Teaching engineering design skills

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ABSTRACT

The Project-Based Learning approach is used to introduce design skills from the freshman all the way to the junior and senior level in the BSAE Program at San Jose State University. The culmination of this effort is a two-semester senior capstone experience in aerospace vehicle design, in which students conceive, design, and often build an air or a space vehicle. The paper discusses a systematic approach for defining and teaching engineering design skills. Although the examples presented in the paper are from the field of aerospace engineering, all the principles apply to engineering design in general.

What makes the teaching of engineering design particularly challenging is that the necessary skills and attributes are both technical and non-technical and come from the cognitive as well as the affective domains. Each set of skills requires a different approach to teach and assess. Implementing a variety of approaches for a number of years at SJSU has shown that it is just as necessary to teach affective skills as it is to teach cognitive skills. As one might expect, each set of skills presents its own challenges.

Keywords: *engineering design, project-based learning, teaching design*

INTRODUCTION

Design is the heart of engineering practice. In fact, many engineering experts consider design as being synonymous with engineering. Yet engineering schools have come under increasing criticism after World War II because they have overemphasized analytical approaches and engineering science at the expense of hands-on, design skills (Seely, 1999 and Petrosky, 2000). As the editor of Machine Design put it, *schools are being charged with not responding to industry needs for hands-on design talent, but instead are grinding out legions of research scientists…*(Curry, 1991). Nicolai (1998) has expressed similar concerns.

In response to this criticism as well as for increasing student retention, many engineering schools, including SJSU, introduce design at the freshman level, as a way to excite students about engineering. Freshman design also helps students put into perspective the entire curriculum, by viewing each subject as a necessary tool in the design process. Design is also globally dispersed in a variety of junior and senior level courses in the form of mini design projects and is finally experienced in a more realistic setting in a two-semester, senior design capstone experience.

The paper first attempts to provide a comprehensive definition of design skills. Subsequently, it presents a model for curriculum design that addresses these skills. What makes teaching engineering design particularly challenging is that the necessary skills and attributes are technical as well as non-technical, and come from the cognitive as well as the affective domains. For example, the ability to define "real world" problems in practical (engineering) terms, to investigate and evaluate prior solutions, and to develop constraints and criteria for evaluation are technical skills, while the ability to communicate the results of a design, to work in teams, and decide on the best course of action when a decision has ethical implications are non-technical skills. Most technical skills are cognitive, however, there are several skills from the affective domain as well, such as the willingness to spend time reading, gathering information and defining the problem, and the willingness to risk and cope with ambiguity, to welcome change and manage stress. All these skills, technical and non-technical, cognitive and affective are essential for engineers, yet each requires a different approach to teach and assess.

DEFINING ENGINEERING DESIGN SKILLS

What is Engineering Design?

To define the skills necessary for design engineers we need to look at the definition of engineering itself.

Engineering is the creative application of scientific principles to design or develop structures, machines, apparatus, or manufacturing processes, or works utilizing them singly or in combination; or to construct or operate the same with full cognizance of their design; or to forecast their behavior under specific operating conditions; all as respects an intended function, economics of operation and safety to life and property. (Wikipedia, from the American Engineer's Council for Professional Development)

Nicolai (1988) offers a simpler definition: *engineering is the design of a commodity for the benefit of mankind.*

Obviously, the word *design* is key to any definition of engineering. Engineers design things in their attempt to solve everyday problems and improve the quality of our lives. As Theodore Von Karman put it: *A scientist discovers that which exists. An engineer creates that which never was.*

Furthermore, it appears that engineers need to be concerned about the economics as well as the broader impact of their designs to individuals, the society, and the environment. This has become more important in our interconnected, globalized world. Pink (2005) adds an additional challenge, one that relates to aesthetics. He argues that because of the 'abundance' of products we have come to expect in the 21st century, the lower manufacturing cost in many countries, and the fact that many engineering tasks can now be automated, *it is no longer enough* (for engineers) *to create a product that's reasonably priced and adequately functional.*

It must also be beautiful, unique, and meaningful. This requirement adds a new dimension to engineering design, a dimension that has much in common with the creative arts.

The Engineering Design Process

The next step in our search for design skills is to look at the engineering design process. Figure 1 is an attempt to illustrate this iterative process, as it takes place in our brain (Nicolai, 1998).

