Design and Manufacture of a Tool-Changeable Robotic Part Manipulator

A Major Qualifying Project

Submitted to the Faculty of

WORCESTER POLYTECHNIC INSTITUTE

In partial fulfillment of the requirements for the

Degree of Bachelor of Science in Robotics Engineering

By

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Class of 2012

Date: April 26, 2012

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Abstract

The goal of this project was to design and produce a tool-changeable robotic part manipulator to be used in the manufacturing industry. Project deliverables include a tool which is capable of being swapped in and out of a Vertical Machining Center's spindle, able to flip a part over for a secondary machining operation, and operate autonomously to enable continuous machine operation. A prototype tool was developed capable of fulfilling each of these requirements as well as programming code to also handle a variety of machine errors.

Acknowledgements

Without the support of the following individuals, this project would not be possible:

William Weir, PhD

Peter Farkas

Michael Gibney

Torbjorn Bergstrom

Adam Sears

James Loiselle

Alexander Segala

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1. Introduction

The Major Qualifying Project represents the capstone achievement in one's field of study and whose completion is necessary to graduate from Worcester Polytechnic Institute. The objective of this manuscript is to document the design and manufacture of a tool-changeable robotic part manipulator designed for the manufacturing industry using Vertical Machining Centers (VMC).

As an aggregative report on the conclusion of this project, this paper discusses the motivation supporting this project, relevant background information to support the motivation, methodology to implement the motivation, discussion of the fruits of the project and recommendations for future innovations on the project as a whole. Additionally, conclusions are drawn from the completion of the project and source code pertaining to the programming of the robot is contained in Appendix A.

2. Project Motivation

One of the primary obstacles to high-production manufacturing is time spent in between machining cycles. The source of this time can be most often narrowed down to part loading and unloading by a human machine tool operator. In today's modern era of machine tool technology, robotic interfaces to machines enable them to operate 24/7 with little attendance required. While an expensive solution, this path enables high-production, continuous manufacturing with fewer scrapped pieces and increased volume compared to a human attendee. The objective of this project will be to develop a robotic, tool-changeable arm designed to minimize human interaction and enable the same continuous production enjoyed by robotic manufacturing cells in a one-machine, self-contained environment.

3. Background

In today's modern manufacturing world, automation is becoming an increasingly significant aspect of a high-volume production shop. One of the primary focuses of industrial automation is to enhance a machine's ability to perform work while unattended by a human. This ability manifests itself in a variety of different applications, depending on the automation requirement and the machine that is being used. For example, on a turning center, two popular examples of automated processes are bar feeding and part loading and unloading.

Figure 1: Turning Center Automation. Bar Feeder (left) and Automatic Parts Loader (right)[1]

Typical examples of turning centers with automated processes are shown in Figure 1. The bar feeder is designed to push a bar into the lathe, which then performs operations on the bar and finally parts the workpiece from the bar, creating a fresh surface for additional parts to be made. The Automatic Parts Loader (APL) is the bar feeder's counterpart; it retrieves pieces of

[1] Image accessed 4/25/2012 from http://techspex.com/objects/haas_sl-20apl.jpeg

pre-cut stock from a table, and loads and unloads them from the lathe onto the table. Each of these solutions can be integrated into and programmed from the machine tool's controller, which is what makes these options attractive to smaller shops that must maintain high volume production but cannot afford to have a robot integration firm develop a solution.

A more complicated solution to part handling is the integration of a "traditional" robot arm into a manufacturing cell. Integration of a robot arm can be rather expensive and involve setting up a large area for the robot to be contained within, with guards to prevent human floor support staff from being harmed while the robot is in operation. Generally, a manufacturing cell involving a robot arm would run continuously for the duration of the project. The manufacturing cell is designed to be as efficient and self-sustaining as possible, only requiring human interaction to handle stock supply and take the completed parts out of the cell.

Figure 2: Haas Factory Robotic Manufacturing Cell.[2]

[2] Image accessed 4/25/12 from http://www.haascnc.com/images/HaasRobotCell.jpg

Figure 2 details a robotic manufacturing cell at Haas' California facility. The robot in the center of the picture handles parts loading and unloading across two lathes and one mill, which increases productivity with continuous operation and reduced machine tool operator error due to fatigue, laziness and improper training. A robot never gets tired, requires only periodic maintenance and never needs to stop unless the cell breaks down or it completes the production run.

The goal of this project is to bring productive robotic automation to machine tools in a much smaller working envelope. In any space-constrained environment, floor space can sometimes be as much of a commodity as the machine tool itself. The primary issue with the floor-mounted robot in Figure 2 is that it takes up a significant amount of floor space; this space could just as easily be reconfigured to fit two or three additional machine tools into the same space. This would boost productivity far more than a robot tending several machines assuming the machines can be as easily tended. So to retain the advantages of robotic machine tending, but without resorting to a floor-mounted robot, the project intends to shrink the robot down in size so that it can be treated as a swappable tool within the machine itself.

The roots of modern robotics can be traced back to the Industrial Revolution. After water had been used successfully to power machines and produce exponential gains in manufacturing and production, the development of small electric motors generated the capacity for small systems of interconnected motors to work together to produce coordinated motion, which yielded the manufacturing sector's first robotic arm. In 1961, the first robotic arm, UNIMATE, came online at the General Motors factory in New Jersey.[3] From there, the relationship between robotics and industry continued to grow as innovations in computing yielded smaller and lighter computers, microprocessors and improved sensors. Innovations in manufacturing and material science produced lighter, stronger frames on which robotic platforms could be built and increased the payload that robots could carry. Innovations in the electronic motor field yielded continually more powerful motors which were capable of positioning more accurately and with increased torque output, which improved the performance capabilities of the robot.

The manufacturing industry has greatly benefitted from the presence of robots in the workplace. Nowadays, robots have become highly specialized, capable of performing tasks with great speed or lifting great loads, with each task completed with a high degree of repeatability.

4. Prior Art

Currently in industry, as was mentioned in the Background, most automation exists at the macro level: large, six-degree-of-freedom robots bolted to the floor and often tend more than one machine at a time. For better or worse, there is no current research or product brought to market which approximates the objectives of the MQP. Thus, it will be important to document each step of the project with great detail so that, if a future prospective MQP group is interested in working on the Project, they can do so with as much background research and detail already made available.

[3] http://inventors.about.com/od/roboticsrobots/a/RoboTimeline.htm Accessed 4/25/12.

5. Design Constraints

In theory, engineers in a professional environment will never design without at least a few general constraints. This MQP is no different from other projects requiring engineering design and manufacturing. One of the functional requirements of the robotic arm is that it be tool-changeable. In order to do this, the robot arm was designed with several design constraints in mind. First and foremost, the robot arm must be small and compact enough to fit inside the tool change carousel. The maximum tool diameter is approximately 6 inches, and the maximum tool weight is 12 lbs.[4] These constraints limit the design of the arm such that it must be compact and lightweight enough to be contained within the tool carousel. This presents several issues: first, the tool must be as concentric as possible with the spindle's axis, such that it does not create excessive torque on the tool pockets of the tool carousel. Functionally speaking, the tool should not exceed 12 inches in length because it would create a significant moment arm when it is lowered into the tool-change position and swapped with the tool in the spindle. Figure 3 illustrates the tool-change position and the orientation in which tools are prepared for storage in the spindle.

[4] http://www.haascnc.com/mt_spec1.asp?id=VF-2&webID=40_TAPER_STD_VMC Accessed 4/25/12.

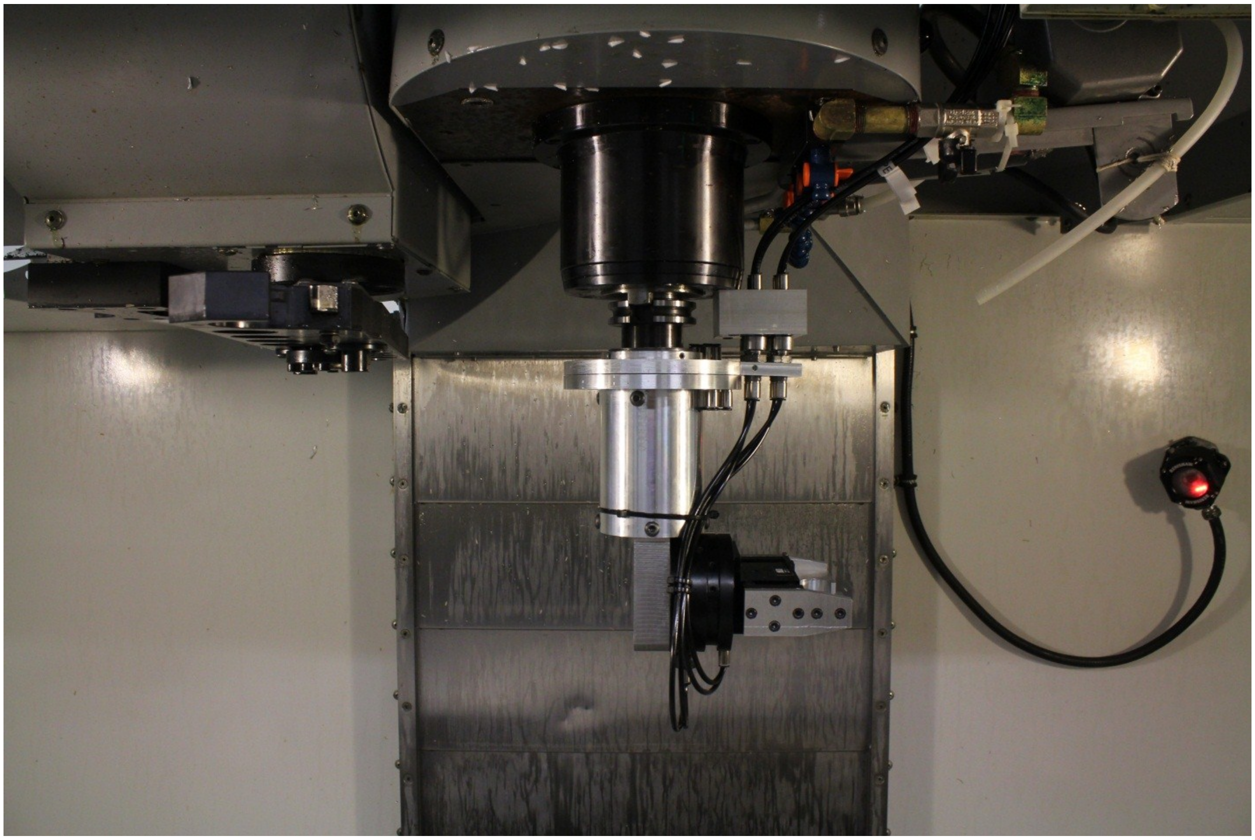


Figure 3: Tool in Working Position

One of the primary advantages of designing a compact robot is that it allows the robot to reach around obstacles bolted to the table, such as other fixturing, parts or tooling. For this reason, the robot was designed to be as compact as possible while ensuring adequate strength was engineered into the physical design. Shown stored in the carousel, it becomes evident why minimizing the footprint and overall size of the robot becomes a priority, in Figure 4.

