Advances in Textile-Based Flexible Temperature Sensors

Y M Gu
Shanghai University of Engineering Science, 333 Longteng Road, Songjiang District, Shanghai, China

Abstract. In recent years, smart clothing, as a hot spot in the current research field, is booming, but mainly because it requires a strong interdisciplinarity, most still adopt the method of attaching sensitive components, and it cannot be called smart clothing in the true sense. This paper introduces the application and development of flexible materials in the development of smart temperature-sensitive clothing from two perspectives: fiber and non-fiber materials, and pointed out the use of fiber characteristics instead of sensitive components as a future research direction to achieve smart clothing monitoring.

1. Introduction
In today's society, along with lifestyle changes and increasing social pressure, health issues have become a hot spot of social focus. Under the busy rhythm of life, it is increasingly difficult for people to take time to pay attention to their own health, and physical changes are a slow and long-term process. As a result, regular medical check-ups have become an important part of ensuring good health. But often people find it difficult to get away from the rush of the day, so it is vital to enable health monitoring in the living or home environment. By continually sensing changes in a user's body temperature, there is an opportunity to prevent more dire situations before they become critical. Based on non-invasive, wearable, flexible temperature sensors that provide a more efficient and cost-effective solution for remote health monitoring, while clothing1. As the medium most closely in contact with the human body for a long period of time, comfortable, convenient and easy to move, it is the best platform for realizing human signal acquisition. It is also the perfect vehicle for sensor bonding.

2. Temperature sensors based on non-fibrous materials
There are three main states of non-fibrous smart garment materials: three-dimensional block, two-dimensional thin film and quasi-zero-dimensional nano-powder. Three-dimensional block smart garments basically take components directly attached to the garment, difficult to truly achieve the purpose of flexible wear. Our main focus is on flexible sensors for temperature sensing in the form of thin films.

Harada2 et al. proposed a new method based on printed poly(3,4-ethylenedioxythiophene)-poly(styrene sulfonate) (PEDOT:PSS) - a flexible temperature sensor of carbon nano-tube composite film with an operating temperature range of 21°C to 80°C. The sensitivity of the device is in the range of 0.25-0.63%. More than just temperature sensing by means of printed conductive thin films alone, 2009, Bielska S3 et al. The new generation of resistive contacts based on gold-plated copper and polymer pastes is based on polyamide foil "KAPTON®" as the base material. textronic temperature sensors and verified their performance in terms of temperature, while ensuring the flexibility of the sensor and its compatibility with the textronic application compatibility, temperature monitoring was achieved through flexible substrates. In the same year, in his PhD thesis, M.Z Meng4 investigated two
types of flexible substrate materials, palirin and polyimide. Based on the unique properties of
the flexible silicon-based film, the MEMS devices on the film are sewn directly onto the fabric with this
fiber, so that since the fibers could serve two purposes: sewing a flexible silicon-based film onto the
fabric, enabling MEMS devices to be embedded in the garment. Secondly, the electrical signal
generated by the MEMS device is drawn out to the external processing circuit, which enables the
MEMS device to be connected to the external processing circuit. Electrical interconnection, also a
measurement of physiological signals by means of a combination of flexible wires and thin films.

Based on thin film-like sensing materials, Zysset C\textsuperscript{5} et al. in 2010 proposed and demonstrated a
Technology that integrates electronic functionality at the level of the textile yarn. Building on the
previous thin-film approach to sensing, thin-film devices, interconnects and contact pads are patterned
and silicon-based integrated circuits are connected to the on flexible plastic substrates. The substrate is
then cut into electronic fibers (e-fibers), which are then woven into smart textiles using a commercial
loom.

Coincidentally, the following year, T. Kinkeldei\textsuperscript{6} et al. developed a flexible polymer foil consisting
of temperature and humidity sensors in a flexible polymer foil. Sensor systems for integration into
textiles by making flexible sensors, cutting sensor strips and weaving them into the fabric of
commercial belt looms. The system can measure humidity and temperature, with ADC readings
directly in conjunction with the strip, which will allow data from multiple sensors only. From a
conductive line is transmitted, which is a further advancement compared to the previous one.

