

The Concurrent Engineering Design Paradigm is Now Fully Functional for Graphics Education

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ABSTRACT

Engineering design graphics education has come a long way in the past two decades. The emergence of solid geometric modeling technology has become the focal point for the graphical development of engineering design ideas. The main attraction of this 3-D modeling approach is the downstream application of the data base to analysis and manufacturing. In parallel to this development, our group has been implementing a concurrent engineering design paradigm for engineering graphics education. Many obstacles to full implementation of this educational paradigm have been encountered. This paper discusses the two major obstacles, design analysis and low-cost rapid prototyping, that have now been overcome. Thus it appears that, with current technology, the true long-term goal of “Art to Part” seems to now be fully realizable for engineering graphics education.

INTRODUCTION

For the past two decades, our engineering graphics group has defined and promoted a “Concurrent Engineering Design Graphics” paradigm (Figure 1) for engineering education (Barr, Juricic, & Krueger, 1994). While the original insight behind the model has proven to be correct, the implementation of this paradigm in educational practice has confronted many software and hardware hurdles over the years. Selection of the proper 3-D solid modeling software for creating the central geometric data base was an early concern, with many different vendors offering products to educators. Slowly, the outdated constructive solid geometry (CSG) approach to solid modeling was replaced by parametric-based, assembly modeling software like SolidWorks© and Inventor©, which have now become mainstream in education.

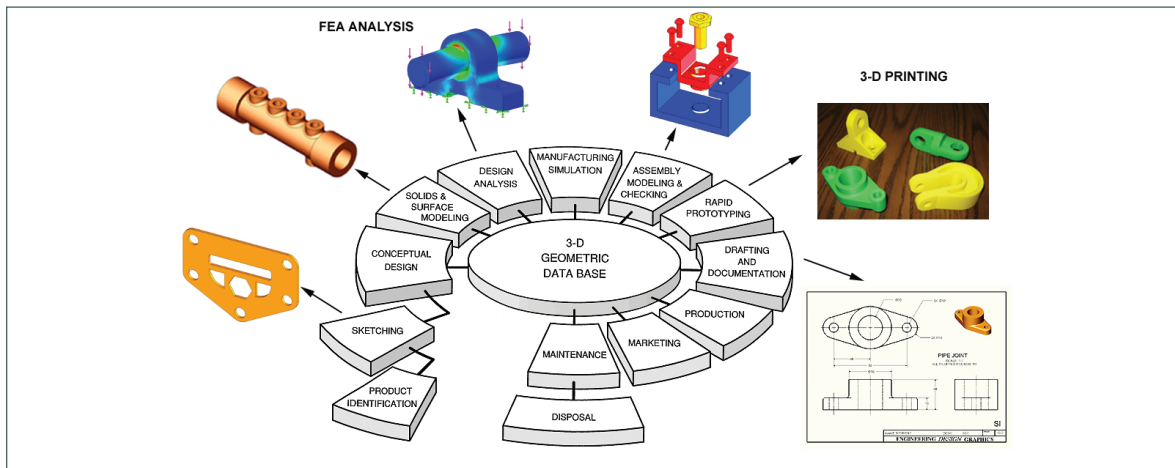
Early efforts to integrate analysis, such as finite element analysis (FEA), into the 3-D modeling curriculum were fraught with failure. Large amounts

of computer memory requirements, convoluted instructions from vendors, and unpredictable computer crashes were commonplace. However, 3-D modeling software vendors eventually realized the add-on value of design analysis to their product, and analysis packages like COSMOSworks© have now been seamlessly integrated into the 3-D modeling menu suite.

Similarly, educational experiences using rapid prototyping (RP) equipment were equally challenging over the past 15 years. The early RP machines for industry were too expensive for education, and the early low-cost systems were not very effective. However, a recent new breed of RP machines, called 3-D printers, has reached a stage where they are both effective and low-cost for educational practice.

While all phases of the “Concurrent Engineering” paradigm in Figure 1 have faced implementation challenges over the years, it has

Figure 1: *The Current Engineering Design Graphics Paradigm is Now Fully Functional with the Seamless Integration of Analysis and Prototyping Capabilities.* (Adapted from Barr, Juricic, & Krueger, 1994)



been our experiences that the Design Analysis and Rapid Prototyping stages have been the hardest to fulfill in an educational setting. Thus, this paper will focus on implementation of those two stages that make the paradigm complete.

