Research on Flexible Capacitive Sensors for Smart Textiles

Yang Wang
School of Materials Design and Engineering
Beijing Institute of Fashion Technology
Wangyang@bift.edu.cn

Abstract. Smart textiles are a new era of smart textiles that not only have traditional textile functions, but also have information collection, feedback, and multiple intelligent interaction functions with users. As a manifestation of the combination of art and technology in the textile field, smart textiles are of great significance to traditional textiles, clothing, home textiles, and wearable devices. From the perspectives of the background, technology, and development prospects of smart textiles, this article systematically analyses the application technology of smart textiles in practice. Starting from the current state of smart textile research, the article explains the promotion of new material technology to the research of smart textiles. Focus on the technical improvement of capacitive sensing equipment based on flexible fabrics, and find a sensing fabric structure with lower hysteresis, fast response time, good repeatability and stability through design experiments.

1. Introduction
Smart textiles have been a hot research field in the world textile industry in recent years. With the research and development of new textile materials, they have gradually attracted the attention of academia and industry. Constrained by the cost of new materials and the immaturity of related supporting technologies in China, there is little exploration and application research in this field. The rapid development of smart textiles is inseparable from advances in many fields such as electronics, nanotechnology, bionics, and materials science and technology. At the same time, smart fabrics, wearable technologies, and smart fibers have brought more humane and practical product performance with the continuous advancement of technology in this field, which has also become the focus of the fashion industry. As a medium for information transmission, various strain sensors, such as piezoresistive, piezoelectric, and capacitive sensors, are indispensable components of wearable devices and have been widely used in human motion monitoring and health care. Textile-based sensors use fabric as a dielectric or electrode, and the flexibility of the fabric can be used to give the entire sensor flexibility. Among them, capacitive pressure sensors based on fibers or textiles have been extensively researched in academia. This paper combs the development history of smart textile technology, focuses on the realization of capacitive sensing devices based on flexible fabrics based on wearable technology, and focuses on flexible fabric-based capacitive sensing devices. The wearable capacitive pressure sensing equipment is improved, the capacitive pressure sensor model is constructed, and the working principle of the sensor is analysed using mathematical formulas.

2. Current research and application status of smart textiles at home and abroad
Smart textiles usually refer to textiles that have a triple functional mechanism of perception, feedback, and reaction at the same time. That is to say, it can simulate the life system, after sensing the change of
the external environment or internal state, through the feedback mechanism, it can actively or passively make real-time corresponding control responses.

![Feedback mechanism diagram](image)

Figure 1: The functional mechanism of smart textiles

In 1996, Georgia Tech scholars took the lead in the research and application of smart textiles in the military field, and created a new smart clothing by implanting optical fiber and conductive fiber technology into products. The smart fabric clothing uses the photoelectric textile products provided by the wearable Motherboard™, which can collect the wearer's body data, transmit the data sent by the sensor to the gateway, use integrated monitoring software to summarize the data, summarize the health advice and send it to the user.[1] The platform constitutes a multifunctional framework integrating sensing, monitoring and information processing equipment, and can be applied to the fields of biomedical monitoring and smart wearables.[2]

![Development of smart textiles diagram](image)

Figure 2: The development of smart textiles

Google and American clothing brand Levi's have developed a pair of jeans compatible with smartphones, MP3, iPod and other products in the smart fabric research (Figure 2). Through the user's touch on the fabric, the product can directly control multimedia devices, such as switching songs or pausing/playing and volume control. This product can support most iPod products on the market.[3]

In recent years, many domestic fiber manufacturers have achieved technological breakthroughs, laying a solid raw material foundation for the development of smart textiles from the fiber perspective, and have successively completed conductive meta-aramid smart fibers, phase-change energy storage viscose smart fibers, and copper series Development of polyacrylonitrile-based conductive fibers, intelligent temperature-regulating regenerated cellulose fibers and other products.[4] The copper-based polyacrylonitrile-based conductive fiber produced by Changshu Xiangying Special Fiber Co., Ltd. uses copper ions to build a conductive network in the fiber, [5] and is prepared by using durable polyacrylonitrile fiber surface conductive layer structure control technology. The fiber has good properties [6]. Electrical conductivity and antibacterial properties, as well as good air permeability and wrinkle resistance, have great advantages in the application of anti-static clothing, electromagnetic shielding textiles and sensing materials. The photochromic regenerated cellulose fiber launched by Xinxiang Chemical Fiber Co., Ltd. uses nano-level materials and uses online addition technology to
solve the problem of difficult and uneven dyeing of regenerated cellulose fibers [7]. In terms of preparation technology, it uses a special photochromic agent, blends it with the textile stock solution, and uses wet spinning to prepare photochromic regenerated cellulose fiber. The product is skin-friendly, soft and has a unique luster. At the same time, it is sensitive to light and has a bright luster [8]. It can absorb ultraviolet rays and has a protective effect. It does not need to be dyed. It solves the secondary pollution of product processing from the manufacturing source [9].

