Introduction to Engineering Design Through a Freshman Reverse Engineering Team Project

Ronald Barr, Thomas Krueger, Billy Wood, and Mostafa Pirnia
University of Texas at Austin, rbarr@mail.utexas.edu, tkrueger@mail.utexas.edu, bwood@mail.utexas.edu, m.pirnia@mail.utexas.edu

***Abstract* - Our group at the University of Texas at Austin has developed the current version of Engineering Graphics based on the pedagogical triad of: 1. engineering graphics fundamentals, 2. computer graphics modeling fundamentals, and 3. computer graphics applications. The engineering graphics fundamentals part covers the traditional topics of sketching, projection theory, orthographic drawing layout, sectioning, and dimensioning. The computer graphics modeling component teaches 2-D computer sketching, 3-D solid modeling of parts, assembly modeling, and the projection of an engineering drawing directly from the 3-D model data. The graphics application part includes kinematics animation, finite element analysis, and generation of a rapid prototype directly from the 3-D data base. In order to motivate the freshmen students in engineering design, and to tie the three pedagogical components into a unifying theme, we have instituted a team project based on the concept of reverse engineering. Reverse engineering is the dissection of a common mechanical assembly into its individual parts, studying the geometry and design function of each part, and then reconstructing the parts into 3-D solid model data bases. The student teams select a mechanical assembly, dissect it into individual parts, make measurements and sketches, build 3-D solid models, apply the solid models to various analyses, and make rapid prototypes. The whole project is eventually documented in a final report with sketches, 3-D model image printouts, various analysis reports, printed 3-D prototypes, and final drawings.**

Index Terms – Engineering Graphics, Solid Modeling, Reverse Engineering, Freshman Team Project.

Introduction to Engineering Graphics

Graphics has always been the language of engineering and the preferred media for conveyance of design ideas [1,2]. The first record of what appears to be an engineering drawing is a temple plan found inscribed on a tablet that is part of the statue of Gudea, a Babylonian builder and governor around 2130 B.C. Ancient Egyptians, dating about 1500 B.C., used a system of strings dipped in ink to make straight grid lines, an early form of drafting. The great Roman builders etched designs of their buildings on pavement at the turn of A.D. During the Renaissance, around 1500 A.D, forms of multi-view projections and pictorial drawings were being produced. In 1795, Gaspard Monge published his well-known treatise on Descriptive Geometry, which provided a scientific foundation for engineering graphics through orthographic projection theory. During the subsequent two-hundred years, engineering graphics used different manual tools that made production of orthographic drawings easier. Drafting boards, T-squares, plastic triangles, and mechanical pencils were common equipment during this era. However, during the 1980's it became evident that freshman engineering graphics would no longer be a "drafting" course. New hardware and software technology was quickly and irreversibly changing how engineering graphics would be taught and practiced.

Modern Era of Engineering Graphics

The first application of computers to engineering design communication resulted in Computer-Aided Design and Drafting (CADD) systems that replaced drawing boards with an electronic tool. However, this CADD era was short-lived and lasted no more than a decade. By 1990 it became evident that an engineering design would start with a 3-D data base, and the current era of solid modeling in freshman engineering education was born. Our group developed an educational paradigm [3] in which the 3-D geometric database serves as the hub for all engineering graphics activities, as shown in Figure 1. The student starts with a sketch of an idea that then becomes a solid model of the part. The solid model not only serves as a visualization modality, but it also contains the solid geometry data needed for engineering analysis, such as finite element analysis FEA). The same geometric database can be used to generate final graphical communications like engineering drawings and 3-D printed parts.

Transforming a century-old drafting curriculum into a modern 3-D modeling course did not occur overnight. Many obstacles to completing the ideas expressed in Figure 1 had to be overcome. Nonetheless, through perseverance and dedication, the 3-D modeling paradigm was fully realized [4] in the past decade, and the solid modeling approach has been firmly endorsed within the engineering graphics educational community ever since [5]-[8].

