Modularization of the Engineering Graphics Computer Laboratory Sequence Based on a Concurrent Engineering Design Paradigm

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Abstract

Our group is developing a modularized approach to the freshman engineering graphics computer laboratory sequence based on a concurrent engineering design paradigm. This educational paradigm starts with the development of a feature-based, parametric 3-D solid model. This 3-D model then constitutes a digital database that can be applied to design analyses, such as mass properties and finite element analysis. An assembly of parts can be mated together, and a kinematics animation of the assembly can be created to demonstrate functionality. The same digital geometry can be further applied to rapid prototyping in order to create a physical realization of the design idea. As needed, 2-D paper documentation of the design can be generated directly from this same model database. This paper outlines this modern engineering graphics computer laboratory sequence and portrays examples of student exercises used in the course. Results of a learning outcomes assessment, conducted in Fall 2002, presents results that demonstrate the students' understanding and acceptance of this educational paradigm.

Introduction

The field of Engineering Graphics has been greatly impacted by the use of computers over the last twenty-five years. Traditionally, engineering designs were conveyed in a 2-D drawing that used orthographic projection and drafting standards. Engineers in the past had to learn these common graphical practices as part of their formal education. With modern computer tools, the conveying of design ideas now begins with the development of a 3-D solid computer model. The model not only creates a visual image that allows the designer to see the geometry, but it also creates a 3-D digital data base that can be applied to all phases of the design process. The freshman "Engineering Design and Graphics" course at the University of Texas at Austin reflects this concurrent engineering design paradigm based on 3-D solid modeling principles.[1-3] This past decade has also unveiled the important applications of the 3-D model to engineering analysis, manufacturing, and downstream documentation. Low-cost analysis, simulation, and rapid prototyping software and hardware systems are now becoming available for educational purposes, and the power of this latest design paradigm is now being realized by the engineering design and graphics education community.[4-8]

Project PROCEED

An engineering student project is an exercise that usually requires integrating several tasks to achieve a defined goal. It can be an individual project or a team project, or even some form of both. The Mechanical Engineering Department at the University of Texas at Austin has embarked on systemic educational reform throughout the ME curriculum. Called PROCEED, for Project-Centered Education, this curriculum reform is an attempt to bring real-world projects into the classroom that underscore the need to learn fundamental principles while adding excitement and relevance to the experience. One important aspect of PROCEED is garnering support from industrial partners who supply project ideas and personnel for the student projects. Two companies, Ford Motor Company and Applied Materials, have already joined the PROCEED effort at the University of Texas, and have supplied projects for the freshmen students.[9] In the "Engineering Design and Graphics" course, the PROCEED project consists of a team of four students who reverse engineer a mechanical assembly. They study the individual parts, make sketches and computer models, perform various analyses, and make rapid prototypes of their assembly. At the conclusion of this integrated graphics and design project, the team assembles a final written report.

Modularization of the Engineering Graphics Computer Laboratory

To facilitate this project-centered approach, the Engineering Graphics curriculum has been organized into a set of learning modules with specific educational outcomes. Table 1 lists the current modularization scheme and learning outcomes. It consists of ten units that serve as individual student projects, plus an integrated PROCEED project that is conducted at the conclusion of the course. With this modularization scheme, the ten individual units train students to develop computer skills and abilities that can be later used in the larger team project, as well in later upper-division courses where CAD skills are needed.

These modern course outcomes, as outlined in Table 1, were fully implemented in the Fall 2002 semester using some preliminary computer graphics laboratory notes written by our group.[10] The initial modules stress individual learning activities, which build the student's confidence in going from 2-D to 3-D solid geometric modeling. Once their confidence in computer graphics modeling is established, the students explore the many design applications for the 3-D model database. In so doing, they experience the concurrent engineering paradigm that underscores the course. Several computer graphics exercises are available for each laboratory module, thus allowing the students some choice in the objects they model and analyze. All objects selected for the exercises are real parts taken from commercial catalogs, or actual parts taken from the machine shop.

Module 1: Computer Sketching I

The first module is an introduction to the modeling software, its menu structure, and on-screen toolbars. The basic methods of creating a computer sketch are reviewed. These include setting grids and units, picking a sketch plane in the 3-D computer space, and selecting view orientation controls. All the basic 2-D sketching primitives are reviewed in lesson one. These 2-D

