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ADDITIVE MANUFACTURING OF PERSONALIZED WETSUITS

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ADDITIVE MANUFACTURING OF PERSONALIZED WETSUITS

by

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June 2021

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Additive manufacturing (AM) provides opportunities to customize parts with precise control of geometry and materials. An application for the Navy is the fabrication of user-tailored wetsuits with superior fit, as well as enhanced thermal and mechanical properties required for dives at cold temperatures and high pressures. The goal of this project is to investigate AM for the fabrication of wetsuit parts. A 3D scanner was used to generate a digital model of a hand, which was modified with a modeling tool to form a glove and sliced for printing. The glove was 3D printed using fused filament fabrication with multiple methods and materials, including thermoplastic polyurethane elastomer (TPU), polyvinyl alcohol polymer (PVA), and polylactic acid (PLA). PLA was initially used to determine appropriate settings for the other materials. A fully TPU-printed glove most closely resembled a wetsuit with an excellent fit. TPU printed at 100% infill proved to be stiffer than neoprene, which might be advantageous for higher external pressures. Alternatively, a water-soluble PVA part was printed to use as a scaffold and a neoprene gel was applied to the outside, which left a thin shell of neoprene upon dissolution of PVA in water. This shell had the flexibility of a traditional wetsuit, but lacked thickness, which would require multiple applications of the gel. The results suggest a combination of these approaches can be used for producing next-generation personalized wetsuits for the Navy.

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ADDITIVE MANUFACTURING OF PERSONALIZED WETSUITS

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Additive manufacturing (AM) provides opportunities to customize parts with precise control of geometry and materials. An application for the Navy is the fabrication of user-tailored wetsuits with superior fit, as well as enhanced thermal and mechanical properties required for dives at cold temperatures and high pressures. The goal of this project is to investigate AM for the fabrication of wetsuit parts. A 3D scanner was used to generate a digital model of a hand, which was modified with a modeling tool to form a glove and sliced for printing. The glove was 3D printed using fused filament fabrication with multiple methods and materials, including thermoplastic polyurethane elastomer (TPU), polyvinyl alcohol polymer (PVA), and polylactic acid (PLA). PLA was initially used to determine appropriate settings for the other materials. A fully TPU-printed glove most closely resembled a wetsuit with an excellent fit. TPU printed at 100% infill proved to be stiffer than neoprene, which might be advantageous for higher external pressures. Alternatively, a water-soluble PVA part was printed to use as a scaffold and a neoprene gel was applied to the outside, which left a thin shell of neoprene upon dissolution of PVA in water. This shell had the flexibility of a traditional wetsuit, but lacked thickness, which would require multiple applications of the gel. The results suggest a combination of these approaches can be used for producing next-generation personalized wetsuits for the Navy.

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TABLE OF CONTENTS

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LIST OF FIGURES

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LIST OF TABLES

LIST OF ACRONYMS AND ABBREVIATIONS

3D	three dimensional
ABS	acrylonitrile-butadiene-styrene copolymers
AM	additive manufacturing
CAD	computer-aided design
FDM	fused deposition modeling
FFF	fused filament fabrication
ONR	Office of Naval Research
PLA	polylactic acid polymer
PVA	polyvinyl alcohol polymer
SLS	selective laser sintering
STL	standard triangle language
TPE	thermoplastic elastomer
TPU	thermoplastic polyurethane elastomer

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I. INTRODUCTION

In 1987, the first commercial use of AM emerged with stereolithography from 3D systems. Since then, and especially within the last decade, the interest and application of AM has grown. Typically associated with automotive or aerospace industries, AM has applications in many diverse fields, spreading from clothing to building structures to machine parts. The focus of this thesis is on the AM of personalized wetsuits that are suitable for cold water temperatures.

A. MOTIVATION

One of the missions of the Navy is to create combat-ready forces that can win wars and maintain freedom of the seas [1]. The Navy's mission revolves around the water, and the best way to achieve the mission is to provide the sailors with the best equipment possible. The growth of AM provides many opportunities for the Navy to not only create new and better equipment, but quickly repair the current equipment in use today. With the Navy focusing its mission in and around the water, it is important that wetsuits worn by divers are properly fitted, and that they are effective at many different depths.

AM provides the perfect opportunity to develop personalized wetsuits to individual divers because precise measurements can be used to create a wetsuit tailored to that person. As AM has continued to grow, the material selection has widened, so there are a variety of different materials that can be selected to achieve a specific goal. The motivation behind this thesis is to use all of the advantages AM provides over traditional manufacturing to develop a wetsuit that is personalized to each person so that the wetsuit is as effective as possible.

B. INTRODUCTION TO AM

Additive manufacturing (AM) is the formal term for 3D printing, and refers to the technology of depositing thin layers of material on top of one another to produce a 3D object [2]. Since the first use of AM, the field has seen tremendous growth as a result of the many advantages that it can provide. With AM, different shapes and geometries in a material can be achieved, and different materials can be used to produce the same object, allowing for greater customization. Throughout the evolution of AM, the selection of useable materials in the process has grown [3]. Currently, AM can be used to print various plastics, resins, rubbers, ceramics, glass, concrete, and metals.

In order to produce objects, there are many available methods; the two most common technologies are selective laser sintering (SLS) and fused deposition modeling (FDM)/fused filament fabrication (FFF), also known as extrusion printing [2]. Prior to the physical printing, the object is drawn up using CAD software. The CAD file is exported as a mesh file, typically with STL extension and sliced up into different layers using slicer software. Each layer has some nominal thickness, but the thinner the layer, the closer the print will be to the design. The machine parameters need to be set to allow for the desired thickness, timing, and material constraints, and then the build can start. The output file from the slicer is typically a GCODE file, which the printer is then able to read and execute to form the part. After the build is complete, the object is removed from the printer and finishing touches are done on the object, such as cleaning up, painting or polishing [4].

