Int. J. Engng Ed. Vol. 22, No. 3, pp. 671–678, 2006
Printed in Great Britain.
0949-149X/91 $3.00+0.00

IDEA: Formalizing the Foundation for an Engineering Design Education*

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At Northwestern University we have recently created the Institute for Design Engineering and Applications (IDEA) within the McCormick School of Engineering. Through IDEA students can obtain a certificate in engineering design alongside their bachelor's degree in their engineering discipline. IDEA was formed with the goal of integrating interdisciplinary design throughout the engineering curriculum, and creating a design community to support innovation. In this paper we discuss the design principles, community-based practices, and central education components of the IDEA certificate program. In addition, we discuss our process for monitoring students' design understanding and performance and how we continue to evolve our design courses based on this data, as well as ongoing feedback from members of the IDEA community.

Keywords: design education; interdisciplinary design; experientail learning.

INTRODUCTION

SEVERAL influential educators have asserted that design is the core of engineering [1, 2] and that experiential learning is the basis for developing meaningful and robust understanding [3, 4]. As Simon states 'design, so construed, is the core of all professional training . . . schools of engineering are centrally concerned with the process of design' [1, p. 111]. Design requires unique knowledge and skills, or habits of mind, common to all engineering disciplines, and it is these skills and habits of mind that distinguish engineering as a profession.

Educational theories that emphasize experiential learning are also consistent with design activity. Dewey claims that 'education in order to accomplish its ends both for the individual learner and for society must be based in experience' [3, p. 89]. Following this sentiment, we reason that design is the experiential activity central to the practice of engineering. It is through the experience of engaging in design that students are able to develop knowledge and skills necessary for professional practice. However, while we acknowledge the educational value of experiential learning, we recognize there are other essential characteristics necessary to create an effective learning environment.

As Schon argues, experience should be coupled with reflection-in-action [5]. Reflection-in-action includes thinking critically about the current situation and generating on-the-spot experiments to test ideas and further refine one's thinking. In this way, reflection is the metacognitive activity that provides meaning and educational value to the experience. In Schon's terms, IDEA is structured to 'educate the reflective practitioner' such that students not only obtain experience in design but also learn how to tackle complex design problems with the capacity to reflect, make well-reasoned decisions, and revise when necessary. Through IDEA we integrate interdisciplinary design throughout the curriculum to enable students to develop the 'intellectually tough, analytic, partly formalizable, partly empirical, teachable doctrine about the design process' [1, p. 113].

Previous work introduced IDEA and presented some of the organizational details of the Institute [6]. The current paper provides more detailed information about the design activities within IDEA and explains how the Institute has evolved over the past year. Specifically, we provide a brief background on IDEA and present details about three specific aspects of IDEA: the design certificate program, the engineering design portfolio, and the Institute projects. Finally, we present some of the formative and summative assessment approaches we are using to evaluate students' design performance and inform the IDEA program.

CONCEPTS OF IDEA

IDEA was formed as a collaborative effort: engineering faculty, McCormick administration, engineering students, and experts from industry worked together to define IDEA's mission and vision and to establish learning goals for a robust design education. We formed IDEA based on input from key stakeholders to ensure our design education is firmly grounded in authentic engineering design practice.

From this collaborative and iterative process

* Accepted 14 December 2005.

several focusing principles of IDEA evolved. Specifically, we believe that:

- the design process is needs-driven (in contrast to specification-driven or hypothesis-driven);
- design is about converting intellectual capital into products and processes that meet societal needs;
- the design process encompasses many phases, and we seek to provide students experiences from design conception to production.

These three principles guided the development of IDEA courses and the types of design projects we integrate into the curriculum. In addition to these three principles, there are two additional features that are built into all of our design work: teamwork and communication. In fact, since the introduction of Engineering Design and Communication (EDC) in the mid 1990s (a course intended for first-year engineering students), teamwork and communication have been integrated into the culture of design activities within our undergraduate curriculum [7].