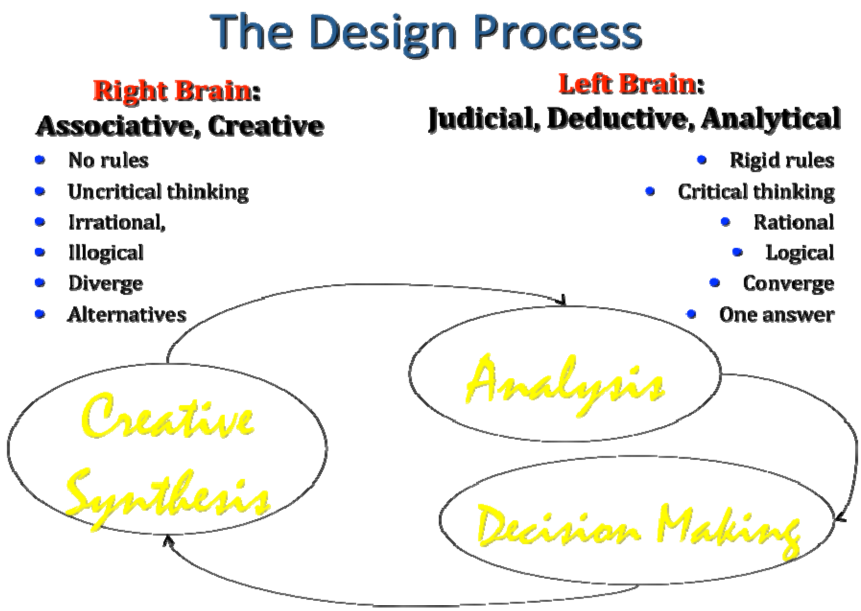

Figure 1: The engineering design process: An iteration between creative synthesis and analytical evaluation (Nicolai, 1998).

Design begins with brainstorming of ideas. This takes place in the right (creative) part of the brain. There are virtually no rules in generating these ideas. In fact, it is desirable to come up with as many ideas as possible and allow for "wild" ideas as well as conventional ones. While storming, the right brain tends to be holistic, intuitive, and highly nonlinear (i.e. it jumps around). It sees things in their context as well as metaphorically, recognizes patterns, focuses on relationships between the various parts and cares about aesthetics.

Subsequently, each idea is evaluated in the left (analytical) part of the brain under very rigid rules. The left brain acts as a filter on all the ideas generated, deciding which ones are viable under the current rules and which ones are not. The left brain tends to be logical, sequential, computer-like. It sees things literally and focuses on categories.

As Figure 1 illustrates, the design process involves an iterative cycling through a sequence that involves creative, imaginative exploration, objective analytical evaluation, and finally making a decision. It is this context, known also as convergent – divergent thinking (Nicolai, 1998), in which one should look for the skills and attributes necessary for a good design engineer.

The iterative nature of engineering design is well established through experience and is attributed to the open-ended nature of design. It is simply not possible to follow a linear, step-by-step process and arrive at a single answer or a unique product that meets our need. First of all, design requires numerous assumptions because there are always many unknowns. Some of these assumptions may be proven wrong down the road, hence the need for iteration. The non-unique nature of design becomes obvious when one looks at the multitude of products available in the market to address a given need.

Design also requires compromise because requirements often conflict with each other. For example, to provide comfort for airplane passengers one needs a large cross-sectional area. But a large cross-sectional area results in greater drag and compromised fuel efficiency, especially at high speeds. A successful aircraft designer must decide where to draw the line between these two conflicting requirements.

Skills and Attributes of Design Engineers

Clearly, engineering design is a very complex process and as such, it requires several, very different from each other, sets of skills. These are briefly discussed in the following sub-sections.

Analytical Skills

The right-hand side of Figure 1 attests to the need for traditional engineering analytical skills: solid fundamentals in mathematics, physical science (e.g. physics, chemistry, etc.), and engineering science (e.g. fluid mechanics, thermodynamics, dynamics, etc.). Outcome 3a of ABET EC 2000 (Engineering Accreditation Commission) highlights this need.

Open – Ended Problem Solving Skills

Design skills build upon open-ended problem solving skills. Outcome 3e of ABET EC 2000 highlights the need for such skills when it states that engineering graduates must be able to *identify* and *formulate* engineering problems in addition to being able to solve such problems.