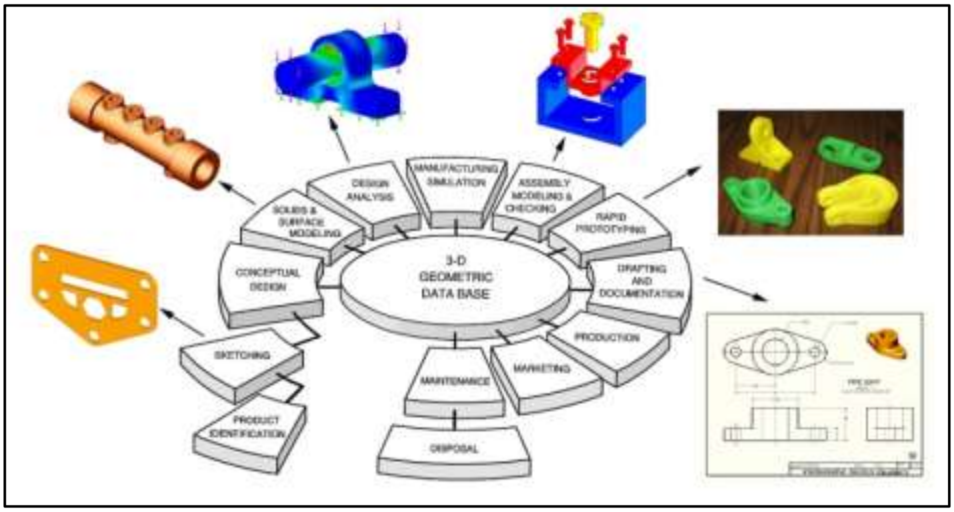

FIGURE 1
THE MODERN 3-D MODELING EDUCATIONAL PARADIGM

While the solid modeling theme has become dominant in engineering graphics, some aspects of the earlier graphics curriculum have been retained. The fundamental ideas of freehand sketching, pictorial drawing, section views, and dimensioning are all still relevant. Figure 2 illustrates the current curricular triad for engineering graphics education. At the top are the fundamental topics that can be delivered in lectures and practiced with freehand sketching methods. At the lower left are the new computer graphics modeling skills that students must acquire. And at the lower right are the applications that tie the educational experience to real-world applications. In order to motivate the freshmen students in engineering design, and to tie the three pedagogical components into a unifying theme, we have instituted a team project based on the concept of reverse engineering.

