Adapting CAD/CAM and CNC Curriculum to Advances in Technology

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One of the challenges faced in manufacturing engineering education is how best to teach important, traditional content while branching out into new areas that are emerging as manufacturing technologies evolve. Dealing with this challenge requires a clear understanding of what is the foundational material for a MFGE student to acquire in each area, and an ability to integrate in new topics that keeps pace with advances of the technology that are relevant to the needs of local and regional industries. One such area of the curriculum is CAD/CAM and CNC. In this paper we will review some important advances in technology in this area that are being integrated into a manufacturing engineering curriculum. These include CAM part programming using sophisticated tool path generation capabilities that promote high speed and high efficiency machining, programming multi-axis machining operations, the use of various measurement techniques to quantify variation and efficiency of CNC operations, and the use of advanced simulation and verification techniques to develop insight into and troubleshoot programs. How these advances can be effectively integrated into courses on CAD/CAM and CNC in a MFGE curriculum will be discussed using examples from two classes offered to majors in the program. To promote effective instruction in these new areas, a substantial investment in resources both software and hardware, and time of staff and faculty is required. This paper will further describe the equipment investments made in this case and explain the rationale behind adopting the resources that were selected. The impact of including these advanced topics on more traditional topics such as manual part programming will be discussed using assessment data and student feedback. Finally, some opportunities for further enhancements of the CAD/CAM and CNC instruction in one of the classes reviewed will be presented.

Introduction

Advances in technology in manufacturing present challenges to engineering programs that must keep their curriculums current so that their graduates meet the needs of the industries that hire them. This is most important in the area CAD/CAM and CNC where new trends in software, information technology and hardware capabilities impact industry practices in machining. One such manufacturing engineering program, the context for this paper, has traditionally maintained a focus on CAD/CAM and CNC in its curriculum that extends back to its roots as an engineering technology program. The faculty in consultation with the program's Industrial Advisory Committee have maintained a mission of graduating majors that have significant hands-on training that they receive through lab experiences and extensive project work. These graduates are valued in the region for their ability to be impactful within a manufacturing environment upon graduation without the need to significant supplemental training. Maintaining this mission is however challenging because of the need for resources that are industrial in scale and complexity. This includes having experienced faculty and staff who are dedicated to this mission which requires effort to keep these resources and their skills current. Part of this is deciding how to balance developing skills using new technologies with increasing sophistication with more traditional techniques such as the use of manual part programming. These skills need to leverage new capabilities in CAM tool path generation to be considered during process planning to improve machining efficiency, the greater ease of programming multi-axis CNC machines, more sophisticated verification tools that can challenge visualization skills, metrology techniques that assist in understanding the impact of planning choices, and even ways to monitor a process during machining such as measuring the cutting forces generated.

In the sections that follow, how these capabilities are impactful to the extent that they need to be included in the curriculum will be discussed. The resources that a program needs to invest in to support doing this will be summarized, and examples of classes where their use is becoming the practice will be presented. As one example of how these changes are impacting the traditional content of CAD/CAM and CNC classes, assessment results, student feedback and instructor observations will be used to assess the value and extent to which manual part programming needs to be taught as a skill to manufacturing engineers.

Related Work

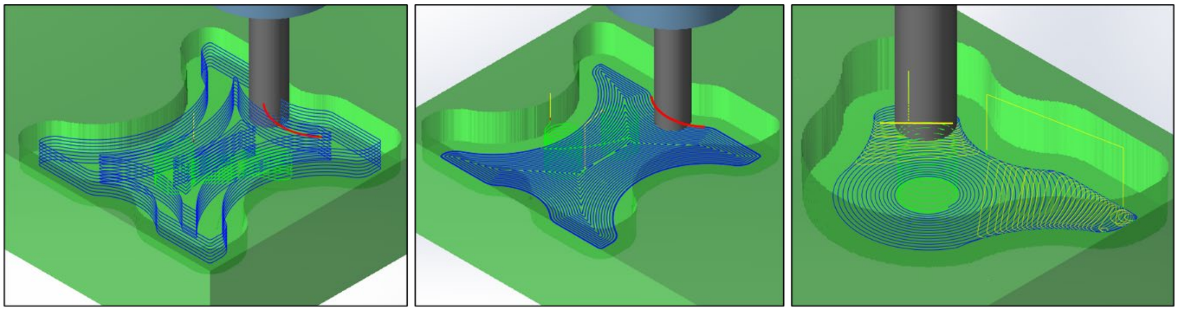
Approaches to the integration and instruction of CAD/CAM and CNC technologies in engineering curriculum have been reported upon in the literature. This is largely divided between its role as core content in engineering technology education and as optional content introduced to build Design for Manufacturability (DFM) knowledge in mechanical engineering students. In engineering technology education, the applied focus and the hands-on requirement for graduates justifies the investment in industrial-type resources that support in-depth treatment of the subject. Ertekin et al. [1] describe their efforts at integrating advanced CAD/CAM and CNC technologies into courses offered at Drexel University to engineering technology majors. Their efforts focus on creating a 3-D Virtual Laboratory that compliments physical equipment. They make the case that having unlimited access to hardware and software simulators enhances learning of students and makes them more effective when they move onto the physical equipment. The virtual laboratory they have developed also supports remote operation of in-house custom-built desktop CNCs which the students can use to machine components for projects. CNC (manual) programming is mentioned as a topic that is covered. Djassemi [2] provides an overview of an integrated laboratory class in CAD/CAM and CNC that is taught to industrial and engineering technology majors. The experiences in this class also introduce other CNC-enabled manufacturing processes such as plasma cutting, 3D printing and encourages students to apply their acquired skills to mold design in their major project. The paper does not explicitly mention that manual programming is taught. Yip-Hoi [3] describes the use of verification to support a CAM and CNC class in a manufacturing engineering technology program. Detailed models of the machine, fixturing tooling and workpiece are constructed in Vericut®, an industrial standard for CNC verification, and used to check correctness of programs before they are executed in the laboratory. It is reported that programming for the labs requiring verification is both manually written and posted from a CAM application. Georgeou et al. [4] make a case for the role that a CNC machining class can play in improving a mechanical engineering technologists design for manufacturability knowledge. They describe a curriculum where majors take a basic manufacturing processes class followed by a more advanced class where they learn the basics of CNC programming. Additional more advanced CNC electives are also available to take. They describe a laboratory, the Haas Technical Center which has several Haas mills and lathes that are used in these classes. The lab and project work include a combination of manual and CAM programming that increases in complexity and that can also be used to support machining work needed for their entry into the SAE Mini Baja competition. In many ways this approach mirrors the experiences that will be described in this paper with the difference being that that target audience here is a manufacturing engineering major. Pierson et al. [5] describe a similar initiative targeting mechanical engineering majors that lays out a CAD/CAM and CNC course they are proposing that will address the recognized weakness in manufacturing related skills in ME graduates. While many of the hardware and software components they identify as critical are similar to what others are using, they propose the use of desktop CNC mills for machining. They correctly point out that this can increase access by reducing safety and damage concerns. While this works up to a point in conveying manufacturing knowledge and may be sufficient for a ME, a manufacturing engineering major's specialized skills development benefits greatly from exposure to processes that run on production scale equipment. It is difficult to study the impact of many process planning choices on desktop CNCs. CNC mill and lathe manual programming are not explicitly proposed as a topic to be taught in this class.

Throughout the work reviewed there continues to be some emphasis on including instruction on manual part programming in classes where more advanced CAD/CAM technologies are used. Its relative importance is however not addressed in the literature though one might conclude that it maintains enough value to want to include in the skill set of an engineering technologist or a manufacturing engineer.

