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Master's Thesis
Academic Year 2021

Exploring 3D Printed Materialities: "Leather" and Creating its Unique Physical Properties

Keio University
Graduate School of Media Design

Grant Biberdorf

A Master's Thesis
submitted to Keio University Graduate School of Media Design
in partial fulfillment of the requirements for the degree of
Master of Media Design

Grant Biberdorf

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Abstract of Master's Thesis of Academic Year 2021

Exploring 3D Printed Materialities: "Leather" and Creating its Unique Physical Properties

Category: Science / Engineering

Summary

In the sphere of additive manufacturing, there is an increasing availability of printable materials which allows users to fabricate objects similar to the real thing. Furthermore, traditional manufacturing in the textile industry creates a wide amount of waste through large industrial plants, unuse of materials, and lack of recycling. This paper hopes to address these statements and explores new methods to recreate, generate, and reuse leather-like material through a 3D printing processing system. The realistic validity of the 3D printed materials are evaluated based on tactile perception.

The first iteration explored was through object replication by measuring physical properties of a common object (shoe). The second iteration was through a user study to identify if there is a perceptual similarity between real and 3D printed samples. The third iteration explored was through pellet extrusion. Using a modified FDM printer with a pellet extruder, varying combinations of thermoplastic polyurethane (TPU) and scrap leather were used to create printable material. The final method and conclusive evaluation was through collaboration with Toyota Boshoku on creating a hardware and software system to classify, generate, and customize new material for the interior of cars. 3D printed samples were evaluated alongside physical samples, generated imaginary samples, and vibration samples.

Keywords:

3D printing, leather, plastic, texture perception, material design

Keio University Graduate School of Media Design

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Joining the Embodied Media Real Project and KMD master's program has given me a search and drive for innovation and the design principles bestowed in the education will never be forgotten. May we design and research again!

Chapter 1
Introduction

1.1. Leather & Textile Industry

1.1.1 Overview

Firstly, what is leather? Leather is an organic material derived from animal hides that is commonly used in the fashion industry such as in bags and footwear, it is used in furniture, and it is used in vehicles such as for interior upholstery. The most common leather is from cattle, however many other animals have been used for their skin such as reptiles, aquatic life like sting rays, and animals in the equine family. Leather making is also an old tradition with historians predicting it to be from 1300 BC. In 2021, the leather goods market value is estimated to be $271 billion and is expected to grow in the future[1].

Leather is a complex material to produce. The leather manufacturing process starts with tanning once bare hide is prepared. Tanning is a process that can have different methods, but any form of tannins- natural or synthetic chemicals that can come from vegetables, treebark, wine, etc. - is used to turn the hide into leather and prevent decay. Next, when the desired material is achieved, the tannins are neutralized from the tanning process. Lastly in post-production, leather can be dyed, softened, or finished with additional treatments.

1 https://www.statista.com/statistics/861562/leather-goods-market-value-worldwide/

1.1.2 Types of Leather

As leather is a form of skin, it has several layers. As demonstrated in Figure 1.1 below[2]. The layers of leather denote the different quality, durability, and physical characteristics. Natural leather has three main layers of the grain, corium, and grain and corium junction. Of these three layers, four different types of leather can be created into material. These are full grain, top grain, split leather, and genuine leather. The quality and durability is highest from the surface (full grain) to the lowest (split or genuine leather).

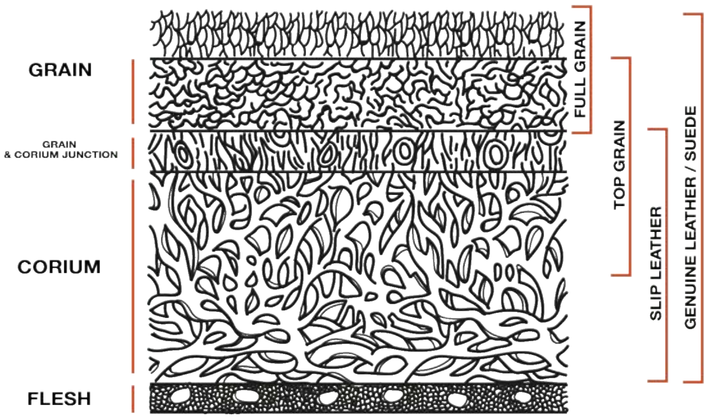

Figure 1.1 Layers of Leather

1.1.3 Leather in the Luxury Industry

As described previously, leather is a material that has many physical properties:

- Breathable
- Hard but flexible
- Softens with age, changes over time

2 `https://www.libertyleathergoods.com/types-of-leather/`

- Biodegradable
- Long-lasting

The leather industry predominantly produces cattle hides. However, leather in the luxury industry (less than 1%) has a multitude of different exotic leathers such as alligator, sting rays, giraffe, turtle, horsehide, among many others. Leather is a popular material in the luxury & fashion industry because it is high quality, durable, exclusive, aesthetic, and often limited and/or customizable to the customer's needs or desires.

What attracted me to research in a topic concerning leather is my work experience in the luxury industry. As an intern for a fashion brand in the quality and management team, I have got an up-close look at the highest quality leather bags, wallets, and belts with exquisite craftsmanship. By touch and by vision, it was evident why consumers are willing to spend large amounts of money on a product that may last them a lifetime. The leather product line of the brand has over 100 different pieces. Surprisingly, twice a year in the spring/summer or fall/winter, a new line is produced often with completely different design, patterns, and colors. This experience made me grow a research curiosity on the possibility of leather customization for the industry. Furthermore, the concept of bespoke tailoring in the fashion industry reinstates that consumers especially with expendable income desire a custom, one-off design fitted to the customer. This is also one of the strengths of 3D printing.

1.1.4 Artificial Leather

The first forms of artificial leather used the process of coating or infusing fabrics with natural substances (rubber, cotton) to recreate the visual and physical aesthetic.[3]. Now, a multitude of new artificial leather-like materials have been created. There is a growing consumer interest in sustainability and environmental protection. Based on the Higg Materials Sustainability Index, leather is the most environmentally toxic, while polyester is the most sustainable textile[4]. In-

3 `https://www.britannica.com/technology/artificial-leather`

4 `https://apparelinsider.com/higg-materials-sustainability-index-updated/`

dexes like these affect worldwide product and material design choices and place pressure on the leather industry to adapt and make more sustainable decisions. Synthetic leather may be the most attractive choice in the future. Although, due to previous forms of artificial leather in history, there is still a cultural stigma of synthetic leather as being low quality, cheap, or not as good as real leather.

1.1.5 Environmental Impact in the Leather Industry

Leather material itself is not detrimental to the environment, however the chemicals associated with it (chromium, sulfide, and others) can create runoff into the local environment, causing contamination and disease in the water and ecosystem. Specifically, chemical runoff causes eutrophication, which is the overgrowth of plant life in bodies of water that depletes oxygen killing underwater animals. The leather industry is also a major cause of climate change due to increased livestock agriculture, water pollution, and deforestation. Kuo-Wen Chen et al. stated "One ton of hide or skin generally produces 20 to 80 m3 of waste water, including chromium levels of 100–400 mg/l, sulfide levels of 200–800 mg/l, high levels of fat and other solid wastes, and notable pathogen contamination". [4].

1.2. 3D printing technology

1.2.1 Types of 3D printing

The five most common types of 3D printing technologies are:

- Stereolithography (SLA)
- Selective Laser Sintering (SLS)
- Fused Deposition Modeling (FDM)
- Digital Light Process (DLP)
- PolyJet

This paper will focus on two technologies, Fused Deposition Modeling (FDM) and PolyJet printing. Fused Deposition Modeling uses thermoplastic material that is melted and pushed out of a nozzle and is the most common type of 3D printer used today. PolyJet printing jets photopolymer droplets layer by layer that is cured by UV light.

1.2.2 Advantages, Disadvantages, Potential

FDM is the only 3D printing technology that uses simple plastics, therefore printing material is among the cheapest compared to other forms of 3D printers. However, a drawback is that the print speed is generally slower than other types of printers. Furthermore, support material used is often rigid and time is required to finish and clean the final print.

Polyjet printing can provide the highest amount of detail of prints quickly and without the difficulty of removing pesky support material. However, the cost of material is among the highest compared to others, making PolyJet not the ideal technology for rapidly printing large-scale objects on a budget.

