University of Southern Indiana

Pott College of Science, Engineering, and Education
Engineering Department
8600 University Boulevard
Evansville, Indiana 47712

Mill Bot Mk1

Re-Implementation of the 5-axis milling robot into the Applied Engineering Center

Ryan Roy and Cristian Dominguez Lopez
Faculty Advisor: Brad Kicklighter, P.E.
MFET 491 – Senior Design
Fall 2024

ACKNOWLEDGMENTS

We would like to acknowledge Dr. Kuban, Mr. Kicklighter, Dr. Ely, Mr. Kevin Nelson, University of Southern Indiana professors, fellow peers, and our parents. Without the help of everyone, this project would not have been possible. The support of those around us means everything and is immensely appreciated.

ABSTRACT

This project was created to re-implement a 5-axis milling robot into the Applied Engineering Center floor space. A senior design team in 2019 created a custom CNC spindle end tool for the Kawasaki RS-03N robot to create a 5-axis robotic mill. A 5-axis mill operates along the standard X, Y, and Z axes, as well as the A (rotation about the X axis) and B (rotation about the Y axis).

However, after the previous team had proven their results, the spindle attachment was disconnected and stored in a cabinet for the last five years with no use. This project's purpose was to design and implement a safety cage and work piece mount for the robotic work cell to keep operators and surrounding personnel safe while the mill is in use. We developed a full-scale three-dimensional computer aided drafting (CAD) model of the work cell to enhance usability for operators in the robot programming software. Additionally, the safety cage will function as a dust containment system for easy clean up after the milling operation has completed. Through this project, the robotic mill was re-implemented for regular use, and process documentation and standard operating procedures were created to train students and staff in the use of the robot mill. Professors may also use the documentation as a resource in their course curriculum for teaching in lecture and lab.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF APENDICIES

1. INTRODUCTION

In manufacturing, there are many processes that can be used to create a desired product. Automated manufacturing is one of the most popular categories used as a whole. One type of automated manufacturing is Computer Numerical Control (CNC) milling, which is the process of machining using rotary cutters much like a drill bit to remove material by advancing a cutter controlled by computer software, into the workpiece. This can be accomplished through varying directions of the cutter on one or more axes, changes in cutter speed, and feed rate. Milling covers a wide variety of different operations on many types of machines, on scales from small individual parts to large, heavy-duty milling operations. It is one of the most used manufacturing processes for machining custom parts to precise tolerances. Reference Figure 1 to understand the basics of a cutting head in a mill.

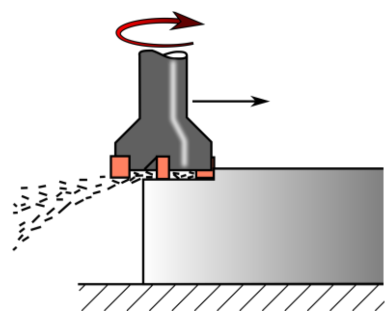

Figure 1: How a Cutting Head Works for CNC Milling [1a]

The two most common types of CNC mills are 3-axis and 5-axis mills. A 3-axis CNC mill operates in the standard X, Y, and Z axes. The 3-axis CNC mill is used when a part has simple geometries such as face milling (creating flat surfaces perpendicular to the tool axis), slot milling (cutting grooves or slots into the workpiece), and pocket milling (removing material to create a recessed area or cavity). The comparison of the two can been seen in Figure 2. However, due to the nature of the 3-axis mill and its constraints, it is not always the best choice for machining a part. The 5-axis mill comes into play when a part containing complex geometries outside of the standard 2-D plane. A 5-axis mill can operate in the X, Y, Z, A, and B axis. The A axis is a rotation about the X axis and the B axis is a rotation about the Y axis. Refer to Figure 3 to visualize the rotation about each of the axes. Adding the A and B axis to a mill's capability substantially increases the capabilities of the machine. 5-axis mills excel at machining parts with complex 3D curved surfaces such as turbine and propeller blades. A 5-axis mill also has increased efficiency due to its ability to access multiple sides of the work piece at one time, which leads to less need for changing setups in between processes. For a 3-axis mill, if the operator needs to machine on a new face, they must stop the machine, take the piece out of the mount, then re-mount the piece with the correct orientation. On that same note, a 5-axis mill can be more accurate for several reasons: Every time a part must be repositioned in a 3-axis mill, there is a chance the part may not be repositioned in the correct spot, leading to inaccuracies. Another example is 5-axis mills can reach complex geometries such as deep cavities, overhangs, and intricate features. A 3-axis mill can process these geometries as well but often requires long tool extensions which can lead to inaccuracies.

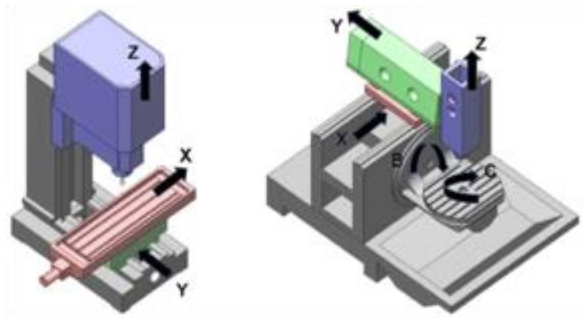

Figure 2: 3-Axis vs. 5-Axis Mill [2a]

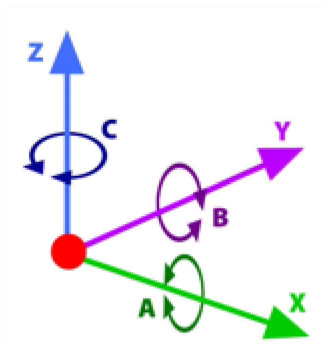

Figure 3: The 3 Axes and Their Rotations [3a]

Back in the spring semester of 2019, Logan Miller and Zachary Rice pursued their senior design project in creating a robotic 5-axis milling system. Throughout their project, they designed a custom milling spindle end tool for the Kawasaki RS03N robotic arm and the electrical system for the motor driver, seen in Figure 4.

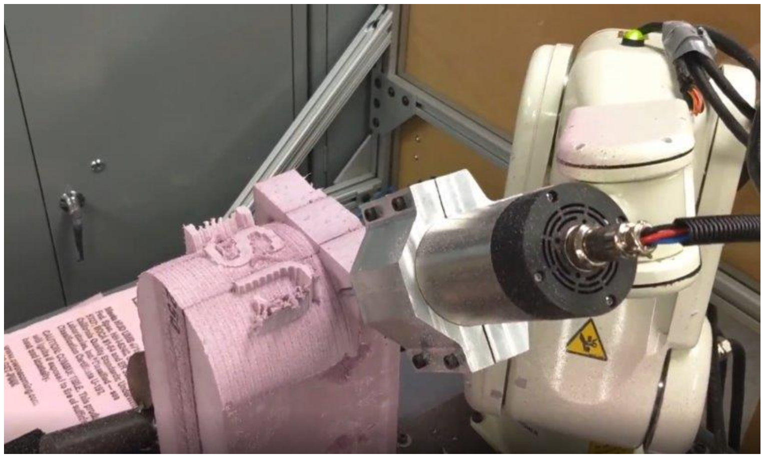

Figure 4: 2019 Senior Design Project

2. BACKGROUND

2.1 STATEMENT OF PROBLEM

The Applied Engineering Center does not currently have a robotic 5-axis mill. The only milling capabilities at the Applied Engineering Center currently are 3-axis CNC milling machines. The absence of a 5-axis milling machine holds back the Applied Engineering Center's ability to manufacture advanced and complex components with efficiency and precision. This limits the scope and complexity of the parts produced for the Applied Engineering Center and Center for Applied Research.

