CONTINUOUS IMPROVEMENT AS A METHODOLOGY FOR INTRODUCING ENGINEERING DESIGN TO FIRST-YEAR STUDENTS

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Abstract *- Developing solutions to engineering problems is often an iterative process with improvement occurring over several generations of a design. For example, after almost 100 years of development of automobiles, engineers still find ways to make them safer, more fuel efficient, more reliable, and more economical. To make this happen, many practicing engineers work on refining existing products and processes rather than creating entirely new ones. Therefore, engineering graduates need to be prepared to work in this environment to design future generations of products, processes, and services.*

We have developed a "Continuous Improvement" laboratory framework that introduces first-year engineering students to design practice. This involves guiding students to systematically improve computer-controlled models of electromechanical systems while emulating the methods followed by practicing engineers. The initial systems were constructed by students in Spring 1999. The first improvement cycle took place in Spring 2000 when teams of first-year students received working systems developed in 1999 along with their full technical documentation. Each team applied the engineering design process to identify opportunities for improving their system and then implemented these improvements. The resulting systems (with revised documents) become the starting models for another cycle of improvement in Spring 2001. Through this project, students develop skills in problem solving, communication, teamwork, and project management.

In this paper, we will explain the motivation for and describe the Continuous Improvement methodology. We will compare this methodology to the process of building a new project. Finally, we will describe our students' experiences with identifying potential project improvements and preparing proposals including examples of specific improvements proposed.

INTRODUCTION

Freshmen design experiences are becoming more common in engineering curricula [1, 2]. Recently, Burton and White [3] presented a survey of 43 engineering schools that offer freshman engineering design courses. They concluded that full-scale, semester long projects provide students with the most comprehensive design experience. However, Burton and White also pointed out that these projects typically have several disadvantages including the need for extensive engineering facilities, the highest cost of teaching design methods, and a tremendous amount of coordination and scheduling.

Prior to 1999, our own efforts at the University of San Diego (USD) to introduce first-year students to the *practice* of engineering were unsatisfactory because students devoted so much of their time to fabricating and assembling their designs. It was difficult to teach them how to properly plan their projects, coordinate the development of the system among team members, and document their work. Each year, students would repeat many of the same "construction" steps that were necessary to have a finished project, but that did not contribute to a better understanding of engineering. Initial planning by students was deficient and there was little time left at the end so that students could evaluate their projects.

In 1999, the required USD freshmen engineering course, ENGR 20 Computer Aided Engineering, was revised to include a more comprehensive engineering design experience. The primary objective was to develop a laboratory methodology where students would develop engineering skills by completing a substantial design project. We were particularly interested in using this project to introduce first-year students to key ABET-identified skills for engineering graduates. These include the ability to solve open-ended engineering problems, to design a system to meet desired needs, to work in multi-disciplinary teams, to communicate effectively (written and oral), and to plan projects and monitor their progress (ABET Criteria 3 c, d, e, g, and k) [4].

A second objective was to improve retention of first-year engineering majors by providing a laboratory experience that students would find entertaining, challenging, and inspiring. Having such a positive impression of engineering has been shown to relate to retention of first year engineering students, particularly those who are in good academic standing [5].

Finally, we wanted to allow our students to spend more of their time engaged in hands-on "engineering" activities and less time working as "technicians." This laboratory would let students exercise their open-ended problem solving skills without requiring inordinate effort to construct their designs.

The result is a laboratory project called the e**N**gineering **I**mprovement in a **F**irs**T** **Y**ear (NIFTY) Design Project. [6,7] In this project, student teams create or improve working

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computer-controlled electromechanical systems that simulate real-world scenarios. They prepare all appropriate documentation and present their work to their ENGR 20 peers and to younger students through a service-learning experience at a local high school.

In this laboratory, the projects are carried over from year-to-year with successive teams of students *improving the existing systems* rather than developing new ones from scratch. This *Continuous Improvement* (CI) component of the laboratory methodology was initially developed as a sophomore-level, industrial automation course by one of the authors (JAM) [8] at Texas Tech University in 1992. However, that work was designed for sophomore students who had already completed a computer programming class and did not include significant evaluation of its effectiveness or interactions with high school students.

Improving an existing system allows students to experience the process of refining a system: an important aspect of engineering most students do not experience. Furthermore, the reuse of systems addresses some of the concerns pointed out in Burton and White [3] by reducing the cost of introducing a design project and the effort needed to administer the laboratory. It also allows students to devote more time developing engineering skills because construction time is reduced even when the projects present many open-ended design opportunities.