DESIGN ANALYSIS

Engineering graphics faculty have reported various efforts over the years to teach finite element analysis (FEA) to lower division engineering students (Howell, 1993; Juricic, et al., 1995; Boronkay and Janak, 1997; Cole, 1999). These early efforts had mixed results. The most notable conclusion was that the software to develop the 3-D model, and the software to perform the analysis, were not seamlessly integrated. For example, a series of workbook exercises were designed to expose the freshmen students to the procedure of design analysis (Barr, et al., 1997). The teaching module used AutoCAD and ANSYS (two separate running software packages) to introduce the students to a simple 2-D FEA study. The exercise required that the students develop a 2-D slice in the CAD software and then create an FEA study in analysis software in which a force was applied to create the stress pattern. This proved to be too cumbersome and time-consuming. In addition to confusing terminology and hard-to-follow instructional steps, the process itself was unreliable and often crashed. However, in the past five

years, the solid modeling software vendors have solved this incompatibility problem with seamless integration of modeling and analysis packages. The following represents a typical, successful process for an FEA study in an engineering graphics course (Krueger and Barr, 2004).

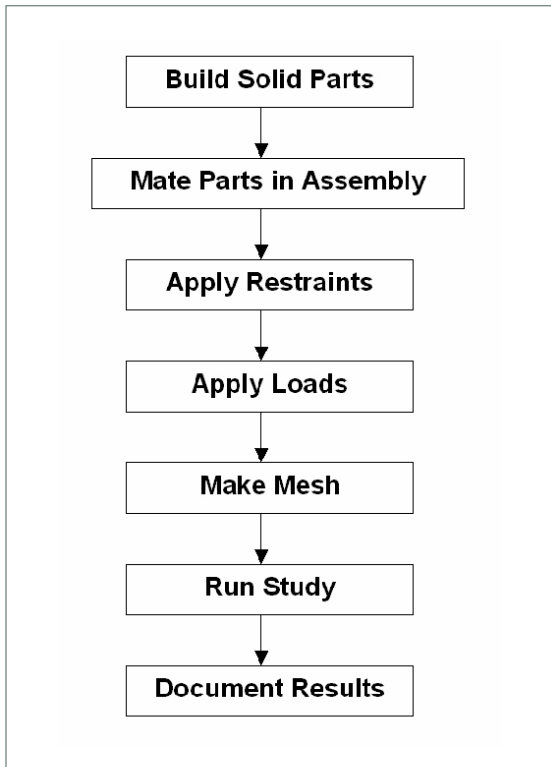
STEP 1: BUILDING THE SOLID PARTS

The overall approach to developing an FEA study is depicted in the flowchart diagram of Figure 2. The process starts with building the solid parts using the modeling software. Typically, a 2-D sketch is extruded or revolved into a 3-D solid. Features like holes and slots are cut into the object, which in this example is a pillow block.

STEP 2: MATING THE PARTS IN AN ASSEMBLY

After the two parts are built the students create an assembly where the shaft is centered in the hole of the pillow block. The assembly will look like the model in Figure 3. At this point the students are asked to save their assemblies in preparation to use the FEA software.

Figure 2: Steps in an FEA Study



STEP 3: APPLYING RESTRAINTS

The students are instructed to carry out a series of tasks to prepare the assembly for analysis. They must first name the study, indicate the type of study to be conducted (static), and identify the mesh type (solid mesh). Following these activities they will assign the type of material to each part of the assembly. The assembly is now ready to have restraints applied to the bottom surfaces of the pillow block assembly (see Figure 4).

STEP 4: APPLYING FORCES

After the restraints are applied to the pillow block, a downward force is applied to the shaft to indicate a load on the shaft (see Figure 4). The force applied to the shaft will test the integrity of the pillow block.