Impact of Advances in Technology

Significant advances have occurred in hardware and software in CAD/CAM and CNC that directly impact learning and skills development. Curriculum that focuses on these areas needs to be adapted to expose students to these advances. The following summarizes the most important of these and their potential impacts on the pedagogy of CAD/CAM and CNC instruction:

1. *High Speed, High Efficiency and Adaptive Engagement Strategies:* A new generation of software tools for tool path generation are now broadly accessible to educational institutions. Amongst these are Autodesk's Fusion360® CAM application and its HSMWorks® plugin to SolidWorks both of which are utilized in the curriculum described in this paper. These tools are both more affordable and emphasize ease of use in programming High-Speed Machining (HSM), High-Efficiency Machining (HEM), and multi-axis machining strategies. This impacts instruction by shifting the focus from purely cutter location planning to consideration of the importance of chip load and material removal rates when deciding what tool paths to apply in machining a feature. Figures 1a and 1b illustrate the differences in HSM and HEM cutter engagement strategies. In the case of the former, smaller axial but larger radial engagements are used. The opposite is the case for HEM. By incorporating the chip load into the activity of programming tool paths, connections can be made to the importance of the cutting tool design for handling different chip sizes (e.g. number of flutes, helix angle), differences in the power consumption as determined by the specific cutting energy needed to generate chips, and the deflection of the tool which changes with the cross section of engagement (i.e. depth-of-cut × width-of-cut). The important point can be made that achieving the same material removal rate efficiencies using different axial and radial engagements does have important implications on other aspects of process planning that cannot be ignored by the manufacturing engineer.



(a) High Speed Machining (b) High Efficiency Machining (c) Adaptive Machining

Figure 1. HSM, HEM and Adaptive Tool Path Generation Strategies

A third engagement strategy now available in CAM systems is called *Adaptive Machining*. This is illustrated in Figure 1c. One of the challenges with conventional tool paths generated with HSM and HEM strategies is that when machining pockets the engagement fluctuates as the cutter encounters direction changes in corners. This results in increases in the cutting forces exerted on the tool which can often lead to chatter. Even when roughing this is undesirable as it can adversely impact tool life. Adaptive machining reduces this effect by moving the tool into and out of engagement along a curve that minimizes the loading on the tool while also running at a faster and more steady feed rate. Trochoidal curves have been used in the past though current systems are likely not limited to this geometric form. Exposure to adaptive machining introduces students to techniques that mitigate problems such as chatter and that provide ways to better utilize the full cutting edge and life of the cutting tool.

2. *Multi-Axis Machining*

Multi-axis machining introduces a significant amount of extra capability to the machining process by allowing multiple sides of a part to be machined within a single setup or by enabling non-orthogonal features to be machined more efficiently. Of greatest significance is the ability to get the cutting action away from the tip of ball and bull-nose tools and out toward the perimeter of the tool where the cutting speed is much higher and much more consistent. The challenges of multi-axis machining can be daunting to students, however. It is challenging to constantly be planning the cutting location on the tool, especially as the surface normal of sculpted surfaces changes across the surface. The order of machining surfaces is not obvious and is almost always a compromise to improve the machining of a previous or future operation. The visualization of toolpaths becomes much more challenging, especially for approaches and retracts which can easily number in the thousands for a complex sculpted surface. Finally, even if one utilizes multi-axis just as a means to perform prismatic machining on multiple sides of a part (referred to as 3+1 or 3+2 axis machining), the students are challenged by the complexity of fixturing the part and of avoiding tool-fixture collisions.

There are, however, great improvements in current path planning software that help the CAM planner to be successful. CAM planners such as HSMWorks® and Fusion360® have greatly simplified the available approach and retract options. This simplification reduces the ability to completely customize the approach and retract strategies, but the default options are much more robust and much less likely to cause crashes between the part and the tool. Additionally, the material removal simulation greatly improves the ability to achieve successful tool paths by identifying collisions between the tool, the tool holder, the part, and fixturing. While the software is still not fully reliable to prevent part/tool holder collisions in its path planning, the simulation identifies collision events and the planning tools are sufficiently capable to give options that will avoid these conditions.

The ability of CAM planners to make use of Dynamic Work Offset and Tool Center Point Control (DWO/TCPC) capabilities in modern machine tools also means that multi-axis planning is very easy for the user. This is especially true for 3+1 and 3+2 machining where conventional 3-axis prismatic machining is performed on different sides of the part after positioning and locking the two rotary axes. For the user, this only requires the selection of a surface normal or an edge to act as the tool axis. The positioning may require careful consideration of approach and retract strategies if the rotary axes position fixtures or axis equipment at similar heights to the part. But the basis of the planning only requires one button and one selection to initiate multi-axis planning. Fully simultaneous machining is more complex, but the machine simulation tools are sufficiently capable to help CAM planners to safely and efficiently plan multi-axis machining.

Finally, while many of the path planning challenges could be avoided by providing the students with Templates for machining operations, we do not do so. This choice is deliberate because these students, once working in industry, will need to know how to make wise machining strategy decisions in order to create templates for others to use. Therefore, we do not provide templates, but instead teach the students how to create their own templates that can then be used to simplify future CAM path planning.

3. *Verification*

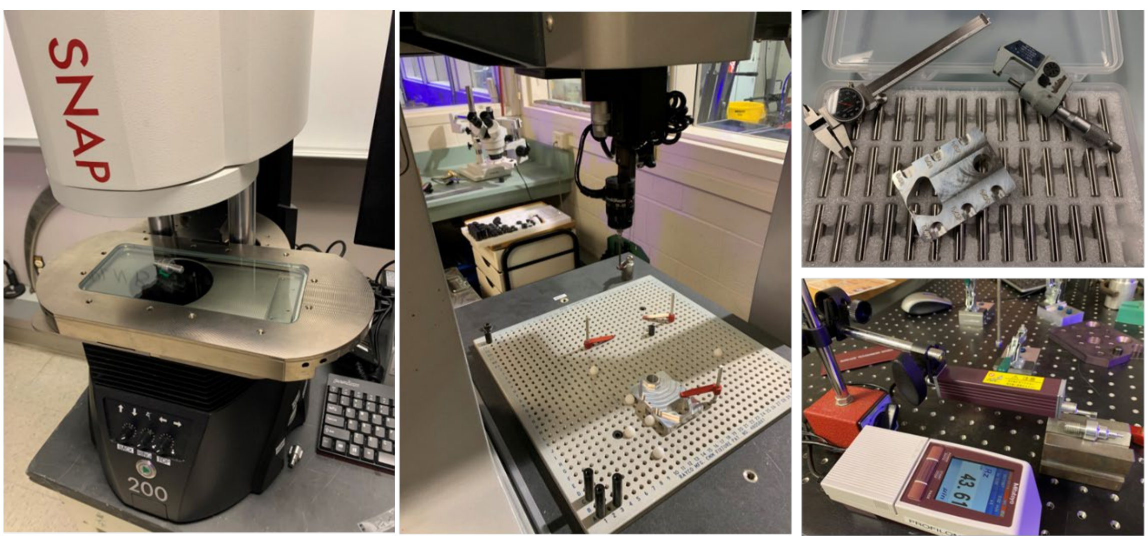
As with tool path generation, verification technologies have become much more reliable and automated. Verification of programs is done in 3 steps. The first step is within the HSMWorks® environment. This provides immediate feedback on the effect of the tool paths generated for an operation identifying obvious programming errors that lead to gouging or excess material. The inclusion of the tool, holder, and fixture geometry is also used to verify proper clearance moves for cutters, to set appropriate tool stick-out distances, and to ensure that the cutting edge is sufficiently long for the desired depth-of-cut. Students must record the stick-out distances (tool from holder, work piece from fixture) on setup sheets that they later use during the lab when assembling cutting tools and establishing the work offset.