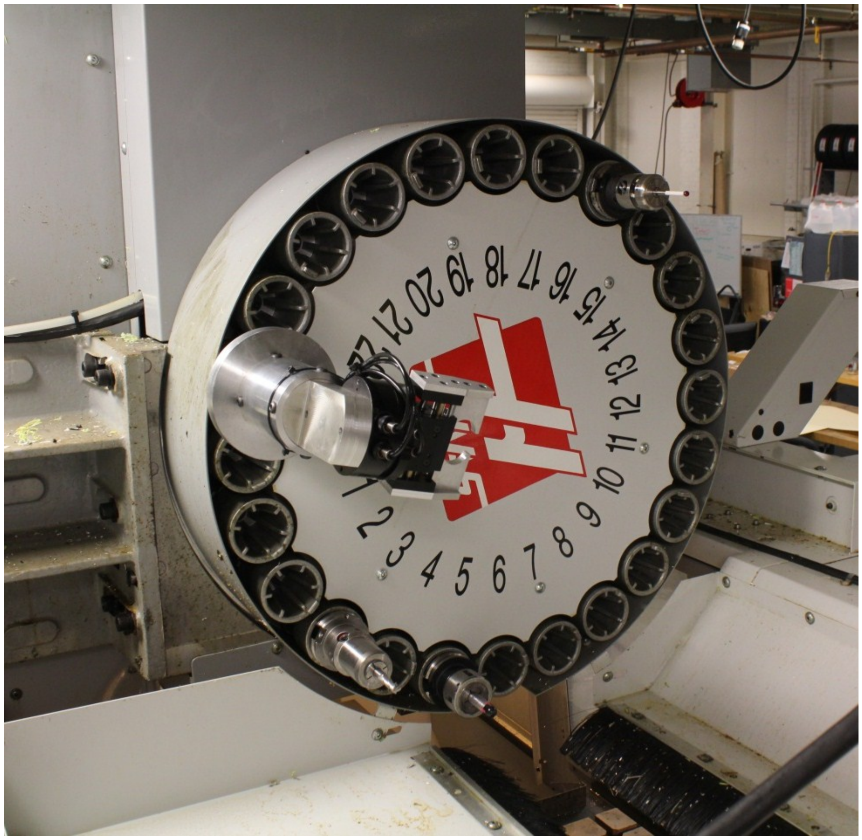


Figure 4: Robot Arm Stored in the Tool Carousel.

6. Methodology

The primary, high-level objective of this project is to develop a robot capable of managing part production and organization within the vertical machining center such that it can be swapped in and out just like any other tool. In order to facilitate this, the arm's design was segmented into several different sections in order to make design and manufacturing as simple as possible.

6.1. Gripper

The apparatus which provides a flipping motion and part gripping functionality was not pre-determined when the MQP began. Therefore, it was necessary to evaluate several different solutions which would provide the aforementioned functionality while maximizing the benefits and minimizing risks associated with each. Figure 5 illustrates three concepts which could be used in this project: bevel-gear driven gripper, pneumatic gripper and electric motor-driven gripper.

	Scale: 1-10	1: Easiest (Best), 10 Most Difficult (Worst)					
	Complexity	Rotary Performance (Resolution)	Cost	Maintenance Costs & Labor	Risk		Sum
Weight	20%	10%	30%	10%	30%		100%
Electronic Stepper Motor	8	1	5	6	10		6.8
Pneumatic Rotary Unit	4	8	5	4	2		4.1
Bevel Gear, Spindle Driven	10	4	4	8	8		6.8

Figure 5: Gripper Decision Matrix

As can be seen in Figure 5, the pneumatic rotary unit proved to be the best compromise between complexity, rotary performance, cost, maintenance, labor and risk. The bevel gear, while a simple design concept, would have proved difficult to implement given the rigid support required to maintain gear contact and mesh. The electronic stepper motor, while offering the best rotary resolution, poses an overwhelming risk of fire and electrical shock since the robot will be operating in a wet environment. In the end, the pneumatic gripper proved to be the best compromise because it is air-powered, which poses the fewest risks to safety and health, requires little maintenance and is fairly simple to implement with solenoid logic control to drive the condition of the grippers. Furthermore, the advantage of the selected gripper, the AGI AGM-10 Rotary/Gripper Unit, provides both rotational motion as well as gripping motion in one compact form factor. This compactness was desired to further minimize the overall footprint of the robot itself.

Once this decision had been made, a search was conducted for a gripper satisfying the design constraints and desired performance. AGI Automation, based in Tolland, CT, manufactures a variety of gripper and rotary configurations. For this project, the AGM-10, a rotary/gripper combination unit, was selected for its compact form factor, pneumatic actuation and tough construction. A donation of the gripper was sought, and after contacting Peter Farkas at AGI, a unit was secured for the project which may stay at WPI into perpetuity so that future MQP groups may use it, either in an adaptation of this MQP or in another project where such functionality is required. Figure 17, shown on page 29, shows the gripper with jaws attached and mounted onto the robot.

6.2. Spindle Interface

Because of the nature of a Vertical Machining Center's (VMC) design, the spindle into which any tool is inserted into is manufactured such that repeatability is estimated to be better than +/- 0.0001". This ensures high repeatability and accuracy when tools are swapped in and out of the spindle, which reduces the number of potential sources of error present in the system that could lead to surface finish problems on a milled part. Because the VMC is designed with a taper-style spindle, it allows the machine to create a pulling force on the tool of approximately 1900lbs[5] which delivers a significant amount of radial stability into the system and allows the machine to perform heavy machining operations at high precision and accuracy. To maximize

[5] Haas 2011 Mechanical Service Manual. Haas Automation, June 2011.

the strength of the overall system, a Kennametal Bar Blank was chosen as the fixed unit around which the rest of the robot would be designed. Figure 6 depicts the raw bar blank as it comes from Kennametal.

Figure 6: Kennametal CV40BB400600 Bar Blank.[4]

From this blank, a custom thread was turned on the outside. It began as a 4 inch diameter by 6 inch long piece of steel rod, which was turned to 2.5 inches on the diameter, onto which a custom 2.5”-16 thread was turned. 2.5 inches was chosen as the major diameter because it would be easy to source stock from which to make the rest of the robot including the extension tube and gripper adapter. It is also a sufficiently large thread to ensure strength and rigidity throughout the robot. Additionally, since the clearances required between the tool-change arm and the robot needed to be accounted for, this diameter would allow the rotary union’s design to begin at a large enough diameter to space out the pneumatic fittings and allow for a

[6] Kennametal Bar Blank. http://www.kennametal.com/images/stibo/web_large/images/18189.jpg. Accessed 4/25/12

pneumatic interface to be designed sufficiently out of the way of the tool-change arm such that it would not collide when attempting to swap the robot in and out of the spindle.

6.3. Pneumatic Control

In order to control the supply of air going to the gripper, individually controllable solenoids were used to configure the logic condition of the gripper. Two conditions on the unit were controlled: the rotation (0 and 180 degrees) of the rotary unit and the open and close position of the gripper. Three Clippard Maximatic 4-position 2-way solenoids were wired into the control cabinet on the back of the Haas VM-3 to provide this switching logic. The first solenoid serves as a cutoff to the control logic; this allows the air supply to be severed in an emergency situation or when the tool is no longer in the spindle. Once the air supply is enabled, it is fed to two secondary solenoids which control the two states of the gripper. Separately configured from the rest of the system is an additional solenoid which controls the logic condition of the pneumatic fixture used as an example application.

6.4. Pneumatic Interface

In order to power the arm's pneumatic gripper and rotary unit, pressurized air must be passed from the machine's 85PSI regulated supply into the tool. This was accomplished using custom-designed fittings with captive sealing o-rings to provide a reliable supply of air. Because the pneumatic unit requires consistent air pressure to it to maintain its position and clamping strength, any leakages of air present an issue to the effectiveness of the gripper's capabilities. To make the tool able to be changed in and out of the spindle, the pneumatic supply must be able to be broken. To ensure the air supply can be consistently disconnected and reestablished, a series of fittings and mating surfaces were designed such that the o-rings on the fittings press against the mating surface on the spindle-mounted block to seal the air union properly. Figure 7 shows the manufactured set of pneumatic fittings, with o-rings installed. The four steel fittings, shown in the center of the picture on the rectangular base plate, contain o-rings that seal the two halves (spindle block and fitting) together to create a pressurized seal.

