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Citation (APA)

Jansen, K. M. B. (2026). From Fabric to Function: Textile-Based Sensors for Continuous Health Monitoring. In *2026 Pan Pacific Strategic Electronics Symposium, Pan Pacific 2026* (pp. 131-135). (2026 Pan Pacific Strategic Electronics Symposium, Pan Pacific 2026). IEEE. <https://doi.org/10.23919/PanPacific70217.2026.11413898>

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From Fabric to Function: Textile-Based Sensors for Continuous Health Monitoring

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ABSTRACT

Wearable sensing technologies are rapidly emerging as essential tools for continuous health monitoring in daily life. Textiles, being in direct and constant contact with the human body, provide an ideal platform for integrating such sensing functions. For sensorized garments to be suitable for home monitoring, they must meet strict requirements in terms of unobtrusiveness and user comfort. Conventional e-textile approaches that rely on rigid electronic components or laminated films often compromise garment breathability, flexibility, and softness, leading to user discomfort and reduced wearability.

This work presents an alternative approach to electronic textiles (e-textiles), in which sensing capabilities are derived directly from the structure, orientation, and interconnection of conductive yarns integrated within the fabric. The proposed concept leverages the inherent properties of textiles—softness, flexibility, and comfort—while enabling multifunctional sensing without the need for bulky or rigid components.

The design focuses on the three-dimensional textile architecture to engineer reliable and accurate sensing surfaces. Conductive yarns can be knitted, woven or embroidered to function as capacitive or resistive elements, enabling the detection of parameters such as pressure, strain, and moisture. Furthermore, arrays of conductive yarns can be configured to form capacitive touch sensors or humidity-sensing grids. Power supply and data acquisition units remain external but can be positioned in unobtrusive locations to preserve wearer comfort.

We present several examples of functional textile sensors, including woven, knitted, and embroidered configurations. By employing computerized textile manufacturing techniques, accurate, reproducible, and durable sensors can be realized while maintaining textile comfort and aesthetics. The elimination of rigid or laminated components further enhances washability and long-term reliability under real-world conditions.

Key words: e-textiles, wearable sensors, conductive yarns, knitting, weaving, embroidery, health monitoring, smart textiles

INTRODUCTION

Two main approaches can be identified for the integration of electronics into textiles: (1) integrating sensors, interconnections, and electronic components onto a flexible

or stretchable substrate that is subsequently laminated onto a garment, and (2) using conductive yarns to create textile-based sensors and interconnects.

The first approach originates from the field of printed electronics and is currently the most common and technologically mature solution. Typically, a stretchable substrate is used as a carrier onto which interconnects and functional elements, such as electrode surfaces, are screen-printed. Electronic components are then mounted using automated pick-and-place processes. To protect the electronics from moisture ingress, an additional encapsulation or insulation layer can be applied. This manufacturing process is largely automated and therefore relatively easy to scale. The resulting electronic patches are subsequently laminated onto the textile garment.

An advantage of this approach is that the textile and electronic components can be manufactured independently by their respective industries and integrated only at the final production stage. However, several disadvantages exist. The printed electronic structures are often less stretchable than the underlying textile, which can lead to wrinkling and reduced wearer comfort. Furthermore, the polymer substrates impede moisture transport, potentially causing skin irritation and discomfort during prolonged use. End-of-life recycling is also challenging, as the electronics are difficult to separate from the textile; this issue may be mitigated in the future through the development of reversible adhesives.

Additional limitations arise when garments require multiple sensors distributed across different locations. In such cases, the necessary interconnect wiring occupies an increasingly large area of the fabric, which can compromise the textile appearance and further reduce comfort.



Figure 1. Examples of flexible printed interconnects and electrodes on textile substrate.

The other approach starts from the textile itself. Conductive yarns are typically composed of metallized polymer fibers blended with non-conductive polyester or cotton fibers, resulting in yarns that combine electrical conductivity with

the softness, flexibility, and processability of conventional textiles. These yarns can be handled using existing industrial textile manufacturing techniques. The most common variant is silver-plated nylon, with commercially available examples including Shildedex, Silverell, Silverpam, Litz wire, and Swicofil. Conductive yarns incorporating ultrathin stainless-steel filaments are also available, such as Bekinox and Thermotech, and typically exhibit conductivities in the range of 1–100 Ω/m .

Carbon-based conductive yarns, including Resistat, Taiexin, Volt Smart Yarns, and Delta Yarns, represent an alternative class of conductive yarns. However, these yarns generally exhibit higher electrical resistance (typically 10^2 – 10^4 Ω/m) and often lack sufficient flexibility to be fully compatible with standard textile manufacturing equipment such as knitting and embroidery machines. It should be noted that conductive yarn technologies are evolving rapidly, and continued improvements in conductivity, flexibility, and mechanical robustness are expected to significantly expand the range of low-resistance yarns compatible with industrial textile processes in the near future.

