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**Rapid Prototyping
with Robotic Milling**

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TECH 471 - Senior Project
Spring 2022

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ACKNOWLEDGEMENTS

In this section, we would like to acknowledge...

Mr. Nelson

Dr. Chlebowski

Scott Lenfers

Kendal Roeder

Douglas Vaughn

Mr. Kicklighter

Mr. Ellert

Mr. Amos

ABSTRACT

The purpose of this project was to further develop and improve upon a previous group's senior project of robotic milling by utilizing the Kawasaki robots in the Applied Engineering Center. This project implemented rapid prototyping with the use of 3D scanning to create a prototype of an object with no previous CAD model or specifications. The project also improved the already existing robotic milling system and its workstation. Designing and fabrication of mounting hardware for the spindle motor was necessary. Development and understanding of 3D scanning was necessary to create proficient scans of objects in order to create a solid model to implement a cutting path for the milling process.

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RAPID PROTOTYPING WITH ROBOTIC MILLING:

POINT CLOUD SCAN AND RECREATION OF AN OBJECT USING A

ROBOTIC MILLING PATH DESIGN AND IMPLEMENTATION

1 INTRODUCTION

The scope of this project includes mechanical aspects, as well as robotic programming, electrical components, software prototyping, and many instances of problem solving and proof of concept. The goal of this project was to pick a complicated shape or object with no previous CAD model and create a prototype using robotic milling. This project builds off a previous robotic milling project. In the previous project, it was proved that an industrial robot can be programmed with up to 30,000 steps to mill out a shape based on a CAD model. However, for this project the team wanted to add on to the process. The goal was to take a step back and create a CAD model using a 3D scanned point cloud before moving on to program the robot. With the use of an Artec Scanner and ArtecStudio Software, the team was able to pursue this project.



Figure 1: Artec Scanner

The first step in this process is to use an Artec Scanner (*Figure 1*) to create a Point cloud of the object. Once the point cloud is completed, the next step is to convert the file to a solid model. Then, a CAM cutting path can be created that the robot can be programmed with to mill out the piece. *Figure 2* is a more detailed process flow on how to produce the prototype part.

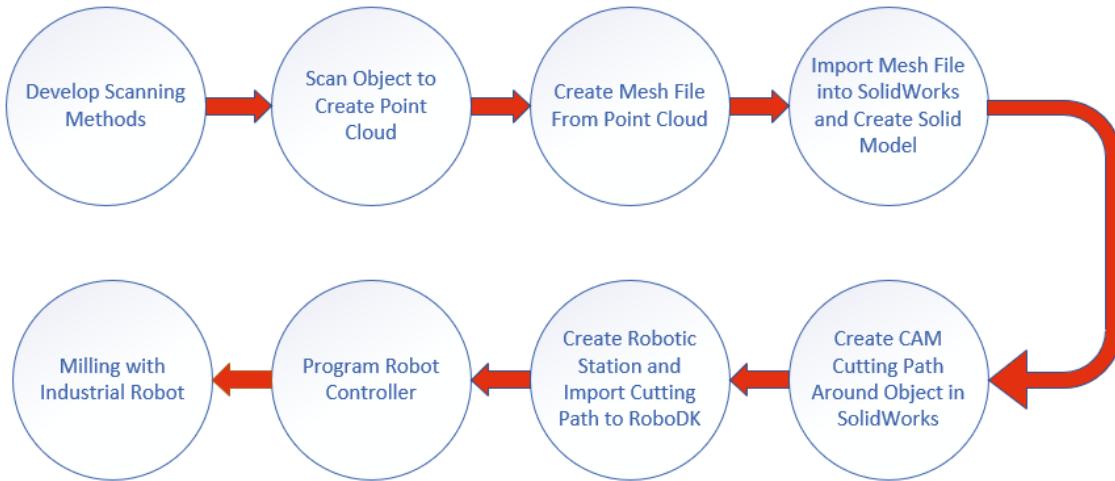


Figure 2: Project Process Flow

Figure 2 is more in detail of what the process would look like based solely on what needs to be done to make the prototype. However, there was more for the team to do. The robot was not built. It needed to be put together and completed alongside the virtual side of the project. The Virtual side included creating scanning methods and learning how to utilize the software for model creation. Below in *Figure 3* is a simplification of both the virtual and mechanical objectives of the project. The dark solid-colored arrows represent the team's progress. The lighter and dotted arrows represent steps that still need to be completed.

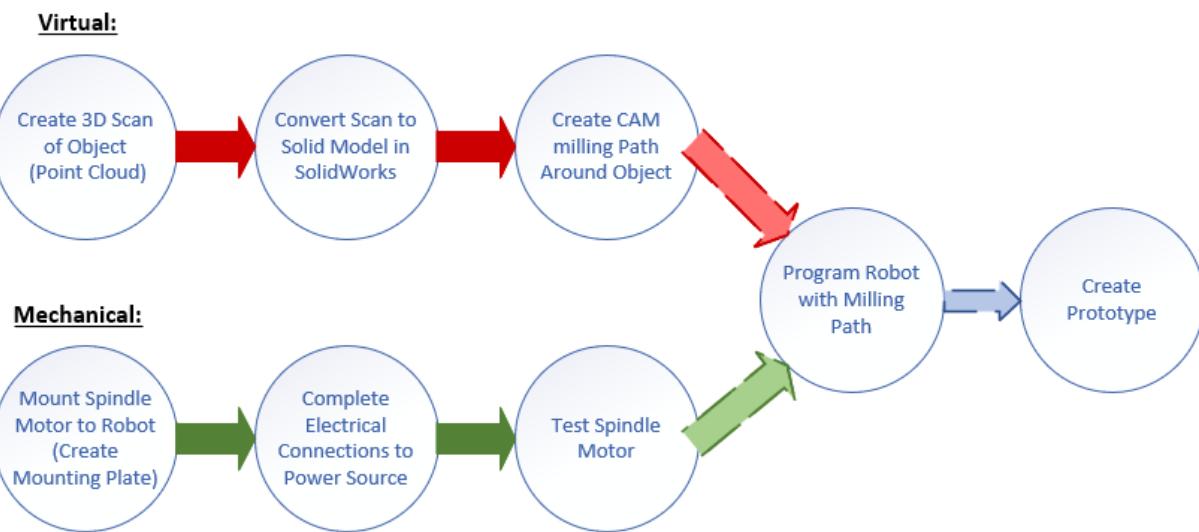


Figure 3: Virtual and Mechanical Path

2 3D SCANNING

The scanner used in this project was an Artec 3D Scanner. The scanner would flash quickly and take pictures of the object in front of it at about 15-16 frames per minute. Each of these pictures are compiled together and layered to create a large mass of points. Although there was another scanner available, it only had the capabilities to scan smaller objects that were non-metals. This scanner used a laser to track the features of objects. If we had used a metal object in this scanner it would not produce any sort of mesh data because the laser that is used to scan features would reflect in a way that the machine could not read. For these reasons we decided to use the Artec 3D scanner.

