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Using Simulation to Improve the Efficiency of CAM and CNC Instruction

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Abstract

The use of industry-type CNC machines, as opposed to "trainers", for learning NC operations in Engineering Technology programs, presents several challenges. Key amongst these is the potential for damage to the machine, tooling, work piece and injury to users from improper operation. To prevent these occurrences, significant effort must be expended on the part of instructors and lab personnel in vetting programming assignments completed by students, and in supervising set-up and operation of a machine. Faced with fewer resources and increasing class sizes, simulation techniques are becoming increasingly useful to help departments better manage their resources, and not just for the educational benefit of the student.

This paper describes efforts to utilize simulation in several courses in a Manufacturing Engineering Technology program that heavily utilizes CNC technology. To do this, accurate digital models of CNC machines have been created using a CAD system, and converted into simulation models within an industry standard NC verification application. For each of the classes that utilize a CNC machine, the simulation model, along with tool and fixturing libraries, are available for students to use in verifying the programs they create for assignments and project work. Students are introduced to the simulation software at the start of an introductory course to CNC operations, through a single homework assignment. The effort in using models is minimal: Selecting tools from a library, adding and positioning stock geometry (and final part when a machining accuracy comparison is required) in a fixture (often a Kurt machinist's vice), setting up the work coordinate system (G54 location), and loading the NC program. These steps mirror those that will be performed by the student on the actual CNC, and so are reinforcing the student's experiences. Evidence of how the use of simulation is helping to increase the preparedness of students, reduce the occurrences of programming errors and machine crashes, and improve the efficiency of time spent in the lab will be presented.

Introduction

CAM and CNC technologies are important subjects in the training of Manufacturing Engineering Technologists. A good grounding in these involves both learning the basic concepts and applying these in various settings to fabricate parts and tooling. The CAD/CAM option in the MET program at Western Washington University is designed to do just this. Students are trained on industry-type CNC machines and utilize these extensively in project work for fabrication. The program is committed to using industry-type equipment as opposed to CNC trainers for the following reasons:

- It develops confidence in students on the type of equipment they will encounter in practice.
- Trainers can convey a false sense of security. Industry-type machines demand a greater attention to safety.
- A wider range of materials can be machined. Students learn to appreciate the role of a material's machinability in process planning.
- Larger work envelops and spindle horsepower support a wider range of fabrication possibilities. For example, machining of molds.
- Better exposure is provided to the challenges in selecting tooling and fixtures.
- Students develop a better understanding of the proper selection of process parameters (speeds, feeds and depths-of-cut) and the trade-offs as materials and conditions change.
- A better appreciation for the challenges in achieving dimensionally accurate parts is obtained.
- Students acquire a more realistic understanding of the efficiencies of machining processes

This heavy use of industry-type CNC equipment does present serious challenges to the instructors and technical staff in the department. Proper management and supervision of their use is essential if these resources are to be maintained, and students are to develop the correct skills and attitudes as operators.

To assist in this, the program has moved decidedly towards the use of simulation to assist students in learning CAM and CNC programming concepts and most importantly for program verification before deployment. The idea is to duplicate as much as possible in a university setting what is becoming standard in industry, where simulation for NC verification is approaching the point where "lights-out machining" is being practiced[1]. There is such a high level of confidence in the use of verification techniques, that programs can be directly deployed to CNC machines with little if any operator input[2]. A similar use of simulation can help mitigate some of the disadvantages of university CNC laboratories utilizing industry-type CNC equipment as opposed to CNC trainers. If a similar goal to "lights-out machining" can be realized in university labs, then a greater range, and more sophisticated uses of CNC equipment is possible. This would occur without the need for increases in instructional resources, or the risk of injury and equipment damage.

An instructional approach with a heavy component in simulation can better prepare MET graduates for using and advancing this technology in industry. From a pedagogical perspective, simulation is often viewed as "something to expose a student to", one of several skills that are to be acquired in a CNC course. However, with current advances in IT, simulation should also be viewed as an enabler of learning. A properly developed and integrated simulation environment can be used by the instructor to explain programming concepts during lectures and labs, and for assisting with assessment. It can be used by students to help develop and hone their skills when completing homework assignments and in preparing for machining labs. A simulation environment can provide a level of instantaneous feedback to students that can be helpful when the instructor is not readily available. Using portable electronic devices, simulation can be made available at the machine tool to assist instructors and technicians in validating and fixing programs.

In the next section, a brief review of related work will be presented. This will be followed by an overview of how a verification methodology utilizing the industry standard Vericut®[3] software has been developed and deployed in the curriculum.

Review of CNC Verification Technology and Educational Applications

A significant body of research exists on the development of CNC Verification methodologies. This dates back to the early 1980s when solid modeling and computer graphics techniques were adopted to simulate the material removal processes. Gossard and Tsuchiya[4] and Volecker[5] both investigated the feasibility of using boolean operations in newly developed solid modeling systems to subtract tool swept volumes from a work piece. It was however the use of Z-buffers and Z-maps from computer graphics, to store changing depths at discrete locations from an engaged cutter, that proved to be most promising. This was first investigated by Wang[6] and Van Hook[7] in 1986 with extensions to discrete vector based methods by Jerard[8] and Oliver and Goodman[9] in the late 80s and early 90s. The commercial verification systems of today such as Vericut® are almost exclusively based on a variant or combination of these discrete techniques.

