An Iterative Approach to Implementing Sponsored Design and Build Projects

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Abstract

Producing usable prototypes in a single iteration in a semester-long course is extremely challenging. A research project was undertaken to determine if iterating designs in subsequent courses would improve the results and usability of sponsored design and build projects in lower division courses.

Assistive technology devices (devices to help people with disabilities) were used in three separate classes to teach students design strategies and reinforce course content. Five separate design challenges were undertaken and iterated at least one time. Each device was designed and built in a single course with iterations performed in following courses.

When iterating a design, documentation of previous iterations is essential to avoid repeating mistakes and pursuing already rejected concepts. When the iteration occurs with different engineering students in different classes, it is crucial that this documentation be gathered, collected, and transmitted to the next team in an effective manner. A web-based tool was developed to allow easy transfer of design documentation from one course to the next.

In some iterations, the web tool was used and in others it was not. The incremental improvement between iterations was enhanced by the use of the web tool. Additionally, students had less of a tendency to "reinvent the wheel" when the previous group's documentation was available as well as their prototype. This saved time and allowed substantial progress to be made in successive iterations.

End users and/or their caregivers were asked to rate each iteration via a survey to determine user satisfaction with different aspects of the prototype. User satisfaction with successive iterations was compared. In all cases, user qualitative feedback on both the design, prior to build, and after use of the prototype was also collected. It was found that successive iterations improved customer satisfaction.

Introduction

The ASME Vision 2030 Task Force has called for the development and deployment of a design spine across the curriculum. The design spine will provide students with multiple opportunities to experience a realistic design challenges before their Accreditation Board for Engineering and Technology (ABET) mandated capstone design-build project.[1,2] The literature shows the importance, effectiveness and student enthusiasm for real-world design projects performed as part of capstone design experiences.[3-5] However, creating exciting, customer driven and relevant design experiences for classes other than the capstone design classes has proven challenging.

In the past the authors have struggled to integrate customer driven design and build projects into existing courses. When a working prototype of a device, ready to give to the user or project sponsor, is expected at the end of the semester, project work can jeopardize learning goals. In addition issues like lead-time on parts, limited design development time, and limited time to iterate have stressed faculty and students as well as decreased student satisfaction with the course. This paper reports on the author's efforts to use the same project in subsequent courses to enable a more meaningful design experience for the students and deliver a more refined and robust prototype to the user or sponsor. Although the high quality prototypes are a desired outcome of these projects, projects should enhance student learning of course content and the design process.

Methodology

Grand Valley State University received a National Science Foundation (NSF) grant to support the development of assistive devices by undergraduate students. Unfortunately, a specific course for the projects could not be created for the development of assistive devices because of the crowded engineering curriculum. Instead the projects were implemented as a component of three existing courses. One course was a traditional content driven engineering course, one course was a design methodology course and one course medical device design course.

The catalog descriptions of the courses involved in the study are below:

Analytical Tools for Product Design—Analytic methods in product design are integrated into a coherent design process that includes: gathering customer requirements, establishing specifications, generating alternative concepts, estimating feasibility, concept selection, embodiment design, design refinement, prototyping and project planning.

Machine Design II— Topics include design of screws, clutches, brakes, belts, gears, journal bearings, roller bearings, and planetary gear trains.

Medical Device Design— Students will learn to design equipment, products, and processes for the medical device industry. The course will cover topics such as standards and regulations, determining and documenting device requirements, hazard and risk analysis, liability, verification and validation testing, and manufacturing quality systems.

The learning objectives for each course differ significantly. In addition, the student backgrounds are different for each class. Analytical Tools for Product Design (ATPD) is a first semester junior level course for Product Design and Manufacturing (PDM) Engineering majors, Machine

Design II (MD) is a second semester junior level course for Mechanical Engineering majors and an elective for PDM majors, and Medical Device Design (MDD) is a senior/graduate level course for required for students in the biomedical minor program and an elective for students in the PDM major. Each of these classes is the first time a given student has been exposed to customer driven design and builds projects. All students have had a cursory exposure to the design process in prerequisite classes.

Projects were begun in each of the three courses. The projects discussed herein with the courses in which they were completed are as follows:

Intensive Care Unit (ICU) sit-to-stand device—ATPD, MD, ATPD
Play and mobility—ATPD, ATPD
Motorized Swing—MD, MD
Hugging Chair—ATPD

In each course, students were required to follow a structured design process with the minimum number of stages described in the table below.

