

Review on the Development of 3D Printing Clothing

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ABSTRACT: 3D printing clothing has made a rapid emergence in recent years, which is deeply affecting the future development of clothing enterprises. However, the research on 3D printing clothing is still lacking. According to the database information of web of science, CNKI and so on at home and abroad, this paper analyzes and comments on 3D printing clothing from nine aspects, such as the trend, raw materials, production technology, equipment, price, quality, customization trend, ecosystem, etc. The research results can provide decision-making reference for the global 3D printing garment industry development, and provide trend judgment and innovative reference for the related theoretical research of 3D printing garment.

KEY WORD: 3D printing, Clothing, Customization, Business model

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3D printing clothing is a new type of clothing produced by 3D printing technology. In recent years, 3D printing clothing has been rapidly put into the market, which has attracted the attention of many clothing enterprises and consumers, and it has become an important driving force to lead the reform of the clothing industry and drive the development of intellectual economy. Under this trend, it is necessary to summarize and analyze the research and development of 3D printing clothing.

I. INTRODUCTION

In recent years, the demand for personalized customization of clothing has increased significantly, and the depth of customization has been continuously enhanced. *The State of Fashion 2018* points out that personalized clothing is becoming more and more important, and consumers are more eager to get products created according to their own needs, rather than express personal style, personal image and even values by passively recommended clothing. Clothing enterprises need to pay more attention to providing data-based customized products to create an "absolutely personalized" consumer experience^[1]. A research of Euromonitor (2018) points out that with the improvement of the values of millennial consumers, they are more willing to seek unique and personalized clothing products to reflect their values, rather than follow a homogenized style^[2]. Another research of Salesforce (2017) points out that in order to obtain more deeply customized clothing products, consumers have already more and more been will to hand over their personal information^[1]. And a survey for American and British consumers from AgilOne (2014) shows that the most of consumers look forward to personalized service, of which more than 70% of American consumers expect personalized shopping experience^[3]. "China's private customized clothing market has reached 102.2 billion yuan in 2016 and is expected to exceed 200 billion yuan in 2020," Xinhua News Agency (2017) reported.

3D printing, also called Additive Manufacturing, is a kind of rapid prototyping technology. It is based on 3D data model files, Using bonding materials such as powdered plastics or metals to construct objects by accumulating layer by layer^[4,5]. *The Economist* points out that 3D printing represents a new trend in the development of the manufacturing industry and will promote the third industrial revolution^[6]. Compared with traditional manufacturing technology, 3D printing has many advantages, such as large design space, high production flexibility, less manpower investment and so on. In particular, it can be made into assembly devices with complex structures through a single process, which is especially suitable for customized production^[7,8].

Under the above background, 3D printing technology is becoming the new favorite of clothing enterprises^[9]. Some clothing companies have begun to use 3D printing technology to customize and produce clothing. Therefore, 3D printing technology is having an important impact on the clothing industry. However, what is the current situation of the research and development of 3D printing clothing all over the world? There is still a lack of research on this issue, which needs to be comprehensively combed, so as to provide decision-making reference for the development of 3D printing clothing industry in China, and provide reference for the related research of 3D printing clothing.

II. METHODS AND DATA SOURCES

Because 3D printing clothing is a new product, the important public data about 3D printing clothing in the past comes partly from academic achievements and partly from official information on the Internet. In view of this, this paper mainly uses the way of literature reading to traverse all the relevant works. It uses Internet data as a supplement by browsing information, then extracts and integrates the viewpoints of relevant literature and information, and finally forms the research results. When searching for relevant data, this paper mainly aims at the Internet information of Web of science core database, CNKI database and some official websites as data sources. So it basically covers the important scientific research achievements and high credibility information about 3D printing clothing at home and abroad, and the data is comprehensive and reliable.

III. RESULTS AND ANALYSIS

Through the collation, analysis and induction of the relevant data and information, this paper abstracts the following research results about 3D printing clothing.

