CNC Technology in the Classroom: Why is it important, and how can we implement it?

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Introduction

Have you ever asked yourself how most things you come into contact with daily are made? You may have seen a few episodes of Modern Marvels watching spark plumes from a sand mold or a timelapse video of vehicles assembled on a manufacturing line. Or have you've just heard that we no longer make things domestically as we should? What if I told you that manufacturing in the States can not only be cost-effective and reliable but also provide a well-paying and reliable job market? All of this can be made true using computer numerical control or CNC machining technologies. CNC is very similar to how your computer mouse moves across a screen or your printer prints the documents you need. CNC machines use a coordinate work system, a 3D graph with many plotted points connected together, combined with advanced computer model-making and programming to create quality products. This allows manufacturing to produce products it hasn't been able to before with incredible speed, efficiency, and reliability. These machines also introduce the possibility of bringing manufacturing and production development back to the United States.

Historically, CNC devices have been segmented within the manufacturing and materials conversion sectors of Technology and Engineering Education and Trade and Industrial Education. Their segmentation and complexity relegated them to either highly specialized or conceptual instruction. The landscape of technology and engineering education has changed dramatically. CNC machines, controllers, and programming have become ubiquitous, appearing in consumer-accessible additive 3D printers, desktop milling and routing machines, and various consumer robotic technologies.

With the ever-changing landscape of manufacturing technologies, technology and engineering educators (T&EE) must understand and incorporate these new concepts into their classrooms. The methods used in the past to create quality, affordable, and repeatable parts and products are no longer financially feasible. Many factors contribute to this, such as labor laws and manufacturing regulations. Therefore, manufacturing had to adapt to preserve production in the United States. The method of production that manufacturing systems have turned to is CNC machines. CNC consists of a computer creating a cartesian work coordinate system that a milling machine, lathe, milling-turning machine, or other additive or subtractive manufacturing machine utilizes. Each of the aforementioned CNC machines is equipped with its own set of computing software and hardware that can interpret and work from numerical code to create high-quality and reliable parts (Musca et al., 2016). These large-scale CNC manufacturing systems require skilled operators to reduce machine downtime and cost (Musca et al., 2016; Selvaraj et al., 2009). A shortage of such skilled operators and setup persons creates an opening for technology and engineering courses to create instructional modules and/or courses appropriate to the discipline, which will prepare students for reliable and high-paying jobs. One challenge, among many, is that many T&E educators now face their own steep learning curve to develop competence and subsequently teach these new manufacturing technologies and methods of application to their workspaces and classrooms.

Beyond the challenge of educators with teaching competence, another challenge for education is the fact that CNC technology and manufacturing systems are predominantly propriety with little to no communication between global manufacturing systems (Newman et al., 2008). The notable differentiation between CNC machine manufacturers and developers creates an educational barrier between machines, software, and students/educators. Beyond the level of educators who must build instructional competence, an entire group of educators need a cursory background in these technologies. For these teachers, incorporating CNC instruction may seem hopeless. Fortunately, many great resources and free software packages exist to promote education in this field, such as Autodesk Fusion 360, which is free to students and educators. For educators with limited access to machines, many toolpath simulation programs, such as the one Nair et al. created using Autodesk Inventor (Nair et al., 2018) or Tormach Path Pilot Hub, are easily accessible and effective in demonstrating conceptually how tool paths behave. While these simulation software can be very effective, teachers must refrain from supplanting hands-on CNC manufacturing activities. While the barriers to accessing full-size CNC machines may be significant, affordable small-scale CNC machines are available to provide hands-on balance to virtual CNC manufacturing activities. The goal of Technology and Engineering Educators should be to provide these experiences for students as they can foster a sense of motivation, purpose, and future for students in an ever-growing industry.

In the paper, we focus briefly on the current state of the CNC manufacturing job market and how it is covered in education systems. After providing a brief overview of the state of the CNC job market and rationale for widescale CNC instruction, we will provide various real-world examples of virtual and physical CNC development, programming, and execution designed to develop instructional competence. The CNC instructional projects and instructional exemplars will be created for each type of CNC machine commonly found in manufacturing and are aligned with the International Technology and Engineering Associations (ITEEA) Standards for Technical Literacy (STELs) (*Standards for Technological and Engineering Literacy (STEL)*, 2022).

Terminology

Before beginning our CNC instructional activities and entering the world of CNC education, we must first define the most important terms that will be used copiously throughout this paper.

Computer Numerical Control (CNC) refers to the machine's operation method. This method uses a cartesian work coordinate system to plot points in space where the device will move a tool head. If programmed correctly, this movement will cut different shapes or patterns into the materials (Yasar, 2023).

CAD- Computer-assisted design refers to a parametric modeling program that allows the user to use a library of tools to create water-tight geometry. These models are solid, meaning they have volume in this virtual space and can be referenced in a CAM program (Anonymous, 2023).

CAM- Computer Assisted Manufacturing is the software that uses your generated solid model and a library of tool path options to plot points for a tool to move around in the machine, cutting or forming your part (Anonymous, 2023).

CNC Vertical Mill- A vertical milling machine is a three-, four-, or five-axis milling machine. Vertical refers to the orientation of the spindle, which turns the tool head. Three-axis machines move in the X, Y, and Z. Four-axis machines will rotate around one linear axis. These are represented by the A, B, and C axis, respectively. Five-axis machines are arguably the most complicated and combine rotating and linear axis moving simultaneously. Five-axis machines provide the most flexibility when creating parts but are more complex and expensive. For all CNC applications, the axis is controlled by a built-in machine controller programmed in the CAM software (Anonymous, 2023).

CNC Slant Bed Lathe- Similar to a CNC mill, a lathe has a linear axis controlled by a built-in CNC controller. However, a lathe orients the axis differently from a mill. The Z axis on many machines runs the length of the machine; the X axis will move the tool into the spinning workpiece, and the Y axis will move the tool head up and down. In addition, the spindle rotation will refer to the rotation of the chick and material. CNC lathes rotate the material to machine parts, and CNC mills rotate the tools (Anonymous, 2023).