3. Smart textiles based on new materials and new preparation technologies

3.1. New materials and new technologies

In recent years, smart fibers based on natural fibers and synthetic fibers have continued to develop towards electro-activation, such as thermochromic yarns and energy harvesting fibers based on silk, or conductive fibers based on nylon and polyester, which have effectively promoted the development of smart textiles.

The existing preparation process of smart textiles is mainly based on electroplating and electroless plating. Because smart fabrics have multiple load-bearing functions and require high reliability, and vacuum coating technology is difficult to obtain thicker coatings, because there is no better technological innovation, the application of smart materials is limited by the shortcomings of physical coating technology [10]. The combination of electroplating and electroless plating has become a compromise solution to this problem. Generally, when fabrics with conductive properties are prepared, conductive fibers made by electroless plating are first used to weave the fabric. The fabric coating prepared by this technology is more uniform than the fabric obtained by direct electroplating technology. In addition, conductive yarns can be blended with ordinary fibers in proportion to reduce costs on the basis of ensuring functions.

3.1.1. Fiber coating technology

At present, the biggest problem with fiber coating technology is the bonding strength and firmness of the coating. In practical applications, fabrics need to undergo various conditions such as washing, folding, kneading, etc. [11] Therefore, excellent conductive fibers need to be tested for durability, which also puts forward higher requirements on the preparation process and the adhesion of the coating. If the quality of the coating is not good, it will cause the coating to crack and fall off in actual application. This puts forward very high requirements for the application of electroplating technology on fiber fabrics.

![Figure 3 Fiber coating technology](image)
3.1.2. Microelectronics printing technology
In recent years, microelectronic printing technology has gradually demonstrated its technical advantages in the development of smart fabrics. This technology can use printing equipment to accurately deposit conductive ink on a substrate, thereby manufacturing highly customizable electronic products on demand. Although microelectronic printing can quickly prototype electronic products with various functions on various substrates, and has the potential of low cost, short cycle and high customization, the cost of this technology is still relatively high at this stage.

3.1.3. Conductive hydrogel technology
The conductive hydrogel technology also shows its unique advantages in the preparation of smart fabrics. Combining conductivity and flexibility, conductive hydrogels can mimic the mechanical and sensory functions of human skin. In the past few decades, they have attracted great attention in the fields of wearable devices, implantable biosensors, and artificial skin. Due to the formation of the conductive network, the hydrogel has fast electron transfer and enhanced mechanical properties. As a conductive polymer with adjustable conductivity, polyaniline can use phytic acid and polyelectrolyte as dopants to make various types of conductive hydrogels. Despite its satisfactory electrical conductivity, its relatively weak and brittle network severely hinders its practical application. Therefore, its practical application has yet to be developed.

3.2. Research and development of smart textiles
With the development of smart textiles, the growing demand for multifunctional textiles requires a strong multidisciplinary approach and the integration of traditional scientific disciplines. By changing the surface properties of textiles, a variety of textiles with different functions can be obtained, which provides the possibility for the development of functional textiles for special purposes.

3.2.1. Shape memory textiles
Shape memory textiles introduce materials with shape memory functions into textiles through weaving and finishing, so that textiles have shape memory properties (Figure 3). The product can be restored to its original shape by some means after any deformation, just like the memory metal. When it reaches certain conditions, it can adjust its shape to the original.