The second step utilizes Vericut® through an interface with HSMWorks® referred to as a cascading post. This interface first generates the NC code using a post processor for the Haas 3-Axis mills used in the CNC lab. It then automatically builds a full 3D model of the CNC machine with fixtures, workpiece and final design in place, and imports the NC program ready for the student to simulate. Students complete a Vericut® tutorial early in the quarter that demonstrates how to run a simulation, verify the result, and troubleshoot warnings and errors that are generated. The automation in the cascading post makes more in-depth knowledge of Vericut®, a very complex piece of software, unnecessary. As such, students are able to execute a simulation within 30 seconds of running the post. Utilizing the same NC program that will be run on a CNC is the most accurate verification that can be performed. By incorporating the machine tool kinematics into the simulation, including acceleration and deceleration rates, students are also able to get the most reliable estimates of machining time. This is helpful in machining their final project which is subject to a machining time constraint.

The final step in verification is performed by the controller on the CNC machine. This is largely proforma in nature to confirm that the correct postprocessor has been used and that the program is fully interpretable by the CNC. Unlike manually generated programs, changes to programs generated from CAM on the controller are almost impossible to make because of the sheer number of blocks of code. However, in some labs students are required to search for specific commands to confirm their presence before executing a program. Examples of these include the proper use of canned cycles and the inclusion of cutter compensation for managing tool wear.

The sophistication and automation of verification changes the emphasis in visualization skills for students. They must be able to process a significantly larger amount of visual input than what is generated for simpler manually generated programs. They must also be able to interpret time variant information. Without proper coaching and review of work by an instructor, students particularly those in a hurry to complete an assignment find ways to ignore and misinterpret what a simulation is showing with consequences of tool breakage and machine tool crashes during labs.

4. *Measurement and Inspection*



(a) (b) (c) – above, (d) - below

Figure 2. Metrology Equipment used in Supporting CAD/CAM and CNC instruction (a) SNAP 200 Optical measurement Machine, (b) Brown and Sharpe CMM, (c) Assorted manual measurement instruments, (d) Profilometer

To help students better understand the impact of their process planning and CAM decisions, measurements using different instruments are performed in almost every lab. In addition to manual instruments for dimensional measurements such as calipers, micrometers and gauge pins (see Figure 2), the students use an optical measurement machine (SNAP 200 from OGP) and a pair of coordinate measuring machines (Brown and Sharpe) to measure critical features on turned and milled components respectively. As will be described in a later section, some of these measurements are used to size a plug and a matching bore with a clearance fit machined using cutter wear compensation. Others are used to confirm programmed pocket dimensions and to check for programming errors. By taking measurements using different instruments (e.g., caliper, gauge pin, CMM) students are exposed to measurement procedures and the limitations of each. Surface finish measurements are also taken using a profilometer on turned surfaces and milled surfaces using different tool path strategies and feed rates. An analysis of the data is used to correlate the finish metrics (R_t) and form of the finish profile with the feed rates and tool parameters (e.g., tool nose radius, number of flutes).

5. <u>Process Monitoring</u>
   A recent addition to the lab experiences is cutting force measurement. A Kistler dynamometer with accompanying amplifiers and data acquisition software and hardware is used to investigate the cutting forces generated using HSM and HEM strategies. Through this the students are able to see that while they might be able to achieve the same material removal rates using different combinations of axial and radial cutter engagements, the cutting forces generated for each combination will be different. This has implications for tool deflection, dimensional accuracy and tool wear.

Required Investment in Resources

The implementation of current CAM planning strategies requires a significant investment in equipment resources. While the authors began this transition using equipment purchased in the late 1990's and early 2000's, the equipment quickly showed that it was not up to the task. The lack of machine controller capability was evident in very slow motions due to low block processing speeds of the controllers, long wait times for program uploads, insufficient machine memory for large program sizes, and very long wait times for on-machine program searches and editing. The hardware also demonstrated a lack of capability with many short, jerky moves and frozen axis motions. To address these limitations, a new set of machines was recently purchased. A set of similar size vertical spindle CNC mills was purchased. Each of these machines has a modern controller with capability for loading, editing, and running large programs with high block processing speeds. Because of good service support in our area, and to match the controllers on lathes and other equipment that we were retaining, the department purchased Haas VF-2 machines. When performing HSM or HEM strategies, a cast base is necessary. While these machines are not as stiff nor do they have have the axis motion speed of higher cost machines, for a reasonable price the allowed a complete retooling of the lab's teaching machinery. All machines were purchased with part and tool probing. Two of the machines were purchased with $4^{th}/5^{th}$ axis trunnions to go with one existing trunnion acquired earlier. One machine was purchase with a 15,000rpm spindle, thru-spindle coolant, and additional controller capabilities to enable advanced projects for students to utilize outside of the normal class projects. One compromise that had to be made in the interest of cost was the purchase of umbrella-style tool changers instead of side mount changers. Interestingly, this has caused a number of problems in lab, but not because of the expected challenges of tools being located over the relatively tall trunnions. Instead, the challenge has been because the umbrella-style machines only provide coolant to one side of the tool rather than all-around the tool perimeter. This has caused some machining problems on the far side of parts.

Along with the 4 new vertical milling centers, the lab retains one legacy Mini-Mill, one legacy VF-1, three Haas lathes along with support equipment like bandsaws, water jet, plasma cutter, and metrology equipment as listed above. Figure 2 illustrates the layout of the lab which was updated with the acquisition of the new equipment. As can be seen, emphasis has been placed on spaciousness to allow two students to comfortably work on a machine with easy access by the instructor or lab assistant as needed.

In the following section examples of classes where these resources are being used will be presented.

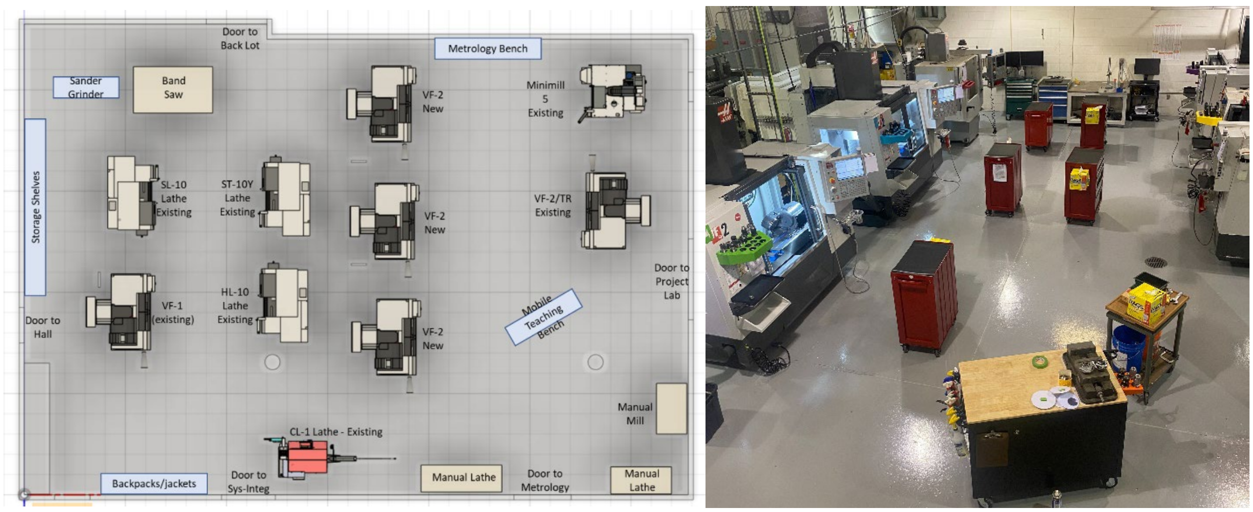


Figure 2. Layout of CNC Laboratory and the New Vertical CNC Mills

Class Example 1: Introduction to CAM and CNC

MFGE 332 Introduction to CAM and CNC is a course required by all manufacturing engineering majors during their junior year. It's the evolution of a course previously reported on in [3]. The hardware and software technology used is summarized in Table 1. As discussed previously, these resources provide students with exposure to industrial-type technologies which capture the realism of what they will encounter in practice. The instructional components of this class are as follows:

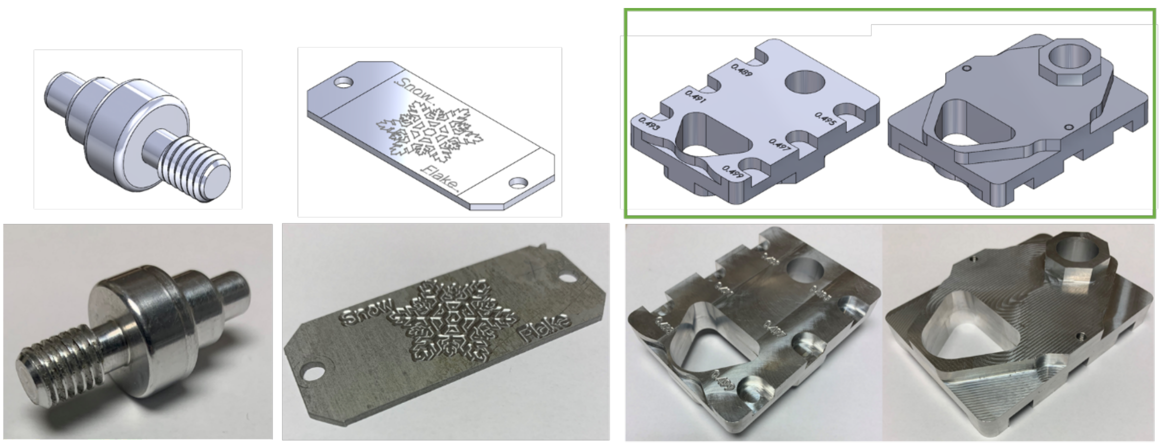
Table 1. MFGE 332 Software and Hardware Technology

	Type	Description		Type	Description
Software	CAD	SolidWorks	Hardware	CNC	Haas VF2 Mills (x4)
	CAM	HSMWorks			Haas TL Lathes (x2)
	Verification	Vericut		Inspection	Brown and Sharpe CMMs (x2)
	Data Processing	LabView			SNAP 200 Optical Measurement Machine
					Mitutoyo Profilometer (x3)
				Process Monitoring	Kistler Cutting Force Dynamometer

1. *CAM Instruction:* Training in CAM using HSMWorks® is accomplished using a flipped classroom approach where students complete training videos on the different tool path generation techniques provided for 2½D machining. This learning is reinforced through

instructor led in-class demonstrations that focus on key principles e.g. the difference between HSM and HEM machining strategies.

2. *Weekly Assignments*: These are designed to complete the CAM programming preparation work that will be executed on the CNC machines during lab sessions. Students complete these assignments with enough lead time to have their work reviewed in class prior to their lab. The use of Vericut® is a critical step in this review. Detailed verification models of the CNC machine, fixturing, final design, and stock used for each lab are generated automatically using a cascading post-processor from HSMWorks®. These models are accurate enough so that when correctly used errors due to collisions, gouging, and excess material can be detected and corrected before a lab session.
3. *CNC Lab Sessions:* Early in the quarter students are introduced to the tooling and machine setup procedures that are to be followed in later labs. They are expected to arrive with appropriate documentation (setup sheets and drawings) to assist them in building and loading the correct tools and in correctly locating the work offset (referred to as G54 location). Probing automation on the CNC mills assists the students in establishing the work offset. During labs students are sometimes required to time operations to help develop their appreciation of the differences between the actual and simulated times that they obtain.



L2 - Bore Tester	L-4 Name Tags	L5 - Mill Operations 1	L7, 9 Mill Operations 2 and 3
CNC Lathe Operations • Haas TL Lathe Setup • Turning Cycles	Intro to CNC Milling Operations • Haas VF2 Setup • Tool Assembly • Tool Setting and G54 Probing	More CNC Milling Operations • Tool Assembly (End Mills) • Setup Sheets (Tool stick out, workpiece overhang)	Advanced Operations • Tool Assembly (drills and taps) • Cutter Wear Compensation

Measurements
• Surface Finish
  • Mitutoyo Profilometer
• Dimensional
  • Manual (Calipers, Mics)
  • Automated (Optical SNAP 200)
	CAM Operations
	• 2D Contour
		CAM Operations
		• 2D Pocket,
		• 2D Contour
			CAM Operations
			• 2D Pocket (HSM and HEM)
			• 2D Adaptive
			• Drill and Tap

	Measurements
	• Cycle Time
	  • Video timed
		Dimensional Measurements
		• Manual (Calipers, Mics, Gauge Pins)
		• CMM
			Measurements
			• Surface Finish
			  • Mitutoyo Profilometer
			• Dimensional
			  • Manual (Calipers, Mics)
			  • CMM

Figure 3. CNC Lab Components and Activity Summary

Figure 3 shows examples of components machined during the laboratory sessions. The turned component (*L2-Bore Tester*) provides the class with an introduction to lathe operations. Though not a focus of the CAM training, this lab helps develop their appreciation of the operations, tooling and setup of a CNC lathe and facilitates the use of a broad range of inspection techniques to investigate sources of variation and to relate process parameters to the surface finishes generated. The name tag represents the first programmed assignment executed on the CNC mills. Each student creates two tags with paths generated using one of the simplest operations (2D Contour) available in HSMWorks®. The simplicity of the part allows each pair of students working on a CNC mill to practice the setup procedures for the CNC mills which are still relatively new to them. Cycle time measurements are taken to help benchmark the simulation times recorded. Students are asked to summarize the differences observed which points to Vericut® being closer to the actual machine times due to its inclusion of the machine tool kinematics.

The milled component is machined in three setups over an equivalent number of labs (L5, L7 and L9). The first setup machines the side with the six side pockets with the width dimensions engraved. These pockets are later inspected using manual techniques (calipers, micrometers, gauge pins) and on a coordinate measuring machine (see Figure 2). These measurements can show issues in incorrect programming of these features such as failure to include a finishing pass or mistakenly leaving a stock allowance. They can also show errors due to tooling setup (loose tool or large stick out) that can lead to excess deflection or chatter. The second setup (L7) machines the flip side minus the triangular through pocket and the circular bore. The focus of this lab is to apply different tool path strategies (HSM, HEM) and feed rates for pocketing operations applied to the four corners. As with the six pockets in the first setup, CMM measurements are taken to confirm key dimensions and profilometer readings taken on the surfaces generated with the different machining strategies. Students are expected to correlate the measured results with what is expected for each strategy in their lab summaries. Finally, the third setup (L9) drills and taps holes and machines the triangular pocket and the circular bore. Roughing of these must be completed using the *Adaptive Machining* strategy described earlier. In addition, the circular bore must be sized to match the outer diameter of the *bore tester* part turned in the earlier lab. This is accomplished by programming wear cutter compensation in CAM for the contour operation that finishes the bore. Each student uses their *bore tester* as a go/no-go gauge incrementally adjusting the wear compensation on the controller and repeating the contouring operation until a go condition is obtained. This exercise helps students learn and appreciate the role that cutter compensation can play in a CAM environment where the challenge of manually programming the tool path center offset from a complex part profile is eliminated by the software.