Table 1. Elements of the design process taught in both courses.

Design Stage	Activity	Result of stage
Discovery	Assessment of users wants and needs.	List of Specifications
Benchmarking	Search for existing similar products.	List of similar products and justification for building a different product
Intellectual Property	Search patent databases for relevant patents.	List of relevant patents
Ideation	Broad search for partial solutions to the problem.	List of partial solutions to the problem
Synthesis of Design Concepts	Combining partial solutions into a set of complete, feasible concepts.	Set of complete feasible concepts
Detail Design	Development of calculations, CAD models and prints.	Calculations, CAD models and prints
Prototype Testing	Comparison of prototype performance to specifications.	Lab report.
Evaluation from User	User’s opinion of the strengths and weaknesses of the prototype.	Memo and results of standard survey

Since each course is different, the depth of coverage of each design phase differs in each course. Design iterations are encouraged because they are essential to any realistic design process and have the potential to improve the final prototype. Design reviews are held with all stakeholders at the concept selection stage, after a design iteration and after delivery of the prototype to the user.

The authors realized that communicating the design information to subsequent design teams working on the same project would be a key to ensuring that the subsequent prototypes were substantial improvements over previous prototypes. In order to facilitate the transfer of information each team documented the results of their design efforts in a Google website. At the beginning of each semester design teams were provided with an introduction page that contained links to pages corresponding to components of the design process. Teams also had the opportunity to add pages that described unique aspects of their projects. The template was intended to be a starting point or minimum expectation for the student teams.

Table 2. Description of Contents of the Google websites.

Page Name	Minimum Required Contents
Introduction Page	Photos, names and contact information for each team member
Stakeholder Research	Documentation of Interviews conducted with users, caregivers and other stakeholders
Specifications	List of engineering specifications that describe the performance of the device
Function Structure Diagram (FSD)	Inputs and outputs of the device along with the functions that transform the inputs to outputs
Concept Generation	The methods and results of the team’s concept generation efforts
Concept Selection	Documentation of a systematic selection of the optimal concept
Project Planning	Gantt chart showing plan for realizing prototype of the selected concept
Detail Design	CAD Models and engineering prints for the prototype
Verification Calculations	Calculations or simulations to show that the detail design will result in a prototype that meets the specifications
Intellectual Property Analysis	List of similar patents, opinions on infringement and

	recommendation whether or not to pursue a patent
Evaluation of the prototype	Analysis of the strengths and weaknesses of the prototype
Design Review	Minutes of all design review meetings

The website template can be found under Google Sites as “EGR 301 Project Site Template”. Each project website was made available to successive student groups for evaluation in the discovery phase of their project. Iterations were completed in successive courses by different students rather than attempting to complete iterations within the same course.

The overall goals of the project were to teach students design skills and to develop refined, usable, assistive technology devices. Each goal of the project was assessed separately. The first goal was evaluated using student self-efficacy and perceptions of learning surveys administered at the beginning and end of each course. To quantify the improvement of successive prototypes a modified version of the Quebec User Evaluation of Satisfaction with Assistive Technology (QUEST) survey for evaluating assistive technology was used.[6]

Table 3 shows the questions in the Student Self-Efficacy Surveys. Students rated their self-efficacy on a Likert scale of 1 to 5 with 1 corresponding to “Not Comfortable/Confident” and 5 corresponding to “Extremely Comfortable/Confident”.

Table 3—Questions for Student Self-Efficacy Surveys

1	How comfortable are you at developing design requirements?
2	How comfortable are you at making design decisions?
3	How comfortable are you at using the machine shop to produce a prototype?
4	How confident are you in your ability to design and build a working prototype for a customer?
5	How confident are you in your ability to interact with a customer to determine their needs from a product?
6	How comfortable are you with benchmarking existing products?
7	How confident are you in your ability to assess the effectiveness of a prototype?
8	How interested are you in the course project?
9	Do you believe the course project will enhance/enhanced your learning of the

	course material?

Table 4 below displays the questions contained in a course effectiveness survey given to students after the class. These also were rated on a Likert Scale of 1 to 5 with 1 being "Not at all" and with 5 being "Considerably".