Figure 3: The Pillow Block Assembly

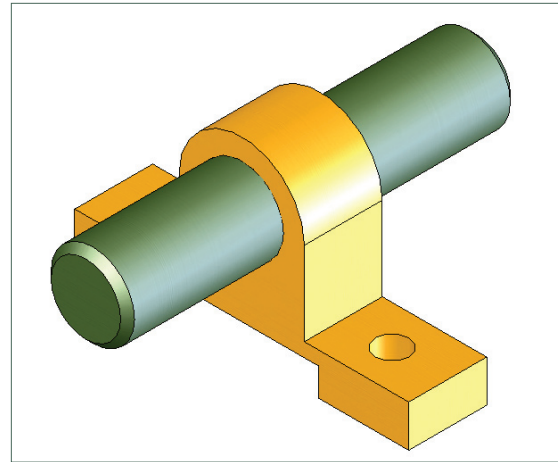


Figure 4: Applying Restraints and Forces, and Then Meshing

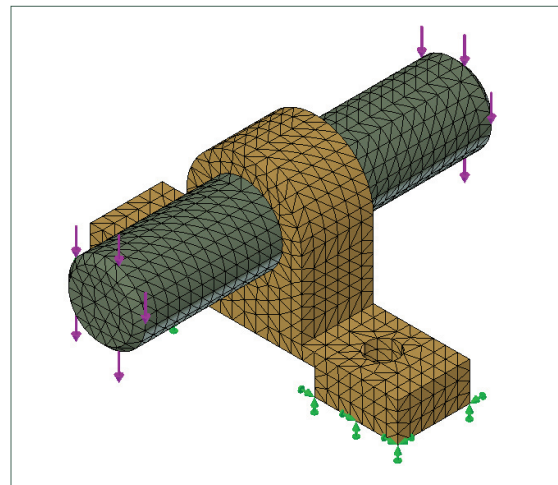
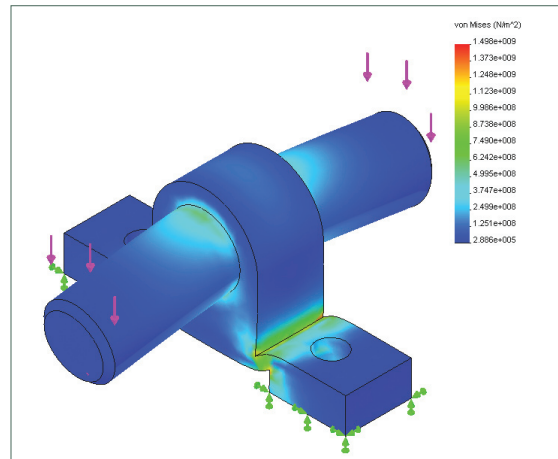


Figure 5: Stress Display



STEP 5: CREATING THE MESH

The next step before the study can be run is creating the mesh. The student opens the mesh dialog box, which allows the user to define the mesh size for the analysis. A smaller mesh yields better results, but takes longer to mesh and longer to run the analysis. Hence it is a tradeoff between mesh size and computation time. At the end of the meshing process, the assembly model is meshed (see Figure 4).

STEP 6: RUNNING THE STUDY

With the “Run” command the program computes the outcomes according to the specified criteria. When the program run is complete, the results will show tabs for Stress, Displacement, Strain, Deformation, and Design Check displays (see Figure 5). Each of these results will display in color to indicate where problems in the design might arise.

STEP 7: DOCUMENTING THE STUDY

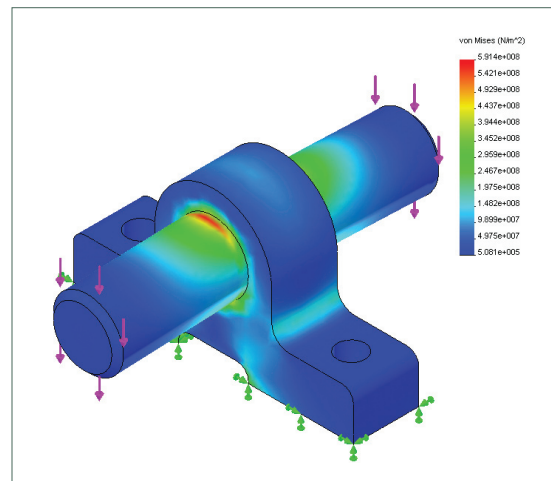
At this point, the FEA software has made all the calculations needed to display the results (Stress, Displacement, Strain, Deformation, and Design Check). All displays, except for the Design Check, can also be animated to show how they react to the force. These display and animation capabilities are very appealing to the student and serve as intuitive insight into the FEA process of analysis.

