Programmable Materials Final Report

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Programmable Materials

Final Report

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Introduction -- Team written

Programmable Materials is a project that revolves around skintillates – an on-skin wearable that mimics a tattoo. It is a fashionable wearable with six layers from bottom to top (Figure 1): an adhesion layer to be placed on top of skin, an electronics layer embedding LEDs, a conductive layer made with medical electrode-grade silver, an ink-jet printed art layer designed in illustrator and a regular temporary tattoo substrate on top. The electronic layer connects to a microprocessor, which handles the data collection and communication with personal mobile device or laptops.

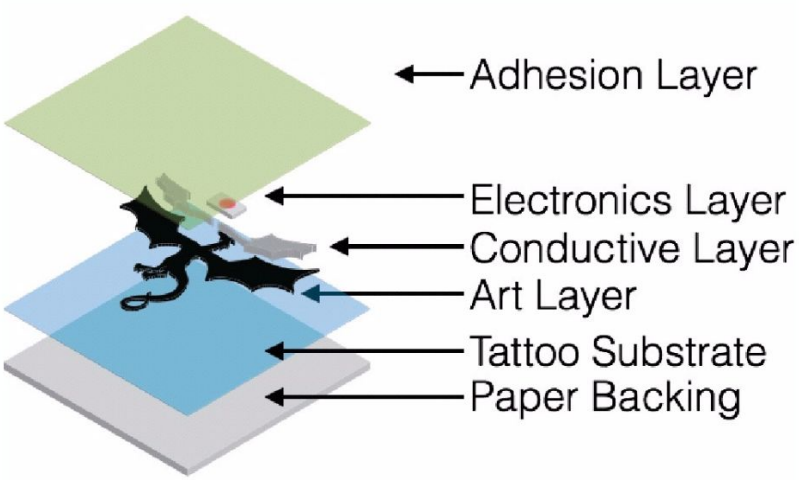


Figure 1 Components of Skintillates

The goal of our project is to develop software applications for skintillates and improve its usability. We started off analyzing the existing hardware problems that might affect user experience. The original skintillates has a lot of wires coming out off the tattoo, linking to a big microcontroller powered by regular batteries or computer. Since it's a wearable to be applied directly onto the skin, the exposed electronics will cause discomfort for the users

who wear it. We addressed the concerns by improving portability, increasing compactness and extending battery longevities. We proposed solutions such as replacing the regular arduino controller with a fingertip-size microprocessor, separating hardware patch from the tattoo, introducing bluetooth connections and experimenting with rechargeable flexible batteries. Besides the hardware aspect, we brainstormed dozens of ideas for applicable software extensions of skintillates. The main ideas included using skintillates for augmented reality, personal health tracking and music player. Then we moved on to learn the techniques of the fabrication process and built two initial prototypes using mbed processors. One used embedded accelerometer to detect motion and light up LED light on skintillates based on body movement. The other prototype had one button on the tattoo which can trigger music on a demo app on Android phone. The prototypes successfully gained attentions from the audience during our exhibition. People are amazed by the power of skintillates and its form factor. At the same, people expressed concerns with battery life and durability of hardware. After the expo we decided to put more efforts into providing feedback to users from the hardware and extending software features. We utilized sensors embedded in RFduino processor and developed mobile apps and website linked to skintillates for user interactions.

Figure 2 below is the task breakdown among our team:

