Engineering Design Graphics as a Communications Tool for Mechanical Design: A Broader View

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Abstract

Amongst the many skills required of newly graduated engineers is the ability to clearly communicate their designs and engineering analyses using both verbal and graphical languages. The new ABET EC2000 criteria emphasize that students must have the ability to communicate effectively, (Engineering Accreditation Commission, 2001) but leave the interpretation of the outcomes that define effective communication to the individual programs. It is desirable for the students to learn these communication skills in the context of their specific disciplines; therefore, the trend has been towards integration of writing exercises through design and laboratory reports in the engineering courses in addition to their courses in the humanities component. Although much emphasis has been placed on the integration of both written reports and oral presentations into the core engineering curriculum, little has been said or done concerning the use of graphics as a communication medium. It has been said that graphics is the language of engineering (Bertoline, et al., 1995). Writing in the humanities does not depend heavily upon graphics. Mechanical design, in particular, requires extensive use of graphics, not only conventional orthographic drawings, but also sketches, solid models, graphical representations of various analyses and experiments, prototypes, and other graphical and physical models to communicate design concepts and outcomes effectively. This paper will present a review of the use of graphics tools by students in a sophomore level introductory mechanical design course and senior design projects with a focus on the use of graphical communication techniques and physical objects to develop and communicate design concepts.

Background

Engineering design graphics has been taught traditionally as the language of engineers (Bertoline, Wiebe, Miller & Nasman, 1995). Graphics is recognized as an important communication tool within the engineering community. Traditional entry-level courses focus on developing students' visualization skills through the creation of standard engineering drawings. Prior to the advent of computer-aided design (CAD), most engineering schools offered several courses in graphics and descriptive geometry. First year engineering students were required to take one or more of these graphics courses.

Recently, a trend towards removing engineering design graphics courses from the curriculum has emerged (Clark & Scales, 1999). This trend is driven not only by the availability of CAD software that facilitates the generation of engineering drawings, but also by pressures to include other topics in the curriculum. Furthermore, many schools have integrated graphics and CAD into other courses. In particular, entry-level introduction to design or introduction to engineering courses often contain a CAD component. The course described by Briller et al. is but one example of many such efforts (Briller, Hanesian, & Perna, 2001). However, many of these courses are electives, and the time spent by students learning graphical communications skills has been greatly reduced.

ABET's general accreditation criteria for engineering programs require that the students demonstrate: 3(g) *an ability to communicate* *effectively,* and 3(k) *an ability to use the techniques, skills, and modern engineering tools necessary for engineering practice* (Engineering Accreditation Commission, 2001). Graphical communication skills are not specifically noted. Specific engineering program requirements likewise do not mention visualization skills, graphics or geometry, with the exception of geological engineering, which requires the ability *to visualize and solve geological problems of a three-dimensional nature* (Engineering Accreditation Commission, 2001). Thus, the individual institutions must define the graphical communications skills and modern engineering tools to be learned and used by their graduates.

This paper will attempt to address the question by reviewing the work of mechanical engineering students in an introductory mechanical design course and in senior design projects with an emphasis on the use of graphics as a design communications tool.

ME2300 Introduction to Engineering Design

This course utilizes a realistic design process to introduce sophomore and junior level students to the methods and techniques for solving engineering design problems. The course focuses on the early phases of the design process, particularly needs assessment, development of product specifications and concept generation. Lectures on design theory and structured design methods such as benchmarking, customer needs assessment, development of product specifications, brainstorming and creativity exercises, and decision strategies are presented. Lectures are also provided to support the specific design projects and may cover a variety of engineering topics such as fluid dynamics, heat transfer, mechanics, statistics, elementary programming, basic circuits and engineering economics. Prior knowledge of introductory calculus, physics and statics is assumed. Laboratory sessions are used to conduct benchmarking experiments and to build, test and demonstrate various prototype designs. The course is designed to provide a broad overview of engineering design (Worcester Polytechnic Institute, Undergraduate Catalog, 2001-2002).

