Teaching Engineering Design Concepts through a Multidisciplinary Control Project

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Abstract

This paper described the design and the implementation of a multidisciplinary project in two-sequential control courses to reinforce students' understanding of engineering design concepts from a system point of view. Such a project had two phases which corresponded to the two courses. In the Phase I of the project, a vague problem idea was given, which required the students to design a (multidisciplinary) mechatronics system. The students formed in teams and collected information to further define the project before drawing their first drafts. Multiple ideas were generated during brainstorming in a team. The final design was a collaborative work contributed by every member in a team. Based on analysis and evaluation, an optimal design including a budget and a timeline was selected by the team members, but it was required to obtain the instructor's approval before the implementation. All teams kept modifying the designs throughout the project as they understood the problem better. Each team was required to have all the necessary parts ready at the end of the Phase I of the project. The system was assembled and tested in the Phase II of the project. To fulfill the pre-defined project goals, each team designed and implemented a digital compensator in NI LabVIEW. At the end of the project, each team gave a presentation on the design along with a demonstration to the class. For the purpose of assessments, the progress reports in Phase I and the final reports in Phase II were used as the students' feedback. A survey was conducted during and after the project. The survey results were compared and the changes of the students' conceptions of engineering designs were discussed.

Introduction

The capability of design has been widely agreed to be one of the most important characteristics of engineers. A good understanding of engineering design concepts and engineering design processes helps engineering graduates to achieve a smooth transition from academia to industry. Therefore, the well-known ABET engineering accreditation criteria[1] requires engineering graduates should be able 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*."

Various methods[2] have been discussed by educators to develop student's conceptions of design through undergraduate engineering curriculums. A project-based approach[3-11] has been considered as one of the most effective ways and has been implemented in different courses. More specifically, capstone design courses[8-11] were notably preferred among these courses. This was because engineering students were required to synthesize their knowledge learned through a whole undergraduate curriculum, and apply their skills in senior designs within real-world settings, such as multidisciplinary needs of industry[10-12]. However, these courses could be challenging too.

In our ABET accredited BSE- Mechatronics program, the scope of the courses included more than one engineering discipline since mechatronics, as one of the fast growing fields in engineering, inherently required an integration of mechanical, electrical and software engineering into appropriate control architectures. Moreover, engineering design concepts (including a block diagram to illustrate an engineering design process) were introduced in a first-year introductory course, and reinforced several times in different higher-level courses (including two control courses). However, it was still challenging for many students to design a system from an idea by integrating the knowledge from different engineering disciplines in the capstone course. Many students knew enough mathematics, understood engineering concepts and theories in different disciplines, and had adequate lab skills. But they lacked the experience to start from a sketch. Although case studies in a seminar course before this capstone course were helpful, it would be better if the students could actually go through such a design procedure at least once before their senior designs. Therefore, a new control project was introduced in two sequential control courses to fulfill this purpose.

The goal of this paper was to describe the design and the implementation of a multidisciplinary control project and assess the changes on students' conceptions of design during and after this project. A survey, built on the study of Mosborg et al[13] and the extended study of Oehlberg and Agogino[14], was conducted at the end of the first and the second control courses. The corresponding survey results were compared and the changes on the students' conceptions of design were discussed. The progress reports and the final reports were also used as the students' feedbacks to assess these changes from a process-focused point of view.

Background

The conceptions of engineering designs and design processes have been described in different ways[13, 15-18]. Typically, engineering design processes were represented as a flowchart, such as the one shown in Figure 1. Although some researchers argued that important factors, e.g. teamwork and communication, were missed in the flowchart approach, Mosborg et al[13] found in their study that most of participating practicing engineers basically agreed with the model shown in Figure 1. Thus, the flowchart in Figure 1 remained in this approach and the activities in the proposed project were grouped based on this six-stage design procedure.

The project proposed in this approach was course-related. Hereby, its topic should be within the scope of the course contents. For many years, control-related topics have been included in undergraduate engineering curriculums. Traditionally, they were taught in the relevant engineering disciplines, such as electrical engineering, mechanical engineering or chemical engineering etc. However, with the increased needs of multidisciplinary engineering designs, fewer controlled systems only contained the devices within the scope of a single discipline. An optimal design of control systems should be achieved from a system point of view, instead of in a certain engineering discipline.