Table 1. Engineering Design and Graphics Curriculum Modularization Scheme	
Module	**Activities and Learning Outcomes**
1	**Computer Sketching I:** Set up the sketch plane units and grid parameters; demonstrate all 2-D sketching primitives; demonstrate all line editing features; make simple extrusions and revolutions to get 3-D geometry. Print hardcopies of 2-D sketches and simple parts for submission.
2	**Computer Sketching II:** Demonstrate the creation and editing of dimensions; set geometric constraints; make simple extrusions and revolutions to get 3-D geometry. Print hardcopies of 2-D sketches and simple parts for submission.
3	**Solid Modeling of Parts I:** Create 3-D extrusions and revolutions of individual parts; use some basic sweep operations; edit the geometry in 3-D; render the parts. Print color hardcopies for submission.
4	**Solid Modeling of Parts II:** Create 3-D parts; add feature-based, parametric design features; use advanced sweep operations; edit the geometry in 3-D; render the parts. Print color hardcopies for submission.
5	**Assembly Modeling and Mating:** Create individual 3-D parts; assemble parts as a mechanical assembly; mate features as appropriate; check for clearance and interference of parts; create color rendering of assembly. Print color hardcopy of the rendered assembly for submission.
6	**Analysis and Design Modification I:** Create individual 3-D parts; perform mass properties analysis; generate a mass properties report; modify the design and compare mass properties before and after modification. Create a design table spreadsheet; make multiple design configurations using the design table. Print color hardcopies of the various designs for submission.
7	**Analysis and Design Modification II:** Create individual 3-D parts; perform a Finite Element Analysis (FEA) study: set up applied forces, fix constraints, perform meshing, display color stress contours, visualize and interpret results. Propose design modifications. Print a color hardcopy of the FEA results for submission.
8	**Kinematics Simulation and Rapid Prototyping**: Create a mechanical assembly; mate the parts of the assembly; simulate motion of the assembly; generate an animation (.AVI) file; play the .AVI file externally on a suitable player. Print a rendered color hardcopy of the assembly and submit it along with the animation file. Create individual parts of a mechanical assembly; generate an .STL file of each part; send the .STL files to a prototyping machine; assemble the rapid prototype parts. Submit the rapid prototype assembly once finished.
9	**Section Views in 3-D and 2-D:** Create individual 3-D parts; make different 3-D section views of the parts; export acceptable color image files of the 3-D section views for presentation purposes. Project 2-D section views of a model; incorporate the 2-D section views into a technical drawing; submit printed hardcopies.
10	**Generating and Dimensioning Three-View Drawings:** Create a 3-D part and make a three-view orthographic projection of the part; use a suitable drawing sheet style; add centerlines where appropriate; dimension the drawing; add a title block and appropriate notes. Print a black and white hardcopy for submission.
PROCEED Project	**Team Design Project:** Assign teams; acquire, study, and reverse engineer a common mechanical assembly; sketch shape and sizes of individual components; build computer solid models of parts and assemblies; perform appropriate computer analyses; make rapid prototypes of parts; generate drawings and other design documentation; propose design improvements. Submit final team project report.

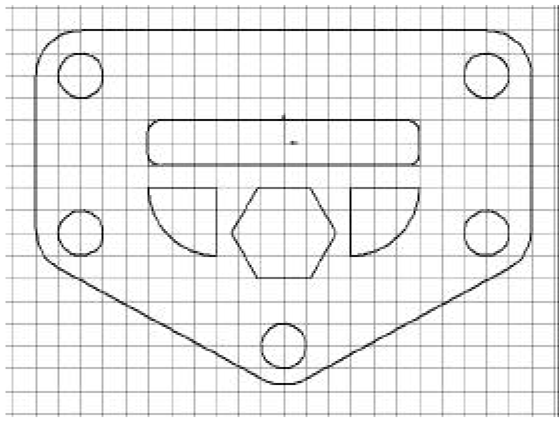

Figure 1: A Computer Sketch of 2-D Primitives on a Grid.

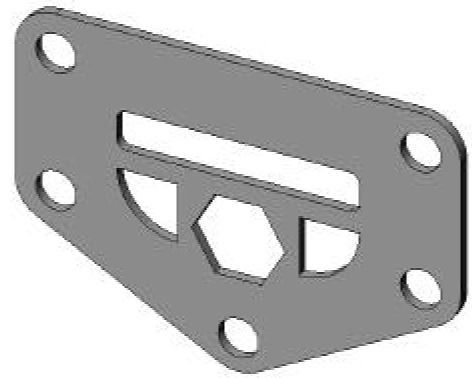

Figure 2: The Sketch Extruded into a Metal Gasket Model.

primitives include such common geometry as line, circle, arc, rectangle, and polygon. Some common editing features are also included in this instruction for module one. The students learn how to trim and extend lines, how to create fillets, and how to mirror geometry about a centerline. They also are introduced to some basic dimensioning practices to fix geometry when a grid system is not used. Figure 1 shows a simple computer sketch with primitives placed on a grid. The finished sketch is then extruded to make a simple 3-D model, in this case a metal gasket, as shown in Figure 2. Other exercises in the module include revolving a 2-D profile sketch to get a machine handle, using an irregular curve (spline) function to create a wall bracket, and extruding cuts to create holes in a round cover plate.

Module 2: Computer Sketching II

The second module continues the instruction on computer sketching, with emphasis on advanced drawing and editing features, such as the creation of rectangular and polar arrays on a sketch plane. For example, the metal grate in Figure 3 is constructed using a 6x3 array of rectangles, whereas the torque sensor model in Figure 4 used a circular array of eight holes.