Graphics and CAD are not covered in the course, and no prior knowledge is assumed. There is no prerequisite graphics course required. However, on the first day of class, the students are given an exercise that highlights the importance of graphics in engineering communications. The exercise is relatively simple. Each student is provided with a structure or mechanism built from a set of standard construction toys such as K'nex, LEGOs or GeoShapes. The students are instructed to describe the object such that a classmate can reconstructed the model from a duplicate set of parts, which may include extra pieces. Invariably, one or more students will ask whether they are allowed to use sketches or drawings in their description, however, the instructor merely re-emphasizes the original instructions to describe the object and communicate the necessary information to their classmates. Virtually all of the students include one or more sketches in their description, mostly pictorials. Fewer than half utilize orthographics; we have not collected data to determine whether those students who sketch orthographic views have also taken the introductory CAD/graphics course. Students are usually fairly successful in rebuilding their models; fewer than 5% fail to construct a model, and approximately 10-20% of the models have minor defects related to color or symmetry. As a conclusion to the exercise, the instructor leads a discussion on the importance of graphics and the use of proper technical terminology in communicating design ideas, noting that the descriptions containing well-annotated pictorial sketches and proper orthographic views were easier to follow than those that did not. Hopefully this insight will remain with the students when they begin to prepare their design reports.

The course runs for seven weeks, during which time the students complete two design projects, each lasting approximately three weeks. Both projects require the students to work in teams of 4-6 students. Students are required to keep informal design notebooks for both projects. The design notebooks are used to record ideas, meeting notes, test results, and any other information that demonstrate the student's work on the project. All work done on the project should be recorded in the design notebooks, including brainstorming sketches, design concepts and notes from project group meetings. Further documentation for the second project includes both oral presentations and formal written reports.

The first project involves the design of a robotic mechanism that is constructed from LEGOs MindStorms kits. The robot is required to perform some function such as navigating a maze or retrieving an object. The only documentation required for this project is the design notebook and an informal, intermediate oral presentation of preliminary design concepts (using PowerPoint). Students are graded based on the number of "quality" entries in their design notebooks, as well as their robot's performance in the final contest. A "quality" notebook entry consists of a concept sketch, written description of a design, test results, notes on programming the robot, decision matrix, photos of candidate designs, flow chart, minutes of team design meetings, etc.

The second project involves the design of an assistive device for a person with a disability. Example projects have included redesign of a headpointer, a laptray, and an adaptive fishing apparatus. The students interview the client to assess user needs, conduct product and patent searches to identify potential solutions and create concept solutions for the client. Documentation includes the design notebook, a formal oral presentation and written report to the client, and a physical prototype or scale model, if appropriate. A review of the documents generated by the students during these two projects shows the use of various graphical elements, as shown in Table 1.

In Table 1, the graphical elements are identified as follows. An informal sketch is hand-drawn, and may be a pictorial, diagram, chart or graph. Most of the informal sketches were pictorials of design concepts. A formal sketch or diagram is created using a 2D drawing package such as MS-Paint, or may be copied from another source such as a textbook.

Average Number of Graphical Elements in Introductory Design Course Documents

	Project #1 LEGOs		Project #2 Assistive Devices	
	Design Notebook (n=30)	PowerPoint Presentation (n=8)	Design Notebook (n=29)	PowerPoint Presentation (n=9)
Informal Sketches	21.5	-	14.4	1.0
Formal Sketch/Diagram	0.1	0.4	0.4	0.1
Orthographic Drawings	-	-	0.4	0.3
Solid Model Images	0.4	0.4	0.7	3.2
Function Plots	-	-	-	-
Photos	2.4	2.3	2.8	2.1
Other	0.3	0.6	0.3	0.4
Total	24.7	3.6	18.9	7.2

Table 1

Orthographic drawings are dimensioned multi-view layouts and may be generated either with a 2D CAD package, from a 3D solid model or hand drawn. Solid model images are renderings of solid CAD models, usually in shaded, axonometric views. Function plots are generally x-y curves and are typically used to represent experimental or analytical data (velocity vs. time, etc.). Photographs consisted mainly of digital images of their robotic prototypes for Project #1, or photos of items related to the disability project (laptrays, wheelchairs, etc.) for Project #2. Other items included miscellaneous graphics such as PERT charts, flow diagrams, organizational charts, copies of patent drawings, and screen dumps.

Table 1 shows that over three-quarters of the design notebook entries are hand-drawn sketches, although these tend to be of variable quality. Figures 1 and 2 show some typical sketches. Using a draw package to create neat, formal sketches is time-consuming and many students do not have the skills to use even these simple graphics packages to demonstrate their designs. Formal sketches are thus only generated when a formal report is required. An additional 10-15% of the graphics are digital photos. Students find this a quick and easy way to document their designs. The digital photos can simply be pasted into their notebooks. Orthographic drawings and function plots comprise fewer than 10% of the graphics used in the design notebooks for these concept designs.

