INTERDISCIPLINARY LEARNING THROUGH DESIGN ACTIVITIES UNITING FUNDAMENTALS OF ENGINEERING CURRICULUM

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Abstract
An interdisciplinary design approach is essential to solve critical engineering challenges, yet few eng. curricula cultivate interdisciplinary design thinking, particularly early on. Most fundamentals courses are taught independently, often viewed as isolated subjects. We consider a framework for core eng. subjects, Structures & Materials and Circuits & Electronics, to gauge if proposed design activities can 1) reinforce concepts taught in each course, 2) enable students to see coexistence of both subjects in applications, 3) advance innovation/design skillsets/mindset and 4) increase confidence in solving interdisciplinary problems. To achieve concrete experience and reflective observation of Kolb's model, three design problems are posed to target challenges in energy, aerospace and healthcare. The activities foster deductive learning based on earlier concepts and require their interdisciplinary application. Participants report more confidence with interdisciplinary design projects and better grasp of interdisciplinary requirements in solving technical challenges ($p<0.05$). Positive feedback from instructors/students indicates attainment of additional desired learning objectives.

Keywords: Design education, design learning, design engineering, designettes, interdisciplinary design

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1 INTRODUCTION

Interdisciplinary approaches are necessary for addressing the most critical technological and socio-technological challenges facing the world today (Borrego & Cutler, 2010). This necessity is reinforced by United States National Science Foundation (NSF) as part of their strategic plan to "emphasize investigations that cross disciplinary boundaries and require a systems approach to address complex problems" (NSF, 2006). To be considered truly interdisciplinary, various disciplines must work together in an integrated manner to solve a complex problem (Klein, 1990). However, despite this need, there remains limited curriculum in many engineering schools to cultivate interdisciplinary problem solving and skill building, particularly in the foundational first and second years of higher education. This paper reports on a new approach to address this need: interdisciplinary curriculum with integrated designettes.

2 BACKGROUND

2.1 Interdisciplinary Pedagogy

When incorporated, interdisciplinary pedagogy activities are often only provided at the capstone design level, or in extracurricular research activities within multidisciplinary laboratories settings. Among the few who have integrated interdisciplinary problem solving into their coursework during more the advanced years in higher education, the following researchers are key educators. Amon et al. created a two semester, multidisciplinary course in which students design and manufacture wearable computers (Amon, Finger, Siewiorek, & Smailagic, 1996). King et al. designed a series of multidisciplinary engineering laboratory courses (MEL I-III) that integrates discipline specific components into systems that require students to connect concepts from different courses in electrical circuits, fluid mechanics and solid mechanics (King, Parker, Grover, Gosink, & Middleton, 1999). More recently, Li and Jean implemented a multidisciplinary course that combines the topics of control systems from electrical engineering with dynamic system modeling from mechanical engineering in a junior level class (Li & Jean, 2013).

It has been shown that interdisciplinary education better prepares students for work and citizenship by developing higher order cognitive skills such as problem solving, critical thinking, and the ability to see multiple perspectives (Lattuca, Voight, & Fath, 2004). The combination of interdisciplinary topics and intentional pedagogy has the potential to promote better learning than in isolation.

There has been evidence that interdisciplinary instructional approaches facilitate learning as early as freshman level classes. Connor et al. collaborated to combine elements of physics and circuits, taught by two separate institutions, into an interdisciplinary research project designing antennas (Connor, Sibray, & Forinsah, 2001). Their students benefited from each discipline's feedback and understood the dependency between scientists and engineers during the process. Shooter and McNeill (2002) implemented a mechatronics course that employs collaborative learning using active learning techniques. The class was composed of students from two different disciplinary programs with the intention of drawing on their diverse strengths in order to advance the learning of the class as a whole. The students taught each other on topics in their domain of expertise, and their self-reported feedback indicated that this method of instruction enhanced their understanding the material. Qualters et al. devised a comprehensive exam using Bloom's taxonomy (1956) to test the students mastery of first year subjects in chemistry, computer science, math and physics (Qualters, Sheahan, Mason, Navick, & Dixon, 2008). These exams helped students self-assess their abilities in each area and understand where greater focus is needed for a deeper understanding of the material.