In our current curriculum, two sequential control courses were required: one on classical controls, and the other on digital controls. Both of them included a two-hour lecture and a two-hour lab per week. In the first control course, a series of lab exercises related to classical control systems were given in MATLAB/Simulink while NI LABVIEW and the related exercises were covered in the second control course. Therefore, in order to reinforce design concepts in a multidisciplinary environment, it was desired to create a project that required students to follow the full engineering design process shown as Figure 1, design a mechatronics system, and implement the compensators in NI LABVIEW.

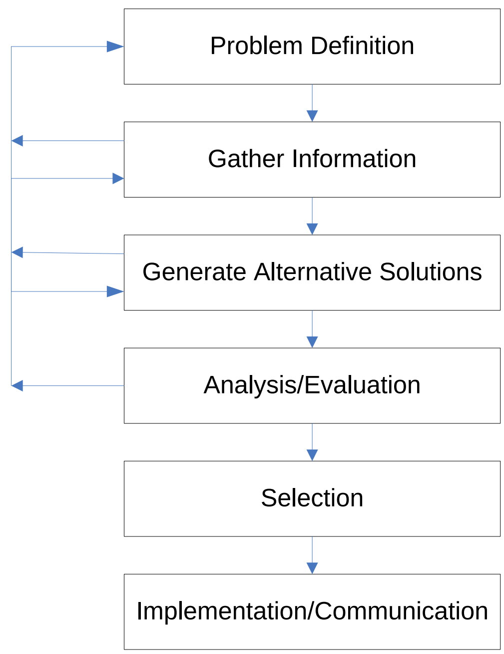

Figure 1: One model of the engineering design process used in the study of Mosborg et al[13]

Project Approach

In Spring 2012, a project of designing an automatic color sorting system was assigned to the students in the first control course. Since the project was associated with two sequential courses, it was reasonable to divide the project into two phases. The Phase I of the project was completed in the classical control course in Spring 2012 and the students continued the Phase II of the project in the digital control course in Fall 2012. A detailed project flowchart was shown in Figure 2. It followed the engineering process model used by Mosborg et al[13].

At the beginning of the project, a design problem was given by the instructor. It was described as: in a working area shown in Figure 3, design and implement an automatic system in the dark green area which can sense the red/blue color of a package in the shaded belt area and deliver it to the corresponding "Red" or "Blue" corner. The students were asked to form in teams and find their partners by considering the required expertise for the project. Five teams with 2 or 3 members in each were built up. And most of them remained in the same team through the project.