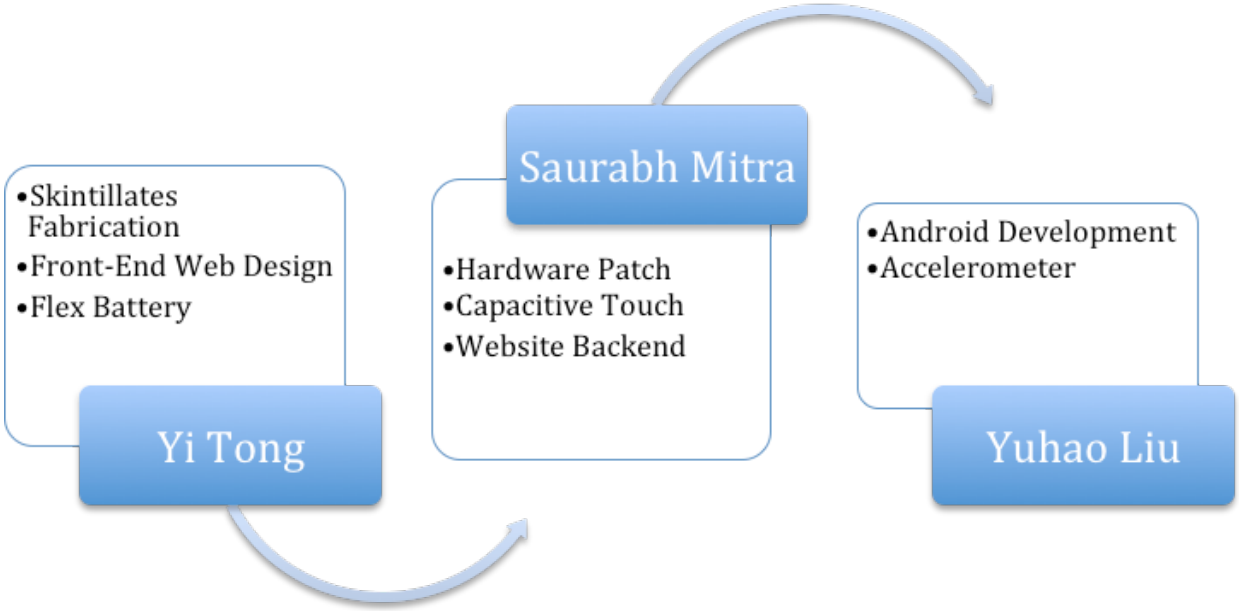


Figure 2 Components of Skintillates

In this paper, I will be focusing on my personal technical contribution, including market analysis, front-end web design, fabrication process, and battery selection.

Market Analysis

Although the concept of wearable technology is relatively new, ubiquitous computing is no longer a fresh concept for most people. Mobile devices added value through transferring most of the functionalities from computers to mobile phones, which enable people to access information and communicate with each other without sticking to their desk. Wearables try to provide some of that functionality, while freeing up user's hand. However, wearables don't seem to be able to add too much distinct intrinsic values that differentiate itself from mobile devices. At the same time, the limitation of display space and battery life pose challenges for wearables to differentiate themselves and become a unique platform. Therefore, it's important to understand the wearable market before we define the direction of Skintillates. In order to grasp the public opinion of wearables, I did some online research about wearables technology and its evolving market.

As computing becomes more and more powerful, there are no such devices that would only bear a single or a few functionalities. One question worth to think about is, whether more functionalities means better product. Phones enable users to do a lot of activities: texting friends, sending emails, checking news, searching for things online, etc. As we stated earlier that wearable might not be the best platform to perform a lot of tasks, due to the limitation of computing power. Instead of just making smaller phone so that it can be attached to our body, we can use wearable as a platform to deliver simpler message to recreate social interaction rather than duplicate a platform for people to complete tasks they can do on mobile. Programmable materials, which can change their physical forms in a

programmable matter[Self-Assembly Lab], opened up such a way to approach wearable computing. Replacing the static expression of our feelings, attitudes, and values, wearable programmable material could let us express ourselves as well as engage with the environment and people around us. Before we merge wearables and programmable material, we should familiarize ourselves with what already out there in their separate market.

For wearables, the application span from smart watches, health care, augmented reality and e-Textile. Let's start from smart watches. Back to early 70s, people were no longer satisfied with the sole function of showing the time. That's when digital watch entered the market. Comparing to mechanic watches, digital watches were much more than a timepiece: people can set alarm; use it as a stopwatch, or do some simple calculation. The second wave of innovation rose when Sony launched Sony Ericsson LiveView in 2010 and extended the display of Android phone onto the watch screen.[Lai 2010] The idea of users not having to hold a device appealed to the major competitors of mobile phone market. A few years later, we now have smartwatch like Apple watch, Moto 360 and samsung galaxy, that let you have all different applications message, viewing information and calling on your wrist. As convenient as it may sounds like, smartwatches are not that easy to use, and a lot of time, it still rely on mobile phone to have a complete functionality. From our observations and interviews with people for smartwatches, most people think that smartwatch is a cool gadget they would like to try out, but they have no motivation to buy since it doesn't do much that smartphone doesn't do and they already have a smartphone.