Interdisciplinary 4-5 week long projects combining English, calculus, and physics were developed by pedagogical researchers at Arizona State University, in which freshmen level students designed and built catapults, trebuchets, and bungee drop mechanisms to experience the integration of these core subjects into real world applications (Roedel, Kawski, & Doak, 1995). Educators have used methods such as product dissection, reverse engineering, and examination of existing commercial products to teach adaptive design, design family variation, and general design methodology (Beaudoin & Ollis, 1995; Otto & Wood, 1998; Otto, Wood, Murphy, & Jensen, 1998; J. Wood, Campbell, Wood, & Jensen, 2005; K. L. Wood & Jensen, 2001). Design competitions have been integrated into curriculum to increase student engagement and motivation, improving learning of design skills (Hussmann & Jensen, 2007). To teach topics such as calculus, chemistry, physics, and even training in using tools, a group of researchers have worked to develop an in depth guitar design course, delivered at more than six higher education institutions in the U.S. (Aikens et al., 2013).

2.2 Designettes

Wood et al. (2012) and Telenko et al. (2014a, 2014b) have pioneered a new approach at Singapore University of Technology and Design to interdisciplinary design-based undergraduate engineering education through the invention of "designettes", or "using the concept of vignettes or 'brief, evocative descriptions, accounts or episodes' to teach engineering design thinking through short-term design experiences." They report on many implementations of designettes within the curriculum, and have found they were able to increase students' awareness of applications, learning of key concepts, and self-reported confidence in solving interdisciplinary problems. In this work, we focus on designettes' pedagogical opportunities of design and integrated subject learning. Drawing on the models and methods devised by Wood et al. (2012) and Telenko et al. (2014a, 2014b), the design activities implemented in this work are advanced exemplars of designettes in action.

2.3 Aims

It is advocated in the above literature that interdisciplinary learning is engaging for students and helps them to connect information from various distinct disciplines. However, apart from the efforts described in the literature reviewed above, there have been limited efforts among engineering schools to cultivate interdisciplinary thinking and problem solving within their curriculum, particularly in the earlier years of degree programs. Currently, fundamental mechanical and electrical engineering courses are most often taught independently, and students view the topics as modular with few or no interconnections. This paper proposes an interdisciplinary learning framework for engineering foundation courses like "Structures and Materials" and "Circuits and Electronics" that can: (1) reinforce the respective concepts taught in the individual subjects; (2) enable students to see the coexistence of the two subjects in various applications; (3) utilize design as a vehicle to integrate subject concepts while developing innovation skill sets and mind set in the students; and (4) increase the confidence level of the students in solving problems that require interdisciplinary knowledge.

Studies have shown that students tend to be more engaged during active learning by applying their knowledge to solving a problem (K. L. Wood, Jensen, & White, 2008). The two courses mentioned in the previous paragraph are essential for a practical product design (Otto & Wood, 2001), and thus, a series of design activities are proposed for an active learning experience.

3 METHODS

Kolb (1984) introduced a theory, as shown in Figure 1, on experiential learning, which has been well accepted as an effective pedagogical model of experiential and constructivist learning. Kolb suggests that for effective learning, students should experience four types of activities as part of their learning experience, namely: (i) Concrete Experience, (ii) Reflective Observation, (iii) Abstract Conceptualization, and (iv) Active Experimentation.

Wankat (2002) cites numerous studies that suggest student attention span for lectures is roughly only fifteen minutes. Hence, the "Abstract Hypothesis and Conceptualization" and "Active Experimentation" stages, as taken from Kolb's pedagogical model (1984), for each of the two courses are decoupled and implemented through integrated, mini, active discussions with in-class questions, hands-on activities, and laboratory experiments to reduce lecture time. A given session of a course becomes a blurred integration of these elements, where, at a given point in time, students will be engaged in any of the elements.

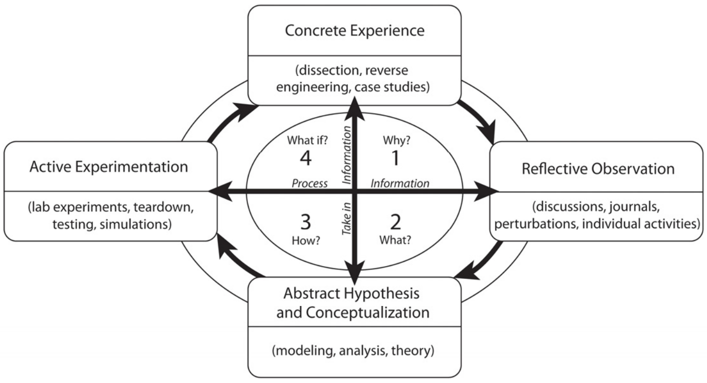

Figure 1. Kolb's Theory of Experiential Learning (Kolb, 1984)