In the area of education applications, research has been presented on the development of virtual CNC simulators that can be used in training. These include work by Ong et al.,[10] Wang et al.[11] and He et al.[12]. These simulators are developed using building blocks that in most cases have been created and integrated by the authors. In some cases they provide unique capabilities such as allowing users to measure cutting forces during machining[10]. However, these papers focus mostly on describing the development and capabilities of these tools. Little is reported in these cases on the deployment and impact in the curriculum. Djassemi[13] does report on an experience in developing a hands-on approach to CAD/CAM instruction that does include verification. While he presents some assessment of the approach based on a exit survey given to students, it is general and does not specifically target the impact of the use of the verification tool. It is also unclear from this paper the type of tool used and the detail required from the students in validating their programs.

A search in Google Scholar using the key phrase “Vericut Educational Applications” returns numerous articles written by Chinese authors that illustrate strong interest in using this particular software tool in that country. Some articles not written in Chinese that highlight use of this particular tool are by Pritschow and Rock[14], Adamski[15] and Wu et al[16]. As before, none of this work appears to focus on the impact on CNC resource utilization in an educational setting or the curriculum.

While there is unmistakedly merit to developing custom simulation tools in a university setting to assist in training, there are certain advantages to the approach described in this paper of using a commericially developed and supported system. First, one can focus more on how to use the application rather than be embroiled in the challenges of developing it. The sophisticated nature of commerical systems makes their setup and efficient use in an educational setting a non-trivial matter as this paper illustrates. Commercial systems often have a higher level of robustness over prototype systems as they must satisfy industry uses which demand that the technology work correctly when needed. Thus, less time is spent in fixing bugs or limiting use to work around deficiencies in the tool. A broadly used commercial tool such as Vericut®, also has a rich user and knowledge base that can be tapped to solve problems and to share models and findings. Finally, students are being exposed to a tool that they will likely encounter again in their future careers. This is important in the training of technologists, and it is a benefit for them to indicate this experience when they search for work.

The Role of CNC Machining in the Curriculum

CNC plays a significant role in the curriculums of both the MET and PET programs that are offered by the ET department. This technology is important both as a primary learning objective and in supporting other classes where fabrication of products and tooling is important. Figure 1 illustrates where CNC is used in the curriculum for MET students specializing in CAD/CAM. This experience differs in the senior year for students who are taking the core MET or PET majors. All students get a brief introduction to CNC technology in ETEC 246. This involves running programs for machining hole patterns on a part that each student must fabricate during their lab sessions. Though this program is written by the instructor, students are given a quick description of what it does, and an overview of G&M programming. They are required under supervision to setup their workpiece, and operate a CNC machine to execute this program. Through this experience, they are able to get a sense of the benefits of automated machining over performing manual operations which constitutes the bulk of their laboratory experience in this class.

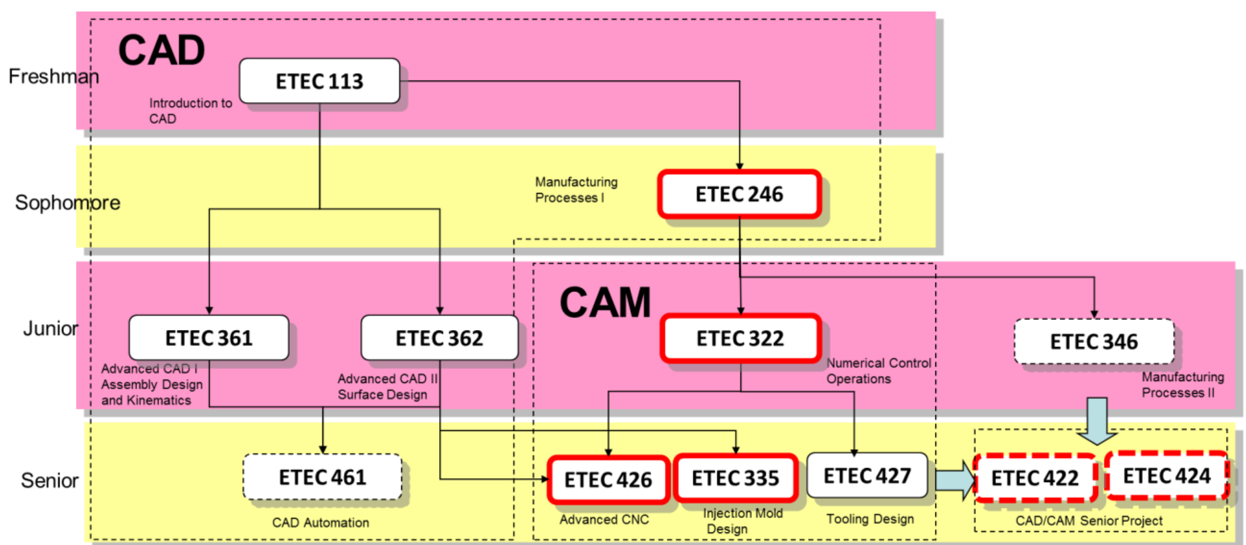

Figure 1. Use of CNC in the CAD/CAM Curriculum

Intensive instruction for all MET and PET students in manual part programming and the operation of CNC machines, takes place in ETEC 322. Students are also exposed to CAM using the Prismatic Machining workbench in CATIA® and Vericut® for NC verification. The laboratory experience in this class involves setting up and running programs (both manual and CAM generated) to machine components that assemble into a mantel clock (see Figure 6). An advanced CNC class (ETEC 426) is required for all CAD/CAM majors and available as a technical elective for others. It has several flavors, the one most relevant to this paper being Surface Machining. This expands the CAM experience in ETEC 322 to 3-Axis and 5-Axis machining. As in ETEC 322, the laboratory experience involves setting-up and operating a CNC machine. Beyond these classes, where learning CAM and CNC are the primary objectives, there are other places in the curriculum where use of the technology is required to complete projects. For CAD/CAM and PET majors, ETEC 335 is an injection mold design and fabrication class. Project work here requires student teams to design and machine an injection mold that will be used to produce plastic parts (see Figure 2). Finally, some though not all students may utilize CNC machines for fabrication work as part of their capstone Senior Project (ETEC 422 and 424).

