ASEE'S VIRTUAL CONFERENCE
At Home with Engineering Education
JUNE 22 - 26, 2020 #ASEEVC
Paper ID #29520

Student Paper: An Engineering Pedagogy for Developing Practical Knowledge and Hands-On Skills Related to 5-Axis Milling and Computer Aided Aerospace Parts Manufacturing Using Current Technology

Mr. John Vincent Kronenberger, Oregon Institute of Technology

John Kronenberger is a senior undergraduate student at the Oregon Institute of Technology dual majoring in Mechanical Engineering and Manufacturing Engineering Technology. Academic interests include CNC programming, 3D design and modeling, and the application of additive manufacturing technology.

Dr. David E. Culler, Oregon Institute of Technology

Dr. Culler has an M.S. and Ph.D. from New Mexico State University in Industrial Engineering and over 25 years experience in using and developing Computer Aided Manufacturing (CAM) systems and teaching topics such as Product Data Management (PDM) and Product Lifecycle Management (PLM).

Alexander Max Ferere, Oregon Institute of Technology

An Engineering Pedagogy for Developing Practical Knowledge and Hands-On Skills Related to 5-Axis Milling and Computer Aided Aerospace Parts Manufacturing Using Current Technology

Abstract

The implementation and effective utilization of advanced computer controlled machines and processes depends on a concerted effort by industry, machine and software vendors, and educators. Specialized and multipurpose machines such as 5-axis mills, turn-mill, and Swiss style lathes are becoming more popular and affordable. Furthermore, their controllers are becoming more versatile and integrated with sensors, probing capabilities, data collection and enterprise level software. Although trade schools do a good job at training operators and CAD/CAM technicians, there is a growing need for mechanical, manufacturing, and aerospace engineering graduates to have experience and a working knowledge of all aspects of component design, process planning, CNC programming, and process improvement so that companies realize a competitive edge from their investments. This is especially true in the aerospace industry, where factors such as part geometry complexity, difficult to machine materials, single setup fixture design, computer simulations, and reduced cycle times through optimization determine the difference between potential and realized gains in capability and efficiency. In this paper, the authors present a set of course modules that address some of the challenges mentioned above and propose a low-cost platform (hardware/software/tutorials) for other educators to get started. As Industry 4.0, the IIoT, Human Machine Interfaces (HMI's), and Machine Control Units (MCU's) become more sophisticated, the need for skilled personnel and good pedagogical tools will grow as well. Finally, the authors developed some tools to evaluate the effectiveness of the modules and gather feedback from students for future improvements.

Introduction and Background

Advances in machine tool technology, CAD/CAM integration, 3D Printing, and Industry 4.0 initiatives are forcing manufacturers across the board to reflect and reevaluate how they design and implement components and assemblies of all kinds. Because of the nature of aerospace parts in general (geometric complexity, tight tolerances, and hard materials) as well as strict industry and FAA guidelines, the use of multi-purpose and multi-axis machines and specialized cutting tools along with the ability to inspect parts right on the machine are a necessity. There is a need for more practical and current educational materials that address this paradigm shift toward designing, programming, and producing these parts using current technologies and skilled personnel at all levels (i.e. operators, process planners, programmers, and

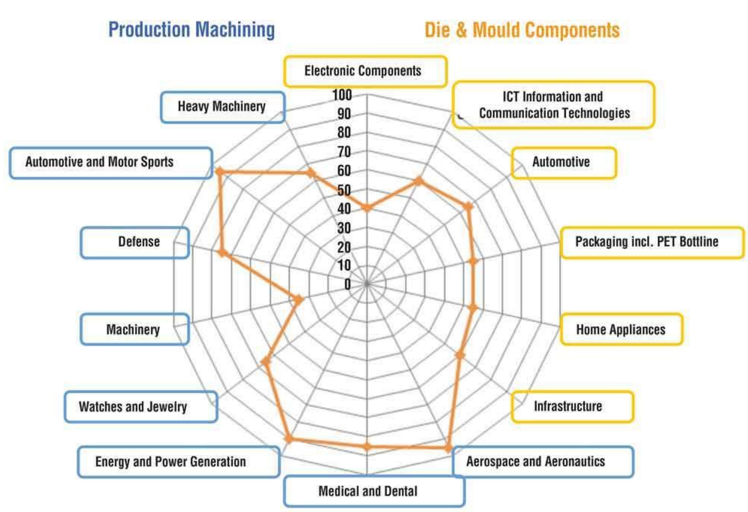


Figure 1: Spider Chart Showing 5-Axis Growth in Diverse Industries

engineers). The expected growth in one particular area (5-Axis machining) across many industries is well documented and shown in the chart above taken from a National Tooling and Machining Association webinar titled: "Main Strategies for Effective Implementation of 5-Axis in Different Areas" shown in Figure 1. [1] This paper focuses on improving engineering education.