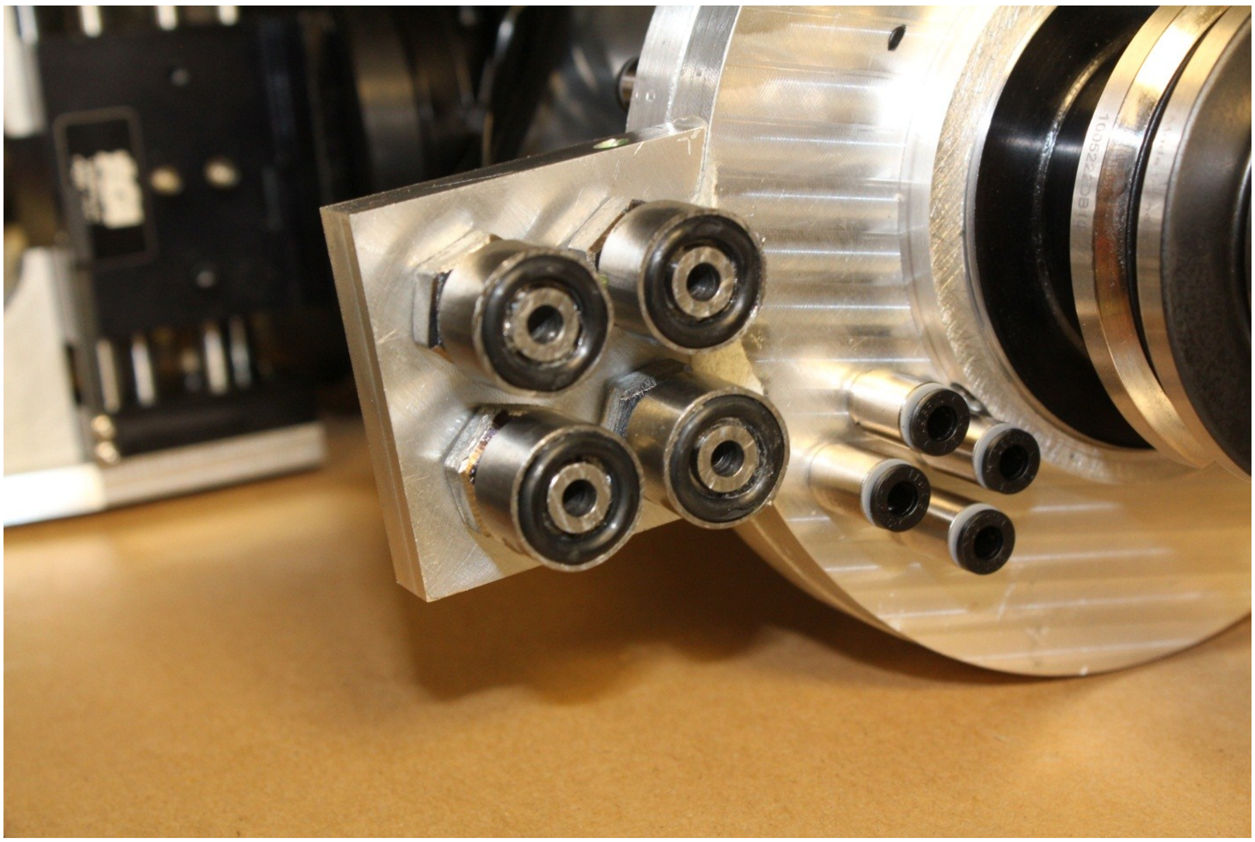
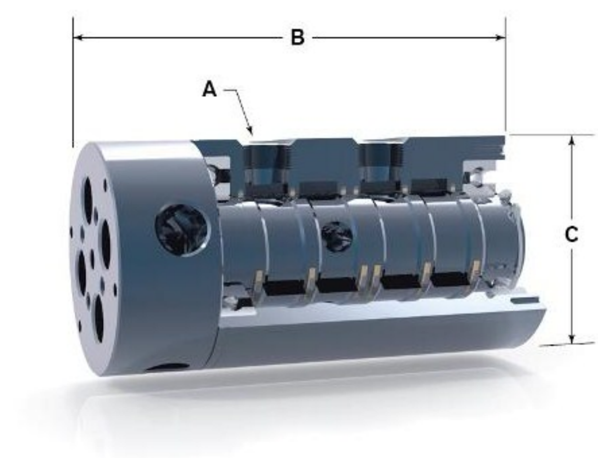


Figure 7: Pneumatic Fitting Design

This design was chosen because of the compliance in the o-rings, which would allow the distance between the mating surfaces to grow or shrink by a few thousandths of an inch as the tool is repeatedly changed in and out of the carousel and still provide an acceptable seal to pass pressure through. Figure 14, shown on page 25, provides the solid model representation of the described interface.

6.5. Air Rotary Union

One of the primary difficulties in achieving the stated objectives is how to provide a continuous supply of air to the gripper while allowing the tool body to rotate in the spindle. To do this, a rotary union was designed with the specific design constraints in mind. It must be no wider than 6 inches in diameter and must be as light as possible to keep it from exceeding the 12 pound limit. Initially, a commercially available rotary union was evaluated to determine whether it was feasible to purchase an off-the-shelf part which satisfied the requirements. One such union was evaluated from Rotary Systems, manufacturers of rotary unions and slip rings, to determine whether their rotary union could be compatible with the design. Figure 8 details the proposed rotary union that was evaluated for this particular application.



Part #	A Thread	B Length	C Dia	Options
016-N-40212	0.125 NPT	4.103	2.200	View Options »

Figure 8: Proposed Off the Shelf Rotary Union[5]

[7] Image accessed 4/25/2012 from http://rotarysystems.com/series-016.

Unfortunately, it was determined that the rotary union that Rotary Systems advertises would be incompatible with the system's design due to excessive length concerns. With the finished length of the bar blank at 2.5 inches, plus an additional 4.103 inches from the rotary union, plus pipe to adapt the rotary union from 2.2 inches to 2.5 inches for use with the gripper adapter plus, finally, the approximately 4 inch gripper adapter puts the overall length at over 11.5 inches, dangerously close to the maximum length restriction. For this reason, a custom rotary union had to be designed and manufactured. It would be designed in such a manner as to make it compatible with the tool block mounted on the spindle head to receive incoming air, as well as permit the assembly to rotate without binding or seizing.

6.6. Sensing and Programming

After a part has been loaded into the fixture, it is necessary to verify that the part was loaded correctly and is in the right location for machining. To accomplish this, the Haas Wireless Intuitive Probing System (WIPS) was used to sense the location of the part, update offsets and ensure that the machine is safe for machining operations. The Renishaw OMP40-2, part of the WIPS package and used to set work offsets, is repeatable up to 0.000004" which makes it an ideal candidate for the Haas machining centers since the machines are repeatable up to 0.0001". This means that the machine will reach its positioning accuracy well before the probe does; that is to say, the system is machine-limited instead of sensor-limited. For the particular part that is being used as an example for this project (1" round bar stock placed vertically), two probing cycles were used: Probe Boss and Z Single Surface Measure. Probe Boss touches the front, back, left and right of the vertical sides of the stock and updates the X and Y work coordinate offsets. The Z Single Surface Measure touches the top face and updates the Z work coordinate offset.

The programming of the system was split up into individual subprograms to compartmentalize functionality as well as provide a segmentation of the program flow to allow errors to be diagnosed. The application which was selected for this project is to load and unload two pieces of 1” round stock, approximately 6” long. To facilitate this, the program was broken up into subprograms as Figure 9 shows:

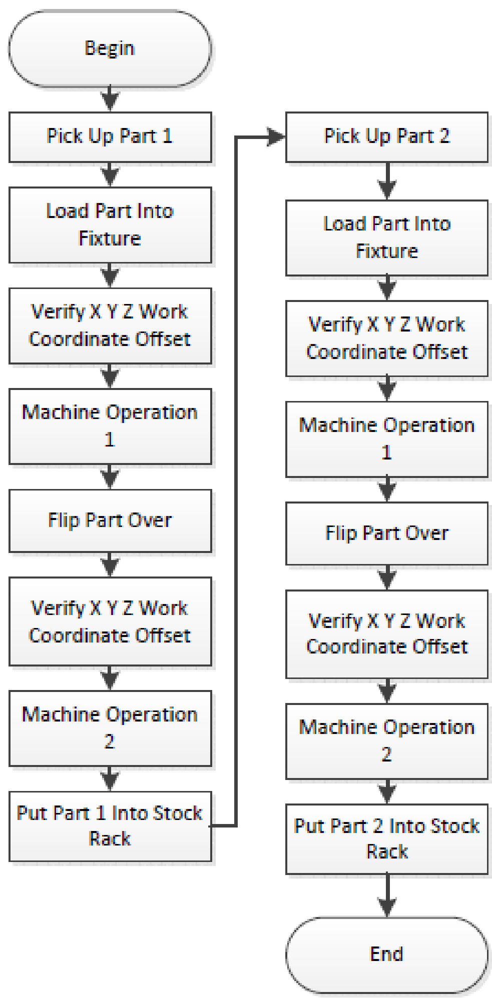


Figure 9: Example Flowchart Illustrating Subprogram Design.

The advantage of splitting the program's operation up into smaller, more manageable subprograms is twofold: first, it allows many subprograms to be re-used each time a new part is selected for machining. For example, the program flow from "Load Part Into Fixture" to "Machine Operation 2" can be reused each time a new part is selected to be machined. Instead of having to copy code and take up space in the control's memory, subprogram calls were used each time a repeatable machine function had to be performed.

6.7. Proposed Design

After all of the design constraints and considerations were taken into account, a prototype was arrived upon which satisfied all of the requirements. The use of SolidWorks to model the entire robot system was invaluable for the purposes of simulation and design verification; without SolidWorks, it would have been nearly impossible to check for clearance issues, mating of parts into assemblies to check for interferences and ensure that, once the design moved into the manufacturing phase, there would be many fewer surprises along the way. Figure 10 depicts the final solid model that was arrived upon.

