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An Interdisciplinary Undergraduate Design Course for 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 presents an overview of our process with both qualitative and quantitative results from these two most recent offerings.

1. Introduction and Background

For a wearable computer to be truly wearable 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.

Although there is considerable work on the inter-disciplinary design teams required for these products [1][2][3][4], most of that work focuses on industry. Besides obvious differences between industry professionals and undergraduates students, participants in academic setting must deal with limited schedules (e.g., a fifteen week semester with about three hours 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. described a set of design guidelines for wearability, which is likely one of the most cited papers to appear at ISWC [5]. McCann et al. presented a design tool to guide designers of intelligent garments [6]. 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, e.g., [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 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 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

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product opportunities themselves as part of the course—the instructors do not specify the particular products to be developed. Over the five years of the course, each offering has covered a different product opportunity area and audience: 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 children. The only constraints the faculty place upon the products are 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 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 an electronics prototyping kit and exercise. Section 4 provides qualitative and quantitative results of the impact of the changes of the course. Finally, section 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 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 section 4.

2.1. Course process

The major elements of the course have evolved over five offerings; the details of that evolution are more fully described in [15]. 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 we are not always successful, as will be described section 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.

We begin the semester with examples of interdisciplinary design teams in industry, such as IDEO [16], 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 four to six weeks.

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

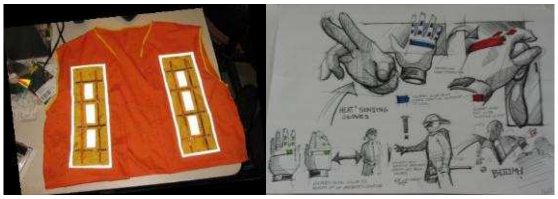


Figure 1. Examples of wearable concepts and final prototypes from the course. Left: intelligent vest for roadway construction sites. Right: information-gathering gloves for firefighters.

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 set up liaisons that are responsible for managing those interactions. There has usually been a product that tied all of the other products together, e.g., a central data collection unit that served as a hub for the other products. We observe that, even though the students are only given 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 Figure 1.

The remainder of the semester is spent developing product concepts, creating business 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 section 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 this 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 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 section 4.

2.2. 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 re-design the firefighter helmet to make it intelligent. This 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 section 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 had the negative effect of elevating the importance of the ID 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 three hours, while in the fall of 2010 it met twice a week for 1.5 hours at each meeting. This 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 two weeks. In some cases, two faculty members traveled on consecutive weeks, which meant the full set of faculty were not present for three weeks. This contributed to a lack of structure in the course.

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 both marketing and electronic prototyping. We also set a time window about 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 section 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 three hours 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 to. Consequently, the results in section 4 are limited to comparing only the two 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 were correct from the viewpoint of conducting a controlled experiment.

3. An electronics prototyping exercise

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. This section describes the Arduino-based prototyping exercise. We omit the marketing exercise because ISWC has mainly a computing and design audience.

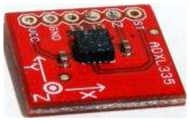
Our major goal for introducing an electronics prototyping exercise was to provide the students with the ability to rapidly explore product concepts while going beyond sketching [1]. Following several good examples such as Igoe [17] and Buechley [18], we opted for a set of sensors and output devices coupled 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" data sheet 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, this is the proper level of abstraction, but this is not the case for designers who simply want to employ the device. Dow et al. addressed this issue by describing *knowledge support* as a key requirement for Ubicomp design tool [19]. As an example of this ability, Dow et al. suggests, "a tool might provide a device catalogue that represents available devices, and how designers might user them in an application." To approximate this catalogue our "user-friendly" data sheet 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" data sheets.

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()*.

The class meeting for introducing the Arduino kit and general computing concepts was dubbed "Prototyping Day" and lasted 75 minutes. 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



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.

Figure 2. Example of user-friendly datasheet

light with a tri-color LED, and playing a note with a simple tone generator. The prototype was programmed 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 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 were 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.

4. Results

The interdisciplinary design class has been offered for the last five years at Virginia Tech. In this paper, we focus on the results from the last two 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.

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 interdisciplinarily integrated: 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 grounds 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 through 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. 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 were 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.

In the following week (week 8), the students were asked to design packaging for their products [20]. This marketing exercise, called "Product Box," helped students think about the intended market and consumers as well as positioning of their products relatively early in the design process. As students further developed the specific features of their products, physical prototyping using form core was encouraged to help them with form development.

In week 10, the Arduino-based prototyping kit described in section 3 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.

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 (real team, compelling direction, enabling structure, organizational context, coaching, team processes, interpersonal processes, and individual learning and well-being). Five items 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.

The TDS results showed improved overall team effectiveness in 2010 versus 2009 (2009: $M = 3.14$, $SD = .65$, 2010: $M = 4.10$, $SD = .54$). For each construct category, the differences between 2009 and 2010 were tested by the Wilcoxon test, a non-parametric equivalent of t-test. From eight construct categories, six categories showed statistically significant improvement. The other two categories (Real Team and Coaching) were not statistically significant, but the difference was in the hypothesized direction as shown in Table 1. Figure 3 shows that in all of the categories, the class from 2010 scored higher than 2009. The changed interventions for 2010 emphasized clear timeline and structure for the project. This change was reflected in a higher mean in the compelling direction and enabling structure categories.

There were three main differences between these two 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 three 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.

Table 1. Team Diagnostic Survey results comparison (2010 value – 2009 value)

Construct	Wilcoxon Test Results
Real team	Z = .55, p < .58
Compelling direction	Z = 3.10, p < .01*
Enabling structure	Z = 2.50, p < .01*
Organizational context	Z = 2.52, p < .01*
Coaching	Z= 1.79, p < .07
Team processes	Z = 2.64, p < .01*
Interpersonal processes	Z = 2.44, p < .01*
Individual learning and well-being	Z= 2.36, p < .02*

*Note: * indicates statistical significance at .05 level*

The prototyping exercise gave students a chance to get their hands on actual electronic components as well as programming 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 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.

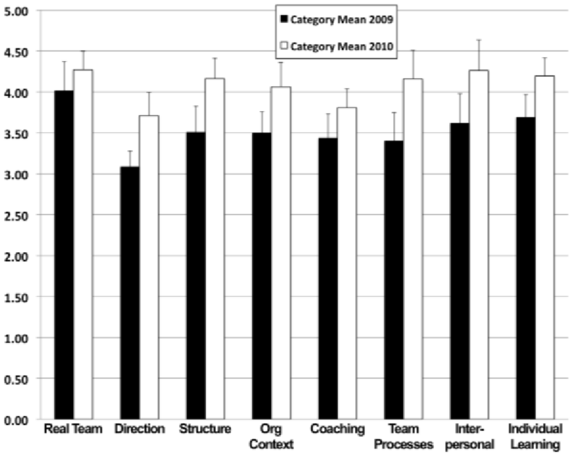


Figure 3. Team diagnostic survey mean comparison

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 [21]. 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-second 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 nor computer engineering while asking them 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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