Specifically, students work in teams on all of the projects within the IDEA program. Students not only work in teams but are also provided instruction and feedback on their team performance in order to develop the teamwork and leadership abilities necessary for high performing teams [8–10]. In addition, starting at the freshman level in EDC, students are required to communicate their design work using multiple methods to a variety of audiences. For example, students communicate design progress with clients, instructors, and peers, using text, graphics, charts, oral presentations, etc. Students receive feedback on each of these communications and are coached on how to effectively communicate design progress and results and to understand some basics communication concepts, such audience, purpose, and genre.

Taken together the three design principles bullet-listed above, coupled with the emphasis on teamwork and communication, characterize the design activity underway in the IDEA program. The next three sections describe three aspects of the IDEA program that bring these principles to life and provide examples of how we enact these principles in the IDEA program.

The Certificate in Engineering Design

The purpose of the certificate program is to enable undergraduate students to develop design knowledge and skills that will provide them a competitive edge in their careers. They also gain an official credential from the university. Any Northwestern undergraduate engineering student is eligible to obtain a Certificate in Engineering Design concurrently with the Bachelor's degree in their discipline. Upon completion of specific design course requirements, students receive an official design certificate and recognition on their transcripts.

The certificate program focuses on innovative engineering design in a team-based, cross-disciplinary setting. 'Innovative design' implies both identifying and solving real-world problems, for actual clients. The basic premise and some of the preliminary requirements of the certificate program have been reported elsewhere [6]. However, since then several changes have been made, and formal University approval has been granted. We focus here on the salient revisions and additions to the certificate program.

To obtain the Certificate in Engineering Design students must complete a total of six design-related courses (five of these courses must be in addition to their major requirements) and create and defend an engineering design portfolio. There are two and a half required IDEA courses:

- IDEA 298 Interdisciplinary Design Projects I;
- IDEA 370 Engineering Portfolio Development and Presentation;
- IDEA 398 Interdisciplinary Design Projects II.

IDEA 298 and 398 tie into a set of multi-year interdisciplinary projects that we call 'Institute Projects.' Additional details about the Institute Projects are provided in section B.3. IDEA 370 is new half-unit course that was offered for the first time during the Winter 2005 quarter. Since IDEA certificate students are required to create an engineering design portfolio, IDEA 370 teaches students best practices in portfolio design and requires students to apply these practices in the construction of their individual portfolios. Additional details about the design portfolio and IDEA 370 are presented in section B.2.

An additional three and a half elective courses are required for the certificate and these courses fall into the following three categories: design, social sciences, and business and society. Example courses focus on topics such as Organizational Behavior, Economics and Finance for Engineers, Cognitive Psychology, and Principles of Human Centered Design. We view design activity as inherently cross-disciplinary, and our elective courses require students to gain as broad a perspective and knowledge-base as possible.

IDEA's Engineering Design Portfolio

Each certificate student must, in conjunction with his or her IDEA Faculty Advisor, create and present an Engineering Design Portfolio demonstrating proficiency in the following areas, as appropriate:

- Design process—evidence of effective planning and successful completion of a design project;
- Design analysis—use of analytical methods for decision-making and/or parameter optimization;
- Prototyping and implementation—evidence that student has built working artifacts;
- Modern software tools—evidence that student has gained proficiency with at least one such tool;

- Effective communication—accessible presentation of technical concepts, persuasion, oral presentation skills.

The Engineering Design Portfolio must be completed and defended to an IDEA faculty committee prior to graduation. Creating and defending an engineering design portfolio are culminating events for an IDEA certificate student. With the design portfolio, an IDEA student showcases his or her engineering work, provides evidence of mastery of specific design and communication skills, and furthers a personal career goal, such as obtaining a position in industry or acceptance into a program of graduate study.

Through IDEA 370 students produce an inventory of their skills, select work products that illustrate mastery of their skills, with an emphasis on technical competency, draft a portfolio that matches their career objectives, get feedback on their portfolio from IDEA faculty and from representatives of their chosen career field, analyze and revise their draft portfolio, and prepare and rehearse a portfolio defense.