2.1 SCANNER CAPABILITIES

A point cloud is a mapping of data points that layer together to build the entire object. These points are just floating in space and do not have much meaning on their own. Our software, Artec Studio 14 Professional, can successfully map and group these points into a mesh file. The points were then changed to sharp polygons making the object look pointy and jagged as seen in *Figure 4*.

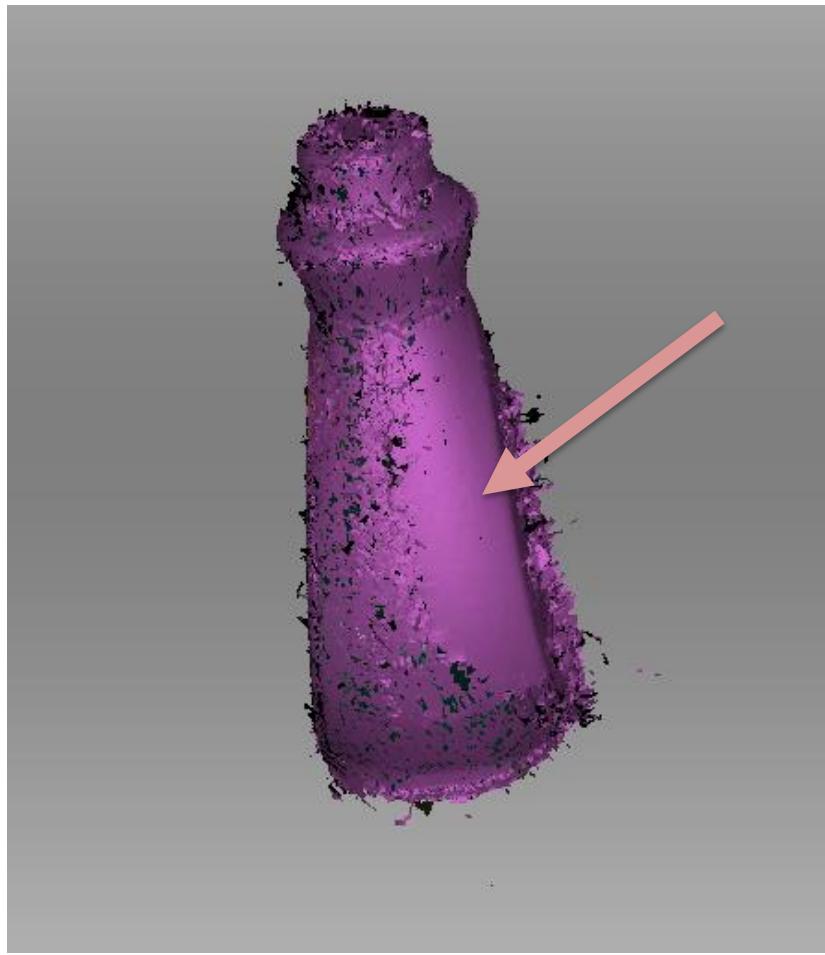


Figure 4: Mesh Cloud with Polygons

This picture is interesting because there is a very smooth side on the bottle. Specifically, this scan was one of the best that the team had taken and ended up being the final scan for this object. Because the scan was well done for this specific section of the bottle, the software easily registered that it was in fact a smooth surface and could determine this from the point cloud alone.

To get a complete scan of the object, the object and the scanner needed to move in order to get the complete 360-degree view to the object. Although we could not scan the bottom surface of the object, we could collect data on every other face and surface that was exposed. Due to the required and accidental movement of the object and scanner, there were quite a bit of fuzzy areas on the model. These “fuzzy” areas are just phantom points that the scanner picked up that did not

really exist on that placement of the object. For example, when testing the scanning capabilities on a mouse, the scanner picked up that the mouse had two scroll wheels. *Figure 5* shows both scroll wheels highlighted.

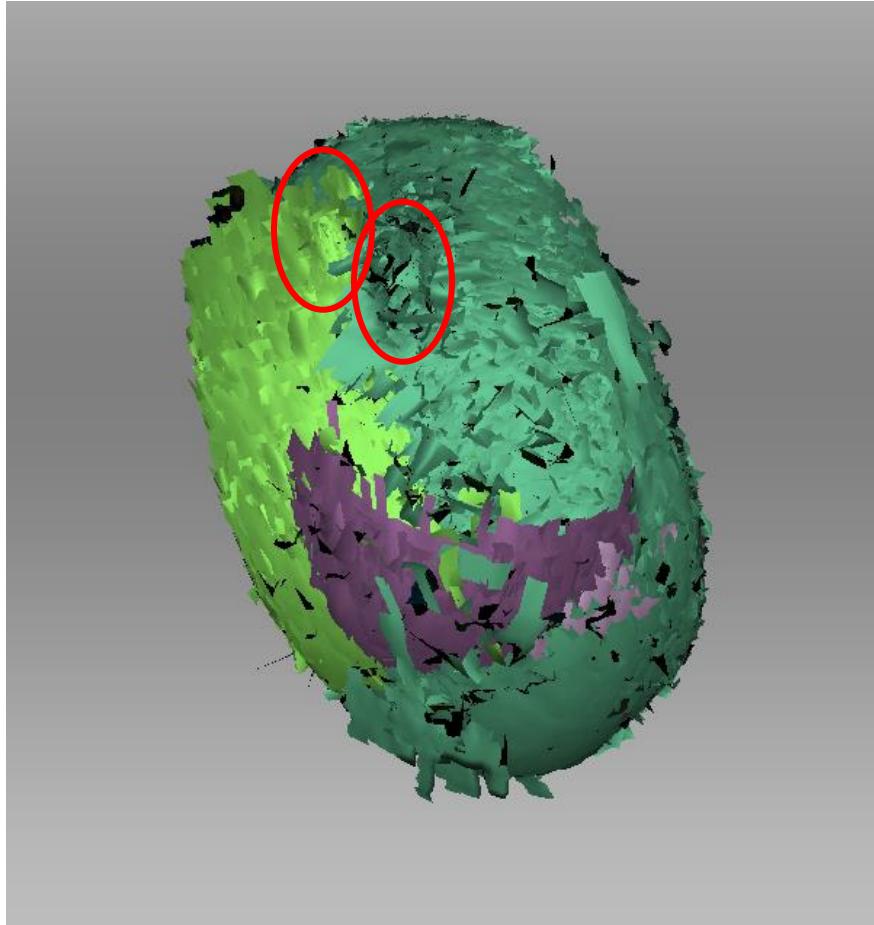


Figure 5: Two Mouse Wheels Picked Up by Scanner

This was a regular computer mouse and did not have two mouse wheels. This additional wheel was added into the model because there was extra movement during the scan. Either the scanner moved too close or too far from the object so that it could not read the object. Thus, the scanner stopped recording and started a new scan, which it then did not line up correctly to the previous one and duplicated the front half of the mouse with the wheel into a different location.

The team also noticed while scanning that sometimes it was not a problem of the scan being interrupted, but of the scanner just losing track. For example, one object used was both too shiny and too uniform for the scanner to detect that the object had even been scanned other than the front face of it. Now this mistake could have been partially due to the method of scanning that was employed, which will be talked about in Section 2.3 *Scanning Methods*.