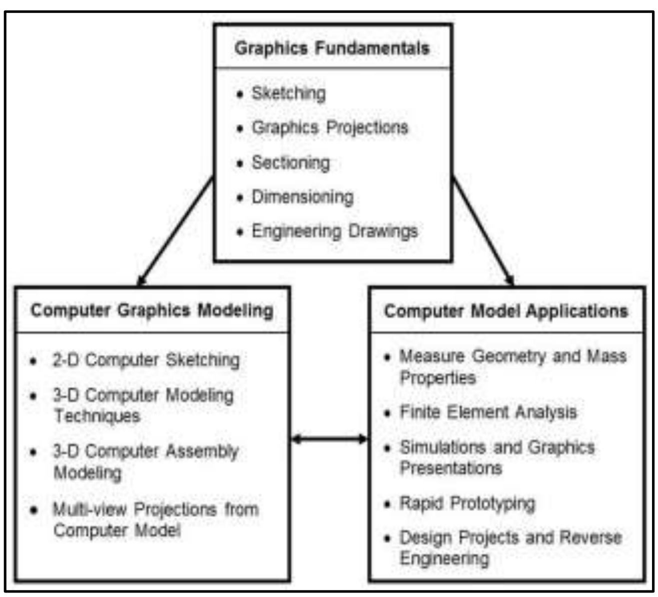

FIGURE 2
THREE ASPECTS OF MODERN ENGINEERING GRAPHICS INSTRUCTION

REVERSE ENGINEERING IN GRAPHICS EDUCATION

Reverse engineering is the dissection of a common mechanical assembly into its individual parts, studying the geometry and design function of each part, and then reconstructing the parts into 3-D solid model data bases. Using reverse engineering to motivate engineering students has been proposed in education since the early 1990's [9]-11]. Sometimes called product dissection, reverse engineering begins when a student team selects a mechanical system for disassembly. The team dissects it into individual parts, makes measurements and sketches of the parts, build 3-D solid models, apply the solid models to various analyses, and make rapid prototypes. The whole project is eventually documented in a final report with sketches, 3-D model image printouts, various analysis reports, printed 3-D prototypes, and final drawings. The following sub-sections present examples of the procedural steps for executing a semester long reverse engineering team project.

I. Selecting the Reverse Engineering Object

The students are assigned to four-member teams for the project, and some concern is given to team chemistry and diversity. Once the teams are assigned, they pick a leader and start to select their object for dissection. Some consideration must be given to the mechanical device, and a list of objects that had been successful in the past are presented to them (see Table 1).

II. Documenting the Selected Engineering Object

The first team task is to document the object selected with a short write-up that outlines the purpose of the device and lists the engineering specifications. They start planning their semester-long project with a Gantt chart. They study their object and create a black box diagram to illustrate the main function of the device, such as shown in Figure 3 for a small kitchen scale.

TABLE I
EXAMPLES OF SOME REVERSE ENGINEERING OBJECTS

Baby Toy	Fuel Pump	Piston Assembly
Bathroom Scale	Gate Valve	Pipe Clamp
Beer Faucet	Hand Tool	Ratchet Tie-Down
Bicycle Pump	Hose Nozzle	Shower Massage Head
Bolt Cutter	Kitchen Scale	Spinning Disk Launcher
Can Opener	Lug Wrench	Sprinkler Head
Corkscrew	Master Cylinder	Stapler
Deadbolt Lock	Model Car Drive Train	Toy Gun
Desktop Clamp	Oil Pump	Trailer Hitch
Differential Gear	Oscillating Sprinkler	Trailer Winch
Doorknob Assembly	Pencil Sharpener	Vise Grip
Flashlight	Pepper Grinder	Water Faucet Valve

They then begin the dissection process with notes and a fishbone diagram. While each object will have a different dissection process, most teams will use small tools to remove all the parts. An example of a fishbone diagram for a trailer winch is shown in Figure 4.

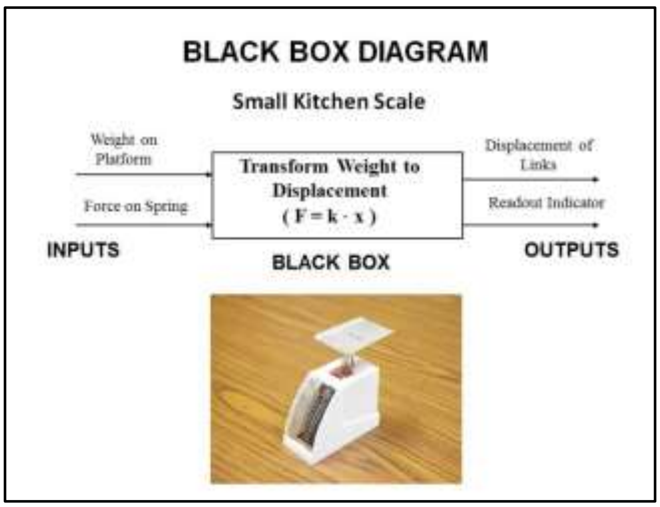

FIGURE 3
BLACK BOX DIAGRAM FOR A SMALL KITCHEN SCALE.

