Intermediate Manufacturing Course for Undergraduate Education

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I. Introduction

Successful manufacturing companies in the modern economy manage to automate their production process while maximizing production flexibility. Automation provides high quality and low unit cost, while flexibility enables the rapid product evolution necessary to adapt to changes in technology and customer demand. The integration of computer-aided design (CAD) and computer-aided manufacturing (CAM) provides this combination of automation and flexibility. CAD/CAM and computer numerically controlled (CNC) machine tools play important roles in modern manufacturing engineering.

Indoctrinating students in the modern production process is crucial. ME 435, the Intermediate Manufacturing course offered by the mechanical engineering department at Christian Brothers University (CBU), addresses this need. First offered in the fall of 1996, the class revolves around the use of computers to integrate the design, analysis, and manufacturing phases of production. Students in ME 435 use the facilities of the Integrated Laboratory for Manufacturing Education (ILME) developed at CBU under a National Science Foundation grant.

Students are first introduced to parametric design methodology, including part and assembly creation and parametrization. The manufacturing module is then introduced, in which students create a manufacturing model, build operation sequences, and manufacture a complex part. Students also learn how to perform structural and thermal analyses using integrated computer tools. Design projects are assigned to student groups in different stages of the class. A final project allows students to apply all techniques including design, analysis, manufacturing, and machining codes. A course outline is provided in Table I.

Pro/ENGINEER is the parametric design tool in this class. Pro/MECHANICA is used for stress and thermal analysis. Pro/MANUFACTURING is used to generate a manufacturing model and to simulate the cutting process trajectory, as well as to generate the CNC code. The hardware portion of the syllabus is structured around a Fadal VMC-15 Vertical Machining Center. Both hardware and software are assets of the ILME.

This class integrates CAD/CAM, design for producibility, numerical-controlled machining, and rapid prototyping into the engineering curriculum, and exposes students to modern concurrent engineering techniques.

The plan of this paper is as follows. Section II discusses the ILME. Section III details the organization and syllabus of ME 435. Section IV presents a discussion of some startup pains as well as a discussion of planned enhancements to the course. Section V gives conclusions.

II. Integrated Laboratory for Manufacturing Education

ME 435 is organized to exploit the facilities of the Integrated Laboratory for Manufacturing Education (ILME).

Christian Brothers University applied for and was awarded a National Science Foundation grant to develop the ILME [1]. The objective of the ILME project is to develop an integrated laboratory to facilitate undergraduate instruction in the complete design-through-manufacturing process. As part of the NSF grant activity, two new undergraduate courses that use the assets of the ILME are to be developed. ME 435 is the first of these courses.

The ILME comprises three subsystems. The design system comprises workstations and software that support CAD at the advanced undergraduate level. The manufacturing system consists of a Fadal VMC-15 Vertical Machining Center (VMC). The integration system includes a server with network connections that link the CAD system with the personal computer tied to the VMC-15. Hardware assets are summarized in Figure 1.

A. Design System

The design system of the ILME comprises seven Silicon Graphics (SGI) Indy workstations together with parametric design software.

We selected Pro/ENGINEER as the parametric design software for use in this course because of its high current use and demand among leading-edge manufacturing companies. Pro/ENGINEER was the first of the current generation of parametric design programs and holds the largest market share among such packages. At the time that ME 435 was taught, we used the latest release, Pro/ENGINEER v17.0.

Under an academic licensing agreement, all modules of Pro/ENGINEER and the associated modules Pro/MECHANICA and Pro/MANUFACTURING are installed. Pro/MECHANICA is used for structural and thermal analysis and Pro/MANUFACTURING is used to generate tool paths and CNC code for transfer to the manufacturing system.

B. Manufacturing System

The manufacturing system is organized around a Fadal VMC-15 Vertical Machining Center, which is a CNC machine capable of three-axis operation, with the fourth axis pre-wired for future need. Figure 2 is a picture of the VMC-15 in the ILME machine shop.

C. Integration System

The integration system includes a Silicon Graphics Challenge L server. The server is available for numerically intensive applications, such as the structural analysis of complex parts, though simpler parts are easily handled by individual workstations. In addition, the server handles network access to the design software.