Table 4—Questions for Student Perception of Course Effectiveness Survey

1	Has your ability to develop design requirements improved as a result of this course?
2	Has your ability to make design decisions improved as a result of this course?
3	Has your ability to use the machine shop improved as a result of this course?
4	Has your ability to design and build a working prototype for a customer improved as a result of this course?
5	Has your ability to interact with a customer to determine their needs from a product improved as a result of this course?
6	Has your ability to benchmark improved as a result of this course?
7	Has your ability to assess the effectiveness of a prototype improved as a result of this course?
8	Are you more interested in the course project than you were at the beginning of the semester?
9	Was this course project worth the extra effort needed in the course?

Results

Student self-efficacy and course effectiveness survey results are shown below in Figure 1 for the MD course and Figure 2 for the ATPD course in Figure 2. Note that hypothesis testing was not conducted on the data to determine differences in the means as the original data was not normally distributed.

Due to high student self-efficacy (average 3.5 – 4.4) in the pre-course survey, significant improvement was hard to document. The authors, and others, have noted student engineers tend to be very self-confident. This characteristic makes the use of Likert scale self-efficacy tests difficult to administer. One notable finding of this research is that it may be more effective to change the Likert scale range to 1 corresponding to "Marginally Comfortable/Confident" to 5 corresponding to "Extremely Comfortable/Confident" on some of the survey questions thereby resulting in better distribution of the student responses and more room for changes in confidence. In all but two questions in the survey, questions three and four, the lowest value recorded in any class was three. For those questions where the range was from three to five, the scale could be modified.