Conductive yarns can be embroidered onto textile substrates using programmable embroidery machines to form interconnect layouts, electrodes, and certain types of textile-based sensors. This technique is inherently scalable from rapid prototyping to mass production, can be applied to a wide variety of fabric substrates, and offers a high degree of design freedom in pattern geometry and layout. Electrical connections to printed circuit boards (PCBs) can be realized automatically through over stitching (as shown in Fig.2), while conductive tracks can be mechanically protected and electrically insulated by additional stitching with non-conductive yarns.



Figure 2. Machine embroidered interconnect circuits

Knitting and weaving are manufacturing technologies in which conductive yarns are fully integrated into the fabric structure. The use of computer-controlled equipment enables precise, repeatable placement of conductive yarns, allowing the creation of textile architectures that respond to strain, pressure, temperature, or moisture. This approach supports the fabrication of large-area sensorized textiles without laminated or rigid regions, while fully preserving the inherent properties of the fabric. As a result, skin irritation is minimized and wearer comfort is significantly improved, making such systems particularly suitable for long-term use. In the following section, we discuss representative state-of-the-art strategies for developing textile-based sensors intended for unobtrusive, long-term home monitoring.

TEXTILE-BASED SENSOR STRUCTURES

Pressure sensing structures

In general the working principle of a piezoresistive pressure sensor is simple: a compressible high-resistance layer is sandwiched between two low-resistance electrodes (Fig. 3a). When pressure is applied, the overall resistance decreases due to reduced contact resistance and the compression of the piezoresistive layer. The recorded resistance serves as a measure of applied pressure. A similar principle applies to crossing conductive yarns with or without an intermediate piezoresistive layer (Fig. 3b). In this configuration, resistance changes occur due to alterations in contact resistance. An alternative design is the planar configuration (Fig.3c), where a piezoresistive layer overlaps two electrode lines on the same plane. Compression leads to a decrease in contact resistance and the resistance of the piezoresistive layer. Capacitive pressure sensors typically follow the stacked configuration (Fig.3a), replacing the conductive middle layer with a non-conductive dielectric layer.

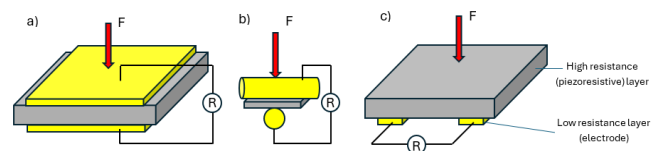


Figure 3. Pressure sensing principles. a) Stacked, b) crossing yarns and c) planar configuration

The realization of the three configurations described above in textile fabrics depends on the chosen manufacturing technique. For example, in knitting, configuration 1a can be implemented to create localized pressure-sensing elements by forming dome-shaped structures filled with a resistive material (Fig. 4). Sensor grids can be produced by knitting a spacer structure with conductive tracks integrated into the top and bottom layers and inserting a compressible dielectric textile in between. By measuring changes in capacitance, the pressure distribution on a seat can be determined accurately (Fig. 5).

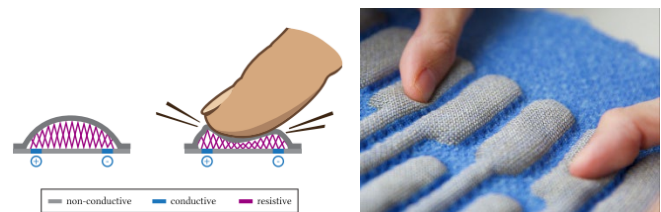


Figure 4. Spacer knit with compressible resistive filler [1]

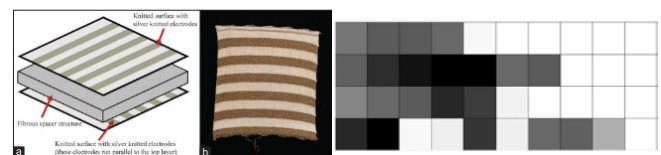


Figure 5. Knitted seat sensor grid (Ma, TU Delft 2020, [2])

For embroidery, configuration 3b is more suitable. Starting from a non-conductive base fabric, conductive yarns can be stitched to form lines on either the top or the bottom surface

(Fig. 6). At the intersection points, changes in capacitance can be measured in a manner similar to that of the seat sensor. Such sensor arrays can be integrated into bed sheets and used to detect pressure sores in chronic patients.