DESIGN MODIFICATION

Upon completion of the initial FEA study, the students are directed to make some fundamental design changes to strengthen the original pillow block. Those changes include adding fillets between the vertical and horizontal parts of the pillow block, reducing the size of the lower cut-out slot, and increasing the wall thickness around the shaft hole. They are given some suggested values for these design revisions, but are also encouraged to come up with their own ideas through a trial and error approach, using some good intuition.

After they have finished these operations, they are asked to reapply the restraints, the forces, and create a new mesh in order to run the study a second time. In so doing, they can verify that the new design has better design performance in the areas of stress concentration and displacement (see Figure 6) than the original design. In so doing, they see that the narrower slot and the added fillets help improve the overall quality of the design.

Figure 6: *Design Modification*



RAPID PROTOTYPING

In the past 15 years, Rapid Prototyping and Desktop Machining systems were in their primary development stages. Some of the early machines used technologies such as Stereolithography (STL), Selective Laser Sintering (SLS), Laminated Object Manufacturing (LOM), and Ballistic Particle Manufacturing (BPM). These early systems were all quite expensive (\$100K to \$500K), and it was rare to find one in an educational setting. Nonetheless, engineering graphics educators (DeLeon & Winek, 2000; Tennyson & Krueger, 2001; Kirton & Lavoie, 2006) have pursued the incorporation of rapid prototyping into their curriculum.

Driven by the desire to perform rapid prototyping in the educational setting, several vendors came up with clever low-cost systems. In 1996, our group purchased the JP System-5 that built

prototypes by cutting layers from adhesive paper. This suited our needs for several years. However, alternative technologies improved and during the 2004-2005 school year, we acquired the funding to purchase a new breed of rapid prototyping equipment, called 3-D printers. We investigated several options as shown in Table 1. Eventually our group selected two Stratasys BST 3-D Printers as the machines best suited for our purposes.

Table 1: Low-Cost 3-D Printing Technology Available in 2004-2005

| COMPANY | COST/UNIT |
|--|-----------|
| Stratasys BST with Educational Bonus Package and 1 year warranty | \$26,000 |
| 3D Systems ThermoJet Solid Object Printer with 90 day warranty | \$28,980 |
| Z Corporation 310 3-D Printer with de-powdering system and 1 year warranty | \$28,420 |

THE STRATASYS 3D PRINTER OPERATION

The Stratasys 3-D printers are depicted in Figure 7. The printers use an ABS filament medium for its building material and it comes in a cartridge that contains approximately 60 cubic inches of build material. The system is clean, relatively strong and can be used to build the parts of an assembly. Figure 8 shows an example of a material cartridge.

Using the software provided by the manufacturer, a build job is set up on the instructor's computer. Objects that have been saved as .STL files are scaled, rotated and positioned on the build board layout as suggested in Figure 9. The most efficient build process is to fill up each build board with as many pieces as will fit. As each piece is placed on the board, the program informs the instructor about the amount of material that will be used for the part and the length of time it will take to build it. Once the build board is

ready for the printer, the operator sends the job to the machine. A build board is placed into the printer and the building process is started. Figure 10 shows a build board in the machine with a built part that was just completed.