And for people who are more adventurous, they don't seems to enjoy smartwatch that much either. We can tell from here that when we brainstorm about what we should build for our project, we should avoid envisioning it as a replacement of mobile phone. Instead, we should focus on what things we can provide that mobile phones can't. Hundreds of smartwatches are available on eBay barely six month after their launch.[2014 Tech Republic] It's an obvious indicator that smartwatch still have a long way to go to be accepted by general audience.

Another wearable that we have to discuss here is Google glass, a head mount display for consumers. People are able to experience augmented reality through looking at extra layer of information on top of the physical world they are in. Application like voice based search engine, photo capturing and recording, and facial recognition become available for Google glass. As a head mount display, Google Glass identify a special domain of providing unobtrusive computing experience. For example, to take a picture, users only have to blink their eyes. Although it's super convenient to capture things, the display is still not ideal for people to clearly see information display. Though it's projecting information at an arm-length distance, it's still too small to display messages for users to read easily. At the same time, the limited computing power confined the complexity of the task. The short battery life also posed an inconvenience since users will often have to charge it, especially if they are using the recording function. After all, Google glass is an interesting device, but not convenient enough to use for the functionality it's providing, as google already stopped producing Google Glass.

Then we come to activity tracker, which also is the most successful one. Products like fitbit and Jawbone tracks how active you are throughout the day by counting the number of steps of walked and steps climbed, tracking your sleeping pattern, as well as recording some personal biometric like heart rate. Activity tracker help us to know the state of our body better. It creates self-awareness of how well we are exercising and how well we are sleeping. It's especially useful because it's hard to use mobile phone during work out. Therefore, logging exercise data through wearable is a very practical use case. Since it doesn't require active input from users, those tracker serves their purpose really well without being obtrusive. It is a great example that a good device doesn't not have to provide as many function as possible to be great.

From the research of wearables in consumer product, we understand the obstacles wearable devices are facing: limited screen space and input portal, short battery life, obtrusiveness, etc. Now it's time for us to delve into academic research, and learn about how programmable material can steer us away from those obstacles and find a better use case for wearables.

Web design

For the software aspect, we are going to have both an Android app to respond to the input from the RFduino and a website handling crowdsourcing request. Besides the Android app that Yuhao has been working on, I built a responsive webpage that could communicate with both the phone app and the e-textile itself. The websites has the basic information for users to find out how nearby users are engaging with the music at a big gathering like concerts or music festival. I am in charge of front-end development of our webpage and visual design for real time engagement from the users. The following image is a screenshot of our web design.