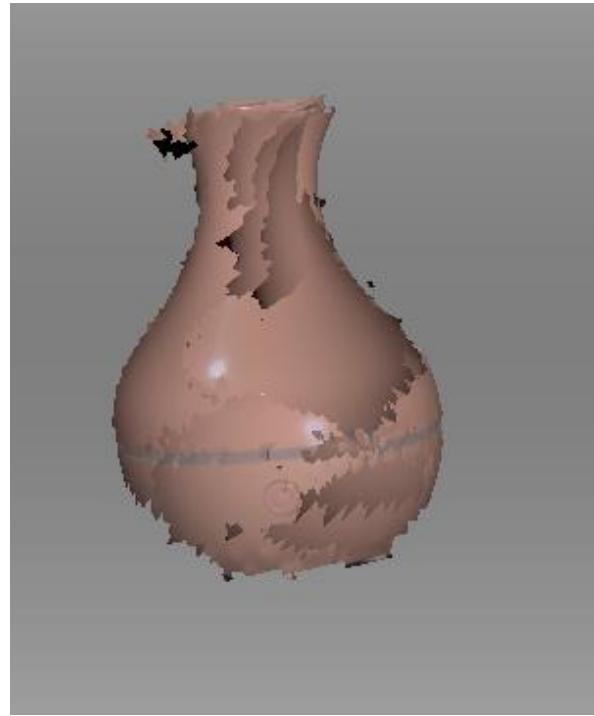


Figure 6: Front Side of Diffuser

In *Figure 6* is the image of another test object that we had used. This object was very round and was made of shiny plastic with almost no discernable features. Although the object looks pretty messy, it still holds the shape of the object very well from the front. However, the backside was a different story.

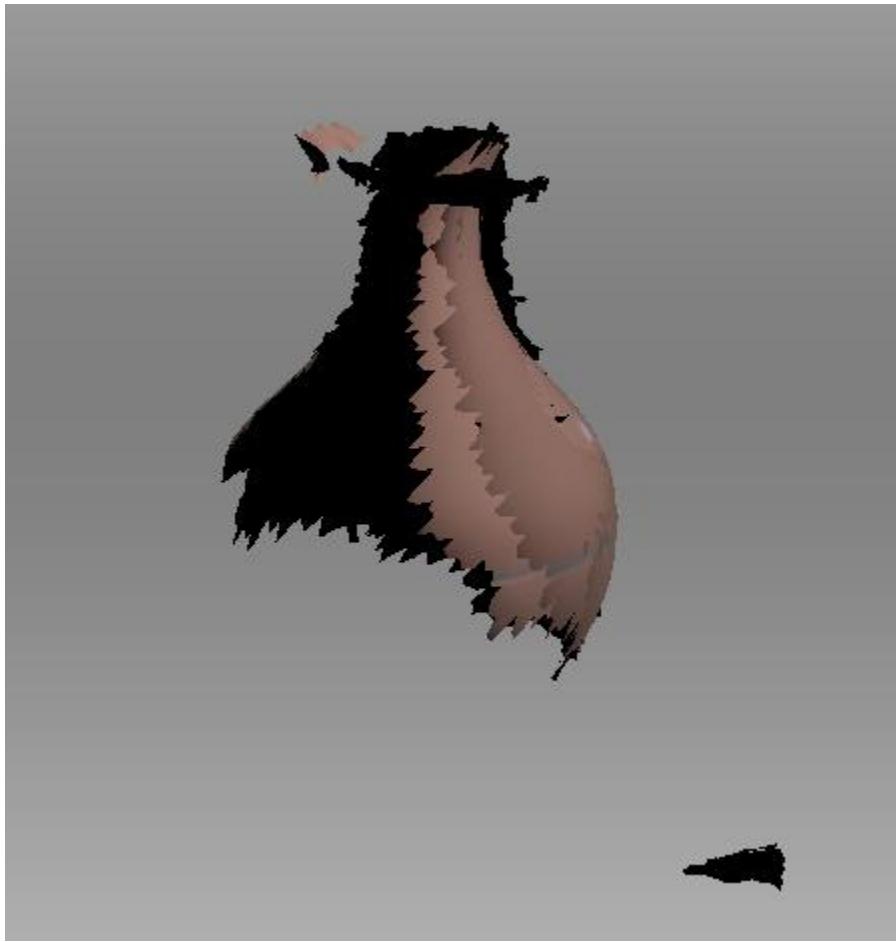


Figure 7: Back Side of Diffuser

Figure 7 shows the back side of the diffuser. The entire back half of the object is missing. The team believes this to be due to the fact that the scanner could not comprehend the movement of the object and saw that only one side of the object had been scanned. In reality, the object had been spinning, it was just not picked up as a change in surface to the scanner. Thus, a failed scan was created.

2.2 OBJECT DETERMINATION

When determining the object, we needed to make sure that the scanner could handle mapping both the dimensions and the exact surfaces of the part. We were not sure what the extent of the scanner's abilities were, so we decided to test it for ourselves. We created a pool of objects to

scan. This included an aluminum sheet (tin) box, a computer mouse, a caliper case, an oil diffuser, a laundry detergent bottle, and a couple others.

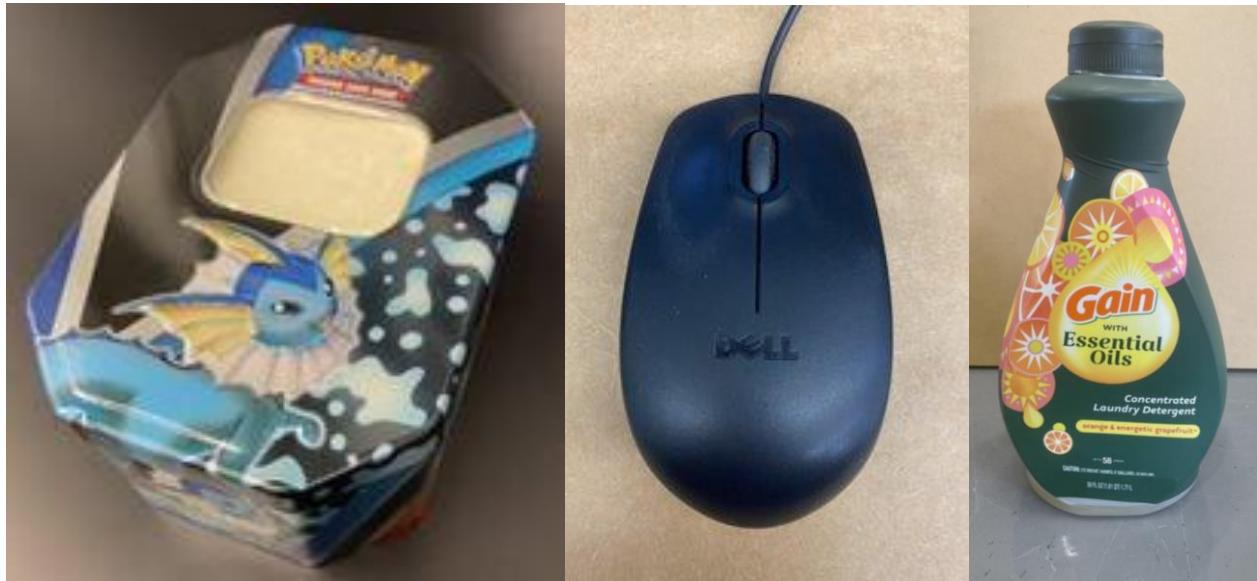


Figure 8 : Scanned Objects (Tin Box, Mouse, Laundry Detergent Bottle)