Students are given a fifteen minute mini-lecture on using PowerPoint, however, there is no discussion of the use of graphics in the PowerPoint slides. None of the teams reported any difficulty in creating slides for their oral presentations. Graphics were incorporated onto about half of the slides. These graphics typically included digital photos (39%), renderings of solid models (34%), and scanned images of their concept sketches (10%). Only three out of nine teams used orthographic drawings in their oral presentations to the

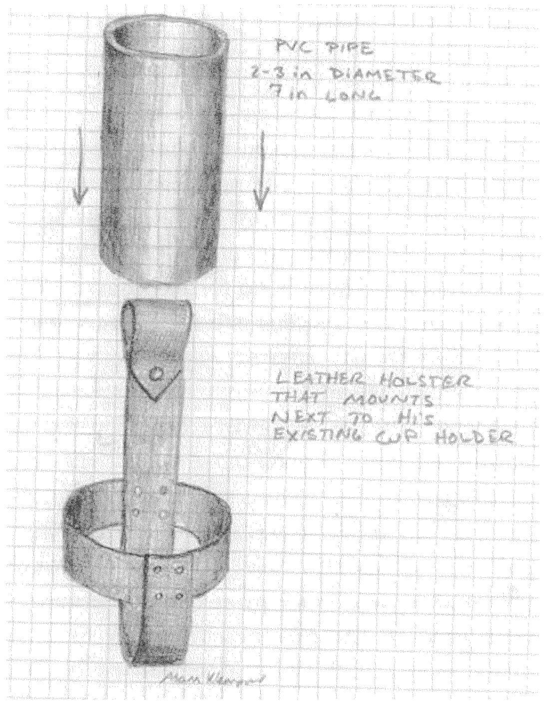

Figure 1 *Example of well-developed student design concept sketch*

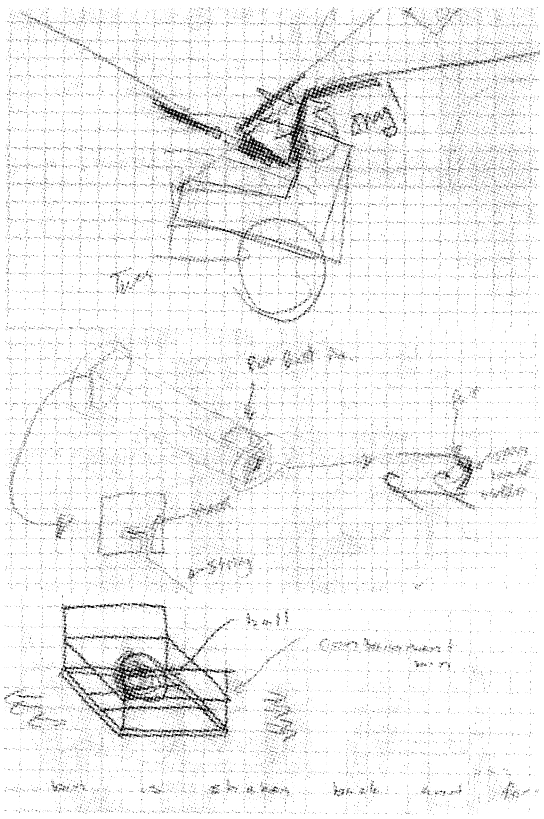

Figure 2 *Examples of rough sketches created by students in design notebooks*

clients for the assistive devices; none were used for the LEGOs robotics projects.

Senior Design Projects

All students are required to complete a capstone design project during their senior year. These projects are usually conducted as team projects and require an effort equivalent to three courses. There is no formal course associated with the project; student teams meet with their faculty advisor weekly during the year. About half of the projects are sponsored by local industry. All teams are required to submit a formal report; most teams will also participate in the annual project poster competition. All of the final reports submitted during the academic year 2000-2001 were reviewed to determine what types of graphics were used in the documentation. A total of forty-two (42) reports were submitted by 104 students, for an average team size of 2.6 students/team. Average report length was sixty (60) pages with an additional twenty-seven (27) pages of appendices. Table 2 shows the use of graphical elements in the senior design project documentation.

For the formal reports, there are wide variations in both the number and types of graphical elements used by the students. The % entry indicates the percentage of total graphical elements in all reports for each type, whereas the Team % entry indicates the percentage of teams that used the element type. Note the large standard deviations and ranges of instances for each graphic element type. This is certainly not unexpected, because of the wide range in topics for these projects. One project may have a large number of finite element analyses, whereas another may contain numerous plots from experimental data. All reports contained some graphic content generated by the students. The most common graphic elements created by the students were x-y plots of experimental data and/or analytical calculations (80%), most using Excel or similar spreadsheet software. Formal diagrams or pictorial sketches were generated by 75% of the teams, and an additional 15% of the reports copied sketches or diagrams from outside sources. Two-thirds used digital photographs taken by the project team; another 10% used digital images from outside sources.