Students completing a traditional B.S. or dual degree in Mechanical Engineering and Manufacturing Technology provide an excellent audience to explore the challenges and opportunities related to designing and making aerospace parts. With the growing prevalence of 5-Axis and multi-purpose CNC equipment, it is inevitable that the way we think about parts will also experience a sort of revolution in the upcoming decade. The idea is to target students that already have basic CAD/CAM and 3-axis CNC knowledge and extend that to the application and theory of 5-axis machining. Utilizing a 5-Axis table-top mill Pocket NC® and a 3D modeling and manufacturing software Fusion 360®, the authors have developed modules for students in the advanced CAM class to teach the theory, applications, and practice of 5-Axis. The didactical nature of the machine (i.e. low risk) and the availability of the software selected makes it a great place to start and is readily transferrable to other colleges/programs that are interested in learning about this exciting technology. The goal is to expose students to both higher levels of design and critical thinking abilities. Other skills pertinent to 5-Axis machining that are covered include Design for Manufacturability (DFM), cutting tools, CAM software mastery, simulators, code reading, and communication with operators. The results will help to identify which tools are effective and which are not for introducing 5-axis, as well as for establishing a roadmap to future enhancements.

Literature Review

One of the recurring themes in researching 5-axis machining is that this technology is often being utilized below its potential [2]. 5-axis, in many situations, is used in the same way that 3-axis technology is used. This can be the case in 3+2 [3] machining where rotational movements only occur between operations to position the part and the actual machining operation is a standard 3-axis machining process. This process can be inefficient from a cycle time perspective. While using 3+2 machining does save time and allows for higher quality parts as compared to traditional 3-axis manufacturing it may not utilize the full potential of the technology. It should be remembered however that at times 3+2 machining can be more optimal than 5-axis by allowing for better part quality. This is dependent on the machine itself, tools available and the nature of the operation performed [4].

Some of the challenges inherent in 5-axis machining are tool collisions, surface finish and tool path optimization. This last challenge is especially important as finding the most efficient machining method can be very difficult given the extreme level of flexibility offered by the technology [4]. This problem of flexibility is not limited merely to 5-axis systems but is an issue faced by CNC machining in general. Even something as simple as using different CAM systems to process operations can result in different cycle times and based on how each system develops its machining strategy [5].

Another important area of research in this field is the study of how to minimize errors due to thin part deflection and vibration. Given the fact that aerospace part machining frequently involves thin bladed parts with high tolerance requirements this is an especially critical field of study. To control the forces that might deflect and deform parts causing defects, studies using finite element analysis and tool orientation optimization have been performed with favorable results [6]. In addition to reducing defects, research is also being undertaken to find more efficient tool path methodologies by determining the ideal tool path layers and flow line arraignment in order to reduce machining waste [7].

In educating students on multi-axis machining principles, an emphasis has been on being able to provide students with improved opportunities to simulate machining operations in a low risk environment. This can be performed through the use of various CAD/CAM software such as SOLIDWorks® or Vericut® that allow students to simulate operations and perform activities such as tool path and machining time optimization [8].

Statement of Need for Engineering Education Related to 5-Axis for Aerospace Parts

From large parts like fuselage sections and bulkheads, to medium sized parts like wing spars and landing gear, to small components and molded parts typical in the aerospace and airline industry, there are common factors that distinguish them from other types of parts. Starting with stock shapes and materials (forgings, castings, roughed out and work-hardened), cumbersome setups and fixture design, high strength, low weight, curved shapes, high tolerances, features located normal to surfaces, long and robust tools for cutting, and clearance space in the work envelope are some of the most commonly identified challenges for machining aerospace parts [9]. These and other issues like machine kinematics, analysis of forces on cutting tools/machine components, and optimization of material removal rates are analytically beyond the scope of training for students with a limited math, physics, materials, and machine design background. "Considering angular limits with different setups is important. When you're dealing with five different axes of movement, the machine can get wrapped around itself when trying to get into various nooks and crannies of those odd-shaped parts. Determining what kinds of angular limits the machine has is key to making your rapids as fast as possible - if your machine needs to unravel itself from a weird angle on a part, that is all off-part motion."[10].

New technology is also influencing the growth of 5-Axis in the aerospace industry. "Machine tool makers and their technology partners are developing solutions to help, including easier-to-use controls and programming complex cuts with support graphics and dynamic collision monitoring (including touchscreen). Machines that easily and efficiently feed data to enterprise systems and machine monitoring programs can offer visibility and analysis to increase competitiveness and profitability. Aerospace has increasingly stringent demands: consistently high surface quality, reliable compliance with tight tolerances, high machining speeds, and documentation/validation of processes accompanying production" [11]. Mastering the art of 5-axis necessitates taking a host of factors into account. Although 5 -axis machining has been around for a while, it is experiencing new popularity, particularly in aerospace and defense applications. These markets are experience significant growth. For example, the commercial aircraft order backlog is at its peak of more than 14,000—with about 38,000 aircraft expected to be produced globally over the next 20 years. "When you look at problems that customers have, very seldom is it machining a part. Typically, the problem that's holding them back is centered around something other than making a chip. It's training, it's having personnel, having communication go correctly from the routing to the machine or knowing before they get started that they're going to have enough tools in the magazine to finish the part when they start on it. The peripheral parts of the business hold them back more than actually making the part" [12]. These statements reiterate the need for a more robust approach and training for personnel beyond the NC programming department and the shop floor.