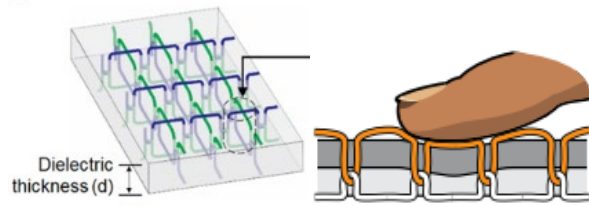


Figure 6. Embroidered structures for pressure sensing [3,4]

Weaving involves interlacing vertical warp and horizontal weft yarns to create a structured fabric. By using only a portion of the warp yarns to form a layer, additional layers can be created. This multilayer capability, typically used for pockets and other textile features, can also be adapted for sensor fabrication (Fig.7). By constructing conductive elements in the outer layers and incorporating an interlayer composed of elastic yarns and high-resistance yarns, a fabric with resistive sensing elements following configuration 1a can be realized (Fig.8, [6]). The elastic yarns provide the restoring force required for the fabric to return to its original shape after compression.

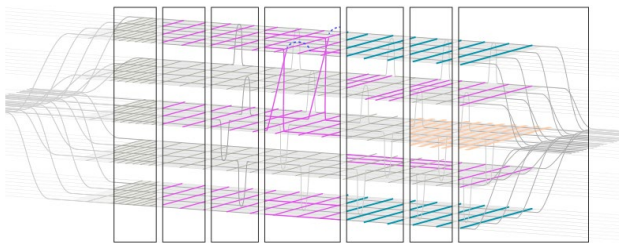


Figure 7. Multilayer weave structure with conductive yarns in different layers [5].

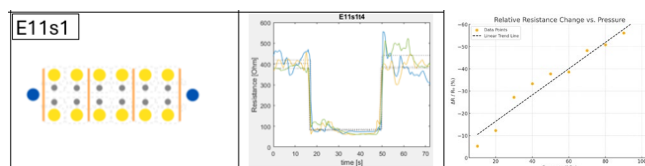


Figure 8. Weave structure and pressure response of a woven sensor [6]

Strain sensing structures

Stretch or strain sensing in e-textiles can be realized in several ways: by integrating stretchable sensing yarns, applying strain-sensitive coatings, or using non-stretchable conductive yarns in combination with fabric structures that convert mechanical deformation into an electrical signal. In this paper, we focus on the latter approach.

The basic operating principles are illustrated in Figure 9. The capacitive variant (Fig. 9a) is based on changes in the overlap area between two conductive elements separated by a non-conductive (textile) layer. Elastic textile components are required to ensure that elongation results in a reversible relative displacement between the upper and lower layers. The second principle relies on a change in electrical

resistance of the textile structure during deformation (Fig.9b). In this case, embedded elastic yarns or the inherent elasticity of the substrate provide a reproducible recovery during unloading, ensuring stable and repeatable sensor behavior.

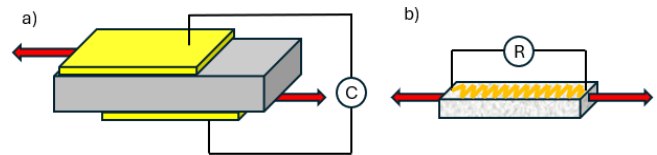


Figure 9. Strain sensing principles. a) Overlap area change, b) Contact area change

An example of a stretch sensor based on the overlap principle and the developed posture monitoring shirt is shown in Fig.10.

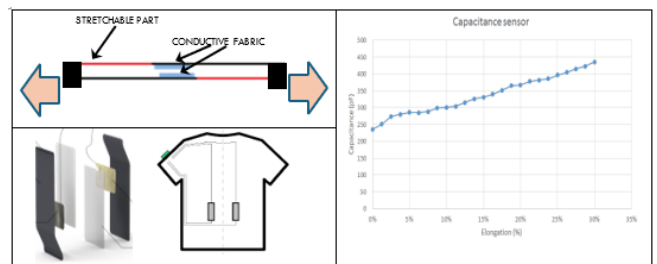


Figure 10. Textile stretch sensor for smart posture monitoring shirt (Grevers, TU Delft 2016)

The contact-area principle can be effectively demonstrated by stitching a conductive yarn in a zigzag pattern onto a pre-stretched elastic fabric [7,8]. This method enables strain-sensitive regions to be easily integrated at various locations on garments such as shirts, trousers, or knee sleeves (Fig. 11).

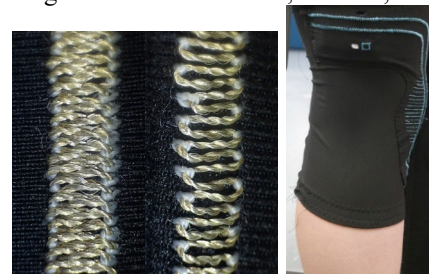


Figure 11. Stitched strain sensors and knee sleeve application

As an alternative, overlap-type strain sensors can be fully integrated into the fabric by knitting conductive yarns directly into the textile structure. During stretching, overlapping conductive loops undergo relative displacement, which results in an increase in electrical resistance. As demonstrated by Bozali et al. [9], a key requirement for achieving reliable strain sensing with minimal hysteresis is the incorporation of elastic yarns into the structure. These yarns ensure consistent contact pressure at the overlap points

and provide a reliable restoring force during unloading (Fig.12).

