Multi-Axis Voxel-Based CNC Machining of Centrifugal Compressor Assemblies

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ABSTRACT

The use of computer-aided manufacturing (CAM) software is essential in the rapid production of high-quality computer numerical control (CNC) machining toolpaths for complex parts. Typical CAM software relies on analytical representations of part geometry, where curves and surfaces are described by parametric functions. This paper proposes the use of a novel way to represent part geometry known as a voxel model. A voxel model uses a three-dimensional array of small cubes to represent a part volume; these cubes, or voxels, are the three-dimensional analog of two-dimensional pixels in an image. The use of voxels for a CAM application enables higher surface complexity, simplified collision checking, and more robust analysis of material removal than would be possible with typical parametric CAM. The unique capabilities of the voxel-based CAM approach described in this paper enable rapid production of high-quality 5-axis toolpaths for machining complex parts, such as the centrifugal compressor assembly that is presented in this work.

INTRODUCTION

This paper explores the feasibility of machining a centrifugal compressor impeller and associated housing using a voxel-based CAM approach. A novel voxel-based CAM system will be described and used to generate numerical control (NC) code suitable for machining each stage of part manufacture: rough and finish turning, boring, and rough and finish milling. The process planning and manufacture of the two key parts to the assembly, the impeller and the housing, will be described from the viewpoint of voxel-based path planning. Tool accessibility analysis using voxel models for the purposes of toolpath planning will be explored in the context of machining the impeller; additionally, quality considerations encountered when machining from voxel models will be addressed. Upon completion of manufacture, the impeller and housing will be assembled to form a functional compressor.

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Traditional Manufacture of Centrifugal Compressor Wheels

Traditional casting of complex geometries often leaves an inconsistent and rough surface finish that is detrimental to a part whose design is driven by flow dynamics; to produce higher quality parts, both research and industrial 5-axis machining plans have been implemented as an alternative to casting. Young and Chuang[1] proposed manufacturing centrifugal impellers with 5-axis flank machining using traditional parametric methods that balanced the depth of cut and resulting error.

However, with such intricate parts, collision checking proves to be a challenge due to the limited accessibility of centrally located features. Chu, Huang, and Li[2] proposed an integrated path planning process that minimizes tool orientation changes and tool retraction while adjusting erroneous tool locations to avoid collisions for parametric 5-axis impeller machining. Chen[3] further investigated optimal tool paths with parametric planning and verified part accuracy with 3D coordinate measurements. While the previous approaches relied on parametric CAM for toolpath generation, this work will leverage voxel-based CAM as an alternative path planning approach.

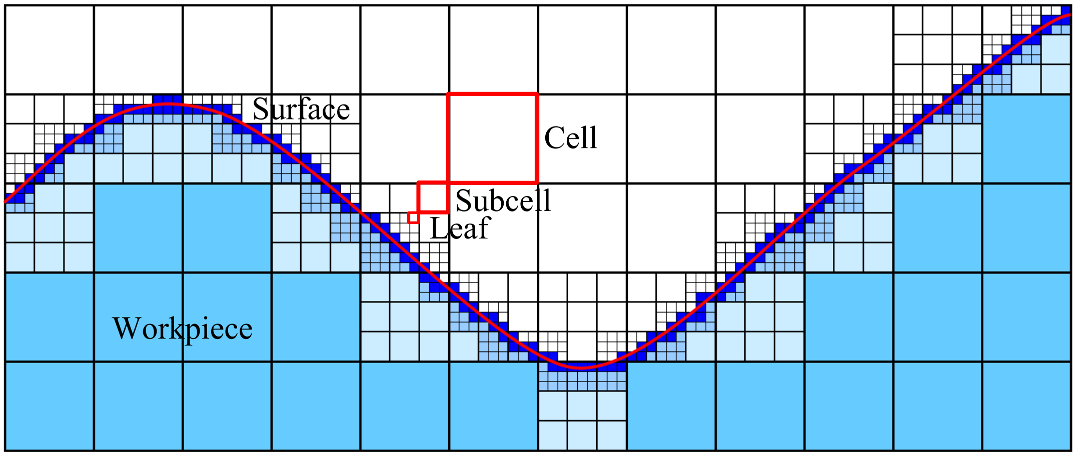


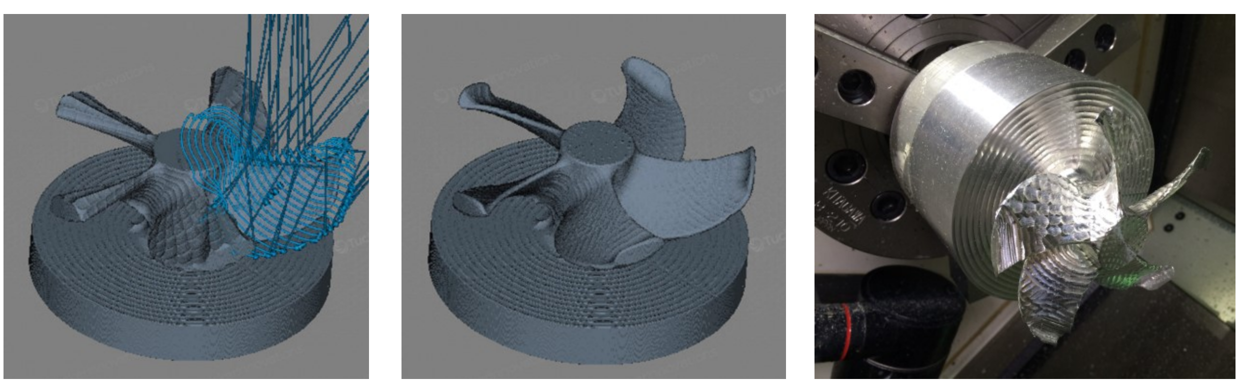
Figure 1. Surface Representation by Voxels