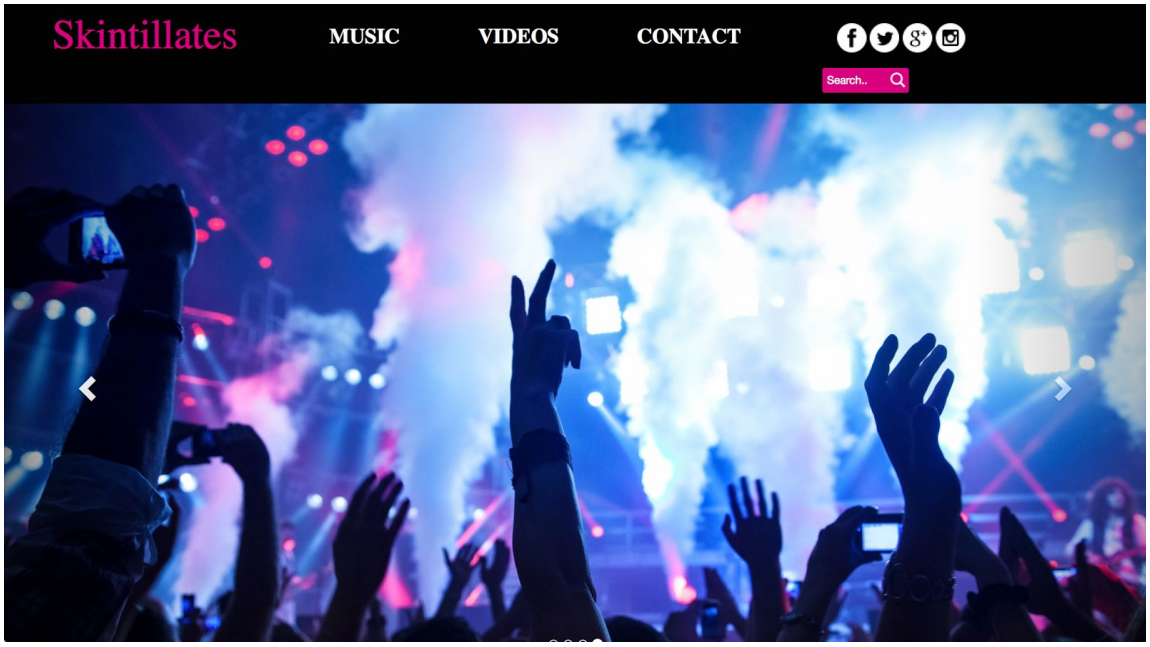
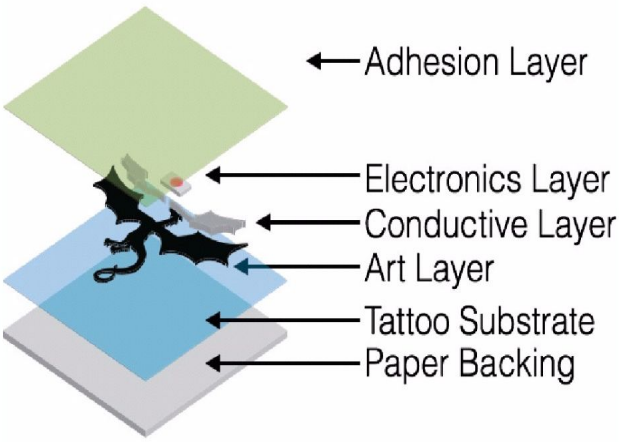


Figure 3 Components of Skintillates

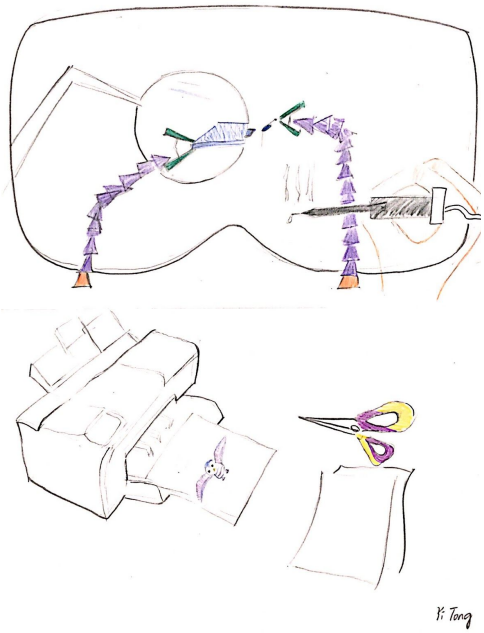
Fabrication process

To make Skintillates a customizable platform with built in core features, we will need to do understand the architecture of Skintillates to support hardware and software developments alongside with research. Experimenting with the process of how a Skintillates is built facilitates our design process and helps us understand what is feasible with Skintillates and what is not. The form factor of Skintillates also largely impact the integration of the tattoo itself of all the electronics.

Skintillates is a combination of a few layers. On the bottom, there is the paper backing so support all the layers before applying it onto the skin. The Tattoo substrate is on top of the the paper back with the art pattern printed on it. And then the conductive layer exists on the art layer that has electronics like LEDs laying on top of it. On the top is the adhesion layer that holds everything together.