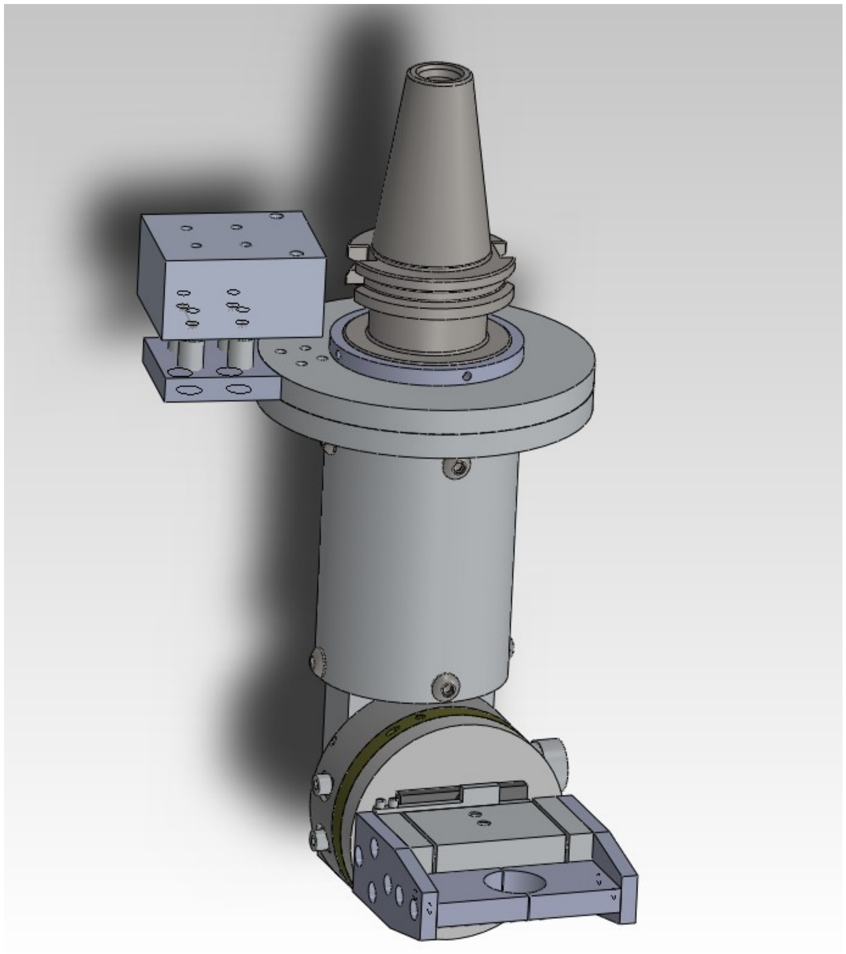


Figure 10: Completed Solid Model of the Robot.

Such a complex assembly would have been extraordinarily difficult to model with paper and pencil; taking advantage of the SolidWorks package offers many advantages, such as the ones mentioned above regarding mating of parts together into assemblies and verification of clearances and interference checks. Another critical and highly valuable tool, SolidWorks Simulation, allows a study to be performed which simulates how a model will react under loading. This portion of the project proved invaluable since it would be extremely difficult to measure the deflection of the robot until all manufacturing had been completed and the robot was fully assembled. If design modifications had to be made after manufacturing was completed, the design may have already been constrained too much to permit further modifications to fix problematic issues with the design. In SolidWorks, discovery of problems in simulation allows re-design to occur before any manufacturing takes place, saving precious time, material and money.

6.8. Mechanical Analysis

To ensure that the robot’s mechanical frame would not fail under loading, a stress test was performed in order to prove the mechanical design would be adequate given the maximum estimated part weight that was expected. After the solid model was simplified in SolidWorks to allow the Simulation add-in to mesh the mechanical structure together, variables such as the direction of gravity, anchor points and loading scenarios were added to the model to obtain an estimated deflection value. The result is contained in Figure 11, which displays the resultant displacement when a 5 pound force is applied uniformly to the top face of the gripper module.

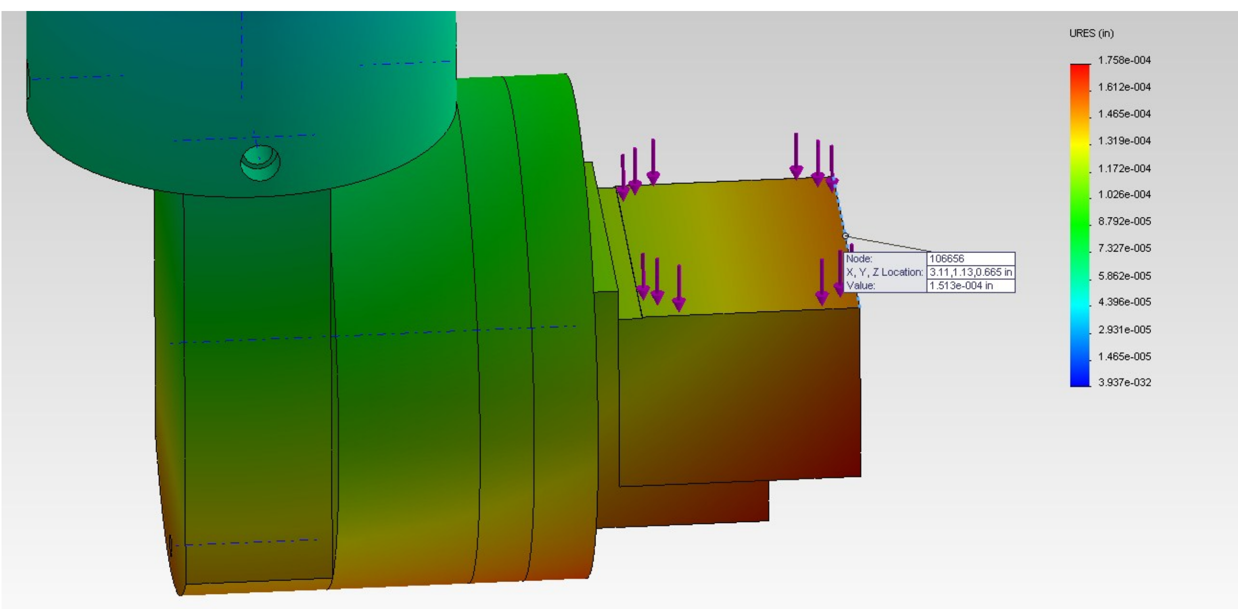


Figure 11: Solidworks Simulation Analysis on the Robot.

The results of this simulation prove that the design of the robot was mechanically sound and that it can withstand much more loading than is practically expected from the unit. A measurement taken at the outermost edge of the gripper shows that, with a 5 pound force exerted downward, the edge deflects 0.00015 inches, indicating that the robot is capable of withstanding reasonable loading and what might typically be expected of it in an actual manufacturing environment. For reference, if the load is increased to 10 pounds, something that, depending on gripper configuration, could cause the grippers to fail before the robot's frame deflects to more than 0.005 inches; the maximum deflection measured at that same point is 0.00028 inches. It is apparent from the simulation that the robot's structure has been designed with structural rigidity and strength in mind to withstand a variety of loads. 0.005 inches was selected as the maximum acceptable deflection because, given the tighter tolerances of the 1 inch collet fixture, more than 5 thousandths of an inch would result in an unacceptable amount of movement and could render the placement of the stock material by the robot unreliable and inconsistent.

7. Results

7.1. Electrical Interface

The electrical interface in the robot system performed as expected. The interface was installed in a matter of hours, after a brief amount of time determining the approach which was to be used to electrically connect all the wires together and wire them into the M-code relay board in the back of the VM-3. Figure 12 illustrates the implemented electrical design.

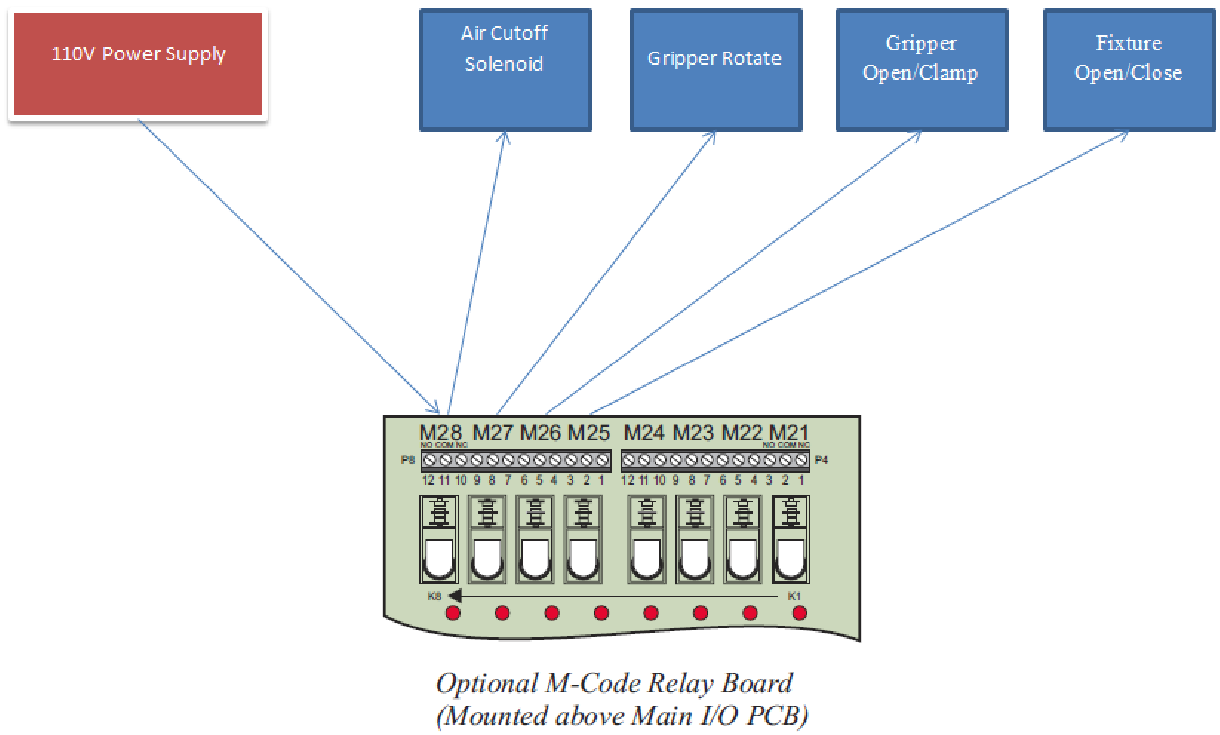


Figure 12: Diagram Showing the Wiring Configuration of the Solenoid Interface

110 volt power was drawn from the auxiliary power supply available on the side of the control cabinet where traditional appliances such as lights can be plugged in. Once power was tapped off that outlet, it was made available to each M-code relay to power each individual solenoid. Because the WIPS package was installed in the VM-3, it was not as simple as addressing M25 through M28 in program execution; each M code aliases to a macro variable, and each relay had to be addressed using macro variable calls to avoid conflicts with the probing system which used part of the M-Code Relay Board. Figure 13 illustrates how each logic condition of the system is addressed. For example, if the user desired to open the gripper, the command would

be "M69 P1145". Each macro variable (P code) and its corresponding relay are turned on (driven high) with the M59 prefix, and turned off (driven low) with the M69 prefix.