Voxel-Based CAM

Analytical part models are advantageous in several ways; namely, they can be scaled without losing fidelity and they require small amounts of memory to store. However, analytical models are not ideal when the absolute accuracy of fine surface details is paramount; this is because the complexity of an analytical model is limited by the precision of the computer used to render and operate on the model. This is particularly consequential to the simulation of a cutting process. Take, for example, the representation of scallops on a part surface that would be introduced after a milling operation. To represent each individual scallop with an analytical model would require an extremely complex non-uniform rational basis spline (NURBS) formulation (or collection of NURBS formulations) to accurately describe the surface[4]; a better approach is to represent the part surface discretely with many small volumes. This idea is similar to that employed in digital photography: a complex image can be described digitally in terms of picture elements (pixels). If the size of the pixels is small enough, the digital image can recreate its equivalent analog (film) counterpart with sufficient fidelity. In the case of three dimensions, pixels can be extended to voxels. Voxels are cubes whose resolution can be controlled to provide sufficient resolution in part surface representation. In a typical machining process, the side length of a voxel is on the order of tens of microns. An example surface representation using voxels is shown in Figure 1[5]. This research employs a graphics processing unit (GPU) accelerated voxel-based CAM software, known as SculptPrint, that can create toolpaths for 5-axis CNC machine tools[6–9]. The use of GPUs in toolpath planning enables more rapid processing of the voxel model than would be possible using traditional computing techniques.

5-AXIS MACHINING FROM VOXEL MODELS

The proposed approach has been successful in producing numerous metallic parts using both turning and multi-axis milling. Of particular interest is the propeller shown in Figure 2[10]. This part was manufactured using SculptPrint in conjunction with a 5-axis millturn machine. The toolpath planning stage is shown in Figure 2a; the toolpath itself consists of the light blue lines on the propeller blade. Figure 2b shows the predicted end product after machining simulation, and Figure 2c shows the machined part. The results from the propeller manufacturing process have been



a. Toolpath Generation b. Simulated Result of Toolpath c. Machined Result

Figure 2. Propeller Simulation and Machining

demonstrated previously[10], and some aspects of the voxel-based CAM software have been published in various venues[5–9,11–14]. However, manufacture of multi-part assemblies suitable for a turbomachinery application using a voxel-based CAM approach has not yet been demonstrated in current literature.

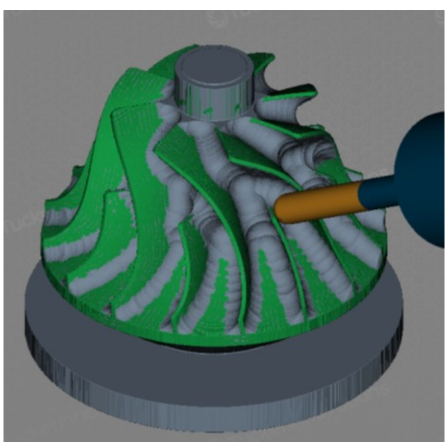
Path Planning and Collision Avoidance

This paper will take advantage of the robust collision checking and simulation capabilities provided by voxel-based CAM to create a centrifugal compressor impeller assembly using a 5-axis CNC millturn machine. The first part of the work will be focused on machining the compressor impeller itself, and the second part will explore turning and boring of a housing that is suitable for the impeller. Both parts will be machined from 6061 aluminum alloy using a combination of turning and milling. Aluminum alloy compressor blades can be used in aircraft engines[15]. Upon successful completion of the manufacturing process, the impeller will be placed into the housing to form a completed centrifugal compressor assembly.

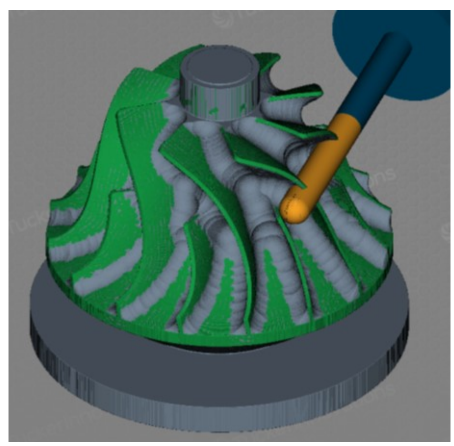
One of the largest challenges in machining an impeller is the analysis of tool accessibility during the 5-axis milling stage. To avoid collisions between the cutting tool and either the workpiece or the fixture assembly, the CAM system must be capable of computing commands for tool orientation that produce a smooth, collision free toolpath; for 5-axis machining operations, the orientation of the cutting tool is controlled by the positions of the rotary axes of the machine. Collision checking in SculptPrint is accomplished using the accessibility map algorithm, which determines a suitable tool orientation progression through the toolpath by checking for overlap of tool, workpiece, and fixture geometry at each unique combination of rotary axis positions[16]. An accessibility map is therefore a two-dimensional array of rotary axis angle combinations, where combinations (tool orientations) that result in a collision are marked with black and orientations that are collision free are marked with white. The white areas are known as accessible space, and the black areas are known as inaccessible space. An example of accessibility map computation is shown in Figure 3: Figure 3a shows the blue and yellow cutting tool in an orientation that does not result in a collision with the workpiece, as denoted by the white region in the accessibility map shown in Figure 3b. In contrast, Figure 3c shows an orientation that results in a collision with the workpiece as the selected tool orientation is in the inaccessible space on the map in Figure 3d.