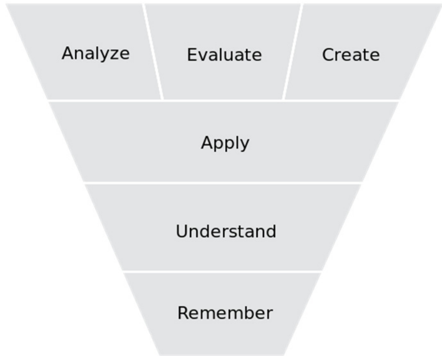

Figure 2. Bloom's Taxonomy of Thinking Skills (Anderson et al., 2000; Bloom, 1956)

Bloom (1956) devised a taxonomy of thinking skills, which Anderson et al. (2000) revised, depicted in Figure 2, which states that creativity, evaluation, and analysis are higher level of thinking skills. In order to address the stages of "Concrete Experience" and "Reflective Observation" of Kolb's experiential learning while incorporating these higher-level thinking skills taken from Bloom's taxonomy, interdisciplinary design problems are incorporated. These open-ended design problems likewise enable students to develop their innovation skill sets while combining fundamental concepts and engineering principles across subject matter.

To enable the students to better relate to industry and study their specialization tracks within an "integrated track pedagogy," the three interdisciplinary design problems implemented in this study primarily target technological challenges in sustainable energy harvesting, aerospace technology and healthcare applications at three instances of the term. The design-related activities are constructed in such a way that they facilitate deductive learning based on concepts taught earlier in the curriculum, and require interdisciplinary incorporation of these concepts to solve the design problems.

3.1 Participants

One hundred and six (106) students were enrolled in fourth semester Engineering Product Development (EPD) pillar courses at Singapore University of Technology and Design (SUTD), all of who volunteered to participate in this study. All 106 students are required to attend and complete "Structures and Materials" and "Circuits and Electronics," which are structured into three cohorts of 36 students to experience Kolb's Theory of Experiential Learning. Institutional Review Board procedures and policies were strictly followed. Among the voluntary participants, there were 39 females and 67 males, ranging in age from 18 to 25. All activities described in this work were performed in groups of students, initially formed by the instructors with the opportunity for students to change groups within the first two weeks of the semester, most of whom did not. After groups were formed, the groups stayed the same for all activities described here.

3.2 Design Activities

The two independently taught parallel courses, "Circuits & Electronics" and "Structures & Materials", both consist of mini active discussions with in-class questions, hands-on experiences, and laboratory experiments, creating effective active learning environments. To demonstrate the link between the two subjects and reinforce the concepts taught, a series of interdisciplinary design activities were designed by the instructors. The learning objectives of these activities include: (1) To reinforce certain concepts taught in the two subjects, (2) to demonstrate the coexistence of the two subjects in various applications, (3) to advance design and innovation skills and mindset through open-eneded, inventive problems, and (4) to inspire greater confidence in working on interdisciplinary projects that involve both mechanical and electrical components.

In addition to the above outlined learning objectives, achieving intrinsic motivation in the students is a priority in the formulation and selection of the design activities. The chosen application areas are of particular interest among the students, the details of which are given in subsequent sections.

Students' time is often a limiting factor due to a compact curriculum and high performance expectations. The authors devised two structured projects and one open-ended project. The first two projects are structured to limit students' required time commitment, each designed to be completed within two hours. The two structured design projects are scheduled such that the concepts used have been previously covered in the respective independent courses. The objectives of the open-ended design project are to give the students an opportunity to be creative, and encourage independent

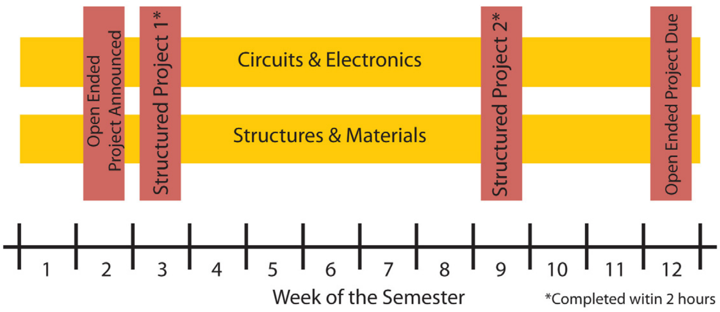

Figure 3. Semester Overview of the Schedule of Projects

thinking, in contrast to following detailed step-by-step instructions. The open-ended design project reinforces some basic design concepts in addition to the material from the two courses. An overview of the timeline is illustrated in Figure 3.