M59	P1144		Close Pneumatic Fixture
M69	P1144		Open Pneumatic Fixture
M59	P1145		Close Gripper
M69	P1145		Open Gripper
M59	P1146		Gripper 0°
M69	P1146		Gripper 180°
M59	P1147		Enable Air Supply
M69	P1147		Disable Air Supply

Figure 13: Matrix Showing how the M-Codes Relate to Solenoid Condition

These M-codes and corresponding macro variables are crucial to the function of the system; without them, it would be impossible to actuate the gripper. These were used extensively throughout each subprogram to modify the condition of the gripper as needed.

7.2. Pneumatic Interface

The design of the interface that would pass pressurized air through the spindle head and into the robot proved to be a tough task to accomplish with the various design considerations in mind: tool-changeable, repeatable and to provide acceptable performance given the design constraints. After many revisions, the design shown in Figure 14 was arrived upon, which represented the most realistic design given the materials and time available.

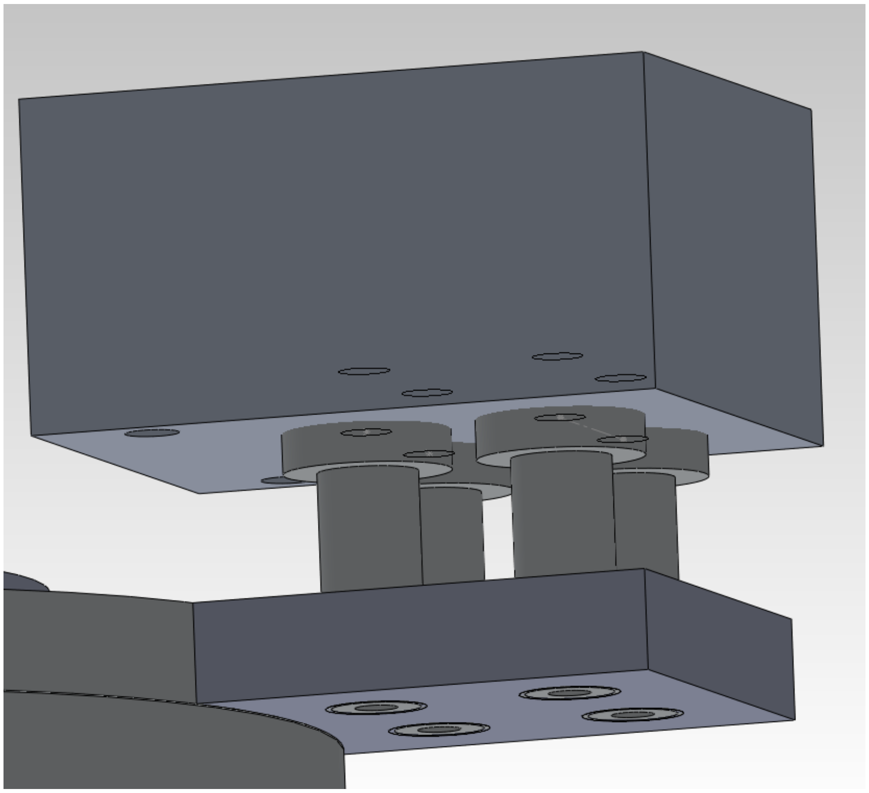


Figure 14: Pneumatic Spindle Interface Solid Assembly.

After slight revisions to the design of the tooling block attached to the spindle head, the pneumatic interface performed well, but did not seal as well as expected. There was a small amount of leakage where the o-rings seal against the spindle block, which was expected as a result of the design change to accommodate the spindle orienting against the spindle head. Figure 15 provides an accurate representation of the robot and the spindle head. The aluminum rectangular block serves as the mating surface, while the four pneumatic fittings contacting it are the fittings designed to accommodate o-rings to seal against the top surface.

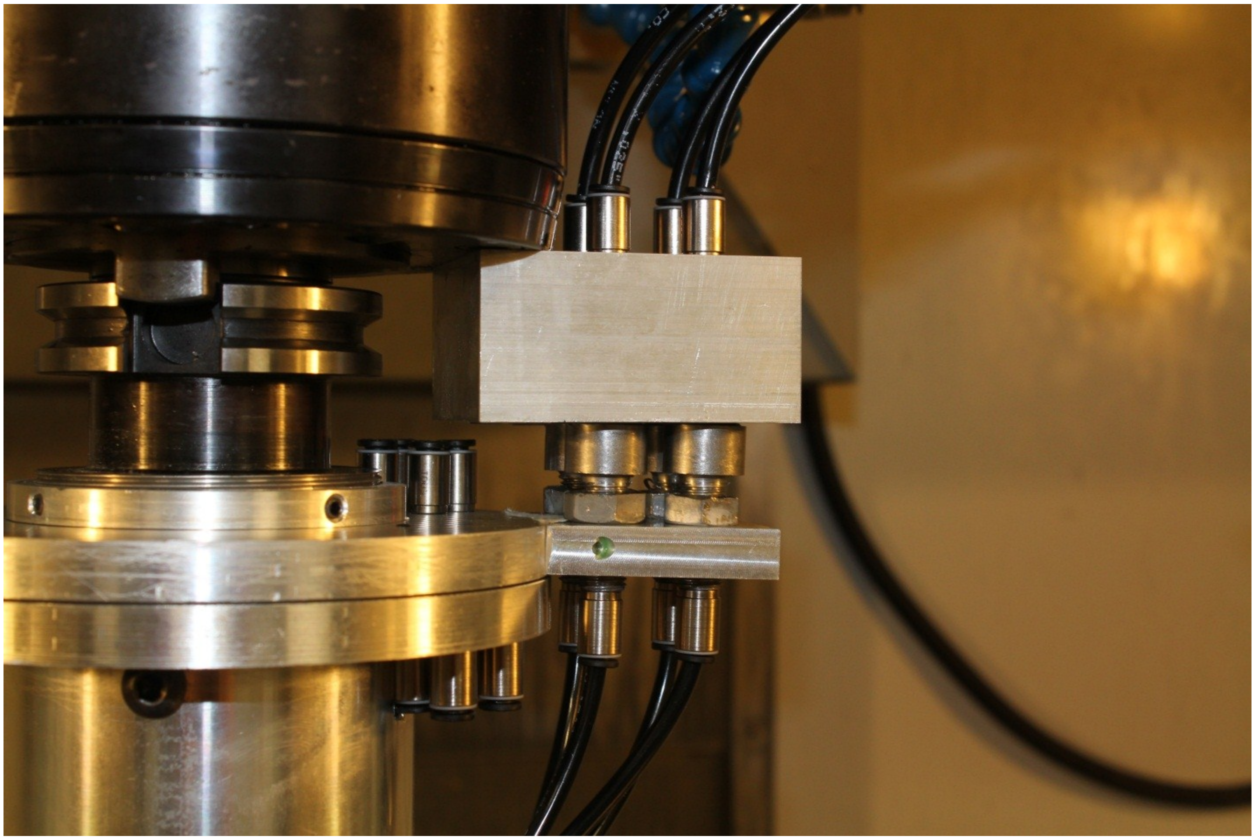


Figure 15: Pneumatic Interface Showing the Robot-Spindle Head Union.

When testing the final design, it was difficult to achieve a complete seal at all four of the pneumatic fittings; once one fitting was tightened up, others would loosen up and leak air. After adjusting the fittings several times, an adequate seal was achieved that would also allow the gripper to rotate and clamp/unclamp reliably. One of the primary causes of this issue was a last-minute modification to the top half of the rotary union to accommodate shifting this pneumatic interface further out of the tool change arm's way. After conducting analysis of the initial prototype, it was determined that it would not be possible to situate the top block in its initial location, closer to the spindle's axis of rotation because it would risk colliding with the tool change arm. After it was decided that a re-design of the interface had to be made, a new top block was made and the top half of the rotary union had to be modified to accept the fittings in a different location. After the fittings were relocated, the base on which the fittings was mounted deflected enough to make achieving a 100% seal of the fittings nearly impossible.

7.3. Pneumatic Rotary Union

The pneumatic rotary union was the most difficult part to design and manufacture throughout the completion of this MQP. Not only did it have to completely seal four individual air channels to prevent air leakage into other channels, it also had to fit inside the SMTC's operating envelope of a practical diameter limitation of six inches. In the interest of minimizing weight and minimizing the overall size of the robot, the envelope was further shrunk to five inches. Figure 16 illustrates the finished manufactured part. It contains five channels, into which five Teflon o-rings were inserted. From these o-rings sealing against the top, smooth half, four pressurized air channels were created which allow the four conditions of the gripper/rotary unit to be actuated (open/close, rotate 0°/180°).