3D Printing technology provides a new direction for the development of clothing enterprises

At present, some clothing enterprises in the world have begun to apply 3D printing technology to clothing production. For example, Mon Purse customizes 3D printing handbags for customers with 3D printing technology and so on[1]. Shoe company JSshoes customizes 3D printing knitted shoes for customers, and buyers can choose their favorite design style and color to buy one shoe at a time. So it fully meets the needs of consumers who are keen to mix their own colors and styles and are at the forefront of fashion, and achieve a high degree of customization. Ministry of Supply which belongs to Ston clothing brand customizes 3D printing seamless men's jackets for customers, whose sleeves and collars are printed directly rather than sewn. And some parts have been appropriately densified or reduced, so as to make the clothes more breathable. At the same time, Knit for you uses 3D printing technology to customize the production of merino sweaters for customers and reduces the cycle time from design to launch from 12 to 18 months to 4 hours.

Generally speaking, 3D printing technology has infused new vitality into the vigorous development of clothing enterprises and provided a new development direction. So it can be predicted that 3D printing clothing will become one of the important core competitiveness of the future development of clothing enterprises.

3D Printing clothing based on different materials is gradually emerging

1. 3D clothing printed with Powdered Nylon material

Hollywood glamour actress Von Teese DITA was unveiled at Ace Hotel in the United States wearing a long black dress made from 3D printing on March 4, 2013. This dress was produced with Selective Laser Sintering and Powdered Nylon. Scottish fashion brand Pringle also showed off "laser sintered nylon cloth" using EOS Formiga P100 SLS system printers at House of Holland 2014.

2. Clothing printed with WOLFBEND TPU Material

Airwolf 3D provides designers and manufacturers with WOLFBEND TPU, a material with rubber-like properties. TPU represents Thermoplastic Polyurethane. It has many properties, including transparency, oil resistance, grease resistance and wear resistance, especially a high degree of elasticity. TPU has many applications, including automotive dashboards, casters, power tools, sporting goods, medical equipment, transmission belts, footwear, inflatable rafts and various extruded films, sheets and profiles. This material is easier to print and produce than other more popular flexible filaments in the market, and is more secure, so that there is no separation layer between 3D printing layers. At present, the colors of the material include transparent colors, red, blue, black and white. The new material costs 2 euros (\$2.60) per cubic centimeter and \$68 per roll (1 pound) (2.88mm diameter), which is more expensive than other materials. While, this is one of the few materials that allow designers to incorporate shock absorption and structural elasticity into their models, gadgets and functional objects.

3. Clothing printed with Elasto Plastic Material

Shapeways provided a white flexible material, Elasto Plastic in 2012. This material can be used to make soft items, such as clothes, decorations, etc. Elasto Plastic is a very flexible elastic rubber, which is granular and has an upper heat resistance of 90°C. High temperature may significantly change the properties of the material. When the thickness of 3D printing exceeds 5mm, it will be very strong. The test shows that its elastoplasticity can reach 19.5mm, and the error rate of the large model is about 10%. In 2013, Shapeways made improvements to Elasto Plastic to provide better options for creators. The new material has incredible durability and very high impact strength, elasticity and compressibility. Because of its special surface texture, the material also has a high level of static friction. Shapeways is currently only available to 3D printing creators to verify the performance of new products. The material is currently available on Shapeways's website and sells for between

\$0.26 and \$0.42 per cubic centimeter.

4. Clothing printed with Nylon 12 Material

The world's first fully 3D printing bikini N12 (short for Nylon 12) has been sold in bulk. The product is designed by Jenna Fizel and Mary Haung, designers of Continuum Fashion Company, and has the characteristics of durability and high flexibility. The product specifications can be customized according to the customer's body size, and then meet the needs of customers. Because Nylon 12 is naturally waterproof, the bikini is currently the only product that is comfortable in wet conditions. The product is currently available on Shapeways's website, and the right cup of a bra costs \$158.