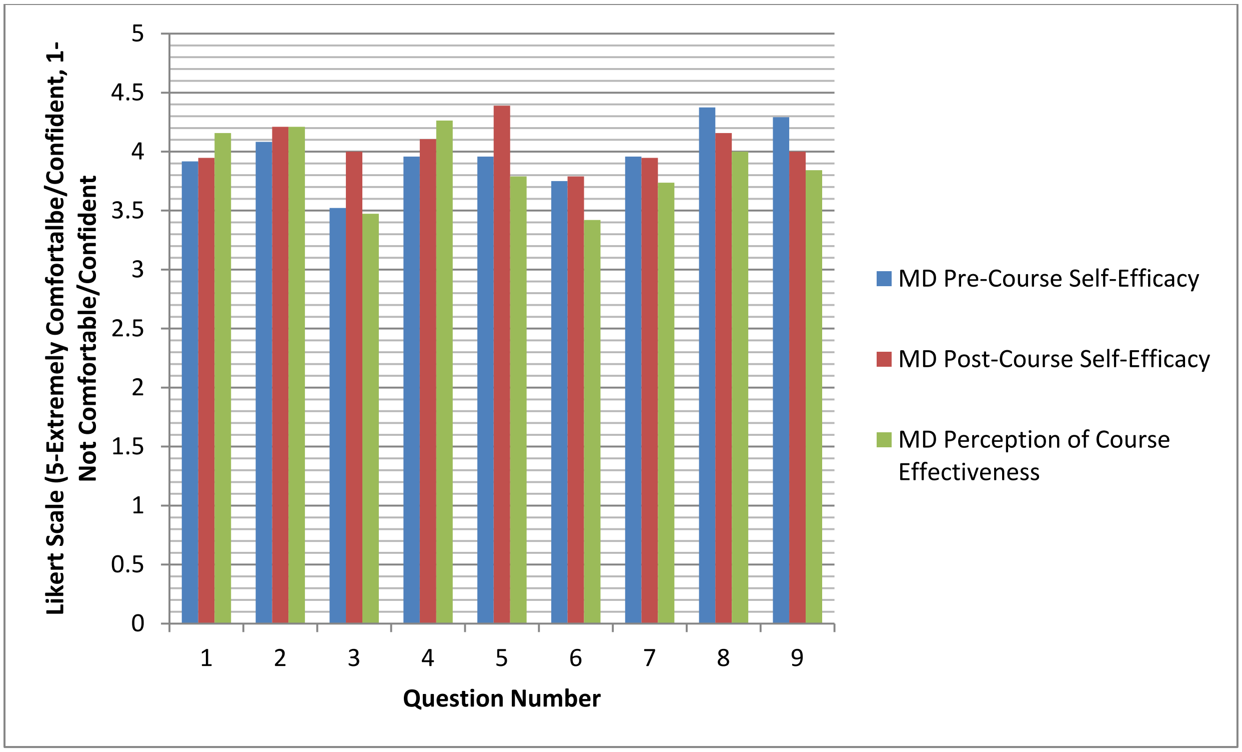

Figure 1—Self-Efficacy and Course Effectiveness Survey Results for the MD Course

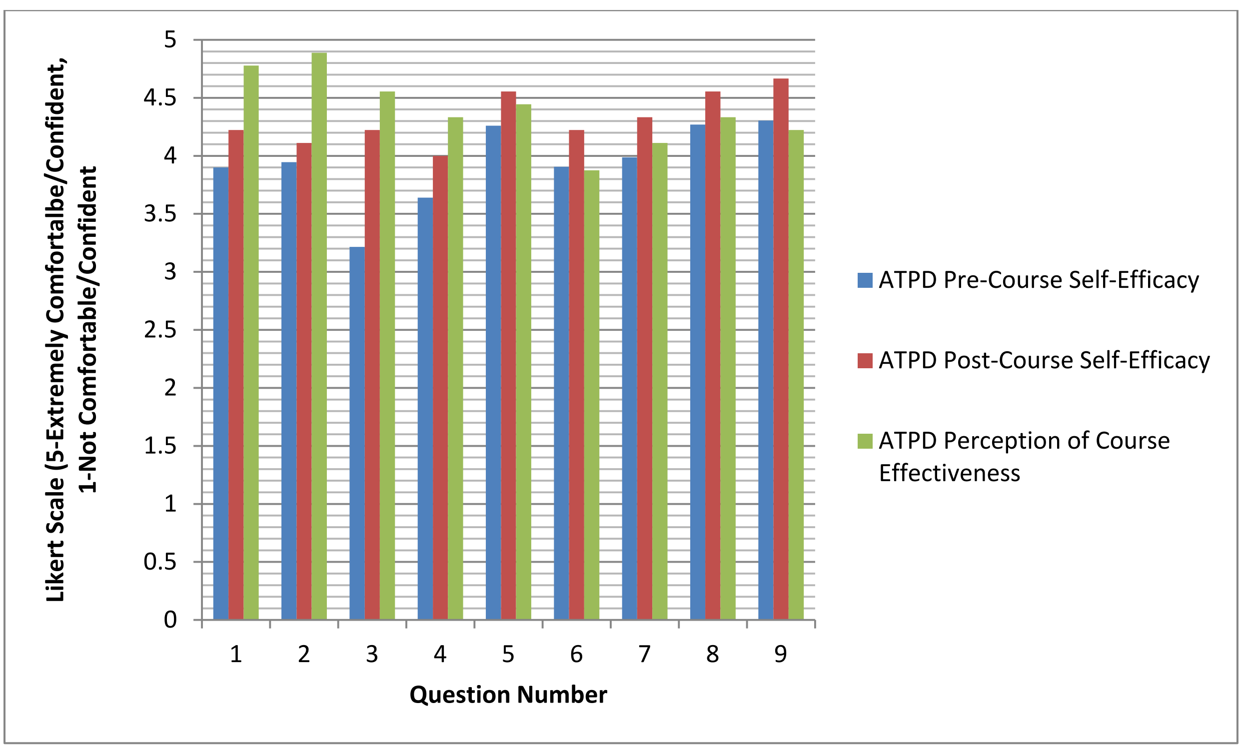

Figure 2—Self Efficacy and Course Effectiveness Survey Results for the ATPD Course

The pre-post comparisons displayed Figure 1 and Figure 2 indicate that students' self-efficacy in the MD course increased for questions 1 – 6 and for all questions in the ATPD course. However, for the MD course, student responses were lower for questions 7 through 9.

Question 7 relates to the students' ability to evaluate a prototype. Since prototypes were completed immediately prior to the end of the course and sometimes after that end date, there was not much opportunity to evaluate the prototypes. Because of this finding, the authors intend to include a more rigorous evaluation of previous semester prototypes at the beginning of the design process for a new semester. This will accomplish two goals: first, students will have the opportunity to develop and apply critical thinking skills to a design and second, subsequent designs should improve more rapidly as a result of this evaluation.

Question 8 queries student interest in the project. Due to the dual goals in the course, maintaining rigor in traditional course content and enhancing design skills through a substantial course project, students were very overwhelmed at the end of the course. This can also be seen in the decrease in scores for question nine which relates to learning of course material. Students saw a disconnect between course content and the project.

In spite of this decrease in their self-evaluated interest in the project and linking to course content, student responses to questions 8 and 9 on the course effectiveness survey were very high (above 4). Therefore, the conclusion was drawn that, although their enthusiasm had waned, they did see the value in the projects they had completed.

