Reinforcing a "Design Thinking" Course by Restructuring Student-Instructor Interactions

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1. Introduction

In the past few years, the study of "design thinking"[1-3] is drawing increasing attentions in the engineering design community. It dates back to Herbert Simon's book "*The Sciences of Artificial*", when the notion of design was being viewed as a particular "way of thinking"[4]. Recently, "design thinking" is increasingly recognized to be an "exciting paradigm"[5] to address many critical problems in many professions such as information technology[6] and business[7]. As the research of "design thinking" keeps gaining momentums, a variety of different "design thinking" courses have been developed by different organizations for different purposes. The development, teaching, evaluation, and refinement of any engineering course must follow a systemic designing process. A "design thinking" course is by no means an exception. To date, nevertheless, relatively few efforts have been devoted to conceptually modeling what constitutes a (good) "design thinking" course, what makes it different from a regular design course, and how to enhance the teaching/learning of "design thinking".

We propose to reinforce a "design thinking" course be means of restructuring the interactions between instructors and students. Unlike a traditional engineering course that is characterized by a linear transfer of domain-specific knowledge (e.g., mathematical equations, optimization models, etc.) from instructor to students, a "design thinking" course features development of the student's domain-independent thinking patterns guided by the instructor. That being said, an important goal of a good "design thinking" course should be to systemically transform the student from thinking like a novice designer to thinking as if an expert designer. We propose that a possible means is to promote higher quality interactions between the students and the instructor (i.e., the student-instructor interactions). In a design class, the student-instructor interaction is analogous to a particular kind of novice-expert interaction. Through which, the instructor (as an expert designer) systemically transfers his/her design knowledge to become the student's (as a novice designer) independent design problem solving capability. The distinctions between novice and expert designers, with respect to their different thinking processes/patterns, have been indicated by many previous studies[9-10]. In practice, unfortunately, a great majority of the student-instructor interactions occurs in an ad-hoc manner as opposed to a structured process. So far, relatively few efforts have been committed to investigating how to make the currently ad-hoc student-instructor interactions more structured, and what are the impacts of a more structured student-instructor interaction process on the student's learning of "design thinking".

2. Conceptual model of a "design thinking" course

We argue that a "design thinking" course can be (and should be) regarded a complex system, and one of the primary functions of such a system is to gradually reduce the difference between the instructor (as an expert designer) and the student (as a novice designer) with respect to their initially different design thinking patterns (i.e., the cognitive process of how a design problem is

framed and solved differently). Here we use the IDEF0 method[11] to conceptually model a "design thinking" course. The IDEF0 method is a well-established functional modeling method, which is commonly used to describe the key functions of complex systems. To date, however, few efforts have been devoted to apply the IDEF0 method to model a design course as a complex system. Next, we explain our interpretation of a (good) "design thinking" course with respect to the four IDEF0 building blocks: input, output, mechanism, and control. The conceptual model is illustrated in Figure 1.

Input of a "design thinking" course includes both design methods and design projects. The former specifies a particular process (or pattern) of performing design, which the instructor can systemically teach step-by step. Whereas the latter allows the students to practice the new methods that they learnt by solving real-world design problems. In some sense, a certain design method can be interpreted as a representation of its creator's unique design thinking. Provided a number of available methods developed by different researchers, the instructor's preference of a certain method (or synthesis of multiple methods) somehow represents his/her own design thinking. With respect to the input of design projects, the application of project-based learning in engineering education has been widely discussed in general[12], and it is commonly recognized to be an important method for teaching design thinking in particular[1].

Output of a "design thinking" course means student's capability to engage in a certain design-specific cognitive activity independent of the instructor's guidance. By definition, design thinking stands for a variety of design-related cognitive activities such as problem formulation, problem analysis, idea generation, etc.[13] Note that, the output refers to the student's capability to carry out design either individually or collaboratively with others, but without any external guidance from the instructor/expert. In the past, a variety of different metrics have been developed to assess the designer's design related capability/outcome such as the idea generation effectiveness[14-17]

Mechanism of a "design thinking" course means the interactions that occur between the students and the instructor (the student-instructor interactions). Unlike most of engineering courses that are characterized by a linear transmission of knowledge from an individual instructor to a class of students, the "design thinking" course often features more intensive student-instructor interactions through which knowledge is being constructed with texts and in contexts. Since we assume that a (good) "design thinking" course must simultaneously process two inputs (i.e., the design methods and the design projects), our focus hinges on two kinds of student-instructor interactions: instructor-class interaction on design methods, and team-instructor interaction on design projects.