5. Clothing printed with composites of Synthetic and Organic Materials

In June 2014, Electroloom made the first 3D printer designed to print softclothing-the "Alpha" (Alpha), a machine that uses electrospinning to automatically produce polyester and cotton blended clothing. The materials used are Composites of Synthetic and Organic Materials. Electrospinning, that is, Field Guided Fabrication, FGF, and this is where Electoloom differs from other 3D printing clothes. Figure 1 shows the development of 3D clothing made by electoloom. At present, the company is developing towards producing durable clothes from cotton printing. It is conceivable that if cotton can be directly used as a raw material for 3D printing clothing in the future, so this will promote a complete revolution in the clothing industry.



Figure 1: The development of 3D clothing made by electoloom¹

6. Clothing printed with FilaFlex Material

Israeli fashion designer Danit Peleg made a "lace-like textile" from FilaFlex material made by Recreus of Spain, and then used a \$1800 Witbox 3D printer to make these fabrics. Danit Peleg has set up a special 3D printing clothing website (<https://danitpeleg.com>), which provides some clothing styles and customization modules to choose from. After the customer has selected the product or completed the self-assembly design, the company can carry out 3D printing production for customers on demand and then deliver it to consumers through global logistics. In 2017, Peleg achieved an important industry milestone when she launched the world's first online customized 3D printing jacket Bomber Jacket, on her website, as shown in figure 3. The jacket is soft and comfortable, and sells for \$1500 each.

¹Source: Electroloom. Website: <https://www.aatcc.org/pub/aatcc-news/1215a-story1>



Figure 2: "Lace like textile fashion" made of filaflex materials²



Figure 3: 3D printing jacket named Bomber Jacket³

7. 3D Printing clothing with WillowFlex Degradable Material

Environmental protection is an important trend in the development of the times. Fashion designer Babette Sperling used WillowFlex organic fiber to print and produce a variety of clothing in 2017. This material was developed by BioInspiration in 2015, a biodegradable environmentally friendly material that can be used as compost recycling (had compost certification at industrial levels in EU and USA). This material has heat resistance and cold resistance, can maintain integrity of items above 100 degrees Celsius, can be used to print cups, also can be used to make ice cubes. Another feature of this material is that it has good elasticity and can be used to print clothes, shoes adult toys, tableware, glasses frames and so on. A 300 grams of raw material spool costs \$28 and a 500 gram spool costs \$44.

8. Printing Bio-Skin Clothing with Polyurethane Fiber Elastic Fiber using Natto Cell

Thanks to the sensitivity of natto cells to temperature, humidity and heat, BioLogic, a research group at MIT, has created a revolutionary Bio-Skin Clothing by printing natto cells in spandex elastic fibers through 3D printing technology. When heat or humidity increases, each natto cell expands rapidly to 50% of its original size so clothing made of this material automatically opens vents. Sports brand New Balance and fashion designers of the Royal Academy of Art jointly designed a sportswear with such functions in 2015. Designers introduce such materials into different parts of clothing to achieve the design of different types of ventilation. So when the athlete's body temperature rises, the special part will open the vents, and when the body temperature drops to a certain extent, the vents will be closed.

Material problem is one of the main obstacles to the rapid development of 3D printing garment industry. Hard and rigid is the impression of early 3D printing clothing, which is often only used by fashion

²Source: <https://danitpeleg.com>

³Source: <https://danitpeleg.com>

models for fashion display. However, from the above-mentioned development in recent years, a positive breakthrough has been made in this area, and a large number of 3D printing clothing products have emerged. The continuous emergence of new materials is promoting the development of 3D printing clothing in a direction that is more acceptable to consumers. Clothing enterprises must respond positively to this important trend, especially pay attention to the customization of 3D printing clothing. Put into practice in technology development, talent reserve, business model innovation and other aspects.

The production technology of 3D Printing clothing is becoming more and more perfect

1. Production with conventional 3D Printer

From the point of view of the existing 3D printing clothing, printing basically relies on the conventional 3D printer for production. These printers include Witbox 3D printers, Mammoth Stereo lithography light-cured 3D printers, Objet Connex multi-material 3D printers, EOS Formiga P100 SLS system selective laser sintering printers and so on. Alpha, a 3D printer specially made by Electroloom to print soft cloth clothing, is the world's first official clothing 3D printer. The printer has its own body-shaped abrasives, built-in a number of customer body programs, engaged in specialized 3D clothing printing production.