1.3. Research Purpose

The leather textile industry has created a waste and environmental problem for the world. Natural leather is continually being produced around the world without strong regulation or control in production. Furthermore, in the fashion industry, unsold leather goods are frequently shredded, burned, or destroyed in order to protect the limited value of the items. Outside of social responsibility, there is also a growing consumer need for customizability. With 3D printing, plastic can be reused or fabricated into relatively anything. By combining these technologies and industries, this paper hopes to address a way to create novel materials with a creative and sustainable impact if 3D printed materials can be created similar to real leather. In this paper, I hope to address two questions: Can 3D printing replicate leather? and Can 3D printed materials be *perceived* as natural leather?

1.4. Thesis Outline

This paper is divided into six chapters as described below:

- Chapter 1 explains the foundational information on leather, 3D printing, and the objectives of the paper.
- Chapter 2 describes related works pertaining to previous material applications, 3D printed materials, and texture generation/perception research.
- Chapter 3 explains the concept of measuring material properties, replication through 3D printing, texture customization using software, and producing the leather-like material through the printer.
- Chapter 4 is the implementation of material measurements, PolyJet and FDM printing tests, a user study, and final evaluation with Toyota Boshoku.
- Chapter 5 summarizes the final thoughts and discusses future works.

Chapter 2
Related Works

2.1. 3D Printed Materials

2.1.1 Leather Applications

Leather has been used throughout history in use for clothing, tools, and housing. However, despite leather being commonplace, it is not heavily researched in the field of interaction design [5].

As e-waste and plastic waste makes a major environmental impact throughout the world, leather as an alternative to these mentioned could be replaced and used as something that is not frequently explored in common devices.

2.1.2 Functional Materials Based on 3D printing

Some research has previously been done in creating different textures via 3D printing such as in "metamaterials" [1]. In this work, textures were created with dynamic transitional phases, not limited to a single texture for one material. Further research in metamaterials explored ways where users can use a design tool to create cell-based material patterns that behave in unique ways for 3D printed structures to transform [6].

In other works, textiles have been embedded with 3D printed objects which change the physical properties of one another. In the work by Rivera et al., the properties of malleability, stretchability, and aesthetics were altered by combining textiles and 3D printed material- creating hybrid materials with greater functional possibilities than before [7]. There is also an emergence of so-called 4D Textures in 3D printing- shapes that are printed in a normal state and then triggered by heat into the new target shape [2].

Figure 2.1 Example of Metamaterial Texture [1]

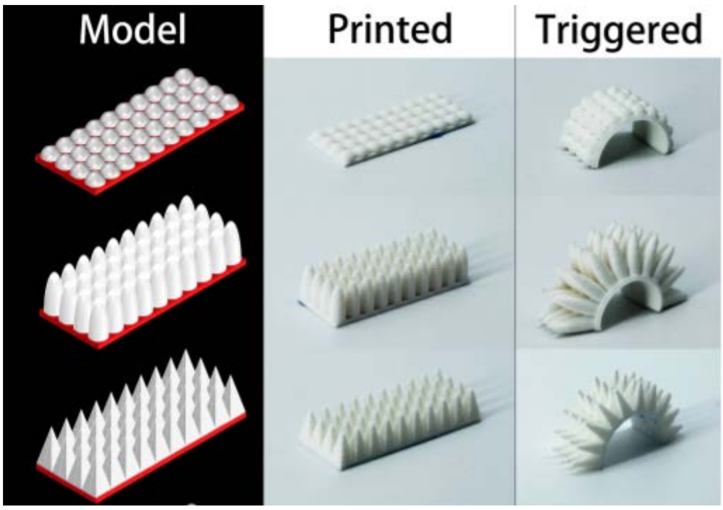

Figure 2.2 4D Texture [2]

2.1.3 3D Printed Waste & Recyclability

Because 3D printing fabricates objects in accordance to the specified object desired, wasted material or need for placement is minimal. By only using the needed amount of material to make the final product itself (besides minimal support for stabilization), it saves between 70% and 90% of material resource compared to former traditional methods like CNC manufacturing or injection molding.[1] Waste from 3D printing can come from failed prints, purge material, or support material. However, plastic materials in conventional FDM printing are the same type, so it can be easily recycled. The quality of recycled plastic has been researched and its effects of continued use. The collected mechanical results as tensile strength, Young's modulus and torsional modulus has shown that interestingly plastic was not significantly affected by multiple recycling processes [8].

2.2. Textile Customization

2.2.1 Auto-interior Industry

In the mass produced society today, cars are being produced with an increasing number of colors, styles, models, and customizations- including the use of textiles inside of it. The increased use of automotive textiles has been fueled by the fast growth of the automotive industry. Automotive manufacturers are standardizing their manufacturing processes to customize the vehicles and satisfy the end users individual preferences. In order to satisfy consumer preferences, the customer/user themselves are becoming the designer. Kabasakal et al. proposes that the customer today is a co-designer in the production process [9]. Forrest et al. [10] sees two main areas that will have the greatest impact— health and comfort, and driver safety.

When hearing the term automobile textiles, you may think of only the car industry. However, the same automobile textiles encompass essentially all transportation vehicles such as airplanes, trains, and buses. These automobile textiles account mostly in the use as upholstery, carpet, and interior trim (such as in side

1 https://www.azom.com/article.aspx?ArticleID=20017

panels) [11].

In the textile industry, there are limited amounts of textiles to choose from in regard to type, quantity, or availability. For the consumer, the traditional textile options consist of a fixed number of swatches. User choice exists, but there is a consumer interest and novelty as Bae et al. states for customization (and comfort) [12]. They also continue that the manufacturing industry is moving more towards mass customization- otherwise known as made-to-order- mainly due to increasingly different lifestyles person to person with unique cultural, and physical needs.

2.3. Texture

2.3.1 Texture Perception

Humans have the inherent ability to recognize different objects or materials simply by sense of touch. However, when textures are complex, it is difficult for human touch to recognize the differences. There are various methods in research to touch something- either through plain touch, active scanning, or emulating scanning through vibration. Kuroki et al. demonstrated a haptic texture discrimination experiment where they found that all methods of touch yielded the same perceptive results [13]. In other words, the method of touch does not impact perception, however complex textures or objects that are not relatively simple are difficult to recognise.

Previous research has been done in analyzing texture perception through the use of 3D printed samples. Sahli et. al [14] demonstrated that in an experiment with 3D printed samples of different levels of roughness and topography, touch perception of the samples largely relied on micro-scale roughness over topographic resemblance. Conversely, visual perception of samples were mostly determined by topographic resemblance.

Texture perception in VR was experimented with by using 3D printed hair stuctures in varying steps to alter the sense of roughness and hardness [15].

Therefore, 'feeling' a texture accurately is something still be explored in research.

2.3.2 Texture Properties

Haptics is applying technology to create the sensations of human tactile touch. In more detail, humans can naturally detect different levels of pressure, vibration, local position, and thermal properties [16]. All of these properties can be replicated using haptics. Different sensors can be used to record these properties. Strese et. al used acceleration sensors to record vibrations of different textures and proposed a classification system that uses perception-related features, such as hardness, roughness, and friction [17].

Object physical properties can be divided into simplified categories of shape, texture, and hardness. Because this paper focuses on leather material that is similarly planar and flat, we focus only on the properties of texture and hardness. Texture describes the properties of the surface of a material. Properties of texture are usually defined in tactile sense as either rough or smooth. Hardness is the measure of the resistance to another force. Hardness can be measured with tools such as a durometer that measures the amount of indentation possible. For soft to semi-rigid materials, a scale A durometer can be used to sufficiently measure leather hardness and what is used in further experimentation.

2.3.3 Texture Generation

Few research has been done specifically on leather texture generation, however Sakurai et al. used cell particle simulation to create a surface texture based on cell shape. Although not the focus of this paper, several researches have been done in generating textures through the form of vibration from images or using GANs [18] [19] [20]. Previously, procedural based textures could only be made mathematically, but can now be generated semantically [21]. One problem with generating textures is the risk of things appearing fake caused by boundary artifacts. However, modern GANs like TileGAN can output large scale terrain maps from low-resolution images.

An artistic/creative way to "generate" textures is through sculpting in 3D texturing programs such as Substance Painter, Zbrush, or Mari. These programs are widely used in the gaming and movie industries. Textures are made through 'texture painting', using a digital brush to make textural strokes with custom image maps or preset tools. Figure 4.1 demonstrates a leather texture designed in Substance Painter.

Figure 2.3 Leather Material Designed in Substance Painter Application[2]

2.4. Artificial Material Technologies

Many artificial leather technologies have been created. Artificial or vegan leather is a growing consumer trend due to reasons such as sustainability, (human) ethical concerns in impoverished countries, animal concerns, and environmental impact of traditional leather.

However, artificial leathers have yet to achieve the same strength properties as real leather, including tensile strength, tear resistance, flex resistance, water permeability, and water absorption [22].