Many of these portfolio practices align closely with design process activities. Portfolio students are required to understand their audience (users and stakeholders), perform research (as in design), develop a draft portfolio (build a mock-up), obtain feedback (user testing), revise their portfolio (design iteration), and receive faculty approval for quality assurance. The mapping of the portfolio process onto the design process is a seamless transition and offers a model that works very well with our IDEA faculty and students [11].

Figure 1 presents a sample page from one IDEA student's draft portfolio. This portfolio was created as part of IDEA 370 during Winter 2005. The sample page presented here describes a bracket design project where the student engaged in several design activities such as making preliminary calculations, modeling and stress testing using Unigraphics software, working in a team, and physically building and testing the device. The bracket design was part of a course project in a mechanical engineering course titled 'Introduction to Mechanical Design and Manufacturing.' The author of the portfolio shown in Fig. 1 is a junior in Mechanical Engineering and is scheduled to complete the Certificate in Engineering Design in Spring 2006.

Research/Education Integration: Institute Projects

IDEA Institute Projects are actual design problems currently faced in research, industry, and non-profit organizations that require students to convert their passive engineering knowledge to real solutions that have direct and lasting impact. Institute Projects are ongoing projects that span multiple academic quarters. Different student teams enroll each quarter, and each team advances the project as far as possible. Student teams complete the project course, upload their project documents to a shared electronic workspace, and a new team enrolls in the project in subsequent quarters. The new team accesses the previous team's project work and begins where the previous team left off. Ideally this process continues every quarter such that Institute Projects evolve through several phases of the design process. There were five Institute Projects underway for winter quarter 2005, including one that has been worked on by six different teams.

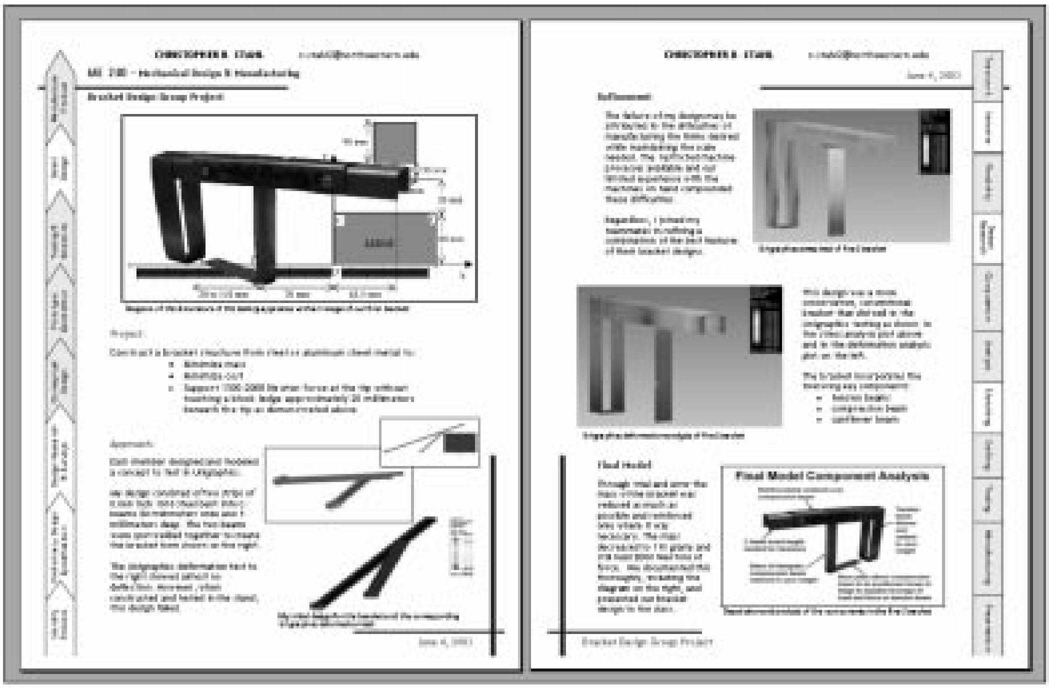

Fig. 1. Example page in one IDEA student's design portfolio.

