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ORIGINAL ARTICLE

Discipline-based instruction to promote interdisciplinary design of wearable and pervasive computing products

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Abstract This paper reports on a design experience for undergraduates in computer engineering, industrial design, and marketing that focuses on pervasive computing devices. Across a broad range of targeted application areas and user groups, many of the student designs have been wearable computers. Consequently, our course will be of interest to the wearable computing community, particularly in terms of our aim of bridging the gap between design and engineering. For the two most recent offerings of the course, we have utilized external observers and surveyed the students in order to validate the impact of aspects of our process and changes to it. This paper is based upon 5 years of experience and 2 years of analysis of our course, and it presents an overview of our process with both qualitative and quantitative results from these two most recent offerings.

Keywords Interdisciplinary design teams · Pervasive computing design

1 Introduction and background

A truly wearable computer requires a balance of design constraints between technology, the human body, human–computer interaction, and social context. If a wearable computer is to be commercially viable, the design constraints must also include business and marketing aspects. Building a design team that can synthesize this broad range of design, engineering, and business constraints is challenging. Most practitioners in these fields gain their interdisciplinary team experience by trial-and-error and sheer luck, if at all. The deeply disciplinary nature of universities does not prepare students for working on the types of design teams that are required for successful wearable computing systems.

The goal of our course is to address the significant professional cultural barriers to interdisciplinary design during the students' undergraduate education such that they will be able to contribute to a pervasive computing product development team. The educational objectives of the course are (1) to provide the students with an appreciation for the value and contributions of the other disciplines, (2) to have them demonstrate their disciplinary expertise within the context of an interdisciplinary design team, and (3) to develop the skills and professional awareness required to contribute to an interdisciplinary design team creating a product concept in response to an open-ended product opportunity area. Students who successfully

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complete the course will be well prepared to work with people from other disciplines to define, design, and implement a pervasive computing system.

Although there is considerable work on the interdisciplinary design teams required for these products [1–4], most of that work focuses on industry. Besides obvious differences between industry professionals and undergraduate students, participants in an academic setting must deal with limited schedules (e.g., a 15-week semester with about 3 h of class time per week) and the differing institutional structures of three different academic units.

Within the wearable computing community, there has always been a recognition that addressing the design aspects of wearable computing is important for the field to move forward and to have broader acceptance. Gemperle et al. [5] described a set of design guidelines for wearability, in what is likely one of the most cited papers to appear at ISWC. McCann et al. [6] presented a design tool to guide designers of intelligent garments. With respect to interdisciplinary teams for wearable computing, Papadopoulos described an interdisciplinary team working on electronic textile garments [7], and there have been several studies of interdisciplinary processes at Carnegie Mellon [8, 9]. The process we describe in this paper has been directly informed by this previous work.

The purpose of this paper is to provide a case study of an undergraduate interdisciplinary design course for intelligent products. In case study research, analysis focuses on describing the case and building explanations for why various outcomes were observed [10]. This method does not intend to obtain a statistically representative sample of the population; instead, the researchers have focused on triangulating multiple sources of evidence by collecting both qualitative data through observation and quantitative data through various instruments [11]. In this paper, we report on the results from observation and the Team Diagnostic Survey (TDS) [12], a quantitative instrument used to measure team effectiveness. The researchers recorded each class meeting through video-recording and through field notes that included their reflections, non-recordable observations, and position in the field [13]. The same case study methods will be applied to future offerings of the course both at its original site and at other universities.

While the focus of the course is on the more general theme of pervasive computing, many of the product concepts and final designs have been wearable or have had a wearable sub-system. Thus, we believe that the lessons learned from this course will be of interest to the wearable computing community, which has recognized the importance of the role of design in developing successful wearable computing systems [5, 14].

Our course brings together faculty and students from computer engineering, industrial design, and marketing to explore product opportunities for pervasive computing. A novel aspect of the course is that the students identify the product opportunities themselves as part of the course—the instructors do not specify the particular products to be developed. Our reason for not providing a product specification is that, for many of the students, most of their previous course experience has been focused on working on a narrowly defined problem to solve. Our open-ended projects are often the first time where, before solving a problem, the students have to figure out the right problem to solve, which Donald Schön calls *problem setting* [15]. Problem setting skills are distinct from problem solving skills in that problem solving skills involve getting the right solution to a problem, while problem setting skills involve defining the problem to be solved: understanding the nature of the problem and deciding upon the relevant parameters and constraints. With respect to design, Buxton distinguishes these two aspects as "getting the design right" (problem solving) and "getting the right design" (problem setting) [1].

Our experience is that having an open-ended product opportunity area where the design constraints must be identified across several disciplines serves as catalyst for the students to realize that there are interactions between constraints across the disciplines. At the risk of over-simplifying, engineering students see a math problem, design students see a form problem, and marketing students see a communication problem. But the nature of most real product designs is that they are a mixture of all of (if not more than) these aspects. A good design is one that elegantly balances all of the relevant constraints, technological, esthetic, business, or otherwise. One of the objectives of the course is for students to develop the skills to work in the margins between traditional disciplines, where the real solutions to real problems often are discovered.

Over the 5 years of the course, each offering has covered a different product opportunity area and audience:

1. Pet care products for the elderly: The elderly can benefit from having a pet in the home, but they have reached a point in life when they are less able to care for the pet. Students developed concepts to help with feeding the pet, communicating with caregivers and veterinarians, tracking the pet around the home, and traveling with the pet.
2. Safety gear for construction workers: Construction is one of the most dangerous occupations. Many unsafe conditions can be detected and potentially mitigated by improved sensing and communication. Students developed product concepts for reducing the potential for struck-by-vehicle accidents on roadway construction

sites, improving communication between crane operators and riggers, tracking exposure to unsafe conditions on construction sites, creating easier-to-use fall arrest harnesses, and providing noise-canceling hearing protection for hard hats.