The possibility of 3D printing of textiles has not been successfully achieved yet mainly because properties such as strength and flexibility of textiles are unique to its different modes of manufacturing and production [23]. 3D printing starts with an initial material and ends with a final product with a makeup of the same

2 `https://magazine.substance3d.com/substance-source-automotive-materials-interior-1/`

Table 2.1 Examples of Artificial Leathers

Name	Description
Muskin	mushroom-skin material made from fungus spores
Kombucha	bio-material made from cellulose nanofibrils spun by bacteria
Desserto	plant-based leather made from Prickly Pear Cactus leaves
Appleskin	leather made from waste recovered from the fruit industry
Vegea	leather from wine industry leftovers (stalks, skins, pips of grapes)
Teak Leaf	material made from harvested teak leaves mended with fabric
Pinatex	fibrous leather-like material made from excess pineapple leaves
SnapPap	cellulose and latex material that resembles thick cardboard or leather

initial material. Meanwhile, textile manufacturing is a multistage process that generally starts with a raw material that is pre-processed, processed, and refined into a final material that is different from the initial.

2.4.1 Material Circulation & Artificial Materials in 3D Printing

Plastic is an efficient circular material because it can be thermally or mechanically repurposed into new usages. In most parts of the world today, recycling networks exist so that it is easy to participate in reducing waste of single-usage plastics. Unfortunately, 8 million tons still leak into the ocean every year because plastic gets misplaced in the environment or put in landfills[3]. 3D printing can be a method to reuse plastic by either purchasing recycled filament or creating your own.

Leather has a difficulty in maintaining a sustainable life cycle due to high water usage during tanning and long processing time [24]. Leather can be a circular material today through the use as reconstituted leather. However, one must consider the economic and energy cost/benefits of these processes. Reconstituted leather must re-enter the traditional manufacturing process to be chemically, mechanically, and thermally treated. Therefore, from an environmental and economic

3 `https://www.ellenmacarthurfoundation.org/explore/plastics-and-the-circular-economy`

standpoint, leather re-use should be produced in a new way such as through 3D printing.

3D printing in the healthcare industry has successfully replicated biological structures such as teeth, muscles, and skin [25] [26] [27]. However, leather replication has only recently been explored such as through the use of silk protein to create similar performance [28].

2.4.2 Material Texture Digitalization & 3D Printing

Advances in material digitalization has made it as simple to recreate a material appearance digitally by just using an HDR photograph [29]. The modern method to recreate textures digitally is through microscopic photography through a digital microscope or fabrication of a 3D scanning tool. Wei et al. digitally reconstructed different fabric swatch samples with distinct texture compositions. By using a scanner on a microscopic level, textures can be discerned more accurately [3]. However, digitalized textures were not recreated such as by the use of 3D printing, and and thus not compared for tactile accuracy.

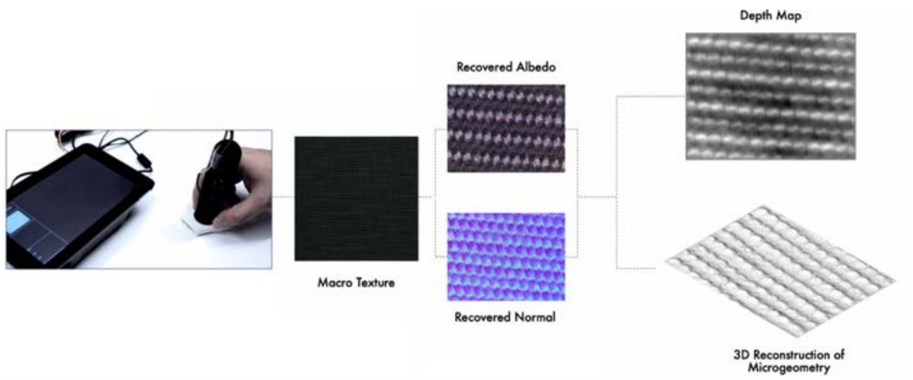

Figure 2.4 Texture Digitalization Process [3]

Chapter 3
Concept

3.1. Overview

In the era of mass customization, this paper proposes a new system for material creation that is not limited by existing materials. We envision a system where users can replicate old and create new materials through digital manipulation and 3D printing processes.

In the future, there will be an ecosystem of materials where present and future materials are recorded and mapped by their own various physical characteristics. Documenting materials are recorded digitally and later produced physically through 3D printing. Materials are "copied" by recreating its innate mechanical and visual properties. First, the correct mechanical properties must be identified, in this case roughness and hardness. Visual properties of materials are recreated through the use of image mapping. Through this, the material can be reconstructed into 3D geometry.

New samples of materials can be reproduced or experienced not only through 3D printing, but also through haptics. With the physical parameters (roughness and hardness) recorded, the material can be sensed digitally through the use of vibrotactile output. Therefore, this enables the user to select, customize, and try materials digitally without actually having the produced material in hand.

3.2. Sustainability

3.2.1 Transparency

A design motivation and principle pertinent to this research is the growing importance of transparency in materials and its creation in the fashion & textile industry. What is the product made of? Tracking from the source of raw material to product is valued in the eye of the current consumer today. By greater classifying and knowing material's properties and structure, it provides stronger identification and recognition to the consumer. Modern textile manufacturing has lengthy industrial supply chains with lack of transparency in where the material may come from, how it was made, where it was made, by whom it was made, and under what conditions. With 3D printing, it comes from a singular source. It is also of importance in the end goal of the 3D printed material being relatively similar based on tactile perception.

3.2.2 Circular Economy and Zero Waste

3D printing is a process that only uses the material needed to make the product, benefiting circularity and material waste reduction.

In traditional manufacturing, problems arise such as what materials are used, in which proportions, how much waste is created, how do they take care of said waste, and how is water used and treated.

In the leather industry, material is routinely destroyed or unused due to several factors. In the manufacturing, commercial, and consumer side, damaged or aged goods are thrown away. In the luxury industry, unsold leather goods are destroyed in order to maintain strong pricing, brand image, and exclusivity. In traditional manufacturing, most excess scrap leather is discarded. It is estimated that in 1000 kg of raw cow hide, 150 kg is processed into leather and 850 kg is determined solid waste [30].

From the macro-perspective in the agricultural industry, leather production is sustainable because it is harvesting a by-product of the meat industry (hide), creating a secondary product that is not being wasted. However, the possibility of the leather industry itself being circular- through the reuse of leather material or artificial material creation is what we imagine, doing material design in a biophilic way in the same way as nature.

3.3. Proposed Applications of Research

3.3.1 Customer Experience of 3D Texture Generation and 3D Printing Customization

Generating and producing textures can be used in the commercial side for textile product customization. Instead of being given samples of swatches, an application in imagined where users can try and customize materials in a graphical interface.

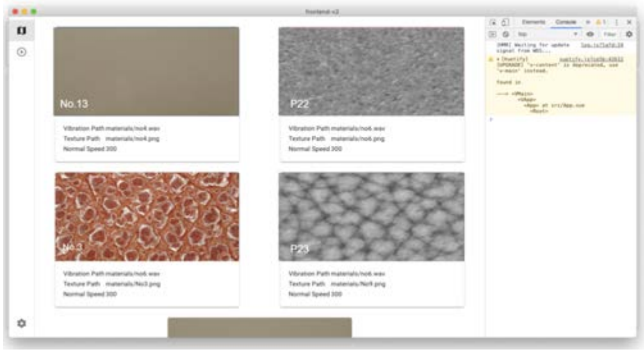

Figure 3.1 Material Customization GUI

3.3.2 Usability and Wearability of 3D Printed Leather Material in Small Leather Goods

This research also is proposed to be implemented in creating small leather goods such as a wallet for longer durability and circular use. The wallet will have a “circular” life where the material can be continuously recycled when worn down, and then sent back for processing to refactor with 3D printing because of its thermoplasticity. Traditionally, a defected wallet or leather good would be tossed into the trash and discarded.

3.4. Material Replication / Set-up

3.4.1 Classification

Materials in this system should be assigned specific values in order to effectively label ascertain what kind of material it is. Materials were classified based on two parameters: roughness and hardness. Classification is essential because it simplifies otherwise complex materials like leather as they could possess virtually limitless visual identities. Limiting classification to hardness and roughness simplifies further evaluation. Category boundaries can be discerned by valued differences of properties. Where hardness and roughness values do not exist, intermediary new materials can be created through new production. Hardness can be measured by tools measuring depth penetration and roughness can be measured by accelerometry. In later experiments, a durometer was used to measure hardness and an accelerometer for roughness.

3.4.2 Digitalization

Leather materials are digitalized by copying the surface texture. Textures are recorded via creating height maps.