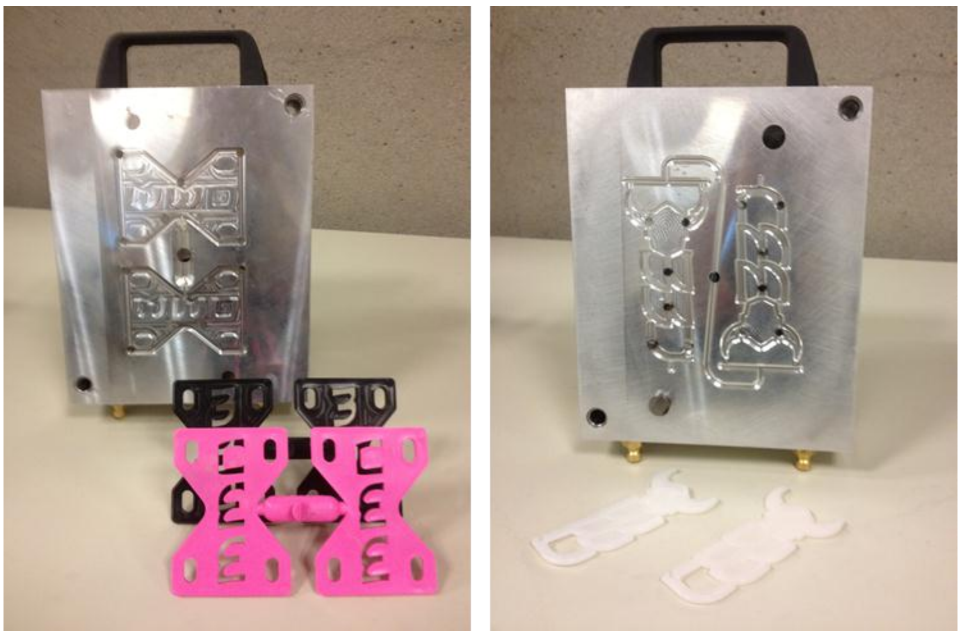

Figure 2. Examples of Molds Machined in ETEC 335

The requirements for project work in ETEC 322, 426, 335 and 422/424 place high demands on the four machines in the department’s CNC laboratory. The use of verification technology is one way to reduce the amount of on-machine programming changes needed, identify errors and streamline the procedures that students must follow before being allowed to execute their work on a machine.

Developing and Deploying the Verification Models

A multi-level development strategy was used to create the verification models for the CNC curriculum. This is shown in Figure 3. The first level focused on the piece of the model that can be used across all classes where CNC is taught or utilized. Key activities required at this level were building the CAD model of the machine tool, creating its kinematic structure and adapting a controller for parsing and executing G&M code programs. One of the challenges in building the 3D CAD model, was obtaining accurate measurements of the CNC machine. Initially, a search was made for the availability of a CAD model for a Haas VF2 milling machine. This proved fruitless. Inquiries brought to light the fact that while machine tool venders likely have created such models, in most cases and probably with good reason, they are reluctant to distribute them. As a result, hand measurements of the machine and tracing of scanned documentation were the methods used. Figure 4 shows the final CAD model created. The machine's work envelop was the focus for the greatest accuracy and level of detail. Within this volume, sizes and locations within ¼" were realized.