Additive manufacturing- This manufacturing method refers to how parts are formed from materials. Additive manufacturing means the material is added to a work plate to build the part. This usually requires more time and money. However, these machines are significantly more efficient. Examples of this process are plastic or metal 3D printers.

Subtractive Manufacturing- Subtractive manufacturing refers to removing material from a larger piece of stock to create a product. This method can be very time-efficient but very wasteful as well.

The following images will provide a visualization of the axis for a vertical CNC milling machine and a CNC lathe.

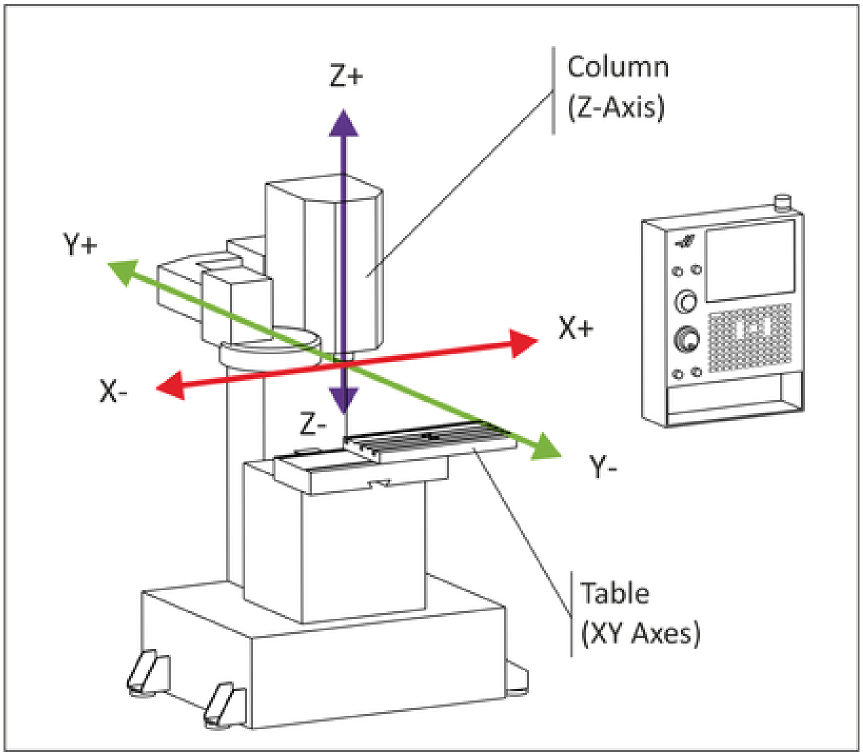


Figure 1. Vertical mill axis from (Deans, 2023)

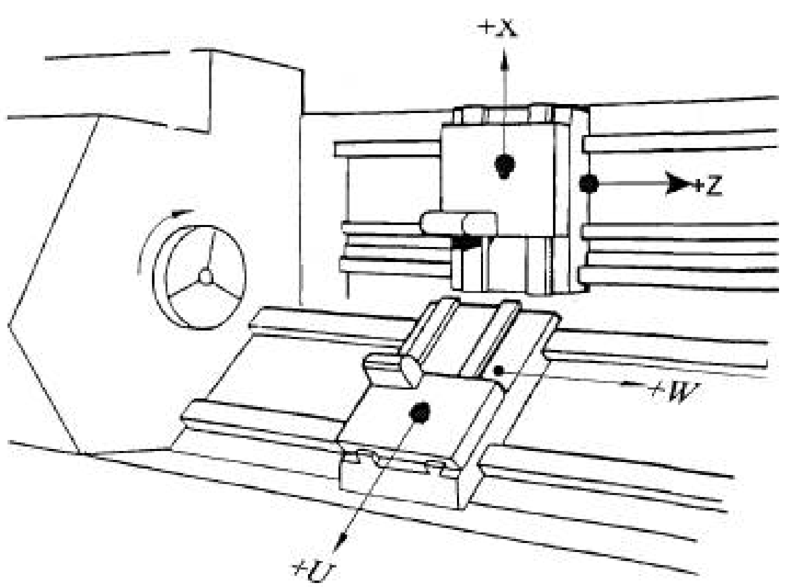


Figure 2. Slant bed CNC lathe (Summaryplanet, n.d.)

Opportunity Statement

When analyzing the educational landscape of CNC operators, it's essential to note where most of the workforce currently stands in academic achievement; according to Careeronestop statistics based on the U.S. Department of Labor, thirty-eight percent of CNC technicians obtained only a high school diploma, and additionally, another thirty percent attended college with no degree earned (Careeronestop, n.d.). In total, sixty-eight percent of the CNC operators working in the United States rely primarily on their high school education and the provided on-site training to succeed in a growing industry. This begs the question of what would be the outcome on the job market if we applied these same CNC operator concepts to our high school and college curriculums.

These statistics provide an exciting opportunity for education and educators. We can provide content in our classrooms that can be directly replicated and applied in the workforce. Therefore, educators must ask themselves if they prepare students to be technically literate and provide career opportunities for noncollege track students. Additionally, many large CAD/CAM software companies are also focusing on education as the future of the workforce, such as Autodesk. Autodesk refers to its new initiative in education and manufacturing as Industry 4.0, focusing on the soft, technical, and interdisciplinary skills individuals need in this field (Autodesk, n.d). Industry 4.0 is also what is being labeled the 4th industrial revolution. This revolution will focus not only on CNC application to production in traditional subtractive methods but also on additive metal manufacturing and machine interoperability/ communication. Additionally, the ability to essentially 3D print metal parts means that assemblies can be designed worldwide and transferred to the production centers, allowing for the sharing of newer and more efficient ideas and manufacturing methods.