A height (also referred to as displacement) map is an image of greyscale values that signify topographical values. In a height map, there is a range from black (lowest points) to white (highest points) that convert to height values. It is a method to display three-dimensional geometry onto a plane, which can be made into a surface texture.

A 24 bit depth, grayscale image from the vertical perspective was used as a heightmap for creating a material. A uniformity of dimensions of 1025 x 769 px was used to maintain consistency and proportionality to physical textures. The device used to record the surface texture was a Keyence VR3000 3D Shape measurement tool.

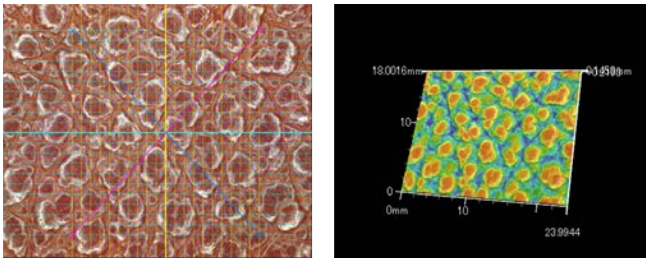

Figure 3.2 Scanned Material Using Keyence VR3000

3.5. Material Customization

3.5.1 Overview

By digitally mixing and altering materials together, novel textures and textiles can be created. Blender, an open source 3D modeling program was used to make STL files for printing. Like natural leather, the 3D model should not be one uniform layer. The model was divided into two layers- the grain and the corium so that individual layer properties could be changed. The dimensions of the top layer of each sample is 1 mm and the bottom 1.5 mm.

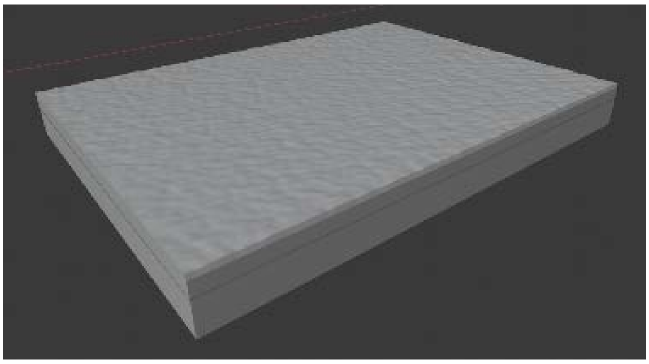

Figure 3.3 Two Layer Leather Sample Model

3.5.2 Python Image Library (PIL)

Python Image Library (PIL) was used to combine and mix the height maps using transparency values. Each material was mixed with the three closest corresponding material to create a median "generated" material. Materials were mixed by manipulating transparency.

```
In [61]: from PIL import Image

In [74]: # Make sure image is in same directory

         image1 = Image.open("No09-hight.png")
         image2 = Image.open("No45-hight.png")

In [77]: # Convert to greyscale
         # 0.5 = mix pattern

         blended_image = Image.blend(image1,image2,0.75)

In [78]: blended_image.save("M6.png","PNG")
```

Figure 3.4 Combining Transparency Values with PIL

3.5.3 Quixel Mixer

Compared to PIL, Quixel Mixer provides more customizability and parameters when combining height maps, which is better for direct consumer application. Furthermore, a 3D plane is generated for easy visualization. Normally used for generating terrain for video games or movies, the material texture can be manipulated with several values inside the program

Height map manipulation can be done by affecting the lowest, medium, or highest greyscale values.

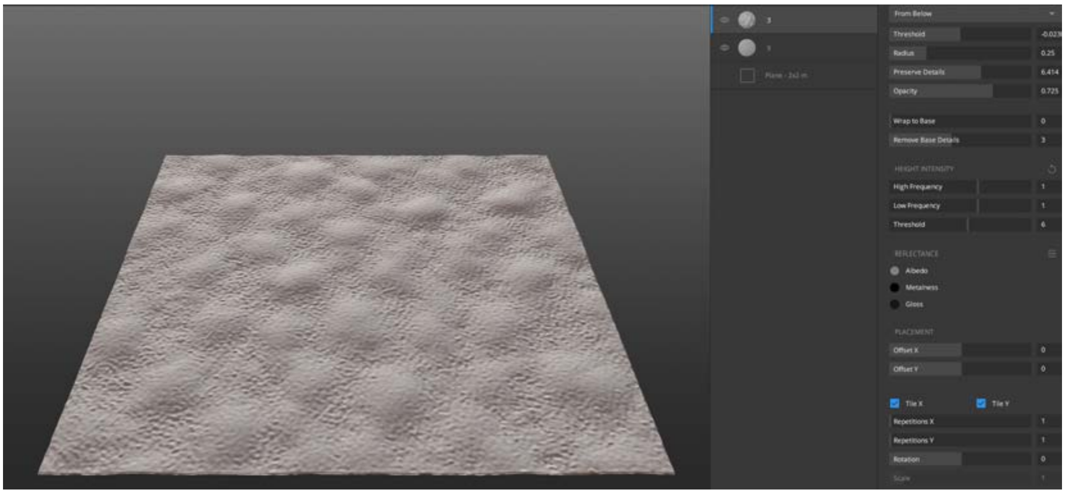

Figure 3.5 Quixel Mixer Material Customization

3.6. Material Creation

3.6.1 Overview

Organic, leather-like material is created by emulating its composition with alternative material selection that is capable to be used in 3D printers. By recognizing and connecting the same physical properties, the closest-to-real can be chosen or otherwise combined in order to be achieved through additive manufacturing.

3.6.2 PolyJet Printing

One method to create high detail textured materials is through PolyJet printing. Choosing the right printing material to match an existing or generated leather material can be easily done with the multitude of selections in PolyJet printing. PolyJet printing can offer a material closely similar to different leathers because the base material resin can be mixed with more hard or more soft resin in order to create a realistic material resembling the same physical hardness properties. Currently, Stratasys, the manufacturer of PolyJet printers, offers 29 different resins that have different characteristics in rigidity, translucency, and transparency. The resin material best resembling leather is Tango, which is normally used for making rubber-like objects. Leather material share the same hardness values.

In the later experiments, an Objet260 Connex 3 printer was used to print leather-like materials.

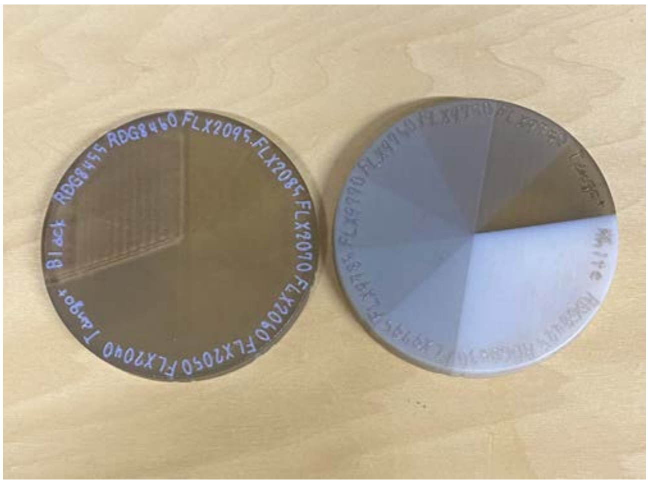

Figure 3.6 Swatch of PolyJet Material Possibilities

3.6.3 Pellet-extrusion Printing

As leather waste is generated from leather production, a way to reuse the scrap leather again to be repurposed into a usable material is proposed through pellet extrusion. Pellet extrusion allows quick customization of material by using different combinations of thermoplastic and organic material such as leather to create a composite material. Composites comprise of a core polymer material such as polyurethane, and a reinforcing material, like chopped or shredded leather scrap. Furthermore, not only leather waste can be used, but also recycled plastic. Therefore, a circular, continuously recyclable material can be created with zero waste. This is pertinent to this research because a new material can be made- one that has the benefits of plastics (reusability, reshapability) and of benefits leather (pleasant to the touch, aesthetically pleasing) into one material.

Chapter 4
Evaluation

4.1. Iteration 1: Shoe Study

4.1.1 Overview

In order to verify that 3D printing can create the same hardness of real-life materials, the different parts of a sneaker's hardness was measured using a Shore Scale A durometer. Initially used for measuring the hardness of rubbers, semi-flexible and flexible materials like leather are also sufficiently measurable.