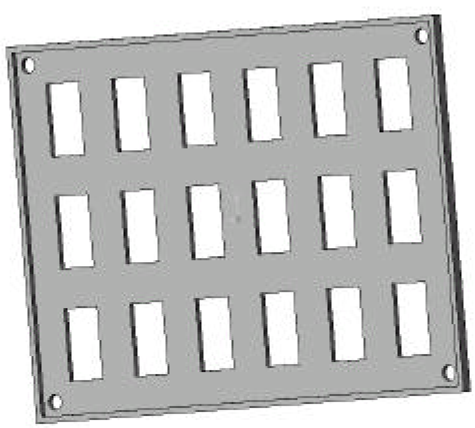

Figure 3: A Computer Model Created Using a Rectangular Array Feature.

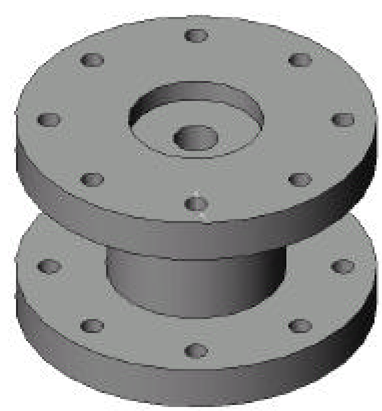

Figure 4: A Computer Model Created Using a Circular Array Feature.

Module 3: Solid Modeling of Parts I

The third module focuses on creating basic 3-D solid models. The unit starts with an exercise on adding geometric relations to a sketch. Figure 5 shows some relations that can be added, such as concentric, tangent, vertical, horizontal, midpoint, coincident, and perpendicular. These relationships are maintained when the sketch is extruded into a solid and then mirrored about its base (Figure 6). The module also introduces the concept of inserting reference geometry planes; mirroring 3-D features; creating linear and circular 3-D patterns; and editing features like 3-D fillets. For example, the air manifold model in Figure 7 was created using a 3-D linear repeat pattern for the four port holes on the top side. On the other hand, the hand wheel model in Figure 8 was created using a 3-D circular repeat pattern for the four spokes. Other choices for modeling were also available in this unit.

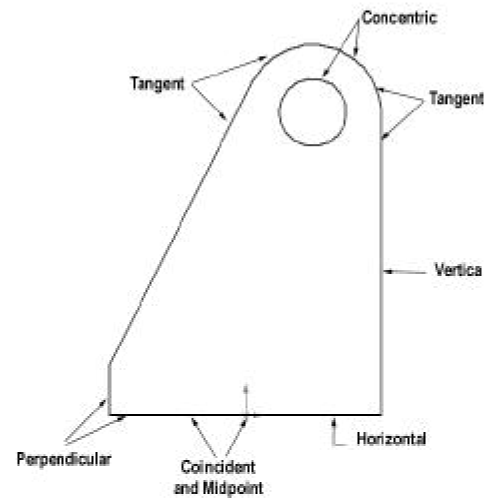

Figure 5: Adding Relations.

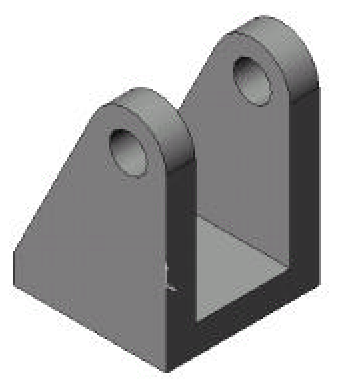

Figure 6: The Sketch is Extruded and Mirrored.

Module 4: Solid Modeling of Parts II

The fourth module continues lessons on 3-D modeling of parts. Advanced 3-D feature commands are explored, including draft, shell, loft, dome, and sweep. For example, the drawer tray model of Figure 9 was created using the shell and draft commands, and the jack stand model of Figure 10 was created using a loft function.

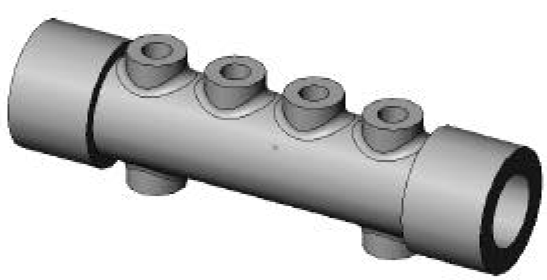

Figure 7. An Air Manifold Model.

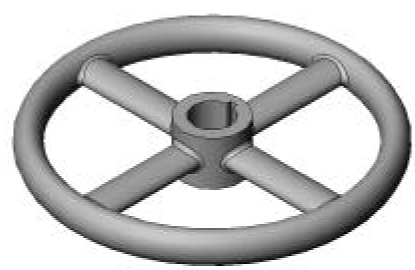

Figure 8. A Hand Wheel Model.

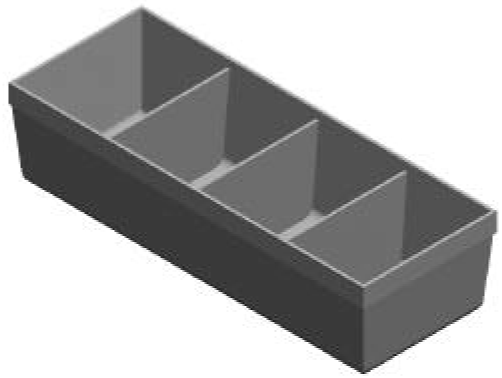

Figure 9: A Drawer Tray Model That Was Drafted and Shelled.

