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Digital Manufacturing Education: Implementation of an Integrated CAD/CAM Workflow to Reduce the Difficulty of Using Complex Digital Fabrication Tools

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Abstract

Traditional engineering curricula place a premium on education related to design and analysis. Often, this leads to little or no formal education related to manufacturing processes. To become more effective designers and analysts, students must gain exposure to advanced manufacturing tools and processes. This paper explores how CAD/CAM technology is being used at a large Midwestern university's Artisan and Fabrication Laboratory to facilitate experience with digital manufacturing techniques through hands-on learning opportunities. Specifically, it describes the development and implementation of an integrated CAD/CAM workflow that reduces the difficulty of learning complex digital fabrication tools so that students can more easily obtain manufacturing experience while building on their design knowledge. This workflow was built utilizing integrated CAD/CAM tools (CATIA v5 and Siemens NX), and features a custom user environment, tool and process catalogs, CNC machine simulation, and process validation. Further, this unique implementation deploys online learning modules, teaching assistant training, and consultations to further facilitate learning and familiarity with manufacturing processes. The result is a fully functional workflow that allows for engineering students to gain experience with digital manufacturing techniques using a project-based learning perspective.

Introduction

Many engineering programs in the U.S. now provide students with access to high-tech "maker spaces" to manufacture their designs for student projects[1]. Yet the engineering curricula, while adequately covering design and analysis, equips students with little or no formal education related to manufacturing processes[2], despite calls from industry to focus more on manufacturing in the engineering curriculum[3]. This lack of knowledge in manufacturing processes makes it challenging from a practical and educational standpoint to help students quickly manufacture their parts on high-tech manufacturing equipment, such as CNC equipment. However, there is an opportunity to leverage the students' knowledge of Computer Aided Design (CAD) software, which students typically learn when focusing on the design process, and carry-over that knowledge to Computer Aided Manufacturing (CAM) software, if it is done in a way to minimize the new knowledge that a student has to gain to quickly utilize advanced manufacturing processes.

This paper describes the success story of how a large Midwestern university developed and implemented a method, utilizing an integrated CAD/CAM toolset as its key component, which allows students with little to no manufacturing experience to manufacture parts for student projects utilizing high tech CNC equipment in very little time. This method focuses on reducing the difficulty of learning manufacturing processes and tools so that students can more easily obtain manufacturing experience while building on their design knowledge and producing the parts that they need for their projects.

The Artisan and Fabrication Laboratory

The Artisan and Fabrication Laboratory (AFL) at a large Midwestern university provides engineering students, faculty, and staff with hands-on access to a state-of-the-art manufacturing facility in a “maker-space” like environment. The mission of the AFL is multifaceted, but highly focused on student learning. Essentially, students are provided the opportunity to manufacture their own parts while being overseen by laboratory staff that provide expert training on not only machine operation, but also on safety best-practices. The laboratory is designed to mimic what students will see in industry, providing the opportunity for students to become more well-rounded designers/engineers.

As the AFL is a student-based operation, it employs a unique model that features a staff that is mostly comprised of students. A full-time staff supervisor with significant industry experience in manufacturing is used to supervise the lab safety, train the student staff, and ensure efficient operation of the lab. The student staff (graduate and undergraduate teaching assistants and volunteers) then provide the primary interaction with the students using the lab. This staff development and skill set diversification model ensures the lab is able to efficiently handle a wide range of student projects.

Figure 1: The AFL featuring CNC turning and machining centers.

The AFL utilizes CNC equipment whenever possible because (1) the vast majority of engineering students will never operate a manual mill or lathe to produce parts in industry, and (2) engineers are more likely to utilize CNC machines and processes in industry and need to be familiar with the capabilities. Using CNC equipment allows students to focus on the high-level aspects of manufacturing while avoiding the roadblocks presented by the fine nuances of machine operation.

To generate the programs necessary to run the CNC machines, the AFL leverages the students' CAD experience that is a part of engineering core curriculum by utilizing a CAM package that is integrated with the CAD package. This has the dual benefit of drastically reducing the learning curve for a manufacturing tool because the student is not leaning a new tool package, and it makes it very easy for the student to go back and forth between the design and manufacturing mode of their project parts and design as it is all integrated in one package.