For the first object the team wanted something that was very simple, just so the team could get used to running the program. Therefore, the team chose a caliper case. It was a simple flat box with a very slight texture. However, this object proved to be too simple, and unreadable to the scanner. It was too flat. The next object was a computer mouse. Although the mouse was picked up by the scanner, it was considerably small and devoid of color. The mouse was a good start, so the team moved to larger objects with more detail. As seen above in *Figure 8*, the tin box was very angular and has more detail and color. So far, the team did not know if the scanner could even pick up color. After completing the scan, it produced a nice solid object. It had picked up all the angles and sides of the tin box. It even included the paint and impressions on the surface of the box. The only thing it did not completely pick up were the sides that were reflecting light as we scanned. However, the computer software took the liberty of filling in these holes giving a smooth surface. Below in *Figure 9* is an image of the raw, unedited scan.

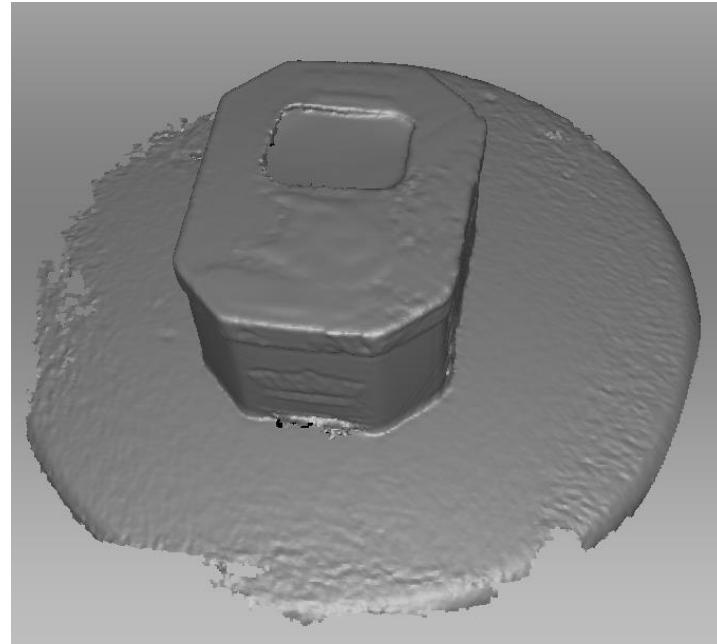


Figure 9: Scan of Aluminum Box with Stool Surface Recorded

Now that the team had completed the scan of a flat faced object, the plan was to test a curved or rounded surface. Two objects were picked for this, one smaller and the other a bit larger. The decision was to start with the small object, the diffuser. As discussed in Section 2.1 *Scanner Capabilities*, the oil diffuser was not recordable by the scanner for the entire object. The diffuser was too shiny and uniform, so we decided to move on to the next object. The final item the team collected was a laundry detergent bottle.



Figure 10: Scan of Laundry Detergent Bottle

Above in *Figure 10* is the scan of the laundry detergent bottle. This is the scan before it has been smoothed. The image proves that the scanner can record a complex shape as well has heavy detail on the object.

2.3 SCANNING METHODS

When scanning we came across many problems. These problems included the object not being within scanner range or moving out of range mid-scan, very patchy unlayered scans, multiple background surfaces being recorded, and the incapability to record clear plastics.

The original scanning method was to hold the scanner above the object and move it over the surface of the object to capture all of its sides. This proved faulty because it caused us to lose our place in the scan. When the object moved out of range, the scan stopped recording. Once it was back in range, the scanner would start recording again. This interruption in scans lead to many layers being created within one whole scan. A lot of the time these captures would layer but not be lined up and would add extra segments to the object. In short, characteristics would be duplicated in the scan. The mouse that came out having two scroll wheels in *Figure 2* (Section 2.1) is a perfect example of duplication and unaligned layers.

To solve the problem with the range and patchy layers, the team decided that the scanner needed to be held static while the object was rotated. By keeping the scanner still, it would keep the distance between the scanner and object constant. With the object rotating in place on a stool, the team could get a smooth scan of the object much quicker. Originally it took about 15-20 mins alone to complete the scanning portion of the object. Now with the addition of the stool, it only took about 1.5 minutes on average to complete a scan recording.

The next step in the process was to use the Autopilot function in ArtecStudio. Autopilot would create the fast track to edit the object. Although it moved into each step of editing, the team had to perform editing and material removal. The editing portion of this process became the bottleneck of the process. It took the longest duration to complete at around 5-15 mins depending on the extra surfaces that were picked up by the scan. Due to this being such a large and variable time, the team looked for a solution to standardize and decrease time. Instead of focusing on speeding up the removal of extra surface when editing, the team turned to a solution in removing them before the scan. To do this, the implementation of one of scanners weaknesses was used as a benefit. The scanner could not pick up clear plastics. So, if the part is set on top of a clear object that could rotate, in theory it wouldn't pick up this clear surface and only record the intended object.



Figure 11: Clear Organizer

Above in *Figure 11* is a picture of the clear organizer that the team was able to incorporate into the scanning methods. This specific organizer was picked because it was clear, tall, and able to rotate. It was able to rotate on the six ball bearings placed in the base of the organizer. The height of the organizer allowed for the objects underneath it to not be picked up through the clear plastic bottom. The first scan using the clear organizer as a stand for the object and spinning it proved the theory true. Nothing extra was included in the scan. After testing this method two or three more times, the team could confidently say that it worked as a valid solution. Since this allowed the team to scan and focus solely on smoothing and fixing, the process had been greatly

expedited. What took about 5-10 minutes now only took around 1-2 minutes. Now that the team had created a process to scan an object, they could move on to the next step in the entire project flow.

3 SPINDLE MOTOR

The spindle motor that the team used for the project was from the previous group (*Figure 12*).

The purpose of the spindle motor is to complete the milling process. The motor drives the spindle and attached end mill or cutting tool. Without the spindle motor, the team would be unable to complete the milling application. One issue the team had with the spindle motor was the bulkiness of the mount. It was decided to design and create a new mounting plate to attach the spindle motor to the tool flange of the robot.



Figure 12: Inverter and Spindle Motor

3.1 DESIGN AND CONSTRUCTION OF MOUNTING PLATE

This mounting plate was designed in Autodesk Inventor. Since the weight of the payload on the end of the robot is critical for range of motion, the plate needed to be as light as possible. The team selected aluminum as the material to create this plate due to its lightweight. For the spindle motor to have a flush fit to the plate, the bolt holes needed to be countersunk into the plate. A boss was also required so that the plate was seated firmly into the tool flange. These features are shown below in *Figure 13*.