In IDEA we seek to use research to support the goals of education. The modern research university provides an ideal environment for learning of science and design process through senior projects where undergraduates work directly with graduate students and post-doctoral staff engaged in frontier basic research. It is the research mission of IDEA to bring to this environment the same level of funded graduate interdisciplinary engineering activity, building the computational and human infrastructure supporting an analogous experience in undergraduate engineering education [12].

Under the recent DARPA-AIM initiative in accelerated implementation of new materials [13], faculty of several departments participated in the development of new interdisciplinary computational engineering tools and their effective integration within the commercial iSIGHT^{TM} process integration and design optimization software. The installation of the resulting 'AIMsight' system of tools brought new capabilities applied under our Office of Naval Research (ONR) Grand Challenge project on 'Naval Materials by Design.' Teams of undergraduates in a junior-level Materials Design class, coached by graduate students, performed conceptual and embodiment designs of a new class of high performance steels for anti-terrorism blast protection, with several students participating in subsequent experimental prototyping of the new alloys under Senior Projects. In parallel with the materials design work, other faculty participated in an ONR-MURI (Multi-University Research Initiative) project on the design, simulation and dynamic testing of novel cellular-core 'sandwich' laminate structures for efficient blast protection. The two ONR-funded programs provided a model IDEA Institute Project for our pilot offering of the IDEA 398 Interdisciplinary Design Projects course in the winter quarter of 2004.

A team of eight undergraduates from four departments integrated the new materials and structures into the design and simulation of highly weight-efficient anti-terrorism blast protection systems for a range of civilian ground transportation systems. With graduate student coaching, the team demonstrated feasibility of their material/structure combination with a realistic fluid–structure interaction computational blast simulation and gave an effective briefing to a representative of the Department of Homeland Security. During the subsequent spring quarter, a continuing IDEA 398 student collaborated with another junior-level materials design class team to design a next generation of blast protection steels responding to new property objectives defined by the winter quarter blast simulations, while working with graduate students to design and build a pressurized water blast chamber (see Fig. 2) for physical testing of the materials and structures. In parallel, a collaborating freshman EDC team interviewed commuters at local train stations and designed an adaptation of the technology for protection of commuter trains. With these projects the collaborating upper level teams became the 2005 winners of the national TMS-AIME (The Minerals, Metals, and Materials Society of the American Institute of Mining, Metallurgical, and Petroleum Engineers) undergraduate design competition. With further simulation, physical testing, and iterative design, this IDEA Institute Project has continued throughout the 2004–2005 academic year.

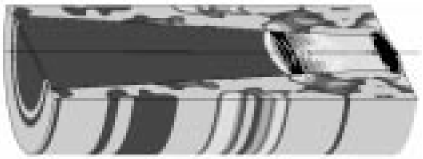

Fig. 2. Example of a numerical blast simulation.

This example Institute Project represents the type of authentic, interdisciplinary, and needs-driven design experiences we are building into our curriculum on a school-wide basis. Institute Projects are where sophisticated domain knowledge, creativity, design process, and problem-solving persistence converge to inspire innovations that meet societal needs.

Monitoring Students' Design Understanding and Performance

We view the IDEA program as a continuous work-in-progress, much like an open-ended design problem. We revise our courses and design experiences to close the gap between what students already know and what knowledge and skills should be further developed. We aim to bring a learner-centered approach to our design education such that courses build on students' prior knowledge, challenge students to develop sophisticated design competencies, and provide meaningful and relevant design experiences [14]. To meet this aim we have implemented a process to monitor student understanding of process and evaluate design performance.

We collect continuous qualitative and quantitative data to inform our curriculum. Students evaluate courses through end-of-course questionnaires and these results inform future course offerings. In addition, we use 'design scenario' assignments to evaluate students' conception of the design process and how these conceptions evolve over time [15, 16]. An example of a design scenario that we have used with our freshman students in EDC is given below.