Control of a "design thinking" course means the distance between the student's actual capability as determined by his/her design performance independent of the instructor's guidance, with the student's potential capability as determined by his/her design performance under the instructor's guidance. This is inspired by Vygotsky's Zone of Proximal Development Theory[18]. Ideally, the distance controls the lever of any student-instructor interaction: as the student's actual capability

increases, the instructor's engagement level decreases. In practice, the distance can be indicated by comparing the student's design outcome between with or without the instructor's participation (and contribution) in the design process.
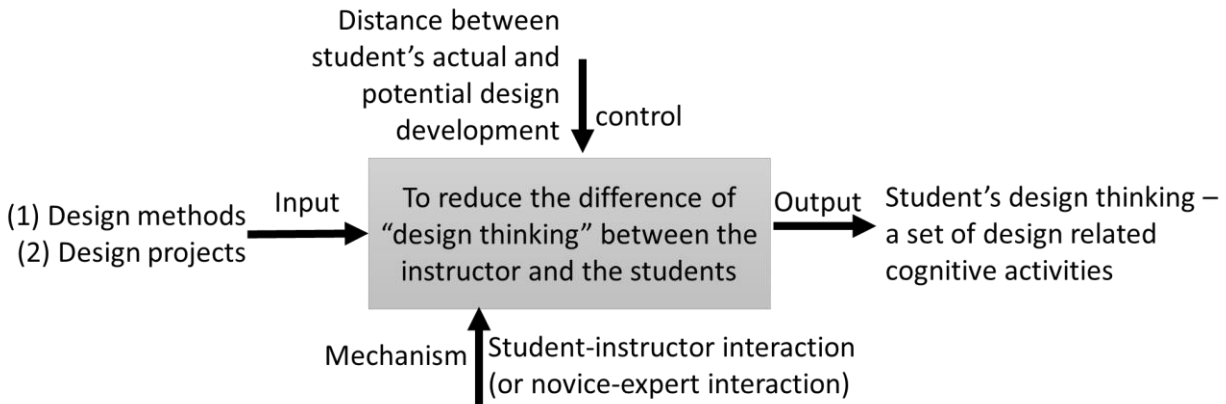

Figure 1: Conceptual model of a (good) "design thinking" course

3. Research questions

Based on the above conceptual model, we hypothesize that the effectiveness of student-instructor interactions determines the quality of a "design thinking" course. This hypothesis leads us to focus on discussing two specific research questions in this paper:

1. How to structure (or restructure) the student-instructor interactions (or the novice-expert interactions) for a "design thinking" course?
2. Whether a more structured student-instructor interaction process improves the student's learning outcome of design thinking?

To address the question (1), we propose a systemic 5-step student-instructor interaction process. The same process is imposed to restructure two types of common interactions occurring in a "design thinking" class: the instructor-class interaction on design methods, and the team-instructor interaction on design projects.

To address the question (2), we implemented our proposed interaction processes on one existing "design thinking" course, conducted a comparison of student's ideation effectiveness between before and after the changes take effect. Note that, design thinking stands for a variety of design-related cognitive activities such as problem formulation, problem analysis, idea generation, etc. In this study, we merely focus on the activity of idea generation.

4. A structured student-instructor interaction process

We prescribe that a structured interaction process includes five successive steps: (1) prepare the mind, (2) collect early feedback, (3) determine an interaction focus, (4) engage in the in-person

interactions, and (5) publish the interaction results. Since the input of a "design thinking" course includes both design methods and design projects, the process can be applied to both the instructor-class interaction on design methods and the team-instructor interaction on design projects. Note that, although the two types of interactions are restructured according to the same process, they differ from each in terms of inputs, outputs, control, and mechanism.

4.1 Instructor-class interaction on design methods

The instructor-class interaction on design methods occurs between the instructor and the whole class of all students. It is driven by the instructor, whereas the students play the role of controlling an interaction's timing, duration, level, and direction. We prescribe the following process to facilitate the instructor to effectively engage the students to participate in a more interactive learning of design methods, which is illustrated in Figure 2.