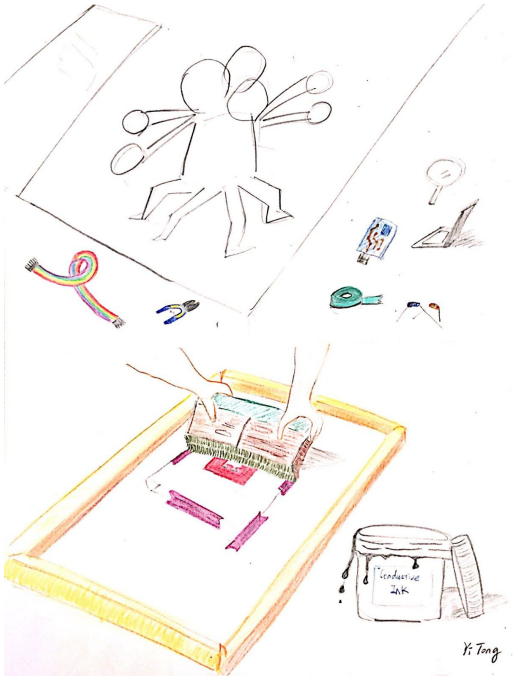


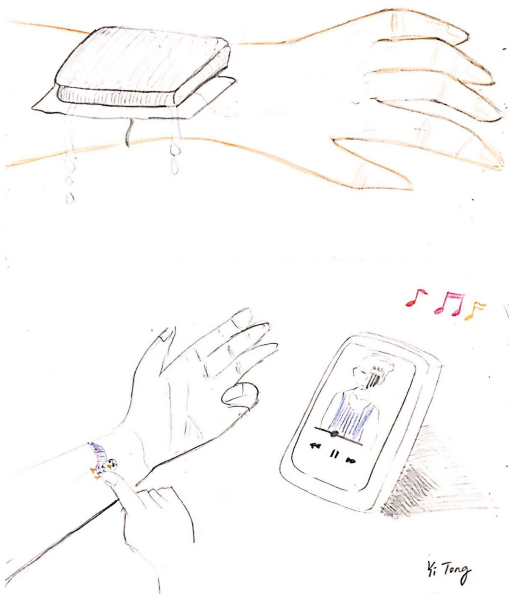
After understand the structure of Skintillates, I started learning the fabrication process: laser printing the art pattern, vinyl cutting the circuit design and screen printing the circuit design using conductive ink, and then laying the electronics on top of the circuit before I apply the adhesion layer. I drew the following storyboard to show the fabrication process of Skintillates:



Soldering electronics

Print out tattoo substrate





Screen printing circuit with conductive ink Finished Skintillates

Looking at the actual working skintillate and physical tools makes planning the trail production more intuitive. Then I went to the lab to experiment with vinyl printing with regular print, due to the extremely high cost of conductive ink made of silver. The technicality of cutting out and applying the vinyl on the screen made me realize the design of the tattoo could not consist of really thin stripes. Printing on the screen and getting the painting on the tattoo paper exposed the challenge of spreading the paint evenly. And directly spreading conductive ink on tattoo paper made me notice that the design of the tattoo needs to be constructed through center pattern to guarantee stable connection.After a few attempts, I made a Skintillates with two LEDs on it. I did a thorough integration testing to check the connections and the functionality of the Skintillates.

After I familiarized myself with the process of making Skintillates, I made a few Skintillates to experiment with the fabrication process and test out our ideas. For the Capstone Expo last semester, we made one LED Skintillates that lights up when it detect that the users is running and. We also have another Skintillates that can wirelessly control an Android app on the phone and place music.

Though the prototype successfully proved our concept, I have encountered quite a few problem and seen some challenge for future development. While making the first few prototypes, I found that Skinillates was not very durable. For example, the LED Skintillates we made for Capstone Expo broke after demoing for 2 hour. Once the tattoo is the broken, there is a gap in the circuits and the connection is lost. And there is no way to fix a broken Skintillate because the conductive layer was in between the art layer and the top layer. Therefore there is no circuit exposed for a quick fix by adding a temporary wire or drawing with conductive ink.