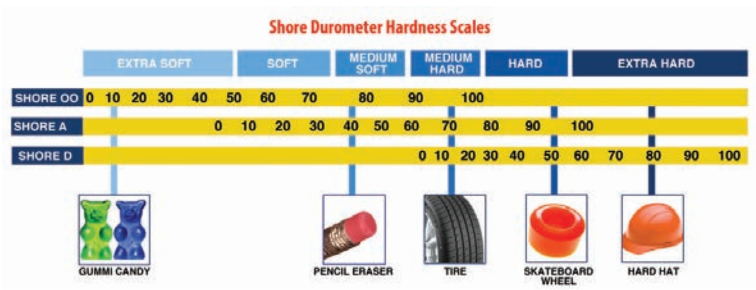

Figure 4.1 Hardness Scale[1]

The parts measured were the sole, cotton upper, side sole, upper sole, and heel. From touching it first by hand, the sections were noticeably different in hardness and flexibility.

Table 4.1 Shoe Hardness Measurements

Part of Shoe	Hardness	Material
Sole	59HA	FLX2060
Cotton Upper	63HA	FLX2070
Side Sole	52HA	FLX2050
Upper Sole	44HA	FLX2040
Heel	67HA	FLX2070

4.1.2 Setup

The 3D printed material was chosen by the relative corresponding hardness value measured. In order to create the 3D geometry of the sneaker, the method of photogrammetry was used using a mobile device.

Figure 4.2 Hardness Values of Sneaker

1 `https://www.smooth-on.com/page/durometer-shore-hardness-scale/`

Figure 4.3 Photogrammetry Model of Shoe

Figure 4.4 Miniature 3D Printed Shoe Model

4.1.3 Results

This was evaluated by 3D printing a smaller version of the sneaker to distinguish if the 3D printed sample and original sneaker had similar hardness levels. The 3D printed sample perceptually did feel similar to the original sneaker. However, when pressing down with extra force, the printed sample feels artificial or rubber-like.

4.2. Iteration 2: Luxury Leather User Study

4.2.1 Overview

I participated in a 7 month internship at Celine Paris, a fashion brand specializing in some of the highest quality, luxury leather goods participating in the quality management team. In this experience, I got a close-hand look at different types of leather materials and construction. Although the managers and staff had vast amounts of knowledge about the leather industry, they had little experience with 3D printing nor 3D printed materials.

4.2.2 Setup

A user study was conducted in order to test the similarity of luxury leather textures and its replicated 3D printed textures. Four texturally different materials were chosen a part of the product line of the brand. The textures chosen were calfskin, grain leather, lizard, and alligator.

Two scorable qualities were tested between the real and 3D printed sample, material relativity and material desirability.

Material relativity was evaluated by a scale of one to five, one noting not feeling related at all to five meaning almost identical. A score of 3 or greater was denoted as positive.

Material desirability was evaluated by giving the user two random unknown materials, and told to answer if material one or material two is more pleasing to the touch. An answer of choosing the 3D printed material, choosing both, or indifferent were denoted as positive.

Figure 4.5 Luxury leathers of Fashion Brand

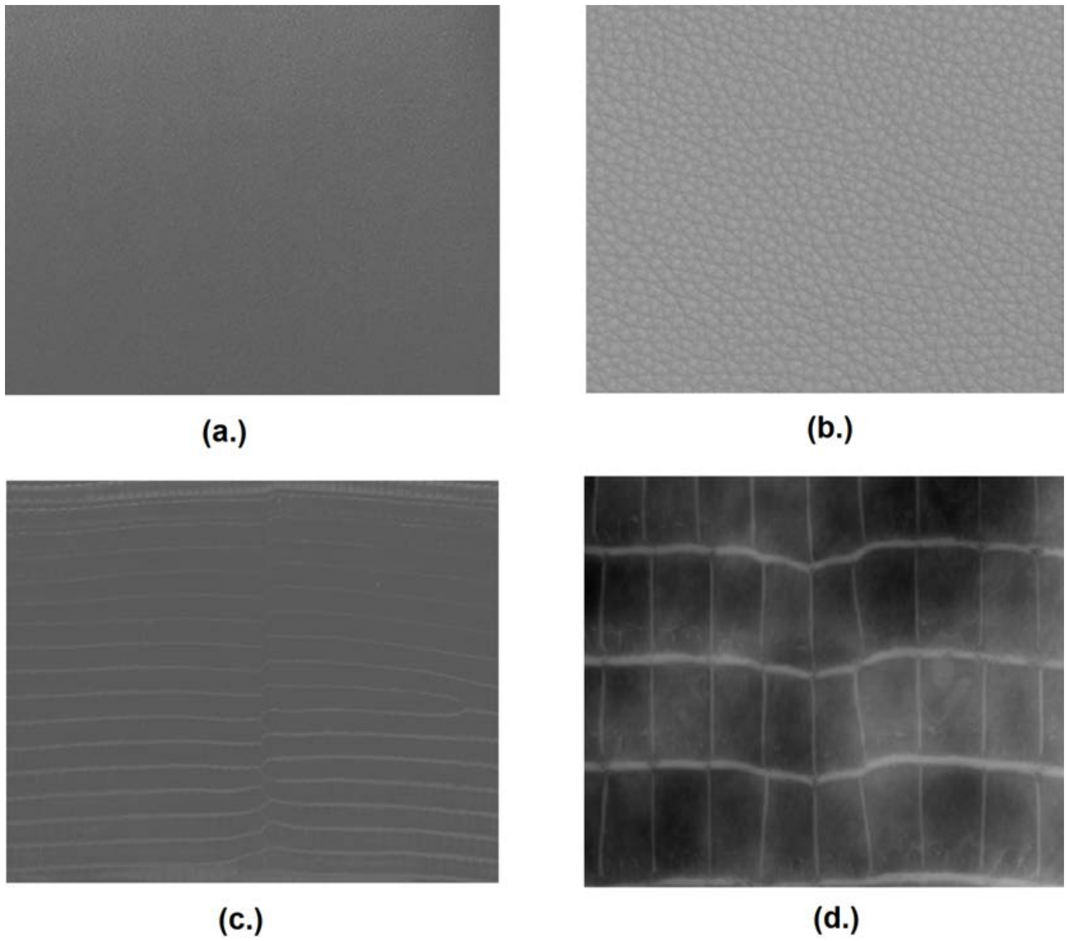

Figure 4.6 Generated Height Maps of (a) Calfskin, (b) Grain, (c), Lizard, and (d) Alligator

4.2.3 Results

Table 4.2 Celine User Test Results

Leather	Relativity	Desirability
Calf Skin	65%	70%
Grain	80%	85%
Lizard	50%	30%
Alligator	65%	55%

In conclusion, 3D printing can relatively make accurate leather materials through hardness and blind user study testing. However, the results indicate that harder materials, such as alligator and lizard, are difficult to emulate with 3D printing. This may be because it is easy for human touch to perceive hard surfaces as plastic and it is a struggle to copy the nuances of semi-hard material.

4.3. Iteration 3: Composite Material Creation through Pellet Extrusion

4.3.1 Overview

This prototype's goal was to test the feasibility of mixing scrap leather waste with flexible plastic in order to directly print a composite semi-organic material. Previous experiments used existingly available printer materials.

A conventional FDM printer (Sidewinder X1) was modified with a MahorXYZ extruder to convert from filament extrusion to pellet extrusion. Different levels of mixtures were used in order to observe the visual appearance.

4.3.2 Setup

A digital scale was used to measure different levels of leather and plastic mixtures. The plastic used was Santoprene 80A, a type of thermoplastic polyurethane (TPU). A 35mm by 50mm plane was printed with a height of 2mm.

Table 4.3 Pellet Extrusion Mixtures

Material	Amount Plastic	Amount Leather	Concentration
Material X	3.83g	0.18g	5%
Material Y	3.56g	0.43g	10%
Material Z	3.10g	0.79g	20%

4.3.3 Results

The results indicated that there is a notable visual difference when adding more or less leather material. As expected, material A is the most uniform. An unexpected finding was that as the leather concentration increased, the more the matter clumped together when printed. The pellet extrusion was a heterogeneous mixture during printing. If done again, greater time will be put into making the mixture more homogeneous for a greater uniformity in the material. Also, because TPU does not directly bond with organic material, the greater amount of leather in the material affected the layer adhesion and accuracy of the shape contours. Future work in this area include mixing the leather and plastic together and making the leather the same size as the plastic pellets. This way, the print may not have a tie-dye effect.