In 2017, Giuseppe Rosace\textsuperscript{7} et al. designed and fabricated new multi-walled carbon nanotubes
(MWCNTs) conductive cotton fabrics, A preparation process for introducing conductive composite
coating into the treated fabric. In fact, this work demonstrates the design and application of
nanostructured coatings based on MWCNTs on cotton fabrics, as well as its as a successful application
of a dual-function sensitive system for humidity and temperature, the purpose of simultaneous
temperature and humidity measurement has been successfully achieved.

3. Fiber-based temperature sensors

Compared to flexible temperature sensors based on non-fibrous materials, the fibers are able to bond
better with the fabric and maintain better fabric properties, making the wearer more comfortable and
reducing physical and psychological rejection.

3.1. Conductive fiber

Conductive fiber\textsuperscript{8} means that under standard conditions (20°C, 65% relative humidity), the specific
resistance is less than 1×10\textsuperscript{7}Ω-cm. The fibers are made from a variety of fibers and have excellent
conductive properties that eliminate static electricity, absorb electromagnetism and detect the
transmission of electrical signals. Fabrics made by knitting or weaving instead of conventional yarns
with conductive yarns have the ability to be woven in a variety of ways depending on external
influences. The function of strain generation under this basis can be used as the conduction part of
flexible sensors in smart clothing. Conductive fibers are often divided into four main categories:
metallic conductive fibers, carbon black conductive fibers, conductive polymeric fibers, and metal
compound-based conductive fibers.

Based on the study of the sensing properties of conductive yarns, many other scholars, have
proposed a flexible temperature sensor based on conductive yarns. Chen W\textsuperscript{9} et al. proposed and
demonstrated the design of a non-invasive neonatal temperature monitoring system(Figure 1). Conductive fibers were used to make the sensor integration and wearable noninvasive monitoring
platform compatible, and a soft bamboo fabric was prototyped as a soft Belt with integrated NTC
sensor for temperature monitoring. NTC Mon-A-Therm 90045 The temperature sensor (2mm x 3mm)
is mounted in the belt and the prototype belt is made of Shieldex\textsuperscript{®} silver-plated nylon yarn(Figure 2).
Made of soft conductive textile threads with no hard wires.
In addition, building a sensing circuit through conductive yarns is also a good means to achieve temperature sensing. In his dissertation, L. Li\textsuperscript{10} designed a flexible woven resistance temperature sensor composed of conductive fibers, and established an equivalent circuit model of a parallel temperature sensor and a series temperature sensor. The weft wire is made of conductive fiber and the warp wire is made of insulating fiber. The electrical connection of the weft wires can be in parallel or in series.

3.2. Carbon based fiber
Low-dimensional carbon nanomaterials are commonly referred to as 0-D, 1-D and 2-D carbon isomers. Their nanometric assemblies also include carbon black and graphite particles. Representatively, in the wearable environment, they are 0-D CB, 1-D CNTs, and 2-D Graphene. 0-D carbon materials also include carbon nanofibers and carbon nanotubes, but they are rarely used in wearable devices due to doubts about safety. Among other things, integrating a temperature sensor\textsuperscript{11} into a wearable electronic system requires good scalability, based on carbon materials such as graphene or (carbon nanotubes), organic semiconductors and nanocomposites can be used to develop flexible and scalable temperature sensors.

The first is a zero-dimensional carbon isotope carbon black, X. Wu\textsuperscript{12} et al. with negatively charged CB, CNC/NR nanocomposites with positively charged CS as the substrate A dielectric, ultra-thin, conductive CPC layer is applied to the surface of the PU yarn. By coating polyurethane (PU) yarns with an ultra-thin, flexible and robust conductive polymer consisting of carbon black and natural rubber. Composite (CPC) layer to fabricate high sensitivity strain transducers (Figure 3).

More widely used are carbon nanotube fibers, for example, Dinh\textsuperscript{13} et al. have developed a carbon nanotube fiber with a negative temperature resistance coefficient (NTC) carbon nanotube thermistor, which decreases the resistance of the carbon nanotube yarn as the temperature increases. The temperature sensor was integrated with a cellulose paper substrate to make a wearable, portable temperature sensor. This temperature sensor showed an approximately linear change in resistance over the range of 25 to 80 °C, and even in cyclic tests, no degradation.
carbon nanotubes with other polymers to prepare polymer/Carbon nanotube (CNT) composite monofilaments were used and tested for sensing activity. The results showed that CPC-PLA/4% CNT monofilament fabric was sensitive to moisture, CPC-PP/PCL/4 CNT monofilament fabrics are sensitive to temperature changes.