MANUFACTURING PROCESS FOR THE CENTRIFUGAL COMPRESSOR ASSEMBLY

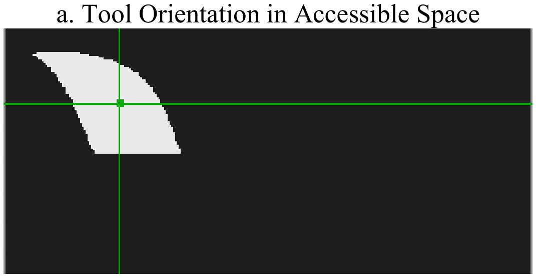
The entirety of the assembly, which includes the impeller, the housing, and a backing plate that holds the assembly together, were manufactured using an Okuma Multus B300II millturn machine. This CNC machine tool is capable of performing simultaneous 4-axis interpolation with a



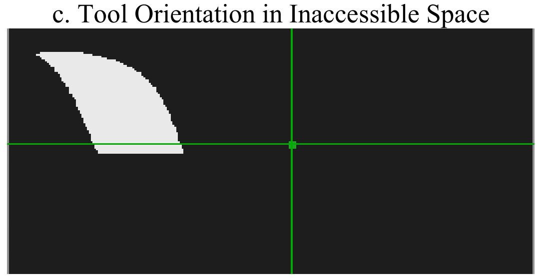
a. Tool Orientation in Accessible Space



c. Tool Orientation in Inaccessible Space



b. Corresponding Accessibility Map Denoting Orientation in Accessible Space



d. Corresponding Accessibility Map Denoting Orientation in Inaccessible Space

Figure 3. Accessibility Analysis for Centrifugal Impeller

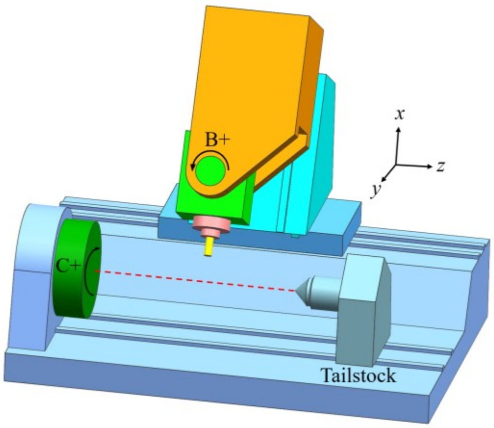


Figure 4. Axis Configuration of the Okuma Multus B300II

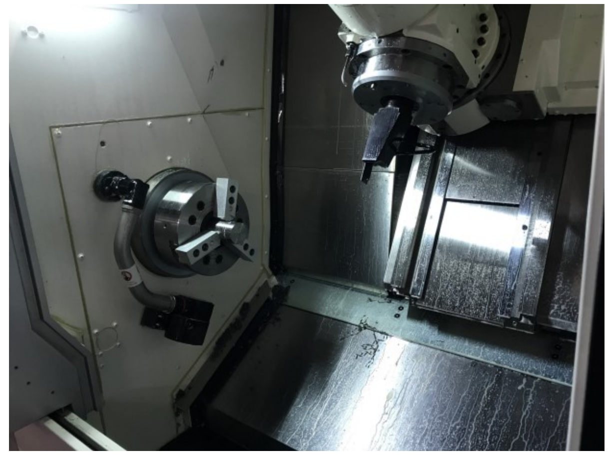


Figure 5. Okuma Multus 5-axis Millturn Machine

selectable turret angle. The axis configuration of the CNC millturn machine is shown in Figure 4[13]. As shown in this Figure, the workpiece is held in a chuck whose position (the C-axis) can be controlled to rotate the part about the Z axis. The milling head (the B-axis) can rotate about the Y-axis and lock in a user-selectable angle. The B and C axes are referred to as the rotational axes of the machine, and the X, Y, and Z axes are referred to as the translational axes of the machine. This machine is not capable of simultaneous contouring using the B-axis, and instead an angle must be selected programmatically before machining begins. The machining area of the millturn machine is shown in Figure 5.

The first step in the process was to design the assembly for manufacturing on the machine. Once the design was completed, process planning for the two major components of the assembly was performed using SculptPrint. The impeller manufacturing process is comprised of turning operations, shown in 7a, and rough and finish milling operations, shown in Figure 7b and 7c, respectively. The housing shown in Figure 8 was turned, bored, milled, and drilled. Finally, an appropriate backing plate and shaft was created to complete the assembly.