SLS uses a high-powered laser to fuse small particles of the material onto a platform to create the desired shape. Objects printed with SLS are made with powder materials, and once the object is printed, they usually do not have to be sanded or altered, as is the case with other methods, however they need to be machined out of the base. FDM/ FFF work by extruding a molten polymer layer by layer to build the object. The polymer used in FFF is continuously fed through the machine, and the process offers low manufacturing costs, flexibility in design, and a safe operation [5].

Despite all of the advantages of AM, some obstacles have to be overcome to ensure continued expansion of its uses [6]. Objects are printed within the build volume of the printer, and most 3D printers have a limited build volume. As the object grows in size, more time is going to be needed for the print to complete, which may detract from the possible advantages of 3D printing. Another disadvantage for AM is the cost associated with the initial printer set-up and material. The commitment to 3D printing and its advancement is quite costly compared to traditional manufacturing, but can be justified for small production batches and personalized objects.

1. Fused Filament Fabrication (FFF)

Extrusion-based technology is currently one of the most popular printing methods. In FFF method, the material is contained in the machine and forced out through a nozzle in a semi-solid state when pressure is applied [6]. A schematic of the FFF process is seen in Figure 1. In extrusion printing, the ideal approach is to have a continuous source of material, so there is typically a chamber in which the material is stored. This material will then become a semi-solid so that it can be pushed through the nozzle. More than likely, the chamber will have heat applied to maintain the temperature of the melt, but it is important to keep the temperature relatively low so that the material does not burn. Material flow through the nozzle is controlled by the pressure drop between the chamber and the atmosphere. Once the material is extruded onto the printer bed, the shape and size should remain the same, however surface tension and gravity have the potential to alter the print. The material will cool after it is printed, and layer upon layer will be added until the final print is complete.

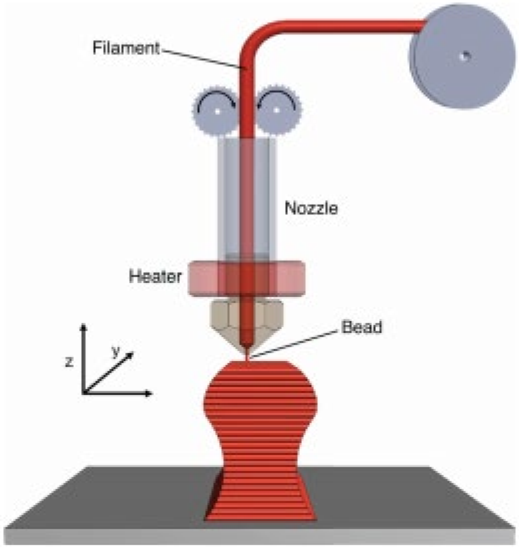

Figure 1. Schematic of FFF printing process. Source: [7].

The quality of the printed product using FFF is determined by various user-inputted printing parameters, such as percent infill, layer thickness, print speed, print temperature, and bed temperature, among others. One of the advantages of 3D printing, and FFF, is that materials can be used that can not be used in traditional manufacturing that can reduce the weight and cost of the final object. There are many compatible polymers that can be used with FFF, and the list is growing every day. There has been success printing with metallic, ceramic, bioglass, carbon, agricultural waste, animal waste, and more, but the selection of the polymer should be made so that the melting temperature of the polymer does not exceed 300 °C [8]. FFF has proven to be a simple print method, however, when compared to conventional technologies available, the quality of FFF is not as good, and the surface roughness and mechanical strength of the components lack. Additionally, as the geometry becomes more complex, volumetric shrinkages can occur, and the surface roughness can be reduced, causing aesthetic deficiencies [8]. Despite these deficiencies, the technology behind the FFF process is changing rapidly, and with improved manufacturing processes, the challenges posed by FFF are likely to be fixed.

2. FFF Materials for Wetsuits

AM has many advantages over traditional manufacturing, but one of the benefits is the wide range of materials available for printing. For the purpose of this thesis, the focus was on using materials that could replicate the neoprene typically found in a wetsuit, so TPU and PVA were primarily used. PLA was used for a lot of testing as it is easily printed.

a. TPU

There has been a large growth of thermoplastic elastomers (TPEs), and thermoplastic urethane (TPU) is one of the main reasons for the growth. TPU was the first homogeneous elastomeric polymer that could be processed with methods commonly used with thermoplastics [9]. The elastomeric properties of TPU are a result of a multi-block structure of phase-separated systems, and has a hard segment and soft segment, seen in Figure 2.

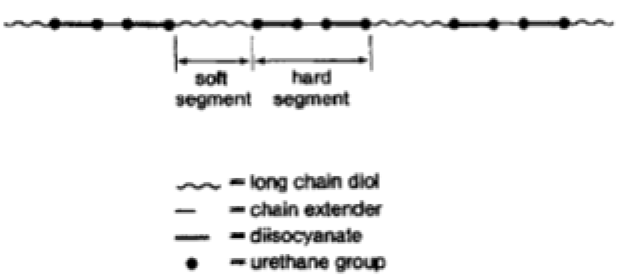

Figure 2. Schematic of TPU. Source: [9].

At room temperature, the hard and soft segments are incompatible, resulting in a separation of the two phases. Each phase has a different melting point, and when the TPU is heated above the hard segment's melting point, the entire polymer melts so that it can be used in the extrusion. After the extrusion and the polymer cools, the two phases separate again, resulting in the elastic properties [9].