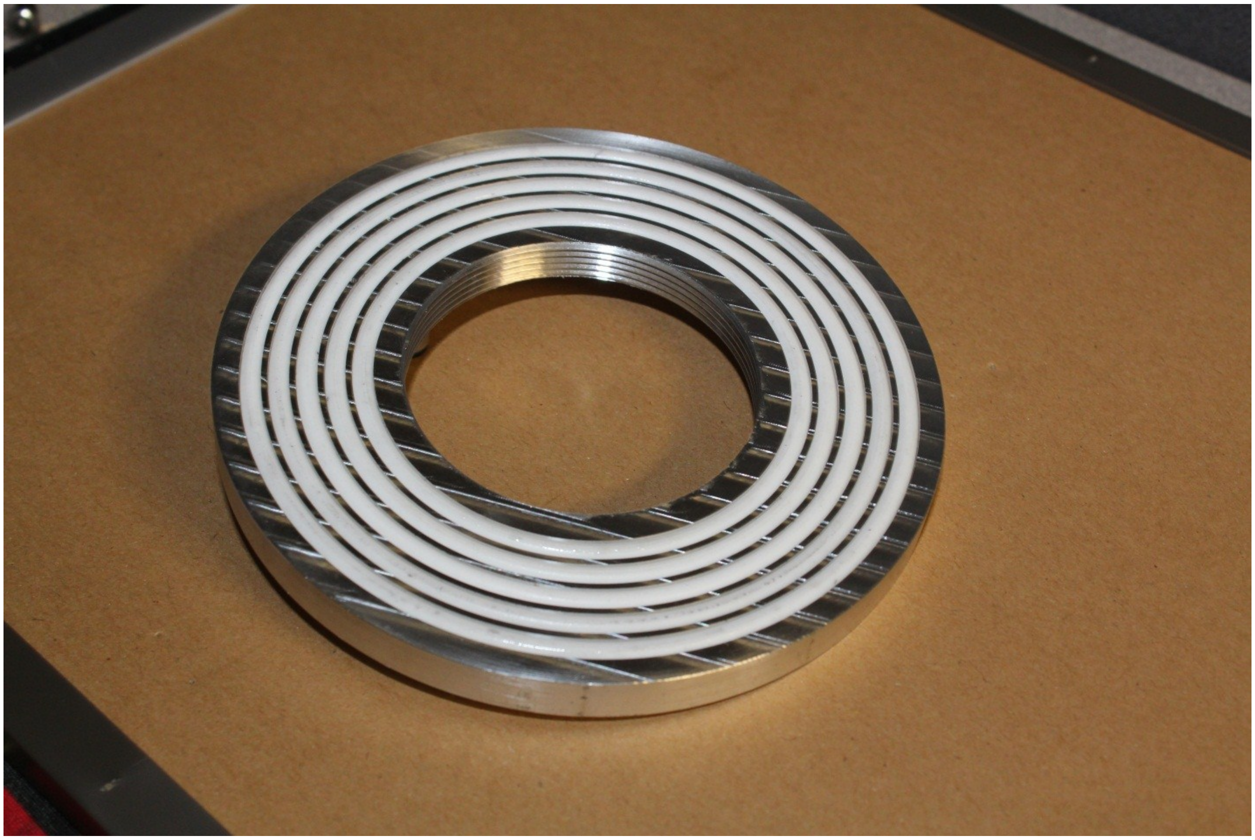


Figure 16: Lower Half of the Rotary Union with Teflon O-Rings

After the two halves of the rotary unit were assembled, with fittings and tubing connected, the rotary union failed to adequately seal. One possible explanation for the failure is that the clamping ring which compresses the two halves together may not have been large enough to provide adequate clamping force to compress the o-rings, creating the desired seals. Upon separating the two halves of the rotary union, it was observed through wear marks on the top half of the union that sections of the middle o-rings were not touching the top plate. Several factors could have contributed to the failure, most notably surface finish, flatness and parallelism across the top plate could have prevented the union from sealing adequately. If the top half of the union was concave in shape, air could leak out of the center of the union and cause the air leaks observed. The design of the clamping ring was a compromise between how large the ring could be made versus clearance considerations for the push-to-connect fittings that were used in the top half of the union. After these constraints were accounted for, the diameter of the clamping ring was maximized such that it would be able to still provide adequate clearance to the push-to-connect fittings.

7.4. Gripper Performance

When the gripper was assembled to the rest of the robot and air pressure was applied to the robot in its final implementation, the gripper exceeded initial expectations. When observing changes in logic condition (rotate, clamp/unclamp), the execution speed was under 1 second, which minimized the amount of time the controller must pause before it can continue program execution. Once the AGM-10 achieved the end of its travel rotationally, the pneumatic holding force acting on the rotary joint prevented any unintended changes in the orientation of the gripper. The same can be said for the gripper actuator; once the jaws had been fully opened or closed, they were held in place with remarkable force. Anecdotally, when the jaws of the gripper were clamped around the 1 inch stock material, it was impossible to get the piece of stock to fall by pulling the jaws apart. The same held true for the rotational section of the gripper; it was impossible to get the gripper to rotate after it had achieved its desired position. Figure 17 depicts the gripper in its final installed state. The fittings used to connect the pneumatic hose were 5/32” push-to-connect fittings which allowed easy connections to be made and allowed quick disassembly for diagnostics if required.

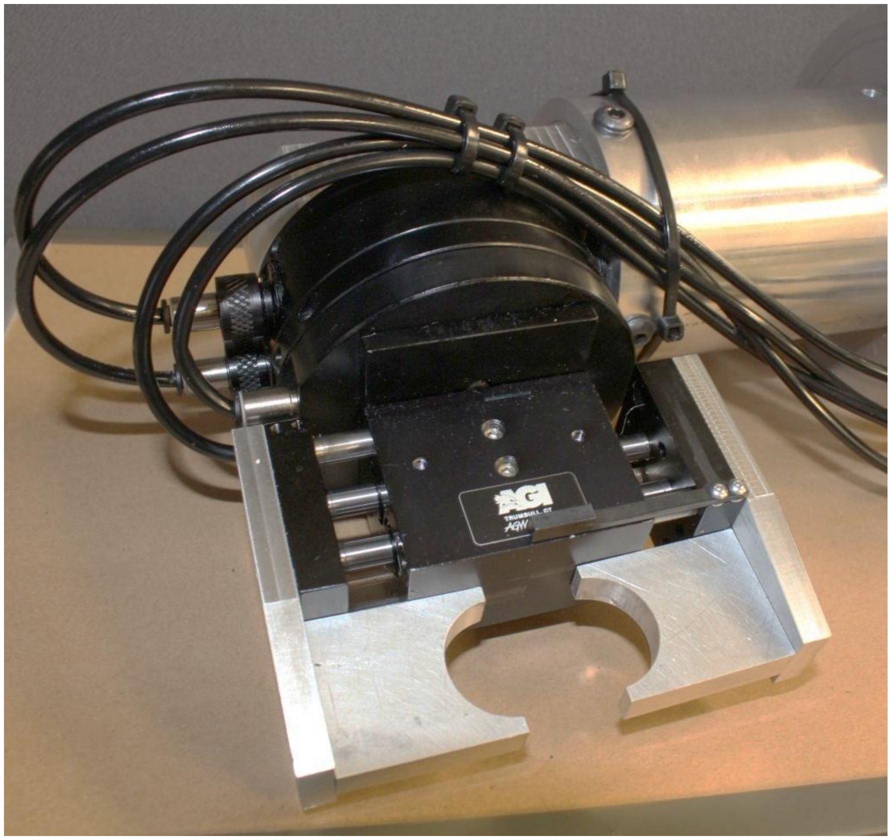


Figure 17: The AGI Automation AGR-10 Mounted and with 1" Round Bar Jaws Attached.

One minor issue that was observed after the construction of the grippers was that they did not align perfectly when the gripper closes; one side of the gripper rests higher than the other. When one jaw rides higher than the other, the stock is tilted slightly out of alignment with the spindle's vertical axis. This could contribute to misalignment in the stock's vertical orientation when it went to place it into a fixture or into the stock rack, which could cause the robot to improperly load the stock into the collet fixture. In the best case scenario, when the jaws released, the stock would fall into the collet and be secured in place; however, relying on luck alone to load parts is an unacceptable way to run a program. The difference in jaw height was attributed to manufacturing tolerances, which despite as much attention to detail as possible, still affected the end result.

7.5. Sensor and Program Performance

At every step in program execution, the overall safety of the system was the main priority. As of 4/24/2012, a new Haas VM-3 costs approximately $89,995 base price.[8] With the $5,195 probe option currently installed, the overall cost of the machine illustrates that ensuring that the machine's mechanical components do not become unintentionally modified is of the utmost concern. To facilitate this end, safety steps in each section of the programming were implemented to make sure that the machine's various conditions (table positions, probe functionality, etc.) and robot functions (gripper and rotary states) were asserted at each step in the part-handling process. In other words, prior to movement of any piece of machinery (robot or mill), every condition was accounted for so that the machine would not crash because of an unknown robot or mill state. An example of safe movement practices can be seen in Figure 18. At the beginning of the program, the machine safely moves the spindle head all the way up so that it can clear any fixturing that it might collide into if it were to move the table in the X or Y direction.

```
%
O09344 (PICK UP PART 2)

G00 G53 Z0 (SAFE Z HOME)
G00 G53 X-38.4176 Y-17.673
M59 P1147 (VERIFY OPEN JAWS)
G00 G53 Z-14.8
G01 G53 Z-16.7 F25.
M59 P1145 (CLOSE JAWS)
G04 P1.
G01 G53 Z-15.1
G00 G53 Z0 (SAFE Z HOME)

M99
%
```

Figure 18: Example Safe Movement Code.

[8] Haas Vertical Machining Center. http://www.haascnc.com/vmc_mt.asp?webID=MOLD_MACHINE_VMC. Accessed 4/24/12.

After the control positions the robot arm above the second part, the control again performs a safety move which verifies that the jaws are open. If the jaws were closed, it would not load the part in the best case scenario; in the worst case, it could shear off the gripper jaws and crash the machine tool. After the jaws are verified open, it moves rapidly down to a safe height, approximately 2 inches above the top of the stock. From there, it performs a fine feed move so that it can gradually engage the stock without a sudden, jerking movement as the robot positions itself to pick the stock up. From there, the program commands the jaws to close, waits one second to allow the jaws enough time to close securely, then again fine feeds up out of the stock rack and then moves rapid back up to machine home. At each step of the way, safety was held in the highest regard to prevent any rapid motion around the stock area to minimize the risk of the robot colliding with a piece of stock. Because the jaws were only lifting a piece of aluminum less than a pound, it would not have mattered as much if a collision had occurred. Consider, however, the robot lifting a piece of 5 pound steel; a similar collision could produce disastrous results.

7.6. Wireless Intuitive Probing System (WIPS)

As was mentioned in the Methodology section, the WIPS system was used to set the work offset coordinates at each stage of the machining process and to verify that the part had been correctly loaded into the fixture. The Renishaw Inspection Plus series of macro programs, loaded into the machine tool's memory alongside the WIPS programming, was used as the main source of macro programming to move the probe around in the Cartesian machine coordinate system, make protected moves and set offsets. Especially in the offset verification subprogram, the available macro inspection programs were extensively used to protect the probe as it moved around the fixture area.

7.6.1. Protected Moves

Macro cycle O9810 is used to position the probe in a protected state; that is to say, it allows the probe to move around the workspace and, if the probe tip touches any object, it will safely bring the system to an emergency stop (e-stop) state. The machine will halt all motion and present the user with an alarm, indicating that a condition has occurred that it cannot recover from without human intervention. This cycle was used after the probe approaches the workpiece area centered over the work offset, and 5 inches above the Z coordinate of the work offset. A value of 5 inches was selected so that, in the event of an extraordinary circumstance that the robot misses loading the stock and it releases the material perfectly vertical, resting on top of the fixture, the probe would be able to catch this condition before it moved down any further into the workpiece and damaged the machine or probe. The objective of this move is so that, if the probe does not encounter any unexpected objects, it will be positioned approximately 0.4 inches above the part's top surface, ready to update the X, Y and Z offsets to prepare for machining. After the X, Y and Z offsets were updated, a protected move was made back up to 5 inches above the workpiece to safely clear away while inside the working envelope of the workpiece. From there, rapid movement was performed to bring the probe fully up in the Z home position.