Although engineers may not do the actual programming or machining of parts, they need to have a working understanding of all aspects of the design, manufacture, and support systems, especially considering the investment in hardware and software required to be successful. The material presented in this paragraph identify some of those skills as described by industry representatives and experts in aerospace engineering. "Training curricula and didactics should be completely re-designed and improved, towards modern know-how, the above skills and extensive practical experience. The increasing variety of materials, applications and relevant technologies in the sector = Young people need understanding of higher developed, more sophisticated technologies; Higher complexity and variety of the tasks (flexibility!) due to the rapidly changing needs and expectations of the customers = needing continuous training to understand ever more complex production processes" [13]. As is apparent in the following job posting from Janicki Industries for a Mechanical Engineer, design and manufacturing are equally important as companies rely on engineers to bridge the gap between departments, including having a skill set and a broad understanding of CNC equipment and processes. The Position description is included here: "Develops, designs, and tests all aspects of mechanical components, equipment, and machinery. Applies knowledge of engineering principles to design products such as: engines, instruments, controls, robotics, machines, etc. May be involved in the fabrication, operation, application, installation, and/or repair of mechanical products. Projects will include large-scale machine tools (i.e. our 5-axis mills), robotic systems, and manufacturing equipment with integral electronics and controls, servo systems, dynamic mechanical components" [14]. The Essential job functions performed as a Mechanical Engineer for this job posting include:

- Assists in the design and development of mechanical systems, primarily in the broad area of manufacturing automation
- Helps create machines for composite and metal manufacturing that will make it possible to produce tooling that is not possible today
- Uses broad knowledge of machines and mechanical components along with well-rounded technical knowledge to deliver production-ready, reliable, highly automated equipment
- Manages multiple simultaneous projects from preliminary design through detail engineering and stress analysis, manufacturing, assembly and production
- Uses hands-on troubleshooting in a live production environment to improve designs.

Approach Used for 5-Axis and Aerospace Parts Project and Module Development

This project builds on the current educational model used in the Mechanical and Manufacturing Engineering and Technology program. Providing additional opportunities for studying advanced topics to help students find jobs is the main objective of the work presented here. It builds on foundation courses in understanding M&G code, process planning for machined parts, CNC machining center operation, cutting tools, setup/fixture of parts, and CAD/CAM integration. The sequence of specific courses for manufacturing and dual (mfg. / mech.) students include the following: MFG 341 – MFG 342 + 5-Axis for Aerospace Parts including:

Applications: *Theory, Fundamentals, Configurations of 5-Axis Machines*
Challenges: *Associated with Aerospace parts: shapes, tolerances, materials, tooling.*
Technology: *MCU's, CAM, M&G Code, Industry 4.0*
Pocket NC Ver.2.0®: *Didactical Platform – Hardware & Software*
Autodesk Fusion® CAD/CAM: *Design, Tool Path Operations, Post Processing*
Sample Part 1: *Process Design, Machine Setup, Coding, Machining*
Challenge Part 2: *Impeller, Process Design, Strategies, Optimization*

Didactical Low Cost Educational Kit

The following section lists the materials and tools needed to implement an education 5-axis machining module. The Pocket NC is affordable in comparison to 5-axis machines used in industry. Tool bits, fixtures, and collet are included with the purchase of the Pocket NC V2-10 and will meet the requirements to successfully implement the pedagogy of 5-axis. Fusion360 is a multifunction software that incorporates both CAD and CAM. The software and Hardware for the curriculum takes advantage of industry 4.0 while remaining affordable.

1. Pocket NC Version 2 costs $5500USD plus shipping
    - Pocket NC Mill V2-10
    - One extended reach tool holder
    - 1/8th Inch ER11 Collet and Nut
    - Single Flute Wood, Wax, and Plastic Endmill - Part 52508
    - Use of Pocket NC Simulator for simulating parts prior to cutting
    - Pocket NC vise and hardware

2. Fusion 360 now has one price point – the $495 / year
   Fusion 360 is free for students, small companies and hobbyists who earn less than $100,000 a year

Hardware

The hardware used for this module is the tabletop sized 5-axis CNC Pocket NC V2-10. This system is a useful didactic platform given its simple interface and small size. The Pocket NC weighs about 30 pounds with an enclose weighing about 25 pounds. The movement and rotations are about the X, Y, Z, A, and, B axes. The B axis rotates about the Z-axis while the A axis rotates about the Y-axis. This allows the user to mill features that are not perpendicular to the surface of the work piece. The interface for the tabletop machine is accessible via an IP address that works for all Pocket NC. The Pocket NC connects to a computer via an input as seen in figure 2 as number 4. This

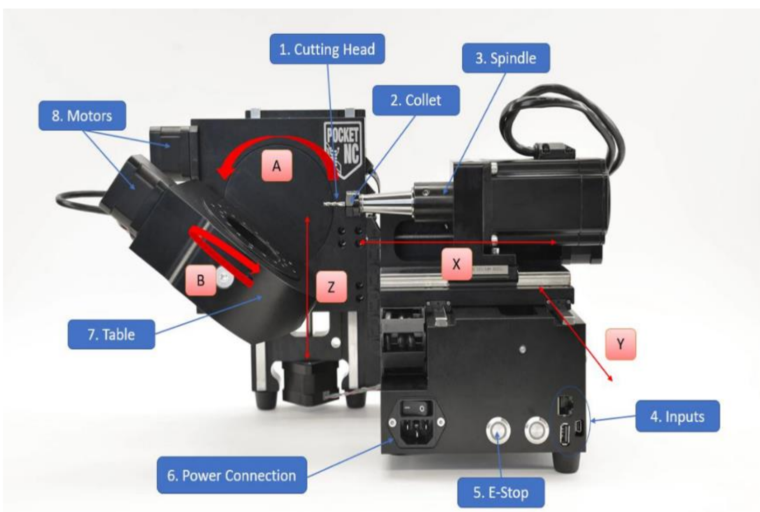


Figure :2 Pocket NC V2-10

interface allows the user to zero the machine by having the tool bit touch a home button that is located within the table of the machine. The benefits of this type of tool tag off is that it is quick and accurate which allows the user to make accurate cuts. A physical emergency button is on the machine along with one on the interface. [15]