The hard segment of the TPU is responsible for many of the material's properties, including hardness, modulus, tear strength, and upper use temperature. The softer segment is responsible for the lower use temperature and elasticity [9]. The proportion of the hard to soft segment will determine the overall properties. TPUs can be suitable as wetsuit materials due to their elastic properties.

b. PVA

PVA is a petroleum-based thermoplastic, and has many different applications due largely in part to it being water soluble. As it relates to AM, PVA is commonly used as a support material [10], because after the object is printed, it can be submerged in water to remove the supports without damaging the surface of the piece. PVA is commonly used in the medical field, however there is little research done on 3D printing with PVA. Due to its high water solubility, the material must be kept in a dry environment as it soaks up any moisture in the atmosphere. As the PVA absorbs moisture, it softens, making it hard for the material to be pushed through the nozzle. Additionally, the softened material may lead to air bubbles to be formed in the extruded material [10]. PVA provides a challenge when it comes to printing because of the natural moisture that exists in the environment. Ideally, PVA should be kept in an environment with less than 10% relative humidity [8]. There has not been a large body of research involved with printing with PVA, however is has been seen that after around 45 minutes, the humidity really starts to impact the material. As a result of this, long duration prints are not an easy option with PVA. In order to optimize the printing time with PVA, it has been suggested to keep the roll of PVA in a ziplock bag and remove the necessary amount for the piece just before printing. This limits the amount of time the PVA is exposed to the moisture in the air, and can help prolong the printability of the material [10].

Another issue that was discovered when looking at dual-extrusion printing with PVA is its inability to adhere to other materials. Testing was performed with ABS and PVA, and there were many inconsistencies found in the adhesion between the two materials. These inconsistencies were a result of moisture in the PVA, as well as a lack of overlap between the materials [10]. Despite the challenges with PVA, it provides a good option for support if the challenges can be overcome.

c. PLA

PLA has been introduced in areas where there is a need or want for biodegradable materials, such as plastic bags, diapers, and disposable plates. PLA is relatively versatile and can be processed similarly to other thermoplastics. The thermal stability of PLA is not as good as that of other thermoplastics, however this can be improved by reinforcing the fibers. Unlike TPU and PVA, PLA is a very rigid and stiff material, so in order to improve the elongation, plasticizers are needed [11].

PLA is very useful for 3D printing due to its low glass transition temperature (60-65°C) and melting temperature (173-178°C). Because these two temperatures are relatively low, the print bed does not need to be heated for printing [12].

C. 3D SCANNERS

There are many uses for 3D scanning from reverse engineering, replicating historical artifacts, creating replacement parts, and generating objects for 3D printing. For 3D printing to work, there needs to be a digital copy of the object, and 3D scanners are used to import physical objects into the digital world [13].

The use of 3D scanners is practical for AM because they help facilitate rapid model creation. For this thesis in particular, the goal is to produce a wetsuit using AM. In order to get the proper measurements of each body part, it would take a lot of precise measuring and the person would have to stand in the same spot for a long time to create the model using a CAD program. Instead of dealing with the hassle of finding all of the required measurements and redrawing the object, a 3D scanner can be used to obtain thousands of points that correspond to the body positions to create the body part [13]. Not only is the scanner doing all the measurements, but the digital version is being created much faster than by hand.

D. WETSUITS

Wetsuits are commonly worn by swimmers, divers, or surfers to insulate the person and help them retain body heat in cold water. A wetsuit is made from multiple layers, including a thick layer of synthetic rubber foam, commonly neoprene [14]. In direct contact with the skin is a thin layer of water that gets trapped and heated up with body heat, seen in Figure 3. The first material layer is typically nylon or some other comfortable fabric that prevents chaffing when it is rubbed against the skin. Some wetsuits will have a thin layer of metal, such as titanium or copper, to reflect the body heat back inside, which would be the next layer. As previously mentioned, the most important layer is the thick neoprene layer that contains trapped bubbles of nitrogen; this is the insulating layer that provides the warmth. The outer layer is made from a durable material to resist any tears that would puncture the wetsuit and cause a leak.

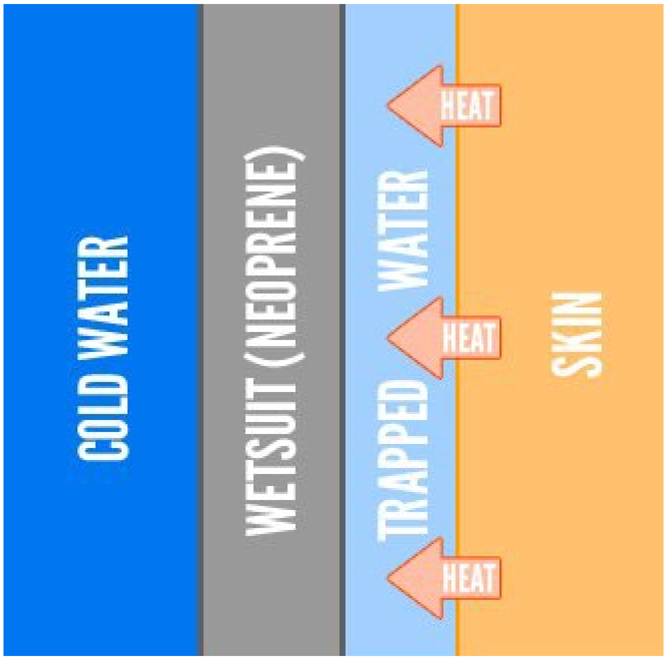

Figure 3. Diagram of wetsuit, water, and body. Source: [15].

Wetsuits work by limiting the amount of water that gets in contact with the body. A small amount of water is necessary for insulation, however if too much water gets in, the body is not able to heat the water, so the wetsuit loses its effectiveness. The proper fit of a wetsuit is necessary to limit the amount of water between the human body and the suit to ensure that the wetsuit can do its job. Another issue with wetsuits is that they are typically designed for certain depths or jobs [16]; for example, a surfing wetsuit has more flexibility than a diving wetsuit, which is focused more on warmth. As the depth of water increases, the pressure increases, which results in the compression of the neoprene layer. When the neoprene compresses, the nitrogen bubbles in that layer shrink, and the thermal performance of the wetsuit is reduced. To counter this loss, a thicker wetsuit should be worn, or a specialized version with high resistance to compression.

While wetsuits are common among recreational activities, they are also relied on in the Navy, particularly with the SEALs and Navy divers. The effectiveness of a wetsuit is based on the fit and durability of the suit. Being able to produce wetsuits that are personalized to each diver and durable would ensure that the Navy is fitting SEALs and divers with the most effective wetsuit for mission accomplishment.