The introduction of a 5-axis milling robot is important for the Applied Engineering Center to bridge the technological divide and enhance its manufacturing capabilities. The proposed project aims to address this deficiency by designing, implementing, and integrating a 5-axis milling robot into the Applied Engineering Center. This solution will extend the Applied Engineering Center's machining capabilities and aid the production of complex components needed for innovative engineering projects. By introducing this robot as an educational tool into the Applied Engineering Center, it will enable students to gain valuable skills in advanced manufacturing processes. The introduction of this robot will also have an environmental impact. The Kawasaki RS03N robots are no longer in use due to a change in the engineering curriculum.

Our Mill Bot will primarily be used by the Center of Applied Research due to its nature. The Mill Bot has low tolerances and would not meet manufacturing standards required in many student projects that use the Applied Engineering Center's resources. However, even CAR will only be able to use the Mill Bot for prototyping. This may be beneficial to CAR as they will be able to provide a prototype to the customer for proof of concept to show.

Our secondary application we have for the Mill Bot is its implementation into course curriculum withing the Engineering Department on campus, which can have a positive educational cultural impact on USI. Currently the Manufacturing Engineering Technology program is under renovation and is creating new classes with a new curriculum. Our robot mill could be implemented into said curriculum for professors to use during lab sessions. For professors to implement our work, they will need documentation of operations for the robot. We will create Standard Operating Procedures (SOPs) and will document all our processes for professors to select what they will implement into their classes in the future. We also find it important to create SOPs for students and staff to become trained on the robot mill.

With the re-implementation of the Robot mill, our goal is to give it a permanent place in the Applied Engineering Center as well as leaving a positive economic impact with the Kawasaki RS03N robots no longer in use. However, like all tools and machines in the Applied Engineering Center, there are risks of injuries while using machinery. Our robot will use a high-speed spindle that can pose many risks to student and staff safety. We will design and implement a safety system/barrier that will contain the robot internally and keep any part of a student of faculty's body from entering the work cell while it is in use. A secondary benefit of implementing the safety barrier is to aid in dust collection. When milling into foam and wood, a large amount of dust is created. This can pose an inhalation risk as well as a fire hazard. Our barrier will contain all the dust that may then be collected by vacuum after the milling process has completed.

2.2 REVIEW OF EXISTING SOLUTIONS AND/OR REVIEW OF RELEVANT LITERATURE

Retrofitting robotic arms with milling spindles is a common practice in some manufacturing industries. Many companies decide to retrofit robotic arms by adding external spindle motors and Variable Frequency Drives (VFDs). This approach creates a cost-effective solution compared to purchasing a dedicated 5-axis milling machine. Our project aims to extend this practice at the benefit of the Applied Engineering Center by retrofitting a Kawasaki robotic arm with a milling spindle, providing high-quality 5-axis milling functionality at a significantly lower cost than buying a new milling machine.

Currently, the Applied Engineering Center does not own a 5-axis mill, which would typically be a large investment. However, they do own several Kawasaki robotic arms. Retrofitting these robots with milling spindles is an economically and environmentally aware alternative. Retrofitting will not only enable the same quality and functionality as a 5-axis mill, but it will also contribute to the center's sustainability efforts by preventing the disposal of obsolete robots as the center transitions to newer collaborative robotic systems. Repurposing existing assets in this way aligns with industry trends toward minimizing waste and optimizing the use of resources.

Universities across the United States are increasingly adopting robotic arms for advanced manufacturing research and teaching purposes. For example, institutions such as Massachusetts Institute of Technology (MIT) and Stanford University are actively using robotic arms with spindle attachments to prototype and fabricate complex components [1] [2]. MIT's Digital Manufacturing Laboratory focuses on integrating robots with high-speed spindles to enable rapid prototyping for aerospace and automotive applications, demonstrating that this technology is not only practical but highly versatile. Similarly, Purdue University has incorporated 5-axis robotic milling into its manufacturing research, allowing for complex geometries to be machined with high precision, further confirming the potential for robotic arms to serve as cost-effective alternatives to traditional 5-axis CNC mills.

Additionally, industry leaders such as Boeing and Siemens have adopted robotic milling for both prototyping and production, particularly in areas requiring highly customized and complex parts [3]. Additionally, industry leaders such as Boeing and Siemens have adopted robotic milling for both prototyping and production, particularly in areas requiring highly customized and complex parts. This wide adoption across both academia and industry highlights the potential of robotic arms to function as flexible and powerful machining tools when equipped with the proper spindle attachments and VFD systems [4] [5] .This wide adoption across both academia and industry highlights the potential of robotic arms to function as flexible and powerful machining tools when equipped with the proper spindle attachments and VFD systems.

In 2019, Logan Miller and Zachary Rice at the Applied Engineering Center designed an initial milling system attached to Kawasaki robotic arms, focusing primarily on the mechanical design aspects. After extensive trials and analysis, they successfully developed a system capable of milling desired designs from foam blocks, proving the feasibility of this setup for 5-axis milling operations. However, since its completion, the spindle attachment has remained in storage and unused. The existing VFD system remains attached to the workstation, but the system encountered issues connecting the VFD to the spindle. Considering this, our team has decided to replace the outdated VFD with a new, updated VFD and spindle bundle to ensure reliable operation and improved performance.

2.3 SYSTEM HIERARCHY

The system hierarchy shown in Figure 5 depicts the breakdown of all the systems of our project. Because the Robot system is owned through USI, it is the highest point in the hierarchy. The robot will be used in academic courses through the engineering department. Due to the electrical requirements and hazards associated with the system, the robot must be based out of the Applied Engineering Center. The robot lies out on the main bay floor of the Applied Engineering Center which is considered lab space for classes. Out on the main floor, the Applied Engineering Center offers multiple machines with different capabilities that can be categorized under four main types of manufacturing: Automated, Manual, Additive, and Printed Circuit Boards (PCB)/Welding/Etc. A robotic system falls under the Automated Manufacturing category along with CNC mills and lathes. The Robo-Mill Mk1 then can be broken down into its subsystems which are covered in section 4.1.