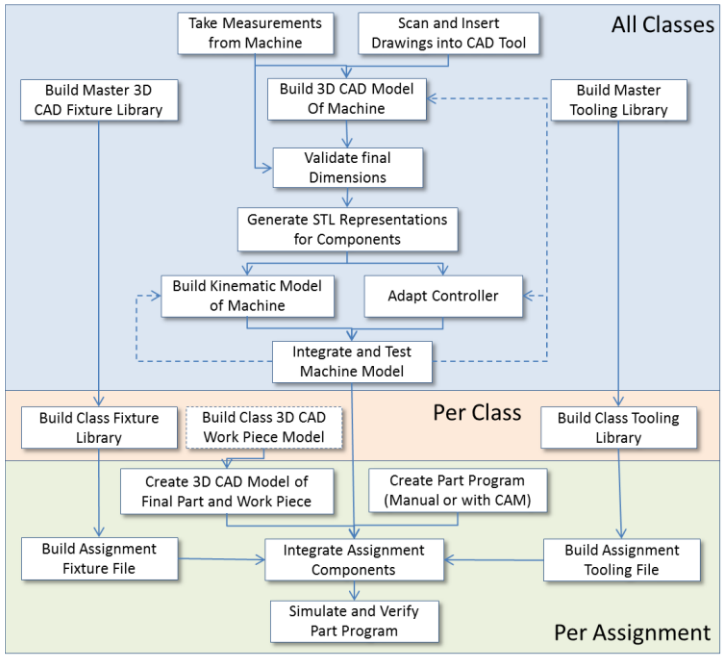

Figure 3. Multi-Level Development Strategy for Verification Models

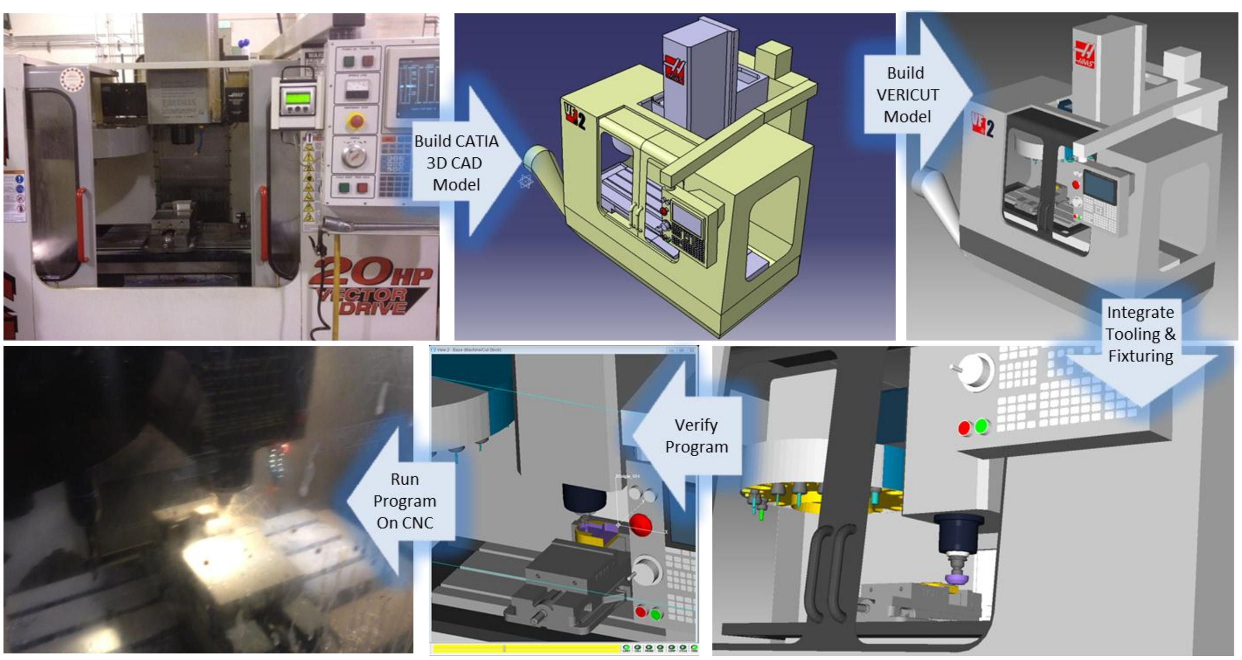

Figure 4. Modeling of a Haas VF2 CNC Milling Machine

At the next level, models relevant to a particular class were developed. These include tooling and fixturing libraries, and the initial work piece geometry if predetermined by the instructor. Finally, at the assignment level students typically need to model the final part geometry and sometimes the initial work piece when this is not given to them. They also need to select or modify fixturing elements. For many assignments, a machining vice with parallels are used. A parametric CATIA CAD model where the jaw spacing can be adjusted is provided for this. After process planning and the completion of the part program, a modified tooling file containing a subset of tools from the class tooling library is created by the student. The final Vericut® model is consequently an integration of models and data obtained from all three levels described.

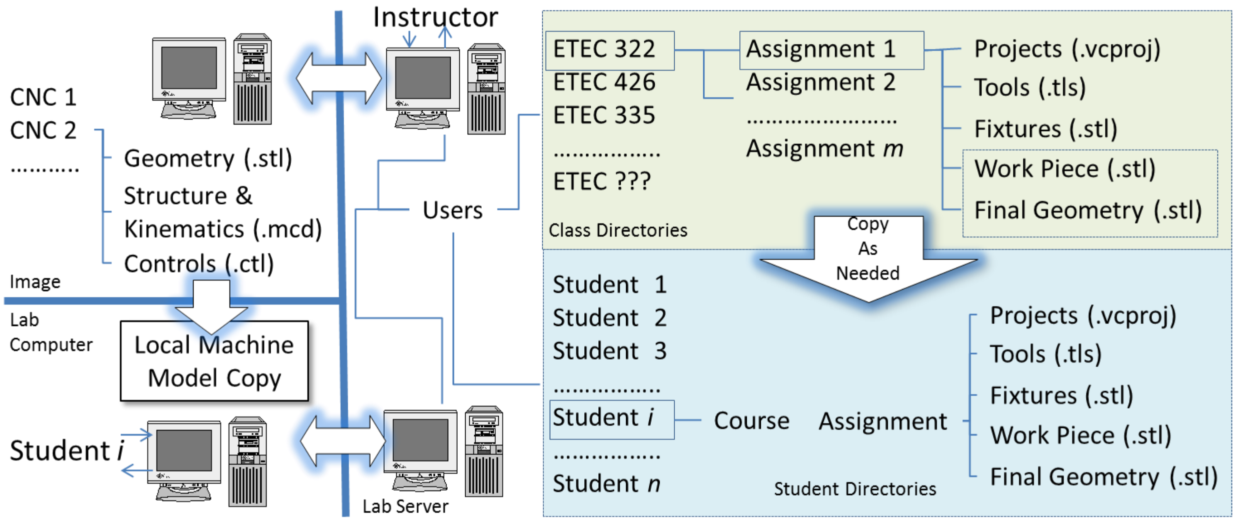

Figure 5. Management of Verification Models Across Classes, Assignments and Student Users

Figure 5 illustrates how the verification models are deployed in the department's CAD/CAM laboratory. The intructors create class directories on the lab server for each class that requires use of a CNC machine. In each class directory, assignment folders are created that contain Vericut® project and tooling files, geometry files for fixtures, the final part geometry (if provided) and the work piece geometry. The machine tool model that is made up of the 3D component geometry, the machine's kinematic structure and the controller for parsing and executing part programs, are built by the instructor, tested and installed locally on the laboratory's computer image which is installed on all 50 lab machines at the beginning of each quarter. It should be noted that all geometry files in Vericut® are stored in the .STL format.

To use a model, each student taking the class in question will copy into their personal directory the files in the assignment directory on the server. When they run the Vericut® project file, it will build the simulation model using the locally stored machine tool model and the files in the student's directory on the server that define assignment specific tooling, fixtures, work piece, final part geometry and part programs.