Ultimately, Siemens NX and CATIA v5 (now referred to simply as NX and CATIA) were identified as the CAD/CAM package that offered the most upside for implementation in a student environment. This is largely due to the fact that NX and CATIA are seen as an integrated engineering tool, allowing for not only design and manufacture, but also kinematics, analysis and project management. Additionally, many students at the university already learn NX and CATIA as part of the required curriculum. To this end, it is possible to leverage learning and build upon an existing knowledge base.

NX and CATIA also offers a level of customization that is integral to its application in the AFL. Using the many back-end features contained in this application, the interface and system settings can be tailored to the specific needs of the AFL. This proves crucial in a controlled setting, as NX and CATIA has been customized to function within the confines of the developed workflow, including custom settings that have been rigorously tested and validated using the equipment in the AFL. Careful design of the workflow provides a firm foundation for implementation on the manufacturing floor.

Design of the Workflow

As the primary users of the lab are engineering students, and not technicians, the focus was on creating a process that highlights the key facets of manufacturing without creating confusion about the finer details. The AFL was able to complete this goal of developing better/more-informed designers/engineers through its focus on simplification.

There are several key elements of the AFL workflow, including the use of a custom NX and CATIA environment, process and tool catalogs, simulation, validation, and execution on a CNC machine. A graphic depiction of this workflow is provided in Figure 2. These elements allow the user to become acquainted with machine fixturing, CNC processing and the resulting code, without requiring an expert level of knowledge on any of these topics. The following focuses on how these are used as constraints in the design of the workflow.

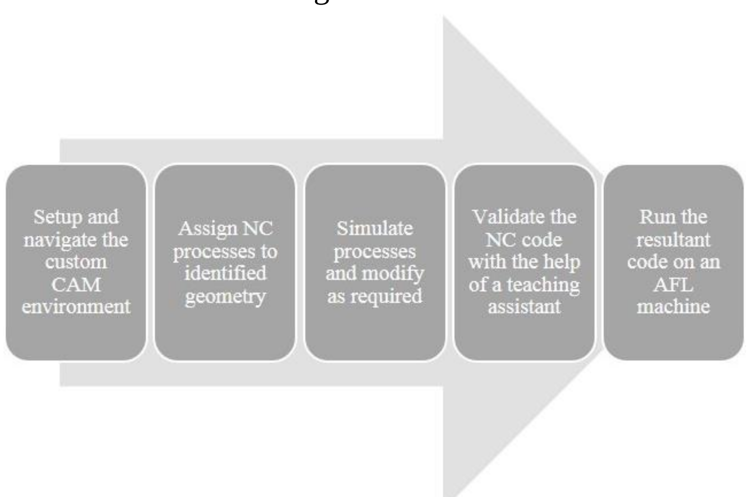

Figure 2: A graphic depiction of the AFL CAD/CAM Workflow.

A Custom NX and CATIA Environment

The first step is seemingly a trivial element of the workflow. Yet, the creation of a custom user environment was likely the single most critical aspect of the entire workflow design. Prior to the creation of such an environment, it was essentially impossible to control an individual's NX and CATIA settings to the degree necessary to maintain consistent interfaces that produced reliable machine code. By creating an environment configured specifically for use with the CAM workflow, it was possible to ensure that a student launched NX and CATIA into an environment that was already fully configured for the tasks they were about to complete. Gone was the need for students to manually point NX and CATIA to required resources or supplementary files. This proved to be the alleviation of one of the largest limitations of the CAD/CAM package.

In addition to custom NX and CATIA settings, the environment also contains a template that students use as a starting point for the CAM work. This template includes full 3D models of the common fixtures used on the AFL machines, which can be seen in Figure 3. The fixture model serves several purposes. First, the students are able to interact with a virtual version of the fixture they will encounter when setting up the actual machines. They will be immediately able to identify if the fixturing approach will be sufficient, or if an alternative approach is required. Further, the fixture model can later be used for simulation and validation of the manufacturing program. If a student were to accidentally program a collision between the tool and fixture, it would be safely identified on the computer, and not at the machine during actual operation. This allows for a possible unsafe scenario to be averted well before any real risks are taken.