The next section will briefly describe the CI approach to engineering design. It will then fully discuss many of the opportunities and benefits that using CI can bring to a design laboratory and will contrast CI with the more common practice of designing and implementing new systems every semester. Following that discussion, an overview of the NIFTY Design Project will be presented. This will describe the scope of student design activities, the nature of the projects that were developed initially, and how CI is being applied to improve these projects.

CONTINUOUS IMPROVEMENT METHODOLOGY

Developing solutions to engineering problems is often an iterative process with improvement occurring over several generations of a design. There are many examples of products that, even after many years of engineering refinement, are still being improved. For example, after almost 100 years of development of automobiles, engineers still find ways to make them safer, more fuel efficient, more reliable, and more economical. Examples of recent improvements include airbags and antilock-brakes. The proliferation of cellular telephones, compact disc players, and camcorders are result of continuous improvement in the design and engineering of these products to make them better and more affordable. In some instances, improvements may be made to improve the reliability of the system in response to customer concerns. Other times changes are made to respond to increased competition and may result in a less expensive system or one that has improved functionality.

At some time during their career, many engineers will be faced with the task of improving an existing system, rather than developing a completely new one. In fact, most product engineering work consists of these improvement activities. Consequently, engineering graduates need to be prepared to work in this environment to design future generations of products.

In engineering design courses, exposure to CI activities may be achieved in several ways. One way would be to have students examine a working product (e.g. a blender), and suggest ways that the product could be improved such as the "Green Coffee Pot" project at Rowan University [9]. Selected improvements could be designed and possibly fabricated and implemented. A second approach might be to have students collect many generations of a product and explore the evolution of the product (e.g. follow the progression of computer mice having 1, 2 and 3 buttons, track balls, wheels, optical tracking, ergonomic shape etc.). A third approach (and the one that we have adopted) is to use projects completed one semester as the starting point for a future project. This approach to teaching design creates opportunities to develop skills and understanding that may be difficult to achieve in other design projects.

Because the students have to identify ways that their projects might be improved, they are required to critically evaluate the performance of an existing system. This can initially be daunting to a student presented with a project that seems to work very well. Closer examination (and prodding by the faculty) will reveal many opportunities for improvement. When students realize that they are able to identify improvements, they should gain confidence in their engineering abilities as they develop their critical reasoning skills.

As the students look for improvements, they will have the opportunity to identify, define, measure, and report system performance measures such as cycle time or mean time between failures. They can also learn to develop goals and commit to achieving specified performance levels from their modified system in the same way that practicing engineers need to identify their system targets then track their progress towards their stated goals.

Because the results from projects are used later, students will become more aware of the importance of maintaining good design documents and reports. This understanding will help them to document their project more completely for the benefit of the next team and should also motivate them to create good documents for their own use in the future.

Compared to a traditional design project, students practicing CI should be able to work more independently at the beginning of the semester because they have a working system and access to all of the design documents. The time needed to make physical or programming changes may be less than the time needed to build a system from scratch. This allows more laboratory time for other activities that are more directly related to engineering practice such as evaluating a completed system and exploring ways to make it better.

We do not expect that the level of faculty effort will be any higher with CI than for a more traditional design project. However, faculty time may be oriented differently. For example, faculty may be needed more for help in identifying improvements but perhaps less for debugging system problems if students are more systematic about making one change at a time.

A final advantage of the CI method is that the reuse of projects can help to manage lab costs. Because new systems are not developed from raw materials each year, it is not necessary to buy as many components as might be needed if projects use consumable materials (e.g. wood, foam, wire).

One possible concern about the CI approach is that subsequent student teams may not have the same opportunities to solve open-ended problems as do the students who build new projects. In fact, the CI students are still faced with these types of design challenges. For example, a student who is designing a catapult for the first time may have no inherent restrictions on what mechanism will be used to fire a projectile. Their problem may just be to build a system that fires. The CI student improving the system benefits from having a functioning system. Furthermore, the CI student must do more than simply fire a projectile; they must shoot it "better" (e.g. farther, more accurately, or with a shorter reloading time). The opportunities for creative solutions still exist but the problems are more focused.

A second reservation about the CI methodology may be the concern that projects will terminate when there are "no further improvements." In fact, it should always be possible to improve a project, but in the unlikely event that no improvements can be identified, a project can be "retired" and replaced by a new project, or returned to a previous state and given to a new student team.