This paper is not a detailed outline of how to start a CNC program in your school or to tell you what and how you should teach these concepts. Instead, we would like to offer our experiences and projects that we find rewarding and exciting. We hope some of these projects inspire others to integrate this technology into their classrooms. For educators already teaching these concepts, we hope this paper brings new ideas for you and a dialogue on what you feel is essential to guide us all to the better CNC workforce of tomorrow.

While this paper is not a guide, we wish it to become more of one. Therefore, before entering the specific projects of each machining classification, detailed instructions, tutorials, and any other teaching materials will soon accompany these projects for educators to use, modify, or build off of. We will use Autodesk Fusion 360 certification exams to classify the following projects as a guide. The Fusion certification exams are organized by characteristics of the machining operations being created, precisely how many axis they use, i.e., two-and-a-half-axis, three-axis, and four-axis. Some may have noticed the omission of five-axis machining. This type of machining is essential in creating complex shapes, parts, and assemblies. It is also out of the ability of the machines in our possession. Moreover, our artifacts will include many of the concepts used in five-axis machining. Therefore, we have chosen to omit five-axis machining to provide tangible standard-based projects.

2.5 Axis - Secret Box

As a long-time metalworker and former CNC operator with early journeyman skills in manual machining, I desire to establish fluency in CAD solid modeling and CAM with a CNC milling machine and lathe. As a CNC operator in the early 1990s, CAD-CAM was rudimentary, complex, powerful, and out of the reach of most tradespersons and machinists. Patrick, our “Setup Lead,” was a magician with the company’s worn-out CNC lathes and several CNC milling machines. My eight-hour shifts as an operator included time to observe and enhanced my wish to be the setup lead rather than a "button pusher." In the intervening years, I've sought opportunities to gain insights into the industry and build my CNC skills, even if my skills have progressed slowly. It's only been within the last few years that I've been able to devote more time to learning CAD and CAD/CAM. I am finally at the point where I can devote my own time beyond rudimentary work with students.

For this collaborative project, I wanted to accentuate the theme of maximizing the power of readily accessible CNC tools and their relative instructional utility. This project is considered a two-and-one-half-axis CNC machining project. Although the Tormach Mill is capable of three and four-axis machining, this project only requires the cutting tool to move and machine in two axes simultaneously. Additionally, I conceived the project as a Secret Box to accentuate high-speed repetitive accuracy and a high tolerance fit, all in a pocket-size form factor. The form factor is designed to minimize material usage, maximize CNC operations, and demonstrate the level of precision and quality that an artisan cannot easily replicate.

After completing a few quick sketches of the Secret Box, I modeled it in Fusion 360 (See Figure 3). Although it could have been modeled in one of many parametric modeling packages, developers from AutoDesk have programmed Fusion 360 to be a powerful solid modeling tool that transitions quickly from design to generative design, rendering, manufacturing tools, and detail drawing tools.

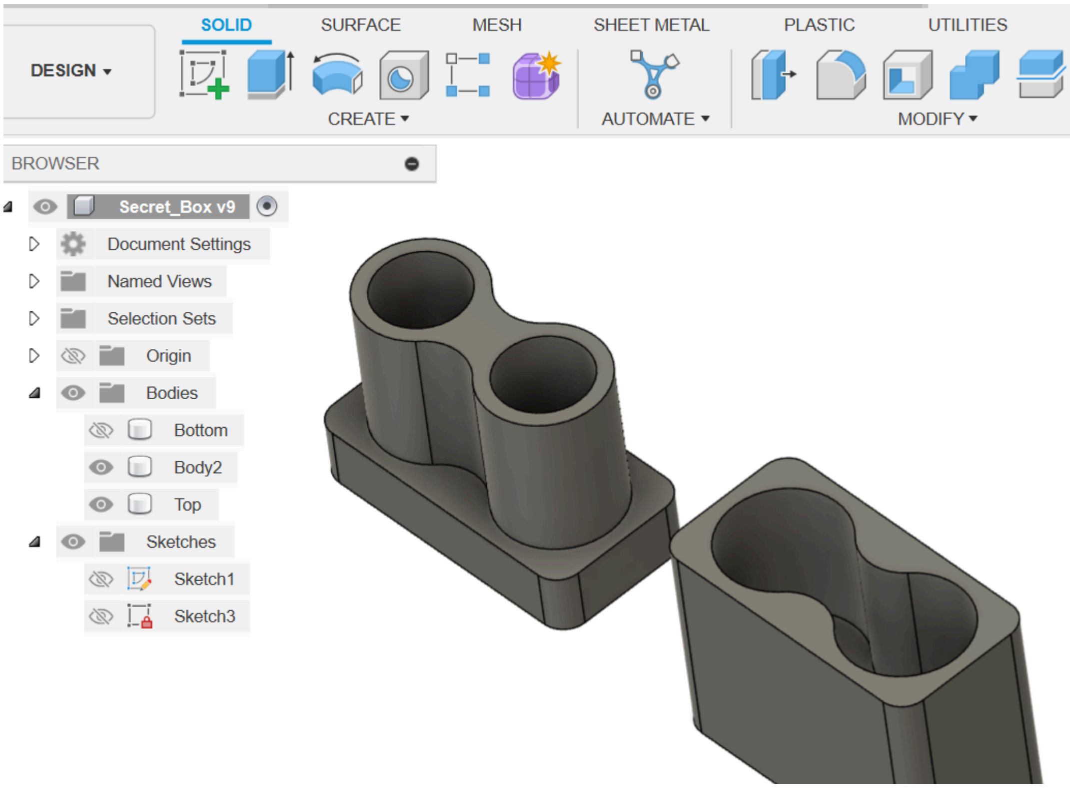


Figure 3. 2.5 Axis - Secret Box - Fusion 360 - Solid Model Bodies

This research project and persuasive proposal suggest that secondary and post-secondary students should conduct such modeling and CNC production - even if the manufacturing production is subtractive manufacturing on desktop turning and milling machines or additive 3d printing technologies. After solid modeling the bottom of the secret box, a new body was created for the top by programming the inverse detail with .0025” clearance on each size. The total of .005” creates a very tight fit. The design intent was a top and bottom box with such close tolerance that the box would remain closed when assembled and require careful force to separate the two halves. After design and modeling, Fusion 360 aided in creating toolpaths.

