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Virtual Hands-on Learning – The development of an online engineering design course with a virtual product inspection portal

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Introduction

The need for high quality online learning materials has accelerated dramatically due to factors including the rapidly changing dynamics of educational workforce development that requires more flexible hours and asynchronous learning. Transitioning engineering design education to an online format is particularly difficult due to the hands-on, kinesthetic, and tangible learning that takes place in physical classrooms. This is especially challenging for a subject such as textiles, which relies heavily on tangibility to communicate material properties and possible applications. While alternatives exist such as shipping each student physical "kits" of supplies they can use in-person, this option is costly and time-consuming, not always possible given the subject matter, and may not be accessible for all students. It can also lead to challenges in guided learning from the instructor as controlling the pace students' progress and complete tasks is more difficult than in a totally physical – or totally virtual – environment. This paper covers the development of an online engineering design course that features the implementation of a virtual product inspection portal to supports hands-on and higher-order learning in a virtual environment.

To provide tangible learning experience in a new graduate-level course titled "Design Analysis of Smart Textile Products", an interactive 3D based "Virtual Product Portal" was developed to assist students in exploring, analyzing, and evaluating smart textile products to propose new design decisions. The course learning objectives focus on higher-order cognitive processing in Bloom's Taxonomy, where students are asked to analyze and critically evaluate commercially available products and then propose new designs to meet constraints and minimize trade-offs. Much of the course involves teaching about hidden factors that can inform the smart textile design process, like balancing a product's performance, manufacturability, cost, and sustainability. The class covers three detailed case studies on textile and smart textile products (electrocardiogram-monitoring compression shirts) spread throughout the semester. For many of the graduate-level textile engineering students, smart textiles will be a new topic with which they are largely unfamiliar. In prior courses, students have gained substantial understanding about the new type of system design and integration methods used by "getting their hands dirty" and disassembling the products in groups in the classroom. While this is not possible in a virtual setting, the Virtual Product Portal was developed to replicate and supplement the valuable hands-on experience.

The main portion of the Virtual Product Portal is an interactive platform where students interact with a 3D model of each product used in the case studies and explore at their own pace, learning about different design decisions and uncovering more detailed information as they navigate the website. In addition, the Portal and accompanying website provide high-quality videos showing the inspection and disassembly process for each of the three textile products led by the course instructor and teaching assistant. Interviews with the product designers are also included to provide insight to the design process. At every point of the Portal and website development, the course learning objectives were carefully considered to ensure alignment between the interactive media features and the design-focused learning outcomes of the syllabus. This course was offered for the first time in Spring 2022 to an initial group of 15 students.

Background

Online education in the United States and worldwide is expanding quickly. College enrollment in the US has been steadily declining (from 20.6 million in 2011 to 19 million in 2016) and is forecast to continue downward. This has been attributed to myriad factors including rising education cost, skepticism in the value of higher education, unwillingness to travel, and cost of commuting [1]. The decline in college enrollment has been accompanied by an increase in online education, thus there is a great need to develop tools that ensure high-quality learning in a virtual environment. Certain tools to supplement online learning exist such as lab kits and video tutorials, but lab kits are costly in both production and distribution, and video tutorials lack the interactive and hands-on aspect that is critical for learning. Gamified simulations are a promising method, showing increased motivation and completion rate [2], [3]. Virtual reality (VR) simulations have been successfully implemented showing increased participation, motivation, spatial understanding [4] and, in some cases, direct translation to physical psychomotor skills [5]–[7]. In fact, virtual reality applications such as flight simulators for pilot and surgical training have been used for decades [8], [9] and show that the psychomotor skills used in the VR activity can transfer when the same activity is performed in-person [6].