> Assume that you are on a design team that has been hired by the Rehabilitation Institute of Chicago, the leading rehabilitation hospital in the country, to design a new device to help stroke patients open doors. Many individuals who have had a stroke are unable to perform bilateral tasks, meaning they have limited or no use of one upper extremity (arm/shoulder). It is particularly difficult for these people not only to unlock and turn the knob but also to

Table 1. Sample items in rubric for basic strategies or techniques one might do when solving a design problem

1. Generate alternatives
2. Prototype/mock-up, build model
3. Perform research (review competition or similar products/designs, conduct literature review on topic, investigate possible causes of problem(s) and existing solutions)
4. Define specifications, requirements, design constraints
5. Obtain feedback on an idea/design (users, peers, experts)
6. Brainstorm

push/pull the door open. Your design team has been asked to create a system that allows a person to unlock and open the door at the same time with one hand. Your design team accepts this challenge and goes to work. Map out a plan, describing how you intend to approach this project.

Complete scenario results will be reported in an upcoming article, but we present here some preliminary data to demonstrate our design scenario approach to measuring students' design performance. Students were presented with the design scenario at the beginning of EDC and again at the end. Student responses to the scenario assignment were coded according to a rubric, and their pre and post responses were compared. The coding was conducted such that if a student response mentioned an item given in the rubric the response received a '1' for this item, if not, the response received a '0'. A subset of the items from the rubric is given in Table 1.

Figure 3 provides the results for the pre and post data analysis. Student responses for all items shown in Fig. 3 had significant gains at the $p < 0.01$ level. Analyzing data at the item level provides useful information about students' approaches to solving a design problem and identifies details about students' conceptions of the design process. In addition, item analysis provides valuable information to the EDC faculty for understanding students' initial understanding of the design process and how the course impacts specific process abilities.

We have also created a 'design scorecard' that lists specific design criteria that student design work must meet. Table 2 provides a subset of some of the scorecard criteria and shows the definition of the scoring system. The scorecard makes our performance expectations explicit to students and provides feedback on the quality of students' design work. While the design scenarios provide information about students' conception of the design process, results from the scorecard provide direct feedback on the quality of students' design performance. We view both of these types of measures as complementary and essential to providing a comprehensive understanding of the impact of the IDEA curriculum.

The scorecard is used by faculty and industry reviewers in the IDEA 298 and 398 project-based courses. During the quarter, and at the end of the course, faculty refer to the scorecard to evaluate student progress and provide structured feedback for improving design performance. At the end of the quarter students are required to give a final presentation to which members of the class, the projects' clients, and IDEA faculty and staff are invited to attend. Faculty and outside reviewers (clients, invited industry guests) use the scorecard to rate design performance. An example of the scorecard results for one project, 'Hand Orthosis', is provided in Table 3.

The client for the Hand Orthosis project is the Rehabilitation Institute of Chicago and the primary goal of this project is to help stroke patients regain strength and flexibility in opening their fingers. Eight reviewers (five faculty, three industry) used the scorecard to evaluate the project and Table 3 presents the average and standard deviation for these reviews. The scorecard results provide a quick summary of the strengths, and areas of improvement, for this team's project work. For example, the Fall 2004 team did fairly well in defining the problem and generating alternatives, but they could have done much better in defining specifications and using appropriate