2. Production with 3D Printing Pen

WobbleWorks introduced the world's first pen specifically for 3D printing to the market in 2013. Two fashion designers from Hong Kong have successfully created a beautiful dress using the 3D printing pen named 3Doodler in 2015. They designed two different clothing patterns and then used PLA material to interweave the dress repeatedly with a 3D printing pen. It took a total of three months to go from fashion design and 3D modeling to adding 3D effects to dresses.

3. Production with Spray Molding

"Instant spray additive manufacturing technology" is redefining the production mode of fashion. Making clothes by spraying through a sprayer may sound like science fiction, but a Spray-on fabric technology invented by Dr. Manel Torres of Imperial College London in 2010 made it a reality. He spent 15 minutes spraying a tight T-shirt on a male model, successfully making the world's first spray-painted clothing, as shown in figure 4. This kind of clothing can be repeatedly cleaned, washed and worn, and can even be dissolved into raw materials to make new clothes. The production process of clothes is to repeatedly cross spray the fibers on the human body through 3D printing, so this kind of products are one-time molding and do not need any dressing.



Figure 4: Spray formed 3D printing clothing⁴

4. Using Cosyflex 3D Printing technology to produce intelligent clothing

A British company named Tamicare obtained a patent for 3D printing technology for textiles called Cosyflex in 2005. The patent integrated elastic materials and textile fiber technology, and produced a kind of omnidirectional retractable non-woven fabric through 3D printing technology. This fabric was mainly made of natural, completely biodegradable materials, with outstanding elongation, recovery and wrinkle resistance, reflecting great flexibility and diversity. In November 2013, Tamicare officially released the world's first 3D printing textile fabric-Cosyflex. In view of the comfort of the fabric and the low cost, the company will start

⁴Source: <http://www.fabricanltd.com>

producing disposable underwear (It only takes 3 seconds to complete). Cosyflex technology also uses a multi-stage, multi-variable 3D printing process, thus allowing unlimited fabric changes. Another important innovation of cosyflex technology is that electronic components can be directly printed into clothing. Designers no longer have to worry about "the products designed face production problems", but can carry out various designs in a more free way. This is a milestone in the development of 3D printing clothing industry.

The above diversified production processes make 3D printing clothing enterprises have more technical choices. They are beneficial for enterprises to carry out the production of 3D printing clothing with the combination of their own technology reserve, talent situation and capital investment. At the same time, they can better meet the personalized production needs of different consumers, so as to attract more clothing enterprises to join in the production of 3D printing clothing products, and promote the development of 3D printing clothing industry.

The production mode of 3D Printing clothing is constantly enriched

1. Direct printing

In 2016, Boston clothing brand Ministry of supply cooperated with 3D printer company Shima Seiki to produce a high-quality seamless men's jacket using the "world's first" 3D printer mach2xs, which can directly print large clothing in stores, as shown in Figure 5. The coat can stretch in four directions, has anti-wrinkle, moisture absorption and perspiration functions, and without any stitching, which is completely directly molded by 3D printing and retails for as little as \$345. The maximum knitting speed of the Mach2XS printer is 1.4m per second, and it takes only about 1.5 hours to print a seamless men's coat. Thursday Finest has also used 3D printing technology to print directly to produce a series of personalized Merino wool bespoke ties. In addition, what is even more exciting is that a prototype 3D printer launched by Intel in 2017 (made by Shima Seiki for \$180000 each) actually allows retailers to produce a piece of clothing in about 45 minutes. Compared with the traditional clothing production process, this speed is greatly improved. On the one hand, it can reduce the inventory of finished products, on the other hand, it can also meet the needs of customers more quickly. There is no doubt that this will greatly promote the development and growth of the 3D clothing printing industry. Besides, the Mach2XS printer basically does not produce any waste in the production process, which will save enterprises a lot of raw material costs compared with 35% of the waste in the past. At present, the main obstacle to this type of production is that a machine can only print one piece of clothing at a time, and the preparation time for printing is slightly longer than that of traditional clothing production, which reduces the production efficiency to a certain extent.