Improvements in self-efficacy were universally better in the ATPD course than the MD course. Additionally, the ATPD course showed improvement in all categories.

Figures 1 and 2 show that in all categories and in both classes, students ranked the courses' effectiveness above the mid-range. Students were more interested in the project, felt the project was worth the extra effort, and that the specific design skills evaluated improved due to the course. This indicates the students perceive both courses as valuable learning experiences when considering the 9 questions contained in the student perception of course effectiveness survey.

Figure 3 shows a scatter plot of change in self-efficacy versus perception of course effectiveness for both courses. Note that the ATPD points are both further to the right on the graph and consistently higher than the MD course. This shows that the students in the ATPD course perceived the course improved their learning of design methodology much more than the MD course students. Additionally, their self-efficacy levels increased more. This is an obvious conclusion when design methodology was the main learning objective of the ATPD course. However, it also points to another, less obvious conclusion. Often we teach design by doing in courses. While over time, methodology may be reinforced in this manner, student self-confidence increases more when they are directly taught the methodology.

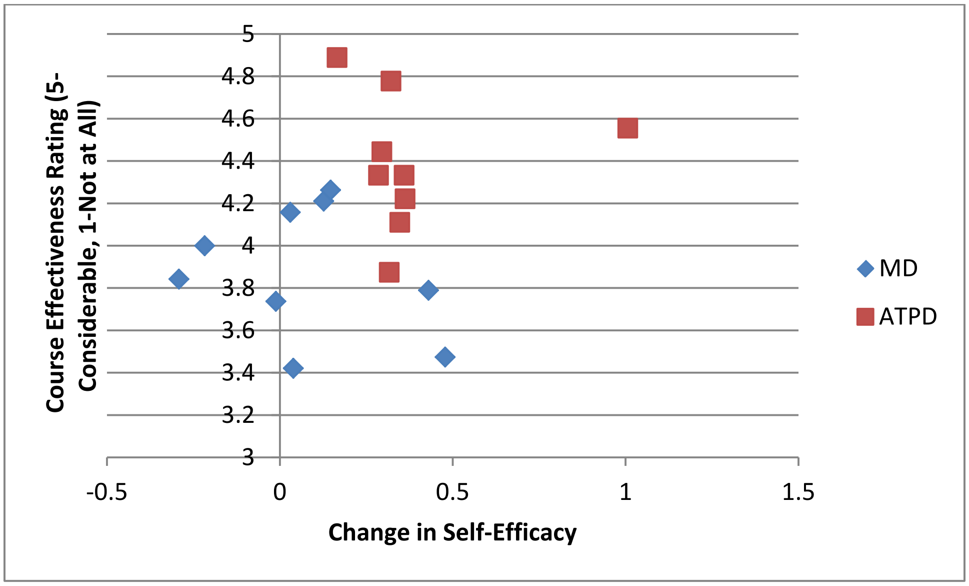

Figure 3—Change in Self-Efficacy vs. Course Effectiveness Rating for Both Courses

Table 5 shows the modified QUEST questions that were used to determine the customers or user satisfaction with the prototype. Users were asked to rate their satisfaction on a Likert scale of 1 to 5 with 5 being extremely satisfied and 1 being extremely dissatisfied.

Table 5—User Evaluation Questions

1	How satisfied are you with the dimensions (size, height, length, width) of the device?
2	How important to you are the dimensions (size, height, length, width) of the device?
3	How satisfied are you with the weight of the device?
4	How important to you is the weight of the device?
5	How satisfied are you with the ease in adjusting the parts of the device?
6	How important to you is the ease in adjusting the parts of the device?
7	How satisfied are you with how the device looks?
8	How important to you is the aesthetics of the device?
9	How satisfied are you with the time it takes to set up the device?
10	How important to you is the time it takes to set up the device?
11	How satisfied are you with the degree to which the device meets your needs?

Student teams completed one or more iterations on three projects; Swing Motor, the Play and Mobility Device , and the ICU Sit-to-Stand Device. In general, these showed either no improvement in subsequent iterations. The notable exception was the ICU Sit-to-Stand Device.

As expected the customers or users were more satisfied with subsequent iterations but closer scrutiny of the projects reveals significant differences. The user evaluation survey scores for the swing motor prototype and the first iteration are shown in Figure 4.