Dividing the model between server and local storage in this way is important. Depending on the level of detail the machine tool model can easily be over 10 Mb in size and made up of 20 to 30 separate geometry files. Having students store and use their own versions of this complex model profilerates data on the server, and invariably leads to wasted time in fixing broken models that have been poorly managed. This approach allows students to focus on an assignment's part programming requirements, with the use of the verification model being similar to setup and running a program on a CNC machine, though in a virtual sense. Updates to a model are also easy to make at any time by the instructor on the image for deployment to all lab computers.

Enhancing Student Preparations for Laboratory and Project Work

In this section, the use of the verification model to enhance preparations for project work in ETEC 322 is described. Students in this class complete a number of labs and a final project that machine the components of a mantel clock from aluminum stock. Figure 6 shows an example of the components, final assembled product along with a listing of the labs that are used to machine each component.

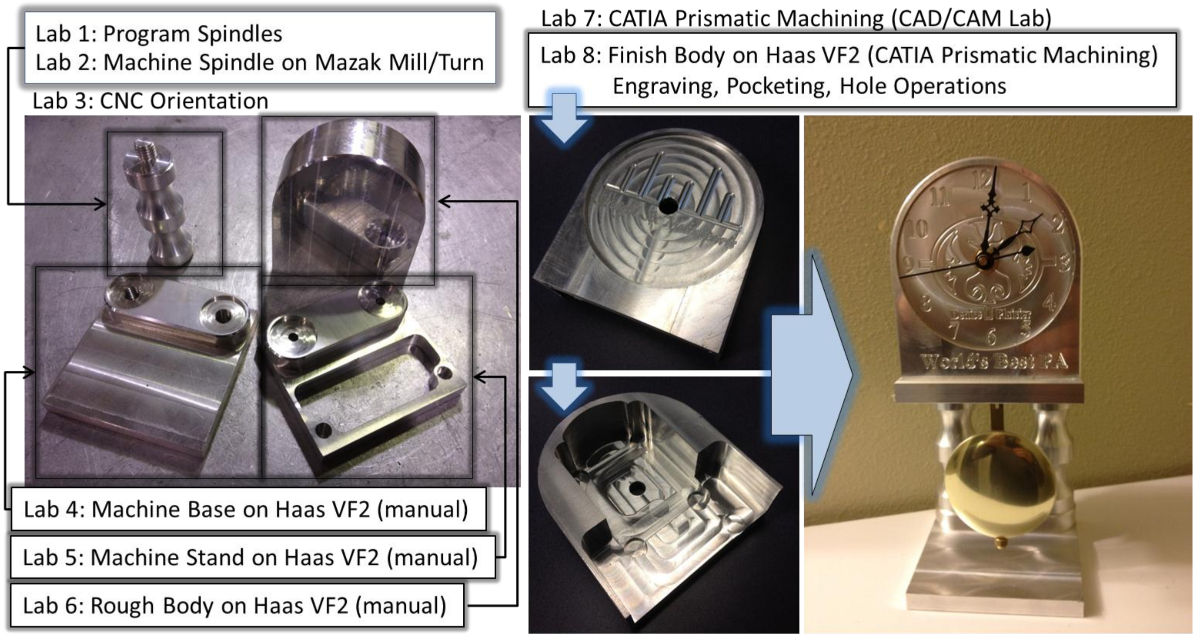

Figure 6. ETEC 322 Manually and CAM Programmed Components and Final Result

Prior to machining a component, each student must complete and provide documentation of the following:

- *Design Work:* This is needed for the final project where students are to design an engraving pattern to be machined on the clock face. A part drawing of the engraving must be created.
- *Process Planning:* Process Sheets are required for each setup showing a list of operations, tools, speeds and feeds that are used. The also include a sketch of the setup identifying the location of the part origin and the axes orientations (G54).
- *Part Programming:* Either manual or CAM generated programs depending on the assignment.
- *Digital Verification*: This shows the execution of the part program for each setup that must be machined using the complete Vericut® model described previously. This verification does two important things. First, it helps to identify rapid or unintended moves that result in

collision between the tool, work piece and fixture. Second, by comparing the machined stock to the design, students verify that the program is cutting the correct geometry.

- *Review of Preparations:* A *CNC Preparation Check Sheet* must be completed for each assignment. This is used to confirm to the instructor that the student has completed all preparation steps. This includes reviewing code for simple errors such as missing decimal points (e.g. F20 means a feed rate of 0.002 ipm) or mismatched values for tool length and diameter compensation (e.g. T10 requires H10 and D10). For the final project, a check-off with the instructor in the CAD/CAM laboratory is required ahead of the scheduled appointment on the CNC milling machine.