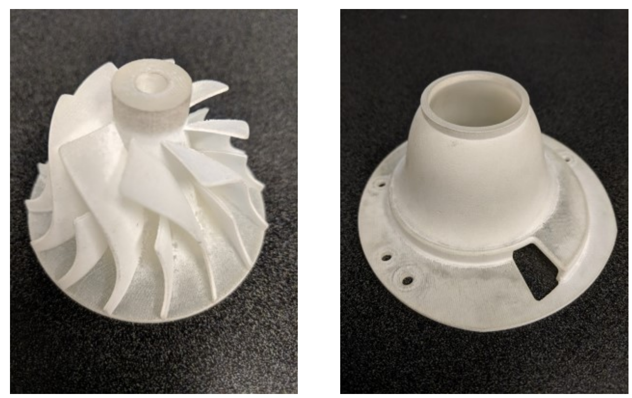
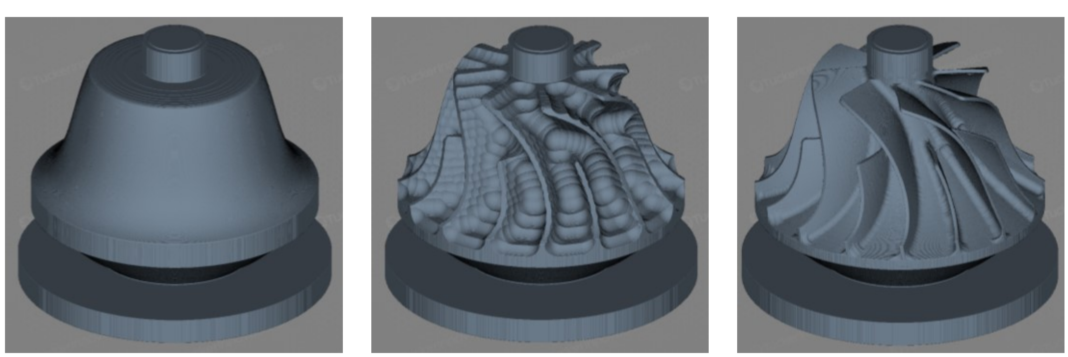


Figure 6. Pictures of 3D Printed Impeller and Housing

Impeller and Housing Design for Manufacturing

The impeller was designed with the manufacturing process in mind. For example, the blade profile was chosen such that a 1/8” ball endmill would be able to access all of the points within the impeller. The blades of the impeller were not designed to be swarfable. If the blades were swarfable, the flank of a tool would be able to access all areas of the blades without any retractions. This was not a concern because



a. Turning b. Rough Milling c. Finish Milling

Figure 7. Overview of Impeller Manufacturing Process

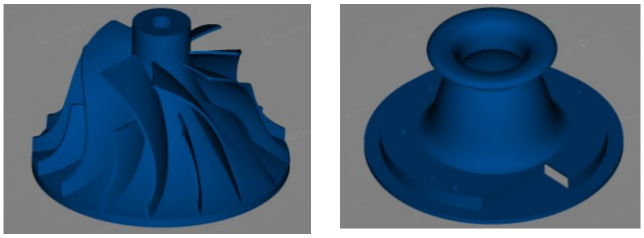


Figure 8. Models of Centrifugal Impeller and Accompanying Housing

currently SculptPrint only cuts with the tip on a ball endmill.

The housing was designed to be centered within 5” aluminum stock. This design choice allowed for a majority of the material to be removed with turning and boring operations.

Before machining the impeller and housing, the assembly was 3D printed to ensure the design was viable, which can be seen in Figure 6. After testing the 3D printed assembly, some changes were made to increase air flow and decrease machining time.

To increase airflow, the inlet of the housing was extended and curved to reduce air pockets. The outer shape of the impeller housing was also changed to be circular where possible to reduce the milling required, as weight and form factor were not a primary concern. The final part models to be machined can be seen in Figure 8. The specifications for the compressor impeller are listed in Table 1.

Impeller Manufacturing Process

The compressor was manufactured from 3” 6061 Aluminum round stock which was 7” long. The stock was cut to be much longer than the length of the part to gain accessibility.

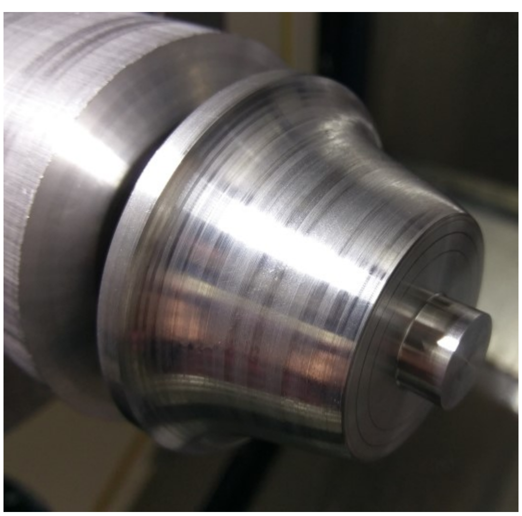


Figure 9. End Result of Turning Outer Profile of Impeller

Table 1. Impeller Specifications

Material	6061 Aluminum Alloy	
Number of Blades	16	
Bore Diameter	6.4 mm	0.252”
Maximum Outer Diameter	69.85 mm	2.75”
Axial Length	44.45 mm	1.75”