As outlined by Telenko et al. (2014a, 2014b) in their formalized methodology for developing designettes, the motivating factors, learning objectives, and prototyping tools were identified for each of the design activities. These attributes, as well as the design briefs, are described next in sections 3.2.1-3.2.3.

3.2.1 Design Activity 1: Structured Project 1

Motivation for Activity Theme

The authors chose to design an activity incorporating the interests of the students, with the goal of increasing intrinsic motivation and engagement with the application area, leading to more effective learning experiences. Green or sustainable energy generation is a topic of great interest among the students; thus, the first structured project, conducted in week three of both courses, is focused on this area of application.

Description of Activity

With increasing fuel prices and higher emphasis on environmental issues, students are tasked to investigate sustainable energy in residential homes, harvesting electrical energy from wind. The assignment for this project is to design and develop a personal energy-harvesting device based on the concept of wind turbines. This device can be used in a residential setting, but can be readily expanded to a full wind farm. This project is planned to be a structured short design activity (designette), which the students are expected to complete within 2 hours. Materials are provided to the students for building a prototype design solution, as well as a scaled down scenario for testing the effectiveness of their designs. Figure 4 depicts the testing environment for the designs, which incorporated a fan to provide the necessary "wind." Figure 5 depicts the collection of materials (prototyping kit) provided to the groups of students.

The students are tasked to use the DC motor to harvest wind energy, and expected to explain how they will do so. They are provided with a concise review of their previously covered material from physics on Electromagnetism. It is noted to the students that in real energy harvesting applications, a DC motor is usually not the ideal choice due to its lower power efficiency and generation capacity.

The students must also design an integrated structure to support the DC motor during the harvesting of wind energy. They are instructed to analyze the structural supports and reaction forces of potential designs prior to building prototypes, reinforcing earlier concepts on Free Body Diagram and combined loading analyses and allowing for crucial consideration of how to achieve static equilibrium. Additional information with regard to the structure is provided as follows:

- The structure must be able to withstand the "wind" (created by the fan) and achieve static equilibrium under wind load. The wind load is estimated to be 0.4 N.
- The design should consider using minimal materials to achieve the task to reduce cost.

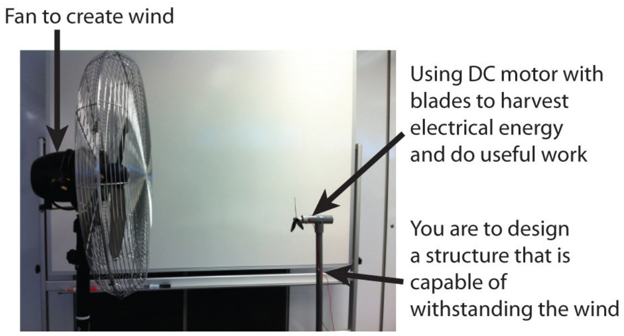

Figure 4. Scenario setup for testing of the energy harvesting device

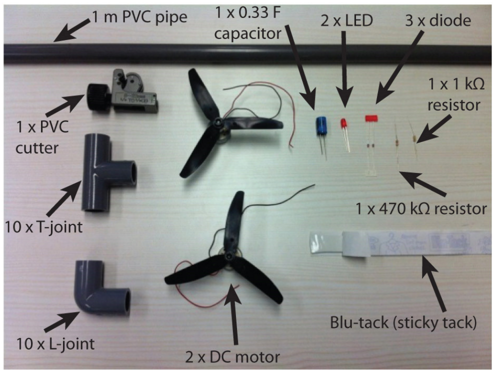

Figure 5. Components given to the student for the first project on energy harvesting

- The mass of the various components are as follows:
  - Motor: 0.0275 kg
  - PVC Pipe: 0.13 kg/m
  - T connector: 0.0314 g
  - L connector: 0.0231g

Harvested electrical energy from wind farms is rarely used directly, usually temporary stored, and not consumed by the industry and residents immediately. The students are instructed to use the provided diode and super-capacitor as temporary energy storage, setting up the electrical components to drive their defined load, such as powering LEDs or driving another motor. The students are to present their circuit designs to the instructors. Questions are then asked by the instructors to encourage critical thinking during the design phase.