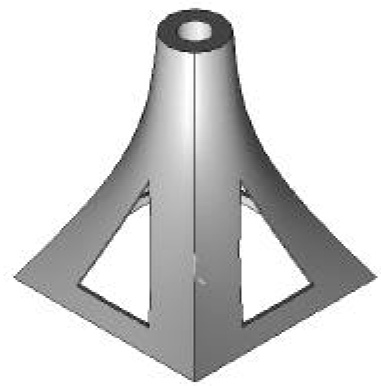

Figure 10: A Lofted Jack Stand Model.

Module 5: Assembly Modeling and Mating

The next module deals with the mating of several solid model parts in an assembly file. The learning objectives for this laboratory are: building multiple 3-D parts that will fit together; starting a new assembly file; dragging and dropping parts into the assembly; moving and rotating components; and mating the parts with different mate types. A typical student exercise consists of building the terminal support assembly, shown in Figure 11 before mating. For this example, the center pin and four rivets are mated with the wing base using concentric and distance mates.

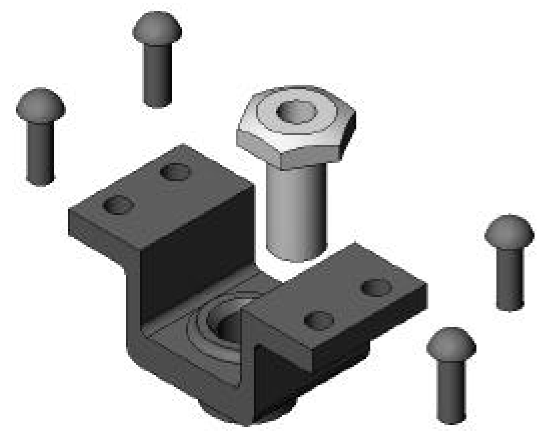

Figure 11. The Terminal Support Assembly.

Module 6: Analysis and Design Modification I

The sixth module begins the application of the solid model to design analysis using the capabilities of the software. The specific analyses chosen here were mass properties analysis and design table analysis. For the mass properties exercise, the students build two versions of the rocker arms shown in Figure 12, and then compare how the geometric functionality differs between the two by generating mass properties reports as shown in Figures 13 and 14.

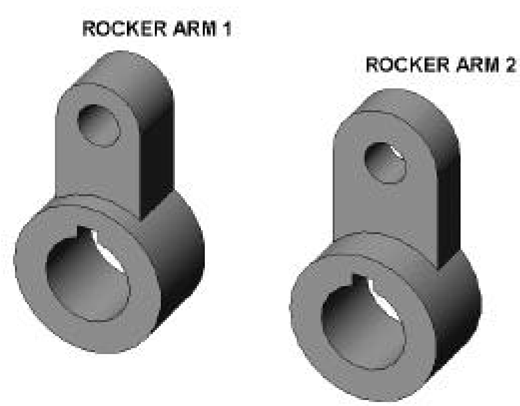

Figure 12: Two Rocker Arms.

Mass properties of Rocker Arm 1

Output coordinate System : -- default --

Density = 0.097 pounds per cubic inch

Mass = 0.236 pounds

Volume = 2.429 cubic inches

Surface area = 17.442 square inches

Center of mass: (inches)
X = 0.000
Y = 0.492
Z = 0.457

Principal axes of inertia and principal moments of inertia: (pounds * square inches)
Taken at the center of mass.
Ix = (0.000, 0.998, -0.065) Px = 0.064
Iy = (-1.000, 0.000, 0.000) Py = 0.182
Iz = (0.000, 0.065, 0.998) Pz = 0.213

Moments of inertia: (pounds * square inches)
Taken at the center of mass and aligned with the output coordinate system.
Lxx = 0.182 Lxy = 0.000 Lxz = 0.000
Lyx = 0.000 Lyy = 0.065 Lyz = -0.010
Lzx = 0.000 Lzy = -0.010 Lzz = 0.212

Moments of inertia: (pounds * square inches)
Taken at the output coordinate system.
Ixx = 0.288 Ixy = 0.000 Ixz = 0.000
Iyx = 0.000 Iyy = 0.114 Iyz = 0.043
Izx = 0.000 Izy = 0.043 Izz = 0.269

Figure 13: A Mass Properties Report for Rocker Arm One.

Mass properties of Rocker Arm 2

Output coordinate System : -- default --

Density = 0.097 pounds per cubic inch

Mass = 0.232 pounds

Volume = 2.394 cubic inches

Surface area = 17.527 square inches

Center of mass: (inches)
X = 0.000
Y = 0.496
Z = 0.416

Principal axes of inertia and principal moments of inertia: (pounds * square inches)
Taken at the center of mass.
Ix = (0.000, 0.992, -0.124) Px = 0.066
Iy = (-1.000, 0.000, 0.000) Py = 0.190
Iz = (0.000, 0.124, 0.992) Pz = 0.225

Moments of inertia: (pounds * square inches)
Taken at the center of mass and aligned with the output coordinate system.
Lxx = 0.190 Lxy = 0.000 Lxz = 0.000
Lyx = 0.000 Lyy = 0.068 Lyz = -0.020
Lzx = 0.000 Lzy = -0.020 Lzz = 0.223

Moments of inertia: (pounds * square inches)
Taken at the output coordinate system.
Ixx = 0.287 Ixy = 0.000 Ixz = 0.000
Iyx = 0.000 Iyy = 0.109 Iyz = 0.028
Izx = 0.000 Izy = 0.028 Izz = 0.280

Figure 14: A Mass Properties Report for Rocker Arm Two.