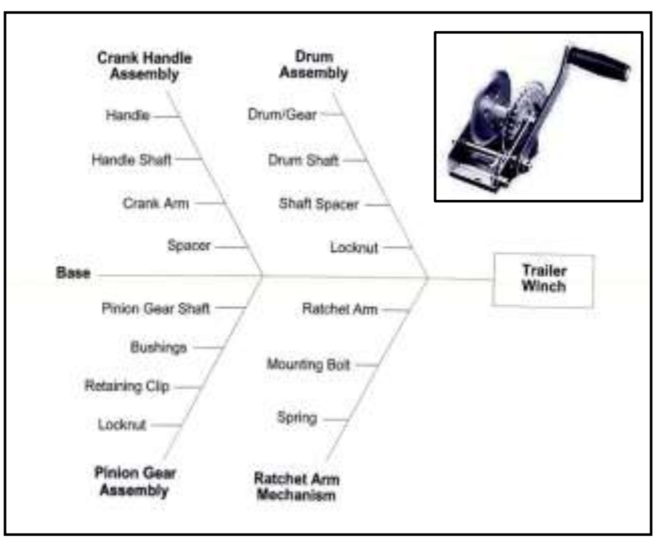

FIGURE 4
FISHBONE DIAGRAM FOR A TRAILER WINCH

III. Sketching The Parts

Once the parts have been separated from the object, the students study the geometry of each part. They make measurements with scales and calipers, and then produce pictorial sketches of the parts. The sketches are done freehand, typically on isometric grid paper, using some suitable scale. In order to show how the parts fit together, an exploded isometric assembly sketch is included in the assignment (see Figure 5). In addition to the sketches, a list of all the parts in the assembly is included in the packet (see Figure 6). The parts list includes: part number, part name, number required, and part material. This stage of reverse engineering, studying and sketching the part size and shape, prepares the students for the computer modeling stage.

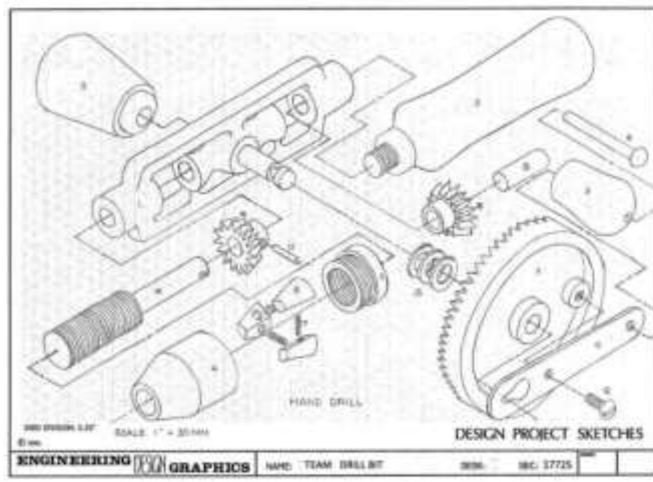

FIGURE 5
FREEHAND SKETCH OF A HAND DRILL ASSEMBLY

Parts List
Manual Trailer Winch

Part Number	Part Name	Number Required	Material
1	Base	1	Steel
2	Spool	1	Steel
3	Spool Spacer	1	Steel
4	3/8" x 4" Machine Bolt	1	Steel
5	3/8" Locknut	1	Steel
6	Pinion Shaft	1	Steel
7	1/2" Locknut	1	Steel
8	Bushing	2	Steel
9	3/8" Radial Retaining Ring	1	Steel
10	Ratchet Lever	1	Steel
11	Spacer	1	Steel
12	1/4" x 1" Machine Bolt	1	Steel
13	1/4" Locknut	1	Steel
14	Torsion Spring	1	Steel
15	Crank Arm	1	Steel
16	Crank Handle	1	Plastic
17	Crank Handle Shaft	1	Steel
18	U-Channel Spacer	1	Steel

FIGURE 6
PARTS LIST FOR A TRAILER WINCH

IV. Building Computer Models of the Parts

The students divide the dimensioned sketches among the team members. Each team member is responsible for modeling one or more component parts (see Figure 7). The students work together to model their individual parts and make sure that the parts are oriented properly so an assembly computer model (see Figure 8) can be made by compiling the part files into a single assembly file. Care is taken to adhere to the dimensions taken from the real parts to assure accurately sized and constructed components. Properly constructed parts will mate in the assembly as they mate in the real product.