Targeted Concepts Related to "Circuits & Electronics" and "Structures & Materials"

The following concepts are targeted to be reinforced during this sustainable energy harvesting design project:

- Analysis of structure stability using free-body diagram
- Application of functional circuit elements, such as diodes, to prevent undesirable discharge of harvested energy back to the generator
- Understanding the effects of a capacitor within an RC circuit
- Working principle of a DC motor
- Faraday's law of induction.

Outcome

The discussion during the design phase, which includes drawing of the free-body diagram(s) and circuit diagram, is one of the most valuable opportunities for the students. In order to avoid a "trial and error" design process, the students are questioned by the instructors, leading to strong analysis of the structures and circuit designs before fabricating the prototypes. In a traditional curriculum, students are often exposed to textbook problems but seldom complete free-body diagram analysis for open ended design problems and prototyping, as they do in this activity. Figure 6 shows some of the designs prototypes built by the students for this design activity.

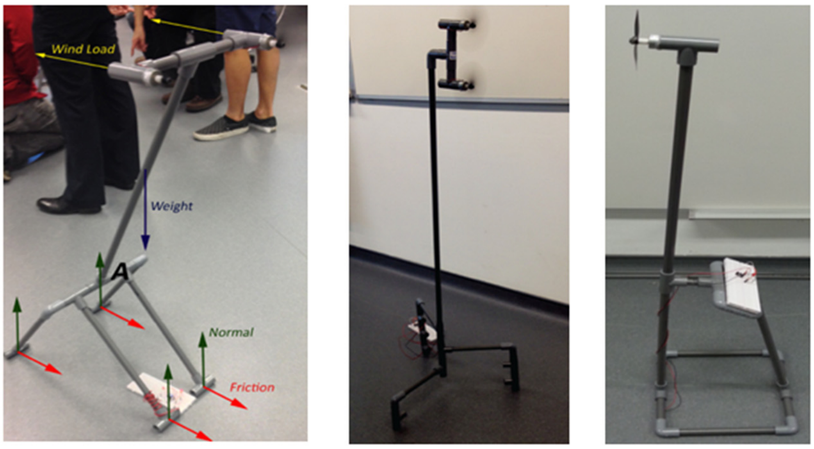

Figure 6. Wind harvesting devices built by the students for Design Activity 1

3.2.2 *Design Activity 2: Structured Project 2*

Motivation for Activity Theme

A number of students are interested in the design and development of flying drones, or, more generally, aeronautical systems. Figure 7 illustrates an example of one of the many drones that are designed and built by the students during extracurricular activities and clubs. One problem that students encounter in the design of flying drones is bending of the structures when the payload weight to lift is substantial. One possible solution is to design a force sensor that is capable of giving a warning when the payload weight is too large or poorly distributed.

Description of Activity

The objective of the project is to develop a warning system for flying drones that indicates when a payload is too heavy or poorly distributed for a drone. Figure 8 shows a warning system that gives a warning if the force exerted by either motors exceed a threshold. To simplify the scenario, downward force (gravitational force imposed by the payload) is used as the triggering force for the warning system. An enlarged view of the indicators is shown in Figure 9. The warning system consists of 2 green LEDs and 1 red LED. Upon detecting a force that is greater than the threshold force, one or both of the red LEDs will light up to indicate a warning, enabling the user to know which motor is exceeding the threshold force.

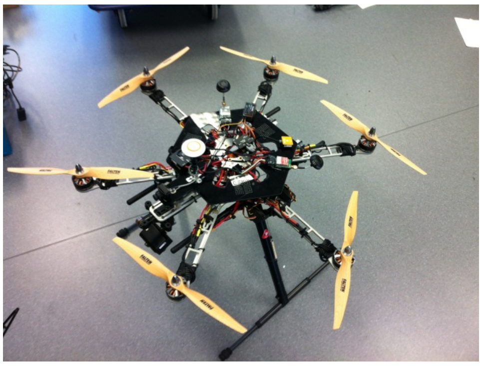

Figure 7. Flying drone designed and developed by the students during their free time