A common problem in engineering education is knowledge retention and transfer between courses and between coursework and industry [10]. Active learning and project-based learning have been shown to improve knowledge retention [11], [12], yet this type of experiential learning has traditionally required resources that only in-person education offers. Engineering design, for example, requires hands-on experience for students to grasp the tangible and practical differences between a digital and physical prototype [13]. In the design process, decisions that are instinctual when made in-person (such as material choice), may be much more difficult when the designer is unable to physically touch and interact with the samples. Design classes taught as capstone projects require hands-on, student centered, and active learning using purchased parts and materials, prototyping equipment/maker spaces, and testing equipment [14]. Product design relies on the ability to inherently understand how material selection dictates the final performance of a product and this ability is typically developed in a hands-on, active learning environment.

One of the key components of product design is benchmarking – determining what solutions already exist for a given problem, and how effective the existing solutions are. This often includes physically inspecting existing products, which can include performing a physical teardown of the product. Another name for this type of product inspection and design analysis process is reverse engineering. Reverse engineering (RE) is commonly misunderstood and can be perceived negatively by both industry and academia. Definitions range greatly, but two examples are:

> "[RE] initiates the redesign process wherein a product is predicted, observed, disassembled, analyzed, tested, "experienced," and documented in terms of its functionality, form, physical principles, manufacturability, and assemblability" [15],

written by Wood et al. (2001) in their key paper highlighting the benefits of reverse engineering and re-design in engineering curriculums, as well as:

> "[RE] is the process for discovering the fundamental principles that underlie and enable a device, object, product, substance, material, structure, or system through the systemic analysis of its structure and, if possible, its function and operation" [16],

defined by Robert W. Messler Jr. in his textbook "Reverse Engineering: Mechanisms, Structures, Systems & Materials", in which he frequently critiques the unethical and illegal uses of RE. While these definitions have an academic setting in mind, the reverse engineering process commonly occurs in industry and government as a part of their benchmarking process [16]–[18]. Benchmarking often involves looking at current products to determine what exists in the market – how they perform, how customers perceived them, and what broad materials and manufacturing techniques are used. Reverse engineering is a, perhaps taboo, term for the same concept. It is backward problem-solving rather than forward problem-solving, relying more on analysis than synthesis. That is, the design process begins with a solution rather than a problem. While reverse engineering comprises many analysis steps, the focus of this work is the disassembly or teardown of the product.

Product teardowns have been previously demonstrated to be very effective when performed in class by the students themselves [15], [17]–[21], but this mechanism for learning is often not conducted as it can be both time consuming and costly. For a large class, it can be difficult to monitor each student group to ensure everyone's participation and that the teardown is being performed correctly. There is a need to explore how product teardowns can be developed for a virtual learning environment that resolves these logistical challenges. There are limited examples of virtual product dissection in the literature. Welsh et al. (2021) determined that students responded well to an augmented reality (AR) disassembly and inspection application and found that learning may be improved by enriched visualization, directed disassembly, and embedded hints [19]. In a separate study by Starkey et al. (2017), the authors noted what while assessment results were not significantly different for different modes of virtual dissection (computer, iPad, and virtual reality), students' perceived learning and satisfaction was greatest with the virtual reality application [17]. While augmented and virtual-reality solutions are a promising method, the research discussed here required desktop and mobile-friendly technologies to be accessible for all students and thus relied heavily on video and interactive computer platforms.

Pedagogy

At the beginning of the project, particular care was taken to align the learning objectives with the goals of the course in terms of their level on Bloom's Taxonomy. Five different courses covering reverse engineering concepts were studied and the action verbs of their learning objectives were analyzed using Bloom's Taxonomy. Figure 1a shows the applicable range over Bloom's Taxonomy for the five courses studied using this method. Each objective was assigned a "score", where 1 = Knowledge/Remembering, 2 = Understanding/Comprehension, 3=Application, 3=Analysis, 5-Evaluating/Synthesis, and 6=Creating/Evaluation. The analysis shows that the offered courses focus on application-level objectives but include high-level synthesis and evaluation action verbs as well. For example, from the reverse engineering course at Philadelphia University in Jordan [22], two objectives are:

- Reveal design problems through the understanding over other developers' design approaches (*evaluation*)
- Disassemble systems and products (*application*)

The analysis of five reverse engineering courses provided good background to develop the learning objectives for this course. The course learning objectives (CLOs) were made to be specific and measurable by breaking them down into the action verb, **measurable topic**, and *specific situation*.