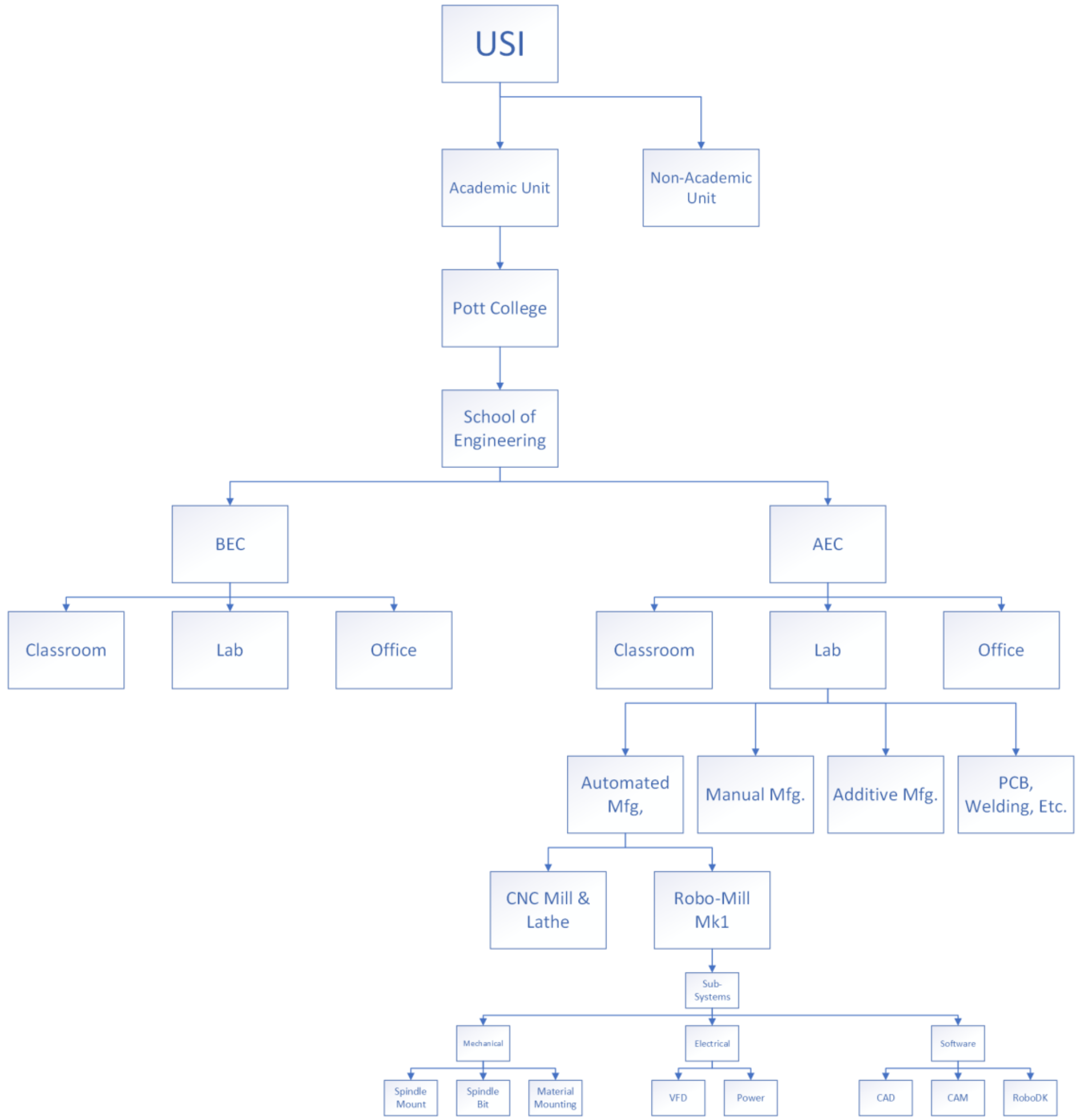

Figure 5: System Hierarchy Diagram

3. CONCEPTUAL DESIGN

3.1 REQUIREMENT SPECIFICATIONS

The specified requirements for Mill Bot MK1 are tailored to the process of the Mill Bot work cell. They focus on the robot's payload weight limit, safety implementations, a dimensionally accurate simulation environment in Robo DK, and dimensional accuracy. The requirements for our project come from the research done by Logan Miller and Zachary Rice as they designed the milling system for the robotic cell. The two main requirement specifications are:

- Weight of Spindle: <≈3 kg
- Physical barrier on work cell to contain dust and protect operator
- A dimensionally accurate robot simulation environment
- Accuracy +/- 0.20 mm

The Weight requirement for the spindle comes from the maximum payload capacity listed on Kawaski's website of the Kawasaki RS03N (Kawasaki Heavy Industries, Ltd. & Kawasaki Business Division, 2020).

For the physical barrier, it is required in the Occupational Safety and Health Administration (OSHA) standard 1910.212(a)(1) that any machinery with moving parts that could pose potential hazards to operators must be safeguarded to prevent injuries. This includes guarding points of operation, pinch points, rotating parts, and other areas where workers might be exposed to dangerous movements or forces.

The creation of the robot simulation environment is required for the visualization of the entire milling process from setup to execution. By incorporating the custom-designed CAD models, the simulation accurately reflects the physical dimensions and configurations of the work cell. This level of detail is critical for assessing the robot's movements, tool paths, and operational limits, enabling operators to find potential issues before implementation.

The accuracy rating for the robot was created by comparing the accuracy of a standard 5-axis mill. The average accuracy rating for a 5-axis mill across all companies comes out to +/- 0.13 mm. This means that the original dimensions of the CAM file will be recreated by the mill within 0.13 mm less or more than the original dimensions. We chose to decrease our accuracy rating due to the nature of our system. While 5-axis mills are designed to have extremely tight tolerances, our robotic system will not consist of high-end machinery and therefore will have very low tolerances by nature. This is one of the main reasons our robot will only be used for prototyping.

3.2 EVALUATION OF ALTERNATIVES

An evaluation of alternatives is important to any project to show why the presented solution should be selected over other alternatives. There are two alternatives the AEC could use to obtain a 5-axis mill. The first option would be to buy a new or used 5-axis CNC mill. The second option would be to create a 5-axis mill from a robot such as our project.

A 5-axis mill from Haas has a starting price of $133,895 [6]. For many manufacturers, this cost would not be large for the return on investment they would see from this large of a purchase. However, the AEC and Center for Applied research simply does not receive enough business from customers to justify this large of a purchase.

If the AEC were looking for a cheaper choice, they could purchase a 6-axis robot and attach a spindle to the end of the robot in the same manner that has previously been done in 2019. Used robot arms can be found for sale online for cheaper prices than buying new ones directly from the manufacturer. A FANUC LR Mate 200iD 7H from eBay can be listed from $11,000 up to $16,500 [7]. While this price may still seem high to some, it is a more manageable cost compared to $133,895 for a Haas 5-Axis mill. The next step would be to select a milling spindle and a VFD. A Spindle and VFD package can be found on amazon.com for $317.00 [8]. The cost of the robot and spindle bundle together is approximately $11,317.00 to $16,817.00.

The AEC currently owns three different types of Robotic Arms. First, the robotic arm we will use for our project is the Kawasaki RS03N [9]. These robots were used for TECH 272 and IME 422. The AEC also owns a Mitsubishi RV-3S-S11, and a Motoman SSA 2000.

4. SYSTEM DESIGN

4.1 SUBSYSTEM HIERARCHY

The Subsystem hierarchy shown in Figure 6 depicts the breakdown of all the subsystems of the Mill Bot Mk.1 by category. The breakdown of a subsystem hierarchy is important to understand the role each subsystem plays in the overall system. The mechanical aspect of the Robo-mill consists of the spindle, its mounting hardware, and the hardware and vise used to hold the workpiece in place. The electrical system contains the VFD to control the Spindle motor and the power to control the VFD and Robot itself. The final subsystem is the software. The CAD/CAM program such as SolidWorks will be used to design the workpiece and create the CAM file [10]. Robo DK will translate the CAM file to a .pg file that the Kawasaki robot can understand [11]. Robo DK also provides a visual simulation to ensure the robot will perform the desired tasks.