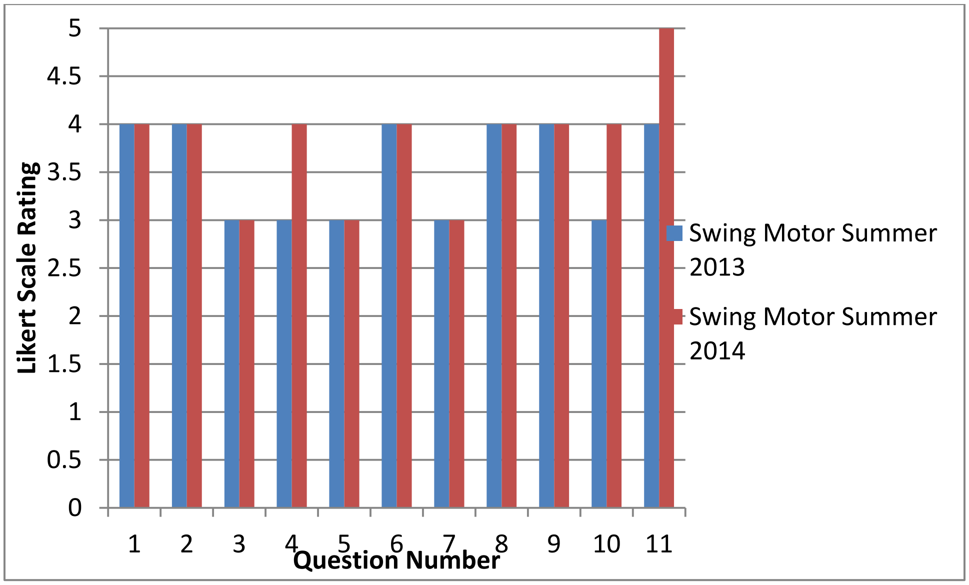

Figure 4—User evaluation survey results for the swing motor

The iteration, or second prototype was judged significantly better in the areas of weight, setup time and the degree to which the device meets the user's needs. All other aspects of the second prototype or judged to be the same as the first prototype. This pattern of specific and significant improvement occurred because the second team was challenged to improve a narrow and well-defined aspect of the design.

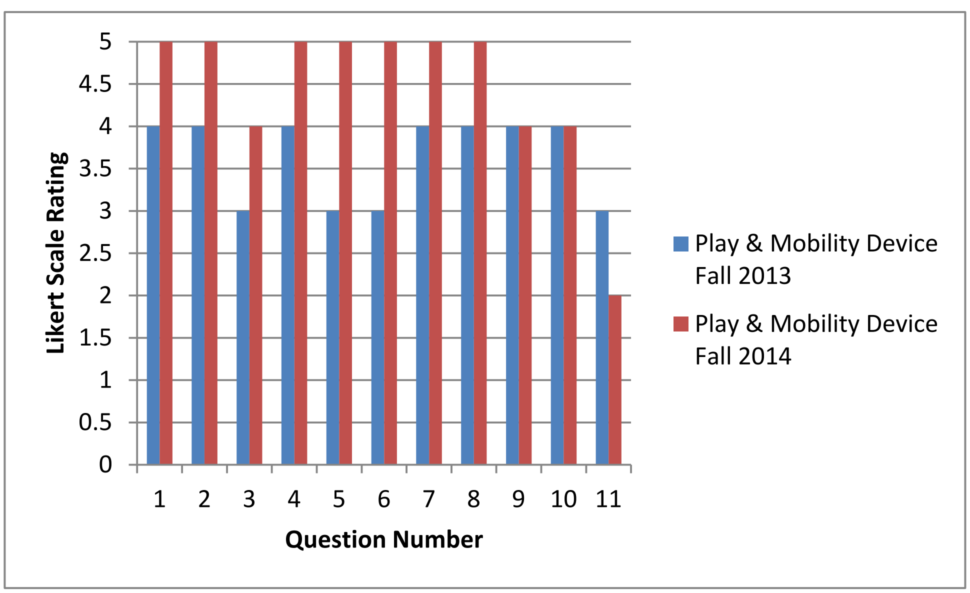

Figure 4—User evaluation survey results for the play and mobility device

The improvement of the second iteration of the play and mobility device is shown in Figure 4. In this case the second team of students was faced with a list of specific complaints from the user that were relatively easy to address. However, the decrease in the user satisfaction with question 11, the usability of the device is not consistent with the gains in the other areas. Obviously, the user survey does not capture all aspects of the prototype that impact user satisfaction.