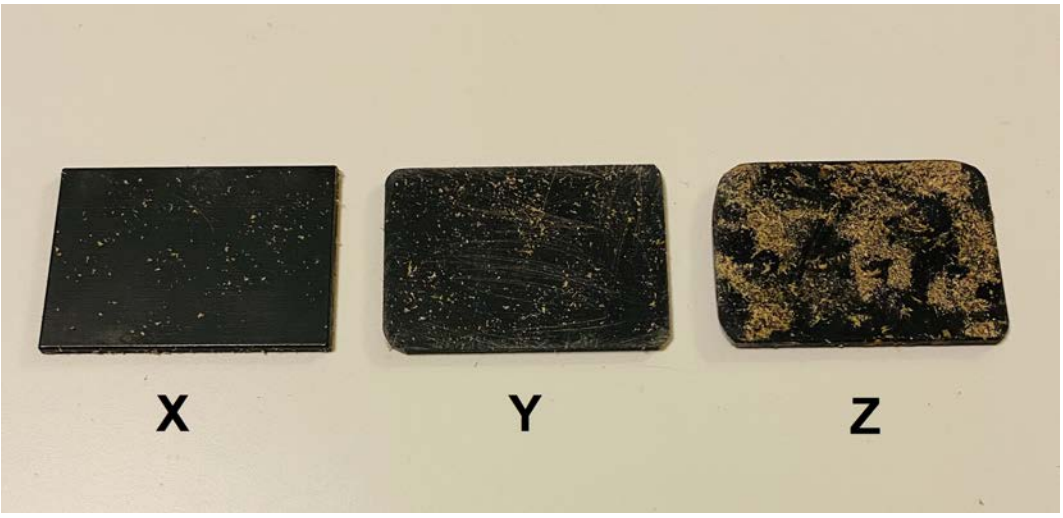

Figure 4.7 Printed Material X, Y, and Z

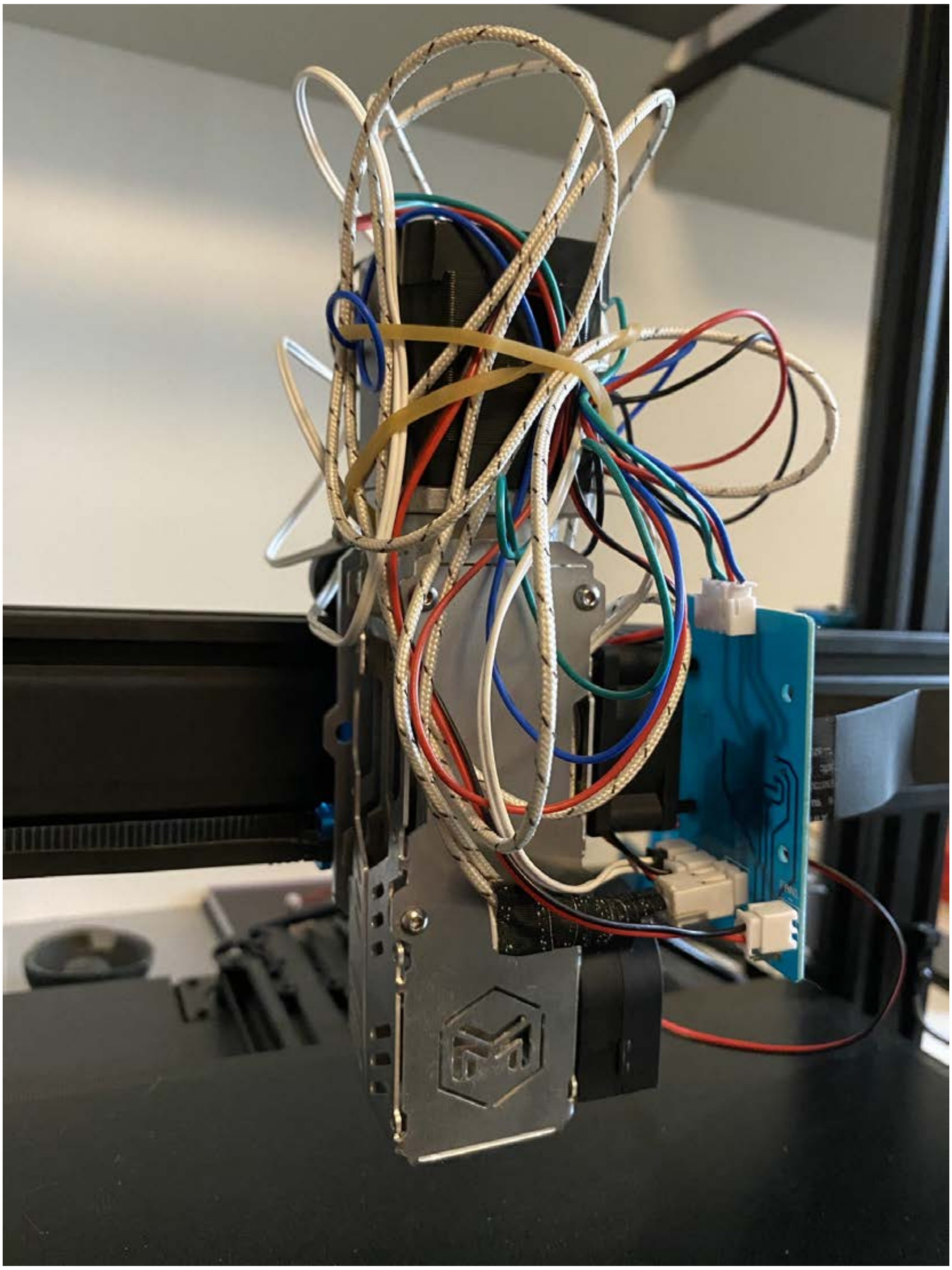

Figure 4.8 MahorXYZ Pellet Extruder on a Sidewinder X1 Printer

4.4. Toyota Boshoku Joint Research

4.4.1 Overview

In collaboration with Toyota Boshoku and Tokyo University, research was done on creating a digitalized system that generates materials for customization of car upholstery.

Figure 4.9 Visual Poster of Project Overview

The non-apparel textile and interior automotive industry is rapidly changing due to increased competition, innovation, and increasing consumer demand for customizability. We proposed a rapid method to customize and combine material textures. This will be accomplished through a multi-step system to quickly digitalize, recreate, and customize leather-based textiles using software, hardware, and 3D printing components. We propose a four step process: mapping materials based on subjective evaluation, mixing vibrotactile data, vibrotactile feedback, and physicalization of a new material. Using a height map image of a leather sample, we created a 3D model of various textiles. The material is then reproduced or modified by manipulating the image, and thus creating a unique material. Then, the desired texture can be confirmed via vibrotactile device. Finally, it can be printed as a proof of concept or given to a customer for tactile feedback to be produced later. Samples of materials are evaluated based on subjective evaluation in a Bayesian structural equation model.

The main members involved in the research project was Dr. Yuki Ban, of Tokyo University Graduate School of Frontier Sciences, Shin Inami and Kunitoshi Ito of Toyota Boshoku Corporation, and Professor Kouta Minamizawa, Professor Roshan Peiris, master's student Makoto Uju, and myself of Keio University Graduate School of Media Design. The role of Tokyo University was to generate vibrotactile textures. The role of Toyota Boshoku was to choose specific leather materials, measure and map the physical properties of the materials, and perform the final testing evaluation. The role of KMD was to facilitate the haptic device prototyping and research direction. My personal main role was to be in charge of 3D printing materials and digitalization.

4.4.2 Setup

Before the final evaluation method, many different leather physical samples were received and tested to confirm the validity that PolyJet printing can print with similar hardness and texture resolution. Based on simple blind touch perception, it was concluded that different levels of hardness and leather textures could be accurately produced through 3D printing.

To cover the varying tactile characteristics of leather, 6 tactile-diverse samples were chosen. They were then mapped based on physical characteristics of hardness and roughness.

To evaluate whether tactile stimuli are well synthesized, stimuli was plotted in a low-dimensional space that can represent human perception.