1) *Prepare the mind:* before engaging in any interaction, first the instructor must prepare the class's minds by providing some relevant media materials (e.g., slides, books, videos, etc.) about a certain design method to be taught. By doing so, the purpose is to make all students develop their initial understandings of the new method.
2) *Collect early feedback:* the instructor collects every student's individual feedback in terms of how "painful" (or difficult) he/she perceives different aspects (e.g., concept, principle, step, operation, process, example, etc.) of the new method.
3) *Determine an interaction focus:* the instructor aggregates all students' individual feedbacks into a set of collective class feedbacks. Based on which, the instructor first identifies those common "painful" aspects of the new method, and next prepares a few additional teaching materials to address these aspects accordingly.
4) *Engage in the in-person interactions:* the instructor lectures the new method to the whole class, with particular emphases placed on the common "painful" aspects determined in the last step. Next, the instructor guides the whole class to solve some simple design problems using the new method.
5) *Publish the interaction result:* after the in-person interactions, the instructor develops a few summary materials to summarize the interaction process and outcome, shares them with the whole class, and elicits any remaining confusions over the new method.
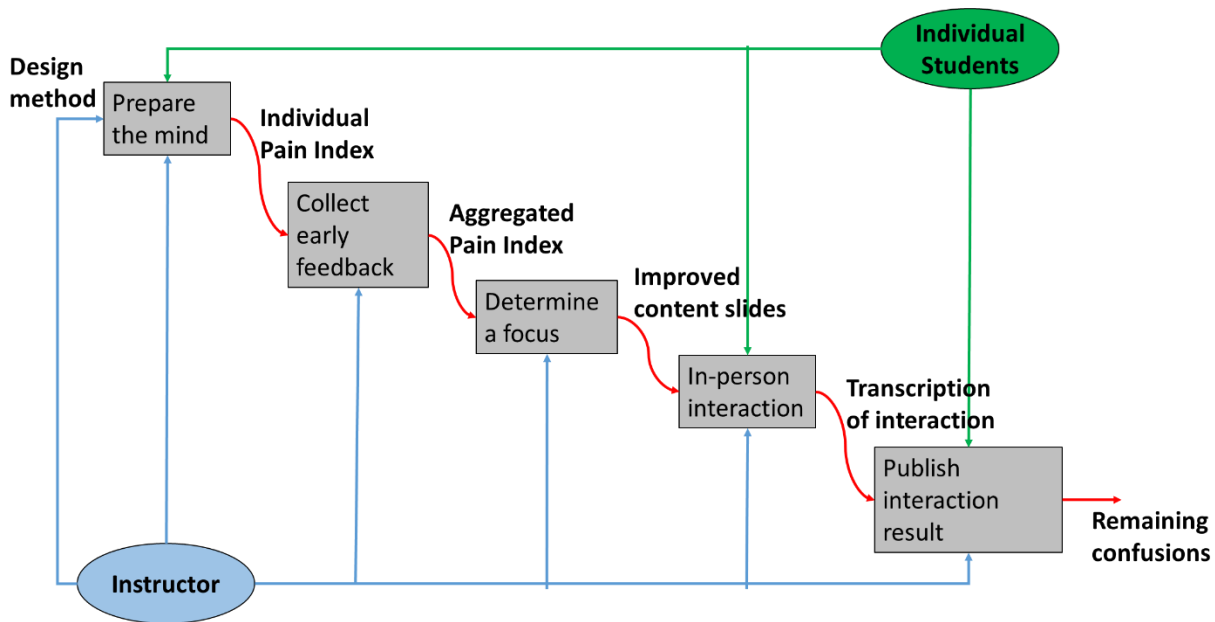
Figure 2: Process of the instructor-class interaction on design methods.

4.2 Team-instructor interaction on design projects

The team-instructor interaction on design projects occurs between the instructor and individual student teams. It is driven by the student team, whereas the instructor serves to control the timing, topic and level of interactions. We prescribe the following process for the student team to effectively engage the instructor to contribute to its design project from an expert's perspective, as illustrated in Figure 3.