Software

To develop operation specific commands and g-code, Fusion360 was used. This software offers great functionality to student user. Fusion360 takes advantage of industry 4.0 by connecting your entire product development process into one cloud-based platform. This makes it easier for user to access different components of the design almost instantaneously. Fusion360 can act as 3D CAD, CAM, and CAE tool systems. The software can also import a variety of different modeling software's that are common among students. Files can be imported such as Pocket NC tooling, tool holders and fixtures that make for fast and accurate simulation. These simulation help reduce the chance of tool collisions.

Storing process attributes provide a useful tool to create machining "templates" that save the user time when features require similar strategies and process parameters. Boundary geometry used to simulate the raw stock may be simple or defined by another model and changes without disrupting the design of the work piece. Making an assembly has become easier with the use of a hybrid component aspect that allows the user to focus on joints and make a crib for the individual assembly parts. [16]

Description of 5-Axis and Aerospace Component Course Content (Modules 1-4):

Table 1: Proposed Outline for 5-Axis Machining of Aerospace Parts Modules

Module	Subject	Content
1	5-Axis Machines	Orientation and Configuration - Theory
2	Aerospace Components	Challenges, Characteristics, Strategies
3	Didactical Hands-On	Pocket NC Machine & Fusion 360 CAD/CAM
4	Complex Part Challenge	Impeller Design and Machining Processes

Module 1

The objective of Module 1 is to introduce the fundamentals of 5-axis machining. Students will have had hands-on experience designing and machining in 3-axis using CAD/CAM systems and will already understanding many of the fundamental machining concepts. The focus of this module is to help students take the knowledge and experience they already have and learn to apply it to 5-axis machining. The main learning outcomes of this module are for students to understand the coordinate system used in 5-axis, the common configurations of 5-axis machines, and some general theory behind 5-axis machining. The breakdown of steps and main learning outcomes are described below.

Theory and Background: This learning outcome is for students to understand the key drivers behind the growth of 5-axis machining. Its benefits to industry particularly the aerospace and advanced manufacturing industry. Students should be able to understand the benefits of 5-axis machining in terms of quality, cost reduction and design flexibility.

5-axis Coordinate System: Upon completion of this module, students should be able to understand the relationship between XYZ axis designations as well as the A and B rotations. Students should be comfortable establishing the coordinate systems used for specific operations based on operation type and the surfaces associated with the features.

5-axis Machine Configuration: Students should be able to understand and describe the differences between head/head, table/head and table/table configurations. The students will also be able to elaborate on the differences between 5-axis continuous machining and 3+2 machining. By completing this module, students will have an understanding of why 5-axis machining is an important technology especially regarding the manufacturing of aerospace parts. They will have learned to identify the key differences between traditional 3-axis machining and the different 5-axis configurations while also being able to identify the different rotations and axes in a 5-axis coordinate system. This module will give them the background necessary to perform the hands-on CAM exercises performed in later modules.

Module 2

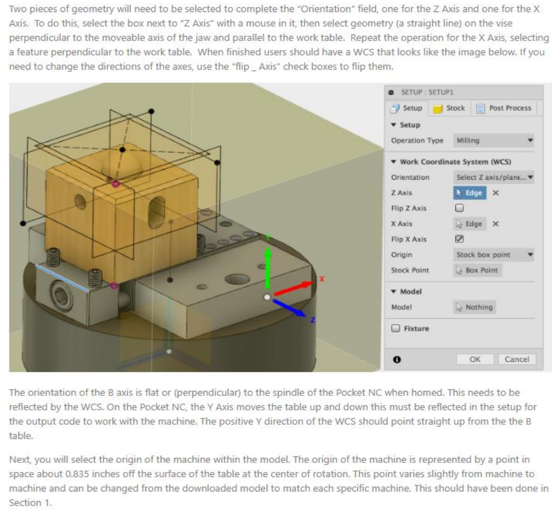
The second module will focus on educating students on the challenges involved with 5-axis machining especially in relation manufacturing for the aerospace industry. The key learning areas are material considerations, tool path optimization and the machining of thin walled parts. In addition to introducing students to aerospace specific challenges, methodologies to overcoming these challenges are introduced. The learning outcomes are described as follows.

Material Considerations: Students are made aware of the commonly used materials used in aerospace manufacturing such as 6-4-titanium and alloys of stainless steels. Students will learn about the machining challenges associated with these materials and how to utilize strategies like cutting tool selection, feed-rate, spindle speed, and specific tool path operations to address them.

Tool Path Optimization: Tool path optimization is critical for reducing manufacturing costs and given the flexibility in choosing tooling paths offered by 5-axis machining is one that is of particular importance. Students will learn methods to compare tool paths and be made of software such as Vericut that assist in optimizing tool path optimization.