Based on the tool library and the setup of the two Secret Box bodies, the tool paths were created and modified to align with the appropriate tool for the process and the existing tools programmed into the tool library (See Figure 4.).

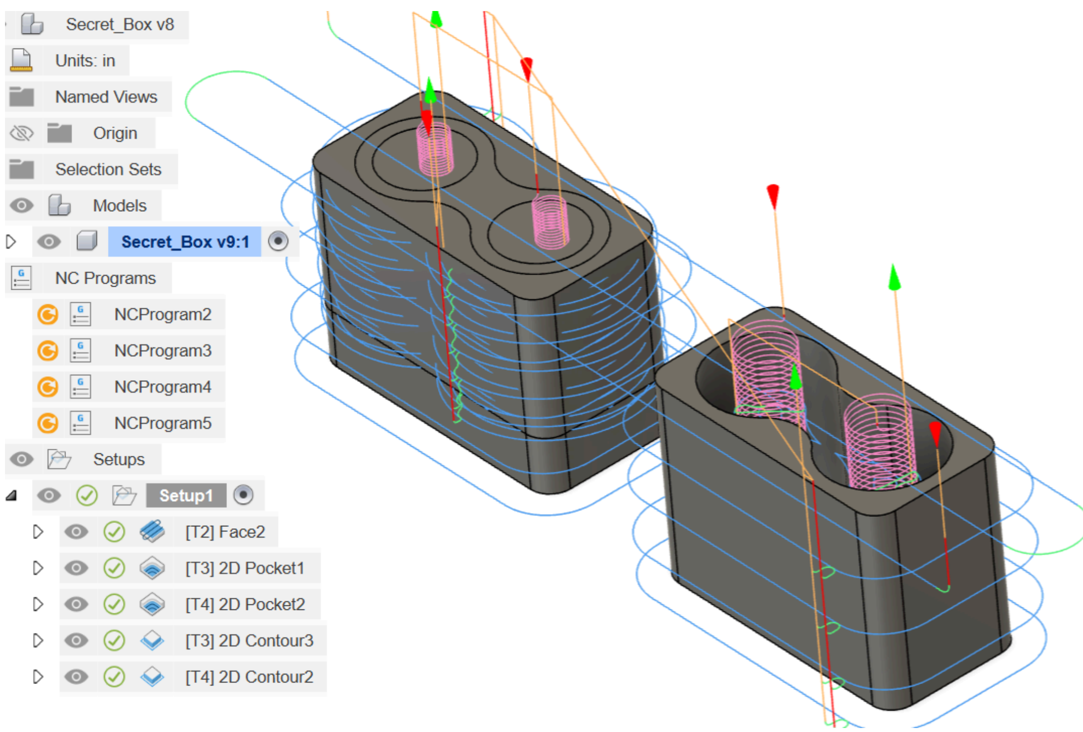


Figure 4. 2.5 Axis Secret Box - Fusion 360 - Toolpaths

After viewing the milling manufacturing simulation in Fusion 360 and determining the viable setup, the tool paths were post-processed and transported to the Tormach Mill. The stock was clamped in the vise, the X0, Y0, and Z0 were set, and we ran the part. After we noticed opportunities for improvement and minor errors, we edited the model, recalculated tool paths, and post-processed the file. Our first attempt required hand-sanding to remove burrs. As you will note with the demonstrator, the accuracy is as planned, and the 2.5 Axis Secret Box functions better than designed.

This 2.5 Axis Secret Box had tremendous learning potential and added production opportunities. While the first iteration of the project was successful, V2 is improved, and the tools have been modified to transition this project into a new student operator project, e.g., they will use the provided stock and a quick introduction to milling machine operation to develop an understanding of the design intent, material, and the process,

3 Axis - CNC Flag

To demonstrate 3-axis machining effectively, we used a method of modeling that creates long sweeping faces that move along all three axis simultaneously. Like a flag blowing in the wind, the elongated curves provide ample opportunity for 3-axis toolpath creation. Additionally, the flag allows students to choose who or what they would like to represent, albeit school-appropriate. This choice provides an excellent opportunity for students to take ownership of their projects and put their twist on them.

The model we created to demonstrate 3D tool paths was a waving flag. The beauty of this project is that combined with Fusion 360, you can create a complex appearing shape relatively simply. Additionally, your machine requires no additional hardware to complete these operations. In terms of making this part, two significant tools will be used. Those are the loft surface and the split body. To create the surface loft, you need lines on different parallel planes. These lines will then be connected to form a flowing thin sheet that will be used to cut the original solid body.