3. Dorm rooms for college students with disabilities: To live on a college campus, students with disabilities often require help with activities of daily, given that they have likely grown up with close supervision from a caregiver and must transition to living independently. Concepts developed for this project included a personal assistive robot, a reconfigurable furniture system with an on-line pre-configuration application so that students can choose furniture before moving into the dorm, a smart mirror for context-aware notifications and reminders, and a tangible interface for developing a social network.
4. Helmets for firefighters: Firefighter helmets have been essentially unchanged for a century. For this offering, we limited the scope to redesigning the helmet. In the end, students went beyond just improving the helmet to developing concepts for breathing apparatus and protective clothing.
5. Diabetes management for children with diabetes and their caregivers. With the increasing incidence of diabetes in children comes a greater need for managing the disease. Students developed concepts for counting carbohydrates, rewarding children for following their treatment regimen, helping children manage necessary treatment items while outside the home, communicating with parents with a wrist-worn device, and sharing health data with doctors and insurance companies.

For each of these topics, the only constraints the faculty placed upon the product concepts were that they must fall within the opportunity area and that they must be intelligent.

When we first offered the course, we were only concerned with the products themselves, and our design process was ad hoc. However, we soon realized that there were important questions to be explored in developing an interdisciplinary design process for intelligent products. We then began to study our process both quantitatively and qualitatively, with two primary goals. First, we aim to provide our students with a high-quality interdisciplinary design experience that allows them to appreciate the role and contributions of other disciplines. Second, we would like to develop a course model that can be followed by other universities, as opposed to depending upon the particular set of people that we have available. Assessing the course provides an objective method for us to continually improve methods for teaching collaboration across disciplines and to formalize a transferable process.

The remainder of this paper is organized as follows. Section 2 outlines the course, with examples of design concepts that have come out of the course. Section 3 describes a major change we made for Fall 2010, introducing discipline-specific modules, including an electronics prototyping kit and exercise. Section 4 provides qualitative and quantitative results of the impact of the changes of the course. Finally, Sect. 5 gives our conclusions and avenues for future work.

2 Overview of the course

This section provides an overview of the running of the course, including our design process and timeline. We begin by describing the origins of the course and summarizing our course process and general schedule. We then describe particular details for the 2009 and 2010 offerings, which are the basis for the results provided in Sect. 4.

2.1 Origins of the faculty team and course

To provide context for the process and for the study, the reader may find it helpful to know the history of how the course developed. A core set of the faculty authors (Coupey in marketing, Dorsa in industrial design, and Martin in computer engineering) first came together for the pet care project in 2006, which was in response to a ten-week design competition sponsored by Proctor & Gamble. That project had four other faculty members as well as students from five programs (industrial design, computer engineering, marketing, graphic design, and industrial/systems engineering). The following year, 2007, Dorsa and Martin worked on the construction site safety with two other faculty colleagues and students from only computer engineering and industrial design. During that semester, as part of an internal university program for funding interdisciplinary research teams, we put together a team that included the four faculty members on the construction site project and Coupey.

We were selected for the program in 2007, and more importantly, we were then asked to participate in a study of interdisciplinary teams being run by a faculty member of the engineering education department. Through the faculty member conducting that study, we were introduced to McNair, who began working with us to introduce team development exercises in the course for the 2008 offering. In the spring of 2009, McNair led a proposal to the National Science Foundation's Engineering Education program, which was funded in the summer of 2009.

We relate this history for two reasons: First, to illustrate to others the serendipity involved in finding team members as well as the changing set of team members with a small core (Dorsa and Martin are the only two involved in every offering of the course, with Coupey involved in every offering except the second one). Second, and more to the point of the paper, the interventions described in Sect. 3 and the results described in Sect. 4 are only reported for 2009 and 2010 because those are the years covered by the research grant.

2.2 Course process

The major elements of the course have evolved over five offerings; the details of that evolution are more fully described in Coupey et al. [16]. Our goal for the course is for the students to gain an appreciation for working in an interdisciplinary design team that must satisfy product constraints that span a wide range of domains. Our teams have senior undergraduates from computer engineering (ECE), industrial design (ID), and marketing (MKT). A major part of the course, particularly early in the semester, is breaking down the cultural barriers that exist between these disciplines. We have found that addressing these barriers explicitly will help the students more quickly and easily work together in teams. An important facet of the cultural barriers is vocabulary—even as simple a word as "model" has a different meaning to each of the three disciplines. By explicitly pointing out these cultural differences for the students, we reduce the number of conflicts that arise later due to poor communication. The faculty also serve as role models for working through these cultural differences, often having frank discussions about them in front of the students.

To maintain balance between the disciplines, we also have equal numbers of students from each discipline and meet in a neutral space. Having equal numbers of students reduces the likelihood that any one discipline will seem to have a greater role in the project (with this aspect we are not always successful, as will be described Sect. 4 with the outcomes of the firefighter helmet project). Meeting in a neutral space makes each group of students feel equally welcome in the space. In one of the prior offerings, we met in dedicated undergraduate studio space in the Industrial Design program, and the non-ID students felt like guests—welcome guests, but guests, nonetheless.

The basic schedule of our course is shown in Table 1. We begin the semester with examples of interdisciplinary design teams in industry, such as IDEO [17], and with examples of pervasive computing products and research. These examples provide initial background for the students on the design process and on the types of intelligent products that they are expected to develop.

The students are then put into research teams, with the constraint that there is at least one member from each discipline. These research teams explore the issues involved in the product opportunity area. As mentioned in the introduction, we have chosen a different product opportunity area each semester: pet care products for the elderly, safety gear for construction workers, dorm rooms for college students with disabilities, helmets for firefighters, and diabetes management for juvenile diabetics. The research teams bring information back to the whole group. Then, each team is given more detailed research tasks to minimize overlap between teams and to maximize the areas covered by the teams. The time spent on the research phase of the course has varied with each offering, but generally lasts for 4–6 weeks.