7.6.2. Z Single Surface Measurement

The Z coordinate offset must be also set in order to properly locate the work offset in 3-dimensional space. Of all the offsets, X, Y and Z, the Z offset can wreak the most havoc in a machine tool. If it is not properly set, it can cause crashes as the machine may think the part is higher or lower than it is in actuality and either plunge the tool or spindle head into the part or fixture and crash the machine. For this reason, a single touch macro was used to segment code execution in the interest of allowing only the Z coordinate to be set at a given time. The rationale behind this decision is simple: if the machine enters an emergency stop mode, the operator in charge of fixing the machine's state would understand exactly which offset was being set at the time, allowing a more accurate diagnosis of the error condition to be ascertained. Figure 19 illustrates the simple Z Surface Measure macro.

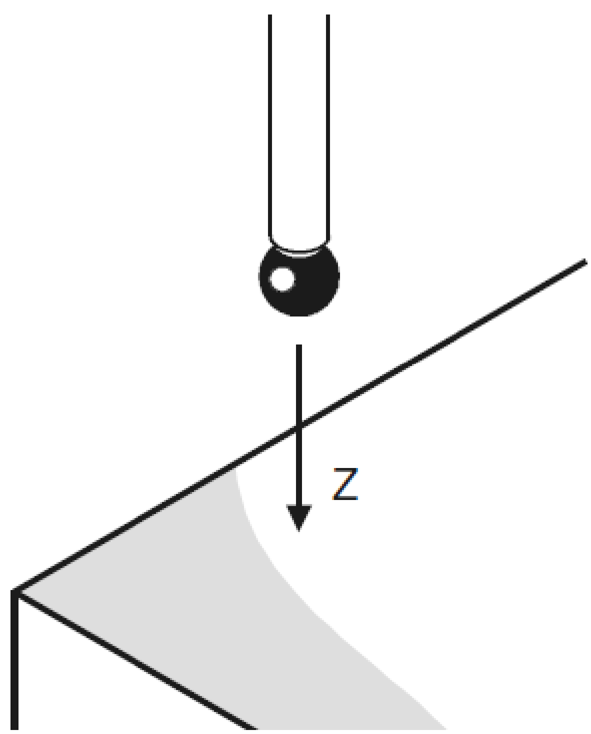


Figure 19: Z Single Surface Measure Macro

The performance of the Z Single Surface Measure macro was excellent, mainly due to two considerations: First, the part was loaded into the collet fixture with a part stop at the bottom to positively locate the workpiece in Z as it is placed into the fixture. This allows the probing cycle to execute at a consistent Z height part after part and adjust only for minute variations in stock length. Secondly, the probe is capable of touching the Z surface with up to +0/-0.400 inches of travel before it alarms out. This allows an acceptable amount of error to be present in the system (part length plus locational error) and still allow the probe to set an offset consistently. This robust program design permits the machine to run for longer because of the built-in allowances in the probing cycle. During testing, when the part was properly loaded into the collet fixture, an alarm condition was never raised due to errors in Z height measurement.

7.6.3. Probe Boss

After the Z surface offset was updated, it was necessary to then update the X and Y work offsets. The “Probe Boss” cycle was used to update the X and Y offset of a round surface it could touch on the outside. Figure 20 illustrates an example of how the Probe Boss macro was used to touch the circular feature on the outside of the workpiece.

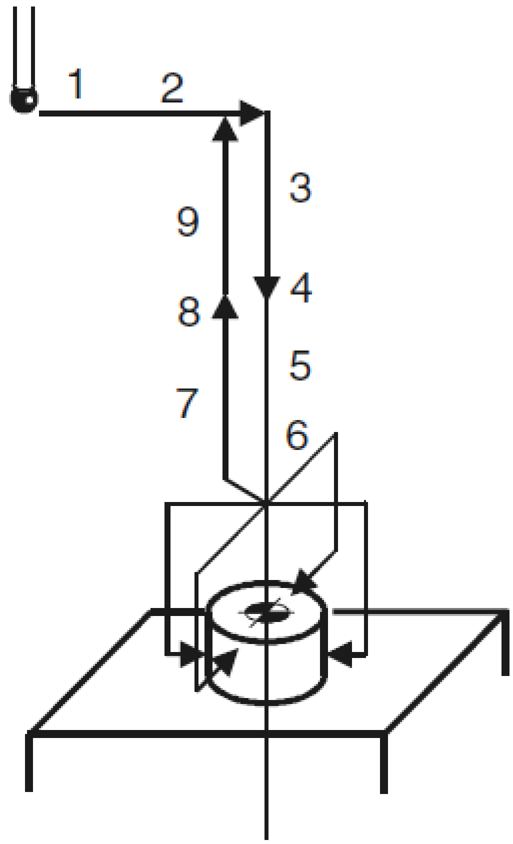


Figure 20: Renishaw "Probe Boss" Macro Example.[9]

In Figure 20, step number 6 in the inspection cycle shows the probe touching four sides of the workpiece. This is done to measure the center of the workpiece in X as well as Y. For the example application, working with 1 inch round stock, this macro was used because it precisely fit the requirement, which was to update the offset to the center of the stock in X and Y.

9 "Inspection Plus software for Haas machining centres." Renishaw, September 2002. http://my.wpi.edu/webapps/lobj-wiki-bb_bb60/wiki/MANUFACTURING-LABS/_620186_1/Home?cmd=GetImage&systemId=Inspection+Plus+for+Haas(2)__0.pdf. Accessed April 24, 2012.

8. Discussion

8.1. Economic and Ethical Considerations

The objective of this project was to design a small-form-factor robot which could operate inside the envelope of a Vertical Machining Center. One of the biggest barriers to entry for companies seeking automation is price, as was mentioned in the Background. In a commercial adaptation, this system could be marketed for $10,000 or less, which puts it in a league that no floor-mounted six-DOF robot could ever reach. Such a competitive pricing point could allow companies looking to make an initial foray into automation more willing to evaluate this product before moving into full-scale automation. Additionally, the ethical concerns of robotic automation must also be taken into account when designing a plan to automate a production line. Without support from floor staff, any efforts into implementing automation will be futile.

Often, when a company attempts to automate a production line and fails, the root cause can be narrowed down to two reasons: first, many operators and floor support staff view robots and automation as a threat to their job; they are therefore less inclined to help with or take any interest in the project. Secondly, the expectations of the customer and those of the manufacturer of the automation system and integration service are often at different ends of the spectrum. While automation can augment and supplement a production team, it cannot replace or supplant it. Keeping in mind that a robotically integrated system cannot maintain 100% uptime, it is inevitable that an error condition and e-stop state will be triggered by the machine at some point in time and require human intervention to solve the problem. Minimizing down time is of the utmost importance to a company's bottom line, but skilled and knowledgeable personnel are required to be present and on-site to address issues that may arise in the program, make modifications to code, and continually improve the process until downtime is minimized as much as possible. For this reason, companies cannot expect that robotic automation will replace their workforce; instead, automation can help make a workforce more productive working alongside human operators.

8.2. Health and Safety Considerations

One of the biggest problems associated with automation is how to ensure that human operators and attendants stay safe while working in and around such manufacturing cells. As was mentioned in the Background, larger floor-mounted robotic systems prevent users from intrusion through the use of cages or light curtains. The advantage of this robotic system is that there is no need for such devices as the robot is already contained inside the sheet metal shielding that makes up the machining center's exterior. This maximizes safety, as no operator would be able to open the machine's doors while the robot was running to access components inside the machine without triggering an e-stop state.

8.3. Reliability Considerations

A major concern in automation is whether a robotic system, once implemented, can operate reliably unattended for extended periods of time without incurring downtime or breaking. While the objective of this MQP was to design a prototype capable of providing a proof of concept, once concerns such as those with the rotary union and pneumatic interface are addressed, the results of the Mechanical Analysis section proves that the robot is structurally sound and capable of withstanding large part weights with miniscule amounts of deflection.

Thus, there is no reason why the robot cannot perform reliably for extended periods of time without human intervention assuming that the programming is sound and loads parts in the correct X and Y coordinate.

8.4. Use of Standards

Since there is very little prior art established to support this project, no standards exist for this application of a robotic interface to a VMC. It hoped that, if a future MQP group were to undertake improvements upon this prototype, a standardized programming hierarchy and format could be established to facilitate easier programming, including part inventory and machine operation management.

9. Recommendations for Further Innovation

9.1. Spindle Pneumatic Interface

One of the most obvious issues facing the project is that of how to obtain proper sealing on all four ports of the spindle interface. Obviously, it is difficult to achieve a perfect seal given the constraints in mind; however, there are several improvements that could be made to facilitate a more consistent and reliable seal.

One potential fix would be to manufacture the entire top half of the rotary union out of a solid billet of material. Unfortunately, during the course of this project, after the top half was machined, clearance issues arose later on that were unforeseen which forced the re-design of the spindle interface. This meant that the bond between the top half of the rotary union and the base onto which the fittings screw into resulted in an interface that could deflect under loading when the pneumatic fittings are pressed against the spindle block. If the top half of the union was manufactured out of a solid billet, this issue would be resolved and would yield a more reliable interface.

The next issue concerns the pneumatic fittings. Because the fittings were custom-designed, it was difficult to prevent them from unscrewing from the base and required the use of locknuts to fix the fittings in place. In a future adaptation, a custom-designed block that contains fittings for all 4 channels in one solid piece of aluminum could solve this issue entirely by removing the potential for movement from the equation.

9.2. Pneumatic Rotary Union

As was discussed in the Results section, the rotary union failed in part due to manufacturing tolerances. An improved design could research a superior method of sealing four pressurized channels of air, which may involve an entirely different apparatus being designed and constructed. Furthermore, a different rotary union from Rotary Systems (or other manufacturers) could be evaluated for this purpose and integrated into the robot, which would provide a professional solution without any of the associated problems of the custom-designed union that the project used.

