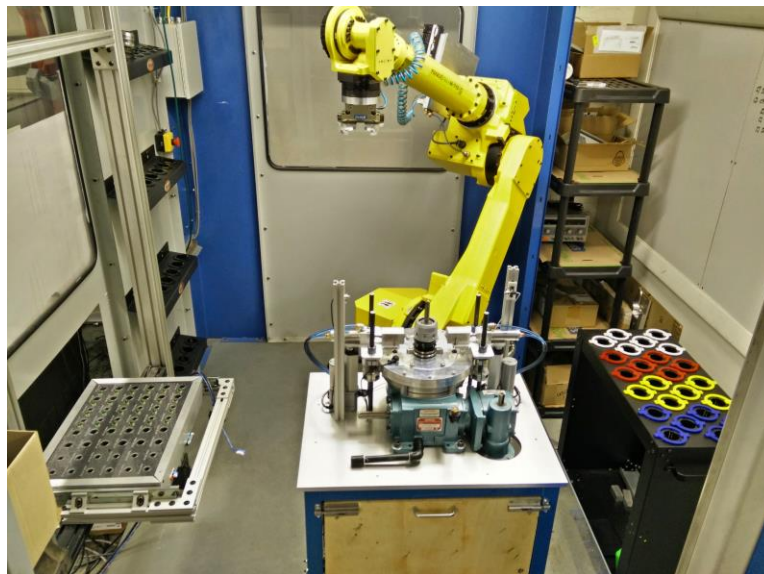
The tool cart dock was another successful implementation. It provided consistent pick and place locations for tooling assemblies. The operator is able to easily roll the tool cart into the dock, and the vision system was able to identify populated pockets within the tool cart. The light fence was installed correctly, and the system stopped if the fence was broken.

The design criterion for the tooling drawer calls for a system that provides storage for twenty-four new cutting tools and twenty-four worn cutting tools. The final design included forty-eight pockets that did exactly that. The operator is provided feedback if a new cutting tool is not properly inserted into one of the pockets. This helps to add reliability to the pick and place location of cutting tools for the robot. The rails that support the tooling drawer are mounted properly, allowing the tooling drawer to slide out of the work cell providing the operator access. When done, the operator can slide the drawer all the way into the work cell.

The tool assembly system successfully processes tooling assemblies. There is enough clearance for the robot to pick and place tooling assemblies on top of the rotator table. The locking nut dogs don't damage the tool holders, but are strong enough to rotate the nut to assemble and disassemble the tooling assemblies. The drop insertion technique was tested and deemed repeatable and safe enough to implement with this system. The tool height setting mechanism was built and successfully sets the tool height to a given value. The assembled physical components of the work cell can be shown in Figure 77 and Figure 78 below.



**Figure 77: Rendered image of the finished work cell**



**Figure 78: Completed state of the work cell**

The control system was able to provide communication between all of these systems. This was a challenge as there was no uniform communication method between all of the sub-systems of this project. The previously installed control system was dismantled and a more modern system was installed. This included rewiring the entire system from the bottom up. This process was properly documented to ensure that future work could easily be done on the system. Four different software packages were used to program this new control system.

To date, the project team has not been able to implement a fully autonomous solution to the problem originally brought by General Electric. Great progress has been made with this project, and it is hopeful that full system integration will be completed before the end of the academic year.

## DISCUSSION

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The GE Tool project was an overall success in developing a proof of concept system to autonomously change the cutter held within a tooling assembly. At the time of writing the full end-to-end solution is still being implemented however each individual sub-system has been tested and proven repeatable in its operation. The project team has performed extensive testing on the insertion and height setting operations both of which have been determined to be the most sensitive and complex parts of the operation respectively.

The project team developed numerous systems to tackle each unique challenge presented by the project. From locating the tooling cart, to removing and inserting the cutter, to manipulating the tooling assembly on the assembly station, and retrieving and disposing of new and worn cutters.

Each task was independently evaluated by the project team and specific solutions were developed through an extensive prototyping and design iteration development cycle. As each system was completed and underwent validation the team began to integrate the systems to form a single cohesive system.

Integration became a more complex task that the team originally expected primarily due to the use of a PLC controller and the lack of experience any team member had with that type of system or ladder logic programming in general. Although a PLC centric solution was chosen to meet the industrial design desired of General Electric it posed a larger than expected challenge for the team. With some additional time and training the team feels confident it would be able to finish the full system integration delivering the complete autonomous system General Electric desires. That said, the team expects to have a fully functioning and 100% autonomous system operation before the conclusion of the academic year.

## Future Work

Although the team developed a system that could accommodate four different types of cutters and two different shank diameters, the tools were required to be placed in a specific set of location in the tool cart. Further work on the project could include the integration of the RFID tracking of tools, previously worked on as part of a GE sponsored MQP in 2014, such that the system could detect the type of tool as it was ingested into the system.

Additionally GE has expressed some desire to remove the precision laser measurement systems out of the CNC machine centers and into a dedicated cutter replacement work cell like the one the project team is developing. GE feels that in combination with the RFID tool identification system this would allow them to utilize fewer laser measurement systems and keep them away from the coolant and harsh manufacturing environments present inside of a CNC machine center. A future version of this system may be able to meet GE's needs in this area.

From a mechanical perspective the tool assembly collar dogs need to be monitored for wear and deformation. The project team manufactured the dogs out of billet aluminum and as a result when used at a high pressure against the hardened steel tool assemblies the nubs present on each dog, which actually lock into the tool assembly, can start to deform and lose effectiveness.

From a controls perspective there are two sub-systems both located on the assembly system in the middle of the cell that could use further integration efforts. The Tolomatic which is used for height setting, and the Pololu motor drivers used to control the Firgelli's both are currently controlled using a control method that does not provide the system with feedback to its current status. Discrete I/O is utilized for the Tolomatic and an analog voltage signal is utilized for the Pololus. Future project teams might consider utilizing the serial capability of both of these devices to gain better control and feedback in the event of an error from the system. The current project team did not implement serial based control due to its original lack of availability with the Allen & Bradley PLC and the additional complexity it introduces that is not critical to base system functionality.

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