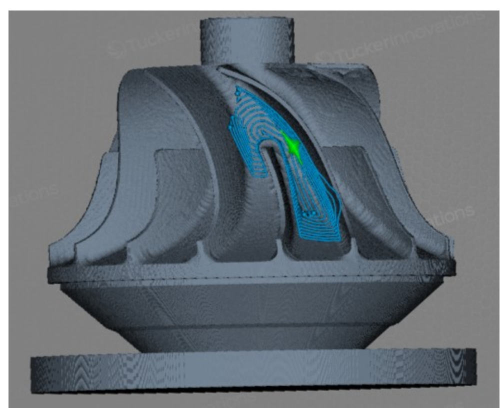
The long stock allowed for the part to sit further from the jaws of the chuck.

Outer Diameter Turning of the Impeller Blank

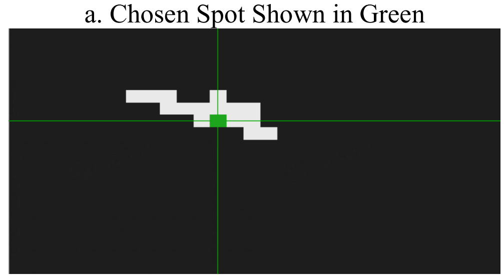
The first operation completed on turbine was a turning pass. This served to form the general shape of the turbine. The operation had a depth of cut of 2mm and utilized a left handed turning tool with a 35 degree insert. Overall, a total of 143,030.20 mm^3 of material was removed with this pass. The end result of the outer turning operation is shown in Figure 9.

Impeller Blade Milling

To complete the blades of the impeller, a series of milling passes were performed using two different sized ball endmills. These passes utilized two tools, a 1/4" and 1/8” ball endmill. The 1/4” ball endmill was used to remove as much material as possible before using the 1/8” tool, which was used in areas with less accessibility. The milling passes left scallop marks on the impeller blades. For this impeller,

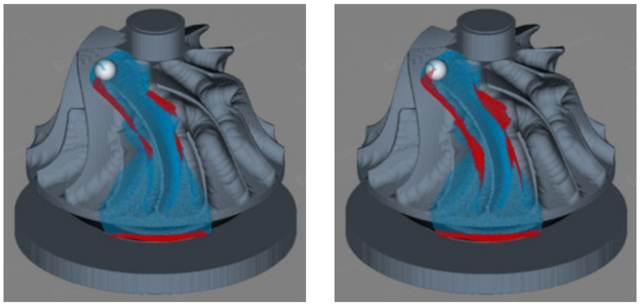


a. Chosen Spot Shown in Green



b. Corresponding Accessibility Map for Chosen Point

Figure 10. Spot Compute Accessibility Map for B Axis Angle



a. Inaccessible Points from 45° B Axis Angle

b. Inaccessible Points from 20° B Axis Angle

Figure 11. Inaccessible Points from Different B Axis Angles

there was a larger focus on machinability of the part versus scallop direction.

<u>B Axis Angle Selection for Milling Passes</u>

Each of the milling passes were executed as simultaneous 4-axis passes with the B-axis fixed at different angles. The B-axis angle is selected programmatically and directly corresponds to the angle ϕ in the tool's coordinate frame. An appropriate B-axis angle was important to ensure the part could be machined. To choose a suitable B-axis angle, a 5-axis accessibility map was created for several points that looked like they would present accessibility issues. The results of this process can be seen in Figure 10, where the accessibility map, shown in Figure 10b was generated for the selected point shown in Figure 10a.

This procedure gave an idea of the ϕ angles that were necessary to access different points of the part. Then a ϕ value, which was accessible for multiple points, was chosen as the B axis angle for the entirety of the pass. This angle was usually near the center of the accessible region for each of the points in which a five axis accessibility map was generated. If the chosen angle did not result in a large number of inaccessible contact points, the angle was used for the given pass. Figure 11 shows the inaccessible points generated for both a 45° and 20° B axis orientation, where the inaccessible points for each orientation are shown in red.

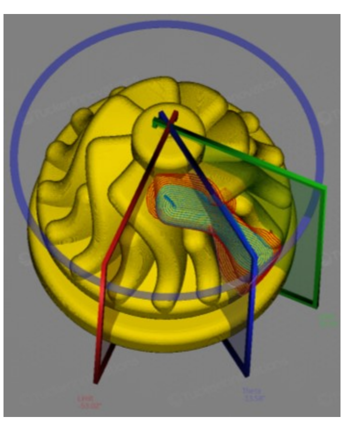


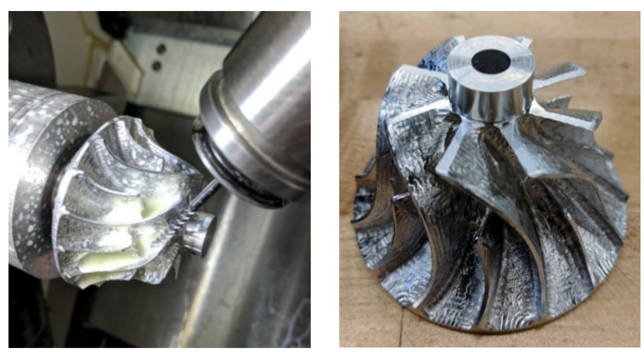
Figure 12. Planes to Restrict Area

It can be seen that the axis orientation can greatly change the number of accessible points.