1) *Prepare the minds:* before any interaction takes place, the student team must prepare the instructor's mind. In practice, for example, the team can send the instructor its current design process/outcome in a certain format, which is preferred (or required) by the instructor, such as report, slides, sketches, etc.
2) *Collect early feedback:* in return, the instructor must provide the team with some early feedback. For example, the instructor can point out the obvious mistakes made by the team in using the design methods, the misunderstandings over the project assignment, the ambiguities that need to be further clarified, etc.
3) *Determine an interaction focus:* based on the early feedbacks provided by the instructor, the team modifies its design process/outcome accordingly, and prepares a few lead-in questions for the in-person interactions.
4) *Engage in the in-person interaction:* during the in-person meetings, the team thoroughly goes through its improved design process/outcome, and the instructor steps in when he/she identifies any step that would have been designed differently from an expert's perspective.
5) *Publish the interaction result:* the team reflects its interaction process with the instructor, redoes the design by itself to generate (and evaluate) new ideas, and sends the instructor a certain update to conclude this interaction and to solicit a new interaction.
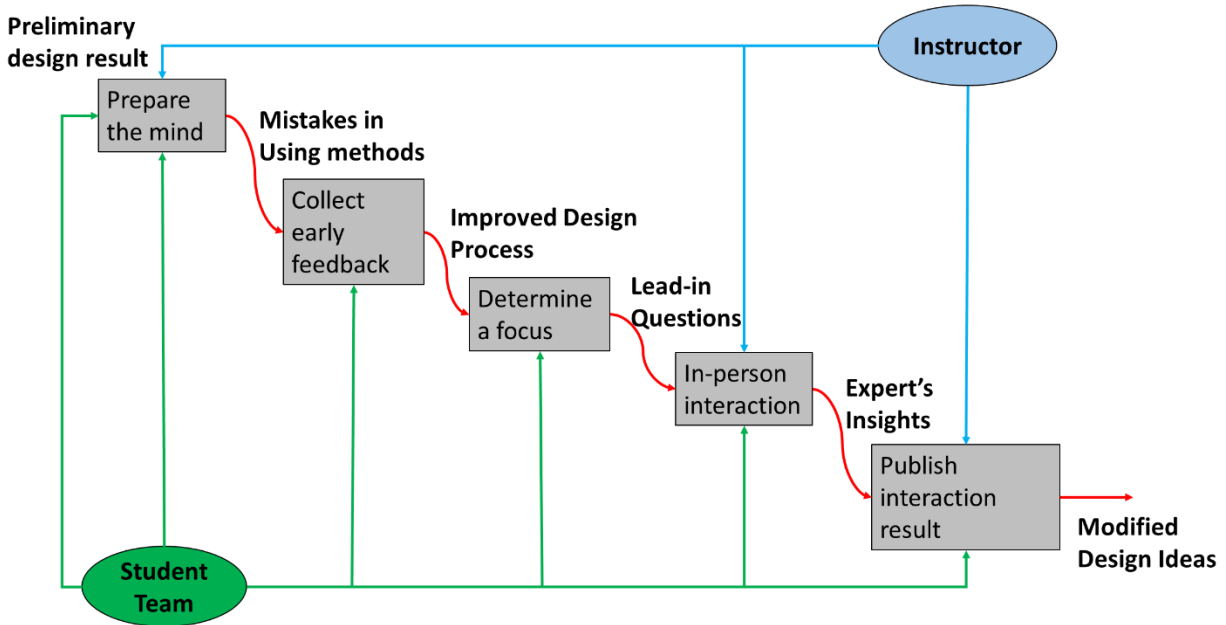
Figure 3: Process of the team-instructor interaction on design projects

5. Case study

This section presents a case study to detail the implementation of our proposed interaction process upon a graduate "design thinking" course offered at University of Southern California.

5.1 Course background

AME-503, "Advanced Mechanical Design – Innovative Design Thinking", is a 3 unit graduate course offered by the Aerospace and Mechanical Engineering department at University of Southern California (USC). This is a degree-required course for the program of Master of Science in Product Development Engineering and Master of Science in Mechanical Design at USC. In the curriculum, this course functions to make a smooth transition from students' undergraduate education in engineering components design (i.e., bottom-up and analysis-based) to graduate-level advanced issues in engineering design (i.e., top-down and synthesis-based). The course instructor, Prof. Stephen Lu, has been teaching this course for over 10 years, and the instructor's own research focused on collaborative engineering, design thinking, and engineering education.

Participants of this course were all graduate engineering students majoring in mechanical engineering, aerospace engineering, and industrial engineering at USC. The final class enrollment was 36, 37, 36, and 31 for the four consecutive semesters during 2010-2012, respectively. Roughly one fourth of the class were Distance Education Network (DEN) students who have full-time, engineering-related jobs.

With respect to course content, this course aims to spread three design phases: functional design (i.e., how to identify and transform customer needs to functional requirements), conceptual design (i.e., how to generate premature design concepts to realize the functional requirements), and concept improvement (i.e., how to further improve the premature design concepts). Different design methods were taught to support different design phases, for instance, Quality Function Deployment[19] and Kano Customer Satisfaction Model[20] for the functional design phase, Axiomatic Design[21] for the conceptual design phase, and TRIZ[22] for the concept improvement phase. In addition, the instructor developed an Innovative Design Thinking (IDT) framework that aims (1) to indicate the analogy, difference, and interrelations between different design methods; (2) to clarify the blurry aspects of each method, and (3) to frame design as a structured reasoning process based on a set of fundamental principles in logic[32]. Current teaching materials of the IDT framework include a collection of over 200 content slides.

In total, the course is composed of 12-14 weekly lecture, and each lecture lasts 3 hours. The instructor spends 3-4 lectures to go through the content for each design phase, which is followed by a review presentation lectured led by the student teams. Every lecture is structured into multiple key design concepts (or principles) whose contents are explained by 6-8 slides. Take the Axiomatic Design for example, its key concepts (or principles) include: "domain", "hierarchy", "zigzagging process", "Independence Axiom", "Information Axiom", etc.

A semester-long team design project is assigned at the beginning of the class. The class is always divided into 6 project teams each with 5-6 students. All student teams are required to follow the design methods that they learnt in class to systemically complete their design projects. This is where the two types of student-instructor interactions become entangled. The assigned problem is "*to design a computer input artifact that avoids and/or reduces the user's repeated stress injuries (RSI) on the dominant hand*". Choice of the design problem is critical to success of the project-based learning. The problem's difficulty (or complication) must properly match the student's knowledge and capability. In that regard, our problem focuses on a widely known issue, which is readily familiar to all course participants but requiring no additional (and specialized) technical knowledge to solve.