9.3. Gripper Jaws

The gripper jaws offer numerous possibilities for additional clamping methods to be examined and potential grippers to be manufactured. For example, flat bar stock, hexagonal stock and square stock could all be used with this gripper and perform exceedingly well. Additionally, the gripper unit itself can be indexed 90 degrees such that rotation can now be done between 90° and 270°. While this may or may not be of functional interest to a future group, it could present unique opportunities to experiment with unique fixturing method and allow parts in unconventional orientations to be manipulated.

9.4. Programming

The programming aspect of this project can be expanded upon greatly and improved tremendously. One such example is the inventory/stock management system. While two parts were chosen as proof of concept, macro programming can be implemented to manage a large stock rack containing hundreds of parts easily. Additionally, there are numerous opportunities to improve and optimize the movement of the machine tool to speed up production, remove unnecessarily long wait times, and improve upon the error handling capabilities of the system. One example would be a family-of-parts, where a fraction of the stock rack is dedicated to one part program, while the other half is dedicated to a different part program. Each of these part sets might require different fixturing, offset measurement and manipulation methods, so there represents a large segment of this project that remains unexplored that could strengthen the marketability of the platform.

One potential Computer Science MQP could focus on external communication with a computer attached to the RS-232 port on the side of the VMC. The program could transmit information from the VMC’s operational status, such as spindle load, e-stop state, running time or cycle time, axis loads, alarm messages and other useful information to the computer. In turn, the computer could serve a website, or even more cutting edge, a mobile app running on an

Android or iOS device which could be viewed remotely to monitor the status of the machine. Additionally, there could be a waterproof webcam mounted inside the machine so that the viewer of the app could see a live video feed inside the machine to see exactly what the machine is doing at any given time. While the video feed and app programming would have to be run on the computer serving the app, the data transmission from the VMC out of the RS-232 port could be done entirely in macro programming to make the monitoring of data seamless and require little external interfacing on the part of the PC.

9.5. Sensor Input

One potentially useful adaptation of the gripper could include the outfitting of low-voltage proximity sensors to the gripper/rotary unit. Each half (gripper and rotary) have pre-fabricated locations to install proximity sensors to detect each state of the gripper. One theoretical project could integrate the sensors into a low-power microprocessor and wireless transmitter housed inside the robot’s vertical tube extension, which would transmit to a receiver and communicate the condition of the rotary/gripper unit to the machine’s controller. One possible application of this could include extra-heavy stock material that may require a long period of time to rotate; the integration of sensors to detect gripper condition could allow the machine to pause until the rotary unit finishes flipping the stock material over. Addition of sensors would provide an additional safeguard against unforeseen circumstances such as air pressure loss, accidental collisions with fixturing or stock slipping out of the gripper jaws thereby increasing the system’s reliability and safety.

10. Accomplishments and Summary

The primary objective of this MQP was to produce a functional prototype robot. Necessarily, a primary focus on mechanical design and manufacturing was required in order to produce a working robot. The student took on the project by himself, with the objective to produce a fully-functioning robot out of an idea and an interest in the automation of the manufacturing industry. With the success of the project in mind, it is a significant testament to the student's determination to see the project through to the end. Given additional group members, additional functionality and an even higher-quality implementation of the project could have been realized.

11. Conclusion

Robotic automation in the field of manufacturing can offer numerous advantages, including higher productivity, the ability to run lights-out manufacturing 24/7, and minimizing scrap rate through consistent and repeatable process management. The objective of this project was to design and manufacture a tool-changeable robotic arm for use in a Vertical Machining Center. Since no specific prior art exists for this particular area of manufacturing automation, this project may serve as a base point onto which future MQPs could build upon if they desire. Through a decision matrix, the AGI Automation AGM-10 rotary and gripper module was selected as the actuator for the robot. After solid modeling in SolidWorks, a completed model was analyzed using stress testing to determine the maximum deflection of the robot with a 5lb. force pressing down on the gripper, which was 0.00015 inches. This demonstrated that the robot's mechanical design was sound and that it could support heavy stock material and remain functional and perform well. After manufacturing the components to construct the robot, the various interfaces were adjusted and evaluated to achieve a working prototype. Issues were encountered with the rotary union and pneumatic couplings failing to seal properly, which forced a workaround to still allow the robot to function albeit without the use of the M19 spindle orient function. After the mechanical issues were resolved, programming code was implemented to interface the robot to the machine tool. After all code had been written, the system was evaluated to see if it successfully was able to satisfy the system objectives. After minor positioning adjustments had been made, the system successfully ran and fulfilled the outlined objectives.

This Major Qualifying Project has been an incredible learning experience that began as an abstract idea, morphed into a rough design evaluation, transformed into a solid model and finally into a concrete physical manifestation of the project inspiration. The lessons learned throughout each stage of the project will prove invaluable in applying the knowledge gained here to project work in a professional environment.

Appendix A: Control Software Source Code

MQP MAIN PROGRAM

```
%
O09337 (MQP MAIN PROGRAM)


(G154P1 FIXTURE OFFSET)
(G57 BACK RACK)
(G58 FRONT RACK)

(G59 PART OFFSET)

(T22 BACK RACK TOOL OFFSET)
(T23 FRONT TOOL OFFSET)

M98 P9339 (PICK UP PART 1)
M98 P9341 (PLACE PART IN FIXTURE)
M98 P9338 (INSPECT PART)
M01 (OP1 GOES HERE)
T24 M06
M98 P9342 (FLIP PART)
M98 P9338 (INSPECT PART)
(OP2 GOES HERE)
T24 M06
M98 P9343 (PUT AWAY PART 1)
M30
M98 P9344 (PICK UP PART 2)
M98 P9338 (INSPECT PART)
(OP1 GOES HERE)
T24 M06
M98 P9342 (FLIP PART)
M98 P9338 (INSPECT PART)
(OP2 GOES HERE)
T24 M06
M98 P9345 (PUT AWAY PART 2)
M30
%
```

INSPECT PART

```
%
O09338 (MQP INSPECT PART)
G103 P1
G00 G53 Z0 (SAFE Z HOME)
T25 M06 (TOOLCHANGE TO TOOL 25)
G43 H25 (LENGTH COMP)
G00 G59 X0 Y0
G00 Z5.
G65 P9832 (TURN ON PROBE)
G65 P9810 Z0.4 F25. (PROTECTED POSITION MOVE)
G65 P9811 Z0 S6 (PROBE Z SINGLE SURFACE, UPDATE G59 WORK OFFSET)
G65 P9814 D1. Z-0.5 S6 (PROBE BOSS 1 INCH DIAMETER .5 DEEP UPDATE G59 XY)
G65 P9833 (TURN OFF PROBE)
G00 G53 Z0 (SAFE Z HOME)
G103
M99
%
```

MEASURE PART LENGTH

```
%
O09340 (MEASURE PART LENGTH)
(T = #20)

G00 G53 Z0. (SAFE Z HOME)
G00 G53 X-8.1776 Y-3.05
G01 G53 Z-12.57 F25.
G65 P9815 T [ #20 ]
G00 G53 Z0
M99
%
```

PICK UP PART 1

```
%
O09339 (PICK UP PART 1)

G00 G53 Z0
G00 G53 X-38.4176 Y-20.21
M59 P1147 (VERIFY OPEN JAWS)
G00 G53 Z-14.8
G01 G53 Z-16.7 F25.
M59 P1145 (CLOSE JAWS)
G04 P1.
G01 G53 Z-15.1
G00 G53 Z0
M99
%
```

PUT AWAY PART 1

```
%
O09343 (PUT AWAY PART 1)

G00 G53 Z0
M69 P1146 (GRIPPER 0DEG)
M69 P1145 (OPEN GRIPPER)
G00 G53 X-16.7346 Y-6.954
G00 G53 Z-14.
G01 G53 Z-15.8642 F10.
M59 P1145 (CLOSE GRIPPER)
G04 P1.
M69 P1144 (OPEN FIXTURE)
G04 P1.
G00 G53 Z0
G00 G53 X-38.3476 Y-20.157
G00 G53 Z-15.5
G01 G53 Z-17.08 F10.
M69 P1145 (OPEN)
G04 P1.
G00 G53 Z0
%
```

PICK UP PART 2

```
%
O09344 (PICK UP PART 2)

G00 G53 Z0 (SAFE Z HOME)
G00 G53 X-38.4176 Y-17.673
M59 P1147 (VERIFY OPEN JAWS)
G00 G53 Z-14.8
G01 G53 Z-16.7 F25.
M59 P1145 (CLOSE JAWS)
G04 P1.
G01 G53 Z-15.1
G00 G53 Z0 (SAFE Z HOME)
M99
%
```

PUT AWAY PART 2

```
%
O09343 (PUT AWAY PART 1)

G00 G53 Z0
M69 P1146 (GRIPPER 0DEG)
M69 P1145 (OPEN GRIPPER)
G00 G53 X-16.7346 Y-6.954
G00 G53 Z-14.
G01 G53 Z-15.8642 F10.
M59 P1145 (CLOSE GRIPPER)
G04 P1.
M69 P1144 (OPEN FIXTURE)
G04 P1.
G00 G53 Z0
G00 G53 X-38.3476 Y-17.673
G00 G53 Z-15.5
G01 G53 Z-17.08 F10.
M69 P1145 (OPEN)
G04 P1.
G00 G53 Z0
%
```

PLACE PART IN FIXTURE

```
%
O09341 (PLACE PART IN FIXTURE)

G00 G53 Z0
M69 P1144 (VERIFY OPEN FIXTURE)
G00 G53 X-16.659 Y-6.944
G00 G53 Z-10.0692
G01 G53 Z-14.0692 F10.
M69 P1145 (OPEN JAWS)
G04 P1.
M59 P1144 (CLAMP FIXTURE)
G00 G53 Z0
M99
%
```

FLIP PART

```
%
O09342 (FLIP PART)

G00 G53 X-16.7216 Y-6.9399
G00 G53 Z-13.
G01 G53 Z-15.8642 F10.
M59 P1145 (CLOSE GRIPPER)
G04 P1.
M69 P1144 (OPEN FIXTURE)
G04 P1.
G01 G53 Z-10.0692 F25.
M59 P1146 (FLIP GRIPPER)
G00 G53 Z-14.
G01 G53 Z-16.1502 F10.
M69 P1145 (OPEN GRIPPER)
M59 P1144 (CLOSE FIXTURE)
G00 G53 Z0
M99
%
```