Multi-Axis Impeller Blade Milling

The first milling pass completed was a turn milling pass using the 1/4" tool. A turn milling pass allows for a large amount of material to be removed with one pass. This pass removed 23409.95 mm^3 of material. The result of this pass can be seen in Figure 7b. Several passes were completed with the 1/4" tool before finishing passes were performed with the 1/8" tool. Each pass was filtered based on the amount of material removed at each point to eliminate machining areas which were close to the desired end volume.

Each pass after the turning pass was created as a millturn pass which only generated G-code for a large and small blade of the impeller. The planes which reduced the workspace considered can be seen in Figure 12, where the bounds of the workspace are seen in green and red. Areas outside of the planes shown were not considered when creating accessibility maps. This reduced the computation time for generating the maps. Another benefit of limiting the number of blades that were used in the toolpath creation was that less time was needed to verify the pass while manufacturing. Once the G-code was verified for one section of the turbine, the rest of the blades were machined with the same G-code with a different work offset that rotated the part. An image of machining in an area with limited visibility can be seen in Figure 13a and the final impeller can be seen in Figure 13b.



a. Milling in Area with Limited Accessibility

b. Final Impeller

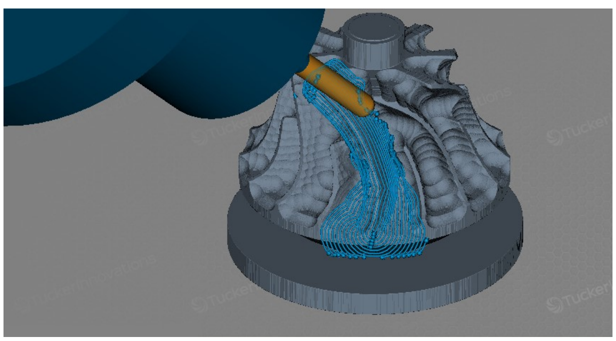
Figure 13. Pictures of Produced Impeller

Inverse Time Programming for Multi-Axis Milling

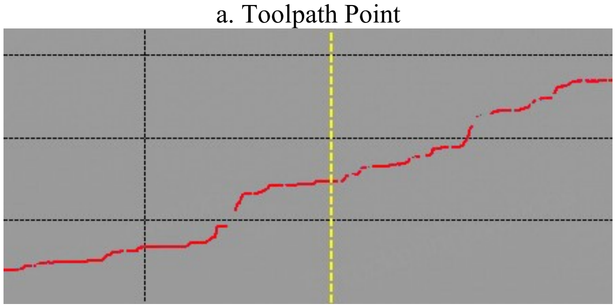
Machining of the impeller required simultaneous movement of both rotary and translational axes to guide the cutting tool along the desired path. Specification of the movement speed of the tool in this case was programmed using time feed commands, sometimes referred to as inverse time feed mode. In this programming method, each point-to-point movement not only specifies the endpoint of the move to the machine, but it also specifies the amount of time permitted to complete the move. Using inverse time feed mode allows both rotational and translational axes to be treated similarly

in the part program; in the case of traditional feed rate specification, where the desired tool movement speed is specified to the machine in the units of distance per time, the movement speed of the rotary axes is not controlled accurately. Using inverse time feed mode allows for enhanced control of material removal rate (MRR) regardless of the distance of the cutting tool to the center of the rotary axis.

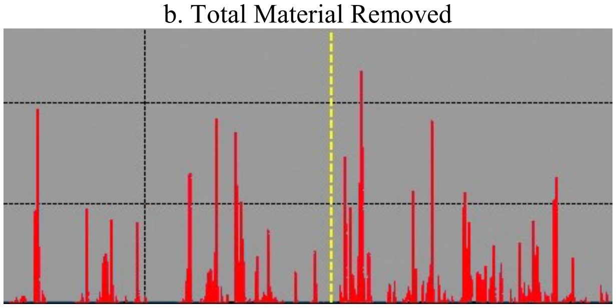
Cutting time commands were generated using SculptPrint by first calculating the amount of material removed at every point-to-point move along the toolpath. Once the material removal had been calculated, desired move completion times were assigned to each movement such that the material removal rate of the move respected some predetermined limit. For the two milling tools that were used to manufacture this assembly, the desired material removal rate of the larger and more rigid tool was higher. Figure 14 shows an example material removal curve for a toolpath on the impeller. The two-dimensional plot in Figure 14b shows the total material removal along the toolpath, where the yellow dashed line indicates the current position of the cutting tool shown in Figure 14a. Figure 14c shows a detail view of the corresponding MRR curve for this path, which is simply the time derivative of the total material removal curve. The goal of the velocity profile creation is to control the MRR to some constant value throughout the entire toolpath for highest machining efficiency, which would remove the peaks and valleys that are present in the MRR curve. However, a constant MRR is not always possible due to the presence of moves to reposition the tool and machine kinematic limits.