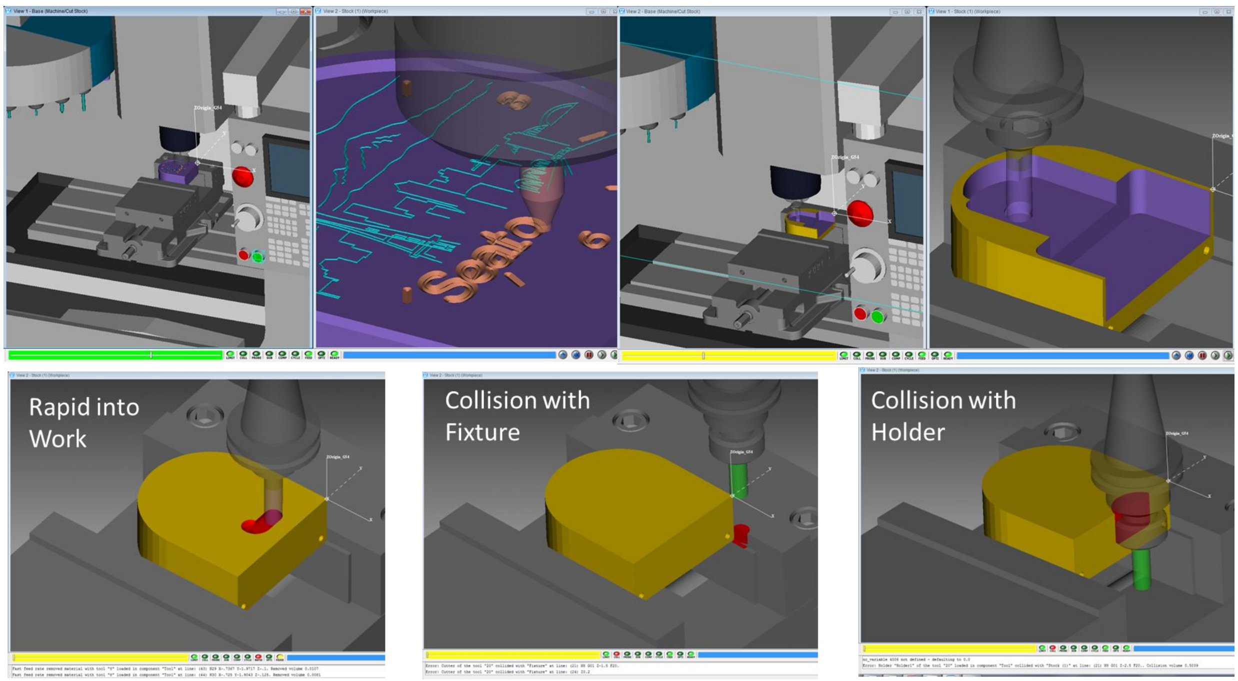

Figure 7. Examples of Verification for ETEC 322 Final Project and Identification of Programming Errors

Figure 7 shows an example of the results obtained from the verification step for the two set-ups required for the final project (Lab 8). The appearance of "red" during the simulation indicates a rapid move into material or any contact of components that is not strictly either the flutted length of the tool or the work piece material e.g. cutter and vice or tool holder and work piece. During manual part programming, this often occurs when students forget to switch back to feed motion (G01) after a rapid move to reposition the tool (G00). Figure 8 shows an example of the result obtained from using the "AutoDiff" feature in Vericut® to compare the machined stock with the design. "Red" indicates gouging and "Blue" excess material. It is rare that novice students get a manual program correct the first time. This feature provides instantaneous feedback that forces them to troubleshoot and correct the source of the error. Prior to the use of Vericut®, most of these problems would be first identified on the CNC controller, if at all. Small differences such as the gouging shown in the figure would likely not be caught until after the part was cut.

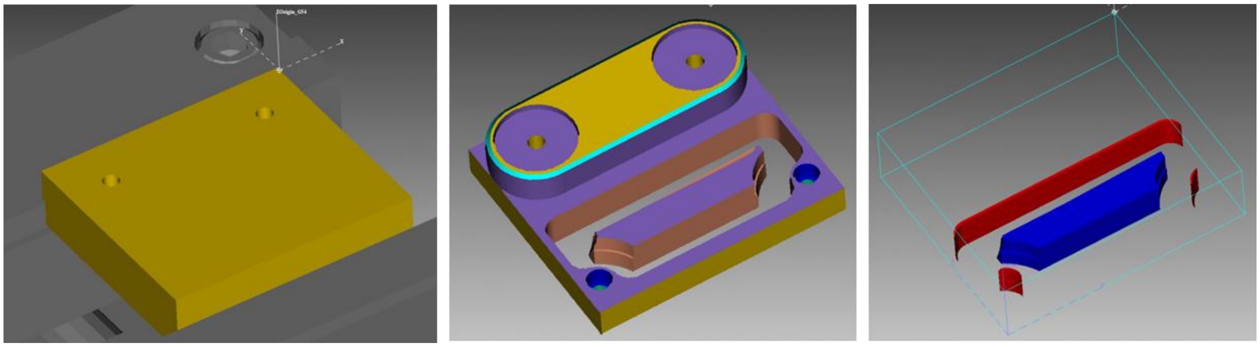

Figure 8. Example of the use of the AutoDiff feature in Lab 4 to indicate gouging (red) and excess material (blue) motions in program

Use of Verification Technology as an Instructional Tool

In addition to the use of this technology by the student to assist in lab and project preparations, the instructor also makes use of it during lectures to assist in explaining manual programming concepts. In ETEC 322, several examples have been prepared that cover the range of topics from linear interpolation through cutter compensation and sub-programming. Previously these examples were explained using a combination of Powerpoint slides and writing on a "Whiteboard". Now students can see in realtime projected on a screen, the simulation execute each command in a program. The single step feature in Vericut® allows the instructor to explain how each block of code is executed before proceeding to the next. These examples are also saved in the class directory so that they can be retrieved by students as they review material presented during a lecture.

Evidence of Impact

This evidence comes from observations by the instructors and technical staff and from student feed back. It is divided into (1) impact on efficiency of use of laboratory time, (2) reduced damage to equipment and tooling, and (3) providing learning assistance for students.