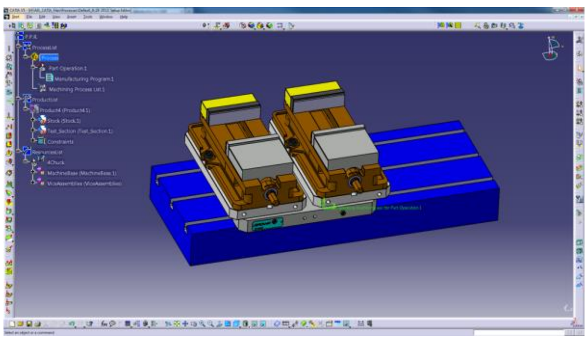

Figure 3: A 3D model is used to replicate the standard machine fixture found in the AFL.

Tool & Process Catalogs

The development of tool and process catalogs was another crucial component of the AFL CAD/CAM Workflow design. Using these catalogs, it is possible to ensure that students adhere to a manufacturing approach that is within the capabilities of the lab. Several tool catalogs were created to reflect the standard tooling kept in the lab's inventory. Use of these catalogs constrained students to the tooling available to them, and served as a more effective way of conveying the tooling capabilities of the lab. Rather than searching for a tool in the lab, a student is able to simply view the appropriate tool catalog in NX and CATIA, and determine if the tool is available. This is not to say that specialty tools cannot be used within the workflow. Rather, it is solely a means to convey the standard tooling capabilities.

The real power of the workflow lies in the creation of a process catalog. A process catalog is the key element that aids in the transition from design thinking to manufacturing thinking. While a designer is likely able to identify a pocket on a part, most do not know how a pocket is processed on a CNC machine. This provides the possibility to leverage learning by associating the CNC operations used to cut a pocket with the terminology a student already understands through their design training.

This approach led to the creation of a process catalog that is comprised of a series of processes used to machine geometry commonly used by designers. Each process was developed, tested, and fine-tuned to provide accurate milling with minimal intervention by the student. In use, the student simply identifies a feature on the part to which they would like to apply a process from the catalog. Once the process is applied, NX and CATIA automatically generates the operations and tool paths required to machine the geometry, using parameters contained within the process. These parameters include values such as depth of cut, climb vs. conventional cutting, tool overlap, and other figures seen as extraneous to the designer.

In essence, the student is able to apply a process to a specific geometric feature without having to be concerned with exactly how that tool path will be generated. They do not need to learn some of the art of machining that is only gained through years working in the field. Further, the AFL staff does not need to be concerned with validating the parameters used in student work, as the prescribed parameters have already been thoroughly tested and validated. Above all else, this provides a level of safety to the students, staff and machinery.

The two types of catalogs used in the AFL CAD/CAM Workflow are inextricably linked. To even further streamline the CAM work that is completed by students, many of the processes were designed to query the tool catalogs and automatically select the optimal tool for the cut. Again, this is an approach that drastically simplifies the validation step of the workflow, as the need to analyze the manufacturing program for optimal tool preservation and machine operation time is drastically reduced.

Simulation

Once a part has been fully CAM processed, the next step is to simulate the resulting tool paths. NX and CATIA offers several simulation options that complement the approach used by the AFL workflow. Each type of simulation offers a different benefit to the user. When used together, the simulations provide a full virtual look into the actual movements of the machine with respect to the stock and fixture.

Two types of simulation are suggested for use in NX and CATIA. First, a tool path simulation may be used to see a graphical representation of the path taken by the tip of the cutting tool. Using this simulation, a student can easily observe the movement of the tool, and identify any inefficiency in the machine operation. This can then be communicated to a member of the lab staff, and an alternative approach can be determined. However, the primary use of this simulation method is for learning purposes. By viewing the simulation, a student can associate the generated tool path with the applied process to gain an understanding of how specific geometrical features are machined.

The second type of NX and CATIA simulation that is viewed by students is the video simulation. The video simulation contains a full rendering of the machine fixture and the material that is being machined. Essentially, it is a simulation of what the student will see when the part is run on an actual CNC machine. This type of simulation can be used to easily identify gouges on the part, collisions between the tool and fixture, and other possibly problematic scenarios.