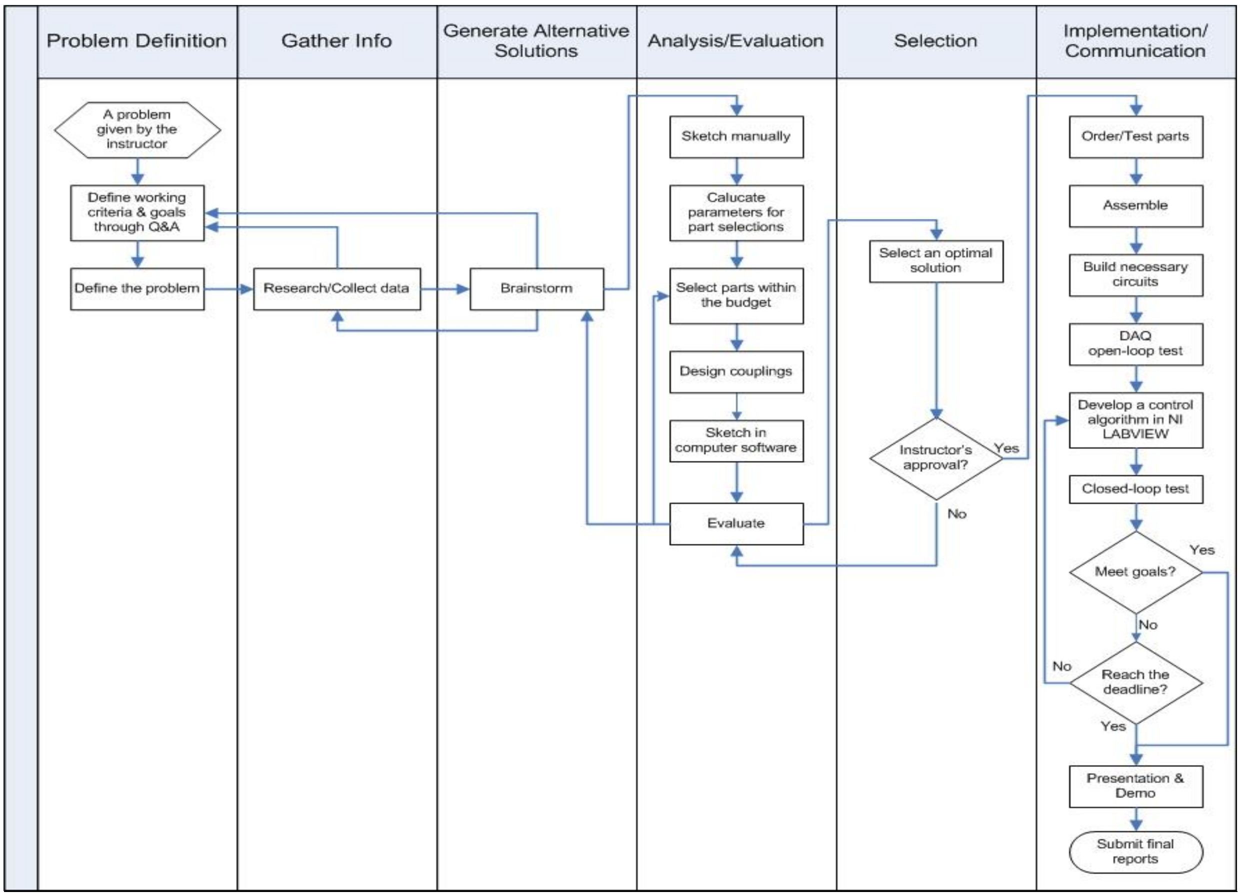

Figure 2: The flowchart of the proposed control project

Apparently, the given problem description was too vague. This was deliberate to force the students to seek more information and help them realize the importance of defining a problem. The questions were collected from all teams, which were related to design goals (e.g. speed and accuracy), assumptions (e.g. the shape of the package) and constraints (e.g. budget and timeline). Some of them were surprisingly good and exceeded the instructor's expectations at this initial design stage. For example, one team questioned the meaning of the color Red or Blue.

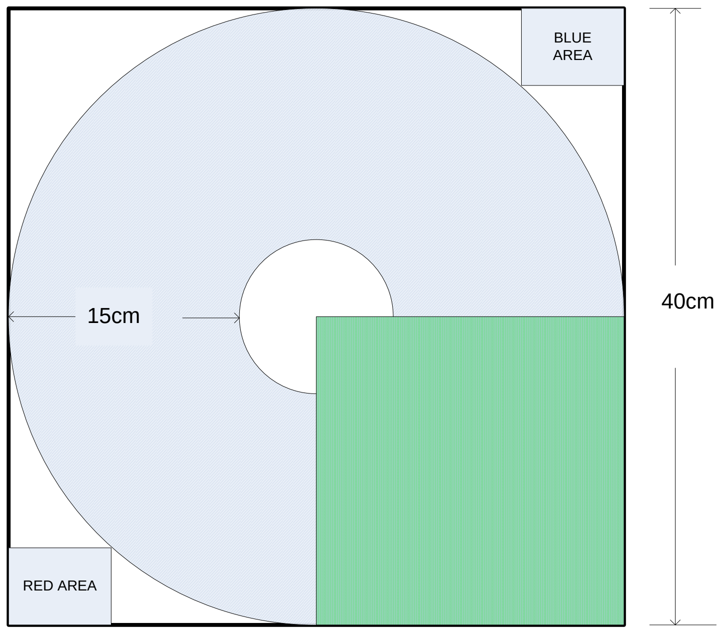

Figure 3: The working area layout of the project

As Aristotle[19] mentioned, "the kind of questions we ask are as many as the kinds of things which we know," the students deepened their understanding of the problem through these Q&A sessions. And the importance of understanding the problem in a design procedure was strengthened during the discussion as well. Then, a more detailed project description was given as: design a sorting system to satisfy the following requirements:

1. The whole system (except arms/sensors) should be placed in the shaded green area in Figure 3;
2. The system should automatically pick up colored (blue or red) packages that were randomly placed in the shaded belt area (one package one time, less than five as a total);
3. Based on the package color, the system should deliver it to the assigned area (the upper right corner for the blue ones, the lower left corner for the red ones);
4. The whole system should stop automatically after searching the whole belt area twice and not detecting any packages;
5. The packages provided by each team should be cubes (not smaller than 2cm x 2 cm x 2cm), weighting less than 200g each;
6. The total cost should be less than $100. If over $100 were spent, the more expensive the more points would be deducted on the grade (e.g. 10% over the budget will cause a reduction of 5% in the team grade);
7. Without degrading the system performance, more points would be awarded to a system with a faster response;

8. And, the whole system should be controlled by a NI LabVIEW program through the data acquisition board installed in the lab.