Table 1 Timeline of course topics and activities

Week	Topic and activity
1	Overview, research teams formed
2	Research to explore design opportunities, sketching/affinity diagraming exercise
3–4	Research to explore design opportunities
5	Product ideation (brainstorming)
6	Final product selection
7	Product teams formed
8	Product concept development, product box exercise
9	Product concept development, storyboarding and physical prototyping exercise
10	Product concept development, computer prototyping exercise and marketing value proposition exercise
11–13	Product concept development: business plan, interface, form factor, physical and functional prototyping
14	Product concept development: preparing final deliverables
15	Final presentations

Near the end of the research phase, the students shift to the product ideation stage by brainstorming on possible products, using techniques that are familiar to the ID students but are new to the ECE and MKT students [4]. Student teams then re-form around the most popular products. As with the research teams, each product team must have at least one member from each discipline. Depending on the products, some teams might have more students from one discipline than another, e.g., two students from ID, and one each from ECE and MKT. Usually students are able to work on their favorite product choice, but some shifting of students is sometimes necessary to make sure each discipline is represented on each team. The products are usually closely enough related that they can be considered part of a family of products that work together. Consequently, the students identify interactions between products and arrange liaisons that are responsible for managing those interactions. There has usually been a product that tied all of the other products together, as, for example, a central data collection unit that served as a hub for the other products. We observe that, even though the students are only given

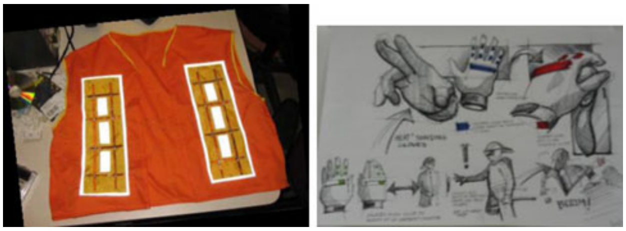


Fig. 1 Examples of wearable concepts and final prototypes from the course. *Left* intelligent vest for roadway construction sites; *right* information-gathering gloves for firefighters

the constraints that the product must be within the specified opportunity area and that it must be intelligent, many of their concepts and final projects are wearable. Two examples of wearable computing devices that students explored as concepts and final projects are shown in Fig. 1.

The remainder of the semester is spent developing product concepts, creating business and marketing plans, and showing technical feasibility. The semester ends with a final presentation to outside evaluators. Student grades are based upon participation, adoption of the interdisciplinary process, and the quality of their final presentations.

With only 15 weeks for the whole project and given the amount of the time spent on research and ideation, there is usually not enough time for students to build a fully working prototype of their designs, so the expectation is that they will prototype the critical aspects of their design at a level that establishes technical feasibility. Part of our motivation for introducing the Arduino-based kit described in Sect. 3 is to enable the students to create prototypes with higher fidelity.

One of the goals of the faculty is for the students to take responsibility for the course. Throughout the stages described above, but particularly in the early weeks of the semester while the students are becoming accustomed to each other and the expectations of the course, the faculty set the expectation for the students to take the initiative. A primary example of having students take the initiative is that the student teams are generally self-organizing, meaning that the faculty let the students pick which research and product teams they belong to, within the constraint of having each discipline represented on each team. When the faculty have been successful in setting this expectation, there comes a point midway through the semester when the faculty are no longer leading the class meetings but are participating as advisors and stepping in only when necessary. The balance between providing structure and allowing the students to have control must be handled carefully, as will be demonstrated by the results described in Sect. 4.

2.3 Changes for the two most recent offerings

We introduced several major differences between the course offerings in the fall of 2009 and fall of 2010. First, in the fall of 2009, we deviated from our normal practice of having a wide-open product opportunity area and instead told the students that they had to redesign the firefighter helmet to make it intelligent. This project was still relatively open compared to the projects students were used to in their other courses, in that we did not specify the new capabilities the helmet should have. In the fall of 2010, we went back to specifying a product opportunity area rather than a specific product, with the area being children with diabetes. As Sect. 4 will show, we believe that the open-area approach gives the students a greater sense of responsibility and that the place for instructor-imposed structure is in facilitating interdisciplinary collaboration by vesting students with roles that allow them to use their expertise in an integrated design cycle.

Second, in the fall of 2009, the final deliverable for the course was an entry into an industrial design competition. This deliverable had the negative effect of elevating the importance of the industrial design discipline and left the marketing and engineering students without concrete ways to contribute. In the fall of 2010, the final deliverable was a presentation to a set of local venture capitalists, which required a well-rounded proposal from each team that addressed the major design, technical, and business issues for that team's product.

Third, in the fall of 2009, the course met once a week for 3 h, while in the fall of 2010, it met twice a week for 1.5 h at each meeting. This scheduling difference might seem like a minor point, but it had major side effects. The most significant of these is that when a faculty member was absent due to travel, he or she missed effectively 2 weeks. In some cases, two of the four faculty members traveled on consecutive weeks, which meant that the full set of faculty were not present for 3 weeks, which contributed to a lack of structure in the course. Considerable time was spent summarizing the previous week for the returning faculty member, and on several occasions, we revisited decisions that were made during the faculty member's absence, which slowed the progress of the student teams.

Finally, the faculty provided more structure in the fall 2010 offering than they did in the fall 2009 course by introducing the students to each discipline by adding hands-on exercises covering marketing, electronic prototyping, and iterative design techniques. We also set a deadline of midway through the semester when the research and brainstorming phases would end and project teams would be formed, with the remainder of the semester dedicated to product development. Furthermore, we required that the final projects include a physical/electronic prototype of appropriate complexity for the particular product. In addition, teams were asked to provide marketing documentation of the concept, in the form of a commercial, or a comparable communications deliverable.

This additional structure vastly improved the outcomes of the course and the satisfaction of both the students and the faculty, as will be shown in Sect. 4.

A point that must be made is that, while from the previous paragraphs it might seem in hindsight that the approach to the course in fall 2009 was obviously poor, it did not seem so at the outset. Several aspects of that approach were conscious decisions by the faculty to address issues that had arisen in earlier offerings. Meeting once a week for 3 h was introduced to make the course seem more like a project in industry. Having a goal of entering the projects in an industrial design competition was meant to provide an external stimulus that had worked well in our first offering of the course but that we had not had in the second and third offerings.