Thin Walled Part Machining: The machining of thin walled parts is especially relevant as many aerospace specific parts such as turbine blades, impellers etc. fall within this category. Students will learn to understand the machining challenges such as tool chatter, part deflection and over/undercutting that can result. Students will gain an understanding of how to resolve these issues with methods such as tool selection, tool orientation and cutting path selection. Upon completing this module, students will have a broad understanding of the aerospace specific challenges regarding 5-axis machining. They will understand some of the tools and methodologies used to overcome these challenges and be able to apply them in their hands-on design projects in the following modules.

Module 3
Within Module 3 students will learn how interact with fusion360 and use the Pocket NC interface. Students will use the knowledge from Module 1 and apply it to Fusion360 and the Pocket NC with a basic part that takes advantage of 5-axis movements. The focus of this module is for students to become familiar with the user interface of these systems, so they can generate and create code for a 5-axis part. The learning outcomes are explained in more detail below.



Two pieces of geometry will need to be selected to complete the "Orientation" field, one for the Z Axis and one for the X Axis. To do this, select the box next to "Z Axis" with a mouse in it, then select geometry (a straight line) on the vise perpendicular to the moveable axis of the jaw and parallel to the work table. Repeat the operation for the X Axis, selecting a feature perpendicular to the work table. When finished users should have a WCS that looks like the image below. If you need to change the directions of the axes, use the "flip _ Axis" check boxes to flip them.

The orientation of the B axis is flat or (perpendicular) to the spindle of the Pocket NC when homed. This needs to be reflected by the WCS. On the Pocket NC, the Y Axis moves the table up and down this must be reflected in the setup for the output code to work with the machine. The positive Y direction of the WCS should point straight up from the the B table.

Next, you will select the origin of the machine within the model. The origin of the machine is represented by a point in space about 0.835 inches off the surface of the table at the center of rotation. This point varies slightly from machine to machine and can be changed from the downloaded model to match each specific machine. This should have been done in Section 1.

Figure 3 WCS setup

Fusion360: With the completion of this module, students will learn how to correctly set up a WCS in Fusion360. Fig. 3 shows the orientation of the WCS that the students will be implementing in on the part, so they can apply their knowledge to a physical part. Students will also gain familiarity with other operations such as stock setup, and the programming of simple machining operations. Students will also learn the how to upload fixture information to Fusion360 while also applying fixture and stock designations.

Pocket NC V2-10: Along with becoming familiar with Fusion360, students will learn how to import G-code into the interface of the Pocket NC as well as creating tool offsets. Students will learn how to load tool bits and setup the stock correctly to match the simulation in Fusion360. Once this module is complete, the student should understand the interface of fusion360 and the Pocket NC. With understanding of Fusion360 and the Pocket NC interface, students will be able to machine their first part.

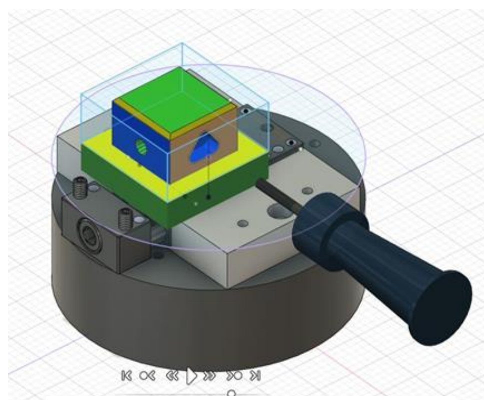


Figure 4 Basic Cube Simulation

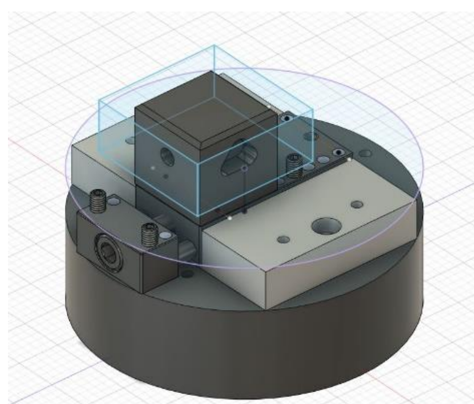


Figure 5 Basic Cube

First Part (simple multi-faced part): The learning objective for the first part is for students to apply the concepts of a WCS and tool path optimization on a simple part that takes advantage of 5-axis movements. Students will become more comfortable applying these concepts through this part that will allow them to create a more complex part. The students will also become familiar with creating boundaries and importing files into Fusion360 if the part was created in a different CAD system. Picking the correct machining operation will also be a learning outcome. Students will also be able to jump between the machining and design component of Fusion360. Students will be comfortable with finding the location of different setting options. The part will consist of a simple cube designed by the student that must include two different pockets, a raised boss chamfered edges and facing operations. In completing this activity, students will also learn how to perform post-processing in Fusion360 for Pocket NC and then simulate their g-code using the Pocket NC simulator. [17]. The Pocket NC UI shown in Fig.6.