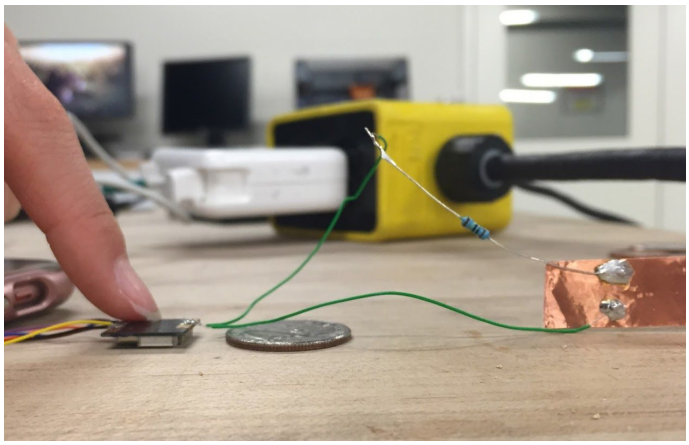
For the next step, we focused on how to make Skintillates more viable, both software and hardware. The challenge was temporary tattoo itself was not a durable medium to embed anything. Therefore I need to look into how to make Skintillates last longer while still being unobtrusive. It can be divided into two parts: one is to shrink the hardware size and find the appropriate microcontroller, which Saurabh will talk about in his report, the other is to do control group experiment to try out fabrication process on different materials.

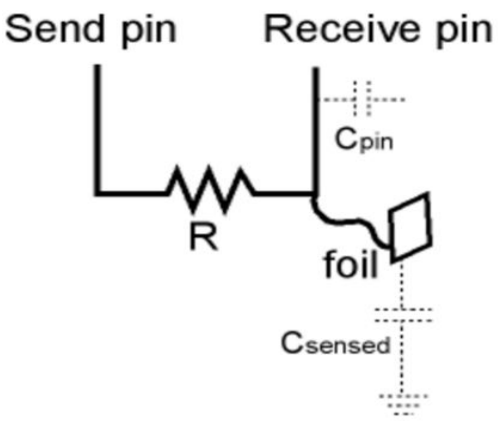
There are a few things I am going to try for the next step. First we can experiment with different tattoo transfer paper to see which ones preserve the design the best and are less easily to come off the skin. Besides embedding smaller and thinner electronics, we can also look into adding another transparent layer on the joins of the temporary tatto and electronics to make sure the connection is still stable. One inspiration is from a Japanese liquid Band-Aid, which can be applied to the wound and dry out to become a traditional Band-aid. We could potentially use similar adhesive to strengthen the connection between the tattoo part and the hardware embedded. Since it's in liquid format when it's applied, it will stick with the tattoo layer on the top and stretch while the skin stretch. Therefore, its conductive layer in the middle will not break and the connection is more stable. We could even explore to make a temporary patch for Skintillates by making the "Band-Aid" conductive so that it can connect with the embedded circuits while it's still in liquid form.

Capacitive Sensing

Capacitive sensing is a way we could get a signal through touch by using human body capacitance as input. Capacitive sensors detect anything that is conductive or has a dielectric different from that of air.[2014 Badger]

The figure below how capacitive sensing works: between the send pin and receive pin, there is a big resistor; the receive pin is connected to a metal foil which would be the contact point for sensing. The two pin can then sense the electric capacity of human body.





First I soldered two thin wires directly onto 2 GPIO(general purpose of input/output) pins the RFduino. One pin is for send and one pin is for receive. I soldered a 1MΩ resister onto the other end of the wire connected to the send pin. Then I soldered the other end of the receive pin onto the metal foil, in our case, copper tape.

The way capacitive sensing work is to have the send pin change the state first, and wait for the receive pin to receive the signal and therefore change its state. The delay between sending pin changing signal and receiving pin changing signal is determined by a time constant, which is the multiplication of the resistor value and the capacitance value of the metal foil plus finger touching the receive pin.[2014 Badger]

After the hardware setup, I imported the capacitive sensing library for Arduino[2014 Badger]. Since RFduino has a ARM based architecture and Arduino has a AVR based architecture, I have to remap the pins defined in the library to make it compatible with RFduino. After loading the program onto the RFduino, the output shows a trigger signal when I touch the copper foil.