A design table uses a spreadsheet approach to design a family of parts. The parent solid model is created, and key dimensions of this parent model are parameterized (e.g. D1@Sketch1). Then the spreadsheet cells are filled-in with the various values for the different design configurations, as shown in Figure 15. Once the design table is completed, the students execute the command that produces the different configurations of the model, for example, as shown in Figure 16.

	A	B	C	D	E	F	G
1	Design Table for: Socket Plug						
2		D1@Sketch1	D2@Sketch1	D3@Sketch1	D1@Sketch2		
3	Config 1	1	2	0.5	1.5		
4	Config 2	1.25	2.5	0.65	1.75		
5	Config 3	1.5	3	0.8	2		
6	Config 4	1.75	3.5	0.95	2.25		
7							
8							
9							
10							

Sheet1

Figure 15: A Design Table Spreadsheet.

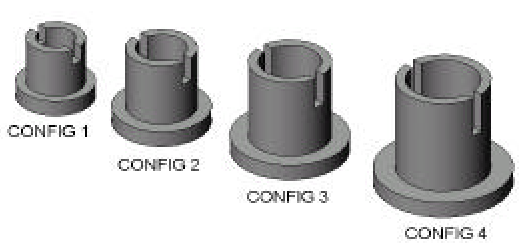

Figure 16: Design Table Configurations.

Module 7: Analysis and Design Modification II

The seventh module deals with finite element analysis (FEA). An example exercise uses a pillow block and shaft assembly to illustrate the usefulness of FEA to analyze and improve upon a design. The students first build and assemble the solid parts. They next declare an FEA study. They assign different material properties to the two parts, and then apply constraints and forces in appropriate places. A mesh is next applied, as shown in Figure 17. They next run a static FEA study, which results in a display of the von Mises stresses, as shown in Figure 18.

The color gradient of the plot is particularly valuable in showing the stress concentrations, which are areas that need improvement in the pillow block design. The students then complete the exercise by modifying the design. In this case, they add fillets in key places to thicken the material where the stresses had concentrated. This final step provides a vivid illustration of the advantage of the FEA method, particularly if they run a new FEA study on the improved design.

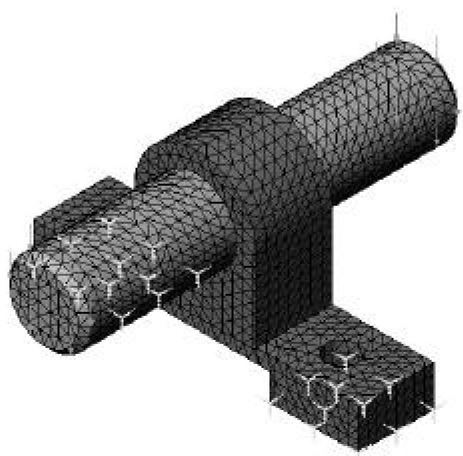

Figure 17: Applying a Mesh.

Figure 18: Stress Concentrations.

Module 8: Kinematics Simulation and Rapid Prototyping

Module eight is concerned with kinematics animation and rapid prototyping. For this module, the students either build a new assembly of solid model parts or use a previously built assembly (i.e. see Figure 11). While the software offers elaborate tools for creating motion pathways for animating 3-D models, a simple approach was taken in this exercise. Once the parts are properly mated into an assembly, the students use an “Explode Assembly” command available in the software. The parts are then exploded along nominal pathways as shown in Figure 19. Next they use an “Edit Path” command for each part to create a new animation schedule. Finally they play the animation on an external viewer and then save it in a universal .AVI file format. This is particularly gratifying, since most of the freshman students had never made an .AVI file before. The instructions are easy to follow, due mainly to the “Animation Wizard” and accompanying tools that were available in the software.

A second laboratory activity for module eight includes building a solid model for rapid prototyping. The students then create a stereolithography (.STL) file from the solid model data, transfer the .STL file to a rapid prototyping machine, and then complete the rapid prototype. Some example parts used as student exercises for this module are shown in Figure 20. The particular approach illustrated here uses the low-cost paper slicing and manual layer adhesion system.

Figure 19: Exploded Assembly for Animation.

Module 9: Section Views in 3-D and 2-D

The ninth module addresses the traditional topic of section views, focusing on both 3-D and 2-D techniques. The educational objectives for this module include: viewing 3-D section views of solid models; projecting orthographic views onto a drawing sheet; setting hatch pattern options; creating the cutting plane line; making a 2-D section view; and printing a section view drawing. An example of a 3-D section view exercise is shown in Figure 21, and a 2-D section view example is shown in Figure 22. In this case, this is a full section view. Other exercise options for this unit include a broken-out section and an assembly section view.