- CLO 1: Apply **reverse engineering principles** *in the context of designing and re-designing textile products.*
- CLO 2: Identify **design criteria and constraints** and explain the necessity of **tradeoffs** *for textile products or for given use cases.*
- CLO 3: Analyze *textile products* to hypothesize why and how **designers and engineers make decisions** *during the design process*.
- CLO 4: Compare and critique **textile products using design knowledge** *gained during the reverse engineering process.*
- CLO 5: Re-design **textile products** *to meet design* ***constraints*** *and minimize* ***tradeoffs***

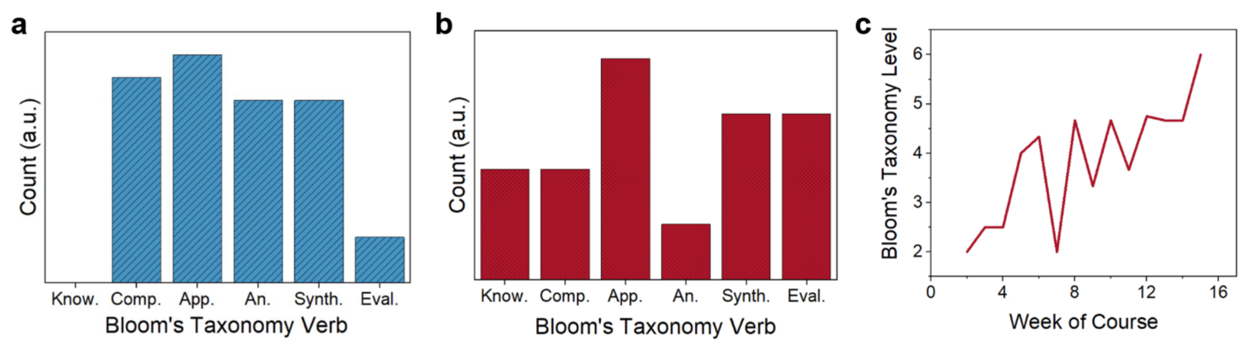

Figure 1: Bloom's Taxonomy Learning Objective Analysis. a Bloom's Taxonomy learning objective spread for benchmarking reverse engineering courses. Verb abbreviations are Knowledge (Know.), Comprehension (Comp.), Application (App.), Analysis (An.), Synthesis (Synth.), and Evaluation (Eval.), **b** Bloom's Taxonomy learning objective spread for "Design Analysis of Smart Textile Products" **c** Bloom's Taxonomy level over the course the 16-week "Design Analysis for Smart Products" course.

These course learning objectives as well as the weekly outcomes result in the Bloom's Taxonomy spread shown in Figure 1b. As with the other RE courses offered, many of the objectives are application-level. However, the emphasis on higher-level 'evaluation' action verbs suggests that this course highlights creativity and design and is appropriate for upperclassmen and graduate students.

Each week has its own specific learning outcomes that contribute to meeting the course learning objectives. To ensure the course provides a good foundation of knowledge and then increases in complexity, the weekly course outcomes were analyzed using the same method as the benchmarking courses. Figure 1c shows how the average weekly 'score' increases over the duration of the course. Early lessons focus on introductory material to build a foundation of knowledge, while later lessons and assessments require the students to use the knowledge they have acquired to analyze, create, and evaluate.