The Office of Naval Research (ONR) is currently working on developing an insulated wetsuit for cold water that is capable of maintaining 75% of surface insulation at 30.48 meters (100 feet) [17]; currently, neoprene wetsuits only provide about 25% surface insulation at that depth. The Navy has a need for better wetsuits, and AM is a reasonable approach to achieve the desired requirements by precise control of structures and materials. The main requirements beside the cold water insulation is to maintain, if not improve, mobility and don on/off times to current wetsuits. Additionally, the goal is to keep each wetsuit cost below $500.

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II. EXPERIMENTAL

The theory behind AM appears quite simple, however there are many steps involved in obtaining the final print. When looking at personalized wetsuits in particular, it is important to generate a 3D object that resembles the body as closely as possible; one way of accomplishing this is to scan the body into the computer to create a CAD file. From the CAD file, a STL file can be created, leading to the GCODE, and finally the print. There are commercial systems that allow real-time scanning of the entire body. However, for the small-scale work here, small portions of the body were being fitted and tested for a wetsuit, such as a hand. To help make it easier to scan the hand with an existing 3D scanner, a mold and cast of the hand was created.

A. HAND MOLD AND CAST

To create the hand mold, the "Perfect Craft Gestures Perfect Cast Molding and Casting Kit" was used. First, a mold was created using the provided molding mix. For this step, it was important that the hand was inserted into the bucket so that the fingers were not touching the side of the bucket, and that the hand was not fully inserted into the bucket. If the wrist was involved in the mold, the remainder of the hand would have been wider than the wrist, so when the hand was removed, it would have ripped the upper part of the mold. After around seven minutes, the mold started to harden, indicating that it was time to remove the hand from the bucket. To remove the hand from the mold, the upper hand was moved slightly to break the seal. When the seal was broken, the fingers were moved slightly and the hand was gently lifted. It was important to be gentle when removing the hand because if the mold was ripped, it would not be possible to get a good cast. Once the whole hand was removed, the cast could be poured using the provided cast materials. The bucket was gently tapped on the table and shook to remove any air bubbles. After the cast set, it could be removed from the rest of the mold material, revealing a copy of the hand, seen in Figure 4. With a cast of the hand, it was able to be scanned into the computer in order to start the process for printing.

Figure 4. Cast of hand

One of the points of worry from the cast was the fingertip region because of the thin features. The resulting cast was not perfect around the fingertips, but the computer software would be able to clean up the region if the scan picked up on the imperfections.

B. 3D SCANNER

There are many different 3D scanners that can be used to produce a computerized version of a body part or object. Initially, the Sense2 scanner from 3D Systems was tested. This was a handheld scanner that was hooked up to the computer and used a program called iScan to capture the image. This scanner did not end up working because it was manually operated, meaning the user had to physically rotate the scanner around the object, and it was hard to keep the scanner focused on the object. As a result, the scanner was not able to fully capture the desired hand, and a full 3D object was not able to be produced. After many failed attempts with the Sense2, a NextEngine 3D Laser Scanner was used. As seen in Figure 5, this scanner is comprised of a main unit with the lasers and a secondary rotating base for the object.

Figure 5. NextEngine 3D Laser Scanner used. Source [18].

The NextEngine scanner weighs about seven pounds, and is capable of sitting on a tabletop. The scanner is connected to a computer via USB and works in conjunction with the ScanStudio software. With the software, the user is able to adjust the type of scan (360, bracket, single), the number of divisions, the precision and speed of the scan, as well as the scan view (normal, wide). Adjusting the settings effects the overall time of the scan, as well as how far from the scanner the object is placed.

When the hand was placed on the scanner, the wide mode was used due to the size of the hand, which meant that the hand had to be placed around 43.18 cm (17 inches) from the scanner. A 360 scan was desired, meaning that the whole hand would be scanned in. The number of divisions was set to 8 with the standard speed selected. This meant that the scan would not be "high resolution," however the completed scan ended up with a better quality than options that resulted in "high resolution." The 360 scan works by combining the individual scans from each division, in the case of this scan, eight. The ScanStudio allows the user to see the overlapped scans, as well as the individual scan. When a new scan is started, the new scanned pictures get included with the previous scans unless an entirely new project is started. ScanStudio shows many views of the completed scan, which allows users to see the overall quality of the scan, as well as any imperfections that would need to get fixed in a postprocessing tool such as MeshMixer. The final scan of the hand is seen in Figure 6. The scan shows that the imperfections that existed in the cast did not really effect the overall print quality near the fingerprints, and there are not any breaks around the fingertips.