Furthermore, a list of the lab constraints (e.g. voltage/current limits) and the requirements of the progress reports were also included in this version of the project description.

Based on this new description, each team collected necessary information from various resources, brainstormed on design ideas and selected an optimal solution based on analysis and evaluation. Several design concepts were discussed during this period. For example, the students tended to forget the constraints listed in the project definition when selecting the parts. One team picked a DC motor based on their calculation on the necessary torque and speed, but neglected the voltage limitation in the lab. Communicating was also emphasized at this stage. Typically, multiple ideas were generated in a team. When a team member tried to promote his/her idea, he or she had to respond to the other's inquiries and negotiate with other's viewpoints. Accordingly, the final sketch became a collaborative work.

Furthermore, multidisciplinary viewpoints were highlighted when different designs were evaluated. For example, one team selected a simple mechanical design without realizing the difficulty in achieving the goals in programming. Another team designed an intricate system for its flexibility in controls, but soon realized the trouble with machining the required couplings. During this period, the teams improved their designs based on the instructor's questions. Although the design had to be approved by the instructor before a team ordered any parts, it was the team that made the final decision on which design was selected for implementation.

Ordering was the next step. Some non-technical experiences were gained during this period. For example, some teams gladly learned to lower the shipping and handling cost by ordering the parts together from the same company. On the contrary, one team was delayed by three weeks after ordering cheaper motors from another country. Furthermore, the majority of the teams decided to machine a couple of parts to fit their design needs or just to reduce the cost. Some teams even created the SolidWorks models of these parts and built up the objects with a 3D-printer. To complete the Phase I of the project, the teams were required to have all parts ready for assembling. Over half of the teams even assembled the system partially. Group progress reports were then collected and accounted for 10% of the final grade for the first control course.

In the following semester, the students were introduced to a graphical programming language NI LABVIEW and a series of exercises were done in the lab sessions of the course. The data acquisition system used in the project was discussed as an example in the course lectures. The hands-on experience on sampling/reconstructions, noise, and digital compensations not only benefited the project, but also enhanced the students' understanding on digital control theories.

In the Phase II of the project, building and testing became critical since the project entered the implementation stage. For example, one team had to modify a sensor location to compensate the weak signal received in the data acquisition system. Another team slowed down the motors' speed to co-operate with the control algorithm for a better searching result.

The importance of planning was learned through a bitter way. Without enough back-up parts, one team wasted a week after the original ones were broken. Another team spent too much time on building the hardware and had not enough time to tune the integrated system for the project goals. Furthermore, almost all the teams had to work late in the last week to catch up the project deadline.

At the end of the semester, each team presented the design with a demonstration to the class. A final group report was also required to conclude their team project. The project accounted for 15% of the final grade in the second control course, which included the demonstration, the presentation and the report.

Observations and Discussions

The assessment of engineering design process knowledge was suggested to be process-focused and at the individual level by Bailey and Szabo[20]. In this paper, the progress reports and the final reports were used as the students' feedbacks with a focus on design processes. At the individual level, a survey was conducted during and after the project.

From a process-focused point of view, the feedbacks from the students' reports were positive. For example, one team concluded in the final report that the project "was very difficult but well worth the effort." The majority of the teams addressed the importance of designing from a (multidisciplinary) mechatronics system viewpoint, such as

- "The project was an excellent way for the team members to acquire familiarity with engineering in all aspect of mechatronics engineering."
- "Hardware is just as important as software in the success of a project… as such engineers must work hard on both."

The students also valued the project on improving their teamwork skills. For example,

- "This project has taught our group a lot about teamwork."
- "Our group management skills improved dramatically and we learned how to keep everyone on task and topic."

All teams mentioned in the reports that the current design was not the original one. Modifications and iterations happened through the project, from design ideas, part selections, to control algorithms. They explained the reasons and described the advantages of the updated design. The feedbacks on other design concepts were discussed together with the related survey results for a comparison purpose.