NIFTY DESIGN PROJECT SYSTEMS

During the Spring 1999 semester, first-year engineering students enrolled in ENGR 20 at USD developed the following 11 projects:

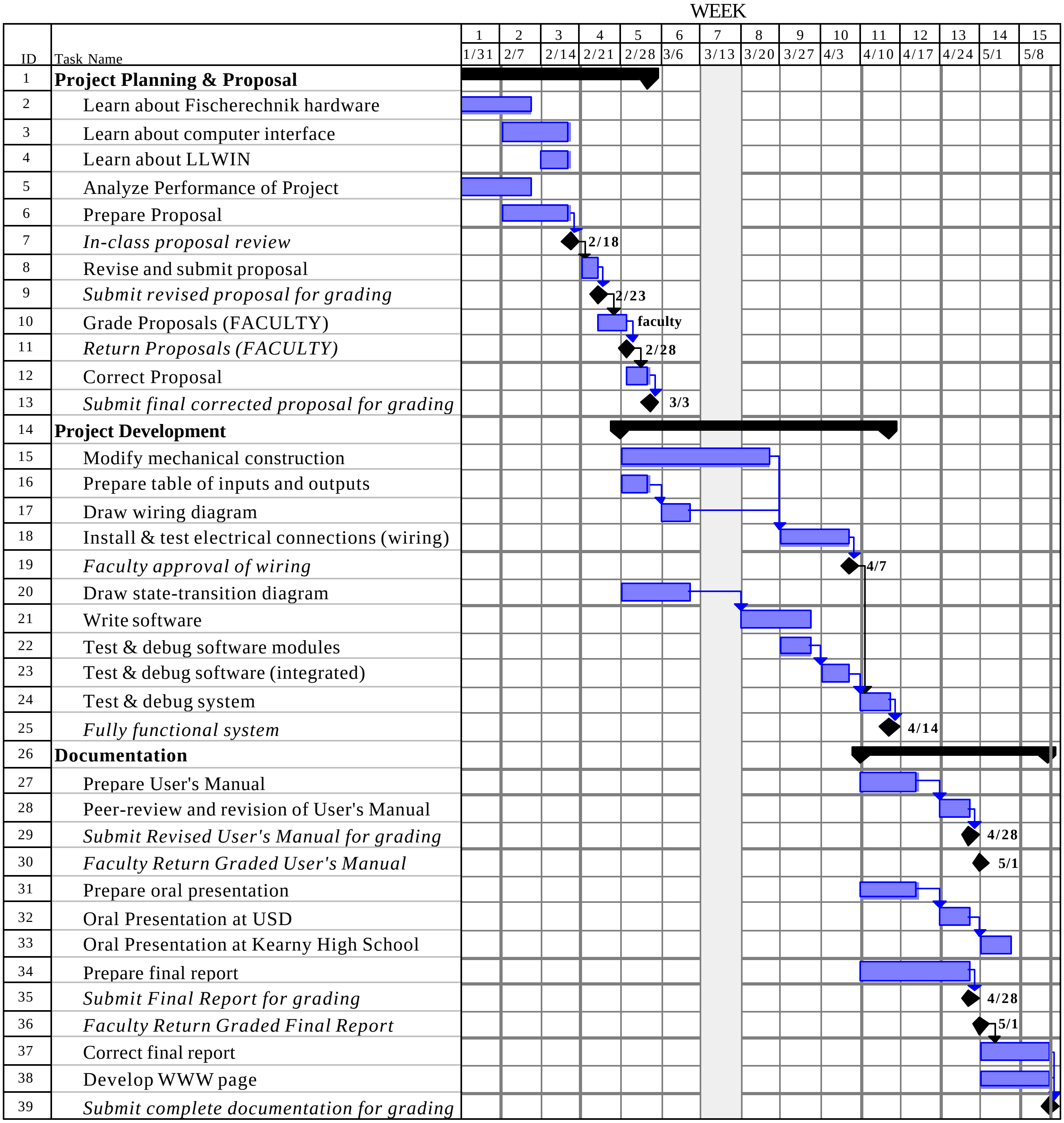
- Drawbridge
- Ferris wheel
- Car wash
- Golf tee loader
- Burglar alarm
- Metal separator
- Cargo elevator
- Candy dispenser
- Barrel filling conveyor
- Water bottle production line
- Food production line

These are all computer-controlled electromechanical systems built using fischertechnik® construction components. These components include a variety of building blocks, sensors, and actuators. Fischertechnik components were originally developed to facilitate engineering prototyping and their durability as well as the ease with which they can be assembled and modified permits students to go through several design iterations in a short period of time. These characteristics make them ideally suited for CI projects where students need to have the capacity to modify a system without damaging the system components.