Efficiency of Use of Laboratory Time: Recent curriculum changes have resulted in both the reduction of scheduled CNC lab times in ETEC 322 from three to two hours, and a doubling of section sizes from six to twelve students. The latter change was accommodated by operating all four CNC machines during a lab session, as opposed to just two that were used in the past. This increases the supervision load on the two instructors assigned to the section. There was significant concern that these two changes would make these laboratory sessions extremely difficult to manage. However, this has not been the case. Over the past three terms that this course was taught, with the incorporation of the verification procedures described previously, over 85% of laboratory sessions and 95% of project sessions were completed within the allotted 2 hour period. In those cases when students ran long, the problem was typically due to a setup error on the machine requiring a rerun e.g. incorrect tool length measurement, improper location of G54, poor seating or clamping of the work piece. Previously when sessions were 3 hours long, a significant portion of this time would be spent fixing programming errors on the controller. Instructors agree that with the requirement to verify before machining, programs are a lot "cleaner" when students arrive to do their lab work. Fewer major programming fixes are needed on the controller. As a result, even with twice as many students in the lab, twice the number of machines running and 50% less time, the intensity and stress level for instructors as they guide students through the labs, is significantly lower than was previously the case.

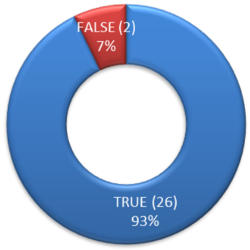

Figure 9. Student Feedback on Avoiding Programming Errors

Reduced Damage to Equipment and Tooling: Though exact numbers are not available, instructors agree that the number of serious machine crashes resulting in broken tooling and scrapped work pieces is significantly lower. During the most recent offering of the course, only one incident was recorded were a tool was rapided through the work piece resulting in tool breakage. Upon investigation it was discovered that the students in question missed, or ignored, the results from the simulation which clearly showed a “red” rapid move. Further evidence of impact in this area came from a survey of students at the end of the term. Figure 9 shows that over 90% of the students agreed that Vericut® helped them avoid a programming error that could have resulted in a machine crash.

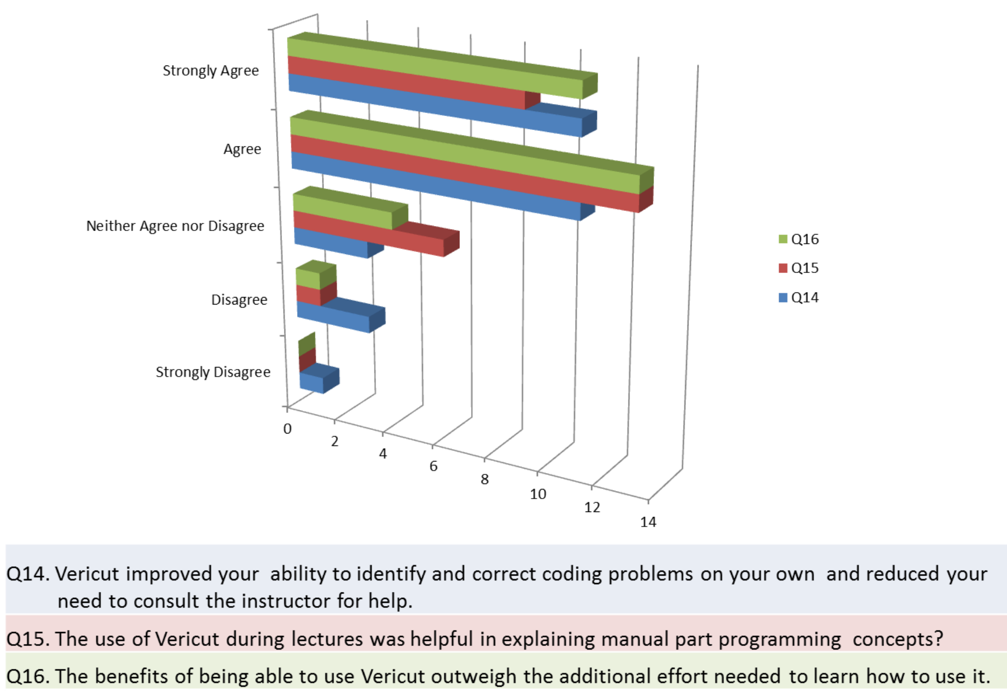

Figure 10. Other Student Feedback on the Impact of Using Vericut®

Providing Learning Assistance for Students: The use of simulation models during lectures has already been explained. Students overwhelmingly agreed that this technique was helpful to them in developing an understanding of programming concepts (see Figure 10, Q15). Further, they also agreed that this helped them identify and correct coding problems on their own (Q14). The ability to get instantaneous feed back on their coding, changes the dynamic of how they tackle and complete assignments. Motivated to learn and do well, this technique gives them the means to take some corrective action to improve their work when previously this was not the case. Many in the past would not have critically checked their work, or even if they had, be knowledgeable or thorough enough to identify many problems present. By being able to engage in validate and update improvement iterations without the direct involvement of the instructor (an impossibility given time constraints), students are encouraged to learn from the mistakes they have made and the fixes they create, as opposed to blindly accepting the first solution they generate. Finally, the majority of students agreed that the benefit of having this tool available for use, outweighed the effort needed in learning how to use it (Q16).

Discussion and Future Directions

The evidence suggests that the application of verification technology as described in this paper has positively impacted the efficiency of CAM and CNC instruction. Further, it has led to a reduction in machine crashes which is important in protecting the investment made in expensive, industry-type CNC machines. While preliminary indications are that this technology also assists students in learning CNC programming concepts, further study is needed to confirm this. One cause for concern parallels that raised on the impact of calculators in developing mathematics skills. Does the availability of the verification tool make students less inclined to commit to memory the syntax, structure and methods of G&M code part programming? With most materials being provided electronically, it is evident that most students "cut-and-paste" code between examples and assignments once they have access to these. In many cases this makes sense, and is encouraged, as it increases programming speed and minimizes errors assuming that the source is correct in the first place e.g. code for program start-up and tool change blocks. However, if this happens before an understanding of how the words in each block function, then the learning process is short circuited.