Design and Development

Course Content

The course content is separated into three distinct 'Blocks': Block 1: Reverse Engineering Concepts, Block 2: Understanding Design Decisions, Block 3: Design Evaluation and Re-Design. Figure 2 shows a flow chart detailing the course progression. Each of the first two Blocks review an inspection of a progressively more complicated smart textile product. In this way, each Block introduces higher order learning objectives, culminating in the application of their learning to a new smart textile design. Block 1 introduces reverse engineering concepts and follows the analysis, teardown, and evaluation of the *Under Armour* compression shirt as the first case study. Block 2 focuses on more in-depth understandings of design decisions and details through case studies of two smart textile products from *Sensoria Fitness* and *Hexoskin* that illustrate how designers and engineers create similar products for different customers. Designer interviews are a large component of this section, as students hear from the designers themselves some of the hidden factors that may have influenced the product design. Block 3 includes a critique of the three products and then focuses on the final project for the class, a re-design of a smart textile compression garment for a specified use case. Students are expected to use the knowledge gained in the course content, product inspections, and interviews to design a new product for a use case different from those already studied.

Each Block contains both Conceptual Learning and Reverse Engineering content and activities. Conceptual Learning encompasses product inspection and smart textile system design theory lecture videos and readings, and addresses Course Learning Objectives 1 and 2. The conceptual learning content aims to provide foundational knowledge, and covers lower levels of Bloom's Taxonomy (*apply, identify, explain*). The Reverse Engineering content and activities involve three case studies of textile and smart textile products supported by Product Inspection Videos, Virtual Product Portal, and Designer Interviews with engineers and designers from the companies of each product. The Reverse Engineering content covers Course Learning Objectives 3-5 and is at the higher levels of Bloom's Taxonomy (*analyze, compare and critique, re-design*).

As the course progresses, the case studies increase in complexity by requiring students to analyze three different compression shirts with incremental functionalities. The first garment is a performance athletic compression shirt (*Under Armour*) with advanced compression design but no electronic components. This garment was included to establish what design decisions are made in creating a high-quality compression shirt. The other products are smart textile compression shirts that monitor physiological signals (e.g., heart rate and respiration). The second shirt (*Sensoria Fitness*) is a heart-rate monitoring garment with low electronic integration complexity, and the third and final shirt (*Hexoskin*) monitors electrocardiogram (ECG) and respiration and has the most complex electronic integration. Each product has been designed with different customers, price points, manufacturing processes, and performance aspects in mind, and the course content for each week mirrors what is being explored in the inspection at that time. For example, the *Hexoskin* shirt is introduced in Week 9 and the lecture content that week is on sensor data collection & quality and the different strategies for smart textiles. This is timely as the *Hexoskin* shirt uses very different measurement techniques than the previous *Sensoria* garment to measure the same signal (heart rate) and it is valuable to compare the two techniques as used in the smart textile industry. Moreover, students are provided with a Google Doc template for each case study and the final project to guide them through the reverse engineering process and prompt them to think critically during inspection, benchmarking, evaluation, and re-design.