The fiber can be modified for temperature conduction by coating outside the fiber, as reported by Chao Ye et al. A fiber, called CSFS, is constructed through a scalable dip-coating strategy in which the natural silk fiber is made from a specially formulated type of hexafluorine. CSF e-textiles were also shown to be sensitive to temperature changes caused by thermal expansion and contraction of the carbon nanotube coating. Under far-infrared illumination, the temperature of the e-textile pattern increased rapidly from 25 to 63.6 degrees Celsius in 30 seconds. Due to thermal expansion and contraction, the resistance of the e-textiles varied with temperature. Repeated cycles between temperature and resistance were detected in the temperature range of 30°C to 65°C.

3.3. Temperature-sensitive fiber
Temperature-sensitive fiber refers to the fiber properties, shape, color, etc., when the temperature changes, then a sensitive response and reversible changes in the fibers. By converting this change into an electrical signal, it is possible to measure temperature changes.

Temperature-sensitive fibers can be modified into special fibers that are more sensitive to temperature by encapsulating thermosensitive resistors into a polymer. This is how Pasindu L et al. encapsulated thermistors into polymer resin microcartridges, which were then embedded into the yarn (Figure 4). A temperature-sensitive yarn is made from the fibers. A fine yarn design was explored and its accuracy in making absolute temperature measurements was characterized.

![Figure 4. A photograph of the textile thermograph.](image)

There are also patents that construct temperature sensors through temperature-sensitive fibers, and in 2017 Donghua University applied for a knitted structure flexible Stretchable temperature sensor (Figure 5). The substrate is a knitted fabric, and temperature-sensitive fibers are integrated into the substrate through knitting technology. The temperature-sensitive fibers are integrated into the knitted fabric in the form of three-dimensional stitches by warp-knitting or weft-knitting technology.

![Figure 5. Temperature sensitive fibers can be woven into the fabric in various ways to achieve temperature sensing.](image)
Based on the above-mentioned patent, Shanghai Kaitai Instrument Co. selected metal fiber platinum wire (diameter: 20 μm), using its own The property of electrical resistance changing with temperature is used as a temperature-sensitive fiber. The temperature sensor of the woven structure has a temperature coefficient of 0.0036°C⁻¹, which is consistent with the sensitivity of ordinary platinum wires. The sensing unit is only 5mmx8mm, and the platinum wire is fine enough and soft enough not to affect the appearance of the fabric and the comfort of wearing, and it retains the breathable and washable characteristics of the fabric, making it ideal for real-time monitoring of body temperature. Temperature, the purpose of simultaneous temperature and humidity measurement has been successfully achieved.

In summary, flexible temperature sensors can be divided into the following categories (Table 1).

| Classification          | Method                                                                 | Main feature                                                                 |
|-------------------------|------------------------------------------------------------------------|------------------------------------------------------------------------------|
| Non-fibrous materials   | Conductive thin film can be printed on a textile substrate, or conductive flexible substrate may be employed | The technology is relatively mature, but temperature sensing is not achieved in a true textile way |
| Conductive fiber        | With its own conductive properties, conductive fibers achieve the purpose of testing and sensing through different materials and weaving methods | No additional processing of the fiber is required, but the sensitivity and temperature sensing performance still need to be improved |
| Carbon-based fiber      | Integrate the carbon material into the fiber, or modify the fiber to achieve the purpose of temperature conduction | Special treatment of fibers is required, and the requirements for cross content outside the textile discipline are high, but the result feedback is relatively good |
| Temperature-sensitive fiber | A special type of fiber that is sensitive to temperature and it can measure temperature by converting electrical signals | The fiber can be directly woven into the textile to form a flexible sensor, but its sensitivity/repeatability/stability remains to be investigated |

4. Conclusion
Fibrous flexible temperature sensor because of its soft and convenient can achieve the purpose of long-term monitoring and other characteristics, or has a larger application potential, the rapid development of new conductive textile materials also provides a certain amount of technical support, how to continue to use the fiber characteristics of alternative sensitive components, retain the advantages of fiber at the same time to enhance the monitoring sensitivity and durability has become a problem, in the intersection of multi-disciplinary knowledge to promote the application of fiber materials in the development of intelligent clothing, the future can be achieved more closely with the human body, convenient and effective intelligent clothing products, to bring people more surprises.

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