Vericut® allows programs to be simulated while being written. Thus, the affect of each block of new code can be visualized before moving on to programming the next step. While using this capability seemed like a good idea at first, it was quickly discovered that some students were getting incorrect results from the simulation and getting stuck spending a lot of time trying to fix code that was actually correct. This problem arose because Vericut®, like a CNC controller often needs to look a block or two ahead to correctly execute the commands in the current block. With a proper understanding of when and how this happens, simultaneously writing and simulating blocks of code could be an effective means of programming. However, given the relative inexperience of students, to avoid this problem it was strongly recommended that they complete manual coding of their entire program before performing verification.

As with other software tools that analyze or simulate, there is a danger of blindly accepting results that contain significant errors. It has already been described how lack of attention to the results during a simulation by students, led to a machine crash with a broken tool and scrapped part. Also, the model in its current form, will sometimes correctly cut geometry in a block of code that will generate an alarm on the CNC controller. It does not catch mismatched H and D values that are used to call up tool length and diameter offsets, numbers with missing decimal points that are interpreted as ten thousandths of an inch, or collisions with tool holders as tool extensions are currently not standardized and captured in the model. Some of these problems will be eliminated in time by enhancements to the model. However, students are continually reminded that there are limitations, and are given a check list to be completed during a final review of their code that is designed to help them identify and fix problems that have been missed. The excuse "It worked correctly in Vericut!" is not tolerated.

For future work, a couple of areas are targeted:

- *Expansion of the model to include 5-axis capabilities:* This step supports the objectives of ETEC 426a, the advanced CNC surface machining class. Students learn use of the multi-axis machining capabilities present in the CATIA® Surface Machining workbench. They are required to complete a project that machines a part using programs generated from this workbench. Due to the to absence of a 5-axis machine in the CNC lab, this has been limited to 3-axis tool paths, even though they learn how to program 5-axis operations. However, with the availability of the simulation models that have been developed to-date, a team-based extention to this project is being planned that will require the following:
    - o Expanding the 3-axis Haas VF2 mill to enable 5-axis machining capabilities by modeling and integrating a trunion table. Figure 11 shows an example of the modeling detail needed to do this.

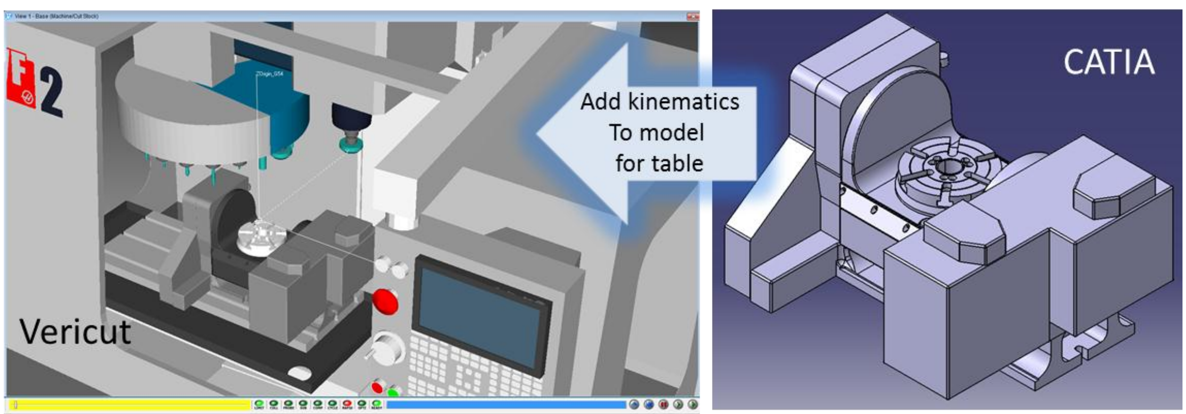

Figure 11. Expanding Haas VF2 to a 5-Axis Mill

    - o Replacing the finishing operations on the 3-axis project with 5-axis operations.
    - o Simulating and verifying the 5-axis tool paths using the enhanced 5-axis milling model.

    Though not a complete experience due to the absence of a real 5-axis machine, it is hoped that by expanding the simulation model and reworking their part programs, the students will develop a better appreciation of how such a machine functions.
- *Developing a Simulation Model for the Department's Mazak Mill/Turn Machine:* As can be seen from Figure 6, Lab 2 requires the use of a Mazak Mill/Turn machine to create spindles for the ETEC 322 clock project. Mill/Turn machines are both difficult to program, and with a fast moving turrent fully loaded with tools, have a high potential for collisions. A project is currently underway to develop a simulation model for this machine. This will allow greater use of the milling capabilities of this machine in classes and for projects. It will also allow this machine to be more efficiently programmed off-line using a CAM application such as CATIA's Mill/Turn workbench.

Conclusions

In this paper, a description of the development and deployment strategy for verification technology in a curriculum where CNC is taught and heavily used has been presented. The commercial system Vericut® was adopted over a custom, in-house solution so that the focus could be on managing the use of the technology rather than on development issues. The approach has resulted in a realistic and sophisticated model of the department's Haas VF2 CNC milling machines being used for multiple assignments and projects across several classes in the curriculum. This model has been set up for ease of maintenance and to allow it to be customized quickly for different assignments and classes. It is also being used for basic instruction during lectures to assist students as they learn basic CNC programming skills. Initial evidence suggests greater efficiency in the use of CNC machines and a reduction in machine crashes as a result. There is also reason to believe that the availability of simulation is assisting students in learning programming concepts though this needs to be investigated further. New and expanded models are being developed for other types of CNC machines that will further extend the use of this technology in the curriculum.

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