Identifying these issues during the simulation stage helps secure the safety of the lab, and reduces the amount of lost time and frustration associated with faulty machine code. Further, it maintains the accessibility of the AFL, as machine time is not spent running code that produces faulty parts. This keeps the machines open to students who have successfully processed a part, and have shown the resulting code to produce a part that meets their design intent.

Finally, an additional simulation option is available outside of the CAD/CAM package. Once manufacturing code has been generated, CNC simulators are used to test the code. These simulators are exact replicas of the controls used on the AFL machines, and can be used to test the actual outputted code. This type of simulation does not provide an accurate visual representation of the resulting tool paths, but it does test the quality of the outputted manufacturing code. This verifies that the entire manufacturing program will run on the CNC machine without any alarms, errors, or other issues that may otherwise result in delays at the machine.

Validation

The validation process used at the AFL ensures that CAM projects processed by students adhere to the manufacturing approach and safety policies put in place in the lab. Essentially, it is a check by a member of the AFL staff that the student-generated process is accurate, complete, and, above all else, safe. All validations are conducted by a senior member of the AFL staff (supervisor, graduate teaching assistant, or adequately trained undergraduate teaching assistant). The validation process includes a review of the applied processes, the tools used, and the resulting simulations. A member of the AFL staff views all three simulations to verify the student's part has been adequately processed. While the student will likely focus on whether the resulting part meets their specification, the staff reviewer will be specifically concerned with the safety of the process. Essentially, the reviewer will confirm that the outputted code will operate safely, and not result in any collisions or other unsafe scenarios.

Execution

Following validation of their machine code, a student user is allowed to run the code on an AFL CNC machine. With the guidance of an AFL teaching assistant, the fixture developed during the CAM process is constructed and proper tooling is loaded into the machine. One final validation of the machine simulation is conducted on the CNC control to ensure both proper code output and successful setup of all required tools. Pending final validation of the NC code, the student is instructed on proper machine supervision, safety protocols, and what to expect as the code is run. Depending on the student's experience operating CNC machinery, they either observe the TA's operation of the machine, or are provided the opportunity to operate the machine under the watchful eye of an experienced teaching assistant. Ultimately, it is a goal of the AFL to have all student's gain the experience of CNC machine operation.

The AFL CAD/CAM Workflow is designed to provide an experience authentic to industrial application. Students are provided the opportunity to enhance their analytical/design skills through hands on experience with manufacturing. Several key factors played an important role in the students' transition from classroom to real-world experience.

Key Factors for Success

The full implementation of the AFL CAD/CAM Workflow includes more than just the information contained in the CAD/CAM package. From the inception of this project, it was understood that a major factor in the successful implementation was the training system built around workflow. This includes not only training for the students, but also training for the teaching assistants that provide direct support to the students. Three key components encompass the implementation: the development of online learning modules, teaching assistant training, and the use of Pre-CAM Consultations.

Learning Modules

Proper use of the workflow is communicated to students through two main avenues: interaction with the AFL staff and through a set of online learning modules. The online modules feature video screen capture of a part being processed in NX and CATIA. This serves to educate the student on the "button clicks" required to complete tasks within the CAD/CAM package; providing a useful introduction to students in a self-paced environment. Using this approach, students can self-evaluate their use of the workflow and ask more targeted questions when meeting with AFL staff. The modules range in length from five minutes to forty minutes, and are delivered via the AFL website. This allows students to learn the material as their schedule permits, and does not constrain them to the operation hours of the lab.

Teaching Assistant Training

The first users of the workflow were AFL teaching assistants for a variety of reasons. First, they served as the initial evaluators of the workflow. As many had previously not conducted any CAM work, they were capable of identifying difficulties in the implementation and possible areas where the workflow could be refined. Concurrently, they were receiving valuable training on the workflow so they could later aid students in learning the material. This model proved successful, as many of the teaching assistants who received the initial training are now some of the most capable users of the package.

Formal training consisted of three two-hour small group sessions that focused on different aspects of the workflow. Following each session, each teaching assistant completed a small project based upon the material taught in the preceding session. This served to reinforce the material taught during the session, and provided a scenario similar to what a teaching assistant would encounter when helping students.