In addition to making parts for their team project, the students also gain valuable skill in computer modeling of intricate parts that may include features such as gears, threads, splined surfaces, slots, fillets, and chamfers. The part images are printed on a title sheet for later inclusion in the final report, and are also saved for later use in the analysis and 3-D printing stages.

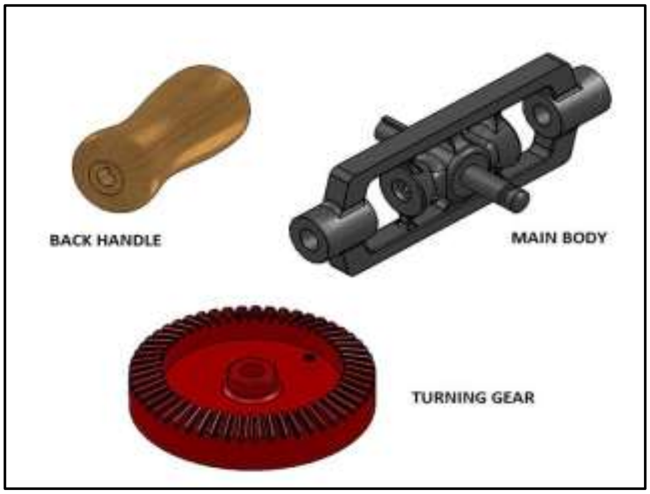

FIGURE 7
SOLID MODELS OF SOME PARTS FOR A HAND DRILL

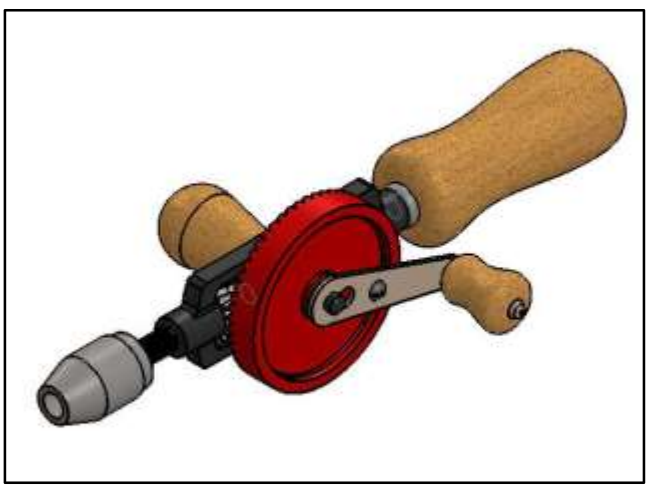

FIGURE 8
A COMPUTER ASSEMBLY MODEL OF A HAND DRILL

V. Computer Analysis of the Parts

One objective of the course is to instill some design "instincts" by having the students assess the overall suitability of a design. The starting point for this assessment is the Mass Properties Report (MPR). After a part model is complete, the students assign material properties, including the material type and mass or weight density. Stock materials can be chosen from a library or custom materials can be defined. The modeling software then automatically generates the MPR, which includes the calculated mass, volume, and surface area of the part, as well as principal axes and moments of inertia at various locations (center of mass, output coordinate system). Figure 9 shows a printout of a typical Mass Properties Report.

The students go through a simple, canned finite element analysis in the course, so some teams may also include a finite element study of key parts. The student teams assign realistic boundary constraints as well as fixed or distributed loads on the part, to mimic real expectations during normal duty. Resulting stress, strain, and/or deformation color plots are then studied to reveal high stress areas, and these plots in turn are included in the final report.