Inami [31] applied Bayesian structural equation modeling to the data obtained by simultaneously conducting a questionnaire while measuring the four physical stimuli of vibration, friction, load displacement, and temperature change when the panelist actually touched the leather sample. They proposed a method to estimate the strength of perception that can be regressed from the features of physical stimuli. In this paper, the features of physical stimuli are narrowed down

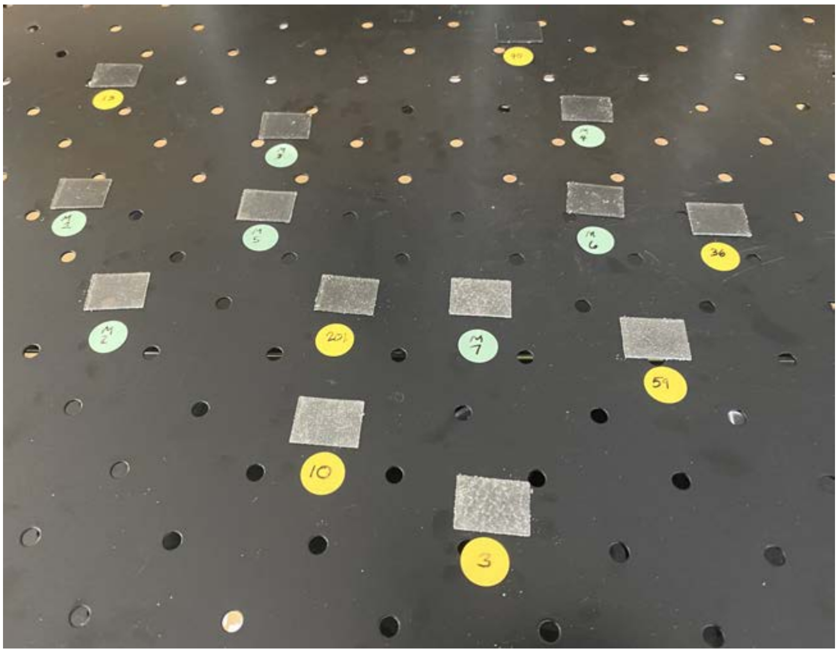

Figure 4.10 Previous Samples Tested Before Determination of Final Samples

Table 4.4 Chosen Leather Samples Description

Sample	Texture
3	Embossing
10	Velour
36	Smooth
40	Smooth
59	Suede
201	Synthetic embossed

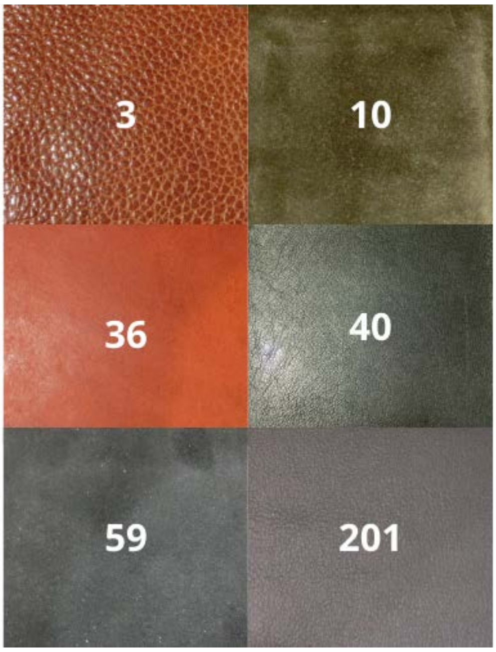

Figure 4.11 6 Chosen Sample Materials for Evaluation

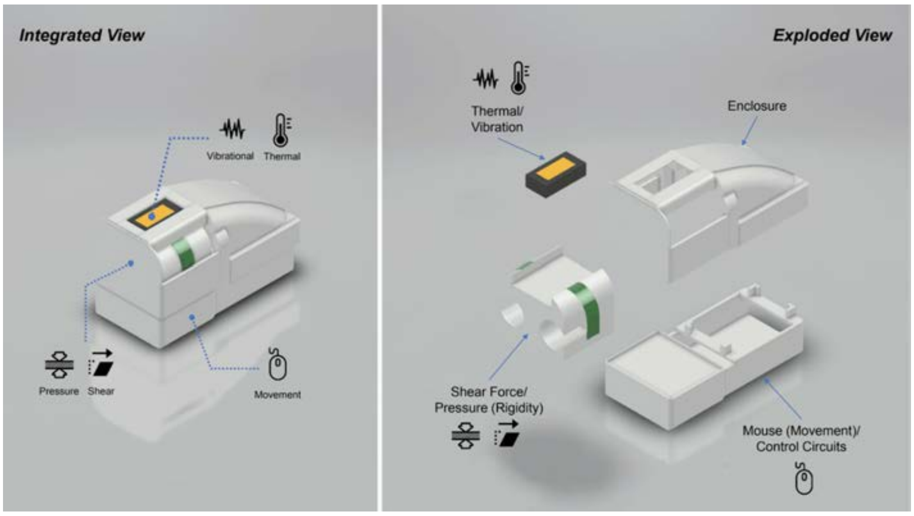

Figure 4.12 Prototype 1 of Haptic Texture Device

Figure 4.13 Physical Prototype 1 of Haptic Texture Device

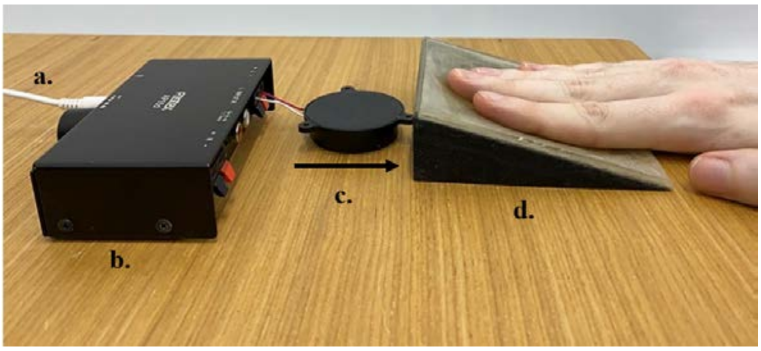

Figure 4.14 Prototype 2 of Haptic Texture Device, Vibration Data is Sent from the PC (a), Fostex Ap15Damplifier (b), VP2 Vibrotransducer (c), 3D Printed Leather Simulation Cover (d)

to those obtained from the time series data of vibration, and the perception is limited to the two axes of "rough-smooth" and "hard - soft", and the tactile space is drawn.

First, the time series data of vibration is analyzed in 1/3 octave band using the python package pyFilterbank, and the time series data of the intensity of each frequency band is obtained. Basic statistics such as average, standard deviation, skewness, and kurtosis are calculated from the time series data of the intensity of each frequency band, and these are used as physical features. The average value of the vibration intensity of each frequency band calculated above is linearly regressed under three conditions of up to the first power, the second power, and the third power of the frequency band. Each regression coefficient, intercept, and the basic statistics of residual were used as physical features.

As a result, the physical features became 98-dimensional data. It was compressed to 8 dimensions by factor analysis in consideration of problems such as multicollinearity and too many numbers of dimensions for SEM. After that, performing SEM in which by setting latent factors for the two-perceptual questionnaires of "rough-smooth" and "hard-soft", and setting regression paths from 8-dimensional physical phenomena, it enables to estimate the perceptual strength behind the answer of the questionnaire. By using the model of prior factor analysis and the model by SEM, the strength of perception when touched by a panelist in the same state as at that time is estimated without conducting a new questionnaire survey. Two indexes of "rough-smooth" and "hard - soft" were used as a result from a regression model, which was built by SEM. Its explanatory variables are feature values from series data of vibration (acceleration) taken from an accelerometer on the finger. The objective variable is the questionnaire result (filtered by SEM). Ideal point coordinates (P) were chosen between existing physical samples available, to later generate textures in the designated space. The specified coordinates are imaginary combinations of surrounding samples. P locations were chosen by discussion and significantly different values. The values of rough-smooth and hard-soft were averaged together in relation to proximity of existing materials. Figure 4.16 indicates the values of proportional difference in mixing of materials. However, at the time of decision to make the haptic map from only vibration data, there was missing questionnaire data on material 201.

Therefore, material 201 was used to generate P samples but was omitted from further analysis and mapping.

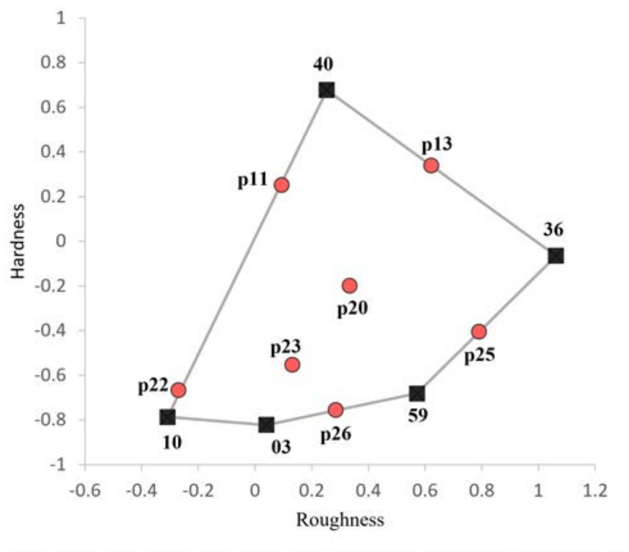

Figure 4.15 Haptic Map of Physical Samples and P-targets

By digitally mixing and altering materials together, novel textures and textiles can be created. Blender, an open source 3D modeling program was used to make STL files for printing. Like natural leather, the 3D model should not be one uniform layer. The model was divided into two layers- the grain and the corium so that individual layer properties could be changed. The dimensions of the top layer of each sample is 1 mm and the bottom 1.5 mm.