4. *Metrology Lab Sessions:* Most lab sessions require some follow-up inspection of the features machined. Critical dimensions on milled features are performed using hand measurements (calipers, micrometers and gauge pins) and by then using programmed coordinate measuring machines or an optical measurement machine (SNAP 200). This helps the students appreciate the limitations of their skill in taking manual measurements and encourages them to consider ways to improve their use of these instruments. Surface finish measurements are also taken using a profilometer on surfaces generated using different machining strategies and with

different process parameters (feed rates). Each student must write a summary of their lab experiences incorporating observations made from the inspection of their machined result. Discussions with the instructors of their results during the measurement labs help them in identifying the causes of dimensional variation they observe. They are also expected to relate the process parameters and tooling information (tool nose radius and number of flutes) to the surface finish profile and measures (Ra, Rt) they have obtained.

5. *Term Project:* This is included to give students the opportunity to demonstrate their ability to process plan and effectively machine a designed shape that they have created. This project is also designed to provide a full CAD/CAE/CAM experience that shows how these technologies are used in an integrated manner during product development. The design for this project is a mountain bike rear suspension pivot as shown in Figure 4. The shape of the pivot is of the student designer's choosing but must conform to Design for Manufacturability requirements for machining. This is enforced largely through tooling size availability and fixturing requirements. The design should be complex enough to allow demonstration of the use of the full range of operations that the CAM training covered. In addition, the design must satisfy a loading safety factor requirement determined through the application of a finite element analysis while attempting to reduce the weight. As shown in Figure 5 this last requirement engages the students in generating design iterations, an important practice in product development.

Figure 4. Example of Mountain Bike Suspension Pivot Used in Term Project

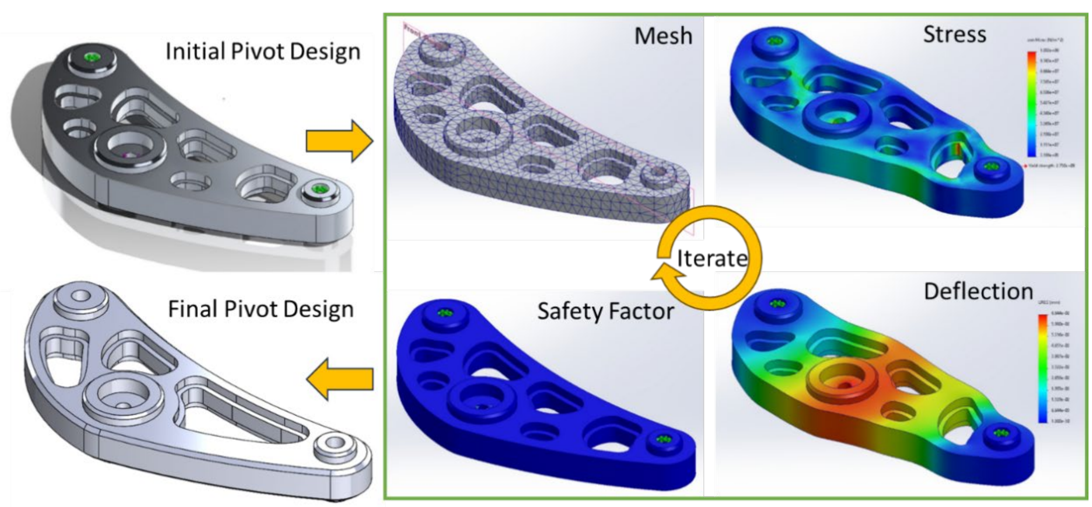


Figure 5. Iterative Design and Analysis of a Mountain Bike Rear Suspension Pivot

All the steps described for the labs to review and verify programming before execution are followed for the pivot though with more rigor given the open-endedness to the decision-making that is allowed. More complex fixturing (locating pins and fixture plate) is utilized due to the unpredictability of the shape. Figure65 illustrates an example of the Vericut® simulation model used by the students and the instructor to verify correctness of the CAM generated program prior to machining. This is found to be highly effective when used correctly to fix problems prior to machining. However, it is not fool proof. A common excuse is for students to claim “It was correct in Vericut” when in fact they missed an important step that the simulation is not designed to check e.g. placing the program origin (G54 offset) at a location that is different from what they will probe during setup in the lab. Appreciating these limitations is an important lesson for them that can be applied to using any CAE application. Also shown in the figure is the same final machined component still mounted on the fixture plate in the CNC machine.

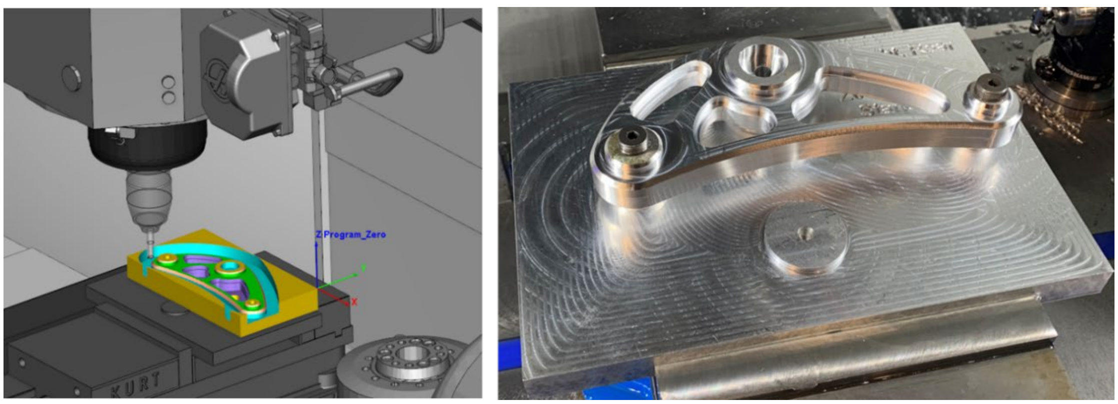


Figure 6. Verification and Final Machined Mountain Bike Rear Suspension Pivot

6. *G&M Code Programming:* Finally, students are still required to learn G&M code programming as part of this class though the emphasis has shifted away from executing manually written programs during the lab sessions. The meaning of codes, the syntax and the structure of NC programs are covered in class. Simple examples are generated using CAM for the class to review to deepen their understanding. Quizzes and questions on the mid-term are used to encourage students to engage in learning the language. Though low stakes in terms of being able to pass the class, knowledge of programming is essential to earn a top grade.

Class Example 2: Multi-Axis and Advanced CAM & CNC

MFGE 434 Advanced CAM and CNC is an elective class that is taken by students wishing to specialize in CAD/CAM. To help the students to step through these challenges, a set of labs has been developed that begins by studying tool-surface interaction and then gradually adds complexity until a final project is machined. Figure 7 shows the parts that are machined in the labs in this class.