All NIFTY projects were designed to be stored in 15"x 21"x 15" cabinets. These initial systems controlled 2 to 4 devices (e.g. motors and lights) and used 4 to 8 sensors (e.g. mechanical switches and phototransistors). The fischertechnik components can control up to 8 devices using as many as 18 sensors. All devices are safely powered using 6-volt power supplies or batteries. Fischertechnik interface boards and LLWin software are used to control the projects using personal computers.

To successfully complete the projects, students needed to design and construct mechanisms, install electrical wiring, develop control software, debug and test systems, and prepare documentation. Several of these activities could be accomplished simultaneously with proper planning and coordination between team members. Students developed and used Gantt charts for project planning and control. Details on the nature of the weekly lab activities and their relationships to ABET goals may be found in earlier papers. [6, 7]

Beginning in the Spring 2000 semester, ENGR 20 students have the assignment of improving the performance of one of the existing systems rather than creating a new system. Each of these unique systems has many opportunities for improvement or elaboration. The first few weeks of the semester are devoted to analyzing the performance of their assigned system, studying the reports created by the earlier design teams, and learning the tools needed to succeed in the course (for example programming, devices, Gantt charts). Figure 1 shows the Gantt chart that was used by students to manage their projects during the Spring 2000 semester. Students identify many of the areas for project improvement, write a proposal stating their intention to implement some of the changes, and then (after receiving project approval) execute the selected changes while fully documenting their work. The following year, the improved system, with updated design documents becomes the starting point for a new group of students, who will further improve the system.



ID	Task Name
1	**Project Planning & Proposal**
2	Learn about Fischerechnik hardware
3	Learn about computer interface
4	Learn about LLWIN
5	Analyze Performance of Project
6	Prepare Proposal
7	*In-class proposal review*
8	Revise and submit proposal
9	*Submit revised proposal for grading*
10	Grade Proposals (FACULTY)
11	*Return Proposals (FACULTY)*
12	Correct Proposal
13	*Submit final corrected proposal for grading*
14	**Project Development**
15	Modify mechanical construction
16	Prepare table of inputs and outputs
17	Draw wiring diagram
18	Install & test electrical connections (wiring)
19	*Faculty approval of wiring*
20	Draw state-transition diagram
21	Write software
22	Test & debug software modules
23	Test & debug software (integrated)
24	Test & debug system
25	*Fully functional system*
26	**Documentation**
27	Prepare User's Manual
28	Peer-review and revision of User's Manual
29	*Submit Revised User's Manual for grading*
30	*Faculty Return Graded User's Manual*
31	Prepare oral presentation
32	Oral Presentation at USD
33	Oral Presentation at Kearny High School
34	Prepare final report
35	*Submit Final Report for grading*
36	*Faculty Return Graded Final Report*
37	Correct final report
38	Develop WWW page
39	*Submit complete documentation for grading*

Figure 1. Gantt Chart for NIFTY Project, Spring 2000

NIFTY IMPROVEMENT EXPERIENCES

During the Spring 2000 semester, ten teams of 3 to 4 students in four laboratory sections were given the task of improving existing systems (the Ferris Wheel project was not needed this semester.). Initially, many of the teams expressed some concern about the prospects of improving their systems. In some cases, the trepidation was caused because the assigned project looked and performed very well. These students initially had problems finding opportunities for improvement because they were so impressed by the projects. Other groups had systems that did not work well and presented so many opportunities for improvement that students were originally daunted by the prospect of trying to fix every observed problem.

During the first weeks of lab, the faculty emphasized that system improvements take many shapes. It was suggested that projects that worked well could be modified to add new functions, more elegant controls, or more visual appeal. Students with projects that performed less well were advised to quantify the performance of the system by recording the incidence of failure, then seeking ways to eliminate the causes of failure. To guide students, the NIFTY faculty created an example proposal that made recommendations for improvements to an example project that the faculty developed during the first year of the laboratory. As students became more comfortable with the wide range of activities that could constitute improvement, they became better able to identify the opportunities that their projects presented.