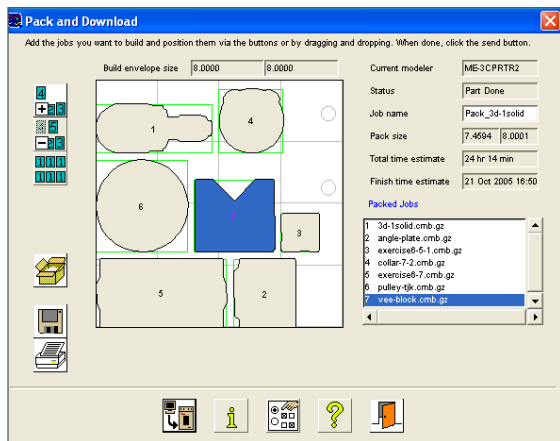
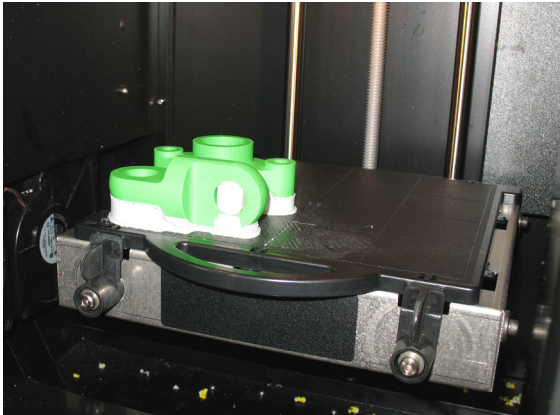
A cost analysis of the 3-D printers revealed some interesting facts. During the first five months of operation, our group produced 635 parts that averaged 1.67 cubic inches of model material and 0.42 cubic inches of support material. Over all we had used 1063 cubic inches of model material or the equivalent of 19 cartridges of material at a cost of \$250 per cartridge. That equates to \$4750 for the 635 parts, or about \$7.50 per part. The materials cost of \$7.50 per part was 25% less than the materials cost for the J-P System-5.

Figure 7: The Stratasys 3-D Printers



Figure 8: The Cartridge with the ABS Feeder

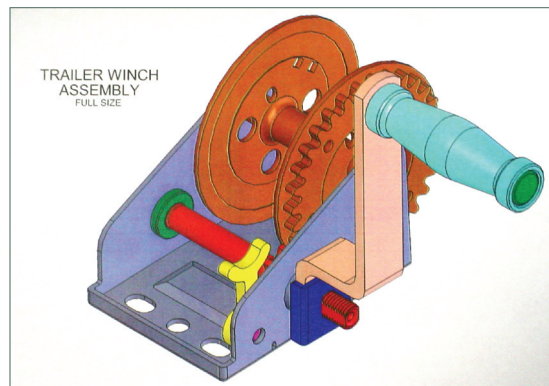


Figure 9: The Build Board Layout**Figure 10: A Part Just Built on the Build Board**

STUDENT PROJECT

The students are assigned to four-member teams and are asked to reverse engineer a common mechanical assembly of parts. An example of a student project, that uses 3-D printing technology, is shown in Figures 11 and 12. In this example, the team selected a trailer winch. Their first step is to build all the parts of the assembly using solid modeling software like SolidWorks®. They then save an .STL file for each part. As part of the overall experience, they create a mated assembly model of the parts, as shown in Figure 11. They also perform a mass properties analysis of each part and make a dimensioned, orthographic drawing of each part. The culminating experience is to submit the .STL files to their instructor, who then prints the 3-D parts. The instructor

sets the files in the appropriate build positions using Statasys software. The build and support materials are activated, and the machine starts printing the 3-D parts. Typically, the full print cycle of a batch of parts (8" x 8" x 12" print volume) takes between 18 to 24 hours. The next day, the parts are ready for the students to peel out the gray support material to yield a clean, hand-held part. The parts for the trailer winch, after manual re-assembly, are shown in Figure 12.

Figure 11: A Software Image of the Mated Assembly of Parts**Figure 12: The Printed Parts Assembled Together**

CONCLUSIONS

Engineering Graphics education has come a long way in the past two decades. Started in 1988, the NSF-funded project on "Modernization of the Engineering Design Graphics (EDG)

Curriculum” (Barr and Juricic, 1990) predicted a future EDG curriculum based on solid modeling, with applications of the computer model to analysis and manufacturing. During the pursuing years, implementation of this ideal EDG curriculum has overcome many obstacles. This paper has shown that, using low-cost technologies currently available, the implementation of the NSF study is now completely feasible for the graphics curriculum. Finite element analysis (FEA) software is now available as an add-on to existing 3-D modeling software. The FEA process is more intuitive and student-friendly, and yields results that can be readily interpreted and animated. The new breed of 3-D printers are cost effective, and the parts that they build are more viable models than earlier low-cost systems. The parts can be handled easily, have the strength of ABS plastic, and can be assembled. With these two final pieces of the concurrent engineering design paradigm (Figure 1) in place, the true long-term goal of “Art to Part” seems to now be fully realizable for engineering graphics education.

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