The survey was based on the study of Mosborg et al[13] and the extended study of Oehlberg and Agogino[14]. In the survey, the students were asked to select up to six most important and up to six least important of 24 design activities. 11 students in the first control course and 14 students in the second control course completed the survey. The survey results were shown in Figure 4 and Figure 5.

It was found that the students' conceptions of design were changed. During the project, the top design activities chosen by over half of the 11 students were "Identifying the constraints", "Planning", "Brainstorming", and "Communicating". On the other hand, at the end of the project, the top design activities chosen by over half of the 14 students were "Testing", "Planning", "Brainstorming", "Understanding the problem", "Making decisions", and "Building". Such changes weren't surprising according to the instructor's observations.

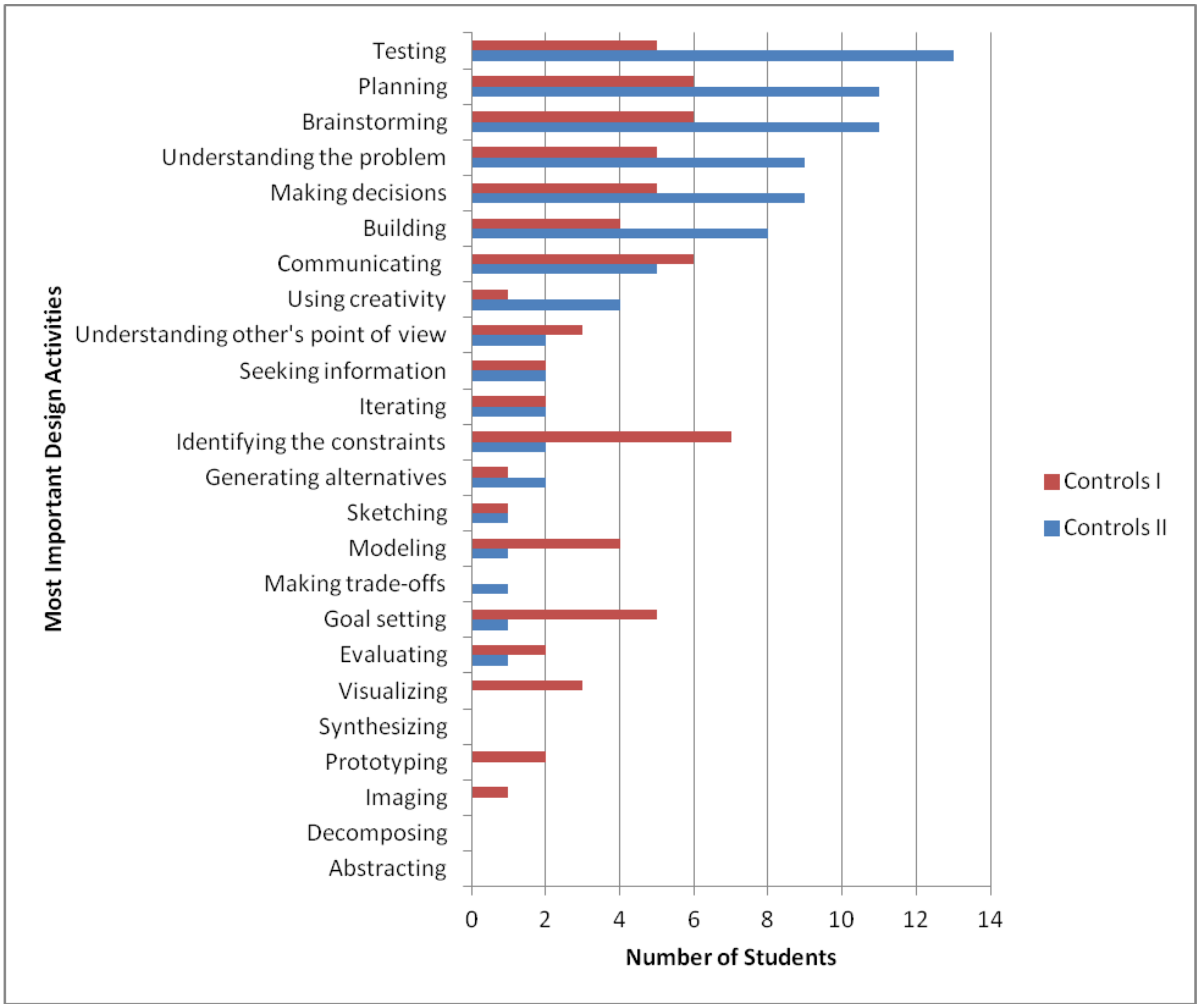

Figure 4: The students' choice of the six most important of 24 design activities. (11 participants in Controls I and 14 participants in Controls II)