Unfortunately, we did not begin formally studying the course with surveys and observations until the fall of 2009, and so we do not have a baseline of data from the previous years to compare both years too. Consequently, the results in Sect. 4 are limited to comparing only the 2 years for which we have data, although from our experience we can make some general comments with respect to the other offerings. While a true controlled experiment would have been preferred, it is difficult to achieve in an actual classroom setting. In particular, we do not want to continue to do things that we thought worked poorly because doing so would not be in the best interests of the students, even it was correct from the viewpoint of conducting a controlled experiment.

3 Hands-on, discipline-specific modules

As described in the previous section, one of the major changes made in the fall of 2010 was to add hands-on exercises for both electronics prototyping and marketing, in addition to the industrial design exercises. This section describes the individual exercises used for ID, MKT, and ECE disciplines. The goal of each of these exercises is to increase the awareness and understanding of each discipline while framing individual students as purveyors of their disciplinary perspective.

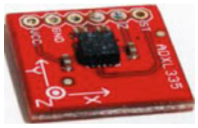
3.1 Electronics prototyping module

This section describes the Arduino-based prototyping exercise. Our major goal for introducing an electronics prototyping exercise was to provide the students with the ability to rapidly explore product concepts while going beyond sketching [1]. Following several good examples such as Igoe [18] and Buechley [19], we opted for a set of sensors and output devices coupled with an Arduino processor. The critical aspect for the kit is that new design alternatives can be rapidly tested, explored, and evaluated. Thus, we balanced the complexity of using the kit against the richness of devices it could build.

The kit consisted of an Arduino Duemilanove board for the microcontroller and an Xbee breakout board for wireless communications. For sensing, the kit included a digital compass, tri-axis accelerometer and gyro, vibration sensor, IR motion detector, ultrasonic range finder, photocell, barometer/temperature sensor, force sensitive resistor, and microphone. For output, the kit contained a piezoelectric buzzer/tone generator, vibration motor, and LEDs. Later in the semester, we added other devices as necessary for particular student projects, e.g., a small touchscreen display for a game that rewarded children for following their diabetes management regimen.

For each piece of the kit, we wrote a "user-friendly" datasheet to explain how the sensor works, its potential uses, and the information that using such a sensor could provide. Current datasheets or specifications are targeted at engineers and mainly explain the sensor's construction and electrical properties. For an engineer, datasheets are at the proper level of abstraction, but they are not at the proper level for designers who simply want to employ the device. Dow et al. [20] addressed this issue by describing *knowledge support* as a key requirement for Ubicomp design tool. As an example of this ability, Dow et al. suggests, "a tool might provide a device catalog that represents available devices, and how designers might use them in an application." To approximate this catalog, our "user-friendly" datasheet describes each sensor in terms of "What It Does," "How It Works," and "What It Tells You." Answers to these questions provide the appropriate level of abstraction that enables the designer to utilize the sensor, as well as providing a mental model to explain how it works. Knowing how the sensor works is critical for debugging purposes by allowing a student to reason about why and how a design failed or did not perform as expected. Figure 2 shows an example of one of these "user-friendly" datasheets.

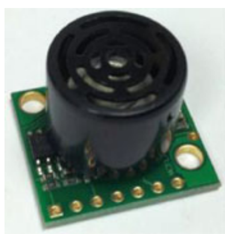
In addition to having "user-friendly" datasheets that provide appropriate levels of abstraction, we encapsulated the interaction of various sensors into high-level function calls that provide a level of abstraction appropriate for design interaction. These function calls directly relate to the "What It Tells You" section of the datasheet, and the values returned are in terms of real-world physical units. By using these abstracted function calls, the particular interaction method of each sensor is hidden from the designer so that they can concentrate on more important aspects, namely authoring the desired interaction. Thus, to find the current distance from the sensor or play a certain tone, one simply wrote *getDistance()* or *playTone()*.



What It Does: The accelerometer measures acceleration in all three axes of movement. Acceleration is the change in the speed of an object. It's the feeling of being pushed into your seat on an airplane during take, or being pushed to one side when a car makes a sharp turn.

How it Works: Each axis has a small arm inside the chip that bends as the accelerometer is moved around. Based on how much the arms bend, the accelerometer knows how much acceleration it has experienced.

What It Tells You: Force is related to acceleration by the weight of an object. If the accelerometer is hit, bumped, or dropped, it will know from what direction and by how much it was disturbed. Also, the accelerometer can determine how much it has been rotated around each axis. Tilt is commonly used to do motion capture for video games, commonly on the Nintendo Wii.



What It Does: The range finder reports the distance to an object in terms of centimeters. This sensor has a range of about 1.5 meters.

How it Works: An ultrasonic pulse is emitted from the sensor that reflects off nearby objects. By measuring the time between sending and receiving a pulse, the sensor can understand how far away objects are located.

What It Tells You: The range finder can tell you the distance to nearby objects. The pulse expands as it moves out so objects not directly in front of the sensor can be seen as well.

Fig. 2 Examples of user-friendly datasheet *Top* Accelerometer; *bottom* Range finder

The class meeting for introducing the Arduino kit and general computing concepts was dubbed "Prototyping Day" and lasted 75 min. Each team was given an Arduino prototype with several sensors already attached. These sensors provided basic interaction in the forms of sensing distance via an ultrasonic range finder, displaying light with a tri-color LED and playing a note with a simple tone generator. The prototype was programed to play a constant tone and show a particular LED color, based upon how close an object was to the range finder.

As presented to the students, the prototype itself was functional but not very interesting. This exercise was intended to challenge them to change the uninteresting basic interaction into an interesting child's toy. Changing the prototype would require editing the source code controlling the Arduino, as well as understanding the capabilities and limitations of the sensors.

We described the design challenge in an abstract way such that they would not consider the individual sensors, but their abilities and the information they offered. The students were instructed to think of the prototype not through its specific sensors, but as something that could control and sense "Light," "Proximity," and "Sound."

The result of the prototyping day was several prototypes that greatly exceeded the ability of the one initially presented to the students. One group created a box that would play the song "Happy Birthday" by utilizing the range finder and the tone generator. When the lid of the box was opened, the song would begin to play and the LED would light up to represent a candle. At the end, the user was expected to "blow out" the candle, and the LED dimmed. Another group created a musical instrument that they "taught" to play "Mary Had a Little Lamb." They reconfigured the Arduino to play other tones based on the distance sensor value and used shoe boxes as "keys" to play their instrument. In practice, the user would line up several boxes in front of the range finder and remove them in sequence and in rhythm to play the song.