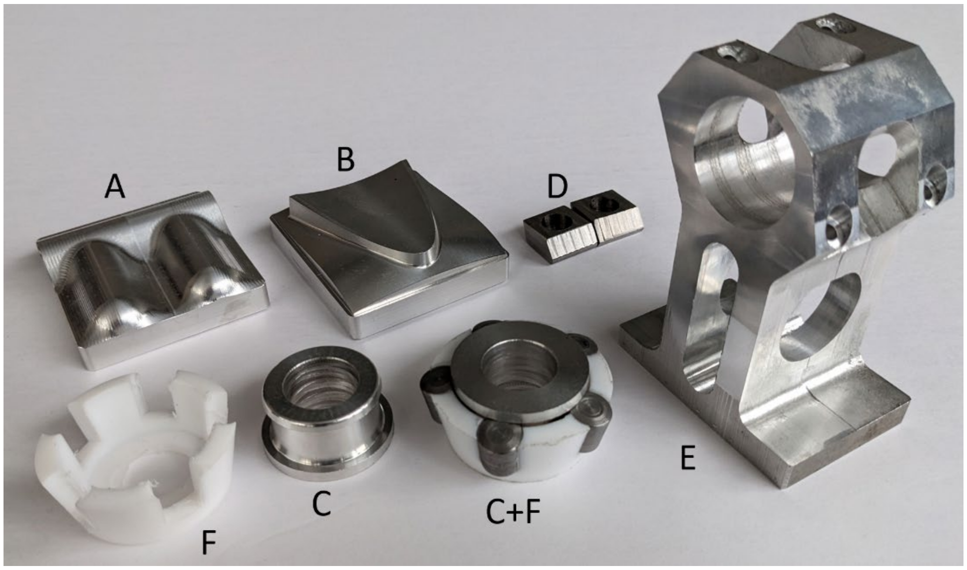


Figure 7. Multi-Axis Parts Used To Develop Student Skills in Advanced CAM & CNC

Part A is the first lab and is used to compare the abilities of bull-nose and ball nose tools, with two different stepovers each, to machine slopes that are parallel and perpendicular to the machining path in 3-axis machining. Part B is the second lab and is a very challenging 3-axis part that requires a deep understanding of the best application of each machining strategy for different concave, convex, and steep features. The blend between the features is very hard to do well. Part C is a lathe part from the third lab which requires achievement of very tight tolerances for use in a roller-bearing assembly. Part D, from the fourth lab, combines the challenges of steel machining with both 3+1 and simultaneous 4-axis machining for a fixture clamp similar to a Mitee-Bite bulldog clamps. Part E, the fifth lab, is a bicycle stem and requires 3+2 machining and carries significant challenge due to tool length limitations for small feature sizes. Part F is the roller bearing carrier from the sixth lab and requires simultaneous 5-axis machining as well as the introduction of machining in plastic while still achieving tight tolerances.


Figure 8. USS Zumwalt (left) and Mt. Everest (right) - Example Final Projects

The students then use these their new skills to fully design a part that is (1) under a certain material volume, (2) requires more than three tools to complete successfully, (3) has more than five machining strategies employed, (4) demonstrates the skills learned in class, and (5) shows that the design was created considering the strengths and limitations of the allowed set of tools. This limits tool lengths, diameter, and type. Finally, the part must have more than one setup or be multi-axis and must be completed in less than four hours including machine setup and cleanup. The designs created by the students are amazing – both in creativity and in challenge. A small set of the final projects are shown in Figure 8.

Changing Curriculum Outcomes and Skills Development

To meet the changes brought on by incorporating the described technologies, the course outcomes for MFGE 332 have evolved to suit. These are shown in Table 2. Notably, outcome 1 has been changed from "Generate programs for CNC machining using manual part programming techniques" to reflect the move away from manual programming to CAM programming. In addition, outcome 5 has been added to reflect the increased role that inspection plays in the course to help students understand the impact of the process planning decisions they make and the sources of process variation that can occur in machining. Each course outcome aligns with a program outcome which is itself a mapping to one or more of the ABET 1-7 outcomes used in assessment for accreditation purposes. The second digit refers to a performance metric for which several are aggregated within a rubric for assessing the ABET outcome.

In addition to the course outcomes, a qualitative assessment of how the course impacts the development of a manufacturing engineer's skills is also provided as motivation for students. As discussed in [?] students are better engaged when they have a broader appreciation of how a given course is developing their skills beyond just the technical content delivered. The Appendix shows a table of the skill set identified by the program and an updated mapping to the course outcomes based on the modification to outcome 1 and the addition of outcome 5. The outcomes of MFGE 332 heavily impact the "Problem Solving" skill set, in particular the ability to "Troubleshoot", "Exercise Engineering Intuition" and "Investigate Cause and Effect".

Table 2. MFGE 332 Course Outcomes

Course Outcomes – Students will be able to:		Program Outcomes
1.	Interpret and modify GM code generated for machining a component on a CNC machine.	1.1
2.	Generate and verify programs for CNC machining using CAD/CAM and simulation software.	1.1, 1.4
3.	Demonstrate knowledge of machining process planning, including cutting tool and parameter selection for operations performed on a CNC machine.	1.1, 1.3
4.	Demonstrate knowledge of the procedures to set-up, program, and operate CNC equipment to produce machined parts in accordance with the specifications on a drawing.	1.1, 3.1
5.	Identify the impact of process parameter selection and sources of process variation using manual and automated inspection techniques.	6.1, 6.4, 6.5
6.	Apply knowledge of safety, health and environmental concerns in operating manufacturing equipment.	4.4

Outcomes Assessment

In the most recent offering of MFGE 332, 23 students were assessed against the outcomes listed in Table 2. This assessment is summarized in Table 3. The program uses an 80% threshold on the number of students demonstrating either a satisfactory performance or mastery to identify those outcomes where an instructional challenge may exist. It is clear from this assessment that students performed poorly in meeting outcome 1, which deals with their ability to interpret and modify G&M code. This finding is consistent with other recent offerings and with the observations of the instructors. Even before the shift in emphasis away from manually written programs, this aspect of learning and skills acquisition was weaker than other areas. Some of this undoubtedly has to do with the assessment mechanism of using quizzes and exams where time pressure and the need to memorize material proves challenging to some. But there is also evidence that a greater emphasis on using computer-aided techniques and the automation they provide when juxtaposed to manual programming is raising value questions with students and producing motivational issues when it comes to learning the latter. In all other areas where the outcomes are related to and measured using results generated by computer-aided techniques the threshold for meeting outcomes is easily surpassed.