a. Toolpath Point



b. Total Material Removed



c. Material Removal Rate Detail

Figure 14. Computed Volume Removal Along Toolpath

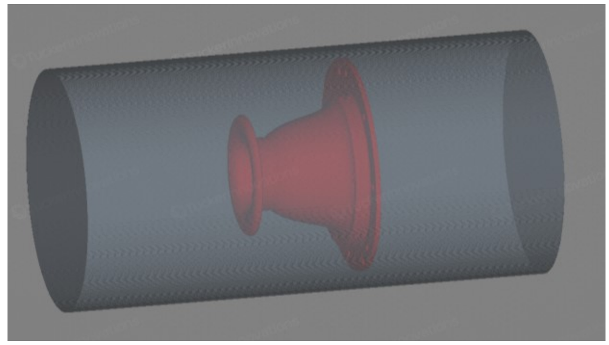


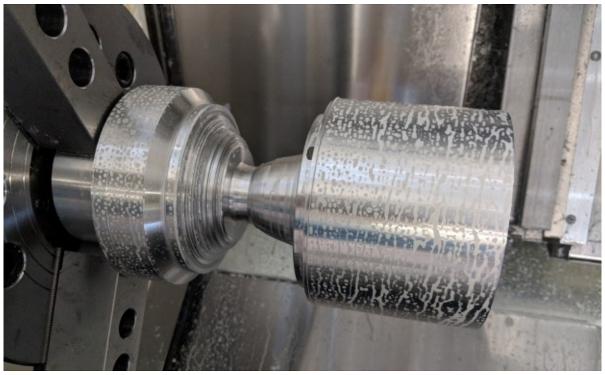
Figure 15. Housing Centered within Stock

Housing Manufacturing Process

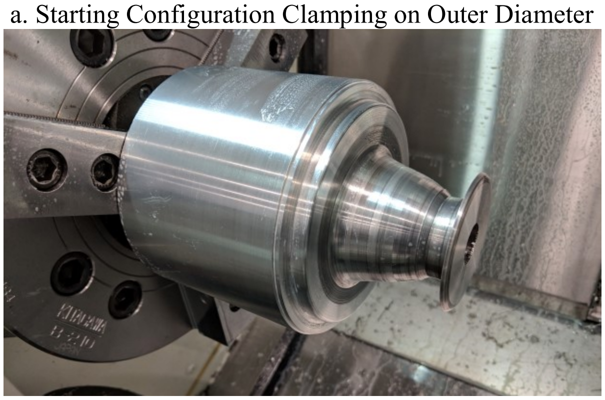
The housing was machined out of 5” diameter aluminum rod stock which was 10” long. In order to hold the stock in the chuck, 2.5” of the stock were turned to 3” in diameter. The housing was 2.75” long and centered within the stock, as seen in Figure 15. The manufacturing process for this part included boring, milling and turning operations. This setup increased accessibility for the turning operation, but reduced accessibility for the boring and milling passes, and allowed for the part to be manufactured without a fixture. The loss in accessibility was compensated for with tooling. For a larger production run, a fixture could be created to reduce the amount of stock used.

<u>Housing Fixture Configuration Suitable for the Millturn Machine</u>

The part was manufactured in two configurations, shown in Figure 16. One in which the stock was clamped on its outer diameter, seen in Figure 16a. In this configuration, the drilling and boring operations were performed to make the pocket where the turbine sits in the final assembly. In addition, a milling pass was executed to create the pocket for airflow. Next two turning passes were performed, one using a left handed tool, and the following using a right handed tool. In the second configuration, the stock was rotated 180 degrees and clamped on the inner diameter that was created from the boring pass, as seen in Figure 16b. This allowed for the final machining to take place which included a turning, boring, and milling pass.



a. Starting Configuration Clamping on Outer Diameter



b. Second Configuration Clamping on Inner Diameter from Boring pass

Figure 16. Clamping Configurations for Housing Manufacturing Angles

<u>Creation of Internal Housing Features</u>

The first pass to be completed for the housing was a boring pass. This served to create the inner profile of the housing and to hollow out the excess material that would later be clamped in the second configuration. This also increased accessibility for the milling pass. The boring operation created some difficulties due to the way the part was set up in SculptPrint. To create passes in SculptPrint, the size of each voxel is set at the beginning of the process. For this part, the voxel size was set too large for the desired depth of cut, which is a function of the voxel size. The original setting for the minimum depth of cut in the program was 3 times the voxel cell size. This was decreased to allow a smaller depth of cut in boring operations.

The next set of passes created the channel for airflow inside of the housing. These were completed as milling passes with 1/4" and 1/8” ball endmills. These tools were placed in long tool holders to allow for increased accessibility. For these passes, accessibility was a concern because the passes removed material deep within the part, which placed the holder inside of the part. The B axis angle was found using a similar method to that used for the turbine. The setup for these passes can be seen in Figure 17.