Prior to attending the training sessions, teaching assistants viewed the learning modules to gain a basic understanding of the workflow. Thus, the focus of the training sessions was not on the mechanics of the interface in NX and CATIA, but rather the underlying methodology used in the workflow. Ultimately, the purpose of the training sessions was not only to raise the level at which the teaching assistants use the workflow, but to also ensure they could accurately conduct Pre-CAM Consultations.

Pre-CAM Consultations

Prior to beginning formal work on a CAM project, students must consult with a member of the AFL staff. During the Pre-CAM Consultation, the staff member views the model(s) provided by the student and discusses the manufacturing approach that will be used to machine the part. This includes a discussion on the proper stock size, the proper fixturing approach, the order in which processes should be applied, among other topics. The purpose behind this consultation is to provide the student with a starting point to begin the CAM work. Also, it ensures they also follow the AFL processes and policies early in the project cycle.

Formal feedback is provided to students during the Pre-CAM Consultation via an interactive PDF form. This form includes a cover sheet that outlines the basics of the fixturing approach, stock size and setup parameters, and subsequent pages that describe each process in the order it should be applied. Students are then asked to take this form and use it as a roadmap during the processing of their part.

Assessment

Being a student centered operation, it is important that all facets of the AFL experience be evaluated from the perspective of a student. In this application, two distinct sets of students exist: those *using* the CAM workflow (students), and those *instructing* on the use of the CAM workflow (teaching assistants). The creation of this workflow has proven mutually beneficial for both students and teaching assistants for professional and academic reasons.

At the end of the 2013/14 academic year, each of the nearly 1200 registered AFL users were asked to complete a brief survey regarding their experiences in the AFL. With a response rate of 15% to this survey, 71% of respondents answered "agree" or "strongly agree" when asked if the AFL provided quality CAD/CAM support for their project. While computer-aided manufacturing can have a difficult learning curve associated with it, it seems as though the AFL has succeeded in implementation and support of the workflow. This is further explained through one student's feedback: "I went from no knowledge of CAM at all, to feeling comfortable following the online instructions to get me going on a project. I'm sure I'd still need to ask for help sometimes, but at least I could do a majority on my own." This shows that the AFL CAD/CAM Workflow has truly been designed to enable students to augment their existing coursework with experiential learning in manufacturing.

A brief survey of AFL graduate teaching assistants reveals that knowledge of the AFL CAD/CAM Workflow has a profound impact on their professional development. For instance, the AFL graduate TAs unanimously agree that their knowledge of the CAM workflow has personally benefitted them in their own degree program. Further, when asked to describe how their experience benefits them personally, academically, and professionally, one teaching assistant responds, “Instructing helps solidify concepts and processes in my own knowledge. In addition, questions posed by others help me look at things in ways that I didn’t originally.” It becomes evident that experience with the teaching the CAM workflow does not only benefit technical engineering skills, but also professional skills such as training and mentoring.

Summary

The preceding describes the development and implementation of a CAM workflow at large Midwestern university’s fabrication laboratory. This workflow is integral to the laboratory’s mission of providing engineering students with the manufacturing knowledge required to help them become more informed designers/engineers. This approach was developed and implemented with NX and CATIA. This software package was chosen due to its capability, as well as the opportunity to leverage learning that is already happening at the university. The workflow was designed using several key aspects: the creation of a custom NX and CATIA environment, the use of tool and process catalogs, extensive simulation, staff validation, and guided machine operation. Learning modules, teaching assistant training, and consultations were key to the full implementation of the workflow. This method has proven successful in providing experiential learning opportunities to engineering students at the university as evidenced by favorable student impressions.

Future Work

After several years of operation with this method, the “weak links” of this method are the TA training and the Pre-CAM Consultations. In general, the TAs tend to get better at one particular software package (typically whichever one they prefer more). A more rigorous and formal TA training would help with the process. The Pre-CAM Consultations tend not to happen as often as they should, meaning students’ do not get the support they need at the start of the project. This can be solved by the AFL staff being more diligent to the overall process.

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