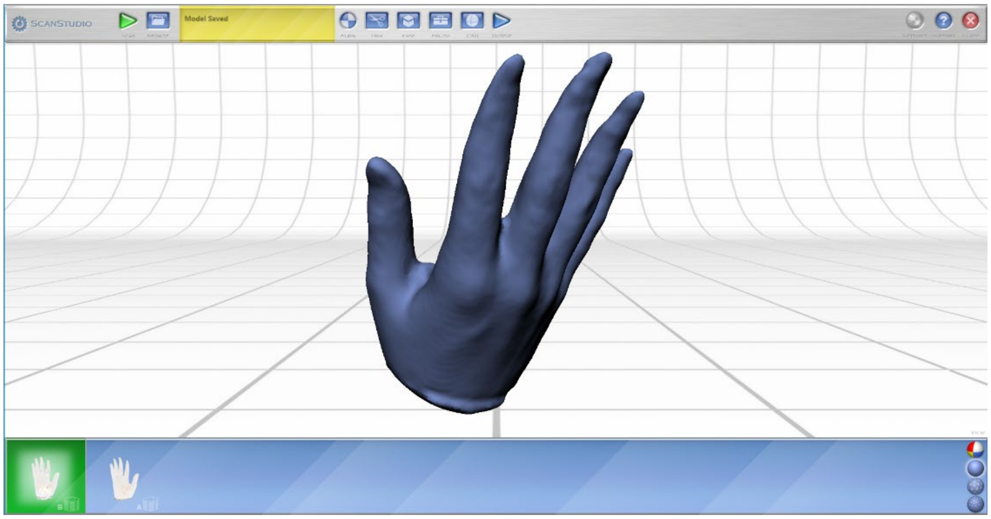
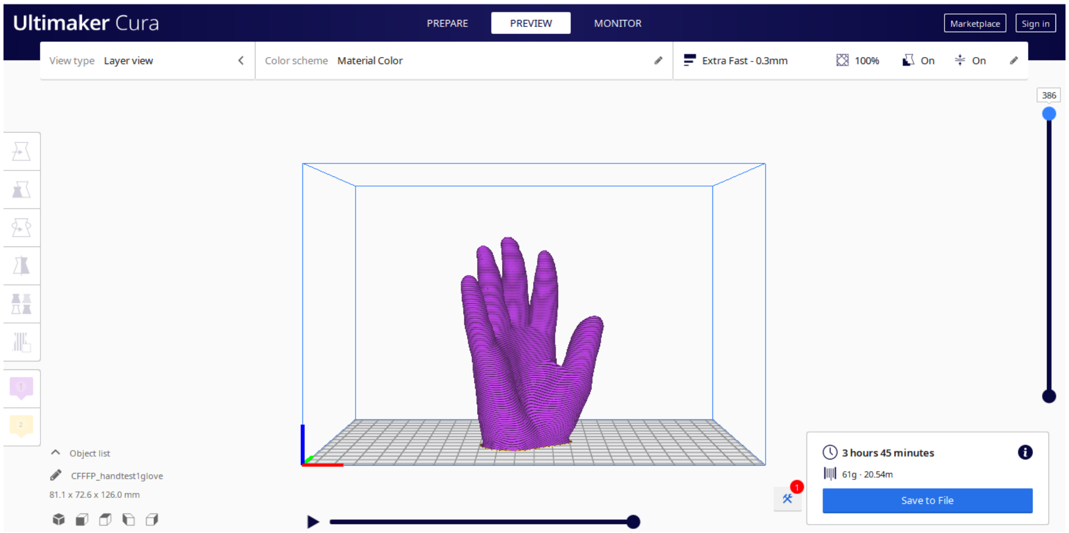


Figure 6. Final scan of the hand in ScanStudio

ScanStudio produced an STL file that can be imported into a variety of different software applications to perform any touch-ups and get the design ready for printing.

C. CURA, SIMPLIFY3D, AND MESHMIXER

While there are many different software applications that can be used to get a design ready for printing, MeshMixer, Cura and Simplify3D were used to prepare the glove. Cura and Simplify3D are slicers, which breaks the design up into different layers for printing, seen in Figure 7. Additionally, they allow the user to select which material to use for different parts, set print speeds and temperatures, add supports, and more. To create the glove, an offset was created from the hand in MeshMixer. This created a gap between the inner and outer walls that could be filled in. Within Cura and Simplify3D, the walls were set to be printed with PVA, and the infill was set to TPU; this would mean that when the glove was done printing, it could be soaked in water to reveal the TPU that had the thickness of the offset. This was done to support the TPU, which is not as stiff as a harder polymer such as ABS and might have sagged after printing large sections. Depending on the quality of the final print, the offset could be adjusted to make the glove thicker or thinner.



View type Layer view

Color scheme Material Color

Extra Fast - 0.3mm 100% On On

CFFFP_handtest1glove

81.1 x 72.6 x 126.0 mm

3 hours 45 minutes

61g · 20.54m

Figure 7. Glove design in Cura getting ready for printing

As previously mentioned, MeshMixer can be used to create offsets, but can also be used to clean up any defiencies prior to printing. Some of the capabilities of MeshMixer include filling in holes, creating cuts, smoothing the mesh, and creating extrusions. Besides the offset feature, MeshMixer was used to cut the bottom of the hand off, which would transform the hand into a glove, due to the inside of the hand being hollow. Due to the quality of the cast and scan, there was very little clean-up work that needed to be done in MeshMixer.

D. QIDI X-PRO 3D PRINTER

When choosing what 3D printer to use, there were many factors that were considered, including cost, size, print method, and what direction the nozzle and bed move. As the AM field has grown, the availability of less expensive and smaller printers has also grown, allowing people to use 3D printers in their homes.

The Qidi X-Pro 3D printer was chosen to print the glove. This printer, seen in Figure 8, has a heated print bed that moves in the z-direction, and a dual extrusion nozzle that moves in the x/y-direction. The printer is compatible with both Cura and Simplify3D. The print bed has a removable plate, which makes removal of the finished print easy. Additionally, there are four sides of turbofans to create a better cooling effect [19].

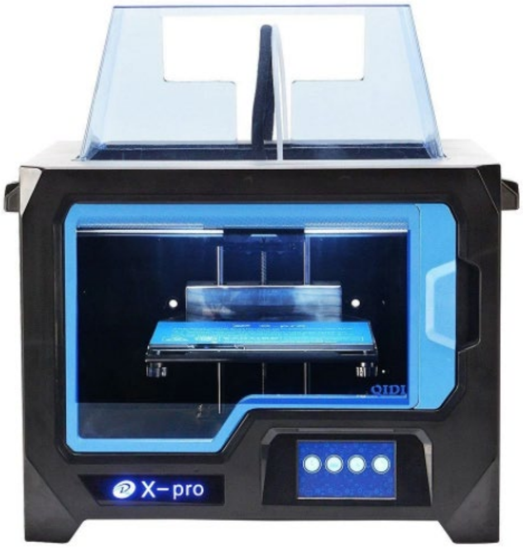


Figure 8. Qidi X-Pro printer. Source: [19].