5.2 Practical implementation of our proposed interaction processes

Below describes the process of how we have implemented the instructor-class interaction on design methods upon the course. Note that, this unique teaching/learning process is analogous to the recently popular approach of "flipped classroom"[23-26], whose core proposition is also to create more interaction opportunities and better personalized experiences.

1) <u>72 hours before class time (prepare the minds):</u> the instructor posts a learning module (i.e., a collection of 20-30 slides, additional reading materials, and relevant videos) on the Learning Management System (LMS) for the class to preview. In addition, all students are required to complete three tasks online:
   - Complete a quiz to indicate that they actually studied the learning module upfront.

- Give feedback to the instructor by filling out a "Pain Index" survey to indicate how easy/difficulty (i.e., very easy, easy, average, hard, very hard) it was for them to understand the content of each slide (i.e., different aspects of the new design method).
- Participate in the weekly discussion board on the LMS.

2) <u>24 hours before class time (collect early feedback):</u> after all students finish the three online tasks, the teaching assistant (TA) aggregates these individual feedbacks into a combined class pain-index (which is easily achievable by using the existing grading functions of the Blackboard system), and sends it to the instructor.

3) <u>6 hours before class time (determine an interaction focus):</u> the instructor analyzes the aggregated feedbacks and prepares multiple additional slides with practical examples in order to address those common "painful" concepts. Furthermore, the instructor creates a new slide that shows the accumulated class pain-index statistics (as illustrated in Figure 4).

4) <u>Class time (engage in the in-person interactions):</u> during the three hour lecture, the instructor explains the improved content slides, elicits different students' answers to multiple "questions to ponder", and addresses any questions from the class.

5) <u>48 hours after class time (publish the interaction results):</u> the TA transcribes some interesting interactions (for instance, the interactions involving several rounds, multiple students, and different examples) that occurred in class, then the instructor summarizes some unique merits of these discussions, finally the TA's transcription and instructor's summary are both published on the LMS for the whole class to review and discuss.
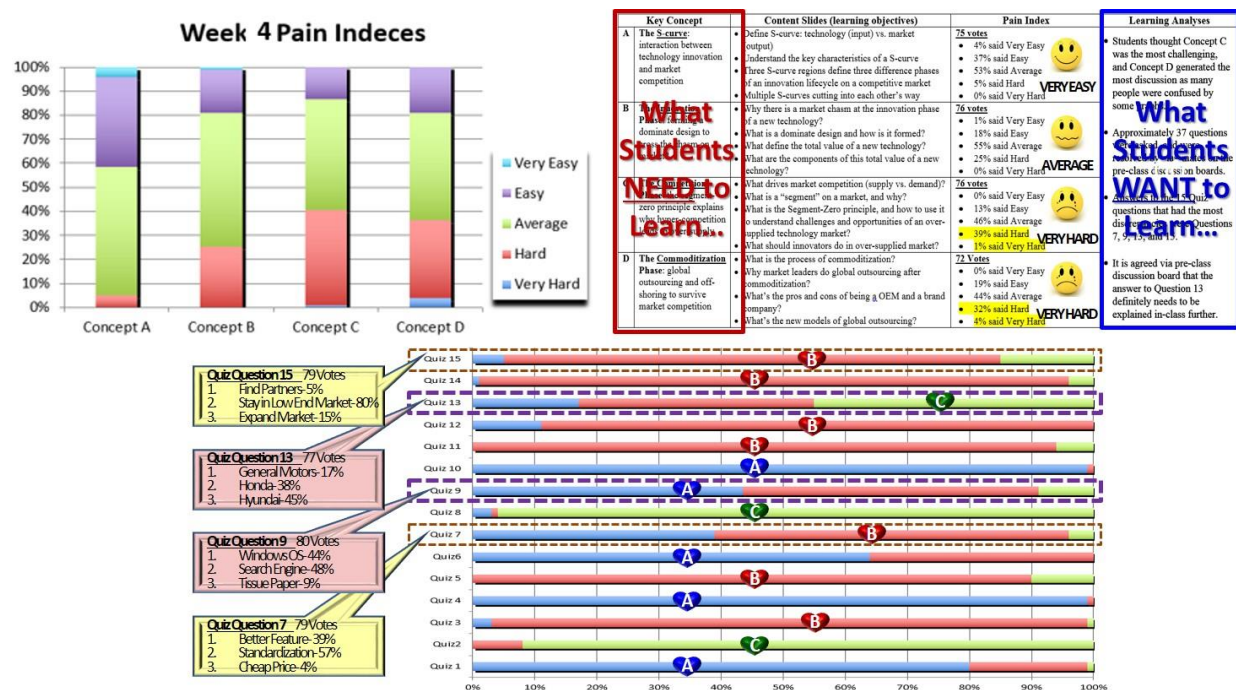