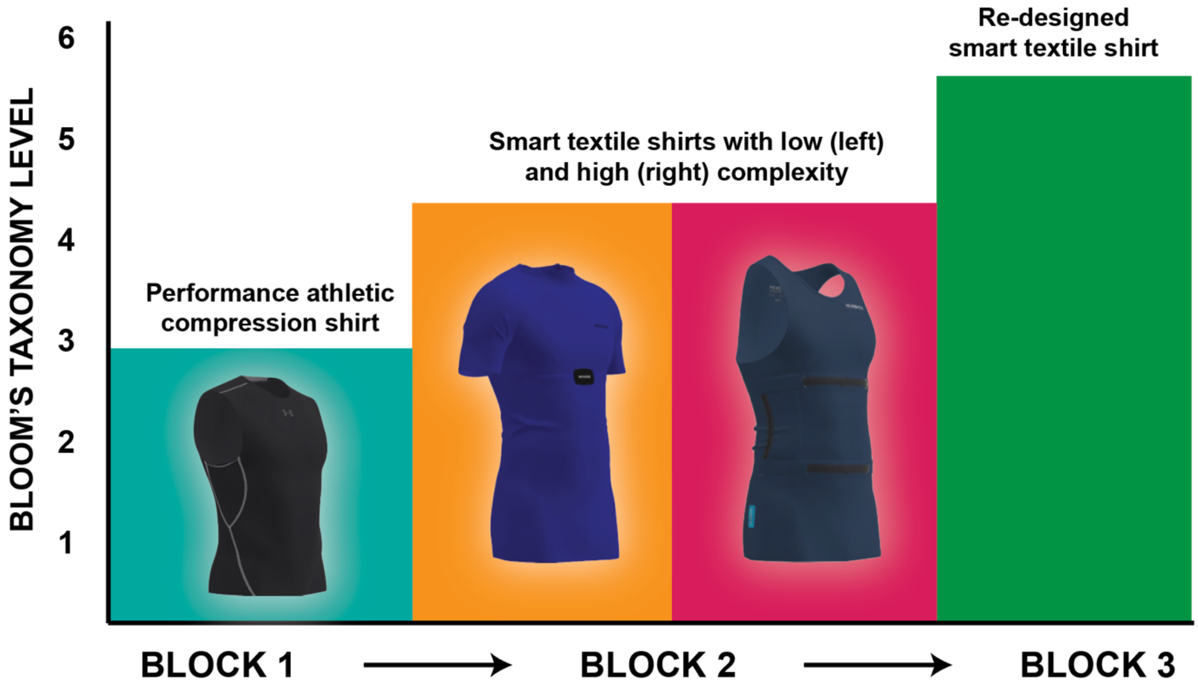

Figure 2: Course Progression Flow Chart. Each block of the course increases in the level of Bloom's Taxonomy, from Comprehension/Application (Block 1), to Analysis/Synthesis (Block 2), to Synthesis/Creation (Block 3).

Additionally, the *Moodle* course site is organized with a graphical "Course Roadmap" that tracks students' individual progress in completing the block learning materials and activities. Details were described in a 2021 ASEE Conference paper [23].

Inspection Videos

For each of the products used in the case studies, three videos were produced: 1) the "Product Overview" video which introduces the product and its main features and functions, 2) the "Product Inspection" video which demonstrates the processes of garment disassembly into individual components and pattern pieces, and 3) the "Component Analysis" video which further discusses each of the garment components including examination under a microscope and resistance testing. Stills from the three videos for the *Hexoskin* shirt are shown in Figure 3. The product inspection portion of the videos took several hours, yet for each product the footage was edited to less than 20 minutes to contain just the most important observations made during the process. The inspectors (the course instructor and TA) provided discussion on their observations during the process. This discussion is important, as Welsh et al. (2021) note that there is "no structured way to teach a novice learner expert-level thinking in analysis of a product" [19]. While the students are not able to physically disassemble the products themselves, they can gain valuable insights by watching the process and hearing the dialogue between the two practiced inspectors.

Figure 3: Product Inspection Videos. a "Overview" video, introducing the garment and its main features, **b** "Inspection" video, detailing the product teardown and inspector commentary, **c** "Component Analysis" video, examining and testing each textile and electronic component further.

The videos are hosted both on the class Moodle page as interactive Playposit videos as well as within the product website which also hosts the Virtual Product Portal and Designer Interviews. By providing a website which compiles all the media for each product, students can explore the garments at their own pace and quickly access all media content when needed.

Virtual Product Portal

The Virtual Product Portal (VPP) is an interactive platform with separate instances for each product used in this course. For each instance, the VPP shows a 3D model of the product on the left side of the user interface and a 2D diagram of the garment pattern pieces on the right. The 3D model was developed using the garment simulation program CLO 3D (*CLO Virtual Fashion*) that allows for the production of realistic full garments including physical properties and textural/colour information. Students can explore and rotate the 3D model and click on highlighted Points of Interest (POI) in the 2D interface to see where that pattern piece is in the 3D model and view embedded media of video and stills from the product inspection and component analysis stages. The portal has four different views: Garment, Seam, Decal, and Electronics. For each view the POI and media collections change to reflect the selection. Figure 5 shows screenshots from the Virtual Product Portal where Figure 5a is the Garment View of the *Under Armour* shirt highlighting the side mesh panel, Figure 5b is the *Sensoria* shirt Decal View highlighting the inner product information tag, and Figure 5c is the Electronics View of the *Hexoskin* shirt, highlighting the respiratory sensors.