The project was associated with two sequential courses. As shown in Figure 1, the Phase I of the project was ended at the beginning of the Implementation/Communication stage in the design process model. In other words, the students focused mainly on implementation in the second semester. Therefore, building and testing were accentuated in the Phase II of the project and ranked high in the second survey. Similarly, the students felt more pressure on making decisions as the project approached to the end, comparing at the middle of the project. Accordingly, they valued the activity of making decisions more in the second survey.

"Brainstorming" was ranked high in both of the survey results; however, according to the students' reports, this design activity served for different purposes. In the Phase I of the project, the students brainstormed for different design ideas. On the other hand, in the Phase II of the project, they brainstormed to seek possible solutions for the problems found in various tests. Similarly, “planning” was the other one that was ranked high in both of the survey results. This was confirmed with the students’ feedbacks in the reports. Some of them commented in the progress reports as

- “One of the main obstacles was the scheduling.”
- “We learned how difficult it can be to schedule time.”
- “We were taught the importance of scheduling, not only in working around everyone’s work schedules, but in creating a timeline for the project and sticking to it as much as possible.”
- “We learned how to manage our time wisely, how to create an accurate timetable and how to abide by the timeline we created.”

Unfortunately, not all of them followed what they planned. In the final reports, some of these plans became lessons, such as

- “The lesson is to start earlier and give adequate time for the small things as well as the big things when completing a project.”
- “A detailed schedule and priority list should be made and strictly followed starting at the beginning of a large project such as this one.”
- “This however teaches a real life lesson of “deadlines are deadlines.”

It was understandable that “Identifying the constraints” was shown in the first list while “Understanding the problem” was included in the second one. Compared to “Understanding the problem,” “Identifying the constraints” was more specific and attached to the initial stage of the project. For example, one team realized “the biggest obstacle was translating our conceptual design to actual physical components with the restrictions;” Another team wished to have “a better understanding of the physical and design limitations” during the initial design. On the contrary, in the Phase II of the project, understanding the problem was more than just identifying the constraints. Instead, it included various aspects, e.g. the logic behind a control algorithm. Therefore, in the second survey, 9 students picked the activity “Understanding the problem” (5 in the first survey results), and only 2 students picked “Identifying the constraints” (7 in the first survey results).

Communicating was ranked high in the first survey results, but not in the second ones. In the progress reports, the students mentioned that they had troubles to “unify one plan from the different ideas” in their teams. Some teams also decided to build “a strong foundation of communication with each other to help the process move forward.” However, only about 35% of the students selected the activity of communicating as “most important” in the second survey. An optimistic explanation to this change was that the students learned from the experience in the Phase I of the project and had less issues on communicating. However, more likely, such a change was due to the lack of time management skills. When the schedule was so tight, the students tended to follow the ones that felt more confident to make decisions in their teams. Then, the discussions became brief and were even skipped on some occasions. However, no comments were found in the final reports to support either of the explanations.

Figure 5 showed the survey results on the least important design activities. Over half of the 11 students chose “Abstracting”, “Sketching”, “Decomposing”, and “Synthesizing” as the least important design activities in the first survey, and over half of the 14 students selected

“Imaging”, “Sketching”, “Making trade-offs’, and “Abstracting” as the least important ones in the second survey. Only abstracting and sketching were ranked high in both of the survey results. Decomposing and synthesizing weren’t on the second list any more. This was reasonable since in the implementation stage the students had to break a complex system down into smaller and simpler sub-systems, test each of them and then synthesize them to fulfill the goals of the project. On the other hand, the activities of “Imaging” and “Making trade-offs” mostly happened at the early stages of a design process, hereby more students chose them as “least important” in the Phase II of the project.