Figure 4: A sample slide of the pain index survey result

Similarly, we also summarize multiple key points of how we have implemented the structured team-instructor interaction on design projects. On average, the instructor meets each project team in-person (or virtually when the instructor is on travel) every 2-3 weeks, and each meeting lasts roughly one hour. These meetings are all scheduled during the instructor's office hours, and the TA is required to be present. In total, that is 6 one-hour meetings for each team, and two meetings for each phase. All project teams are required to email the instructor (and copy the TA) their preliminary design process and result at least 3 days prior to the in-person meetings. The preferred formats include PowerPoint slides and Word documents. The second step, "provision of early feedback", is normally carried out by the TA under supervision of the instructor, focusing on pointing out each team's obvious mistakes in using the design methods. In contrast, the instructor concentrates on providing insights during the in-person interactions. After the in-person meetings, the team is required to submit its modified design result to conclude this round of interaction. Additionally, every team is required to designate one student to be the liaison, who is responsible for facilitating communications with the TA.

5.3 Evaluation and comparison of ideation effectiveness

We evaluated and compared the idea generation effectiveness of 12 team design projects, which were collected from two adjacent semesters (i.e., 2011 fall and 2012 fall, and 6 projects for each semester). These 12 design projects can be classified into two subject groups: the 6 projects (i.e., numbered from #1 to #6) in Subject Group I were all collected before the proposed interaction processes were implemented, whereas the 12 projects (i.e., numbered from #7 to # 12) in Subject Group II were all collected after the proposed interaction processes were implemented. That being said, a direct comparison between the two subject groups, in terms of the ideation effectiveness, will provide some indirect evidence of the practical usefulness of the proposed interaction process. Table 1 summarizes the final design concepts generated by different project teams, and every concept is described from functional, physical, and embodiment viewpoints. Figure 5 shows the final concept sketch generated by the team #4, as an illustrative example.

To date, a number of approaches have been developed to assess the designer's idea generation effectiveness based on different representations such as sketches, reports, and journals[27-28], and a variety of predefined metrics have been suggested. We choose to use the set of metrics (i.e., variety, quality, quantity, novelty[29-30]) prescribed by Shah et al. for two primary reasons. First, Shah's metrics were initially developed to be domain-independent, hence, they can be applied to different product categories. Second, Shah prescribed a systemic and relatively objective evaluation procedure in order to calculate the numerical score of every metric. In the past, Shah's metrics have been widely used to facilitate addressing different kinds of design cognition problems[27, 31]. Besides, the authors have previously used Shah's metrics to evaluate the data that were collected from the same course but to address a completely different research question, and the detailed evaluation procedure can be found in the reference paper[32].

Two evaluators, who were both PhD. students majoring in Mechanical Engineering, participated in the assessment process in order to obtain an averaged result. By doing so, the purpose is to

reduce the effect of the evaluator's subjective bias on the assessment result. In addition, because Shah's method includes subjectively assigning numerical weights (e.g., importance weights for different functions), a sensitivity analysis was conducted to test the stability of every metric under varying weights. The final evaluation results are summarized in Table 2.