The local area network (LAN) at CBU is configured to support the network file system (NFS) standard. One of the 4 GB drives on the Challenge server is dedicated to holding the temporary files created by the structural and thermal analysis modules of Pro/MECHANICA. This disk

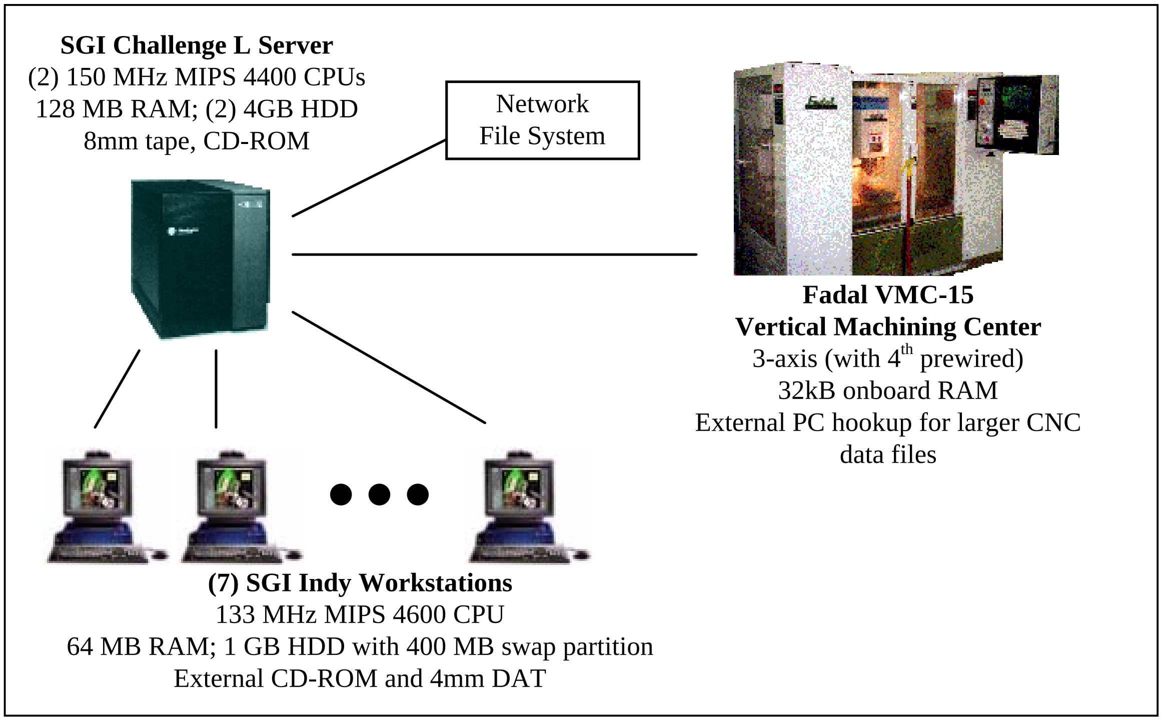

FIG. 1. ILME Hardware Assets. Solid lines are TCP/IP network connections.

requires little upkeep, since Pro/ENGINEER removes its temporary files after an analysis is completed. However, this “scratch” disk is an essential part of the overall system configuration, since the temporary file storage can easily exceed several hundred megabytes even for pedagogical applications.

Students can create CNC codes on their workstation and FTP them directly to the PC attached to the VMC-15 over the 10 Mbps LAN.

III. Class Organization

The Intermediate Manufacturing class is organized into three major phases: familiarization, manufacturing, and advanced analysis, as summarized in Table I. Additional elements of the course round out the students’ exposure to modern manufacturing.

A. Pro/Engineer Familiarization

The first third of the course is dedicated to familiarization with Pro/ENGINEER and its principal modules. Students typically enter the course with minimal exposure to the UNIX environment, but with some background in design and manufacturing from their earlier course work.

After a brief tutorial on the UNIX operating system and the X Windows environment, students begin learning Pro/ENGINEER. Starting with basic navigation of the Pro/ENGINEER menu structure, they learn to create simple features like extrusions, slots, rounds, etc. Subsequently they are introduced to blends, patterns, and other more complex features. They are exposed to the creation of assemblies of parts, though most of the class focuses on parts alone. Early in the syllabus they are instructed in the principles of parametric design, including the creation of relations among dimensions, parent/child relations, and family tables.