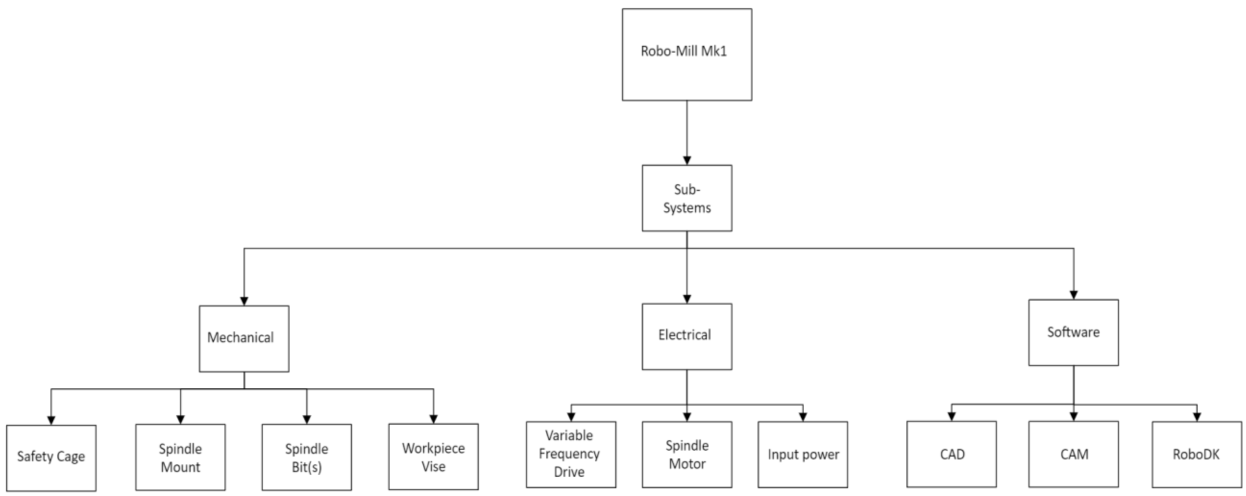

Figure 6: Subsystem Hierarchy

4.2 FUNCTIONAL BLOCK DIAGRAM/PROCESS FLOW

A process flow diagram can aid in the visualization of the process steps taken to execute the desired task. In Figure 7 the diagram shows the flow of the Mill-Bot process from digital creation to the physical creation of the desired part. The user or customer will create their part/workpiece in SolidWorks or their 3D CAD program of choice. They then must create a .nc file from their CAD file to send to the AEC to be processed. A nc file also known as numerical control code, is a programing language that instructs a CNC machine how to operate. Once at the Applied Engineering Center a student worker will upload the CAM file into Robo DK [12]. Once the file has been uploaded and the robot code has been written, it will be uploaded to the EC 8 teach pendant via a USB thumb drive from the computer to the robot. After the code has uploaded, the user will mount the workpiece to the worktable via a vise that is placed in a pre-defined space relevant to the robot's coordinate system. After the workpiece has successfully been mounted, the user will begin the robot program and let it take its course. After the program successfully executes, the user may remove the finished workpiece from the fixture and rejoice in their newly created part.

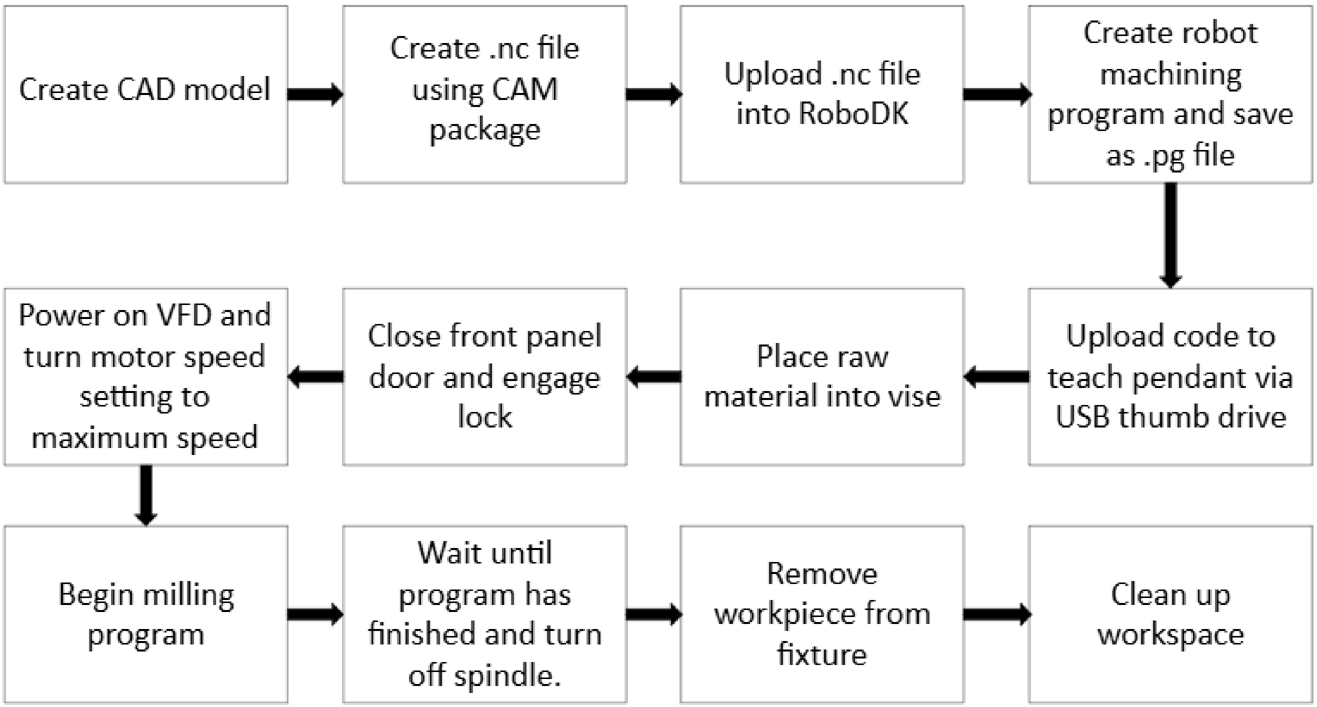

Figure 7: Process Flow Diagram

4.3 SAFETY CAGE DESIGN

OSHA standard 1910.212(a)(1) mandates that “any machinery with moving parts that could pose potential hazards to operators must be safeguarded to prevent injuries [13]. This includes guarding points of operation, ingoing nip points, rotating parts, and other areas where workers might be exposed to dangerous movements or forces.” While designing a safety cage to enclose a robot 5-axis mill, this standard would require that the enclosure be structured to prevent any operator from accessing the hazardous zones while the mill is in operation. The cage should be made of materials strong enough to withstand potential impacts from the machine's operation and should use secure locking mechanisms to ensure the machine cannot be activated unless the enclosure is correctly secured. By implementing such a design, the enclosure is aligned with OSHA’s requirements to protect employees from accidental contact with dangerous parts of the mill.