Students who are open-ended problem solvers exhibit the following attributes (Woods, 1997):

a. Are willing to spend time reading, gathering information and defining the problem.

b. Use a process, as well as a variety of tactics and heuristics to tackle problems.
c. Monitor their problem-solving process and reflect upon its effectiveness.
d. Emphasize accuracy rather than speed.
e. Write down ideas and create charts / figures, while solving a problem.
f. Are organized and systematic.
g. Are flexible (keep options open, can view a situation from different perspectives / points of view).
h. Draw on the pertinent subject knowledge and objectively and critically assess the quality, accuracy, and pertinence of that knowledge / data.
i. Are willing to risk and cope with ambiguity, welcoming change and managing stress.
j. Use an overall approach that emphasizes fundamentals rather than trying to combine various memorized sample solutions.

Mourtos, Okamoto, & Rhee (2004) classified these attributes in Bloom's taxonomy of educational objectives: b, c, e, h, and j belong in the cognitive domain (Bloom, 1984), while a, d, f, g, and i come from the affective domain (Bloom, Karthwohl, & Massia, 1984). The observation that some of these attributes are associated with the affective domain suggests that engineering design is not all about cognitive skills; it is also about acquiring the right attitudes. Although it is not difficult to illustrate the need for such skills in class, their assessment is more challenging and requires special rubrics. Mourtos (2010) presents an example of a set of rubrics developed to assess open-ended problem solving skills.

A View for Total Engineering

Design engineers must be generalists and acquire a basic understanding of a variety of subjects, from within as well as outside their major – in fact, even from outside of engineering – to develop a view for total engineering. For example, an aircraft designer must have a good understanding of the basic aeronautical engineering disciplines: aerodynamics, propulsion, structures and materials, stability and control, performance, weight and balance. In addition, he/she must develop an understanding of how each part is manufactured and how its design and manufacturing affects the acquisition and operation cost of the airplane.

The example above illustrates the multidisciplinary nature of engineering design. Clearly, being an expert in one of the fields involved and inadequate in one or more of the rest, will not work well for a design engineer. Furthermore, engineers must take into consideration a variety of constraints when they design a new product. Some of these constraints are technical; some are non-technical. This expectation is stated in Outcome 3c of ABET EC 2000:

Engineering graduates must have an ability to design a system, component, or process to meet desired needs within realistic constraints such as economic, environmental, social, political, ethical, health and safety, manufacturability, and sustainability.

The importance of taking into consideration non-technical constraints (e.g. social, political, ethical, safety) is further reinforced in other ABET outcomes as well, where engineering graduates are expected to have:

> *3f: an understanding of professional and ethical responsibility.*
> *3h: the broad education necessary to understand the impact of engineering solutions in a global, economic, environmental, and societal context.*
> *3j: a knowledge of contemporary issues*

In summary, the design engineer must develop an aptitude for systems thinking and maintain sight of the big picture, which is often influenced by technical as well as non-technical factors. Clearly, it is very difficult to quantify a set of specific skills to describe the ideal design engineer. Nevertheless, in an effort to facilitate the teaching and assessment of these design skills, the BSAE Program at SJSU adapted the following set performance criteria:

Aerospace engineering graduates must be able to:

a. Research, evaluate, and compare aerospace vehicles designed for similar missions.
b. Follow a prescribed process to develop the conceptual / preliminary design of an aerospace vehicle.
c. Develop economic, environmental, social, political, ethical, health and safety, manufacturability, and sustainability constraints and ensure that the vehicle they design meets these constraints.
d. Select an appropriate configuration for an aerospace vehicle with a specified mission.
e. Develop and compare alternative configurations for an aerospace vehicle, considering trade-offs and appropriate figures of merit.
f. Apply aerospace engineering principles (ex. aerodynamics, structures, flight mechanics, propulsion, stability and control) to design the various vehicle subsystems.
g. Develop final specifications for an aerospace vehicle.