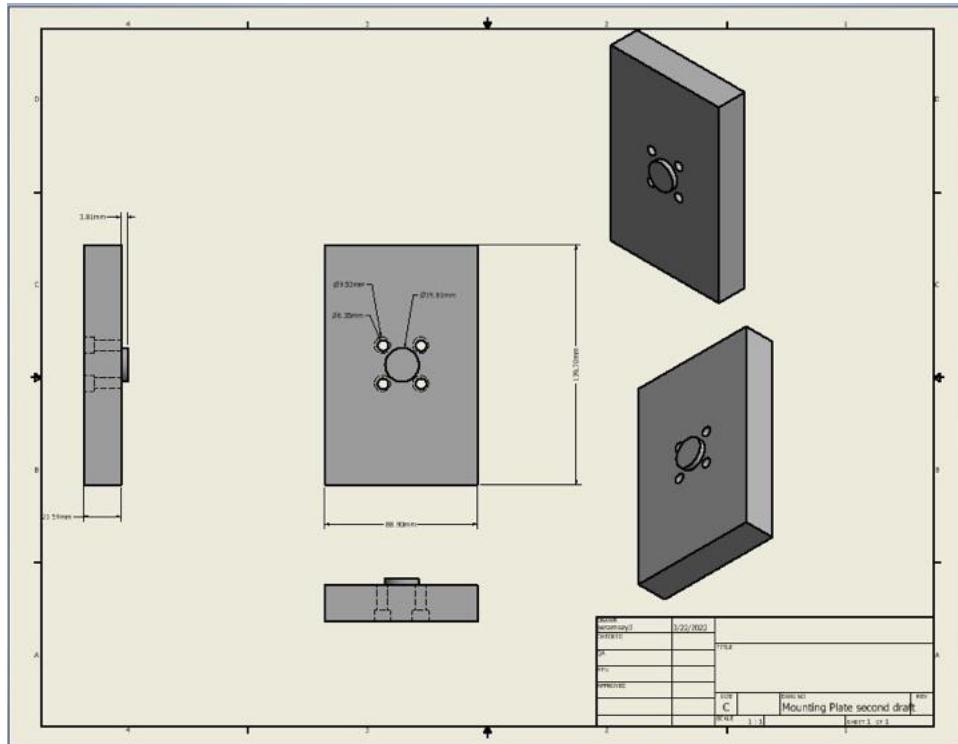


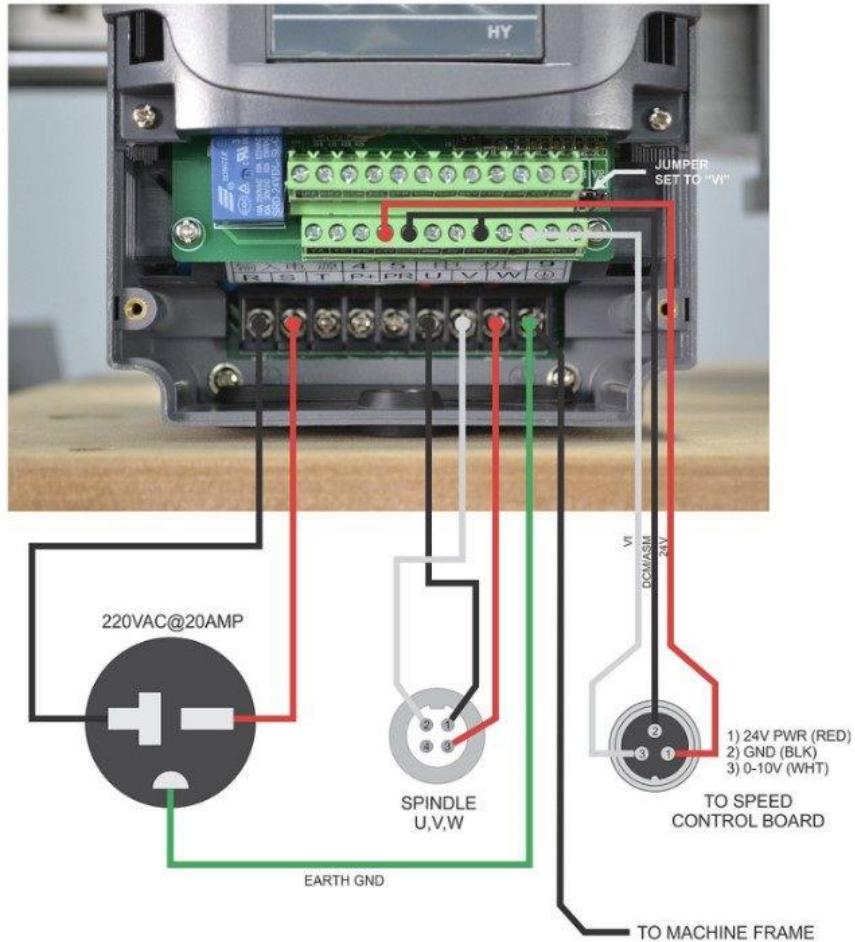
Figure 13: Mounting Plate Drawing

Once the plate was mounted to the robot, the group then needed to mount the spindle to the plate. In order to keep the spindle attached securely to the plate, threaded holes were drilled into the plate to keep the mechanism together. This allowed for a cleaner fit and more secure assembly.



Figure 14: Finished Mounting Plate

3.2 ELECTRICAL WIRING DIAGRAM



NOTE: Internal wiring of Chinese spindles is not consistent. If spindle spins in reverse, swap U & V

Figure 15: Electrical Info Found by Electricians

3.3 ATTACHMENT

The tool flange of the robot was factory designed with four tapped M5 bolt holes for end of arm tooling attachment. Therefore, the group used M5 bolts to attach the mounting plate to the tool flange of the robot. Once the plate was mounted to the tool flange, the spindle motor was then bolted to the plate using M6 bolts. The group designed the mounting plate with tapped holes so

that the spindle motor could be mounted securely to the plate. This also allowed the assembly to maintain a secure fit while the robot arm was in motion.

3.4 TESTING

Once the assembly was in place, the team was able to test the range of motion of the robot arm with the spindle motor attached. Joints 1-5 of the robot arm had zero limitations in respect to the added end of arm tooling to the tool flange. Joint 6 however, had some limitation as the power connection to the spindle motor was attached to the top of the motor. When joint six was rotated 360 degrees in one direction, strain was added to the power wiring of the spindle motor and had to be “unwound” in the direction it initially rotated. This was deemed not a critical issue due to the cutting applications that the spindle motor was to be used for.

3.5 POWER AND WIRING CONSIDERATIONS

In order to power our inverter and spindle motor, the team used a 50A-250V power source provided in the AEC. The team accessed this with a three prong 250 V plug which connected to a 10A breaker. This was the same power connection used by the previous group. The 10A breaker served as the main on/off switch to power the inverter. Some modifications were made to the electrical housing/wiring to improve the overall system. The electrical housing for our power source and breaker was mounted to the side of our workstation. This allowed for easy accessibility to the breaker in case anyone needed to cut the power to the inverter or spindle motor. Additional length in wiring was added from the breaker to inverter in order to mount the inverter in a safer location on the back of the workstation. This allowed the inverter to be clear of the workstation and workspace during operation of the milling process. Spade lugs and ferrules were added to both the power wiring and spindle motor wiring for better connection. This also allowed for quick and easy connection and disconnection. Spiral wrap was also added to clean up loose wiring within the system.