The safety cage is built with these standards in mind, ensuring that operators cannot access hazardous zones during operation. Ensuring both operator safety and compliance with OSHA standards. The cage provides a sturdy structural foundation while facilitating ease of assembly and disassembly being constructed from 1.5-inch by 1.5-inch T-slot aluminum. The choice of T-slot aluminum enhances the cage's structural strength and allows for future modifications or expansions, if the project requirements evolve.

Polycarbonate panels were selected for the windows of the safety cage due to their strength and impact resistance, providing a transparent barrier that allows for visibility into the work cell while providing protection against debris generated during the milling process. The decision to use polycarbonate over traditional glass was decided by its lightweight properties and higher safety ratings, reducing the risk of shattering, and promoting a safer working environment.

The design process began with an assessment of the robot's workspace envelope, including the length and width of the table it occupies, and the maximum vertical reach of the robotic arm. While the length and width of the cage are within the work envelope of the robot, the end tool can crash into the frame and polycarbonate panels. Later, the discussion of the Robo DK model will show how that error is avoided. In Figure 8 the workspace envelope can be seen and its location within the safety cage. Robo DK has three options to choose from for displaying the workspace envelope. We chose the “Show for current tool” option. This workspace envelope displays the maximum reach of the tool center point located at the very end of the mill bit.

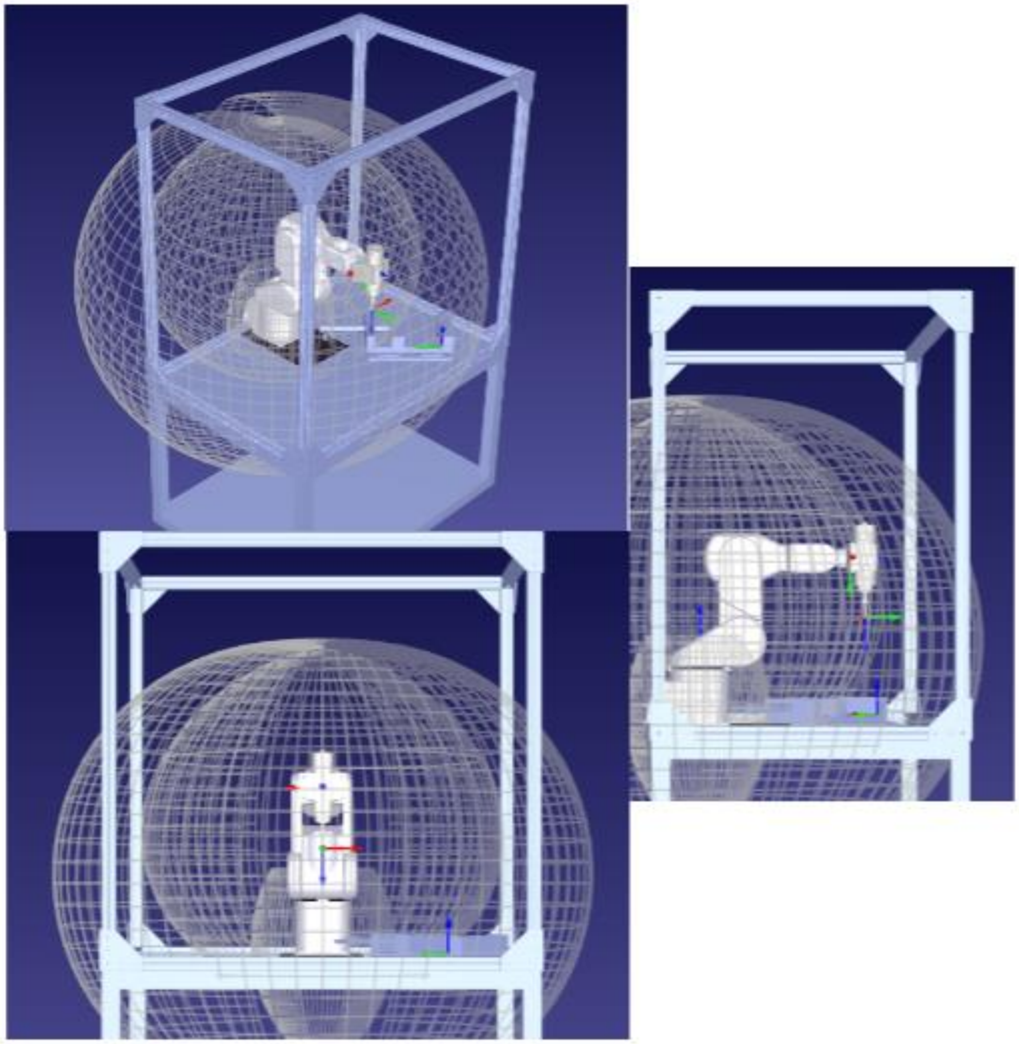

Figure 8: Workspace Envelope of Robot End Tool

A front-access door equipped with a handle and lock was integrated into the design, giving easy access to the interior of the work cell. This feature was carefully considered to balance accessibility with safety, allowing operators to enter the enclosure quickly while ensuring that the door could be securely locked during the robot's operation. The overall design was inspired by a previous senior design project that effectively used similar materials to enclose a vertical storage carousel machine. By getting inspiration from this existing design, the safety cage not only meets functional requirements but also shows some of the best practices in engineering design for operational safety and efficiency. One important safety feature is non-existent in our system. When the front-access door is opened, there are no safety sensors to pause the system operation. It is heavily recommended a future team implement this system to ensure safety compliance [14].

4.4 CAD FILES

The creation of a 1:1 scale work cell in Robo DK required the development of several critical CAD files, each representing important components of the robotic work cell. This process involved the design of the worktable, spindle motor and mount, safety cage, and vise, ensuring that all elements were accurately modeled to ensure realistic simulation and programming within the Robo DK environment. In the text below, a photo of the CAD model will be placed next to its real-life counterpart.

A key distinction in this project compared to previous design efforts is that the prior team relied on generic 3D models provided by Robo DK in their simulation. While these models allowed for a basic representation of the robotic system, they lacked the precision and visual representation needed for a detailed understanding of the workspace dynamics and interactions between components. By creating custom CAD files, a much more accurate representation of the work cell was provided, ensuring that the simulation environment mirrored the actual setup.

Starting with the worktable seen in Figure 9, a sturdy structure that serves as the foundation for the milling operation was designed. The table's dimensions were carefully calibrated to align with the specifications of the 5-axis robot worktable. Using CAD software, features such as mounting points and slots for clamping fixtures, which are essential for securing components during machining operations were used. The safety cage, previously discussed, was also modeled in CAD to ensure that it aligns perfectly with the physical dimensions of the assembled structure. This modeling was crucial for visualizing spatial relationships and confirming that the robot could run safely within the defined enclosure.