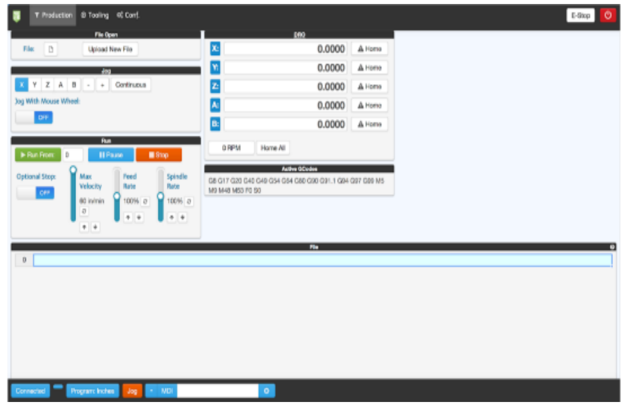


Figure 6 Pocket NC UI

Module 4

The objective of module 4 is for student to learn to machine a part with complex curved surfaces that would be similar to those seen in aerospace. Students will take their knowledge from the previous three modules and create an optimal machining process. This module will allow students to have a chance to use their concepts in a hands-on application. The learning outcomes for the complex part are explained below.

Complex Part (impeller): The creation of the complex part mimics that of a common aerospace part. This part will be using more continuous 5-axis movement to help students apply the concepts they have previously learned. The outcome of this part is for students to focus on machining a thin walled part while keeping optimal tool paths. This part will challenge and test students' knowledge of concepts relating to 5-axis parts. Some important learning outcomes for students with this part is for them to be able to create operations for curved features while being aware of machining thin walls. Students will have the opportunity to experiment with different operation types and see their effect on outcomes such as machining time and surface finish. Overall, this activity will allow students to practice the more advanced functions within Fusion360 while also applying what they have learned regarding 5-axis machining to a real-world manufacturing challenge. Students will gain experience critically examining different machining operations while balancing the different objects of part quality, machining time and effective tool use. Students will have the opportunity to test their designs both using simulators and using the Pocket NC to machine the part out of plastic. This allows them to gain more hands-on machining practice and better understand the physical and practical implications of their design decisions. See Figs. 7, 8 & 9 for examples taken from the challenge part module.

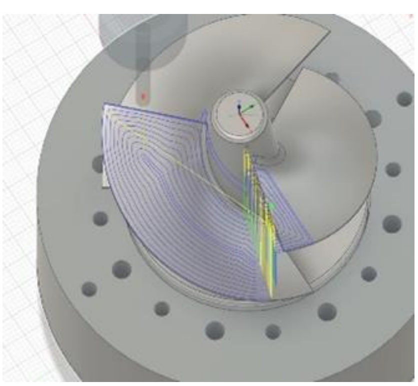


Figure 7 Tool Path Simulation

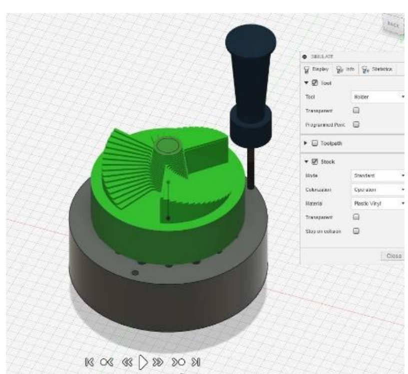


Figure 8 Impeller Machining

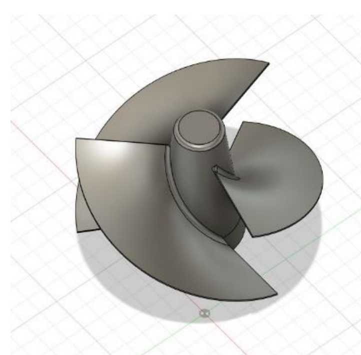
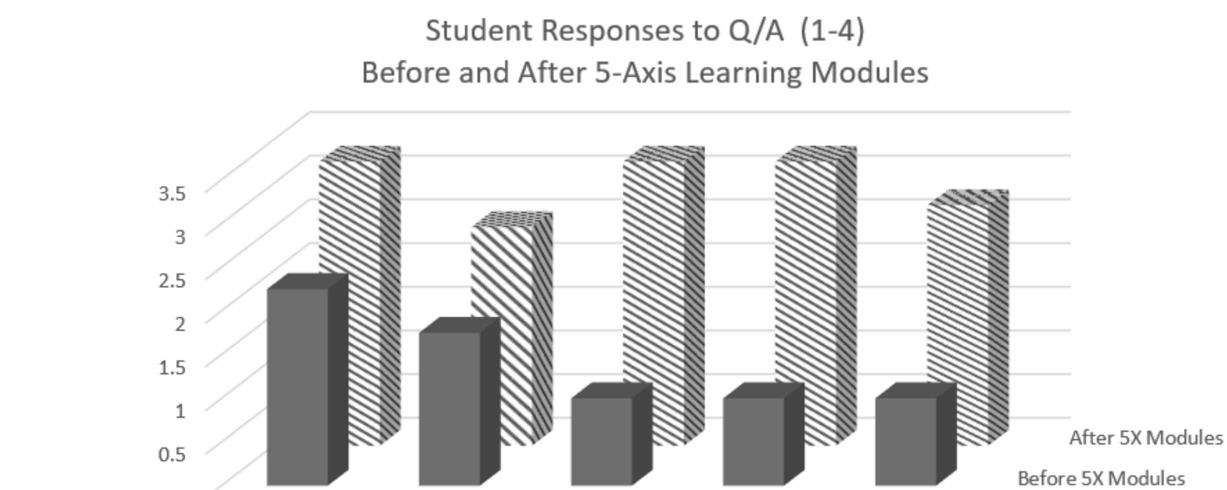