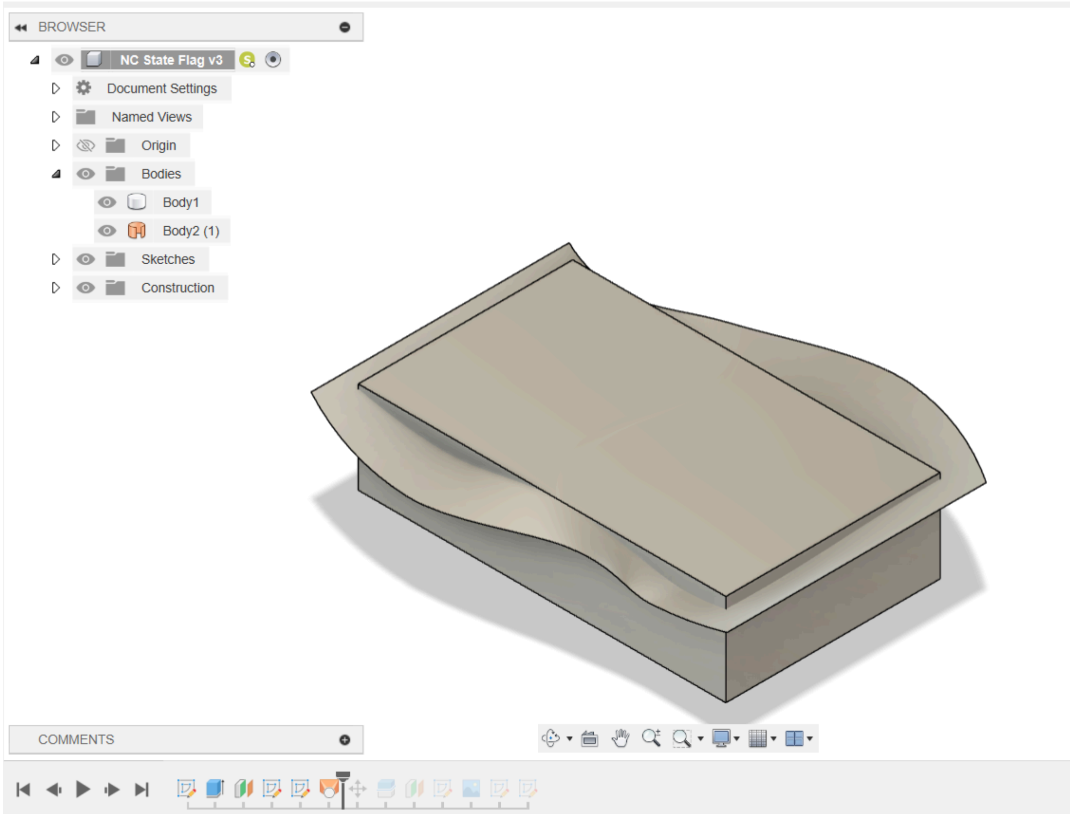


Figure 5. 3 Axis CNC Flag Loft Split Bodies

After creating the surface loft, the next step is to use that reference geometry to split the singular body into two. This process demonstrates an interesting yet usually under-utilized tool in solid modeling. The combining/splitting features in solid modeling provide significant power in modifying solid parts and theoretically changing how students view these models. It also allows students to think of the models as real-world objects and modify them how they would outside the program (i.e., cutting with a tool or gluing two pieces together). A visual representation of the cutting tool is shown below.