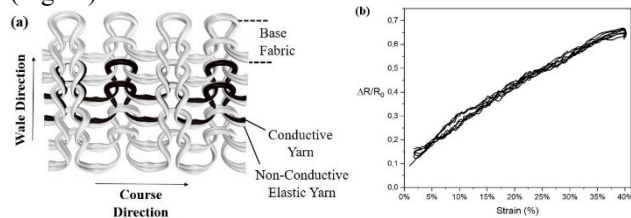


Figure 12. Structure and performance of a low hysteresis knitted strain sensor [9]

As shown by Jansen et al. [10] these sensors can be reliably used to monitor respiration rate derived from chest expansion measurements (Fig.13).

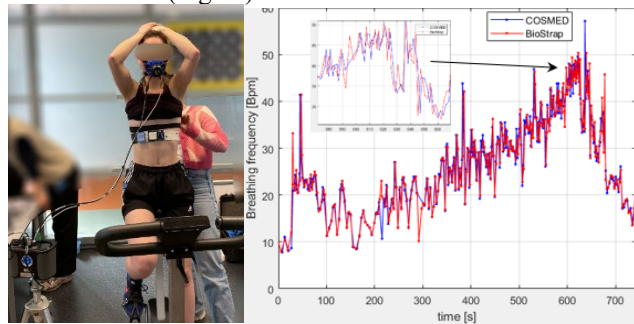


Figure 13. Validation study of chest strap with knitted strain sensor for respiration monitoring [10]

Other textile sensor types

Not all sensing functions can be realized using sensors composed entirely of textile elements. For example, commonly used inertial measurement units (IMUs) and pulse oximeter sensors for monitoring blood oxygen saturation currently have no straightforward textile-based alternatives. Nevertheless, partial textile integration is possible for several sensing modalities.

A prominent example is the replacement of conventional gel-based electrodes for electrocardiography (ECG) and electromyography (EMG) with textile-based electrodes to improve comfort and wearability. These electrodes can be fabricated by knitting or embroidery using conductive yarns [11–13], and have been shown to provide performance comparable to that of standard disposable gel electrodes.

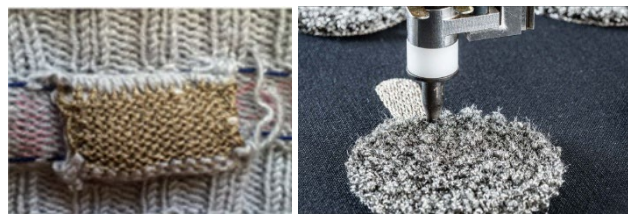


Figure 14. Knitted and embroidered ECG electrodes [11,13]

Smart textiles also provide an effective means of monitoring skin temperature at multiple locations on the body in an unobtrusive and reliable manner. By embroidering conductive yarns and measuring their resistance variation with temperature, the average temperature over an area of several square centimeters can be obtained [14]. This area-

based measurement offers a distinct advantage over conventional thermocouples, which provide only single-point temperature readings.

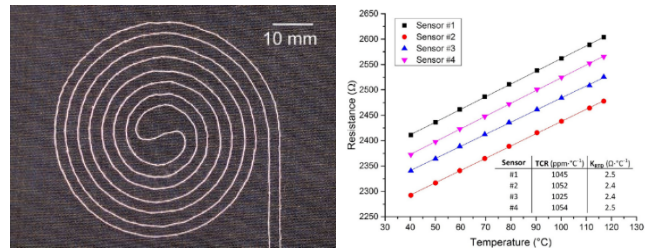


Figure 15. Textile temperature sensor and performance [14]

CONCLUSIONS

This paper has demonstrated how sensing functionalities for continuous health monitoring can be directly embedded into textile structures by exploiting the geometry, material properties, and interconnection of conductive yarns. By moving beyond rigid components and laminated films, textile-based sensors preserve the inherent comfort, flexibility, and breathability required for long-term wear. Examples of capacitive, resistive, and contact-area-based sensors illustrate the versatility of woven, knitted, and embroidered approaches for measuring parameters such as strain, pressure, respiration, moisture, and temperature. The presented designs show that reliable and reproducible sensor performance can be achieved through careful textile engineering and the incorporation of elastic elements where necessary. Furthermore, computerized textile manufacturing enables scalable production while maintaining consistency and durability. Although certain sensing modalities still require conventional electronic components, their integration can be minimized and made unobtrusive. Overall, textile-integrated sensors represent a promising pathway toward truly wearable, user-friendly systems for continuous health monitoring in everyday life.

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