For every metrics (i.e., quantity, variety, quality, and novelty), a one-way analysis of variance (ANOVA) was conducted. The ANOVA result shows that overall the Subject Group II outperformed the Subject Group I in terms of the "quantity" of ideas generated. Therefore, we can conclude that the implementation of our proposed interaction processes is positively correlated to a partially enhanced ideation effectiveness. There are certain limitations that must be considered when interpreting this conclusion though. Idea generation is a complex cognitive process that is easily affected by a variety of internal and external factors. This is especially true for the team-based idea generation, which is the case of our study. As a result, it may not be fully convincing to attribute the observed enhancement solely to the implementation of our proposed interaction process, although it was indeed the largest change imposed on the course during the 2012 fall semester to the best of our knowledge.
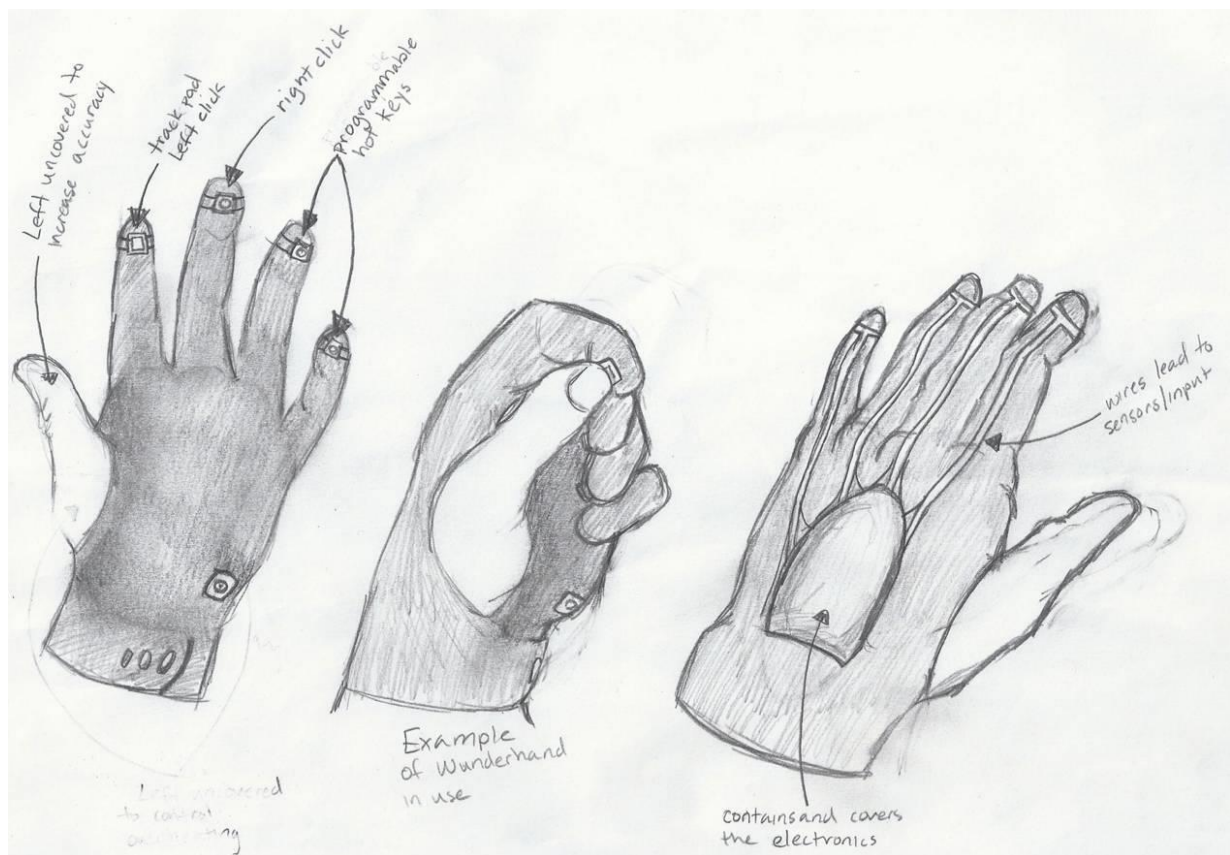

Figure 5: Final concept sketch generated by project team #4

Table 1: Summary of the final design concept for all 12 team projects

Subject Group	Project	Functional	Physical	Embodiment
Subject Group I (before the course was redesigned)	1	Self-adjusting	Separable	Combinational mechanism
		Customization	Multiple setting	Multiple layout
	2	Free dominant hand	Body control	Chair shaped
		Customization	Structure	Adjustable damper
	3	Ergonomic	Mounting	Wrist mounted
		Self-adjusting	Resizing	Expandable mechanism
	4	Increasing DOF	Using in the mid-air	Glove shaped
	5	Reducing actuation force	Tactile button design	Touchpad mouse
		Providing extra support	Wrist support	Soft cushion
	6	Providing extra support	Wrist support	Wrist band
		Ergonomic	Layout	Videogame controller layout
		Customization	Multiple setting	Interchangeable joystick heads
Subject Group II (after the course was redesigned)	7	Ergonomic	Shape	Cylinder shape
		Free dominant hand	Using two hands	Two piece device
		Self-adjusting	Change orientation	Circular track
	8	Ergonomic	Mounting method	Wrist mounted
		Free dominant hand	Voice control	Voice recognition
	9	Additional usable viewing	Auxiliary screen	Scissor lift-like mechanism
	10	Ergonomic	Shape	Curved design
		Free dominant hand	Involving both hands	Two piece device
	11	Free dominant hand	Voice control	Voice recognition
		Customization	Multiple setting	Adaptable layout
	12	Customization	Interactive feedbacks	Pressure sensor and accelerometers

Table 2: Assessment of ideation effectiveness for all 12 design projects

Subject Group	Design Project	Quantity	Variety	Quality	Novelty
Subject Group I (before the course was redesigned)	#1	7.714	7.905	8.425	8.033
	#2	7.214	8.280	6.325	6.112
	#3	7.857	6.033	8.950	6.508
	#4	6.571	7.800	7.000	7.220
	#5	8.357	7.533	7.025	7.179
	#6	8.857	6.750	8.050	6.662
Subject Group II (after the course was redesigned)	#7	8.357	6.500	8.050	8.033
	#8	9.000	7.800	6.325	7.104
	#9	7.857	6.500	8.950	8.763
	#10	7.217	8.700	7.025	6.475
	#11	9.250	7.905	6.325	6.573
	#12	7.214	7.800	6.500	6.666