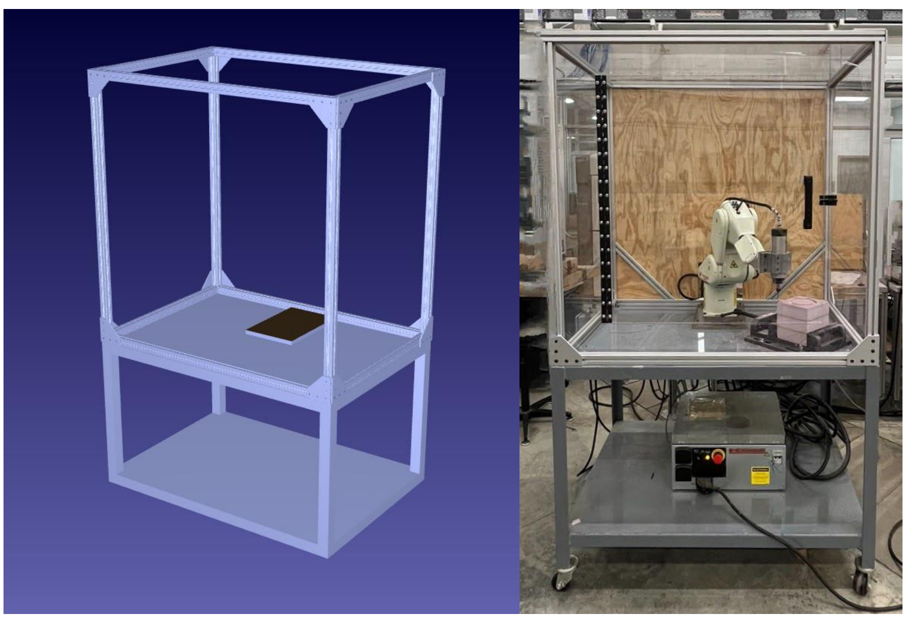

Figure 9: CAD Model of Worktable with Safety Cage

Next, the spindle motor and its mount seen in Figure 10 were focused on. The spindle is a critical element in the milling process, responsible for driving the cutting tool. A detailed model that includes the motor housing and mounting brackets was created. Special attention was given to the alignment, orientation of the spindle, and dimensions of the length as these factors directly affect the milling accuracy and efficiency. By accurately modeling these components, simulation of their interactions within the work cell could verify the robot's range of motion during operation.

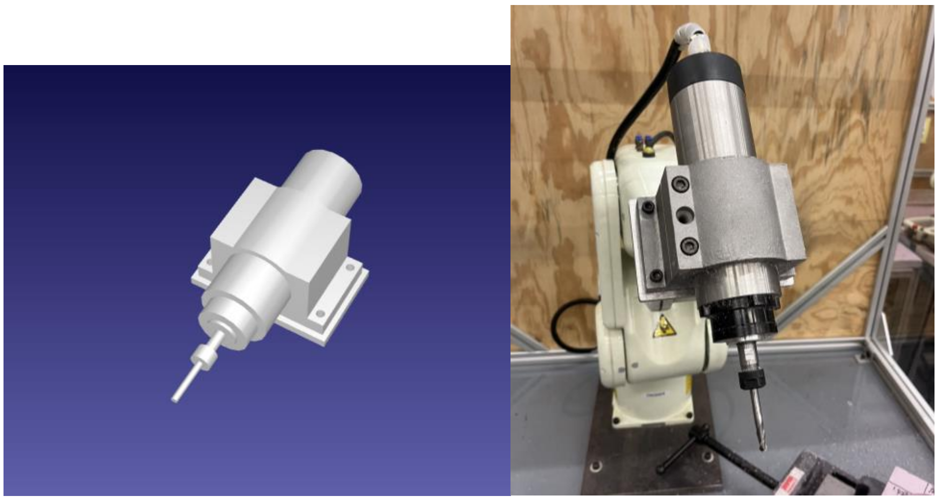

Figure 10: Spindle Motor and Mount CAD Model

Finally, the vise seen in Figure 11, was created to securely hold the workpiece during milling operations. The vise was designed to accommodate various workpiece sizes while providing a firm grip to prevent movement during machining. The CAD model included all necessary details, such as clamping mechanisms and alignment features, which are vital for achieving precise machining results.

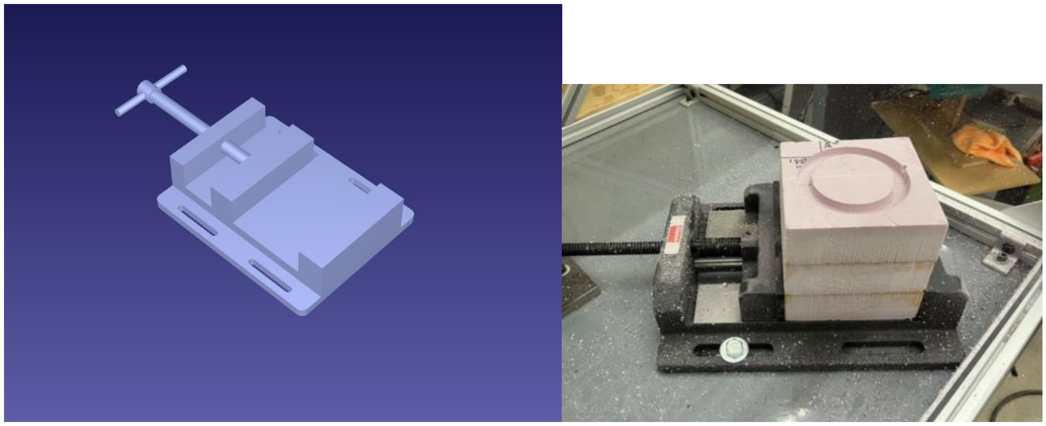

Figure 11: Part Vise CAD Model

The culmination of these CAD models created a cohesive representation of the entire work cell within Robo DK, enabling effective simulation and programming of the robotic operations. This virtual environment allows optimization of tool paths, collision detection, and process validation before implementation. By meticulously crafting each part in CAD, it was ensured that the digital model closely mirrored the physical assembly. In contrast to the previous team's approach, which relied on generic models, this comprehensive CAD approach provides a foundation for future enhancements and optimizations in the robotic milling workstation.

4.5 ROBO DK MODEL

The integration of custom CAD models into Robo DK played a significant role in developing a precise 1:1 scale simulation of the work cell for the Mill Bot. While Robo DK offers a model to scale of the Kawasaki RS03N robot itself, the remaining components such as the worktable, spindle motor and mount, safety cage, and vise were designed and imported to create a comprehensive virtual environment. This detailed approach ensures that all aspects of the work cell are accurately represented, creating effective simulation and programming.

An important feature of Robo DK to the design project is its built-in Robot Machining program, which aids in the simulation experience by allowing users to import .NC files. This functionality translates the G-Code instructions into executable tool paths for the robotic system, enabling the robot and its end tool to follow the created movements in a realistic manner. This capability is particularly valuable for assessing the milling operations, as it ensures that the simulated paths relate precisely with the intended machining operations.

The simulation environment in Robo DK allows for the visualization of the entire milling process, from setup to execution. By incorporating the custom-designed CAD models, the simulation accurately reflects the physical dimensions and configurations of the work cell. This level of detail is critical for assessing the robot's movements, tool paths, and operational limits, enabling operators to find potential issues before implementation. A picture of the Robo DK model can be seen in Figure 9.