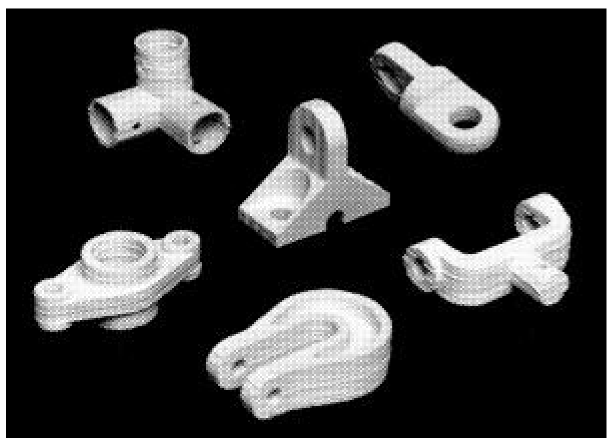

Figure 20: Rapid Prototypes of Student Parts.

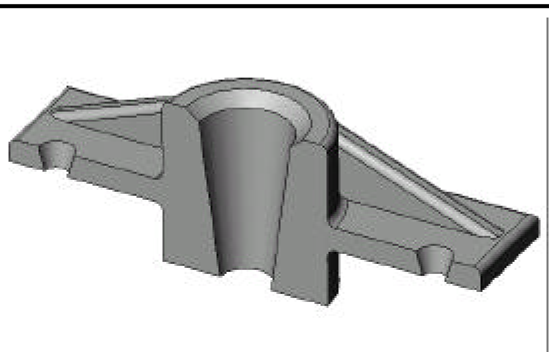

Figure 21: 3-D Section View.

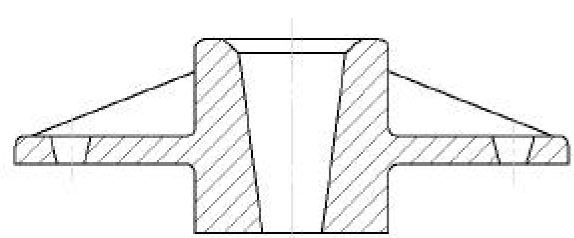

Figure 22: 2-D Section View.

Module 10: Generating and Dimensioning Three-View Drawings

The final module focuses on the traditional need to generate an engineering drawing for final design documentation. The learning activities and objectives for this module include: inserting a drawing sheet onto the screen; setting the drawing sheet options; projecting three orthographic views of a solid model onto a drawing sheet; adding centerlines; dimensioning the drawing; adding title block and annotations; and printing the drawing. A typical student exercise for the pipe joint computer model is shown in Figure 23, and its projected and dimensioned engineering drawing is shown in Figure 24.

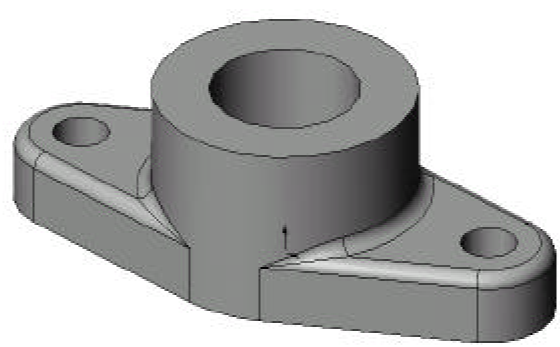

Figure 23: A 3-D Pipe Joint Computer Model.

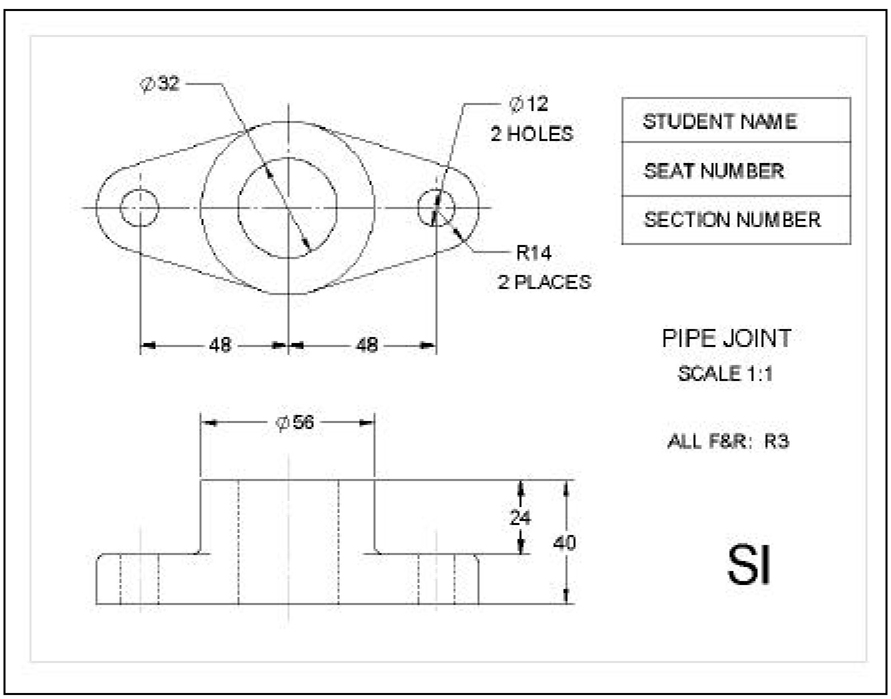

Figure 24: A Dimensioned 2-D Drawing of the Pipe Joint Model.