Ability to Use Design Tools

Freehand Drawing and Visualization

Drawing is the ability to translate a mental image into a visually recognizable form. Eventually any design drawing is rendered as a Computer–Aided Drawing (CAD) with the help of appropriate software. However, CAD is not the best medium when a creative design engineer wants to convey an idea of "how things work" to nontechnical people. Freehand pictorial drawing is most easily and universally understood. Furthermore, a freehand drawing can be a very effective and quick way to communicate ideas in three-dimensions when concepts evolve quickly, as is the case during the early stages of design (e.g. brainstorming), at which point it is not worth investing time and effort in a CAD.

Leonardo da Vinci (1452 – 1519) was one of the earliest engineers who demonstrated mastery in freehand drawing, making it possible for us today to visualize how his inventions worked and appreciate his genius (see for example Figure 2). Freehand drawing is a right-brain activity because it is free of technical symbols and it is closely associated with our ability to visualize things in three dimensions, an indispensable design skill.

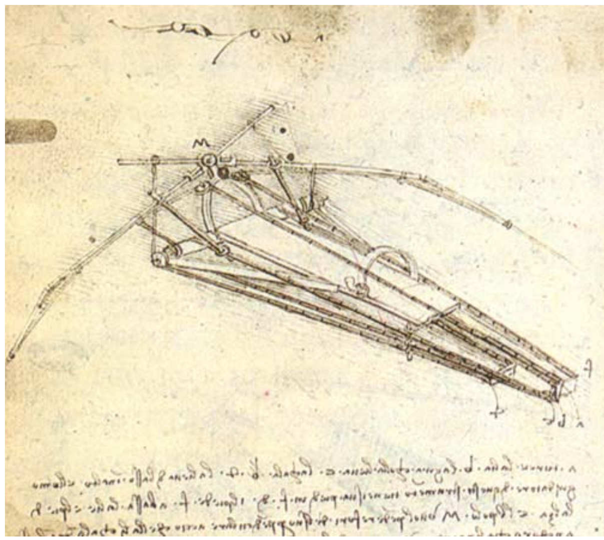

Figure 2: Design for flying by Leonardo da Vinci (The drawings of Leonardo da Vinci).

Computer – Aided Drawing and Computer – Aided Design

Unlike freehand drawing with its artistic flavor, engineering drawing is a precise discipline based on the principles of orthographic projection. In contrast to freehand drawing, engineering drawing emphasizes accuracy, something that has been greatly enhanced by the use of modern computers and graphic capabilities. Today a CAD is much more than a computer generated engineering drawing; it involves an extensive database detailing the attributes of an object and allows it to be rotated, sectioned, and viewed from any angle. This capability is indispensable in the design of complex engineering equipment, such as an airplane, because engineers can now superposition the various subsystems and immediately see potential conflicts. CAD has led to Computer-Aided Manufacturing (CAM), where the machines that manufacture the various components receive their operating instructions directly from the database in the computer.

Kinematics

A design engineer needs skills in kinematics since the various parts of an engineering product move, rotate and may also expand / retract or fold. An understanding of kinematics (e.g. selecting the proper mechanism and visualizing its operation) allows the design engineer to evaluate what will work and what will not work. For example, in the design of an airplane landing gear, the designer must be able to visualize how the gear will fold and retract in its proper space and make sure that it will not conflict with other components in the process.

The skills described in this section fall under Outcome 3k of ABET EC 2000, which states that *engineering graduates must have an ability to use the techniques, skills, and modern engineering tools necessary for engineering practice.*

Interpersonal, Communication, and Team Skills

Interpersonal & Team Skills

Archimedes designed his screw pump (Wikipedia, 2007) alone. This was not uncommon in the ancient world. Similarly, Leonardo da Vinci designed his engineering devices, such as the one shown in Figure 2, alone. Today, working alone to design an engineering product is, for the most part, a thing of the past unless, of course, the product is a very simple one. The complexity of modern engineering products requires engineers to work in teams; in fact, sometimes several teams must work together. For example, in the design of a new transport, it is typical to have a team of engineers from each of the disciplines mentioned above (aerodynamics, controls, manufacturing, etc.). These teams work closely together to meet the same set of mission and airworthiness requirements, while at the same time making sure there are no conflicts between the various airplane sub-systems.

Hence, although in section 2.3.3 we expressed the need for design engineers to be generalists to appreciate the multidisciplinary requirements that come into play in the design of a new product, it is not possible for an individual to have enough expertise in each and every one of the technical areas to adequately perform the detail design of all the subsystems, not to mention the analysis of the impact of a new product in a global, economic, environmental, and societal context.