The build plate size is 230*150 mm (8.8*5.9 in), and the overall printing size is 225*145*150 mm (8.8*5.9*5.9 in). The dual extrusion nozzles are adjustable, so different sized nozzles can be used. TPU and PVA are both relatively hard to print, so larger nozzles were put on the printer to improve flow and reduce print times by up to 5 times. The goal with the larger nozzles were to provide a more constant flow that would not bunch up and jam the print. The TPU was printed through a 0.8 mm nozzle, and the PVA was printed through a 1.0 mm nozzle.

E. PRINT SETTING

Within Cura and Simplify3D, there are many print settings that can be adjusted, such as print temperature, bed temperature, and print speed. Since the printer has dual nozzles and the print uses two different materials, it is important to input the material specific properties into the software. Initial prints were performed using only polylactic acid (PLA), which is very easy to print with. The bed temperature was set to the default 60°C, the print temperature was set to 220°C, and the print speed was set to 60 mm/s. The print temperature was on the higher end of PLA printing temperatures, however many print settings are printer dependent, and this print temperature worked with this printer.

Printing with TPU and PVA together was slightly more difficult, especially with the initial nozzle size of 0.4 mm and more settings were adjusted. TPU requires a very low print speed, and a print speed of 10 mm/s was used. The temperature was set to 220°C, and the bed temperature was reduced to 50°C. When printing with both TPU and PVA, there can only be one print bed temperature, and TPU was more affected by the bed temperature than the PVA, so the temperature was based on what worked best for the TU. PVA requires a lower print temperature of 190°C, but the print speed could be faster; it was set to 20 mm/s to keep it relatively close to TPU, even though the material can technically be printed at a faster speed. For later prints where the glove was printed out of only PLA, the bed temperature was set to 50°C, the print temperature was set to 210°C, and the print speed was set to 60 mm/s. For many materials, there is an acceptable range for print temperature and speed, and in this instance, PLA was printed with two different temperatures, but both produced decent results. Table 1 summarizes the print settings used for the various materials.

Table 1. Print settings

Material	**Bed Temperature (°C)**	**Print Temperature (°C)**	**Print speed (mm/s)**	**Nozzle Diameter (mm)**
PLA (test prints)	60	220	60	0.4
PLA (glove)	50	210	60	0.8
TPU	50	220	10	0.8
PVA	50	190	20	1.0

III. RESULTS

When working with AM, the final product is a culmination of the print preparation and the actual printing. Without the proper print preparation, it is unlikely that the final print will turn out as expected; because of this, in AM, the actual printing of the pieces only accounts for a fraction of the work, but produces the actual results.

A. TEST PRINTS

In order to gain experience with the software and printer, many simple trial prints were performed using PLA, seen in Figure 9. Initially, a simple cube was printed, and then dual-color prints were conducted to replicate the TPU and PVA. Printing with the two colors was successful, despite some offset issues. This success proved that the printer would in fact be able to print with both nozzles on the same print.

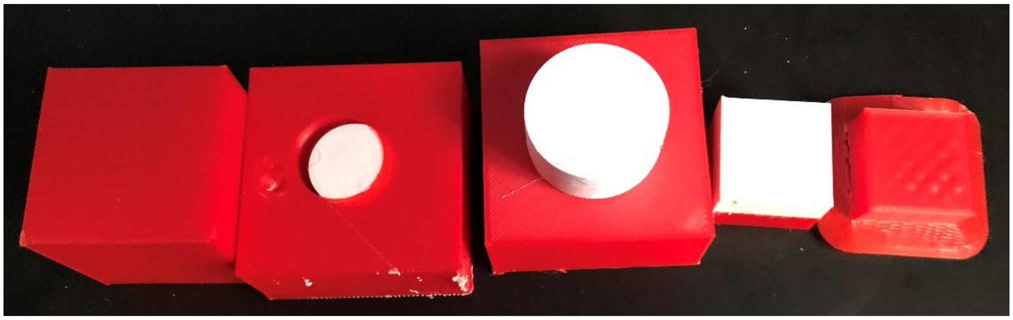


Figure 9. Practice prints with PLA

B. GLOVE PRINTS

After learning the basics of the software and printer, the hand was scanned into the computer for a test print with PLA. In an effort to speed up print time and save material, the glove was scaled to 70% for the PLA print. With the hand being more complex than a simple cube, supports were added internally, and under the thumb. The supports had little effect on the end result of the glove because for the final print, the supports would be printed with PVA, which would dissolve away in water. For the PLA print, the external supports were able to be torn away, and the internal supports could be ignored. The print resembled the hand, and there were not any holes or breaks. The glove was then scaled down to 25% for a print with TPU and PVA. A comparison of the parts can be seen in Figure 10.

Figure 10. Cast hand, 70% scale PVA print, and 25% scale TPU print

While the 25% scale print turned out decently well, there were many issues that were discovered. The print was set to print with a shell and supports in PVA and an infill of TPU. As seen in Figure 10, there was no PVA present, and the internal supports were made of TPU, not PVA. This was a result of confusion between Cura and the printer for which extruder was “Extruder 1” and which extruder was “Extruder 2.” This was a simple problem that resulted in the TPU and PVA “switching” places, which is why the supports were printed out of TPU; this problem was easy to fix and was quickly addressed. A not-so-obvious fix was the discovery that when the model was scaled down, the wall thickness was also scaled down. This means that the offset applied in MeshMixer to provide a 3mm infill of TPU was shrunk, as were the wall thicknesses. The wall thickness in Cura was set to 8mm, but when the scale was changed, the set wall thickness over-took the model dimensions for the infill, resulting in no possible infill. Combining the two problems resulted in the print only consisting of a shell of TPU, seen in the figure. To address the scaling issue, the model was scaled in MeshMixer prior to using Cura and Simplify3D.