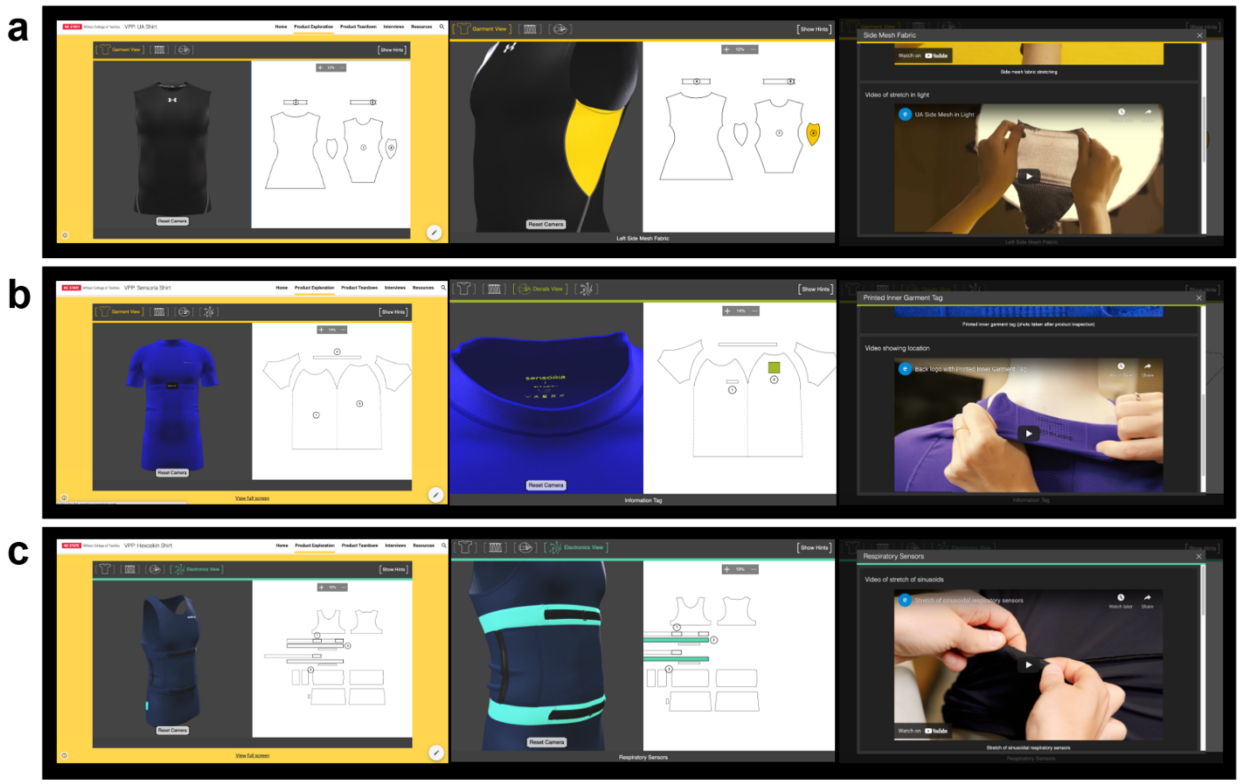

Figure 4: Virtual Product Portal. Screenshots from the Virtual Product Portal showing user interface and embedded media for the **a** *Under Armour*, **b** *Sensoria*, and **c** *Hexoskin* shirts.

Each product has 30+ points of interest (POI) that students can explore and identify via the Virtual Product Portal. 'Hints' can be toggled on or off which control whether the POIs are visible, numbered links or are invisible until a cursor hovers over the area.

The goal of this portal is to enable students to explore and interact with the garments in a virtual environment as they are unable to perform the product inspections physically. Ideally this portal provides a more tangible inspection process than watching videos with no interaction. We understand that the product teardown process is hands-on and much of the learning comes from doing. We wanted to replicate this as close as possible in a virtual medium.