Overall, this day engaged the other disciplines in the engineering process and made them familiar with using computing elements. With the design challenge presented in general terms of "Light," "Proximity," and "Sound," as well as providing accessible commands to control the sensors, the students easily extended the basic prototype.

3.2 Marketing modules for defining product benefits and characteristics

To provide computer engineering and industrial design students with an introduction to marketing, the marketing professor gave an overview lecture that explained the role of marketing not just as a strategic business function, but also as a means of developing insight into the unmet needs of consumers. A focus of the lecture was the interface between marketing practice and technological innovation, with the goals of stimulating students from all three disciplines to think about product concepts that could be brought to a desired target market by leveraging technological advances, such as wearable computing, coupled with knowledge of people/product interaction, via appropriate industrial design techniques. Background materials on the development of business plans and marketing plans were made available to the class.

Two exercises were used to provide students with hands-on experience in the application of marketing and business principles to product design and development.

In week 8, the marketing professor, in collaboration with the ECE professor, tasked students with the design of a

Fig. 3 Examples from the product box exercise

product package in an exercise called "Product Box" [21]. The purpose was to have students consider the benefits of the product that customers would desire. A key learning objective of the exercise is to make all students recognize the importance of being able to articulate a shared vision of what the product provides to a target market, in terms of benefits or value, and to determine whether the manner in which the product is presented is commensurate with the understanding and evaluation of the product by the target market. By designing the product box, the students had to consider their target market and highlight what elements of their product would be most compelling for that demographic. Students were provided with general crafts materials, including cardboard, markers, and crayons, and they were given the length of class (75 min) to design their box. Each group presented their box at the end of class. At this stage in the course, only general product areas and their associated needs had been determined. In addition to the marketing aspects, the constraint of placing the product in a retail box seeded the first considerations about the product's size, shape, and overall form. Two examples of the product boxes are shown in Fig. 3.

A second activity in week 10 required students to work as teams on three exercises: (1) developing a value proposition, (2) identifying target markets, and (3) crafting a business model. Students were presented with visual and verbal descriptions of several unusual products (e.g., a bed moat for entrapping bedbugs and a handkerchief with a nose pouch). In the first exercise, students had to articulate the value proposition for their selected product and explain why the target consumer would choose their product over that of a competitor. This exercise is intended to underscore the importance of developing a product concept and positioning that is clearly targeted to a defined demographic, readily understandable, credible, valued, and capable of competing effectively by dint of differentiation and clear sustainable advantage. The second, related, exercise required students to identify market segments, using standard criteria, and then to evaluate the attractiveness of each segment, including size, accessibility, and ability to craft an effective positioning statement to address segment needs. In a third exercise, attention shifted to the development of a viable business model for the selected product, given the value propositions and target markets identified in the first two exercises. The primary learning objective of the exercise is for students to recognize the importance of being able to identify key income drivers and key expense drivers associated with a particular value proposition. In an interdisciplinary setting, this exercise proved useful for spurring conversation about what types of features and capabilities were necessary and desirable in a product, given characteristics of the product concept and of the potential target markets.

3.3 Industrial design modules for user-centered design

Sketching is an effective means to express and communicate ideas and is used widely used in industrial design. In an interdisciplinary setting, non-ID students have been observed to be resistant to sketch their ideas because their work may not be as polished as the sketches produced by the ID students. The difference in quality puts the non-ID students at a disadvantage when discussing their ideas. In order to overcome this issue related to sketching and provide students with an ID-based tool (sketching) they can use during the design process, the Industrial Design faculty member introduced two activities that encouraged students to sketch their ideas as a "step-up" from having to verbally describe form or function. The two activities were "Thumbnail sketching," which showed students that they could convey the same idea regardless of artistic quality, and "Round Robin," in which students from each discipline sketch and comment both positively and negatively on each other's sketches. Both of these exercises are based on long-standing ID methodologies; however, the formalization of these exercises was first presented to the ID faculty member by Chris Pacione from the LUMA Institute, which teaches User-Centered Design Workshops [22].

Thumbnail sketching was an exercise to show that all students can sketch and effectively convey their ideas without regard to artistic quality. Every student was given a pad of sticky notes, and the exercise was to sketch the object, phrase, or idea, given by the instructor within a short amount of time (20 s). This short amount of time was used to limit the difference in quality of the sketches between the ID students and the students from the other students, who generally have less sketching experience. The prompts ranged from simple things like "worm" or "apple" to more abstract concepts like "conversation" or "e-commerce." At the end of the exercise, the sketches were collected for each word and placed on the board. For each word, a student was selected to cluster the sketches based upon similar characteristics they perceived (e.g., whether the apple had a stem or not). This affinity clustering exercise was intended to show the students what each thought the key part of an idea was and how visual elements reflected that. The overall result of having a large collection of sketches with varying degrees of quality, but yet still conveying the same idea, showed the students that sketching was a viable form of communication regardless of quality. More generally, the affinity clustering exercise helps the students to quickly organize data and to abstract away from details to identify underlying themes. Figure 4 shows examples from the thumbnail sketching exercise after the sketches have been clustered by the students.

The Round Robin exercise involved groups of three students. Each student was given a form divided into three sections where the students were to describe an idea, list its benefits, and its drawbacks. The challenge in this exercise was that one student would complete a section and then pass it on to their neighbor. Through this exercise, the students were able to have the experience of what it was like to be the creator, and also recipient, of praise and criticism for their ideas. Overall, the intention of these two exercises was to give students in all the disciplines practice in industrial design processes and to increase everyone's comfort level with sketching and open-ended design.