Figure 5: 3D printing men's seamless coat products by direct printing⁵

2. Compression printing

The Nervous System design studio has developed a compression printing system called Kinematics. The system combines computational geometry technology and rigid body physics theory, combines origami technique with 3D printing, and provides a method of using 3D printing technology to transform any 3D graphics into flexible structures. It can compress large objects in space through computer simulation technology (the volume of objects is usually reduced by 85%) to meet the requirements of 3D printing. Kinematics systems can also produce complex wearable devices that can be flexibly aligned with the body.

⁵Source: <https://digiday.com/events/glossy/ministry-supply-betting-big-power-3d-printing>

3. Splicing molding

At present, the vast majority of 3D printing clothing in the world are not printed completely at one time, but are basically modular printing, and then stitched together by manual participation, especially in the early 3D printing fashion. The 3D printing black dress worn by Hollywood glamour actress Von Teese DITA, the brown dress and cloak dress by Dutch designer Iris van Herpen, the Verlan dress and 3D printing dress designed by Bitonti are all spliced 3D printing clothes.

The above different types of 3D printing clothing production methods show that driven by 3D printing technology, consumer market demand, the promotion of industry and academia, 3D printing clothing production mode has developed from the early simple splicing to the following compression printing, even the most advanced direct molding. The evolution of the mode of production reflects that the application feasibility of 3D printing technology in the clothing industry is improving day by day, and it will make outstanding contributions to improve the production efficiency, product quality and personalized customization of 3D printing clothing.

Large scale production of 3D Printing clothing has become a reality

With the continuous improvement of 3D printer performance, clothing design and production procedures, the production efficiency of 3D printing clothing is improving rapidly. At present, danit Peleg's printing time for a 3D printing jacket has been shortened from 300 hours to 100 hours. And it takes about 4 hours for adidas flash store to print a finished Merino sweater. And it takes only 1.5 hours for Ministry of supply to print a man's seamless jacket. On average, Thursday best can print a tie for direct sale in 20 minutes. Surprisingly, Intel's latest 3D printing prototype can print a garment in about 45 minutes. The shortening of printing time has removed an important obstacle to the development of 3D printing clothing industry. Although it still can not achieve the production efficiency of assembly operations, but for 3D printing customized production, this speed has been able to meet the daily needs of customers. Therefore, this greatly promotes the development of 3D printing clothing industry. On the other hand, production capacity has been an important obstacle to the industrialization of 3D technology. Subject to this obstacle, clothing 3D printing still exists this problem. However, there have been some delightful changes in recent years. British Tamicare's Cosyflex textile 3D printing technology has achieved low-cost, high-density production, which can print the finished product in just "a few seconds". In November 2015, the company's first production line with an annual capacity of 3 million pieces has been officially put into operation, realizing 3D printing technology for the first time in large-scale textile production, greatly increasing the large-scale production capacity of 3D printing clothing.

In the process of marketization of 3D printing clothing, small batch production has always been an important obstacle to its cost control. The above technological development can undoubtedly speed up the process of large-scale industrialization of 3D printing clothing. It can be predicted that more and more clothing enterprises can use 3D printing technology for mass customization production, so as to reduce the cost of 3D printing clothing through a certain degree of large-scale production.

The price of 3D Printing clothing is gradually decreasing, and the quality is getting better and better

In recent years, with the technological progress of 3D printing clothing raw materials and the improvement of 3D printing production efficiency, the price of 3D printing clothing products has shown a gradual decreased trend that the emergence of a lot of goods that ordinary consumers can afford to consume. For example, 3D printing knitted shoes made by JShoe sell for \$89 per pair and 3D printing men's jackets sold by Ministry of Supply sell for \$345 per pair, while 3D printing sweaters sold by Adidas sell for \$215 per pair. The decline in price has played a great role in promoting the development of 3D printing clothing industry. On the other hand, with the progress of 3D printing clothing raw materials and the improvement of 3D printer accuracy and color expression, the quality of 3D printing clothing is getting better and better. As far as the mainstream 3d printers in the world are concerned, the color resolution of objet connex 500 is up to 600 DPI on X axis, 600 DPI on Y axis and 1600 DPI on Z axis with accuracy of 0.1 mm, while the highest accuracy of EOS formiga P110 is 0.06mm. These data have proved that 3D printing clothing can have good performance. In addition, 3D printing clothing has made a good breakthrough in comfort, using Powdered nylon、WOLFBEND TPU/Rubber-like、Elasto Plastic、Nylon 12、Composites of synthetic and organic materials and FilaFlex has covered a variety of types from soft underwear to comfortable coat, many of which have been fully sold in the market.