Table I. Syllabus for ME 435: Intermediate Manufacturing

1. Basic tools for computer-aided design
   a) Basic part creation, datum planes
   b) Slots, rounds, chamfers, etc.
   c) Blends, patterns, etc.
   d) Assemblies
   e) Relations, Parent/Child dependencies, Family Tables
   f) Drawings and other graphical output
2. Interface to numerically-controlled machining
   a) Part specification and design
   b) Manufacturing model
   c) CNC code practice
   d) CNC code development
   e) Machine shop
3. Structural analysis
   a) Part development
   b) Stress and deformation analyses
   c) Optimization and sensitivity studies
4. Thermal Analysis
   a) Part development
   b) Temperature and heat flux analyses
   c) Optimization and sensitivity studies
5. Field trip
6. In-class reports
7. Final design project

Figure 3 shows a typical part. This is a gear that is eventually realized in hardware later in the course. The student begins by extruding a disk. They then sketch the section cut that defines a single tooth. The sketch involves drawing and dimensioning the multiple curves and line segments that define a tooth profile. The tooth feature is then patterned to create the gear.

It should be emphasized that we view Pro/ENGINEER as simply a useful tool in this course. ME 435 is not a “Pro/ENGINEER course” but rather a course providing practice in aspects of the modern design, development, and production cycle. Other candidates for parametric design software, such as EDS/Unigraphics, are considered in our annual review of course content.

<u>B. Manufacturing Module</u>

The second phase of the course is devoted to the process of taking a part from design through to manufacture. In this phase, students create a manufacturing model for the gear-shaped part of Figure 3, including the workpiece as well as the part itself. The students are taught how to set up the machining operation and how to create different NC sequences. After each NC sequence is completed, tool path and cutting-motion simulations can be performed on the workstations. After creating all necessary sequences, the cutter-location data file and NC machine-control-code data file can be generated for manufacturing. An example drawing of the manufacturing model for the gear part is shown in Figure 4. Tool paths are deleted for clarity.

FIG. 2. Fadal VMC-15 Vertical Machining Center installed in the Integrated Laboratory for Manufacturing Education.

Students learn to write CNC code manually as well as to generate code with the NC/POST facility of Pro/MANUFACTURING. They also learn how to upload the CNC code to the VMC-15 for manufacturing. Every student has to set up their own tools with fixture offset and tool length offsets. This sequence gives students hands-on experience from design to manufacturing.

A photograph showing the cutting of a gear on the VMC-15 is provided in Figure 5. The student is

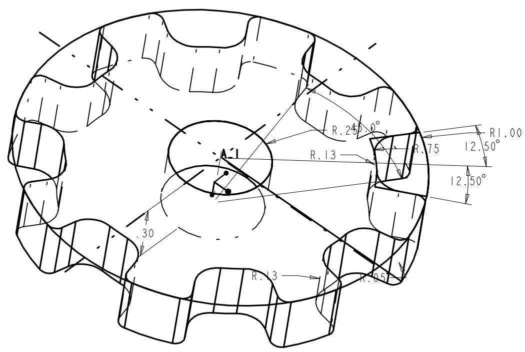

FIG. 3. Part drawing for a gear-type part.

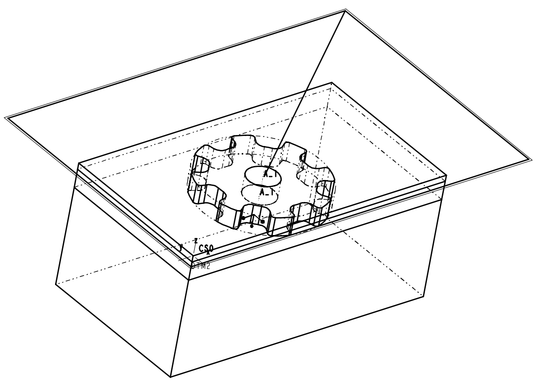

FIG. 4. Manufacturing model for the cutting of a gear-type part.