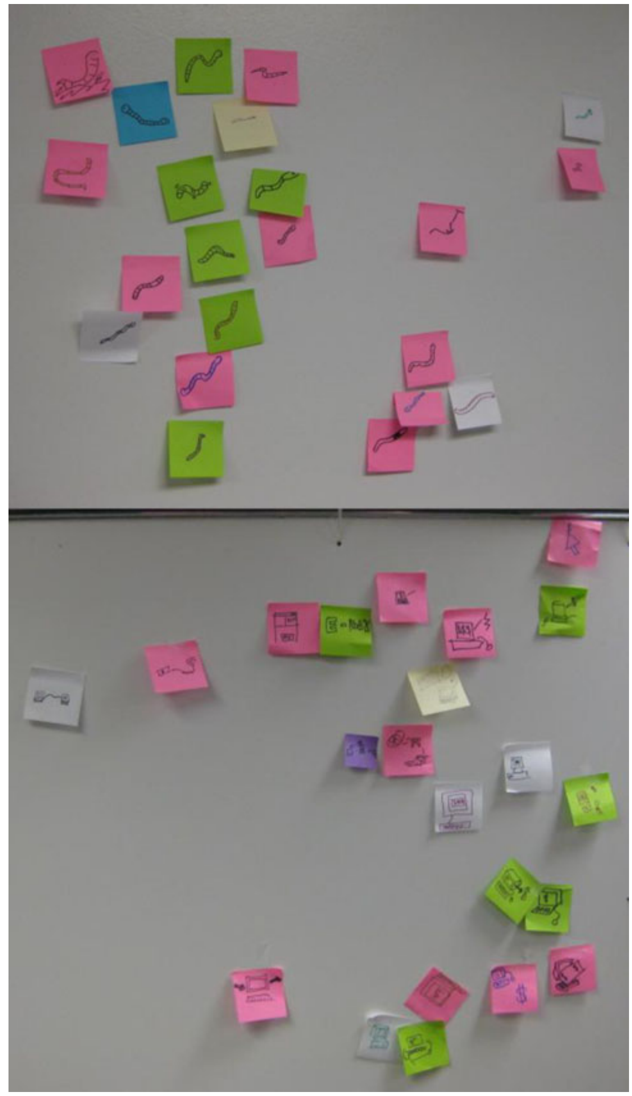


Fig. 4 Examples of the thumbnail sketching exercise after affinity clustering. *Top* Worms, which have been clustered into four groups. *Bottom* E-commerce, which has been clustered into three major groups with a few on the borders between groups

4 Results

The interdisciplinary design class has been offered for the last 5 years at Virginia Tech. In this paper, we focus on the results from the last 2 years (2009 and 2010) to highlight the impact of the prototyping exercise, as well as the disciplinary balance in interventions. In both years, senior level students from electrical and computer engineering (ECE), industrial design (ID), and marketing (MKT) departments participated.

4.1 Observation data

In 2009, a total of twelve students (four from each discipline) participated and four instructors (two from industrial design, one each from computer engineering and marketing) led the class together. The students were asked to design firefighting equipment that uses pervasive computing technology. In 2010, a total of 21 students (seven from each discipline) participated and three instructors (one from each discipline) led the class. The students were asked to design pervasive computing devices that help children with diabetes.

In 2009, students struggled in a self-managed teaming environment in which little explicit design structure was provided. That is, the course was loosely structured by an interdisciplinary instructor team with a final deliverable consisting of an entry into an ID design contest. The contest's requirements were distributed, and these criteria served as the main assignment. Although the class was evenly divided between the three disciplines, the ID design culture dominated the group work processes. By week 10 of the 16-week project window, the teams had still not decided on their final product goals. At this time, the students met without the instructors and took control of their own projects by defining each component and breaking into their own majors to begin the final phase of their projects. Team composition shifted throughout the semester, which eventually resulted in a general composition of all students perceiving themselves as members of one large team. By the end of the semester, they had completed contest entries that described a system including four components—a vitals-monitoring shirt and mask, self-contained breathing apparatus (SCBA) gear, and a helmet that provided situational awareness. During this process of creating a complex system design, they also gained experience working in a large, interdisciplinary group on an ill-defined problem set. However, the design process was not fully integrated across disciplines: the final project was completed by single-discipline groups, the projects did not demonstrate strong ECE components, and the project as a whole was later submitted to the contest by just one of these single-discipline groups after the end of the semester.

To resolve these issues, the interventions in 2010 focused on balancing the presence of all three disciplines. Also, the instructors gave students a clearer timeline from the beginning of the semester. The students were informed that, by week 6, they would have formed into final product teams and selected design concepts to develop for the rest of the semester. Similar to 2009, the first week was dedicated to establishing groundwork for each discipline by having instructors give a lecture on their field and explain what role that field plays in the design process.

After the first week, students participated in opportunity exploration, concept generation, and a selection phase from week 2 to 7. This phase heavily depended on industrial design processes such as sketching, pin-ups, and on-spot evaluations of concepts, establishing personas for product ideas, etc. During the "opportunity identification" module guided by the industrial design instructor, students worked across disciplines by engaging in sketching and critiques. This module is intended to assist students in moving beyond simply designing things properly and putting the focus on establishing what is the "right thing" to design. For example, the ID instructor encouraged students to rethink not just the design of an existing device, but rather the issues that users face when using such device: "So, we're not asking you to redesign a glucose meter. So I thought, you know, get the cheap one; but I also thought it would be interesting for you in the empathy category to not just stick your finger, but try to figure out—if you got one of these things, could you actually operate it? Read the owner's manual, see what people are up against." Following these instructions, students struggled with using the device and the manual just added to the confusion. After difficulties with basic operation of the glucose meter, an ECE student in one group identified a problem: "It's the depth adjustment. I got it. I think maybe…" and then concluded, "there's much better ways." By the end of week 7 (a slip of a week from the initial schedule), students decided on the final product ideas and formed five interdisciplinary product development teams. The five products were (1) an intelligent portable scale for counting carbohydrates, (2) a backpack that could warn a parent and child if a diabetes management device was left behind, (3) a handheld game that rewarded the child for following their diabetes management regimen, (4) a wrist-worn communicator for parents and children to manage blood glucose levels, and (5) a data collection unit that shared information from the other devices with the primary care physician and insurance company. As students further developed the specific features of their products, physical prototyping using foam core was encouraged to help them with form development.