PROCEED Projects

The ten modular exercises serve as individual learning activities for the students, which can then later help them in their PROCEED team projects. Two example PROCEED projects are the piston assembly (Figure 25), sponsored by Ford Motor Company, and the robotic arm assembly (Figure 26), sponsored by Applied Materials. The company supplies the physical specimens of their signature products, and the teams of 3-4 students participate in reverse engineering the assemblies.

The teams dissect the assemblies into individual components and study each part's geometry. Measurements are made with calipers, scales, pencil, and paper. Isometric sketches are produced to document this dissection process. Using the sketches and other data, the students make solid geometric computer models of each part of the assembly. The parts are then assembled and mated together to illustrate the whole mechanical system. At this point a kinematics simulation of the mechanical assembly could be made. The students next generate .STL files of each individual part. These .STL files are transferred to the JP System 5 prototyping system and physical mock-ups of the parts are constructed. To culminate the experience, the team produces orthographic engineering drawings of the parts.

All of these graphical images and documentation are arranged into a final written report. The report and the physical prototypes are boxed together and submitted to the instructor for grading. The final project grade is shared by all students on the team, and contributes a significant percent to the student's final letter grade.

Figure 25: Piston Assembly.

Figure 26: Robotic Arm Assembly.

Student Program Outcomes Study

A survey of student program outcomes was conducted across all ten sections of the "Engineering Design and Graphics" course in the Fall 2002. Program outcomes are defined to be the knowledge, skills, abilities, and attitudes engineering graduates should be able to demonstrate at the time of graduation. Table 2 lists the ten program outcomes for the Mechanical Engineering Department at the University of Texas at Austin. Included in the table is the mapping to the ABET prescribed *a* through *k* outcomes.[11]

Table 2: ME Program Outcomes
1. Knowledge of and ability to apply engineering and science fundamentals to real problems. (*a*)*****
2. Ability to formulate and solve open-ended problems. (*e*)
3. Ability to design mechanical components, systems, and processes. (*c*)
4. Ability to set up and conduct experiments, and to present the results in a professional manner. (*b*)
5. Ability to use modern computer tools in mechanical engineering. (*k*)
6. Ability to communicate in written, oral and graphical forms. (*g*)
7. Ability to work in teams and apply interpersonal skills in engineering contexts. (*d*)
8. Ability and desire to lay a foundation for continued learning beyond the baccalaureate degree. (*i*)
9. Awareness of professional issues in engineering practice, including ethical responsibility, safety, the creative enterprise, and loyalty and commitment to the profession. (*f*)
10. Awareness of contemporary issues in engineering practice, including economic, social, political, and environmental issues and global impact. (*h,j*)

***** Mapping of ME program outcomes to the ABET prescribed *a* through *k* outcomes.

A survey was conducted to determine the level of improvement in these ME program outcomes from the beginning (pre-) of the class to the end (post-) of the class. The same pre-/post- survey form was used and it asked the students to "describe their skills and abilities supporting each outcome at the beginning (or end) of the course" using the following 5-point scale:

5 - Very significant skill/ability
4 - Significant skill/ability
3 - Some skill/ability
2 - A little skill/ability
1 - No skill/ability

Results of this survey for all the responding students (N = 163) are shown in Table 3 and in the bar chart of Figure 27. It can be noted that all ten ME program outcomes improved from the pre- to post- condition, ranging in percent improvement from 11.3 to 67.0 %. This is quite gratifying since the students felt that the graphics course was contributing to the overall departmental goals.

Table 3: Results of ME Program Outcomes Survey (N = 163).				
ME Outcome	Pre-Score	Post-Score	Change (Post-Pre)	Percent Improvement
1	2.74	3.38	+0.64	+23.4%
2	3.06	3.59	+0.53	+17.3%
3	2.24	3.74	+1.50	+67.0%
4	2.62	3.36	+0.74	+28.2%
5	2.60	4.13	+1.53	+58.8%
6	3.13	3.91	+0.78	+24.9%
7	3.25	4.20	+0.95	+29.2%
8	3.45	3.84	+0.39	+11.3%
9	2.64	3.22	+0.58	+22.0%
10	2.41	3.15	+0.74	+30.7%