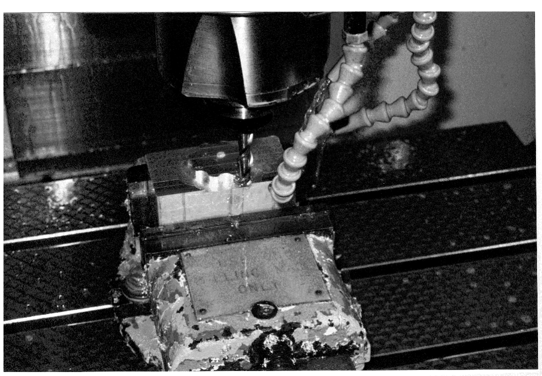

FIG. 5. Manufacture of gear-type part on VMC-15.

required to perform all phases of production, from code creation to workpiece installation to monitoring the running of their CNC program on the machining center.

C. Structural / Thermal Analysis

The last phase of the course exposes students to advanced techniques of integrated analysis. They learn to take parts that they have created within Pro/ENGINEER and conduct structural and thermal analyses on them. Pro/ENGINEER is equipped with a module called Pro/MECHANICA that is capable of numerous different kinds of structural, thermal, and motion analyses. In the first offering of ME 435, we did not have time to address motion analyses, though we plan to incorporate this subject into the syllabus in the future.

A key part of this phase consists of several in-class optimization exercises. The class is gathered as a team and given an open-ended structural design problem and asked to map out and execute an optimization plan. In the space of a single class period two iterations on a design concept can be accomplished. A typical problem is to find an economical way to support a 500 lbm weight at a specified distance from a vertical wall. The class is asked to brainstorm several reasonable design approaches, to design the parts within Pro/ENGINEER, and to conduct multiple parallel structural analyses using the workstation resources at their disposal. Though the rapid turnaround requirement sacrifices a truly optimal solution, the exercises provide valuable lessons in the need for organization, integration, and concurrency in the modern manufacturing process.

Figure 6 shows the fringe pattern resulting from a typical thermal analysis. The part shown was the first pass at a heat sink for an integrated circuit. The student chooses which dimensions to parametrize, designs the part in Pro/ENGINEER, and invokes Pro/MECHANICA. Heat loads and boundary conditions are specified, and the thermal analysis is run. The student modifies the design parameters until some design goal, such as a limiting temperature, is met.

The final project of the course involves the optimization of a tension joint. Students are asked to minimize the weight of an assembly that carries a given tensile load. This exercise provides practice in both the design and structural analysis phases of the course.

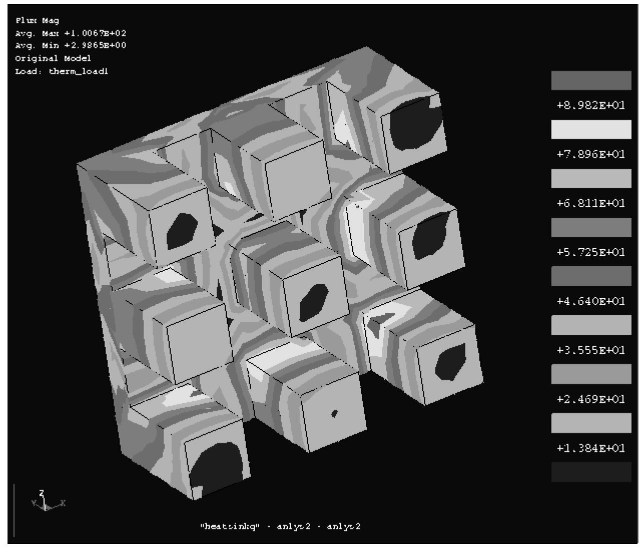

FIG 6. Typical output of Pro/MECHANICA. This is part of a thermal analysis of a heat-sink part, showing the heat flux through the surface as a function of location.

<u>D. Additional Elements of the Syllabus</u>

To provide exposure to actual production environments, we conducted a field trip to the Smith & Nephew Orthopaedics division, located in Memphis, TN. Smith & Nephew is a leader in medical products manufacturing, and their engineering division makes extensive use of the integrated CADM techniques that this course addresses. We were shown the design and manufacture of an artificial knee joint, which involves sophisticated geometric modeling combined with parametric design. Such trips are an invaluable addition to the learning experience.