Figure 4 Conceptual model of shape memory textiles

Shape memory polymer textile products mainly include cotton, silk, woolen fabric and hydrogel fabric shape memory finishing. A shape memory textile developed by the Hong Kong Polytechnic University is made of cotton and linen, which can quickly recover smooth and firm after being heated, and has good moisture absorption, will not change color after long-term use, and is chemically resistant. Products with functional requirements such as insulation, heat resistance, moisture permeability, air permeability, and impact resistance are the main application platforms for shape memory textiles. At the same time, in the field of fashion consumer goods, shape memory materials
have also become excellent materials for expressing design language in the hands of designers, giving more products a unique expressive effect.

3.2.2. Modular technical textiles
The fabric prepared by integrating electronic components into textiles through modular technology is the technologically optimal solution that smart fabrics can now achieve. Google is committed to achieving the modular application of smart fabrics through the "Project Jacquard" project. Laurent, Adidas and other brands have cooperated to launch a variety of smart fabric products for different consumer groups.

3.2.3. Electronic intelligent information textiles
In recent years, the main research focus of multifunctional textiles has been to optimize materials and structures. The first important aspect is the preparation of high-performance conductive fibers. However, a lot of research work needs to be done in the preparation process and structure optimization. The second focus is the coating of active substances on textiles. By implanting flexible microelectronic components and sensors in the fabric, it is possible to prepare electronic information intelligent textiles. Therefore, research and manufacture of strain sensors with high stretch and high sensitivity will be an important research direction for smart multifunctional textiles.

4. Research on pressure sensing equipment based on flexible textiles

4.1. Flexible sensor model design
Flexible wearable electronic devices are smart devices that can detect external (physical and environmental) signals and can respond to them. When dry, the dielectric layer has no free electrons and conductive ions, which is a good medium for capacitors. For parallel plate capacitors, the capacitance is proportional to the effective area between the electrode plates and the relative permittivity of the dielectric, and inversely proportional to the distance between the plates. According to the working principle, capacitive sensors can be divided into three categories: Pitch variable capacitors, area variable capacitors, and dielectric variable capacitors. This article uses a variable-pole-pitch capacitor with a fixed parallel plate area.

4.2. Experimental process design

4.2.1. Fabric thickness pressure test
Use the ALJ-50HB pressure tester to measure the thickness of the fabric. The sample is placed between two glass slides. The contact area between the glass slide and the sample is 10 cm². The sample is slowly compressed, and the pressure and thickness are displayed in real time from the
display terminal. Each sample was measured three times at different locations to find the average and standard deviation.

4.2.2. Fabric capacitance pressure test
Choose three pieces of fabric for capacitance-pressure test. The fabric is woven under standard laboratory conditions. The warp yarn undergoes warping and sizing processes, and the PVA slurry is applied to the surface of the carbon fiber to make it have good abrasion resistance. In the later test, the coated PVA slurry played a role in preventing the carbon fiber from dispersing during the working process, so as to make the shape stability or the integrity of the sensor under pressure deformation. During the treatment process, a thin layer of conductive Graphite-33 is brushed on the surface of the PVA slurry to electromagnetically shield the carbon fiber bundles. The coating layer on the carbon fiber bundle has a good shielding effect on the electrode and is not affected by the outside world. In the capacitance-pressure test, the wires of the capacitance tester are connected to the carbon fibers of the warp and weft respectively. The fabric is placed between two compression instruments, the diameter of which is 2 cm. During compression, the ever-changing capacitance value is recorded through the development board chip and corresponding software.

4.3. Sensor principle analysis
For capacitive pressure sensors, the initial capacitance is shown in formula (1):

$$C_0 = \frac{\varepsilon_0 \varepsilon_r A}{d_0}$$  \hspace{1cm} (1)

Among them, $C_0$ represents the initial capacitance (F), $\varepsilon_0$ represents the vacuum dielectric constant, 8.85x10^-12 F/m, $\varepsilon_r$ represents the relative dielectric constant of the medium between the plates, and $A$ represents the effective area of the plates (m^2), $d_0$ represents the initial spacing between the plates. Under the action of force, the capacitance of the capacitive sensor changes. Because of the polyester yarn dielectric between the carbon fibers, the pressure cannot make the strain of the sensor reach 100%, that is, $\Delta d/d_0 < 1$. When the pressure applied to the sensor is greater, the distance between the plates is smaller, and the capacitance of the capacitor is greater. In this paper, the relative capacitance change rate uses a first-order exponential model (see formula 2), and the relationship between distance and force uses a cubic root model (see formula 3)

$$\frac{\Delta C}{C_0} = \frac{\Delta C_{\text{max}}}{C_0} \left(1 - e^{-\left(P/P_c\right)}\right)$$ \hspace{1cm} (2)

$$d' = d_0 - \frac{\sqrt[3]{\sigma P}}{P}$$ \hspace{1cm} (3)