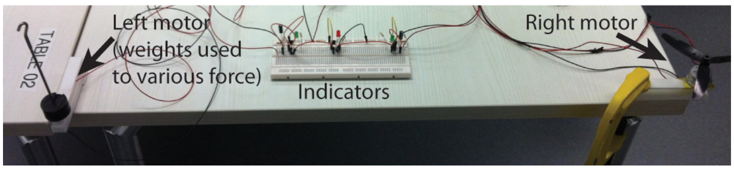

Figure 8.Scenario setup for testing the energy harvesting devices

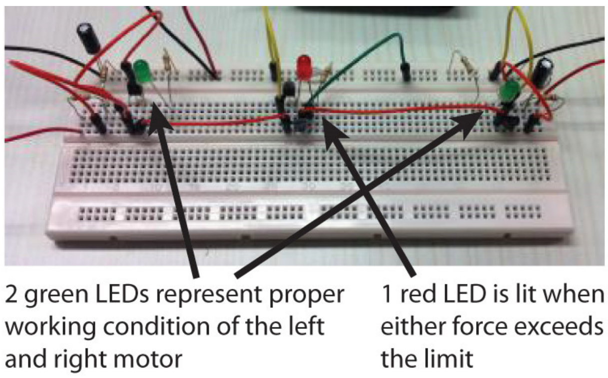

Figure 9. Enlarged view of warning indicator

Figure 10 shows the working principle of the simple threshold force detector. When a force is applied, a bending moment is generated and the "beam" bends, as taught in "Structures & Materials." Students are provided with a formula table to assist their analysis during the design of the sensor beam. Data from a tensile test of the provided plastic material is also given to the students to obtain the Young's Modulus of the given material.
As shown in Fig. 10, electrical connectivity of the metal wire and steel screw is used to determine whether the threshold force has been exceeded. The adjustability of the screw enables the designer to adjust it to the desired threshold force.

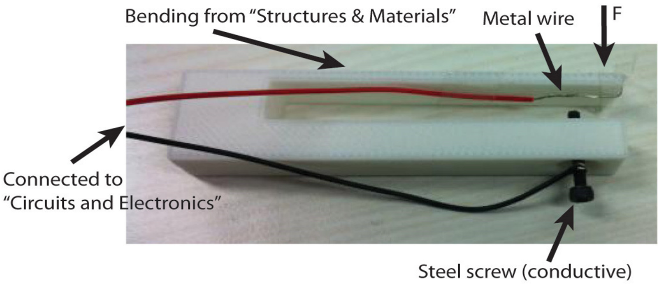

Figure 10. Working Principle of the Threshold Force Detector

The students are tasked to develop the warning system with the following information:

- Threshold force is set at 0.45 N
- Evaluation settings:
  - 0.4 N (normal condition): Green LED
  - 0.5 N (warning): Red LED
- Achieved by using MOSFET electronic devices as switches

In addition, the students are limited to the following provided materials: 1 x 1 kΩ resistors, 1 x 10 kΩ resistors, 4 x NMOS MOSFET (2N7000), 2 x Green LED, 1 x Red LED, 2 x Yellow LED, 1 x 1 μF Capacitor, 1 x breadboard, batteries, plastic sheeting, weights, glue, G-clamp, cutter, ruler, tape. The students are to present their beam design and circuit design diagram to the instructors. Questions are asked by the instructors to gauge whether the students understand the fundamental concepts from the two courses, and to encourage the students to iterate with their concepts during the design phase.

Targeted Concepts Related to "Circuits & Electronics" and "Structures & Materials"

The following concepts are targeted to be reinforced during the threshold force detector design project:

- Deflections due to bending moment
- Obtaining Young Modulus based on actual tensile test
- Digital electronics principles
- Using MOSFET devices as digital switches
- Pull down and pull up resistors

Outcome

The discussion during the circuit design phase once again proves to be an enriching experience for the students. Students are required to analyze the circuit and modify the circuit design accordingly. This activity gives the student an opportunity to reinforce their logic thinking in digital electronics. Instructors observed excitement from the students during their engagement in this design activity. This activity sheds light on how to take advantage of deflection behavior due to bending moments in an innovative way through integration with sensing technology, reinforcing fundamental principles while illustrating real world applications.

3.2.3 Design Activity 3: Open-ended Project

Motivation for Activity Theme

Healthcare is another area in which a number of students have interest, amplified by an increase in governmental grants for innovative start-up companies in the area of healthcare. Thus, the open-ended project was targeted at the application area of healthcare.

Description of Activity

The objective of the open-ended design project is to give the students an opportunity to be creative and encourage independent thinking, rather than following detailed step-by-step instructions, a skill needed to excel in industry. In addition to the topics from the two parallel courses, this project is intended to reinforce their previously learned design skills, tools, and methods.

Students are tasked to design and develop a product for the healthcare industry. No specific device or area of opportunity is specified, and the students are to perform stake holder needs analysis, ideate and decide on a particular healthcare design problem that they would like to engage. Students were provided a list of potential project ideas.