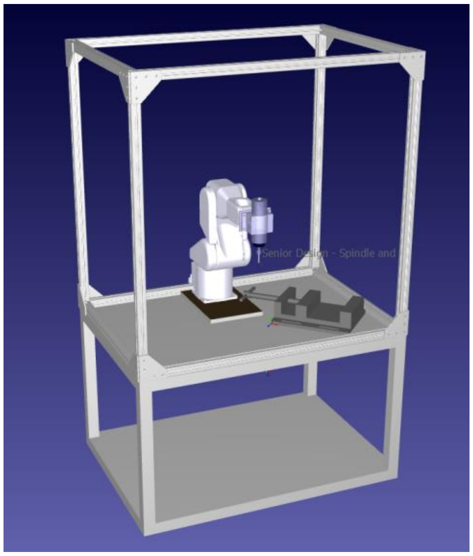

Figure 12: Robo DK Model

5. CONCLUSION

In conclusion, our goal through this project is to re-implement the robotic 5-axis mill back into the AEC for use by Professors in lab, and the Center for Applied Research. It has been proven back in 2019 that the Kawasaki RS03N is capable of milling into foam for rapid prototyping but was never successfully implemented into the AEC floorspace. It is believed that this occurred due to the lack of scope from the previous projects. There also is no documentation on how to use the robot and create the program from a CAM file, which leads to a lack of knowledge of operation that caused the robot to be forgotten.

While we were not able to successfully create a 5-axis milling program, we did successfully create a standard 3 axis milling program seen in Figure 14. After taking dimensions from the CAD model and comparing them to the dimensions of the milled part in figure 14, the accuracy was found to be 98.6%. The depth of the letters was dimensioned at 1 inch in the CAD program and measured 1 inch on the milled part. The width of each letter was set to be 0.35 inches and was measured to be 0.36 inches. After taking the average of the percentages from both measurements, we found 98.6% accuracy. We narrowed the problem down to RoboDK. When the NC file created from the CAM software was uploaded into RoboDK, all of the tool paths oriented themselves based off of the coordinate reference frame connected to the part vise. Reference Figure 13 for the illustration of this issue. It is recommended that future teams investigate this issue and utilize RoboDK's extensive online documentation and help forums.

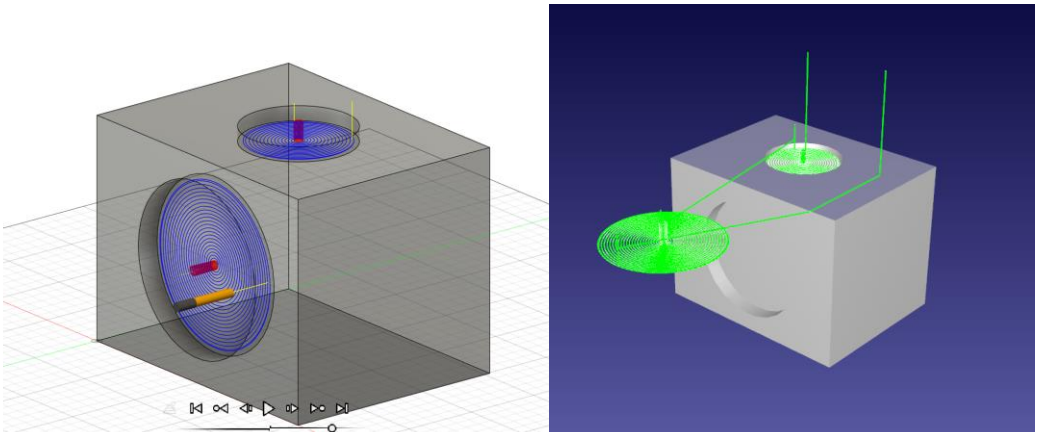

Figure 13: Desired Tool Path vs. RoboDK Tool Path

Through the course of our project, we created a safety enclosure for the work cell to protect operators from hazards within, fully documented the entire milling process and created a thorough and illustrated standard operation procedures document, and a virtual robotics simulation environment for ease of programing the Mill Bot Mk.1. We hope through our project and documentation, if a senior design group in the future picks out our project to continue upon, our resources will aid and ease their creation of their project.

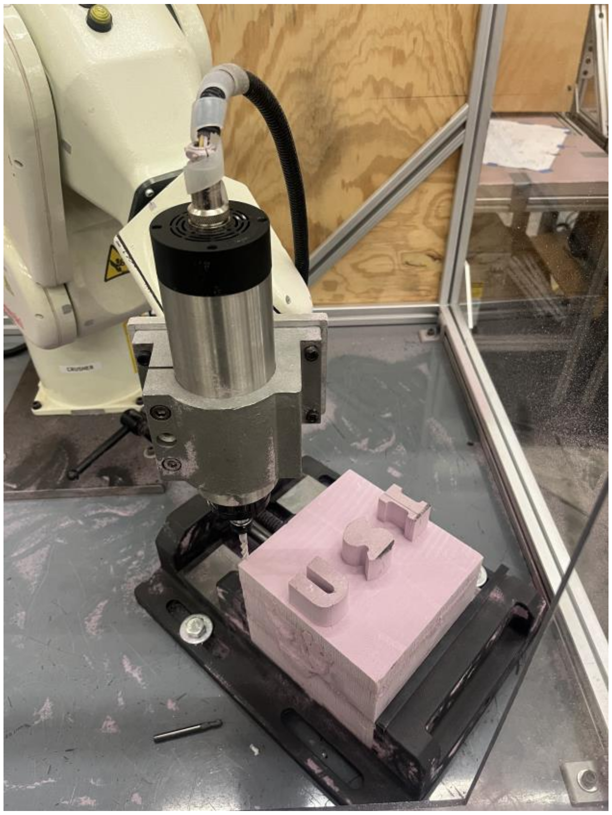

Figure 14: First Successful Milling Operation

6. FUTURE RECCOMENDATIONS

For future improvements and optimizations, it is recommended to further explore and experiment with various CAM software, including Solid CAM, to enhance the development of efficient 5-axis milling programs. Finding and selecting a software solution that fully supports 5-axis CAM capabilities, such as Fusion 360, will be critical to maximizing the precision and versatility of the milling process. Testing on a diverse range of materials, starting with wood, plastic, and progressing to metals, will offer deeper insights into material-specific machining strategies and toolpath optimizations. Additionally, experimenting with different types of milling bits, such as flat end, tapered, and roughing bits, will help find the most effective tools for specific tasks and materials. Finally, integrating and fine-tuning an automated tool change system will streamline operations, reduce setup times, and improve overall production efficiency.

REFERENCES

[1] M. I. o. T. (MIT), "Digital Manufacturing Laboratory," Massachusetts Institute of Technology, [Online]. Available: https://meche.mit.edu/research/digital-manufacturing. [Accessed 25 October 2024].

[2] S. University, "Stanford Robotics Lab," Stanford University. [Online]. [Accessed 25 October 2024].

[3] P. University, "Robotic Assisted Manufacturing Lab," Purdue University, [Online]. Available: https://engineering.purdue.edu/RAMLab. [Accessed 25 October 2024].

[4] M. Lombardo, "Boeing St. Louis - Advancements in Robotic Manufacturing," The Boeing Company, [Online]. Available: https://www.boeing.com/company/about-bca/boeing-st-louis/. [Accessed 25 October 2024].