The next step, I am going to explore how to build more capacitive sensor onto rfduino. Since there are only 7 GPIO pins on RFduino, I will have to do more research on whether multiple capacitive sensor can share either the send of receive pin together.

Conclusion

Based on the original Skintillates prototype, we enabled wireless communication with mobile phone, input through capacitive sensing and crowding sourcing through a web server. Instead of being a stand-alone wearable device, Skintillates is now highly customizable and adaptable for different designs, applications and platforms. These

distinct features make it a great starting point to become a platform to build " internet of things". We envision Skintillates to become a breakthrough for wearables market given its unique form factors, unprecedented fashion elements and affordability for individual creativity.

Chapter 2

Engineering Leadership

1. Introduction

Skintillates are on-skin wearable electronic devices that mimic temporary tattoos. Although skintillates were originally prototyped in the Hybrid Ecologies Lab at UC Berkeley, our project extends their potential by developing software applications and

improving the consumer usability of hardware components. Our goal is to move "Skintillates" from a standalone interactive device project to a consumer product that belongs to the internet of things. The concepts covered in Engineering Leadership all apply heavily to any aspect of the conversion of an academic project to a marketable product. In this paper, we will first analyze the industry we are entering in order to plan our technology strategy and marketing accordingly.

2. Industry Analysis

In traditional Industry Analysis, six criteria are used for defining a company: customer, geography, status, product, form, and industry. In our case, form, status, and geography are not applicable since we do not have a startup company. We did some initial market analysis last semester based on research papers and market reports gathered from IBIS and Mintel. Back then we still has a broad project scope and were exploring the whole wearable electronics industry. This semester, our project is more defined, and we realized that skintillates have some unique features that are not comparable to traditional wearables like smartwatches and Fitbit.

Our product consists of a smart electronic tattoo that communicates with a mobile app. We define our industry to be an intersection of smart wearables and tattoos. Skintillate is an electronic tattoo in terms of hardware, but our application will extend it to the "Internet of Things" field by connecting it to a smartphone app. Therefore, this industry definition fits much better to our project. The cases we studied in the industry analysis module help us accurately define our product and find our niche in the crowded market. Instead of

becoming another player in the consumer wearables, we linked our project with the fashion industry and the wearable industry while being under the umbrella industry "Internet of Things".

Our entire team is based in Berkeley, California. Proximity to Silicon Valley also gives us the advantage of being exposed to different projects in incubation programs and having early access to the latest research breakthrough. Since the wearables market evolves quickly and is becoming fairly crowded, it is important for us to differentiate Skintillates from other wearable devices. The first step in distinguishing our project from existing competitors is to be well aware of events and progress in the field and know about new features of wearables at once. Our customers will be discussed in the next section in combination with tech strategy.

3. Marketing

Skintillates was initially a research project. The original prototype connects to laptop or smartphone with wires and used normal Arduino microprocessor and coin or regular batteries attached. In the marketing module of our leadership bootcamp we learnt to create persona and propose differentiation for our product in the market. Our persona for skintillates is someone who is young, fashionable, tech-savvy, passionate about new gadget and always excited to try new things. To attract customers within this persona category, we have to improve usability of skintillates.

First of all, our customer will not spend effort or time on programming and porting code onto the microprocessor and compile it every time. To accommodate this, we developed applications for different user scenarios including Android app and webpage. These applications also help us extend the breadth of our user base for marketing purpose.

Our second concern is with usability of skintillates. Since it can be marketed as a fashionable wearable, portability is the top concern. We replaced the wire connections with bluetooth low energy to send signals from microprocessor to mobile phone. Therefore users can take skintillates everywhere and it will not interfere with their normal activities. We bundle battery, microprocessor and sensor together into a hardware patch. The hardware details are safely hidden from the customers. Another usability concern is with the discomfort of batteries or microprocessors attached to skin. The hardware patch mitigates this problem as well. We replaced original Arduino board with RFduino, a mini-microprocessor that is as small as a fingertip. We embedded flexible batteries that are more suitable to place on arms than normal batteries.