The students are instructed that their project must use at least one concept from "Circuits & Electronics" and "Structures & Materials." They are instructed to follow the design process previously covered in their freshmore "Introduction to Design" course, which includes knowledge of how to gain understanding of the design opportunity, ideation techniques, concept selection processes and tools, and prototype development. The instructors meet with the students throughout the course, offering advice when the students encounter issues with which they require guidance. The instructors did not give any detailed instructions to the students, but rather only general facilitation, direction and advice.

Each group is given S$300 to develop their prototype, which includes the prototypes developed during design process, sourcing for components, and redesign according to the materials available in the market, allowing them to experience design with simulated real-world considerations and conditions. As illustrated in Figure 3, this information is given to the students in week 2, and a final presentation with the working prototype is due in week 12.

Targeted Concepts

Students are instructed to incorporate at least one fundamental concept from each of the two courses, but no one specific concept from either course is targeted to be incorporated. They are required to employ and advance their previously learned knowledge of the design process in order to achieve a successful outcome, and are given few constraints or detailed instructions for their project, encouraging independent and self-directed thinking and problem solving.

Outcome

The purpose of this activity is to give the students significant space to be creative. Various concepts are proposed by the students for their final projects. Figure 11 shows some examples of the prototypes built by the students, all of which clearly require knowledge from both mechanical and electrical engineering domains and have enabled students to appreciate the importance of interdisciplinary learning. Overall, the faculty and students were greatly impressed with the creativity and demonstrated technical competency from the project results.

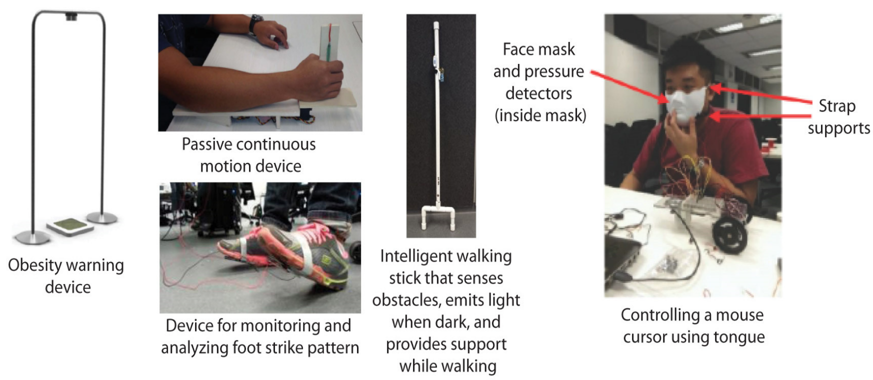

Figure 11. Examples of the Final Prototypes Built by the Students for the Healthcare Industry

4 RESULTS

4.1 Self-Reported Student Outcomes

A survey was voluntarily completed by 77 undergraduate, fourth semester, students enrolled in both "Structures and Materials" and "Circuits and Electronics" at SUTD while completing the two courses running in parallel. In this survey, the students are asked to provide an honest assessment of their abilities and confidence (self-efficacy) before and after the two courses. No compensation is provided to the participants. The 15 question survey can be completed in less than 10 minutes.

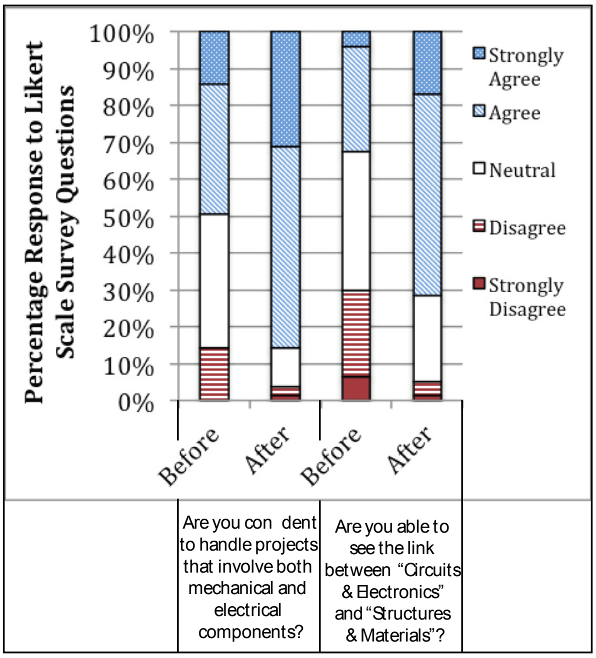

Figure 12. The students' confidence in handling multidisciplinary design projects and their ability to approach a design problem from a system perspective