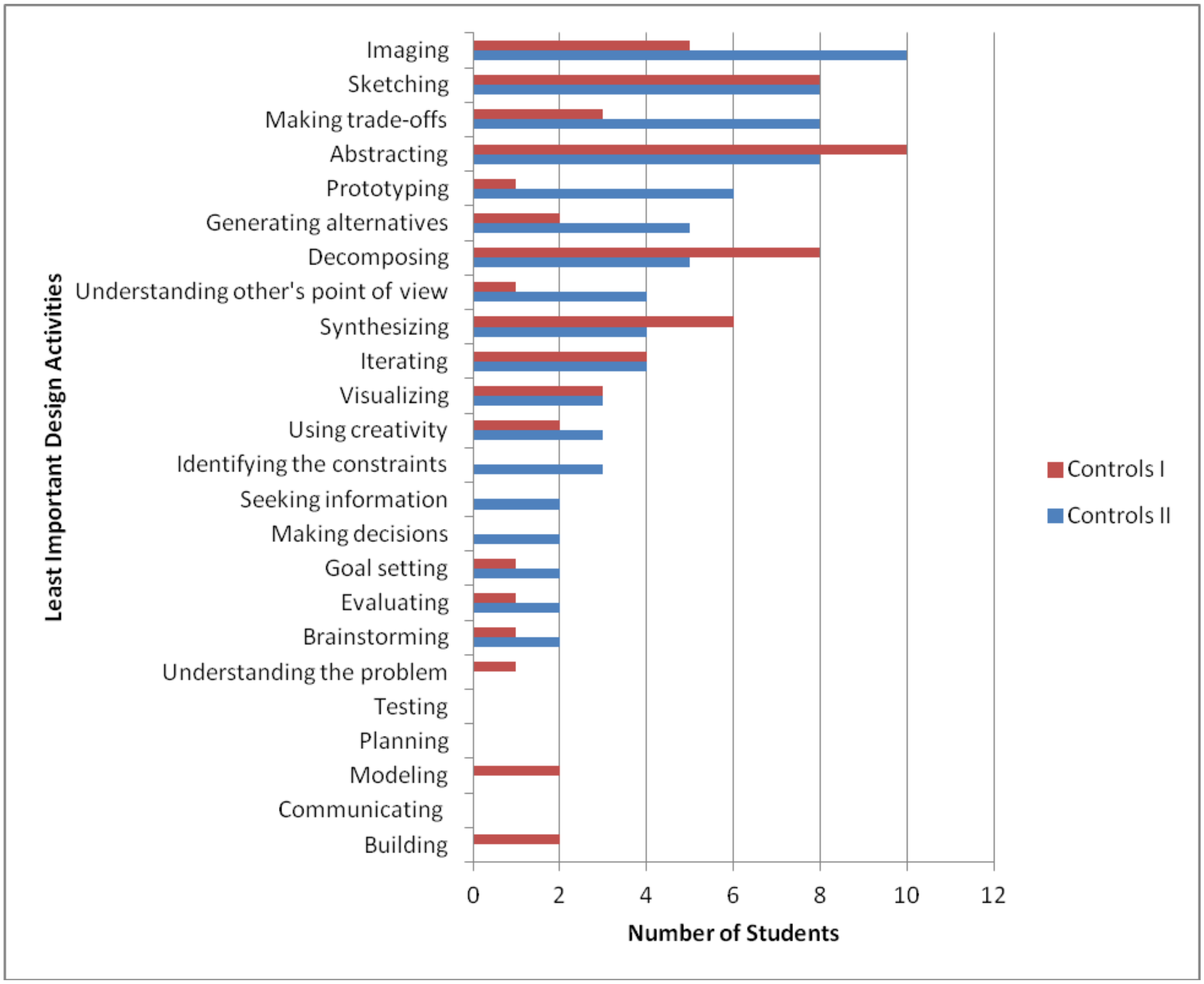

Figure 5: The students’ choice of the six least important of 24 design activities. (11 participants in Controls I and 14 participants in Controls II)

In summary, the students’ conceptions of engineering design were changed through the proposed control project. They tended to rank the importance of design activities based on their most recent experience, instead of from a general point of view. One possible reason was the lack of design experience since for most of the students, this project was the first one that required them to start from a sketch and end in a prototype. It would be worthy to conduct the same survey with this group of students in their senior design course and illustrate the development of their conceptions of design.

Conclusions

A two-semester long control project was introduced to our engineering program to reinforce the students' understanding of engineering designs, especially for a multidisciplinary problem. A survey was conducted during and after the project. The corresponding results showed the changes on the students' conceptions of engineering designs. The students' feedbacks in the progress and final reports were positive. As a future work, the survey will be conducted in a senior design capstone course to track the development of these students' conceptions of engineering design.

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