Table 3. MFGE 332 Outcomes Assessment (F23)

Outcome	Assessment Method	Performance*			
	(M- Mastery (>90%), S- Satisfactory (>80%), D- Developing (>70%)	M	S	D	U
1	Quizzes and Part A of Midterm	2	1	6	14
2	Milling Lab Preparation Assignments	22	1	0	0
3	MT Bike Pivot Final Project CAM and Verification Work	18	5	0	0
4	Execution of Final Project in CNC Lab	15	5	0	0
5	Cummulative Summaries of Lab Experiences and Inspection	19	4	0	0
6	Lab Instructor's Observations of Adherance to Operating Procedures	23	0	0	0
* M- Mastery (≥90%), S- Satisfactory (≥80%), D- Developing (≥70%), U-Unsatisfactory (<70%)					

Student Feedback

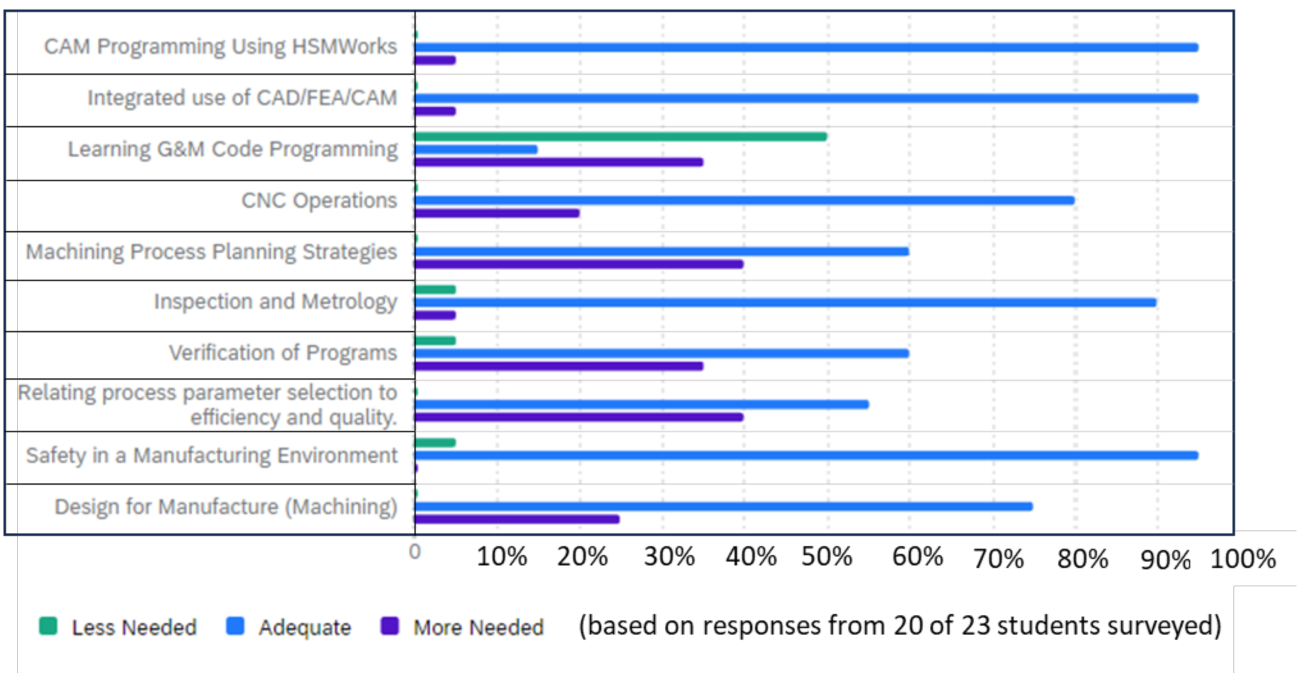


Figure 9. Student Feedback on Adequacy of MFGE 332 Learning and Skills Development Components

To better understand the outcomes assessment results, students in the section were surveyed on their opinions of the adequacy of 10 areas of learning and skills development covered in the course. The results of this survey are summarized in Figure 9. In six of these areas over 75% of the class indicated that coverage was adequate. This includes the CAM training they received, CNC operations covered in their lab sessions, and their experiences on inspection and metrology. About 35-40% of the class felt that more was needed in the areas of applying process planning strategies, verification of programs and relating the selection of process parameters to efficiency and quality. Not surprisingly, the class was divided on the question of their learning of G&M code programming with 50% indicating that less was needed, 35% wanting more and the remainder satisfied with what they learned.

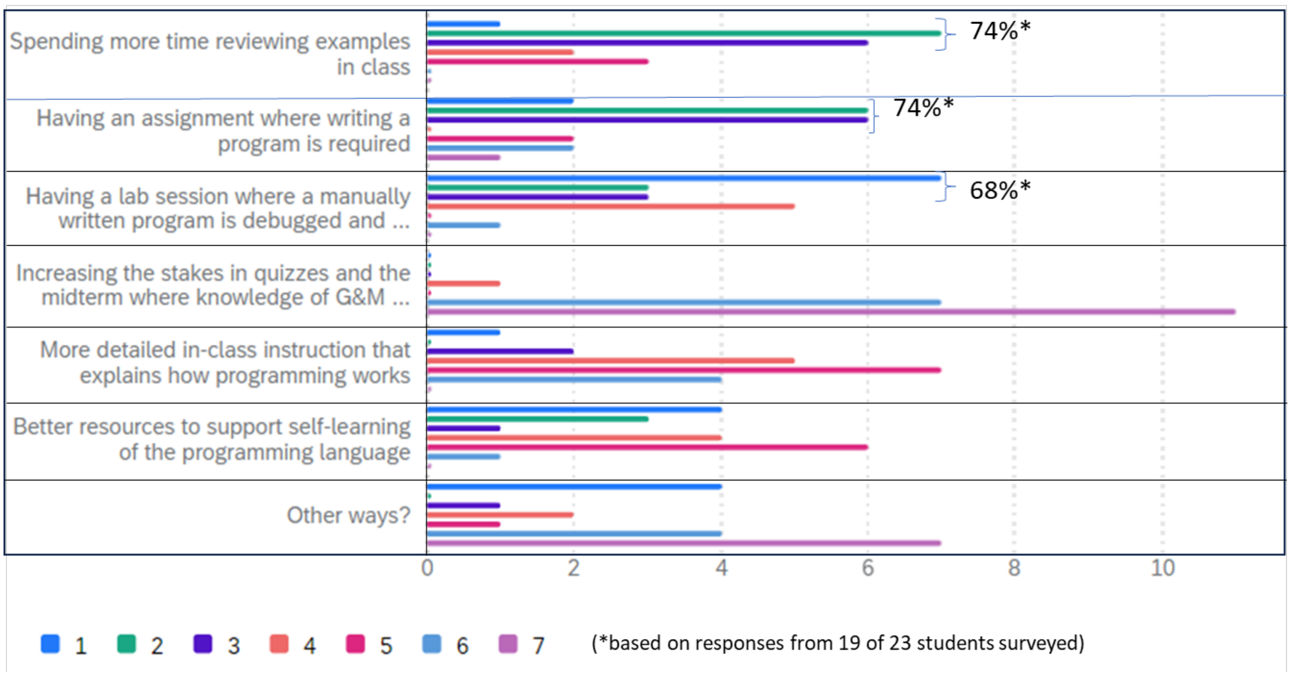


Figure 10. Student Feedback on ways to Improve Engagement in Learning Manual Part Programming

A further survey question asked the class to rank six approaches that can be taken to improve engagement in learning G&M code program and to suggest others. The results of this question are shown in Figure 10. These responses suggest that students are amendable to including additional activities that give them more practice using the programming language such as reviewing additional examples in class (74% rank 1^{st}, 2^{nd} or 3^{rd}), assignments that focus on manual programming (74%), and editing programs in labs on the controller (68%). Few indicate that more direct instruction is needed though some would like better resources to support self-learning. Not surprisingly, few supported the approach of increasing the stakes in quizzes and exams that test learning.

Discussion

Though a single sample, the assessment results are consistent with what has been observed across multiple offerings of this course as the emphasis has shifted away from manual part programming to using advanced CAM techniques for tool path generation. Students are generally satisfied with their learning of the CAM, verification and CNC operations skills. However, there is a fundamental question of the value of learning manual part programming which is compounded by the fact that this is rarely the way a program is generated today in industrial practice. It's quite possible that a manufacturing engineer may never look directly at the code generated from a CAM application in the same way that files generated for 3D printing are opaque to their creator. Of course, the process of executing a program on an industrial-type CNC machine is much more involved than running a 3D printer and a risky venture if the operator is ignorant of the program being executed. Since in industry manufacturing engineers are not typically hired to operate CNC machines, it can be argued that familiarity with a program in this context is needed primarily to enhance protection of the equipment and safety in the department's CNC laboratory where the students must work.