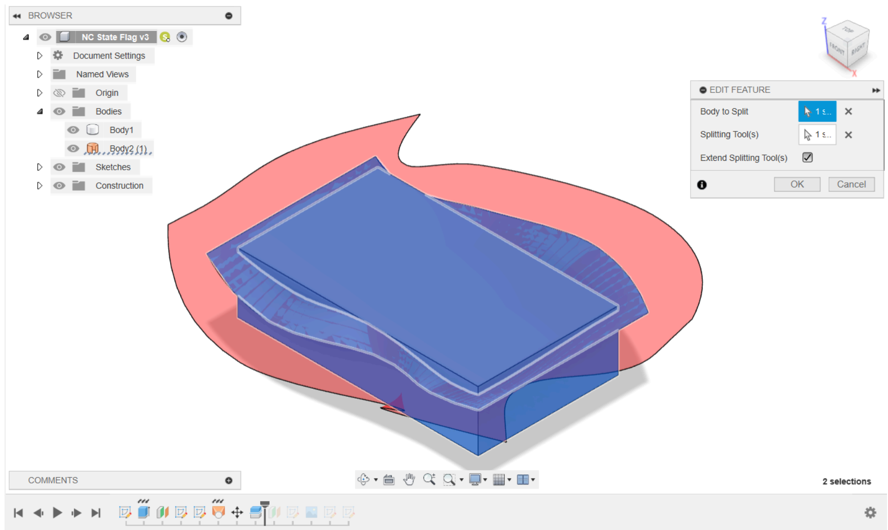


Figure 6. 3 Axis CNC Mill Flag Reference Geometry

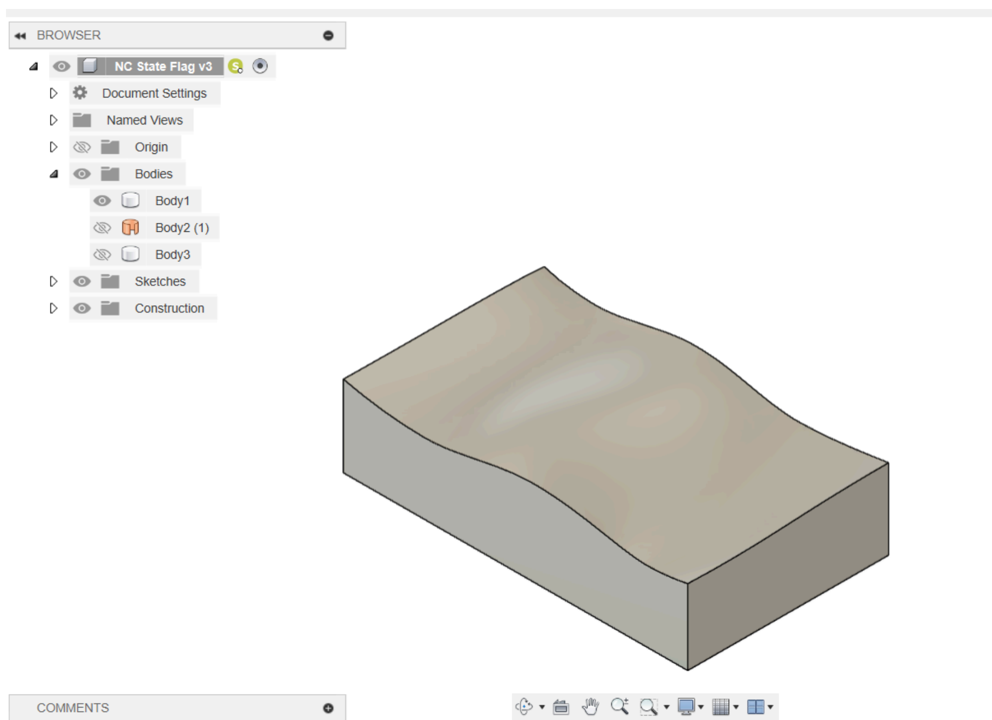
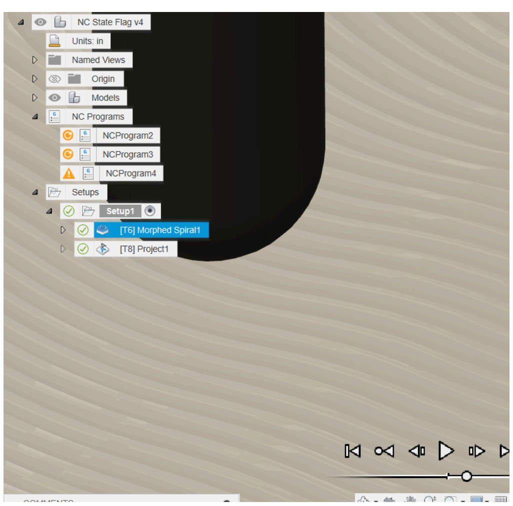


Figure 7. 3 Axis Contour Milling Procedure

The final step of the design process is to create the design geometry above the actual stock. This also provides an excellent opportunity to demonstrate designing for manufacture and designing for visualization. CAM toolpaths use lines or models to create boundaries and cut parameters. That means that, in many cases, it is easier to create simple line geometry and then use the tool's geometry to create the complex contour. For example, we used an offset plane in the image to the right to generate the geometry the tool paths will reference. We then used ball end mills to cut the contours, leaving a radiused groove throughout the part.

For toolpath creation, Fusion 360 has an extensive and comprehensive set of 2d and 3d toolpaths along with 4th-axis and swarf/5-axis tool path generation features. Only two tool paths were created for this part, the first being a 3D morphed spiral, which made the flag geometry and a 3D projection tool path. Both of these operations can be completed with the same tool, and in this case, that would be some form of bull nose or ball end mill. 0The mill's radiused end allows the tool to create complex contours without leaving flat bottoms. However, it is essential to note the ball end mills require small stepover tolerances to remove all the materials and remove cusps. The tool path generation and simulation features are incredibly useful in predicting the part's surface finish. It is important to note with students that the smaller the step over, the better the surface finish, but the longer the toolpath takes. Below is an example of how the simulation can detect surface finish and cusp heights.



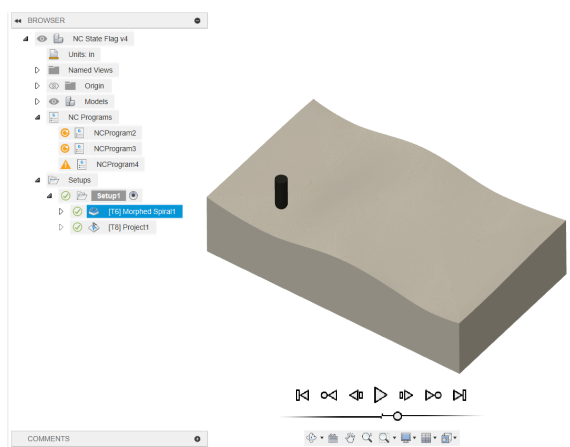


Figure 7. 3 Axis Mill Tooling, and Figure 8. 3 Axis Contour Milling

The final toolpath operation for this part is the projection. Again, this is where students can experiment with different tool path geometry and depths to see how the simulation reacts. A combination of tool geometry, depth, spindle speed, and feed is required to create an adequate surface finish that requires little to no finishing operations.