The proposals that were submitted by the students identified an average of 8.7 possible opportunities for improvements with a minimum of 5 and maximum of 12 improvements noted. The scope of the suggestions involved all aspects of the projects including mechanical construction, the use of electrical components, programming, and aesthetics. Some of the changes were proposed to correct operational flaws in the current systems, some improved the performance of the system, and others added functionality. The following list illustrates the types of changes identified by these first-year students to give an idea of the scope of their suggestions.

Improvements to correct operational flaws

- Make conveyors more stable so objects being transported do not fall.
- Replace mechanisms to make system more reliable and reduce the percent of cycles that malfunction.
- Replace the cable material that raises a mechanism with a material that does not stretch.
- Replace non-fischertechnik components (e.g. rubber bands, dental floss and paper clips) with more durable materials.

Improvements for enhanced performance of the system

- Increase speed of objects being transported through the system to reduce the cycle time.
- Add delays or timers at specific points during the operation of the system for better synchronization of events.
- Increase the efficiency of the system by changing the program to allow simultaneous processing of several objects in the system.
- Add two speed motor to mechanism.

Improvements to add functionality

- Add an “emergency stop“ button and make the corresponding programming changes.
- Allow the user the option to reset the system at startup if the mechanisms are not at their home or initial position.
- Increase user interaction with the system (e.g. let user select among several options such as specify the number of items to be processed).
- Add lights to signal to the operator status of the system.

Improvements for aesthetics purposes

- Simplify the mechanical construction to make it easier to see the system operation.
- Reroute wires to reduce clutter (several projects).
- Use Lego® people in system.
- Use real candy in candy dispenser.

While students were trying to identify improvements, the faculty emphasized that the students were not expected to implement all the identified improvements. It was expected that students would be able to identify many possibilities, then select a subset to be performed. Students appeared to have some problems embracing this concept. During lab sessions students identified many improvements that did not appear in their proposals. The groups proposed executing between 5 and 9 improvements with an average of 7.1 planned changes. Thus, students proposed to implement over 80% of their identified changes. Furthermore, 5 of the 10 teams proposed making all of the changes that they identified.

One of the open questions about the CI approach to design projects is whether students will react as enthusiastically when they revise a project as when they have the opportunity to create a system that was entirely their own. One measure of achievement is the student's perceptions of how the project helps them develop engineering skills. Table 1 presents a brief comparison of the two approaches at USD. The numbers reflecting student perceptions of the skills acquired were derived from anonymous surveys administered at the end of each offering of the NIFTY project. It is important to note that the authors were the instructors for all sections in 1999 and for three of the four sections in 2000.

Table 1. Comparison of NIFTY Design Project results in 1999 (first offering of NIFTY) and 2000 (first Continuous Improvement offering)

	Spring 1999 (New Projects)	Spring 2000 (CI Cycle)
% of Students reporting NIFTY helped them learn to solve open-ended design problems "Significantly" or "A great deal"	80.0%	64.7%
% of Students reporting NIFTY helped them learn to plan projects "Significantly" or "A great deal"	94.3%	75.9%
% of Students reporting NIFTY helped them learn to complete projects "Significantly" or "A great deal"	77.2%	55.9%

The table shows that in both offerings, students believed the NIFTY project helped them learn to solve open-ended design problems and to plan and complete projects. In general, students in 2000 did not think that the CI cycle was as beneficial as the 1999 students found building initial systems. When the complete set of survey results is examined, this pattern continues. However, the students in both semesters universally recommended that we continue to use NIFTY projects in the future. It is difficult to assess the extent that this difference in attitude is due to the CI cycle and how much is due to other confounding factors such as changes in faculty and in the university calendar.

Student responses to open-ended questions also revealed some differences in attitudes. In 1999, the most common "single highlight of the semester" was seeing their project run for the first time. In 2000, it was giving their presentations to the high school students.

With respect to the actual projects, essentially all of the system modifications proposed at the beginning of the Spring 2000 semester were successfully implemented. Some teams were able to make additional non-planned improvements. Once again, the semester ended with all projects working. Significantly, every team's final report identified ways that the Spring 2001 team can continue to improve the NIFTY systems.

CONCLUSIONS

In this paper we have introduced the Continuous Improvement approach to conducting a first-year engineering design project. The motivations for using the CI approach have been explained along with details on how the CI approach has been implemented within USD's NIFTY Design Project. A preliminary comparison of the CI methodology to more traditional design projects has been presented. Further detailed analyses will be conducted as more experience with the CI methodology is acquired.

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