4 POINT CLOUD TO SOLID MODEL

The next step in the process was to import the Artec point cloud file into SolidWorks as solid part file. Once imported the team need to convert the mesh into a solid model to create a SolidWorks CAM Cutting Path.

4.1 IMPORTING FILE

One of the main roadblocks in this project was importing the Mesh file from Artec to SolidWorks. The group had access to the Artec Studio 14, and older version of the software. Newer versions, Artec Studio 16 had the command to directly import to SolidWorks from the import menu. Due to the newer software having this, all the help pages available did not mention another route for file. Eventually after saving many different types of files through Artec, the team was able to get a file that was able to be imported. The next few paragraphs explain steps the team took in the project and serve as instructions for future teams or recreation of the project.

In Artec Studio the file needs to be saved as a *.ply file. There are probably other ways to convert over, but this is the way the group got to work best. Once saved as a .ply file, it can then be opened from SolidWorks. To do this, click “open file” and go to where the mesh file was saved. Once found the folder, in the bottom right of the screen is the file filter (*Figure 16*).



Figure 16: File Filter

The next step was to change it from “All Files” to “Mesh Files”. This selection should include *.ply as a file choice. An example of what this looks like can be seen below in *Figure 16*. Once this is selected, the mesh file should show up and be able to be opened.

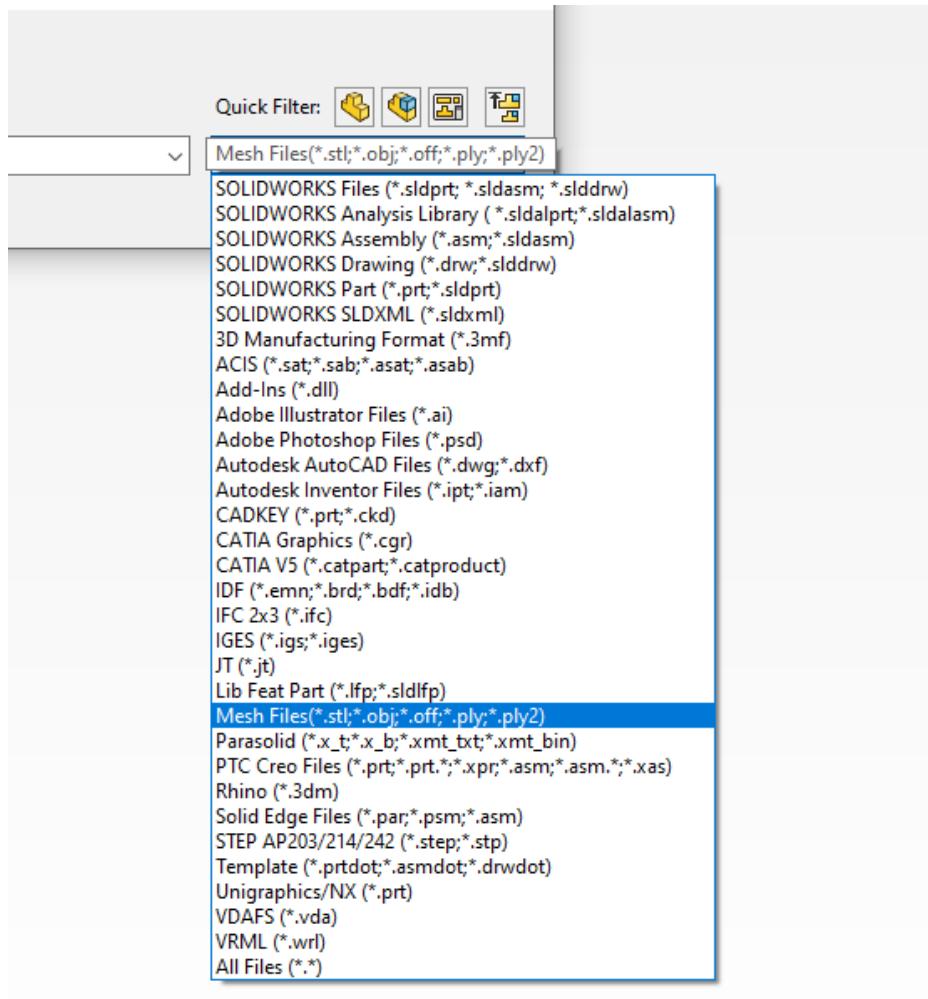


Figure 17: Select “.ply” File

Now that the Mesh file is open in SolidWorks, it was proof that there is a way to import the file over with our current software. After this had been proved, the team moved on to work on if we could turn the Mesh file into a solid model in SolidWorks.

4.2 CONVERTING TO SOLID MODEL

Similar to importing the file, the team also had some difficulty converting the mesh to a solid. Many, if not all help pages and blogs referred to the use of a third-party plug-in called Geomagic. With this program, it states that a mesh could move directly into SolidWorks and Geomagic would automatically change the file to a solid model upon opening. However, it cost \$7,000 to purchase or use the plug-in. As well as having to purchase the plug-in, we needed to

purchase Artec Studio 16 for compatibility. The new software itself would cost \$2,000. So, to purchase both for the process, it would cost roughly \$9,000. The cost of this was not feasible, therefore we had to look for a different way to make the mesh a solid model.

After looking through many different help pages and learning the software myself, we believe there is a way to make a solid model without purchasing the expensive plug-ins and software. After reading through some SolidWorks help files, the team found a lead within the options menu. The help file included instructions to make a surface out of mesh facets. This was the tool the team was going to use to begin with, however, each of these facets, or triangles in the mesh file, had to be selected. There were upwards of 10,000 triangles on the top face alone, so it would take a lot of time to click every single one. As well as having to click every single one, there was also a 5-20 second delay for the computer to register a newly clicked point. So, to cut down time the team looked for a different route using the options menu (*Figure 18*). The Next few paragraphs will explain the movement through the menus as information for any continued projects or research.

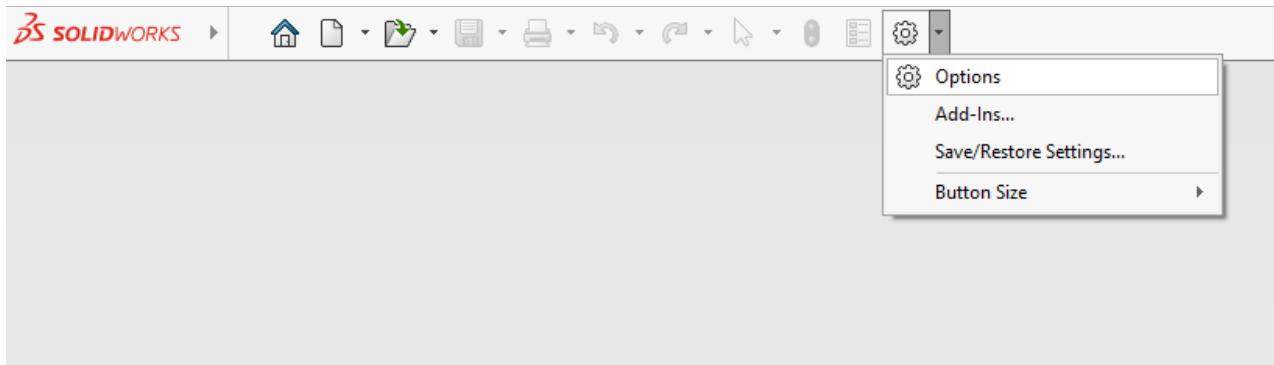


Figure 18: SolidWorks Options Menu

Once the options menu is found and clicked on, the next step is to find the ‘Import’ section of the settings. Below in *Figure 19* is a picture of the ‘Import’ section in the menu.