Designer Interviews

A key aspect of this course is the designer interviews which give students access to insights on design decisions directly from the individuals that were involved in the development process. For each of the three products' companies, 1-2 designers and engineers were interviewed on via video conference (*Zoom*). The interview lasted around 1.5 hours and involved a series of ~15 questions in four categories: Introduction to Designer/Company, Designing for the User, Designing for Manufacturing, and Designing to Minimize Tradeoffs. Examples of questions from each of the three categories are:

- Can you give a brief introduction to yourself and your company? (*Introduction*)
- Who is the desired customer for the product? (*User)*
- How did you determine the electronic integration methods? (*Manufacturing*)
- What constraints did you have to consider when bringing the product from a concept to a prototype to a finished product? (*Tradeoffs*)

Once the interview was complete, the full recording was edited into four separate videos, one for each of the question categories. The videos were uploaded to the learning management system *Moodle* as interactive *Playposit* videos with embedded discussion questions.

Preliminary Results and Discussion

The course was first offered to students in Spring 2022 with an enrollment of 15 undergraduate and graduate-level students. Students were given an early-semester survey to collect initial feedback before the end of the course for this publication. In a brief survey using 5-point Likert scales, students were asked to evaluate the Teardown Videos, Virtual Product Portal, and Designer Interviews on how they effective they were in:

- replicating the physical experience of disassembling a product,
- giving insight into design decisions, and
- communicating product function.

They were then asked to rate their confidence in their ability to:

- complete a physical smart textile product teardown, and
- design a smart textile product for a given use-case.

The final question allowed students to provide general feedback on the course and media content. Following this survey, an end-of-semester survey was sent out to the students to evaluate if their confidence has increased in their ability to complete a physical smart textile product teardown and design an smart textile product for a given use-case.

Overall feedback from the survey was positive. One student reflected that the material was well organized and easy to navigate. Each tool was described as being effective and serving their intended purposes. The Teardown Videos were viewed as the most important tool to replicate the physical experience of disassembling a product, followed by the Virtual Product Portal, and then the Designer Interviews. All three of the educational tools were perceived as important for communicating product function. The Designer Interviews and Virtual Product Portal were both important for giving insight into design decisions.

The production quality of the Teardown Videos was emphasized in the survey responses. One participant commented on how the production quality improved their learning experience: "[The videos are] very professional and probably made me feel more serious about the videos and the class than a poorly produced video would have made me feel". One student suggested that they would have liked to see every stage of the product teardown, rather than it being edited down for time. In terms of the Virtual Product Portal, one student suggested additional testing and evaluation data of the products would be useful for comparison. The feedback on the Designer Interviews was positive, although some students commented that they would have liked more specific responses to the questions asked.

The survey responses suggested that their confidence to design a smart textile and complete a teardown had improved over the course of the semester. Early in the semester, the average student was "slightly confident" to design a smart textile product for a given use case, and "somewhat confident" to complete a physical smart textile product teardown. At the end of the course, these increased to "somewhat confident", and "fairly confident", respectively.

Conclusion and Future Work

This work describes the development of an asynchronous, online engineering design course and several media tools (Teardown Videos, Designer Interviews, Virtual Product Portal) designed to meet the course learning objectives. Course content is divided into three blocks that sequentially increase in their level of cognitive processing (Bloom's Taxonomy) from foundational reverse engineering and system design concepts, to smart textile design decisions, and finally to a complete re-design of a smart textile product. An interactive Virtual Product Portal (VPP) was developed to give students a virtual hands-on experience of navigating and inspecting garments while watching their disassembly and listening to interviews from the designers themselves. The class was given to an initial group of 15 students in Spring 2022. Student feedback was positive and promising. Future work will include the re-design of the course and media tools based on the student feedback. This re-design will incorporate a recently developed virtual reality tool for interacting with fabric samples.

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