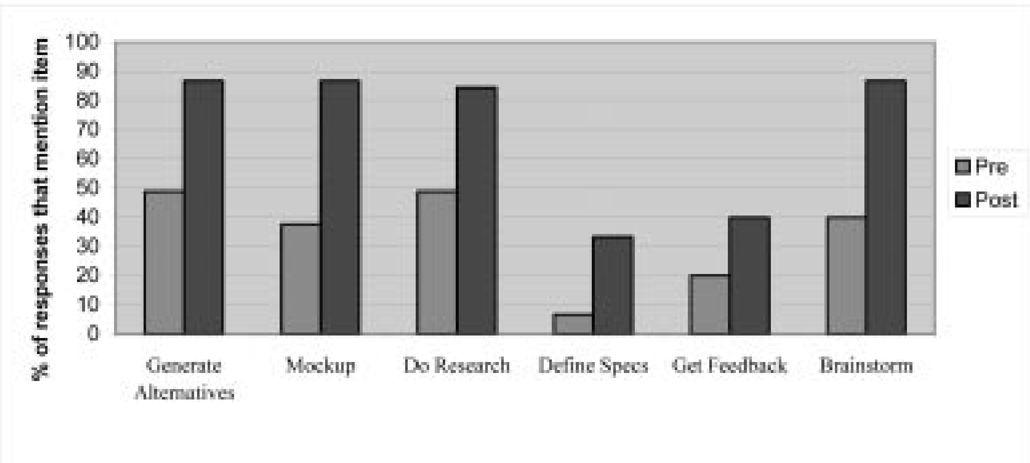

Fig. 3. Pre and post responses to design scenario, $N = 45$.

Table 2. Example scorecard criteria, and score guide, used to evaluate IDEA project work

Design process	Score
Clearly stated design problem	
Performed appropriate research to understand problem and/or solution	
Developed feasible design alternatives	
Obtained feedback from users, experts, peers	
Defined specifications, requirements, design constraints	
Met project design goals that were established at the beginning of the quarter	
Application of disciplinary knowledge in design . . .	
Used appropriate design techniques, tools, and processes	
Performed quantitative analysis of alternatives	
Conducted modeling, simulation and testing	
Demonstrated analytical refinement of the design	
Discussed assumptions and sources of bias	

Score	Explanation
9–10	Outstanding performance; exceeds expectations
7–8	Above average performance
5–6	Average performance
3–4	Below average performance
1–2	Substandard performance; not acceptable for idea
Nm	Item not mentioned or addressed
N/a	Item not appropriate for stage of project

analytic tools. These results not only provide feedback to the team but also inform the IDEA program. For example, we can look at the scorecard results across projects to determine if there are criteria that consistently score high or low. Consistent trends would indicate where the IDEA program is doing well, or in contrast, could better support specific design activities. Since we only have one scorecard data set, when we collect additional data future analysis will explore possible trends in performance.

Finally, IDEA functions very much as a community of practitioners such that ideas are encouraged and input is solicited from all participants (including staff, faculty, and students), and decisions are made collaboratively. Community plays a central role in how IDEA operates and as such is embedded in our assessment and evaluation process. For example, IDEA has a student advisory board that meets twice per quarter to provide the students' perspective on courses and projects. In addition, we hold bi-weekly faculty meetings to discuss any issues with courses or projects to get an update on project status and student performance, and to address any needs that may arise. We discuss and address issues as they arise and negotiate appropriate changes that need to be made.

SUMMARY

IDEA was formed as a collaborative effort with the goal of integrating interdisciplinary design throughout the engineering curriculum and of creating a design community to support innovation. This paper presented an overview of the guiding principles of IDEA and details about the central education components of the IDEA certificate program. Specifically, we described the requirements for the design certificate program,

Table 3. Scorecard results for the 'Hand Orthosis' project, Fall 2004

Scorecard criterion	Average score	Standard deviation
Clearly stated design problem	6.75	0.89
Performed appropriate research to understand problem and/or solution	4.75	0.71
Developed feasible design alternatives	5.63	1.77
Obtained feedback from users, experts, peers	4.14	2.34
Defined specifications, requirements, design constraints	3.86	1.07
Met project design goals that were established at the beginning of the quarter		
Used appropriate design techniques, tools, and processes	5.00	1.15
Performed quantitative analysis of alternatives	2.80	0.84
Conducted modeling, simulation and testing	4.20	2.17
Demonstrated analytical refinement of the design	3.25	1.50
Discussed assumptions and sources of bias	3.80	0.84

presented details about the engineering design portfolio, and provided details about the Institute Projects. In addition, we presented some of the formative and summative assessment approaches we are using to evaluate students design performance and inform the IDEA program. Through IDEA we provide the environment that enables students to be creative and use their formal engineering knowledge and skills to develop innovative solutions to real societal needs.

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