Figure 9 Impeller Practice Part

Discussion and Analysis of Results

A variety of evaluation methods and tools were used during and after the implementation of the learning modules described in this paper. Review questions and discussions were used to clarify and expand on the reading material related to 5-axis milling concepts and challenges related to designing and machining aerospace parts. Direct observation of the students while they performed the hands-on portion of the exercises was very useful to address questions related to the software and hardware, keep the students moving at a steady pace, reinforce desired learning points, and avoid damaging the machine or tooling due to their lack of experience. In order to try and determine the effectiveness and popularity of such a course module we took a survey data before and after running the modules by asking 5 general knowledge questions and a few questions to capture student feedback. The results were gathered using a scale of 1-4 with 1 being little to no knowledge to 4 being very knowledgeable. The results were generally what we expected for the class before the modules began. Students were somewhat knowledgeable of 5-axis NC programming beforehand, but knowledge of aerospace specific parts manufacturing was limited. None of the students had any experience using Pocket NC or Fusion before taking this module. The graph below summarizes the student feedback and results for the learning modules.



	Ques.1	Ques.2	Ques.3	Ques.4	Ques.5
Before 5X Modules	2.25	1.75	1	1	1
After 5X Modules	3.25	2.5	3.25	3.25	2.75

Q1 - Do you know how 5-Axis NC Programming, Coordinate Systems, and Machining Work?
Q2 - Can you identify and explain some of the challenges with machining aerospace parts?
Q3 - Do you know how to design parts and create NC code for 5-Axis milling using Fusion 360?
Q4 - Do you understand how to setup the stock, establish offsets, and load tools on Pocket NC?
Q5 - Are you familiar with the Pocket NC configuration, user interface, and running NC programs?

Figure 10: Summary of Results Collected from Students

The questions regarding the actual hands-on knowledge of using Fusion 360 and Pocket NC showed the greatest improvement. This validates our goal of giving the students a greater hands-on experience in physical machining systems. The area of least improvement was in learning about the challenges of machining aerospace parts. This could be due to the challenges of teaching something that is potentially a very broad topic and with concepts that are difficult to reinforce in a class focused on hands-on machining application. Aside from this area the students did see marked improvement in all other areas. Both in abstract understanding of 5-axis machining principles and in the technical application using Fusion 360 and Pocket NC.

A scoring rubric was developed to summarize the performance of the students based on their work and progress demonstrated during the use of the modules. Student ability to learn new technology related to 5-axis milling and aerospace part manufacturing was implemented in the MFG342 course that was taught in winter term 2020. The following table summarizes the performance of the 4 students included in the study.

Student Performance Observed on 5-Axis and Aerospace Parts Module Readings / Exercises	
Observed Performance > ***Module Content*** ∨	Level 1 -Difficulty with concepts, answering questions or applying knowledge. Level 2 -Able to understand concepts and answer questions but difficulty in applying. Level 3 -Fully understand material and able to answer questions / apply knowledge. Level 4 -High level of ability to understand / apply concepts and hands-on tasks.
Use of readings to gain knowledge of 5-axis machining	All 4 students performed at Level 3 on foundation knowledge related to 5 axis machining. This was mostly related to understanding 5-axis machine configurations and the addition of A & B rotations, including the difference between continuous 4 and 5 axis machining versus the 3 + 1 (indexing) and 3 + 2 (for part face features).
Use of readings to identify challenges with aerospace parts manufacture	3 of the 4 students performed at Level 3 on answer questions related to aerospace parts manufacturing and 1 student performed at level 2. In general, students were able to talk about materials, tolerances, thin walls, and complex geometries as the main challenges, as well as talk about strategies to address these items.
Use Fusion360 to generate tool paths, run machining simulations, make G-code	2 of the 4 students adapted quickly to the Fusion360 integrated user interface and the tools for designing parts and creating 5-Axis tool paths (Level 3). The other 2 students had more difficulty, and needed assistance from the advanced students and faculty (Level 2). All students commented on enjoying the new experience with Fusion and the GUI.
Setup and operate 5-Axis PocketNC machine (stock, tooling, Gui, offsets, run)	All students adjusted quickly to the setup and operation of the tabletop 5-axis machine. Understanding the coordinate systems, establishing the origins, and the A&B axis rotations to machine 5-axis features were explained / repeated (Level 4).

Table 2: Summary of Results Collected from Students

Conclusions

The results support our initial premise that a class that teaches diverse aspects of designing and manufacturing aerospace parts using 5-Axis milling is a useful, and practical addition to the engineering curriculum. The aerospace manufacturing industry is experiencing rapid growth in technologies aimed at improving the efficiency and quality of manufacturing processes. In order to take advantage of these developments, engineering professionals who are crossed trained in these technologies are becoming increasingly more valuable. It is important that the training and understanding of these technologies is not confined to trade schools and for the benefit of NC programmers and machinists only. The engineering students and professionals who rely on these systems and who will be designing parts produced by these systems must have a stronger background in these areas.

In developing the modules one of the greatest challenges came in identifying what should be the focus in terms of learning objectives. One challenge was to decide what to make available to teach students, as it was important to narrow the focus to what we could teach in a short time frame while also allowing students the chance to gain needed hands-on experience in the technology. It was critical that students be able to practice using a 5-axis system to gain true understanding within a practical real-world context of attempting to manufacture a complex part (representative of aerospace component machining) using 5-axis. That was the reason for choosing the impeller part that had complex geometry, thin walled features, and exercises the 5-Axis capabilities of the machine. However, it was also important that students gain the theory and background behind these machines.