The price and potential of clothing products are important factors affecting the development of clothing enterprises. When 3D printing clothing has made positive progress in these two aspects, consumer demand for 3D printing clothing is likely to achieve explosive growth, which undoubtedly provides an important driving force for the development of 3D clothing industry.

The customized garment demand of 3D Printing clothing is strong, and the profit of single product is rich

"Personalized customization" has become an important trend of global economic development. In this context, clothing customization is also an inevitable trend of the times[10]. Foreign brands Fendi, Gucci, Burberry, Ralph Lauren, Uniqlo and Nike have all launched their own customized services. In China, well-known brands such as good Saint Angelo, Red-collar group, Baiyuejiayi, YBREN, HUAFU TOP DYED MELANGE YARN CO., LTD, Lafeng customization and other well-known brands are also making great efforts to develop clothing customization business. There are two main driving forces that drive these enterprises to develop clothing customization business. First, the market demand is strong. Take the Chinese market as an example, the space size of China's mass clothing customization market in 2016 is 102.2 billion yuan, and it is expected to reach 200 billion yuan in 2020. According to a survey from Taobao, 63.6% of Mobile Taobao's active users are willing to customize their clothes[11]. Second, individual products are highly profitable. For personalized customized clothing, consumers are more willing to pay higher prices than ordinary goods[12].

As 3D printing technology has more personalized production and design advantages in the process of clothing customization, it can be predicted that the customization demand of 3D printing clothing will be increasing. In addition, in view of the fact that the custom clothing produced by 3D printing has a higher technological content than the conventional custom clothing, it will also have a higher profit margin. In the future, clothing enterprises can use 3D printing clothing as a new source of profit.

The market has not yet formed a business model ecosystem of 3D Printing clothing industry

From the development of 3D printing clothing industry in recent years, although all kinds of 3D printing clothing products continue to emerge and the performance of these products continues to improve, until now, it has not formed a business model ecosystem based on the industry chain yet. At present, we only see the 3D printing clothing products displayed by individual designers, and individual designers have set up 3D printing clothing customization websites, and individual clothing companies carry out 3D printing services. However, these business forms have not formed a systematic business model covering partners, sales channels, sources of income, cost structure, value proposition, information transmission and other elements, which will hinder the market-oriented development of 3D printing clothing enterprises and industries.

IV. CONCLUSION AND PROSPECT

In this paper, 3D printing clothing is reviewed from the aspects of 3D printing clothing raw materials, 3D printing clothing production technology, 3D printing production mode, 3D printing clothing price, 3D printing clothing quality, the customization trend of 3D printing clothing, 3D printing clothing industry business model ecosystem and so on. It is found that 3D printing technology provides a new direction for the development of traditional clothing enterprises. Based on all kinds of 3D printing clothing with different materials have emerged one after another, the production technology of 3D printing clothing is becoming more and more perfect, the production mode of 3D printing clothing is becoming more and more abundant, and the large-scale production of 3D printing clothing has become a reality. the price of 3D printing clothing is gradually reduced and the quality is getting better and better. the demand for customized clothing of 3D printing clothing is strong and the profit is huge, so it is imperative for 3D printing clothing enterprises to carry out business model innovation.

In this study, the conventional literature reading method is selected to carry out the review research, and this method is insufficient in the visualization effect. For this reason, with the increase of 3D printing clothing-related literature information, we will further use scientific metrology and other visualization methods to deepen the relevant research in this paper. In addition, in view of the huge impact of 3D printing on the traditional business model of garment enterprises, we will also try to make a special study on this issue in the follow-up research.

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