Average Use of Graphical Elements in Senior Design Project Documents

	Final Report (n=42 teams)						Poster (n=26 teams)		
	Avg.	**SD**	**Min.**	**Max.**	**%**	**Team %**	**N**	**%**	**Team %**
Informal Sketches (hand drawn)	3.1	10.8	0	65	6	17	0	0	-
Pictorals/Formal Sketches	6.6	7.0	0	31	14	90	28	10	42
Orthographic Drawings	4.8	11.7	0	74	10	55	3	1	-
Photographs	8.4	9.8	0	53	17	76	123	44	81
Function Plots	15.9	24.1	0	102	33	80	72	25	69
Solid Model Images	5.4	8.2	0	35	11	60	37	13	15
Other Graphics	5.0	9.1	0	46	9	57	19	7	-
Total	49.2	34.5	5	137	100	100	282	100	100

Table 2

About three-fourths of the teams prepared either orthographic drawings or solid models (71%); solid models were slightly more prevalent at 60%, with orthographics in 55% of the reports. One-fourth of the teams with solid models did not create orthographic drawings. Only 17% of the teams that created orthographic drawings (4 teams) did not generate them from solid models.

Fewer than one-fifth of the teams included informal sketches, and only two reports contained copies of patent drawings. Statistical formats such as bar charts and pie charts were used occasionally. Other infrequently used graphics included flow charts, organizational charts and trees, electrical schematics, screen dumps and spectral plots.

In addition to the types of graphics used by each team, it is interesting to compare the number or frequency of use in each report. Surprisingly, since these are capstone design reports, there are very few orthographic drawings, averaging fewer than five (5) drawings per report, or about 10% of the total graphic content. Renderings of solid models appear with only a slightly higher frequency of 11%. Only informal sketches have a lower frequency at an average of three (3) per report or 6%. Pictorials and diagrams occur at a frequency of about 14%, however, approximately half of these graphics are scanned images from outside sources and were not created by the students. Digital photographs are easily obtained and occur with an average frequency of eight (8) per report, or 17%. Many of these photos have been enhanced or annotated using software such as Adobe PhotoShop. Finally, function plots comprise nearly one-third of the graphic content, with an average frequency of sixteen (16) per report, and tend to dominate the graphic content. The majority of these plots represent experimental data collected during prototype testing, benchmarking, or studies using analytical models.

Posters prepared by the students for their final presentations show similar trends, with the exception of the lack of orthographic drawings. Students used photographs more frequently, with a slight reduction in the percentage of data plots and images of solid models. Since specific details of the design, analysis and testing are less important in a brief presentation such as the poster session; digital photos serve primarily as an opening to the discussion with viewers of the poster, and technical detail is omitted. A general audience more easily interprets photos as compared to traditional technical graphics. During the poster session, students were provided desktop space and access to computers and video equipment. Many teams elected to display prototypes, utilize computers for software demonstrations, simulations and animations, or show videos of experiments. The use of these multimedia graphical communication tools enhanced the students' presentations.

Discussion

Students in mechanical design use a wide variety of graphical elements to document their designs. These include not only conventional "engineering graphics" such as orthographic drawings, but also digital photographs, function plots of experimental and analytical data, both formal and informal sketches and diagrams, statistical graphics such as bar and pie charts, patent drawings, images of solid models, and various other miscellaneous graphical elements. Students at our institution do not have access to rapid prototyping equipment, so there were no 3D graphical objects generated from their solid models, but students did use conventional prototyping materials and methods to prepare mock-ups or models of their designs.

Informal sketches are useful at the concept generation stage and for discussions with fellow students; however, the sketching ability of most students is not well-developed. Students working informally need sketching skills, as evidenced by the frequent use of sketches in their design notebooks. Some training in sketching would help to improve their skills in this area.

Digital photographs are a very popular method of documentation in student design reports. Many of the digital images were annotated or enhanced using either image editing software or within the word processor. Quality of photography may vary, but digital photos are easy and cheap, so only the best are presumably included in the reports and presentations. Nonetheless, it would be useful for students to have a better understanding of basic photography and digital image manipulation.