VI. Printing 3-D Parts of the Assembly

At this stage, the solid model geometric data is complete and ready for each part to be sent to the 3-D printer. The students save each part as a stereo lithography (.STL) file extension, which is the data format that 3-D printers use. The STL files for each team are gathered by the instructor and systematically cued into the 3-D printer. It may take several days to a week to complete the 3-D printing of all parts for a class of 6-8 teams. Figure 10 shows 3-D printed parts for the trailer winch: a. the pinion gear, b. the turning handle, and c. the long pin.

Mass properties of CRANK ARM (2) (Part Configuration - Default)
Output coordinate System: -- default --
Density = 0.2854 pounds per cubic inch
Mass = 0.4896 pounds
Volume = 1.7153 cubic inches
Surface area = 18.9277 inches^2
Center of mass: (inches)
X = -0.3781
Y = 0.1050
Z = -0.5578

Principal axes of inertia and principal moments of inertia: (pounds * square inches)
Taken at the center of mass.
Ix = (0.9603, 0.0001, 0.2789) Px = 0.1290
Iy = (0.2789, 0.0003, -0.9603) Py = 1.5414
Iz = (-0.0002, 1.0000, 0.0003) Pz = 1.5879

Moments of inertia: (pounds * square inches)
Taken at the center of mass and aligned with the output coordinate system.
Lxx = 0.2388 Lxy = 0.0001 Lxz = 0.3782
Lyx = 0.0001 Lyy = 1.5879 Lyz = 0.0000
Lzx = 0.3782 Lzy = 0.0000 Lzz = 1.4316

Moments of inertia: (pounds * square inches)
Taken at the output coordinate system.
Ixx = 0.3966 Ixy = -0.0193 Ixz = 0.4815
Iyx = -0.0193 Iyy = 1.8102 Iyz = -0.0286
Izx = 0.4815 Izy = -0.0286 Izz = 1.5069

FIGURE 9
MASS PROPERTIES REPORT FOR THE CRANK ARM OF A TRAILER WINCH.

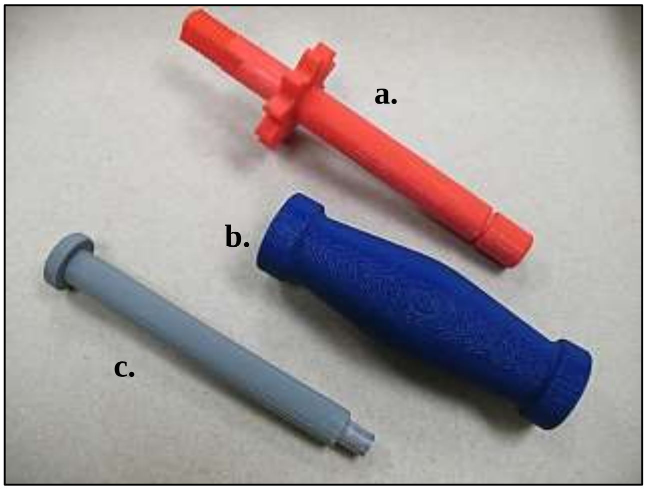

FIGURE 10
PHYSICAL PROTOTYPES FROM A 3-D PRINTER

VII. Generating Engineering Drawings of the Parts

The final design documentation effort for the project is to make a set of engineering drawings. This is done through the development of multi-view orthographic projections from the solid models of the parts. The students chose drawing standards (e. g. ANSI or ISO style, units, tolerance, precision) and convert the 3-D model into a set of orthographic views (front, top, right side) on a 2-D drawing document. Then the students construct, complete, non-redundant dimensions in the appropriate views following conventional dimensioning practices. Shaded isometric pictorials, auxiliary views, notes, and section views are added to the drawing for clarity as needed. The drawing sheet has a designated title strip where the team can add their name and other information. When finished, a paper copy of the drawing is printed for inclusion in the final report. An example of a student project drawing is shown in Figure 11.