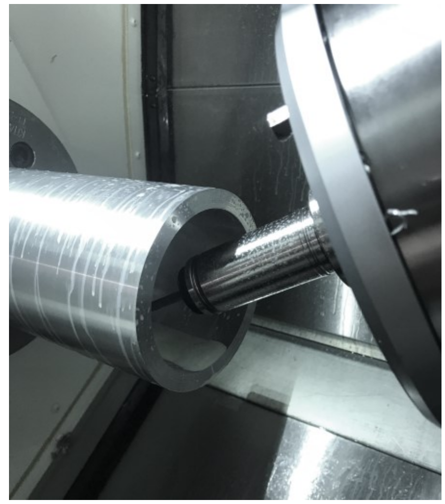


Figure 17. Setup for Milling Internal Housing Pocket

<u>Creation of Outer Housing Features</u>

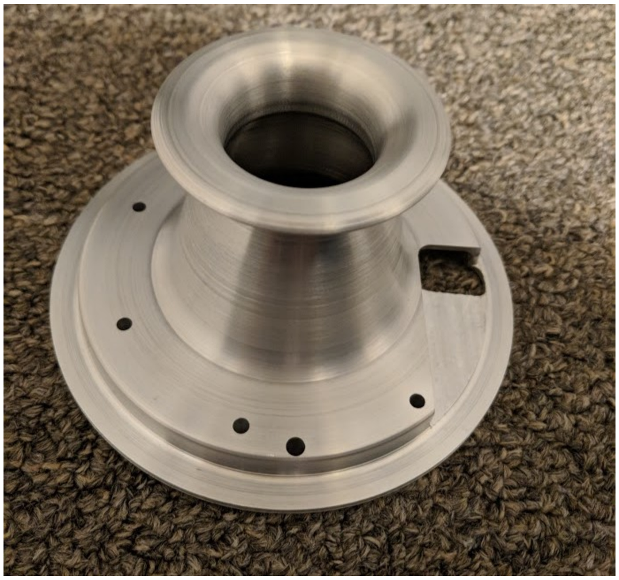
After the completion of the inner features of the part, the outer profile was turned in two separate passes. For these passes, both a right and left-handed facing tool with 35 degree inserts were used to create different features of the housing. The right handed turning tool was used first, then the left handed tool was used to clean up the material left behind.

Next, the part was taken out of the machine, and the material that was clamped in the chuck for the previous operations was cut off in a horizontal band saw. This reduced machining time by removing a lot of material quickly. A similar result could have been achieved by using a parting tool on the machine. The part was then flipped in the machine and clamped on the inner diameter created from the previous boring pass, as seen in Figure 16b.

The first feature to be machined in this new configuration was the shape of the air inlet for the housing. This was created using the left handed facing tool. Next, the inner features that were not accessible in the first configuration were bored out. These points were not accessible due to the length of the boring bar used, and concavity of the features. Next, the outlet of the housing was machined using a 1/2" square endmill, and the holes for the bolted assembly were added. Finally, the housing was parted from the stock. A completed picture of the housing and bolted assembly can be seen in Figure 18a and b.

CONCLUSIONS

This paper demonstrated a successful application of the voxel-based CAM approach to toolpath planning for the manufacture of an operational centrifugal compressor and associated housing. Both the impeller and its housing were machined with the use of a 5-axis Okuma millturn center. Roughing cuts for the impeller's profile were primarily completed with turning operations, while 1/4" and 1/8" ball



a. Housing for the Compressor Impeller Assembly

b. Completed Compressor Impeller Assembly

Figure 18. Machined Housing for Compressor Impeller Assembly

endmills were used to sculpt the blades. The impeller's housing was manufactured almost exclusively with turning and boring operations, leaving small non-axisymmetric features to be machined with a 1/8" endmill.

Accessibility maps were heavily employed to determine tool orientation angles for milling operations. These plots provided a consistent method of resolving potential crashes before machining many of the impeller's features. The inherent design of an impeller provided a significant challenge to find appropriate orientations for the milling operations. Inner features of the compressor impeller (such as locations near the base of each blade) were extremely difficult to reach. However, accessibility maps provided a robust way of computing and selecting the most appropriate tool orientation from the small range of possibilities.

The impeller and housing were assembled into a functioning component. A 1/4" bolt with matching lock nut and appropriate hardware was used to fasten the assembly together, as seen in Figure 18b. The impeller was rotated to confirm functionality and produced compressed air. The final impeller and housing assembly verifies voxel-based CAM manufacturing processes as a viable method for producing functional precision aerospace components.

The continued development of this technology is critical to constrained manufacturing operations. Combined with additive technologies in hybrid machining centers, production of operational precision parts radically expands the capabilities of a single machine where space and resources are limited. For example, forward combat operations require the use of multiple machines with extremely large and costly footprints to maintenance critical military equipment. Rapid production of operational parts through the combined use of additive and subtractive metal machining provides an extremely flexible precision manufacturing platform in a single machine footprint.

Future Work

The typical pock-marked or scalloped surface finish indicative of voxel-based CAM path planning software was evaluated throughout the manufacturing process to ensure dimensional and functional specifications were met. The scalloped surface finish on the impeller resulted from milling operations. Very few marks are present on the housing as the nature turning operations results in a symmetric part. While undesirable, the impeller's marks are highly controllable and predictable; each scallop was accurately predicted and modeled within the CAM software. Scallop marks can be engineered in future parts to achieve a desired fluidic effect. In particular, the directionality of the scallops can be homogenized or varied according to the desired fluidic drag. Additionally, the size of each scallop can be controlled by varying the toolpath's radial depth of cut in that region. Controlling these two parameters, scallop directionality and size, provide the potential to vary the impeller's performance to a desired range without changing its fundamental design.

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