Students in ME 435 are also asked to conduct a literature search on a modern manufacturing technology of their choice, and report their findings to the class with a PowerPoint presentation. The presentations from the first offering of the course are available for viewing at the course Web site [2].

IV. Observations and Future Plans

Most of the startup pains associated with this class revolved around software configuration. In particular, Pro/ENGINEER uses a sophisticated “floating license” arrangement to assure that no unauthorized use is made of he program. Too often, however, program crashes would tie up licenses without releasing them within the class period. The utility provided to “flush” the licenses operated erratically and required continual reconfiguration, especially when a new release of Pro/ENGINEER was installed.

Buried in the documentation for Pro/MECHANICA is the important observation that appropriate configuration of scratch space – distinct from swap space – is vital to the operation of the program. After numerous perplexing crashes, we finally determined that setting aside a 2GB scratch partition went a long way towards improving the stability of the program. This was true even for configurations that nominally required less than 10 MB of temporary storage.

Until recently, there were few textbooks on Pro/ENGINEER that were appropriate for this class. We need results-oriented content appropriate for a lecture course whose primary focus is the production process, not Pro/ENGINEER per se. This situation seems to have been remedied with the publication of a two-volume set by D. Bradshaw [3]. The lack of a textbook made the development of comprehensive introductory content more difficult.

Several lecture styles were explored. We were faced with the question of whether to synchronize all the students with vocal instruction, or to rely instead on printed (or Web-based) instructions and self-paced in-class exercises. The drawback to synchronous vocal instruction is that some students' difficulties stall progress for the entire class. But the advantage is the immediate feedback given to the instructor – and to the rest of the class – of difficulties, misconceptions, and common missteps. The drawbacks to asynchronous, self-paced instruction include uneven class coverage of the course material, as well as the additional preparation time required to formulate and to publish detailed, step-by-step instructions. The advantage, however, is that the student gets to absorb material at his own optimum pace, and also gathers a compendium of useful instructions for accomplishing common tasks. On balance, we judge that the optimum lecture style uses written instruction, with mandatory completion of each assignment before the next class period.

In the next semester, we plan to provide a more comprehensive tutorial in advanced analysis, including the motion analysis capabilities of Pro/MECHANICA. Generally, we were unable to provide as much coverage of assemblies, as opposed to individual parts, as might be desired. We plan to expand coverage of assemblies in the next year, including some exposure to robotic assembly. We plan to consolidate and edit some of the introductory material in order to provide class time for these enhancements.

We are exploring means of including exposure to stereolithography techniques in this course. Pro/ENGINEER is capable of directly exporting SLA files from the Pro/MANUFACTURING module. Stereolithography is an integral part of rapid prototyping in many industrial applications, and exposure to this technique is certain to be rewarding for our students. Because of its low per-unit cost, this technique can potentially be implemented without extraordinary expenditure.

In order to have more thorough integration of CNC technology into the curriculum, CNC coding and operations on the Fadal VMC-15 are now introduced in the sophomore-level ME 201 (Manufacturing Processes). This enhancement will eventually allow more coverage in ME 435 of advanced manufacturing issues, such as design for manufacturing and design for assemblies.

As part of the course development that is mated with the ILME, the CBU mechanical engineering department plans to offer another elective, ME 445, entitled Concurrent Engineering. ME 445 will be documented in a separate publication.

V. Conclusions

We judge the course to be highly successful in meeting the educational goals of the ILME. Students enter the class with no experience with integrated manufacturing, and leave with considerable exposure not only to Pro/ENGINEER but also to the principles of parametric design, computer numerical control, and advanced analytical techniques. All this is accomplished in the context of an integrated design, development, and manufacturing environment.

VI. Acknowledgments
The authors gratefully acknowledge the support of the National Science Foundation [1]. We are especially grateful to Smith & Nephew Orthopaedics, which hosted a field trip for the students of ME 435.

References
[1] National Science Foundation Grant number DUE-9551466.
[2] The Web site for ME 435 is http://www.cbu.edu/~bbbeard/me435.htm.
[3] D. Bradshaw, *S.T.E.P.S. to Pro/ENGINEER*, (Green Leaf Graphics, Rainbow City) 1996.

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