In the following week (week 8), the students were given the "Product Box" exercise described in Sect. 3.2 [21]. This marketing exercise helped students think about the intended market and consumers as well as positioning of their products relatively early in the design process. The MKT instructor tried to tap into students' inherent abilities and to help them extend their own practices into a marketing activity: "What we're asking you to do is be yourself, be an astute marketer, product designer and engineer, and also, at the same time, to be your own consumer." Again, students practiced skills and adopted perspectives not native to their home disciplines. In addition to the MKT students, ID and ECE students presented designs geared toward specific consumers. One ID student explained that his group "wanted to make this fitness and gaming piece kind of like a cool thing that the kids wanted to have" but that the parents would care about. Another ID student described how his group was "expecting to sell it to a mom, so the reading level should be targeted toward an older generation." An ECE student said that his group also wanted to target kids and that kids were a digitally sophisticated audience: "it's not going to be very cheap…we looked at some DSs and see what they were packaging, and they liked the black/silver combo, like whites and silvers and black makes it seem like you're getting something that's really classy and advanced." The MKT students were positioned as content experts by the MKT instructor: "The marketing students, they're not responsible for doing all of this…you are going to be feeding stuff into them. What they are going to ask from you and what you are going to give them." In one exchange, the students fulfilled this role while developing the image for their product. An ECE student used an example of another product: "Like Sperrys, they didn't come up with perfect kids before they marketed Sperrys" and MKT student: "No, they *did* come up with perfect kids, but they didn't say 'for perfect kids.' They developed an image. That's what we want to do." ECE student: (laughing) "Ok, so what kind of image do we want to—" and ID student: "So maybe we should throw some more adjectives, or even synonyms, just something to get us better understanding of what exactly it is. Family? Family slash community?"

In week 10, the Arduino-based prototyping kit described in Sect. 3.1 was introduced to the students. In this exercise, the students were asked to think about different ways the sensors could be used in different products. During this exercise, the ECE students served as mentors for the other team members. Students from other disciplines asked ECE students questions about what the kit did, how the sensors worked, how the code was structured, and what was doable and not doable with the equipment they had. The ECE instructor stressed that this exercise was intended to demonstrate "what sensing, computing, and getting output meant to non-ECE folks." During this exercise, students from other disciplines heavily depended on ECE students in their groups, but they also participated in an integrative manner to create functions "beyond what we just programmed it to do," as the ECE graduate assistant encouraged them to do.

From observations, it was evident that the students from the other two disciplines appreciated ECE students' expertise in this area. In the following week, electronic and mechanical feasibility became a topic during the design discussions. For example, as the ID student sketched the final form factor of the communicator device, the ECE student was constantly being consulted to make sure the size and range of the electronic components would support the design that he sketched. In the same week (week 10), a marketing exercise of developing value propositions and positioning statements, with a broader goal of articulating a business model for a given product, was conducted in class. After those exercises, students further developed their designs and created prototypes.

4.2 Team diagnostic survey data

Quantitative data also confirmed better performance of the 2010 class. Since this class depends on team-based projects, successful teamwork can be an indicator of a successful class. Hence, to measure the effectiveness of teams, the Team Diagnostic Survey (TDS) was administered at the end of the semester both years [12]. The survey measured students' own perceptions of the team processes and the effectiveness of their teamwork during the course. The questions were divided into eight categories based on the team-related constructs. These constructs were related to external environments given to teams as well as internal processes within teams.

The TDS constructs related to external environments were the following:

- *Compelling direction,* which refers to a team having a challenging and consequential specification of its overall purpose.
- *Enabling structure*, which relates to the composition of the team, its expectations for the conduct of the team members, and the alignment of task with the team's purpose.
- *Organizational context,* which describes the organizational support and material resources the organization provides.
- *Coaching,* which refers to external leadership that helps the team with coordination and motivation, with avoiding getting into inappropriate routines, and with sharing their respective expertise to better accomplish the team's goal.

The TDS constructs related to internal processes were the following:

- *Real team*, which refers to the boundaries that distinguish members from non-members, the interdependency of the team members, and the stability of the membership.
- *Team processes*, which is related to the amount of effort the team spends on the task, the qualities of the team's strategies to accomplish the task, and how effectively the team employs its members.
- *Interpersonal processes*, which is based upon the qualities of the interpersonal relationships and the satisfaction with those relationships.
- *Individual learning & well-being,* which relates to the internal work motivation and the overall satisfaction with the team.

Five items from the survey were dropped because of relevancy and confusing wording. Seventy-four items from this eighty-item survey asked the students to rate their responses to statements describing team constructs on a five-point Likert-type scale ranging from *1: Highly inaccurate* to *5: Highly accurate*. To ensure that the participants paid attention to the items throughout the survey, thirty-three items were reverse coded and converted back to the normal scale after the administration.

Table 2 Team Diagnostic Survey results comparison (2010 value − 2009 value)

Construct	Wilcoxon test results
Real team	$Z = 4.03$, $p < .01$*
Compelling direction	$Z = 3.17$, $p < .01$*
Enabling structure	$Z = 3.82$, $p < .01$*
Organizational context	$Z = 3.46$, $p < .01$*
Coaching	$Z = 2.72$, $p < .01$*
Team processes	$Z = 3.27$, $p < .01$*
Interpersonal processes	$Z = 3.85$, $p < .01$*
Individual learning and well-being	$Z = 4.51$, $p < .01$*

* Indicates statistical significance at .05 level

The TDS results showed significantly higher overall team effectiveness in 2010 compared to 2009 ($Z = 4.28$, $p < .01$). For each construct category, the differences between 2009 and 2010 were tested by the Wilcoxon test, a non-parametric equivalent of *t* test. All eight construct categories showed statistically significant improvement as shown in Table 2. Figure 5 shows that, in all of the categories, the class from 2010 scored higher than 2009. The changed interventions for 2010 emphasized a clear timeline and structure for the project. These changes were reflected in a higher mean in 2010 for the *Compelling direction* and *Enabling structure* categories of the TDS survey.