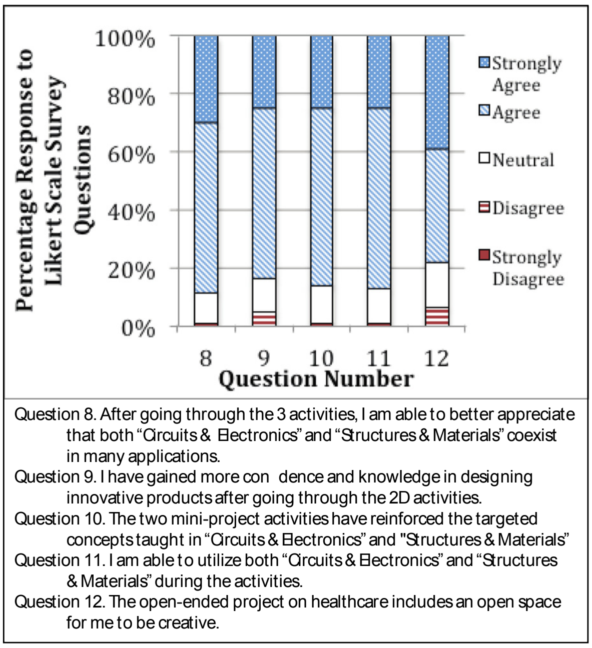

Figure 13. Additional Student Survey Responses

Figure 12 shows the average Likert scale ratings of student responses on their self-reported confidence in handling multidisciplinary design projects and their ability to approach design problems from a system perspective. The results are evaluated on a Likert scale of 1-5, where 1 is strongly disagree and 5 is strongly agree. An analysis of variance analysis (ANOVA) (two factor without replication) shows that there is a statistically significant difference among both the population means ($p \approx 0 < 0.05$). The results indicate that the students feel that they are more confident and able to view design from a system perspective after completing the three design activities. Fig. 13 shows other relevant results from the survey, reinforcing our findings. In particular, the confidence level of students to combine subject matter content from very distinct and different courses is greatly increased and enhanced. While responses to the survey questions shown in Figures 12 and 13 are majority positive, there are some students who disagreed with the statements in the surveys. In particular, the disagreements came with respect to the statements shown in Figure 12 that deal with feelings of confidence in seeing the link between the two domains, and being able to complete projects that involve both domains. In Figure 13, Question 9 and Question 12 had disagreeing responses, dealing with level of confidence in doing design, and feelings about creativity within the chosen design problem space. It is to be expected that there will nearly always be a distribution of positive and negative responses in any survey of this kind. Aside from this explanation, feelings of maintained low confidence in interdisciplinary projects, design and creativity may stem from lack of engagement in the projects, lack of experience of comfort with these areas of open-ended and complex thinking, or personal disinterest in the topic areas. Based on informal feedback from the students, working on the projects in groups was a source of continued lack of confidence due to lack of opportunity to experience working on all the various components on their own.

4.2 Instructor Feedback

The course instructors' observation is that the students were fully and enthusiastically engaged in the activities and have utilized, adeptly and with creativity, the necessary concepts. The discussion phase of the design activities is the portion that deepens the students' analytical skills and theoretical understanding of the concepts, while the actual implementation of the design through prototyping improves their skills in creativity and hands-on capability. The students are very motivated as they apply what they have learned through industry-related design problems.

5 CONCLUSIONS

Responses from both instructors and students are positive and indicate the achievement of the desired objectives of these activities, including increasing student confidence in working on interdisciplinary problems and systems level design, as well as reinforcing the key fundamental concepts from the two core courses. Kolb's experiential learning is utilized in these two courses, and interdisciplinary design problems are proposed to attain the "Concrete Experience" and "Reflective Observation" of Kolb's experiential learning. Students engage in the thought processes of creativity, evaluation, and analysis through the three design activities, which are among the higher level of Bloom's revised taxonomy. The design activities are industry-driven, targeting the areas of sustainable energy generation, aerospace engineering and healthcare applications. These design activities are constructed in such a way that they facilitate deductive learning based on the concepts taught earlier in the curriculum, and students are required to apply the material in an interdisciplinary way to solve the design problems. This work outlines innovative techniques to help students integrate knowledge from separate courses, while also developing crucial design and problem solving skills.

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