For product differentiation, our main marketing point is that skintillates is fashionable and relatively cheap compared to other wearables such as Fitbit and smart watches. The introduction of sealable hardware patch was a great point to reduce cost. Since the hardware patch is separable from skintillates itself, the customers can reuse hardware patch for different designs of skintillates. Since the substrate layer of Skintillates is temporary tattoo and is fragile, the hardware patch can save the customers from throwing away processor and batteries after use or going through the effort of reconnecting

everything when they replace the tattoo layers. The flex batteries we use the power the microprocessor is rechargeable, saving lifetime cost of skintillates.

The customer positioning and marketing strategy we learn in the leadership module helped us a lot in defining the direction and goal of our final product. We aim at making our product user friendly with a clear and precise targeted persona definition.

4. Tech Strategy

Although we are not aiming to launch our product to market by the end of our capstone project, it is still helpful to make decisions about the market segment and go-to market plan (Friedman 2012). From the Virgin Mobile case (Srinivasa 2003), we learned that one of the most important aspects of tech strategy is choosing the correct market segment. Virgin Mobile was attacking a stable industry with a difficult barrier to entry: the cellular telephone market (Srinivasa 2003). With the amount of infrastructure it takes to set up a cellphone network combined with the acquisition of customers who are likely under a contract with another company, an early-stage cell phone provider has little likelihood of success. However, Virgin Mobile realized that there was an untapped market segment that could potentially benefit from cellphones, but were not targeted by existing giants like AT&T: young people. Because young people are likely to earn less and be less willing to follow long-term contracts, Virgin Mobile changed their business model to accommodate these types of customers, while adding features to excite the specific target demographic (Srinivasa 2003).

Similarly, the most important part of launching a Skintillate venture is appropriately targeting the right audience. Since Skintillates are still in research phase and the market is still emerging, our target audience would most likely be tech savvy young professionals who are willing to try new gadgets and have a sense for fashion. From the market research we did on wearable market, we realized that even though almost 80% of general population are familiar with one type of wearable devices and their concepts, only 21% of them would actually become a consumer (PWC 2014). And the people who have became wearables consumers are mostly well-educated people with stable financial income. Among them, almost half of them are between age of 18 and 34 (PWC 2014). Therefore we decided to target the similar group of audience, but appeal them with our key differences: "wireless" and "aesthetic" (Ramasamy 2014). The popular products in the market right now are mostly focused on functionality, rather than the decoration purpose. However the younger population would care more about their appearances. Even though wearables might have new features they want, they would still care about how wearables change their look. We are hoping to market Skintillates as customizable wearables where the users can decide the design of what the tattoo is going to look like, while the core functionalities remains.

5. Conclusion

Skintillates are thin, on-skin, and aesthetically pleasing wearable devices. These unique characteristics open up an opportunity for them to become a platform for "Internet of Things". By enables wireless connection and expanding the capacitive touch capabilities,

we are building the infrastructure for Skintillates to be customized to different interactive devices. The first generation of panel control and crowdsourcing applications we are building are great stepping stones for "Skintillates" to become a fully-fledged platform to democratize wearable technology.

Reference

Self-Assembly Lab et al.

Programmable Materials, http://www.selfassemblylab.net/ProgrammableMaterials.php

Lai, Richard

2010 Sony Ericsson LiveView review,

http://www.engadget.com/2010/12/01/sony-ericsson-liveview-review/

Tech Republic

2014 Wearables have a dirty little secret: 50% of users lose interest"

http://www.techrepublic.com/article/wearables-have-a-dirty-little-secret-most-people-lose-interest/

Paul Badger

2014 Capactive Sensing Library

http://playground.arduino.cc/Main/CapacitiveSensor?from=Main.CapSense

Friedman, Lawrence

2002 “Go-To-Market Strategy. Oxford: Butterworth-Heinemann.”

Ramasamy, V. et al.

2014 “The basics of designing wearable electronics using microcontrollers.”

PWC LLP

2014 Consumer Intelligence Series: The wearable technology future.

R. Srinivasa