There were three main differences between these 2 years: clarity of the structure, prototyping exercises, and disciplinary balance. In 2010, the students were given a deadline for forming the final teams and selecting final product concepts in the third week of the semester. Thus, they were aware of the fact that concept generation and exploration phase would end by a certain date and that helped them cope with the confusion. However, in 2009, the students were not given a deadline for deciding on the final concepts, and the concept generation and exploration phase lasted 3 weeks longer than 2010. Out of a 15-week semester, this three-week difference was significant. In 2009, the students showed frustration and confusion in week 10, when the students said that they were "still not clear about the project goals." In contrast, the 2010 class showed no sign of confusion in week 10. During the same week, the 2010 students were already developing detailed features of their products, physical forms, and marketing plans, along with the prototyping exercises.

The prototyping exercise gave students a chance to get their hands-on actual electronic components as well as programing activities. Because students could physically interact with the sensors and draw certain outputs as a result, participating in this exercise helped them understand the inner-workings of the electronic components and their relationships to computation and outputs. It was critical for them to understand the concept of sensing, computing, and obtaining output, since they were designing pervasive computing products. In 2009, the students never had a first-hand experience with electronic parts. The ECE students used circuit diagrams a few times during the semester in an attempt to explain how sensors would work to detect harmful conditions that firefighters may face, but they were not able to demonstrate the point as effectively without actual working parts. Combined with the structural difference that they were not specifically asked to build a prototype or demonstrate features at the end of the semester, the 2009 structure led to a low level of ECE component integration in the final product. From the end-of-semester interview, the ECE students said "it would have been better if they actually built something" rather than just talk about the concepts. In contrast, the students from 2010

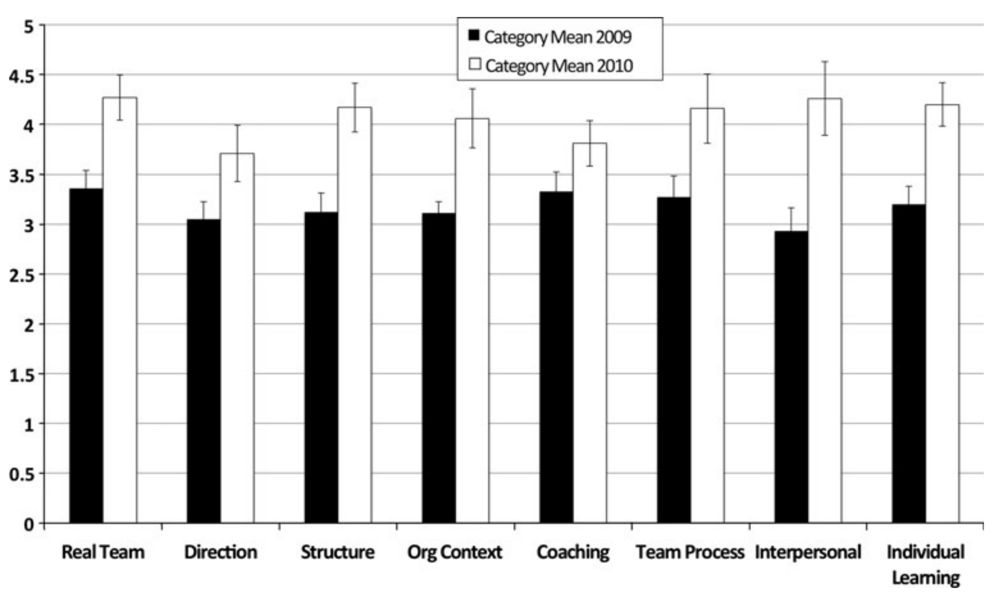


Fig. 5 Team diagnostic survey mean comparison

class who built electronic prototypes showed strong integration of electronic components in their final products. In the final presentation, three out of five teams demonstrated some features of their products with simple electronic parts, software, and interfaces, even though this component was not required for their grade.

The balance among the three disciplines was another critical factor in the success of the class. A previous study has identified the need for establishing disciplinary grounding for each participating major. In this study, end-of-semester interviews with students suggested that ensuring balanced contribution might be critical for the students to feel confident and secure [23]. By implementing carefully balanced hands-on exercises and lecture modules from all three disciplines, the students could establish disciplinary grounding, which provided them with an important role and improved communication across disciplines. Having a balanced number of instructors might have played a role as well. In 2009, two industrial design faculty members were present as opposed to one from each field in 2010. Also, the final deliverables for the course were carefully selected to balance the presence of all three disciplines in 2010. At the end of the semester, the students were required to complete a design book with technical specifications and feasibility report and a business plan. In the final presentation, they were asked to pitch their ideas to venture capitalists with sufficient design and technical details. Also, they were asked to either produce or do a storyboard of a 60-s commercial for their product. In contrast, in 2009, the students were asked to submit a final document that was structured based on an industrial design competition application. The format did not ask for specific deliverables from marketing or computer engineering, although students were asked to include design sketches.

In summary, adding clear structure, prototyping exercises, and balance among disciplines led to a more successful execution of our interdisciplinary design course.

5 Conclusions and future work

An interdisciplinary design approach is necessary for successful wearable computing systems. We have presented a case study of a course for giving undergraduates an interdisciplinary design experience in wearable and pervasive computing. The students are given an open-ended design problem of identifying the potential for a product within an opportunity area. They then work in self-organized interdisciplinary teams to develop their product concepts. We believe that our course makes the students better prepared to work in interdisciplinary design teams by showing them how to work across disciplinary boundaries. This paper has focused on describing continual improvements to our pedagogical approach. We have shown that using the problems of the 2009 class to inform the 2010 process was a critical factor in the improvement.

Within our own course, we have two plans for the immediate future. First, we are developing tools that will provide simultaneous views of a physical computing device to both industrial designers and computer engineers, which we believe will help to span the gap between the physical and computational domains. Second, we plan to add a second semester to the course, so that the teams can more fully implement their designs.

More broadly, our plans for future work are to start similar courses elsewhere. We are currently preparing to start courses that use our process at two other universities. Our hope is that this paper will encourage other institutions to create similar courses. We believe that the process is viable across a wide range of application areas, not just wearable and pervasive computing.

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