Outcome 3d of ABET EC 2000 states that *engineering graduates must have an ability to function on multidisciplinary teams*. In today's multicultural world, this outcome also implies an ability to collaborate with people from different cultures, abilities, and backgrounds. The following performance criteria have been chosen to assess this outcome in the BSAE Program at SJSU:

Students must be able to:

a. Participate in making decisions, negotiate with partners, and resolve conflicts arising during teamwork, seeking consensus and exhibiting positive attitudes.
b. Set goals related to team projects, generate timelines, organize and delegate work among team members, and coach others as needed to ensure that all tasks are completed.
c. Demonstrate leadership by taking responsibility for various tasks, motivating and disciplining others as needed.

d. Demonstrate adequate understanding of other fields (ex. different branches of engineering / physical sciences, economics, management, etc.) to participate effectively on multidisciplinary projects.
e. Communicate ideas relating to aerospace engineering in terms that others outside the discipline can understand.

Communication Skills

In addition to the skill described in (e) above, design requires clear and effective communication between team members, as well as between the team and third parties (management, customers, etc.). Communication usually takes two forms, oral and written and can be informal, such as between team members or formal, such as when the team presents information to third parties. All four types are crucial for the success of a project. The need to communicate effectively is outlined in Outcome 3g of ABET EC 2000. In the BSAE Program at SJSU the following performance criteria were selected to express the skills embedded in this outcome:

Ability to:

a. Produce well-organized reports, following guidelines.
b. Use clear, correct language and terminology while describing experiments, projects or solutions to engineering problems.
c. Describe accurately in a few paragraphs a project / experiment performed, the procedure used, and the most important results (abstracts, summaries).
d. Use appropriate graphs and tables following published engineering standards to present results.

CURRICULUM AND COURSE DESIGN FOR TEACHING ENGINEERING DESIGN SKILLS

Like any set of skills, design skills must be introduced early, practiced often, and culminate in a realistic design experience if students are to achieve the level of mastery prescribed in ABET EC 2000 and expected in industry. The following subsections describe how design is introduced at the freshman level, is dispersed throughout the BSAE curriculum, and finally culminates in a senior design capstone sequence. The Project-Based Learning (PBL) pedagogical model is used in all courses where design is taught and students work in teams for all design projects.

First – Year Design

At SJSU engineering design is first taught in our Introduction to Engineering course (E10). E10 is a one-semester, two-hour lecture/three-hour laboratory course for freshmen, required by all engineering majors. Engineering design is taught through hands-on projects (PBL) as well as through case studies in engineering failures, which also bring up the subject of engineering ethics. For each project, students work in teams to research, brainstorm, design, build, test, and finally demonstrate a device in class (Mourtos & Furman, 2002). Typically, students participate in two or three projects during the semester. This course design followed well-established research, which shows that first-year design courses help attract and retain engineering students (Ercolano, 1996).

E10 students report significant gains in their understanding of design and ethics, design report writing and briefing skills (Mourtos & Furman, 2002). They report slightly lower gains in open-ended problem solving skills, including estimation and mathematical modeling. On the other hand, they report low gains in team skills. This is probably due to the fact that team skills were not taught explicitly at the time of the assessment. Despite a significant amount of time spent working in teams, students needed more guidance and coaching on skills like conflict resolution, task delegation, decision making, etc.). These skills are now taught more explicitly.

In addition to student self-reporting, authentic assessment data from course instructors show that engineering freshmen perform fairly well in their design assignments.

Design Globally Dispersed

In the BSAE Program design is dispersed throughout the curriculum, so students have an opportunity to practice design in a variety of subjects. Originally, design was introduced through projects in several junior level aerospace engineering courses. For example, in aerodynamics (AE162), students designed an airfoil and a wing, which met very specific requirements for a particular airplane. Similarly, in propulsion (AE167) students designed a compressor and a turbine and they subsequently matched them for placement in a jet engine with specific thrust requirements.