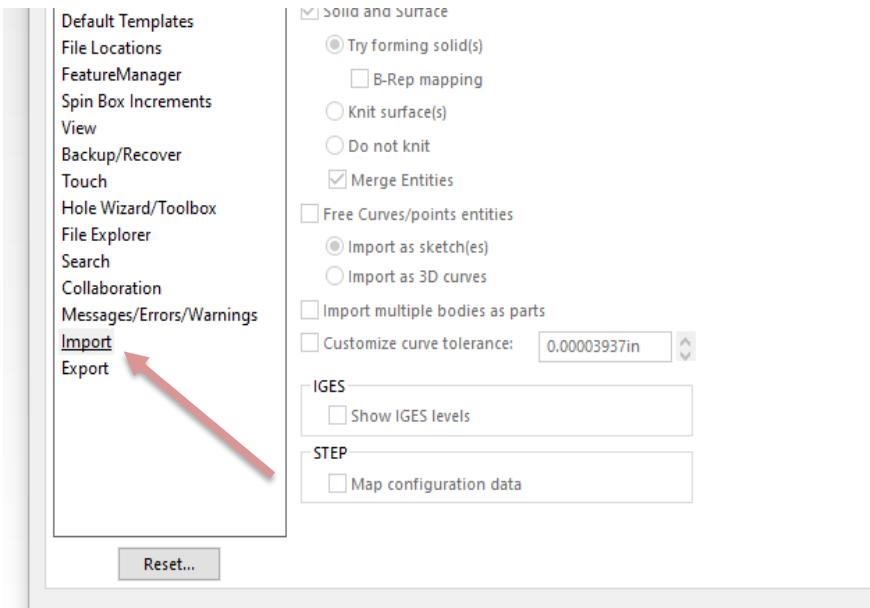


Figure 19: Import Options

Next, the file format needs to be change from General. The drop down arrow will allow this to be changed. The preferable file format needs to be ‘STL/OBJ/OFF/Ply/PLY2’. This is the second option, or the option highlighted blue in *Figure 20*.

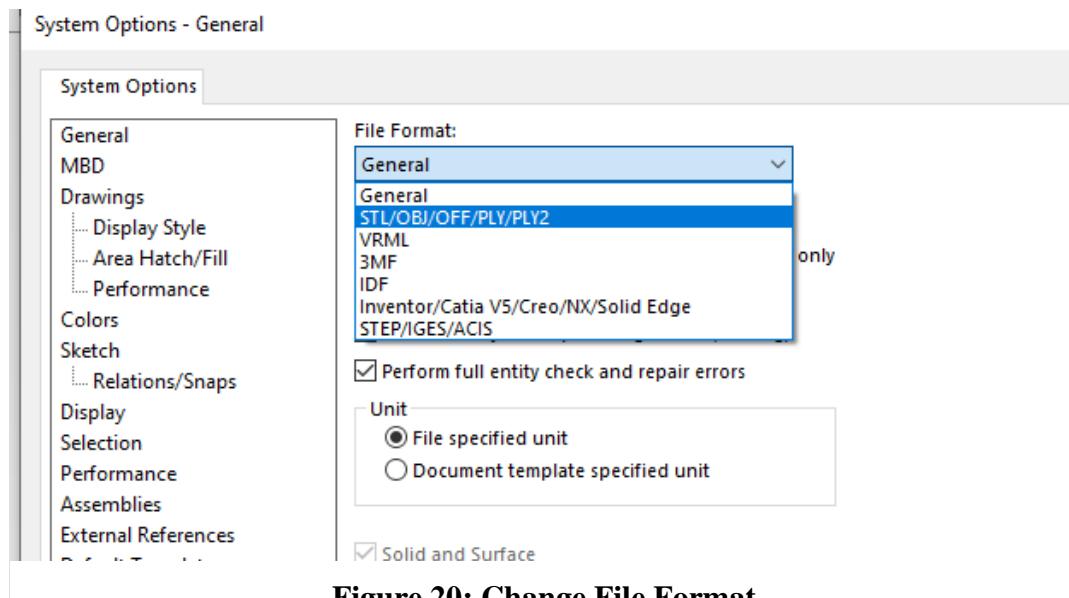


Figure 20: Change File Format

After the file type is selected, new options will appear. Below in *Figure 21* are the three options that need to be selected so as to import a solid model on opening a *.ply file.

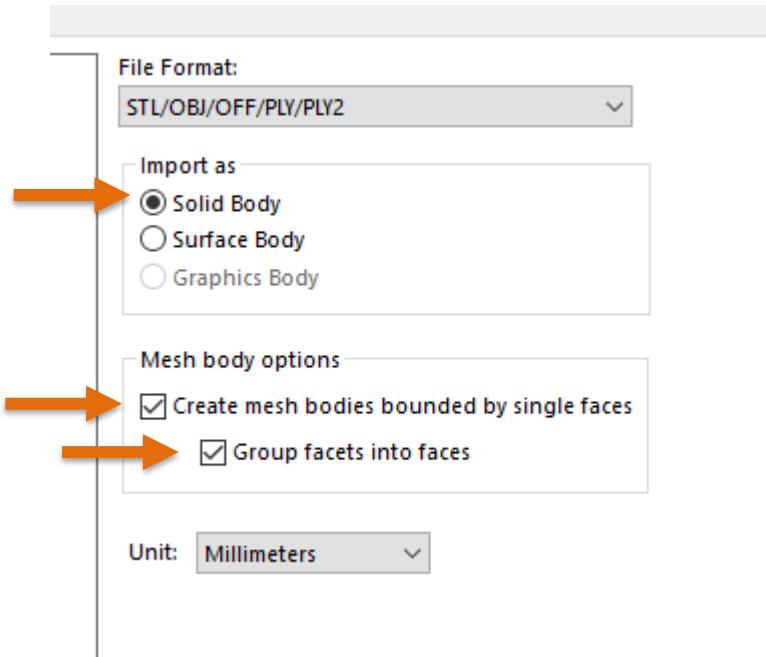


Figure 21: Select These Options for Importing Solid Model

When these have all been selected, the next step is to open the file. Using the same methods described in the previous Section 4.1 *Importing File*, a solid model can be imported immediately.