Formal reports often include function plots. Experimental data and results of design analyses are often displayed with x-y plots or other figures or diagrams. The display of various types of information for scientific purposes can take on many forms, and the use of simple function plots may not always be the best tool for scientific visualization (Tufte, 2001). Figure 3 shows a plot of experimental data comparing various design options. Note the use of multiple scales along both axes, which has the effect of superposing and sorting the data in this multi-dimensional representation, and allows the presentation of multiple design variables for comparison. Engineering students generally receive no formal training in scientific visualization methods, but would be well served to study this topic.

Diagrams, sketches and pictorials for reports and presentations are generated using 2D computer drawing packages or scanned from outside sources. Students seem to readily acquire basic skills with simple draw and paint type graphics tools, however, it can be time-consuming to create formal diagrams and sketches using computer software. This might be avoided with better sketching skills.

Conclusions

This study demonstrates the wide variety of graphics elements used by mechanical engineering students to document their designs, in both formal and informal settings. The documents surveyed in this report include only notebooks and reports, and do not include additional multimedia graphics or rapid prototypes that could be used in design presentations. These forms of graphics are coming into more widespread use in engineering communications. Although this is a limited survey conducted at a single institution, it may provide some insight regarding the use of graphics as a communication tool by student design-

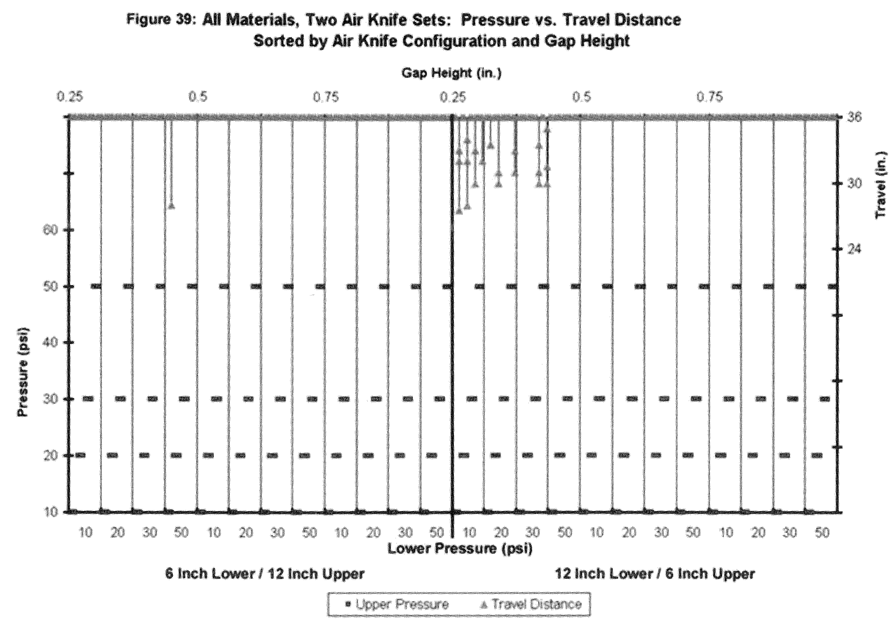

Figure 3 *Multi-dimensional plot of experimental data from a design experiment*

ers and the needs for changes in focus within the graphics curriculum.

Recommendations

Further research is needed to replicate this study across a broader spectrum of students in engineering and technology programs. A comparison of graphical communications skills used not only by engineering students but also by practicing design engineers would help to define the range of topics that should be covered in the engineering curriculum. All types of graphical or non-text communication media should be studied, including multimedia animations and 3D models such as rapid prototypes.

Based on this limited study, we conclude that our engineering students need more than just CAD skills to effectively communicate design concepts. The curriculum in Engineering Design Graphics has seen a reduction in content at many universities over the past few decades, particularly since the introduction of CAD. Students were previously taught sketching as well as skills needed to prepare formal engineering drawings, with or without CAD. This study shows that sketching is an important skill for design engineers, however, few students have good sketching skills and therefore find it difficult to produce informal sketches that can be interpreted by others. Furthermore, students utilize other graphical elements for visualization of complex data. These may be in the form of 2- or 3-D function plots, color contour plots, and various other forms of scientific visualization tools to display the complex data that are generated by sophisticated analysis techniques such as Finite Element Analysis and Computational Fluid Dynamics packages and experimental data collected with devices such as signal analyzers and data acquisition systems. Rather than reducing the emphasis on graphics in the engineering curriculum, students should be taught how to use a much broader range of graphical elements to communicate their design ideas.

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