Table 3: Comparison of ideation effectiveness between the two subject groups

Measure	Performance	Average Score	Effect ($\alpha = 0.5$)
Quantity	Subject Group II > Subject Group I	8.68>7.76	Significant
Variety	Subject Group II > Subject Group I	7.53>7.38	Insignificant
Quality	Subject Group II < Subject Group I	7.63<7.20	Insignificant
Novelty	Subject Group II > Subject Group I	7.27>6.95	Insignificant

5.4 Lessons learned

Based on our observations, the effective instructor-class interaction on design methods develops in an iterative manner. For example, when teaching a new design method to the class, the instructor needs to repeatedly answer similar questions raised by different students, and to explain a certain aspect of the method using different examples. The practical dilemma is that most students are averse to "aimless" iterations of the "easy" (or "boring") content that they have already understood, while they desire "purposeful" iterations of the "difficult" (or "interesting") content that they have not yet acquired. In that regard, our proposed pain-index survey (see Section 5.2) becomes critical in the sense that it facilitates the instructor to determine which aspects of the design method need to be iterated in what ways and to what extent.

The importance of mental iteration to design has been indicated by a number of previous studies[23-37]. For example, it was suggested that the frequency of certain types of design iterations is positively correlated to the designer's idea generation effectiveness[33]. In general, there are two viewpoints over design iterations. One viewpoint regards design iteration as a transition between information processing and decision making, whereas the other viewpoint regards design iteration as a looping between different cognitive activities[33]. In some sense, the iteration occurring during the instructor-class interactions is analogous to the iteration occurring during the design process. For example, the instructor decides to repeat a certain aspect of the design method mostly because he/she recognizes some difficulty of interacting with the class over this aspect. This resembles the former viewpoint of design iteration (i.e., the transition between information processing and decision making). To date, however, few efforts have been devoted to investigate the impacts of teaching iterations on the development of student's design thinking.

Unlike the instructor-class interaction on design methods, the team-instructor interaction on design projects involves fewer iterations. In fact, most teams tend to unconditionally cater to every suggestion raised by the TA and the instructor, hence few back-and-forth iterations occur during the interaction on design projects. In other words, instead of considering the TA as a "consultant" and the instructor as a "collaborator", most teams treated the TA and the instructor each as a "coordinator" and a "team leader", respectively. Based on our observations, the effective team-instructor interaction on the design project develops in an abductive manner. Here the notion of "abductive" is derived from the notion of abductive reasoning, which refers to the reasoning pattern from a general observation to a particular hypothesis. Abductive reasoning is not foreign to the design community. It is widely recognized to play a key role in supporting design synthesis and spurring design creativity[38-40]. In practice, an abductive instructor-team interaction process proceeds as follows: first the instructor identifies an interesting idea from the team's current design outcome; then the instructor proposes his/her hypothesis (or intelligent guess) of how this idea was oriented; next the team verifies if (and to what extent) the instructor's hypothesis is consistent with what actually happened; if different, the instructor further explains why and how he/she would design differently.

Traditionally, the team-instructor interaction on design projects mostly takes place during the review presentations in class. For example, after all teams present their design process/outcome to the whole class, the instructor interacts with each team during the limited Q&A minutes. The disadvantage is that the instructor often spends a significant amount of the interaction time correcting every team's similar mistakes in using the design method instead of demonstrating how the instructor would design differently. As a consequence, it is common that the grading of design presentations is largely determined based on "how correctly the methods were used" instead of "how creatively the problem was solved".

6. Conclusion and future works

This paper presented our proposition to reinforce a "design thinking" course by means of restructuring the student-instructor interactions. Using the IDEF0 method, we modeled a "design thinking" course as a complex system that functions to transform the input of design methods and design projects into the output of student's independent design problem solving capability, via the mechanism of structured student-instructor interactions, and controlled by the distance between the student's actual capability and his/her potential capability guided by an expert. We prescribed a 5-step process to restructure two types of student-instructor interactions: the instructor-class interaction on design methods, and the team-instructor interaction on design projects. The proposed interaction processes have been successfully implemented on an existing "design thinking" course at University of Southern California. A comparison of the project teams' ideation effectiveness between before and after the proposed changes took effect partially validated the practical usefulness of our proposed interaction process. In addition, we observed that the effective instructor-class interaction on design methods develops in an iterative manner, and the effective team-instructor interaction on design projects features with an abductive pattern. Multiple future works are currently in progress. First, we intend to develop a set of metrics to characterize, classify, and quantify the effective student-instructor interactions. Next, we aim to perform a correlation analysis between the interaction effectiveness with the design performance. Finally, based on the lessons learned, we will prescribe and test new approaches to further enhance the student-instructor interactions.

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