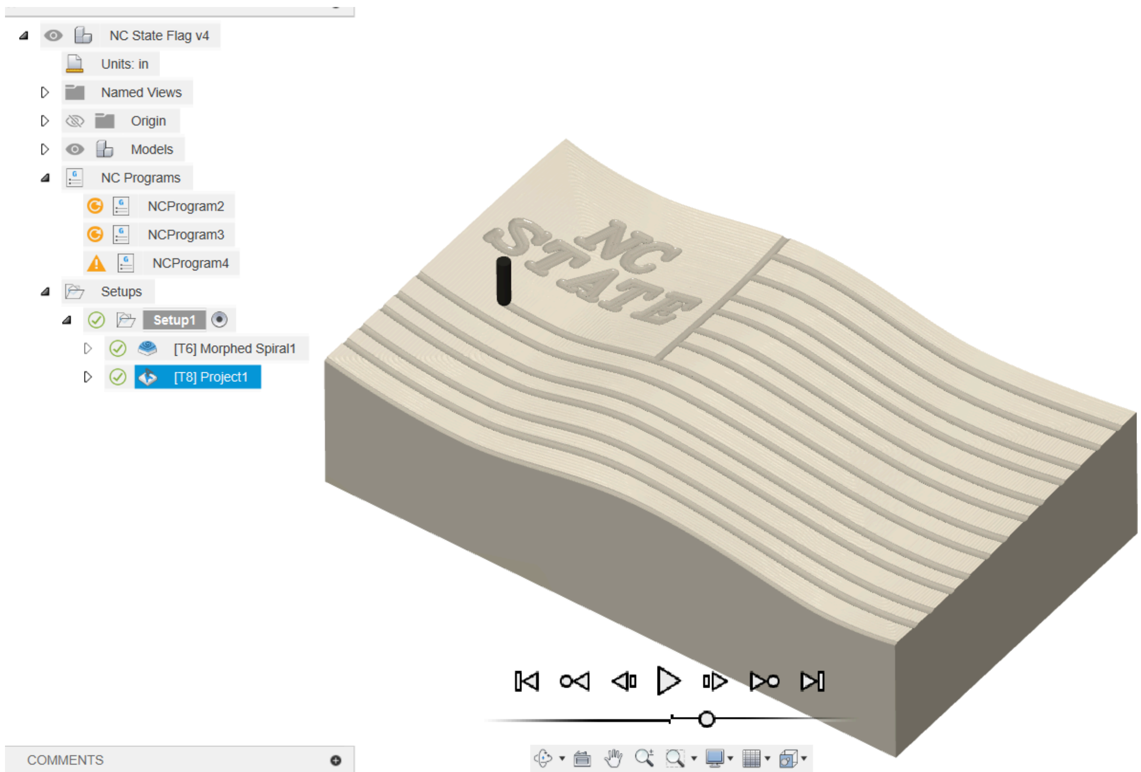


Figure 9. 3 Axis Miller - Ball Countour Mill and Engraving

Overall, this project provides many essential learning experiences for students, including what 3D tool paths are and how simultaneous 3d machining is implemented in manufacturing and machining, along with tool definitions, geometry, and tool selection. Necessary drawing skills such as surface loft and split/combined bodies are also demonstrated, which provide valuable insight into the power of parametric modeling. This part is also easy to set up (you can use a simple vice and stop block for work holding). We hope you enjoy this project as much as we did.

4 Axis - Prop Hunt

The author's love for different movies and movie props inspired this project. What started as just a creation of a custom lightsaber soon turned into the idea for an extensive array of prop recreation ideas. The main challenge when recreating anything oddly shaped or cumbersome, such as the ornate props seen in today's blockbusters, is working holding. One of the central core concepts of CNC machining is the idea of work holding or fixturing. There are many different options for work holding, from super glue and painter's tape to expensive and elaborate vacuum tables. The question always comes down to “How will you hold it?”. 4th-axis machining provides an exciting solution to this problem.

4th axis or rotary axis works by adding another degree of motion. In this case, it is rotational movement along the x, y, or z axis. When represented in gcode, rotary motion is measured in degrees like a circle. The axis is labeled by which of the three principal axes the center of the rotation is parallel to. For example, a rotary axis rotating around the x-axis would be marked in code as an “a” axis, similar “b” represents rotation around the y-axis, and “c” represents rotation around the z-axis. Due to this rotation, many aspects and features of a part can be machines in one setup simply by rotating a part around. Additionally, rotary axis tables usually accept various chucks, making work holding even easier. Another consideration is that rotary axis tool paths are not limited to only rotating and cutting. The rotation can be stopped at certain degrees to complete 2.5 or even 3-axis tool paths on one side of the part, then rotated again to the next toolpath. These characteristics of 4th-axis machining make it a perfect candidate for the recreation of ornate movie props such as light sabers, hammers, shields, or even your favorite cinema car body.

For this project, the authors decided to try making a custom lightsaber. With overall success, many lessons were learned in both the CAD and CAM experiences. Firstly, the CAD portion of this project provides an excellent opportunity to experiment with pattern features.

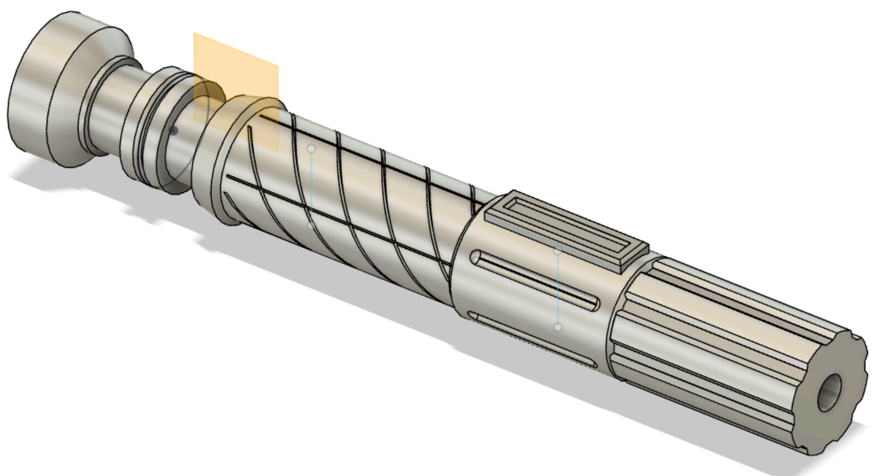


Figure 10. 4th Axis Milling - Light Saber

As seen above, almost all elements of the lightsaber are created using the pattern tool. The overall shape of the hilt was created using the Revolve tool. However, the features toward the bottom and the spiral inlays were designed once and then duplicated around the body's circular face. Similarly to the 3-axis machining project, this allows students to experiment with the more advanced and underutilized tools in solid modeling. Understanding the theory of moving features in linear and circular patterns can be crucial in successful 3d modeling. As for those who would like to attempt to make a lightsaber hilt for themselves, more resources and tutorials will be developed and shared.

Moving on to tool paths provided their unique challenges. Creating tool paths on rotary axis parts can be nuanced and ambiguous for even the more experienced 2.5 and 3-axis machinists. While many tool paths from the previous projects can be used in 4th-axis machining, their application and modification to fit a curved surface may cause unwanted distortion or modifications. To solve this problem, many types of reference geometry are used to wrap tool paths. References such as planes, lines, and squares were used to create a machining boundary and then wrapped around the cylindrical face of the object, as seen below.