After the initial challenges were overcome, a full-scale print with TPU and PVA was prepared in Cura. The goal for the print was to have the PVA act as an inner and outer shell to provide support, and the softer infill would be TPU. With a successful print, the PVA would be able to be dissolved away, leaving just the TPU. When it came time to print, more issues were discovered. Due to TPU's low melt flow index and rubbery texture, it frequently got tangled in the extrusion gears; this resulted in the fans needing removal, the TPU getting cut away, and more material being thread in. PVA also frequently got tangled, and due to the moisture in the air, there were times when the PVA was not able to be extruded through the nozzle. Additionally, since TPU and PVA have different print temperatures, it is important that the printer adjusts the temperature when it switches between the materials. Cura has a bug that was unknown at the time that set a constant temperature for both heads, regardless of the material. This led to many print issues, which is why Simplify3D was used for the remainder of the prints.

Using Simplify3D solved the temperature issues, and enabled the print to be completed, as seen in Figure 11. The tips of the fingers did not get printed because they exceeded the print volume. The end print did not end up perfect as evidenced by the breaks in the PVA, however it was discovered that the TPU did not require both an inner and outer shell. The strings that appear are a result of the break points, or the point on the design where the printer stops printing and changes direction. Most of these strings were from the PVA, which did not affect the final product as the PVA would be fully dissolved away. The TPU has a few strings where the PVA did not cover, as well as at the TPU break points. After this print, it was thought that the TPU strings might not be as much if only one PVA shell was used, forcing the TPU to be a wall instead of an infill. Using Simplify3D, a new file was created for this print, seen in Figure 12.

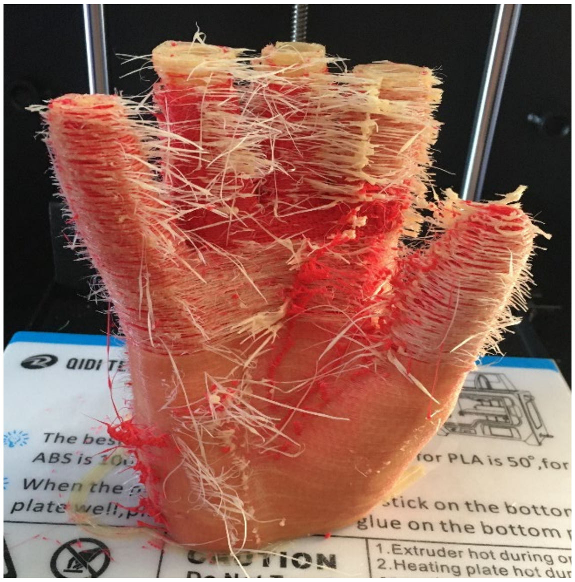


Figure 11. Full scale glove with TPU and PVA

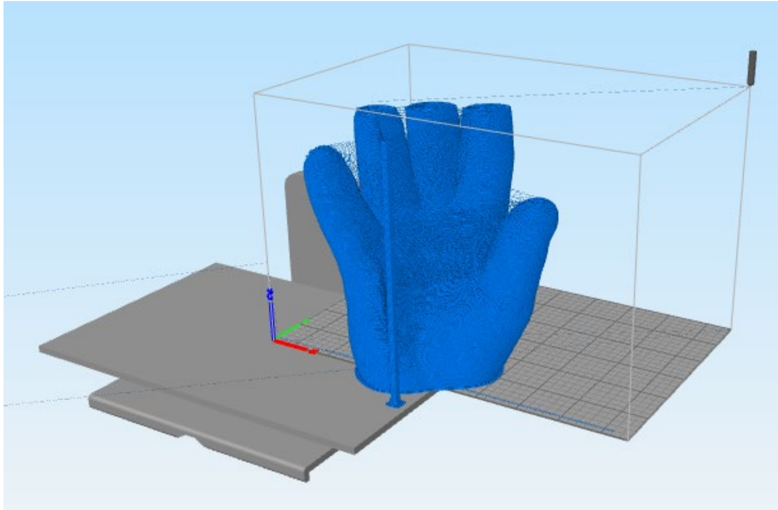


Figure 12. Simplify3D file for glove with TPU wall

Prior to printing the new glove, the PVA was dissolved from the glove in Figure 9, revealing only the TPU. This was done by simply leaving the glove in room temperature water for a few hours. Occasionally a toothbrush was used to scrub any PVA from between the fingers or anywhere else on the hand. The final result was a partial glove that fit perfectly on the hand, seen in Figure 13.

Figure 13. Partial glove with TPU after PVA dissolved away

After the PVA was dissolved, the only remaining material was the TPU. The little strings were still present, but the end product looks more final than it did with the PVA. While TPU does have elastomeric properties, it is very stiff when on the hand. Typical wetsuits use neoprene, which allows the user to maintain normal motion. With the TPU glove on, it was very hard to move the fingers and hand.

With the goal of using TPU as a solid wall instead of a zig-zag infill to try and reduce the amount of stringing and wasted materials, the new file that was generated for this model was printed. This print did not go as planned, but a lot of valuable insight was gained. When this model was in the process of printing, the PVA spool got caught on the back of the printer, which ultimately prohibited the PVA from being printed. Initially, it was thought that the TPU would need to be paired with the PVA because the TPU would not be able to support itself. After a few layers were printed without the PVA, it was observed that the TPU was supporting itself, likely due to the larger nozzle size and slow print speed, allowing it to set faster. The completed print is seen in Figure 14, which shows the PVA present at the base of the glove, but TPU being the only material for the majority of the print.

Figure 14. TPU glove with attempted PVA wall

Unlike the previous prints, this glove was printed with the fingertips, which means that the bottom portion of the glove was cut off in order to fit in the print bed height limitation. Even though the final print resembles a glove, a worry was that the print would be warped due to the high printing temperature and initial uncertainty around TPUs ability to be printed without another support material. The glove was tried on (Figure 15), and there were no deformities in the print, proving that for this model, the glove would be able to be printed using only TPU. This was beneficial because it would save the PVA material, which decreases the print time and overall cost. Printing with the PVA and TPU took upwards of 10 hours for the printing to be complete, whereas with just the TPU, the overall print time was around 4 hours. Additionally, by only needing to print with one material, Cura could be used as the slicer because the printer would not need to switch between printing temperatures.