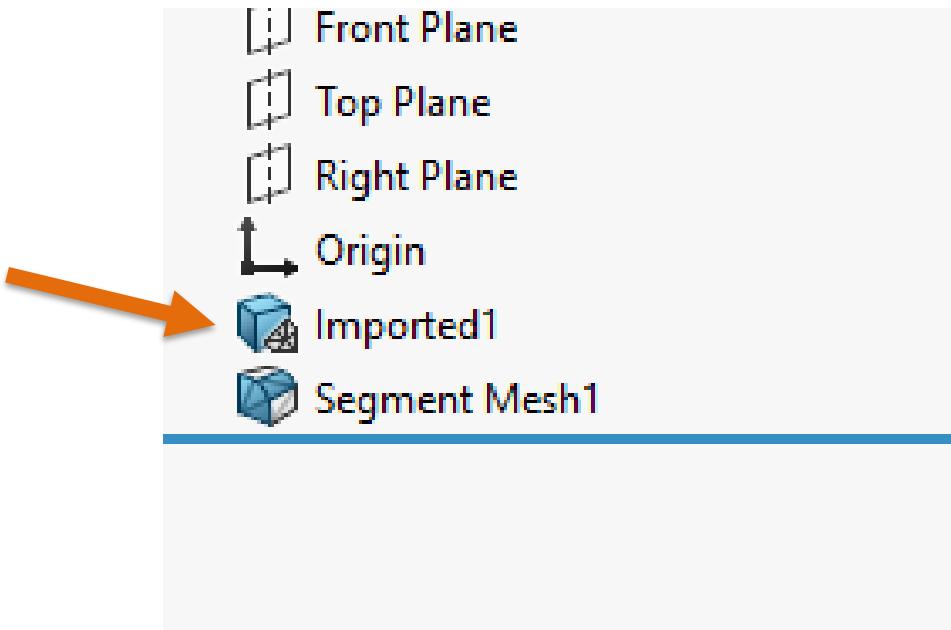


Figure 22: Solid Model from Mesh

After the setting changed and the file is reopened, the icon above should be visible (*Figure 22*). This symbol means that a solid shape was made in reference to an imported mesh body. This was exactly what the team was working towards.

4.3 CUTTING PATH

As for the cutting/milling path, the team did not get this far. The main focus of this project was spent on creating the point cloud and improving the process of scanning and well as creating the Robot workstation. However, since every part of the team's project was building up to this point, it is recommended that another team may pick up where the project was left off.

5 CONCLUSIONS AND RECOMMENDATIONS

5.1 CURRENT PROGRESS

The first half of this project has been completed. This includes both the virtual path and the mechanical. The team created scanning methods and learned how to best use the Artec scanner. From there, the team imported the point cloud into SolidWorks as a mesh body. Next, the team created a solid model out of the mesh body. Alongside this work, the team also completed the mechanical side of building the robot. All components were mounted including the spindle motor, inverter, and electrical box. The components were then all connected to the power source, creating a full functional milling robot.

5.2 FUTURE RECOMMENDATIONS

5.2.1 Milling Path

The next step in this project would be to research and build a CAM path in SolidWorks. The team did not create a full milling path for the robot, leaving it completely open to the next project team. Once created, the next step would be to import the CAM path into RoboDK and implemented into a virtual robot station. These instructions can then be smoothed out to make sure the motions are fluid and accessible by the robot arm. From here, the RoboDK robot programming language would be sent into the robot controller to drive the robot.

5.2.2 Improve Solid Model creation

The team felt that our method of solid model creation was not very easy to use or very understandable. It was found that it was possible to purchase a third-party plug-in to convert a mesh to a solid file. This proves that there is another way to convert the file. However, the \$9000 cost for this software was not feasible. If the next team could find another route, or even contact the plug-ins company to possibly get a trial version, this would further improve the process of solid model creation.

5.2.3 Develop Safety Shut Off

We recommend that an emergency shut-off be implemented into the system. This would be beneficial for the milling process in case of mechanical failure of the spindle motor, inverter, or robot. This also would regulate safety issues with the use of a high-speed cutting tool in an open work area.

5.2.4 Build and Improve Workstation

It is recommended that the workstation be improved by adding a protective enclosure with ventilation for the work area. This would prevent debris from being thrown around the AEC causing safety hazards. The milling process creates dust particles that can be inhaled which can be harmful to anyone within the vicinity. By implementing a ventilation system, it would also allow for less clean up after the milling process is complete.

5.3 CONCLUSION

After completing this project, the team realized that although it was an interesting project, there was a lot to completed. Scanning methods were developed and the robot was made functional. However, there was still a lot more the team wanted to do in a short period of time. Instead of continuing to work on what was in front of them, the team decided it would be best to look towards the future. This includes plans for continuing to build the process, as well as implementing improvements. This project was very challenging and allowed for the team to build new skills and learn along the way. The ultimate goal of from here is to pass on the information gathered to the next group willing to take this project on.

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APPENDIX A

Task	Due Date
Develop process follow plan	Jan 17
Create 16-week plan	Jan 17
Meet with Dr. Chlebowski (learn to use Artec software)	Jan 24
Lab safety refresher	Jan 28
Collect spindle motor and inverter	Feb 4
Find object to scan	Feb 4
Take measurements of robot	Feb 9
Design Mounting plate for robot	Feb 11
Develop scanning methods	Feb 11
Improve scanning methods (stool)	Feb 18
Contact electricians (1 st meeting)	Feb 25
Complete wire connections research	March 4
Acquire 20v plug	March 4
Connect spindle, inverter, and plug to power/together (2 nd meeting with electricians)	March 4
Test spindle motor	March 4
Collect new scanning material	March 7
Improve scanning methods (part 2) (clear organizer)	March 9
Create final scanned model	March 15
Create and approval of Mounting plate drawings	March 15
Design and mount electrical box	March 17
Fabricate mounting plate	March 24
Mount Spindle motor to robot	March 25
Design Project Review	April 1
Design and mount inverter	April 5
Implement modifications to inverter	April 7
Import mesh file to solid works	April 7

Draft Report to advisor	April 8
Research Importing solid model	April 15
Import solid model from mesh to SolidWorks	April 18
Research CAM path	April 22
Final Presentation	April 22
Project Clean up	April 28
Poster Session	April 28
Finish Report	April 28

APPENDIX B

Bill of Materials (parts needed to recreate system)			
Part Description	Price	Qty	Subtotal
Spindle Motor Components			
Spindle Motor and Inverter package	234.00	1	234.00
220V Plug	60.20	1	60.20
Circuit Breaker	45.67	1	45.67
10A Power Cable(10ft)	15.50	1	15.50
VFD Wiring	28.00	1	28.00
Component Mounting Parts			
#6 Hex nut	2.78	1	2.78
#6 flat washers	2.78	1	2.78
#6 32x1 in screws	2.78	1	2.78
#6 32x1.5 in screws	2.78	1	2.78
Flanged Button Head Socket Cap Screw	0.77	2	1.54
Plywood Sheet 4'x8'	38.72	1	38.72
Aluminum Plate 12" x 12" x 0.5"	83.99	1	83.99
M5 socket head bolt	N/A	4	N/A
M6 socket head bolt	N/A	4	N/A
Scanning			
Clear rotating organizer	15.00	1	15.00
Tin Box	35.00	1	35.00
Subtotal for Complete Single Robot			
Complete functioning robot	N/A	N/A	