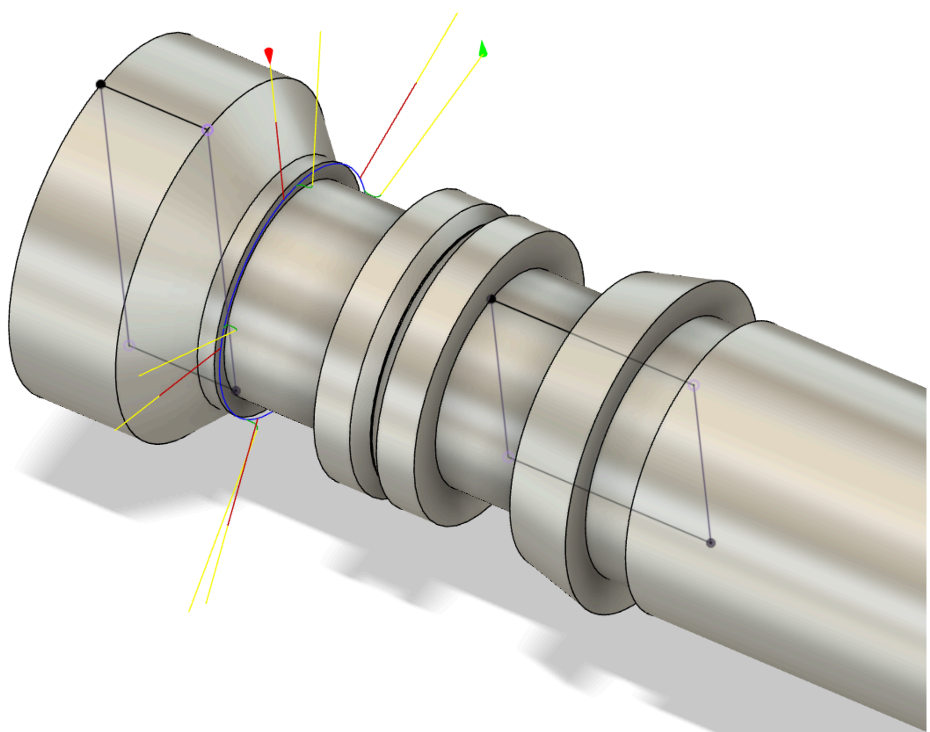


Figure 11. 4th Axis Milling - Light Saber Detail

Once the 2d and 3d tools paths were finished, we moved on to the rotary tool paths. Fusion 360 offers three types of rotary tool paths used in other circumstances. These circumstances primarily refer to how far along in the operation you are, labeling them as finishing or roughing tool paths. The difference is that finishing tool paths prioritize surface finishes, and roughing tool paths prioritize material removal. This concept is fundamental for students to understand to create efficient machining operations. The rotary processes are demonstrated

below.

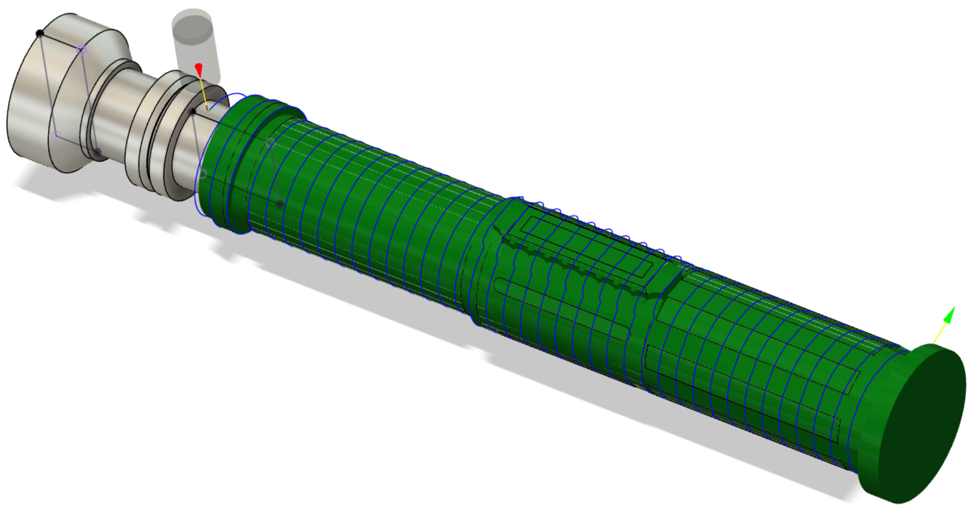


Figure 12. 4th Axis - Light Saber Final Detail

Overall, this is a rewarding and challenging project not limited to lightsabers. The ability to rotate and easily hold material provides a unique opportunity for students to create something memorable and special while also challenging their CAD abilities.

Additionally, these processes are quicker than traditional rapid prototyping and can utilize various materials. While 3D printing can be seen as a one-stop shop for producing student projects, it is also limited by time, material, and printer quality. Not to mention the drastic waste of time and material a print fails.

With the availability of new and easily accessible CNC subtractive technologies, the methods in classrooms we rapidly prototype have an opportunity to become more efficient and effective.

Conclusion

This experience of working together on these projects has been both rewarding and informative. We've enjoyed creating new things and challenging each other to do more with the equipment available. When faced with these challenges, the authors want to mention the Autodesk Forums. These have been “lifesaving” resources for machinists, T&E educators, and CAD users. The forums comprise many new and veteran users and Autodesk representatives, who are quick to help with any issue you may have. It is also a great place to receive the latest updates and resources on the software and what problems others may be experiencing. The forums are well organized and populated and should be used by all Autodesk users seeking troubleshooting solutions.

We hope this paper provides more ideas on how you can implement new CNC technologies in the classroom. If you have any questions, please contact the authors for any additional details. We hope these projects inspire you to keep working with innovative technologies. We hope they bring you as much joy as they did us.

Resources

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