One argument presented for manual programming is that it does help develop many of the problem-solving skills listed in the "Skill Set for Manufacturing Engineers" in the Appendix. Most important amongst these being 3D visualization and spatial thinking, troubleshooting, systematically following prescribed procedures and protocols, and working with precision. However, a counterargument exists that CAM-based learning does the same skills development though in different ways. For example, a significant amount of 3D visualization and spatial reasoning is needed to interpret how the work piece is being modified using different tool path strategies and in the cutter engagements and resulting chip load being generated. It would be difficult and time consuming to create manually generate programs that create this visual complexity.

Another major argument for manual programming looks more broadly at how a manufacturing engineer might need to engage CNC operations in practice. They might be called upon to manage the integration and automation of CAM and verification for a variety of different types of CNC machines in a shop or in production. This would include working with vendors to develop post-processors that generate G&M code that is tailored to the controllers and practices being used. These practices typically use a subset of the many G&M codes that are available and the structuring of programs to align with the way a company machines its parts. It would be impossible for a manufacturing engineer to manage these activities and systems without extensive knowledge of G&M code programming. There is a strong argument for G&M programming to remain a part of CAM and CNC skills development for manufacturing engineers. The challenge is in incorporating activities that elevate its value in the minds of student so that they are motivated to engage in its learning.

Opportunities for Future Development

The question of G&M programming aside, Figure 9 shows that some students having taken MFGE 332 feel that more emphasis is needed on teaching machining process planning strategies, and in relating process parameter selection to efficiency and quality. These two topics are in fact connected as different engagement strategies such as HSM, HEM and adaptive machining do impact efficiency. However, process planning extends beyond engagement strategies, and includes the way the stock is reduced through a sequence of operations. Training materials can be used to demonstrate different operation sequencing strategies while simultaneously explaining the mechanics of CAM tool path generation. Unfortunately, the available materials tend to focus on the CAM mechanics and not the strategies. This is true of the materials developed by the instructors which mirrors training developed when MFGE 332 used the CATIA Prismatic Machining Workbench. With increasing experience using HSMWorks® in the curriculum, a second generation of training materials is envisaged that addresses this deficiency. On the question of quality, the use of the CMMs to systematically detect dimensional errors and to troubleshoot their causes needs to be further developed. This might require that potential sources of error be deliberately introduced into the tooling (e.g. excessive tool stick out) and work setups so that their effects can be captured in the measurements. Another place where errors can be demonstrated is by using cutting force measurements. Poor tool assembly or defective tool holders that introduce runout can be identified from variations in the peak force generated by the opposite cutting edges on a 2-flutted cutter. This can be further confirmed from dimensional measurements on a CMM. There are also opportunities to introduce statistical quality control. For example, the L2 – Bore Tester lab can potentially be enhanced to perform statistical analysis of measurements on batches of parts that are machined over multiple course offerings. Causes of variation due to set up, tool wear, stock differences, and use of difference CNC lathes can be investigated.

Improvement in lab operations is ongoing. As mentioned earlier, the inclusion of automated tool setting and probing on new CNC machines has drastically reduced the time taken in a lab to measure and record tool length and work piece offsets. These were previously measured manually and together with tool assembly could take over 50% of the lab time. The procedures were also prone to error leading to more lost time when tool paths are executed out of the correct position, and worse if the result is a collision. Students are now able to reduce their setup time by at least half. Improvements are being made to the fixturing used for the bike link project shown in Figure 6 that reduces the setup time and minimizes the potential for misalignment when the part is flipped. Finally, students are expected to maintain a paper lab bid with documentation they prepare to assist them with tooling and machine set up for each lab. Plans are underway to utilize MS Teams to support paperless lab documentation. This will require tablet devices at each CNC machine that can load and display documents as well as record student comments and instructor feedback and markup.

Conclusions

Keeping pace with advances in technology is a challenge for all engineering programs. This is particularly true for manufacturing engineering and the specialization of CAD/CAM and CNC operations. This paper highlighted some of the recent advances in CAM and related technologies being integrated into courses in a MFGE program. These give the practicing engineering a broader range of tools to efficiently machine a part and to more systematically inspect and relate the quality of the final result to the process planning decisions that are made. Examples of the type of work conducted by students in two courses from the curriculum were presented to highlight the way in which these technologies are being used and the impact. Feedback from the students and instructor observations show that these new technologies are well received but pose challenges in motivating learning of more traditional topics such as manual part programming. Important reasons remain for continuing to include this topic, but more work is needed to find new ways to better integrate its instruction into the class and lab experiences. Improvements in training materials that tend to focus on how to use the software tools at the expense of process planning strategies need to be developed. Lab operational efficiency has been improved through recent purchases of replacement CNC machines with greater automation to assist in tooling and work piece setup. Further operational enhancements to improve fixturing for term projects where students have greater flexibility in the shapes they can machine, and to replace paper lab documentation with digital media are planned for future class offerings.

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Appendix A

	Skill Set for Manfuacturing Engineers						
	A practicing Manufacturing Engineer should have the ability to:						
1. Problem Solve:		1	2	3	4	5	6
a	Visualize in 3D and think spatially	X	X				
b	Abstract/Deconstruct a problem into solvable chunks			X			
c	Troubleshoot	X	X	X	X	X	
d	Exercise engineering intuition		X	X	X	X	
e	Investigate cause and effect		X	X	X	X	
f	Systematically follow prescribed procedures and protocols	X	X	X			
g	Identify, Interpret and specify realistic constraints	X	X			X	
h	Innovate and think creatively		X				
i	Work with precision	X	X			X	
j	Incorporate uncertainty into decision making					X	
2. Communicate and Collaborate:							
a	Express ideas and opinions verbally						
b	Express ideas and opinions in writing						
c	Communicate technical information	X	X	X	X	X	
d	Work in and promote a workplace culture that values diversity						
e	Assume responsibility and lead in accomplishing tasks						
f	Resolve conflicts						
g	Critique the work of others and provide thoughtful feedback.						
3. Manage and Act Professionally:							
a	Recognize and exercise a duty of care to society						X
b	Act with integrity						X
c	Practice effective time management	X	X		X		
d	Plan activities, budget and manage resources		X				
e	Effectively utilize and manage technology	X	X		X		
f	Take and manage risk						
4. Practice Lifelong Learning:							
a	Learn independently						
b	Receive, analyze and act on feedback	X	X				
c	Discover and interpret relevant information about a problem						
d	Discern the credibility of information						
e	Observe and adapt to changes						
f	Continuously improve in quality and efficiency		X				

	MFGE 332 Course Outcome
	Upon completion of the course, students will be able to:
1	Interpret and modify GM code generated for machining a component on a CNC machine.
2	Generate and verify programs for CNC machining using CAD/CAM and simulation software.
3	Demonstrate knowledge of machining process planning, including cutting tool and parameter selection for operations performed on a CNC machine.
4	Demonstrate knowledge of the procedures to set-up, program, and operate CNC equipment to produce machined parts in accordance with the specifications on a drawing.
5	Identify the impact of process parameter selection and sources of process variation using manual and automated inspection techniques.
6	Apply knowledge of safety, health and environmental concerns in operating manufacturing equipment.