Product visualization can be done directly in Blender to see how the texture is displayed on an automotive seat.This is important for the commercial aspect in that customers can quickly see how it may look, change the color, and also feel it using the created haptic device.

A Stratasys Objet Connex Polyjet printer was used in order to yield high detail textures in prints (less than 20 µm). The primary material used is a proprietary Tango® material with a range of tensile strength options of MPa 1.3 to MPa 10.0 and shore hardness (A) of 35 to 95. Selection of proper printed material was done by matching to closest physical parameters and trial error to the nearest similarity.

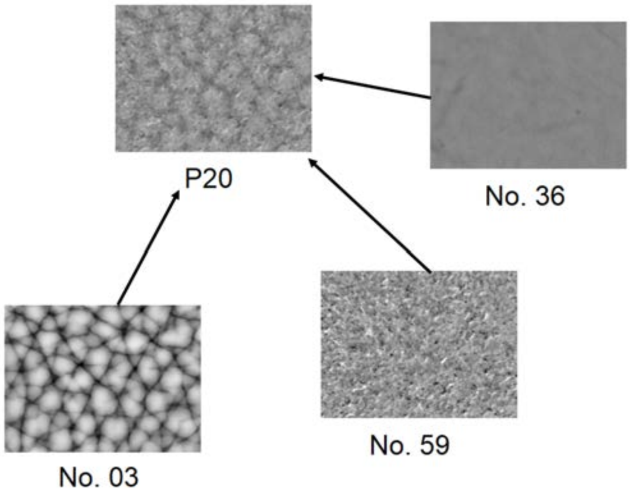

Figure 4.16 Example P20 Mixes 32% of Sample No. 3, 28% of Sample No. 36, and 26% of Sample No. 59 to Create Target P-texture

Figure 4.17 Example Material on Car Seat

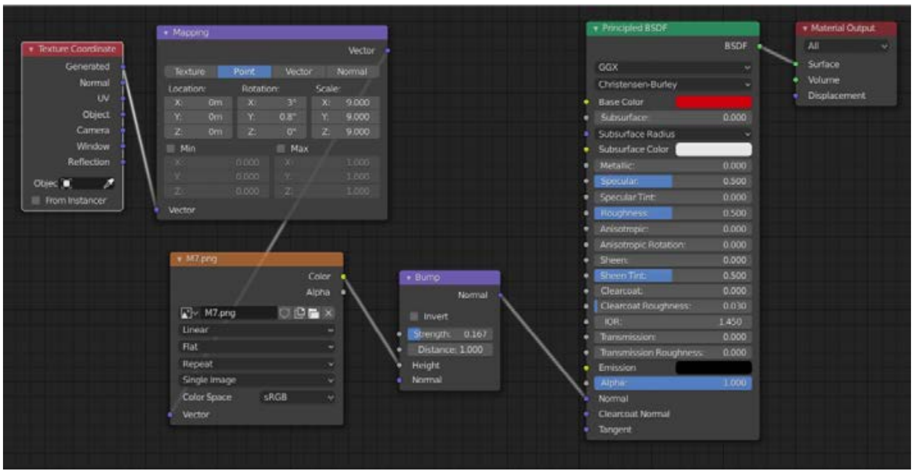

Figure 4.18 Material Visualization Configuration using Blender

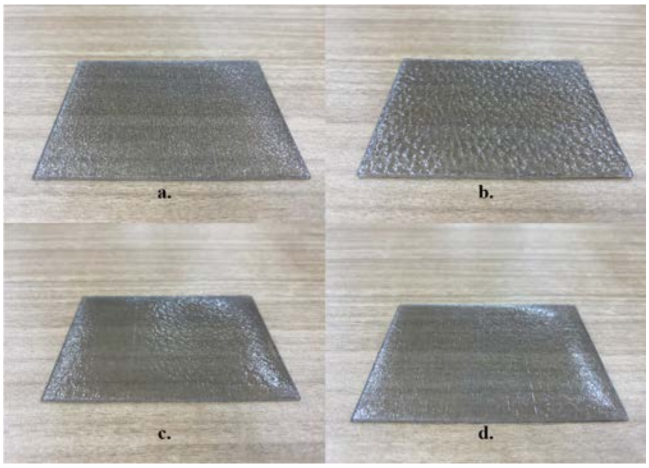

Figure 4.19 3D Printed materials No. 59 (a), No. 03 (b), No. 36 (c), and Generated P20 (d)

Table 4.5 Original Samples, Generated Samples, and Corresponding PolyJet materials by Layer

Sample	Top Layer	Bottom Layer
03	TANGO	2040
10	2040	2040
36	2060	2085
40	2085	2060
69	2040	2070
201	2060	2040
P11	2070	2060
P13	2070	2070
P20	2060	2070
P22	2050	2050
P23	2050	2060
P25	2060	2085
P26	2040	2060

4.4.3 Results

We compared the physical leather samples with the digitalized vibrotactile signals and 3D printed samples on the same haptic feeling map in Figure 4.15.

Here we think this map should show psychological perception about vibrotactile sensation. The vibrotactile textures & 3D printed textures were mapped by a SEM regression model. In Fig. 4.20, a regression model indicates the results of the relation of the physical samples to the generated P points, vibration samples, and 3D printed samples. The results on the map indicate drift between each categories. The vibration samples results were a P-value of 1% correlated. However, vibration and 3D printed sample had no correlation.

In previous discussion, 3D printers lack the degree of freedom of surface material (except for hardness) So the real sample and printed sample had different contact conditions especially in friction, which may have caused an unfavorable correlation. In the future, increasing the amount of tested samples would help increase the number of observations and decrease the critical p-value. The critical issue of the research was the limitation of measurement. Despite careful consideration, recording the acceleration between materials and fingers should be virtually perfect for accurate data.

Figure 4.20 Regression Model of Physical, Vibration, and 3D Printed Samples. The Red Points are the P-targets, the Black is the Physical Samples, the Blue is the Vibration Samples, and the Green is the 3D Printed Samples.

The goal of our research was to create a unified system to classify, generate, and produce leather textiles. We proposed a rapid method to customize and combine material textures. The current limitations include 3D printing processing not at the level of precision for replicating intricate physical parameters of roughness & hardness. 3D printing can be used to demonstrate qualitatively positive tactile perception to the user, however qualitatively not correlated to roughness and hardness parameters. We can say that in conclusion, textural perception of 3D printed samples versus the real physical sample can be improved when combingin vibrotactile sensation. Overall, we hope to continue testing the system with more materials and apply it to the consumer market.

Chapter 5
Conclusion

I became motivated to research about the leather industry for a variety of reasons: because of my work history, because it is a controversial material, and because it has a long history of usage.

This research explores various ways of applying leather materials in 3D printing processes. This includes through investigating material properties, material digitalization, and material customization. The research has helped me understand what the current 3D printing technology is capable of and how close it can be to organic materials. Overall, performed evaluations determined that there are many methodologies in creating leather-like materials, and research in this area has not been frequently published. I was surprised that there is not a large bridge of research between 3D printing and leather. However, previous work has shown both texture and artificial materials research is an active topic in the academic community. Meanwhile, the increase of plastic in our daily lives has made leather a coveted item in the apparel industry.

Overall, the results were conclusive that 3D printing will leave the hobbyist arena it is in now and be a major industry in the future autonomous, independent, and customize-centric society. The only limitations found was the lack of ability to print large textile-sized materials because of the build time, build plate size, and cost of material in the case of PolyJet printing. User studies indicated a fascination and interest in 3D printing as the average person may not be exposed to the technology yet. I believe more people will actively participate in the 3D printing community as it can also provide methods in reusing plastic when applied from a circular perspective. Plastic usage in Japan is the second largest in the world per capita only second to the United States of America.

In future work, I plan to look closer at plastic recycling and the usage in combination with leather recycling. Furthermore, with 3D printing, I would like to apply the technology in assembling ready-to-be-made leather-like goods that are customizable by texture, hardness, and color. To make an impact in Japanese society specifically, collaboration with plastic manufacturers such as Daisaku Co. Ltd., the largest plastic recycler in the country to initiate a grass roots movement to reuse plastic, a 3D printer can be placed in any home and easily learned. In conclusion, yes- 3D printed materials can replicate leather, and in some cases, be better than natural leather, because it is innovative, adaptable to the user, and the future of Industry 4.0.

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