In an effort to address the compartmentalization of traditional engineering curricula this approach was modified in 2005. In each of the junior fall and spring semesters, students now define their own design project that involves applications from at least two courses, taken concurrently in the particular semester (Mourtos, Papadopoulos, Agrawal, 2006). For example, one project involved the design of a ramjet inlet and required integration of compressible flow (AE164) and propulsion principles (AE167). Another, more ambitious project involved the design of a flexible wing for high maneuverability and required integration of principles from aerospace structures (AE114), aerodynamics (AE162), flight mechanics (AE165), and computational fluid dynamics (AE169).

This project-based integration of the curriculum offers students an opportunity to appreciate the multi-disciplinary nature of aerospace engineering design on a smaller scale, before they delve into a much more demanding senior design experience.

Senior Design Capstone Experience

In their senior year, aerospace engineering students have the option to take a course sequence in aircraft design (AE171A&B) or in spacecraft design (AE172A&B). Although only one of these course sequences is required, a few students choose to take both in lieu of technical electives. Both courses involve the conceptual and preliminary design of an aerospace vehicle. If the vehicle is small (e.g. SAE[1] Aero-Design Competition or AIAA[2] Design/Build/Fly Competition), students also carry out the detail design of the vehicle, build it, and test it. Often engineering professionals from the aerospace industry mentor students in their designs. In addition to participating in these competitions, students also submit and present papers to student as well as professional conferences (e.g. Johnson et al, 2009; Casas et al, 2008).

Safety, ethics, and liability issues are addressed in the course through aerospace case studies involving accidents. Students research background information for each case, make a class presentation, and argue about the various issues in class. A written report is also required.

To introduce students to freehand drawing collaboration has been established with the SJSU School of Art and Design. A team of students from the graduate class Artists Teaching Art Seminar (Art 276) visits the aircraft design class and offers a three-hour workshop on freehand drawing, which includes contour drawing, gesture drawing, and perspective. Both groups of students have been very positive about their experience: the art students because they are given an opportunity to practice their teaching skills in a realistic setting; the aircraft design students because they get an opportunity to express themselves creatively within the context of a very demanding engineering course.

ENGINEERING DESIGN COMPETENCE OF FACULTY WHO TEACH ENGINEERING DESIGN

An additional challenge in teaching design is the competence level, as far as design skills are concerned, of the faculty who teach design courses. To provide a thorough analysis of this issue is beyond the scope of this article, however, it is worth mentioning two very distinct reasons, which contribute to this challenge:

(a) A successful completion of a Ph.D. degree, required for a faculty position at most engineering schools, entails primarily development of analytical (left brain), research skills but not necessarily design skills.

(b) To earn tenure and promotion in an academic setting engineering faculty are required to perform research, publish in refereed journals, and seek external funding. To maximize their chances for success under this kind of pressure, engineering faculty continue the same line of research they did in graduate

[1] Society for Automotive Engineering
[2] American Institute for Aeronautics and Astronautics

school. After all, the venues available for publishing design work or seeking funding to do such work are limited compared with traditional areas of engineering research.

Hence, when a faculty member is asked to teach a design course, they often find themselves unprepared. One way to address this deficiency is to require engineering faculty to undergo some training in engineering design before teaching a design course. There are many workshops on design for faculty members as well as for engineers who work in industry, sponsored by professional societies, universities, and engineering companies. Professional societies also offer summer Fellowships for engineering faculty willing to spend a summer in industry working alongside design engineers.

CONCLUSION

An attempt has been made to provide a comprehensive list of skills, technical and non-technical, for design engineers. These skills include analytical, open-ended problem solving, a view for total engineering, interpersonal and team skills, communication skills, as well as fluency with modern tools and techniques used in engineering design. In addition to these skills, design engineers must develop certain attributes, such as curiosity to learn new things and explore new ideas, self-confidence in making design decisions, taking risks by trying new concepts, thinking out-of-the-box, and persistence to keep trying when things don't work.

The paper touched briefly on the challenge of engineering faculty competence in design skills. It also presented course and curriculum design from the BSAE Program at SJSU that addresses these skills and attributes. Some of the elements in this curriculum were introduced several years ago, have been assessed extensively and indicate that students indeed acquire an adequate level in some of these skills. Some of these elements, such as the teaching of freehand drawing through the collaboration with the College of Arts and Design, were introduced only recently and have not yet been assessed. In any case, the attributes of a design engineer, as described above, are difficult to measure and will require the development of special rubrics.

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