Figure 15. TPU glove with attempted PVA wall on hand

One consistency throughout all of the printing was the stringing and blobs. In an effort to identify the cause of the stringing, PLA was used as the printing material because it is the easiest material to print compared to TPU and PVA. As seen in Figure 9, there was still stringing with the PLA. It was thought that the stringing was a result of retraction not being enabled. Retraction prevents unwanted filament from oozing out of the nozzle. This feature was disabled for previous prints due to the printing difficulty with TPU and PVA. By increasing the retraction distance, the goal was to decrease the stringing. Figure 16 compares a retraction distance of two millimeters and three millimeters. Compared with all the previous prints, it was clear that enabling retraction did help the stringing. The difference between the two millimeters and three millimeters was not as noticeable as the difference between retraction and no retraction, however the greater retraction distance resulted in less string blobs.

Two millimeter retraction (left) and three millimeter retraction (right)

Figure 16. PLA prints with retraction enabled

When investigating the little strings more closely during the printing, it was identified that the string blobs were occurring when the nozzle moved across an open area after completing a section. For example, when the thumb was done receiving its layer, the nozzle would travel back and start on the rest of the hand. The first point of contact on the rest of the hand from the thumb would result in the little blob. This is why the blobs start to appear after the thumb gap forms, where it is not possible for the printer to print in a continuous stream. While these blobs still formed on the PLA, it is expected that if printed with TPU, the retraction distances might need to be adjusted, but similar results should be expected.

C. NEOPRENE COATING

As previously mentioned, the TPU was the best available material, however it does not replicate the wetsuit material exactly. Additionally, the printed materials were porous, which negates the benefits that wetsuits provide because water is easily able to enter and exit. An Aquaseal Neoprene Contact Cement gel coating was used on the outside of the printed gloves to help decrease the porosity and to try and create a glove with a more traditional wetsuit material.

Coating was applied to the thumb of a partially printed PLA glove and a PVA finger, seen in Figure 17. A total of two coatings were applied to both pieces. The gel coating adhered like a glue, so it was not able to be removed from the PLA. For an actual wetsuit, the PLA is not a suitable material because there is no flexibility in the printed material; however, by coating with the neoprene gel, the porosity decreased by covering up any minute holes that were left after printing. This proves that the gel is capable of decreasing porosity, which could be an important step for successfully completing a wetsuit using AM.

Figure 17. PVA and PLA parts with neoprene gel coating

The neoprene gel coating was applied to a PVA finger to test how the neoprene coating would behave on its own once the PVA was dissolved away. After the coating dried on the PVA, it was placed in lukewarm water overnight to try and dissolve the PVA away. Unlike the previous attempt at dissolving the PVA from a larger portion of the glove, it was much more difficult to get the PVA out of the fingertip. Despite this, when a majority of the PVA was dissolved away, the neoprene coating was able to fit on the finger. The neoprene gel coating, seen in Figure 18, had the flexibility that is needed for a wetsuit, however the coating ended up being one millimeter thick, which is very thin for a wetsuit. A typical wetsuit is between four and five millimeters, and deep sea wetsuits can be up to eight millimeters thick. To improve the thickness on the coating, more applications of the gel coating would need to be applied. Another challenge that was noted with this coating was that it takes the exact shape of the print, so any strings or minor deformities in the prints would appear on the coated part. This problem would be easily resolved by cleaning up the printing issues, or performing minor fixes after the print before the coating was applied. As more layers are added, the deformities become less noticeable.

Figure 18. Neoprene gel coating after dissolving PVA

IV. CONCLUSION

This project was filled with challenges, from the scanner to the computer software to the actual printer. Throughout all of these challenges, a lot has been learned that will be applied to future prints.

After Cura bugs were discovered, Simplify3D was able to be used to slice all prints. It was important to use MeshMixer to "clean-up" the individual components and apply the offsets before using Simplify3D so that the end print would have the proper overlap. When printing using just one material, it was important to make sure that the spool was properly wound prior to printing, and to ensure that the flow from the nozzle was good. Since the larger prints take over a day to print, ensuring that the extrusion was working properly was very important. This was checked by printing test blocks prior to printing the larger gloves.

A cast hand was successfully scanned into the computer, and TPU, PVA, and PLA have been used to create the glove (at varying sizes). Being able to print a glove with each individual material revealed a lot, and proved to be very beneficial to the overall goal. PLA is a very easy material to print, so a lot of troubleshooting and tests were performed with the PLA. TPU most closely resembles a wetsuit, and once it was discovered that TPU could be printed without a supporting material, a lot of material was saved and the print time decreased significantly. PVA was nice because it is water soluble, so it created the perfect scaffold for the neoprene gel coating, as well as the initial prints with the TPU.

A lot more testing is needed, however, the results indicate that through a combination of the approaches and materials printed, AM can be used to produce personalized wetsuits.

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V. FUTURE WORK

One of the biggest areas for improvement is figuring out exactly what material to use. With the prints that have been completed, the TPU glove had the most elasticity, but compared to a typical neoprene wetsuit, it was relatively stiff. While this might be beneficial for the lower depths with more external pressure, more testing will need to be done. The neoprene gel coating that was applied to the PVA had the desired flexibility, but it was too thin. More work will need to be done to see if the desired thickness can be achieved by applying more layers to the coating, or if there are other alternatives.

The goal of this project was to test the feasibility of printing a customized wetsuit, however more testing will need to be done before the concept gets put into practice. A wetsuit works to trap water to insulate the body. To date, there has not been any thermal testing done to see if the materials are capable of insulating the body. Additionally, when a wetsuit is used at greater depths, the external pressure on the wetsuit increases, compressing the wetsuit material. This can be tested by printing sections of the desired material, applying the neoprene gel, and subjecting the material to a low-load compression test. The low-load compression test would simulate the external pressure, so it could be determined how the material would hold up under pressure. From these tests, further tests could be conducted to determine how the thermal properties of the wetsuit parts would change at greater depths, and if it is still able to perform its job.

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