Finally, the case of the ICU sit-to-stand device shows another interesting pattern. Figure 5 shows the results of the user satisfaction survey for device.

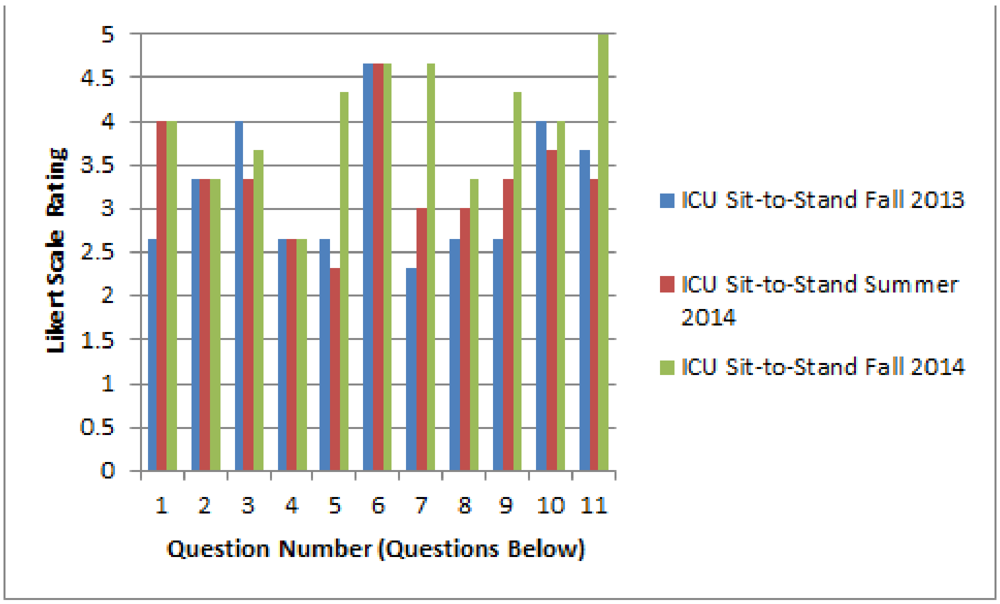

Figure 5—User evaluation survey results for the ICU sit to stand device

The customer was less satisfied with the second iteration than with the first and third iterations in the weight of the device, ease of adjustment, and the degree to which the device meets their needs. In this case the second design team was confronted with a complex and difficult challenge. The concept of the 1st prototype had significant performance deficits. The second team's new concept received mixed reviews from the customer. However, the third design team learned from the first two prototypes and implemented a new, innovative and significantly more successful solution to the problem.

Conclusions

In order to secure high quality sponsored projects, engineering programs need to be able to provide useable results. This is very difficult to accomplish a single semester iteration which only leaves time for one prototype. Performing design iterations in subsequent courses may supply a means of achieving this end. However, more work must be done to ensure a reliable pedagogy to achieve effect prototypes while simultaneously ensuring course learning objectives are met.

As expected, designs improved on successive iterations, although not as much as was hoped. Although design documentation of previous iterations was supplied to students, anecdotal evidence suggests students make minimal use of this information.

An activity is needed at the beginning of the semester, along with the discovery phase, that requires student groups to review the previous iterations' design documentation, prototype and feedback from potential users. At some point in the design process, students and instructors should decide together if refining the current concept or the development of a new option is the best course of action. This will minimize cost as well as encourage truly iterative design rather than each group "reinventing the wheel". Additionally, it will serve as a learning opportunity for students to develop their prototype assessment skills.

Not surprisingly, self-reported student learning of four design methodology topics, ability to develop design requirements, ability to make design decisions, ability to use the machine shop, and ability to interact with the customer, was higher in the course emphasizing design methodology over that teaching mechanical element design. However, the student self-efficacy scores were only significantly different in two categories—developing design requirements and assessing prototypes.

Future Work

When enforced, students effectively documented their designs using the websites. These websites are available for review. This documentation was useful for evaluating student work. However, anecdotally, it was not used much by successive student groups. The tool itself is useful and future iterations will include improvements to teaching materials referenced therein to better guide students in the various steps of the design process. Additionally, a step will be added to the formal design process that includes reviewing previous designs and making informed decisions on the usefulness of those designs in the current iteration.

Acknowledgement

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