[5] S. AG, "Factory Automation and Digitalization in Robotic Milling," Siemens AG, [Online]. Available: https://new.siemens.com/global/en/company/topic-areas/factory-automation.html. [Accessed 25 October 2024].

[6] I. Haas Automation, "UMC-500 Universal Machining Center," Haas Automation, Inc., [Online]. Available: https://www.haascnc.com. [Accessed 24 September 2024].

[7] ebay, "FANUC LR Mate 200iD 7H Robot Listings," eBay Inc., [Online]. Available: https://www.ebay.com/itm/204779050702. [Accessed 25 September 2024].

[8] Amazon, "2.2KW Water Cooled Spindle Motor & VFD Inverter," Amazon.com, Inc, [Online]. Available: https://www.amazon.com/s?k=2.2kw+spindle&hvadid=580535057889&hvdev=c&hvlocphy=1017086&hvnetw=g&hvqmt=b&hvrand=6294891922034569676&hvtargid=kwd-

24816234190&hydadcr=23726_13490095&tag=googhydr-20&ref=pd_sl_1x2oj9sy6p_b. [Accessed 25 September 2024].

[9] K. Robotics, "RS03N Robot," Kawasaki Robotics USA, [Online]. Available: https://robotics.kawasaki.com. [Accessed 25 September 2024].

[10] D. S. S. Corporation, "SolidWorks CAM Tutorials," Dassault Systemes SolidWorks Corporation, [Online]. Available: https://my.solidworks.com/training/path/80/solidworks-cam. [Accessed 2 April 2024].

[11] R. Inc., "RoboDk Robot Machining," RoboDk Inc.. [Online]. [Accessed 2 April 2024].

[12] R. Inc., "Getting Started," RoboDK Inc., [Online]. Available: https://robodk.com/doc/en/Getting-Started.html. [Accessed 2 April 2024].

[13] O. S. H. A. (OSHA, "1910.212 - General Requirements for All Machines," Occupational Safety and Health Administration, [Online]. Available: https://www.osha.gov/laws-regs/regulations/standardnumber/1910/1910.212. [Accessed 30 October 2024].

[14] O. S. H. A. (OSHA), "1910.119 - Process Safety Management of Highly Hazardous Chemicals," Occupational Safety and Health Administration, [Online]. Available: https://www.osha.gov/laws-regs/regulations/standardnumber/1910/1910.119. [Accessed 30 October 2024].

[1a] Wikipedia Contributors. “Milling (Machining).” Wikipedia, Wikimedia Foundation, 11 Nov. 2019, en.wikipedia.org/wiki/Milling_(machining).

[2a] What Is CNC? The Complete CNC Guide - CNCSourced. 11 Nov. 2020, www.cncsourced.com/guides/what-is-cnc-complete-cnc-guide/.

[3a] Winndeavor. “5-Axis CNC Machining Explained -.” Winndeavor - Where Innovation Meets Precision, 12 Nov. 2019, winndeavor.com/5-axis-cnc-machining-explained/. Accessed 4 Dec. 2024.

Appendices

A: BILL OF MATERIALS

Item	Qty.	Price/each	Total
220V Plug	1	$0.00	$0.00*
Circuit Breaker	1	$0.00	$0.00*
(10 ft) 10A Power cable	1	$0.00	$0.00*
VFD Wiring	1	$0.00	$0.00*
Spindle & VFD Package	1	$299.99	$299.99
Robo DK Academic License (2 years)	1		$145.00
1.5 in. X 1.5 in. T-Slot Aluminum framing custom cut – 48 inches	4	$0.56/in	$107.52
1.5 in. X 1.5 in. T-Slot Aluminum framing custom cut – 45 inches	4	$0.56/in	$100.80
1.5 in. X 1.5 in. T-Slot Aluminum framing custom cut – 31 inches	4	$0.56/in	$69.44
8 in. Low profile drill press vise	1	$159.99	$159.99
1-1/12 in. x 48 in. Square Radius Matte Black Continuous Hinge	1	$12.93	$12.93
2-1/2 in. Black Barrel Bolt Lock	1	$3.98	$3.98
24 in. x 48 in. x 0.220 (1/4) in. Clear Acrylic Sheet	3	$87.98	$263.94
FATH flat plate, silver, 90 degree, 5 holes	16	$12.00	$192.00
FATH button head socket cap screw, black, 5/16-18 – pack of 10	10	$5.25	$52.50
FATH economy T-nut, black, 5/16-18 – pack of 10	10	$6.50	$60.50
		Total:	**$1468.59**

*INDICATES MATERIALS ALREADY PRESENT IN AEC

Table 1: Bill of Materials

B: FMEA FOR CHOSEN ALTERNATIVE

FAILURE MODE AND EFFECTS ANALYSIS

Item:	Robo-Mill FMEA	Responsibility:		FMEA number:	
Model:		Prepared by:	Ryan Roy	Page :	1 of 1
Core Team:				FMEA Date (Orig):	4/24/2024 Rev: 1

Process Function	Potential Failure Mode	Potential Effect(s) of Failure	Sev	Potential Cause(s)/ Mechanism(s) of Failure	Occur	Current Process Controls	Detec	RPN	Recommended Action(s)	Responsibility and Target Completion Date	Action Results				
											Actions Taken	Sev	Occ	Det	RPN
Design part in CAD	CAD program does not launch/work	User cannot create workpiece/Whole process cannot continue	10	Computer error/program won't launch	1		1	10							0
Create CAM File	CAM file corrupts or improperly generates	RoboDk cannot load file and create program	10	Error in CAM program	1		1	10							0
Create robot program in RoboDK	RoboDK program does not launch/work	Robot code cannot be generated	10	Computer error/program won't launch	5		1	50							0
Upload Code to Kawasaki Teach Pendant	Code does not upload or gets corrupted	Robot cannot run program or improperly runs	10	Computer error	2		2	40							0
Insert workpiece into mount	Mount is not tightened enough	Workpiece may dislodge and become damaged or missplace itself resulting in no work done on workpiece	10	User error/fault	3		5	150	Ensure workpiece is properly secured in mount every time before beginning program						0
Activate Spindle VFD	Spindle does not power on	Program may not continue due to no possibilty of material removal	10	Loose wires/electrical fault	1		1	10							0
Run Milling Robot Program	Program does not run or runs improperly	Undesireable results on workpiece	10	Program was improperly created/sloppy programming work	3		8	240	Double check all programing work from the beginnig all the way from CAD work to RoboDK. Perform a test run before milling on work piece						0

Table 2: FMEA Analysis

C: DESIGN FACTOR CONSIDERATIONS

ABET Outcome 2 states "An ability to apply engineering design to produce solutions that meet specified needs with consideration of public health safety, and welfare, as well as global, cultural, social, environmental, and economic factors."

Design Factor	Page number, or reason not applicable
Public health safety, and welfare	Page 16, 17
Global	There is no global impact from the project. A 5-axis mill used for educational and business purposes does not have an impact on a global scale.
Cultural	Page 8, 9
Social	Page 8
Environmental	Page 10
Economic	Page 13
Ethical & Professional	Page 7, 11, 13
Reference for Standards	Page 12, 16

Table 3: Design Factors Considerations