Some things that students enjoyed the most was being able to interact with a physical system and to have an understanding of how 5-axis is applied, and not just read about it. Students also liked seeing applications of 5-axis machining beyond just aerospace manufacturing. They provided useful feedback on what can be done to improve the modules. One area identified is that students would have liked more time to explore and understand the capabilities and functionality of the Fusion 360 software and specific part features that require 5-axis milling. This highlights one of the challenges of a 3-week course in that there is a large amount of material and not enough time to focus on specific topics for better knowledge retention. Another recommendation by the students was to have an assignment that could have been worked on outside of class in order to allow them to practice using the various CAM software functions.

What can we learn from this initial implementation of the modules? First it was definitely confirmed that engineering students were interested and excited to learn more about this technology. The students also felt that they gained valuable knowledge that will help them in chosen career. Students would have liked the opportunity to learn at their own pace and to have time to experiment with the technology. This could be fixed by giving students their own licenses to Fusion360 and the PocketNC simulator so they can work from home. Students found it challenging to understand aerospace component machining issues while at the same time learning the nuances of 5-axis CNC.

References

[1] National Tooling and Machining Association, “Main Strategies for Effective Implementation of 5-Axis in Different Industries”, https://www.canadianmetalworking.com/canadianmetalworking/article/metalworking/6-strategies-to-get-the-most-from-5-axis-machining, accessed on Dec. 15, 2019.

[2] Saxer, M, N de Beer, & DM Dimitrov. "High-Speed 5-Axis Machining For Tooling Applications." *The South African Journal of Industrial Engineering* [Online], 23.3 (2012): 144-153, accessed on Dec. 12, 2019.

[3] A. Mazakas, “Simplified 5-Axis Machining” DP Technology Corp. 2011.

[4] R. Endl and J. Jaje. *The Challenges for CAM Systems and Users in 5-Axis Machining,* Sescoi 2008.

[5] G. M. Minquiz, V. Borja, M. López-Parra, A. C. Ramírez-Reivich, M. A. Domínguez, and A. Alcaide, “A Comparative Study of CNC Part Programming Addressing Energy Consumption and Productivity,” *Procedia CIRP*, vol. 14, pp. 581–586, 2014.

[6] T. Huang, X.-M. Zhang, and H. Ding, "Tool Orientation Optimization for Reduction of Vibration and Deformation in Ball-end Milling of Thin-walled Impeller Blades," *Procedia CIRP*, vol. 58, pp. 210–215, 2017.

[7] Fan, H.-Z., & Xi, G. "Efficient tool path generation for five-axis machining of a difficult machined centrifugal impeller". *Advances in Mechanical Engineering*. 2017.

[8] L. Qian "Teaching Multi-axis Complex Surface Machining via Simulation and Projects" *American Society for Engineering Education Annual Conference & Exposition,* 2005.

[9] C. Perry, "5-axis CNC machines for aerospace", *Aerospace Manufacturing and Design August September 2018,* https://www.aerospacemanufacturinganddesign.com/article/5-axis-cnc-machines-for-aerospace/, accessed on Oct. 27, 2019.

[10] B. Hess, "5-Axis Machining and Milling", *Astro Machine Works Inc. Website*, https://astromachineworks.com/services/5-axis-machining-milling/, accessed on Nov. 15, 2019.

[11] I. Wright, "The What, Why and How of 5-Axis CNC Machining", *Engineering.com, Inc.*, https://www.engineering.com/AdvancedManufacturing/ArticleID/11930/The-What-Why-and-How-of-5-Axis-CNC-Machining.aspx, accessed on Oct. 23, 2019.

[12] R. Lineberger, "2020 Global Aerospace and Defense Industry Outlook", *Deloitte Aero. & Defense Inc., https://www2.deloitte.com/global/en/pages/manufacturing/articles/global-a-and-d-outlook.html,* accessed on Dec. 10, 2019.

[13] B. Maes, "The Future of CNC Manufacturing Education – CNC Manufacturing, Education Reform & Change Management News", *World Press,* https://bertmaes.wordpress.com/report-skills-shortage/, accessed on Dec. 17, 2019.

[14] Janicki Industries, "Job Description for Entry Level Mechanical Engineer", *Janicki Industries Inc.*, https://www.janicki.com/job/270-mechanical-engineer-entry-level/, accessed on Jan. 3, 2020.

[15] Pocket NC , "*Pocket NC V2-10*" , [Online]. Available: https://pocketnc.com/products/pocket-nc-v2?variant=11607895998511, accessed on Jan. 3, 2019.

[16] "Cloud Powered 3D CAD/CAM Software for Product Design: Fusion 360," *Cloud Powered 3D CAD/CAM Software for Product Design | Fusion 360*. [Online]. Available: https://www.autodesk.com/products/fusion-360/overview, accessed on 15-Dec-2019.

[17] Q Rothing September 26, "V2 Series First Part Tutorial," *Pocket NC FAQ & Resources.* [Online]. Available: https://support.pocketnc.com/hc/en-us/articels/360018909893-V2-Series-Part-Tutoria, accessed on Oct. 4, 2019.