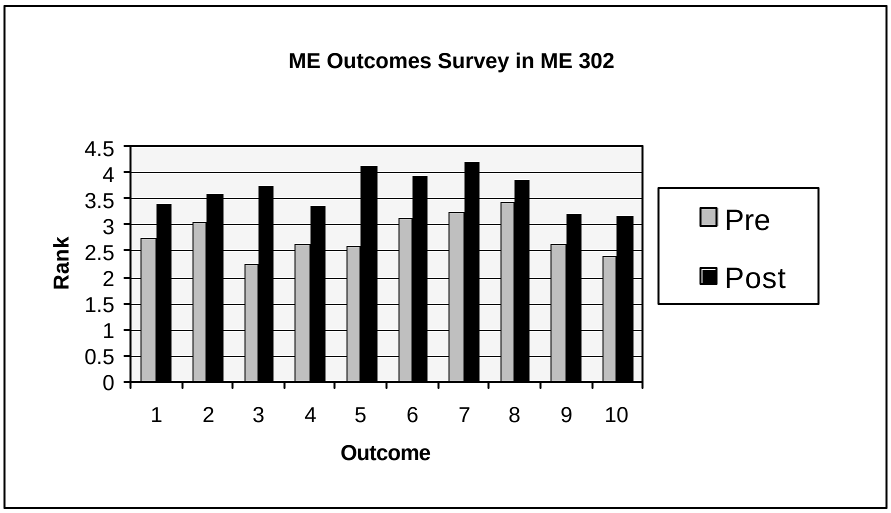

Figure 27: Results of ME Program Outcomes Survey (N = 163).

It is interesting to study which of the ten outcomes showed the greatest improvement, as self-reported by the students. Figure 28 shows a bar chart of the level of improvement from the pre- to post- condition. It can be noted that outcome 3 (ability to design mechanical components, systems, and processes) and outcome 5 (ability to use modern computer tools in mechanical engineering) received the two highest values of 67.0 % and 58.8%, respectively. This is a pleasing result, since the underlying objective of the course is to teach the modern design process using an integrated series of computer graphics exercises.

No single course could realistically contribute significant improvement to all ten ME program outcomes. So there is some “halo effect” in these student ratings. For example, there was little course content on contemporary issues and global impact (outcome 10), even though the students rated it at a 30.7% improvement. Nonetheless, this survey raised an awareness in the students’ minds concerning all the intellectual issues that ME faculty deem important during the students’ undergraduate engineering studies. That awareness is certainly of benefit to the ME freshmen.

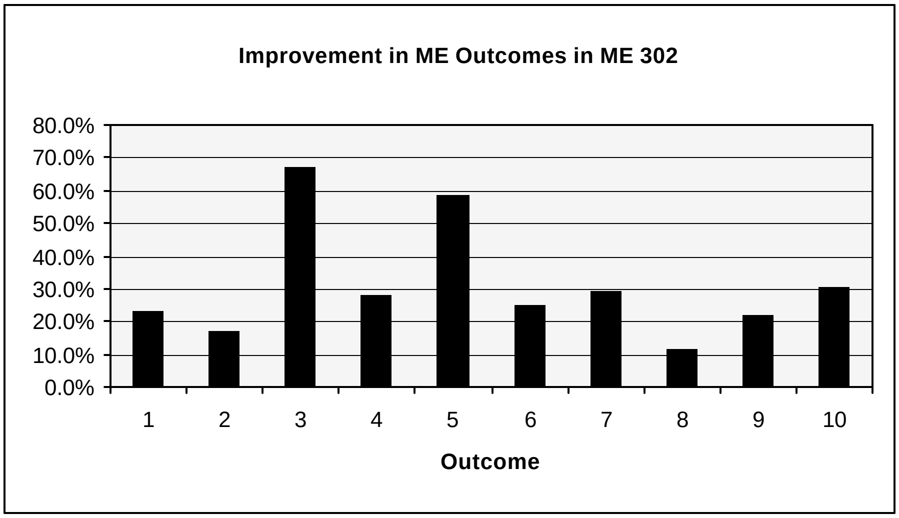

Figure 28: Improvement in Ten ME Outcomes for Fall 2002.

Discussion and Conclusions

The freshman "Engineering Design and Graphics" curriculum has evolved to a new era in which 3-D geometric computer models, and the design applications of the digital database, are the center of instruction. Table 1 lists a sequence of engineering graphics learning modules that systematically introduce the students to this new engineering design and graphics paradigm. This modular sequence was fully implemented in the Fall 2002 semester in all sections of the engineering graphics course at the University of Texas at Austin. This paper has presented example student exercises that underscore this concurrent engineering approach to design education. The ten exercises also seem to prepare the students well for later team projects, such as project PROCEED, which present more open-ended challenges to the students.[9] Informal observations by the faculty suggest that the students enjoyed performing the modules and that many of the exercises seemed relevant to real-life engineering problems.

An outcomes survey was conducted in Fall 2002 to measure the improvement in the ten ME departmental program outcomes during the course. These ten ME outcomes are listed in Table 2 and are the same ones used for the ABET EC2000 accreditation process. Results of this second study for all students in the course are listed in Table 3. A positive improvement was noted in all ten outcomes as depicted in Figure 28. In particular, the students rated the "ability to design" and "ability to use modern computer tools" as the top two outcomes achieved. This was gratifying, since it directly coincides with the major course objectives. While it is not surprising that engineering students would report that they learned something in a course, the overwhelming positive trend of the outcomes survey conducted in this preliminary assessment suggests that, as a minimum, the course is well-received by the students and is on the right track. As a result of the learning activities achieved in this freshman course, it can be said that the students are prepared to meet the challenges of the ME program outcomes in subsequent upper-division courses.

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