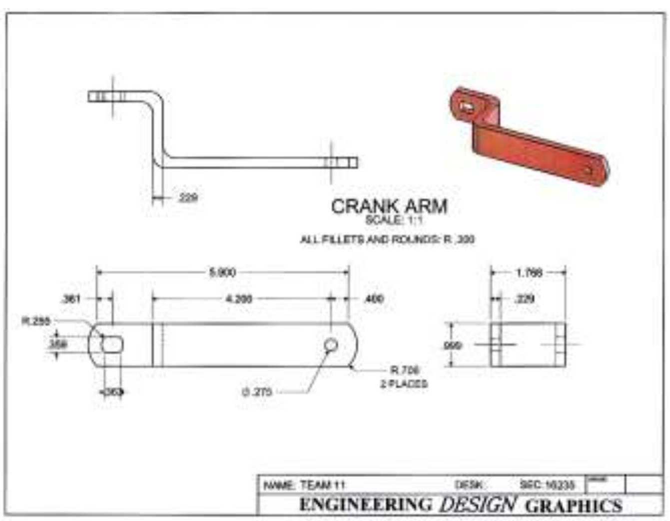

FIGURE 11
ENGINEERING DRAWING OF A PART FOR A STUDENT PROJECT

VIII. Submitting the Final Project

At the end of the semester, the students compile all of the earlier reports, graphs and charts, computer printouts, and engineering drawings, and bind them into a final report. The students are required to find a suitable box that will hold the bound report as well as the 3-D printed prototype parts (see Figure 12). The instructors provide the teams with a checklist (Figure 13) to help the students in this final submission requirement. This final team project represents the final grading effort in the course and is given in lieu of a final exam. Once the projects are graded, the boxes are returned to the team members at the end of the semester.

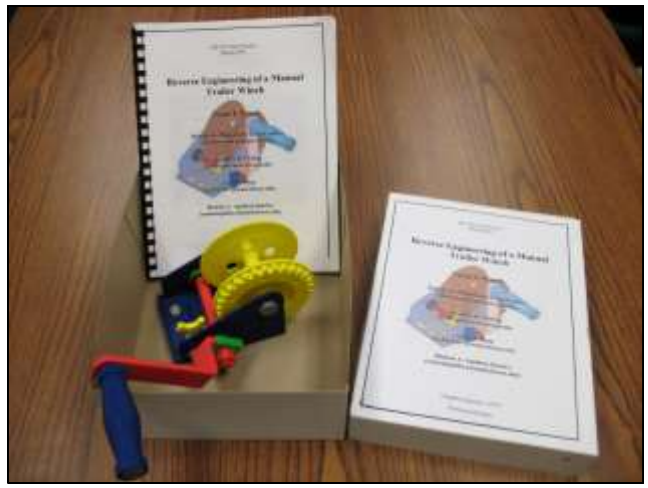

FIGURE 12
SUBMISSION OF THE FINAL REVERSE ENGINEERING PROJECT

REVERSE ENGINEERING TEAM PROJECT CHECKLIST

Team Name: ______________________ Section No.: ________

Initial of Who Did This Task

Cover Page ____
Table of Contents ____
Written Description of Reverse Engineered Object ____
Black Box Diagram Showing Object's Major Function ____
Gantt Chart Showing Planning of Project ____
Dissection Notes ____
Fishbone Diagram Showing Object Dissection ____
Exploded Assembly Sketch of Object Dissection ____
Complete Parts List Showing Part Number, Part Name, Number Required, and Material ____
Isometric Sketches of Individual Parts ____
Color Printouts of Assembly Model and of Each Individual Computer Model Part ____
Mass Properties Report of Each Individual Computer Model Part ____
Materials and Manufacturing Analysis of Two Parts ____
Rapid Physical Prototypes of Selected Individual Parts ____
Digital Picture of Rapid Prototype Parts with Caption ____
Dimensioned Orthographic Drawings of Each Part Prototyped ____
Grading Sheet Handed Out in Class ____
Team Member Contribution Sheet ____
Assembled Final Report With Suitable Binding, Box, and Outer Label ____