Among them, $\Delta C_{\text{max}}$ represents the maximum capacitance change value of the sensor, $P$ is the applied pressure, and $P_c$ is the characteristic pressure when the capacitance change reaches the maximum value. $d_0$ is the original thickness of the sensor, $d'$ is the thickness of the sensor under pressure $P$. The $\sigma$ is based on the fit factor of the fiber material and fabric structure.

4.4. Experimental phenomena
This paper constructs a fiber capacitive pressure sensor model based on the structure of carbon fiber fabric, using 150D/48F PET FDY (PF) and 3K carbon fiber bundle (CF) as warp yarns, and 150D/48F PET DTY yarn (PD) and 3K carbon fiber bundle as weft yarns. Test fabric sensors with a variety of textile structures, showing mechanical robustness and flexibility under various deformations (such as folding, twisting, stretching, etc.), and test whether the capacitance structure is stable and whether the capacitance parameters are stable during the entire sensor deformation process Changes with the stretching or macro-folding of the sensor.

5. Conclusions and prospects
Smart textiles have huge development potential and application requirements in the fields of protection, sports, medical care, and military. The development of sensor technology based on flexible
fabrics has not only driven the clothing and textile industry, but also promoted the development of computers, electronics, chemicals, materials and other fields.

This paper combs the development process of smart textiles, focuses on the development prospects of wearable technology in the field of smart textiles, designs a capacitive sensor test process based on flexible fabrics, and tests fabrics of various structures in order to obtain a more ideal, A flexible fabric-based sensor structure with high sensitivity and excellent application pressure range. In the later stage, the sensor’s sensitivity, hysteresis, response time, repeatability, stability and several important parameters will be tested, and the fabric will show mechanical robustness and mechanical robustness under various deformations (such as folding, twisting, stretching, etc.). Flexibility, design a sensor fabric with low hysteresis, fast response time, good repeatability and stability.

References
[1] Xu Fan, Wang Gaoyuan, Zhao Jing. The development of smart textiles and clothing [J]. Progress in Textile Science and Technology, 2013 (5): 1-5.
[2] Zhang Guanglei, Du Yanliang. Intelligent materials and structural systems [M]. Beijing: Peking University Press, 2010.
[3] Huang He, Yan Haojing. Smart textiles [J]. Printing and Dyeing, 2005, 31(7): 47-49.
[4] Liu Renzhi. Smart fabric and electroplating technology [C]. 2011 National Electronic Plating and Surface Treatment Academic Exchange Conference. Proceedings of the 2011 National Conference on Electronic Plating and Surface Treatment. China: Shanghai, 2011: 40-43.
[5] Ye Hui, Li Dongping, Xia Zhilin. Development and application of silver-plated fiber [J]. Textile Herald, 2006 (6): 54-56+94.
[6] Xu Fan, Wang Gaoyuan, Zhao Jing. Development of Smart Textiles and Clothing [J]. Progress in Textile Science and Technology, 2013 (5): 1-5.
[7] Su Xuzhong, Liu Zhongyu, Xie Chunping, Zhao Qijun, Wang Xiaolan. The development and application of shape memory fibers [J]. Textile Herald, 2012 (10): 70-71.
[8] Chen Dong. "Shape memory textile" was successfully developed in Hong Kong recently [J]. Functional Material Information, 2004 (3): 69.
[9] Leitch, Jiang Hong, Chi Kedong, Zhao Shuqing. New materials in the new millennium-interactive textiles (2) [J]. Textile Technology Abroad, 2000 (11): 8-11.
[10] Yin Bo. Research status and development trend of smart textiles [J]. Textile Report, 2017 (7): 39-42.
[11] Luo Yifeng. The latest development of functional fibers and smart textiles [J]. High-tech Fiber and Application, 2019, 44 (01): 1-17.