FIGURE 13
REVERSE ENGINEERING TEAM PROJECT CHECKLIST

DISCUSSION AND CONCLUSION

A course on Engineering Graphics has been a staple in the freshman engineering curriculum for over a century. The course has evolved over the time as new tools and technologies have arrived. During the past quarter century, new hardware and software capabilities have transformed the traditional 2-D drafting course into a 3-D computer modeling course. The current educational paradigm for Engineering Graphics, as reflected in Figure 1, is a fulfillment of 25 years of work to deliver a robust course based on the solid modeling approach to engineering design. During this journey, many obstacles to realize this paradigm were encountered. These obstacles included incompatible software and hardware systems, user-unfriendly analysis software that frequently crashed, high costs for prototyping equipment, and lack of training for instructors. Nonetheless, gradually these hurdles were overcome, and the educational paradigm is now fully functional for design graphics education. Indeed, with this new paradigm, the concept of "graphicacy" (or graphics literacy) will likely spread from engineering into more general education as 3-D modeling and printing become mainstream in society [12].

This new educational paradigm has opened rich opportunities for graphics applications and projects for freshmen engineering students beyond the graphics fundamentals. In addition to building 3-D solid models and assemblies, they can also analyze the models and print 3-D parts. This paper focused on a reverse engineering student project that not only exercises the graphics and modeling fundamentals, but also extends the student activities to analysis and prototyping, as reflected in Figure 2. In doing so, the teaching environment for Engineering Graphics can now be extended deeper into design practices that will serve the freshmen students well in later engineering courses.

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AUTHOR INFORMATION

Dr. Ronald E. Barr is Professor of Mechanical Engineering at the University of Texas at Austin, where he has taught since 1978. He received both his B.S. and Ph.D. degrees from Marquette University in 1969 and 1975, respectively. His research interests are in Biosignal Analysis, Biomechanics, and Engineering Design Graphics. Barr is a recipient of the ASEE Chester F. Carlson Award, the Orthogonal Medal, and the EDGD Distinguished Service Award. Barr is a Fellow of ASEE and ASME, and served as ASEE President from 2005-2006. He is an ABET PEV and a registered Professional Engineer (PE) in the state of Texas.

Dr. Thomas Krueger is a Senior Lecturer in the Mechanical Engineering Department at the University of Texas at Austin. He received his BS in Ed in 1966 and his M. Ed and PhD in 1971 and 1975 respectively from Texas A&M University. Since 1994 he has taught Engineering Design Graphics in the Mechanical Engineering Department. Dr. Krueger is Member of ASEE, SME and ASME.

Mr. Billy H. Wood is a Senior Lecturer in the Mechanical Engineering Department at the University of Texas at Austin. He received his BSET in 1974 and his M. ARCH. in 1977 from Texas A&M University. He joined the ME department at UT in September 1980. He taught Engineering and Architectural Design Graphics until 2000, and has continued to teach Engineering Design Graphics ever since. In recent summers, Wood has organized a study-abroad Engineering Design Graphics course in Austria and Germany. He served twelve years as the Undergraduate Advisor for the ME department.

Mr. Mostafa Pirnia is a Senior Lecturer in the Mechanical Engineering Department at the University of Texas at Austin. He received his BS in Physics in 1963 and MS in Nuclear Physics in 1965 from Tehran University, Tehran, Iran. He received a fellowship from American Nuclear Energy Commission to study Nuclear Reactors in the Nuclear Engineering Department at Penn State University in 1967-1968. Since 1981 he has taught Engineering Design Graphics in the Mechanical Engineering Department as well as College and Engineering Physics in the Physics Department at Austin Community College.