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Mass Production of E-Textiles Using Embroidery Technology †

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Abstract: Embroidery, once a symbol of craftsmanship, has transformed into a cutting-edge technology blending tradition and innovation. This article delves into the multifaceted applications of embroidery technology in smart and e-textiles, showcasing its precision in integrating electronic components and PCBs and embroidering complete electrical circuits. Addressing challenges in reliability and mass production, the article provides research-backed solutions, offering guidelines for reliable embroidered interconnections and conductive traces. Positioned in mass production, embroidery's automation and scalability seamlessly extend industrial practices to e-textiles, establishing this technique as a dynamic force shaping the future of smart-textile technology.

Keywords: embroidery; reliability; automation; scalability; mass production; e-textiles; smart textiles

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1. Introduction

Embroidery, rooted in historical artistry, has evolved into a pioneering technology at the crossroads of tradition and functionality. This article highlights the modern applications of embroidery in the field of smart and e-textiles. Bridging traditional fabrics and cutting-edge technology, e-textiles find applications across diverse sectors, like automotive, aerospace, sports and fitness, medical, home textiles, and wearable technology. The precision and automation of embroidery make it an ideal tool for seamlessly integrating functional elements like sensors, actuators, and antennas into textiles. By using conductive threads and specialized attachments for the automated integration of electronic components, embroidery techniques, originally developed for aesthetic purposes, now enable reliable and scalable e-textiles' production.

2. Challenges and State-of-the-Art Solutions for the Mass Production of Embroidered E-Textiles

In the literature, numerous smart and e-textiles solutions showcase academic prowess, often supported by proof-of-concept devices. However, transitioning these innovations into marketable products faces hurdles, particularly in reliability and mass production. This section identifies primary challenges and unveils state-of-the-art solutions through embroidery technology.

2.1. Reliability

Reliability is pivotal for any product, especially in the realm of functional and technological devices. E-textile products must meet textile requirements like everyday durability and washability, as well as electronic device standards for proper function and safety.

In the following, we focus on the reliability aspect of embroidered interconnections between the soft fabric and the rigid electronic components, as well as the reliability of embroidered conductive traces as a medium for power and signal transmission.

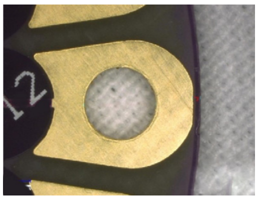
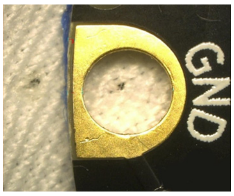
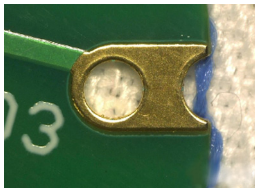
2.1.1. Embroidered Interconnections

Establishing a robust interface between the flexible fabric and rigid electronic components stands as a primary challenge in e-textile production, irrespective of the chosen production technology. Embroidery technology addresses this challenge by automatically stitching electronic components and PCBs onto textiles, ensuring both mechanical and electrical connections using conductive threads. Our team's research resulted in guidelines for the PCB design and stitch sequence, allowing the creation of highly reliable embroidered interconnections without the need for additional solder materials or conductive adhesives.

(a) PCB design guidelines

In the course of our research, we scrutinized various off-the-shelf PCBs explicitly designed for manual integration into textiles in hobbyist projects. Notable examples include the "Lilypad Arduino 328" and the "Adafruit Circuit Playground Express". Additionally, we introduced a custom-designed PCB named "ZSK E-Tex-Board", tailored specifically for embroidery, and conducted a comparative analysis against the off-the-shelf counterparts. The geometric properties of these three PCBs are summarized in Table 1.

Table 1. PCB geometry feature comparison between the three examined PCBs [1].

PCB Geometry Feature	Lilypad Arduino 328	Adafruit Circuit Playground Express	ZSK E-Tex Board
PCB shape	Round	Round	Round
PCB diameter	50.0 mm	50.6 mm	40.0 mm
PCB thickness	0.8 mm	1.5 mm	0.5 mm
Contact pads count	22	14	21
Contact-hole-to-PCB-edge distance	1.8 mm	0.6 mm	1.0 mm (castellated holes)
Contact hole diameter	3.0 mm	3.5 mm	1.5 mm
Embroidery pad geometry			

To evaluate the different PCB geometries quantitatively, we subjected them to washing tests. The resistance of the 3 mm long embroidered conductive traces, including the contact resistance to the PCB, was measured. The Madeira HC 40 conductive embroidery thread was used for all samples. The results are illustrated in Figure 1 and underscore the significant advantage of the E-Tex Board in terms of both mean and standard deviation values.

(b) Stitch sequence guidelines

In a subsequent investigation, we examined the impact of various stitch parameters, such as number of stitches, stitch orientation, and stitch-to-PCB-edge distance. Figure 2 illustrates all the scrutinized stitch sequences employing the Madeira HC 40 conductive embroidery thread and the ZSK E-Tex Board. Following this, washing tests were conducted, systematically measuring the resistance of the 3 mm long embroidered conductive traces, including the contact resistance to the PCB. The findings, as depicted in Figure 3, underscore the considerable influence of the stitch sequence on the reliability of the embroidered connection. Small distance between stitches and PCB edge results in more tight and therefore more durable connections. The smallest mean value and standard deviation of the resistance was achieved with three crisscrossed stitches and a 0.75 mm distance to the PCB edge.

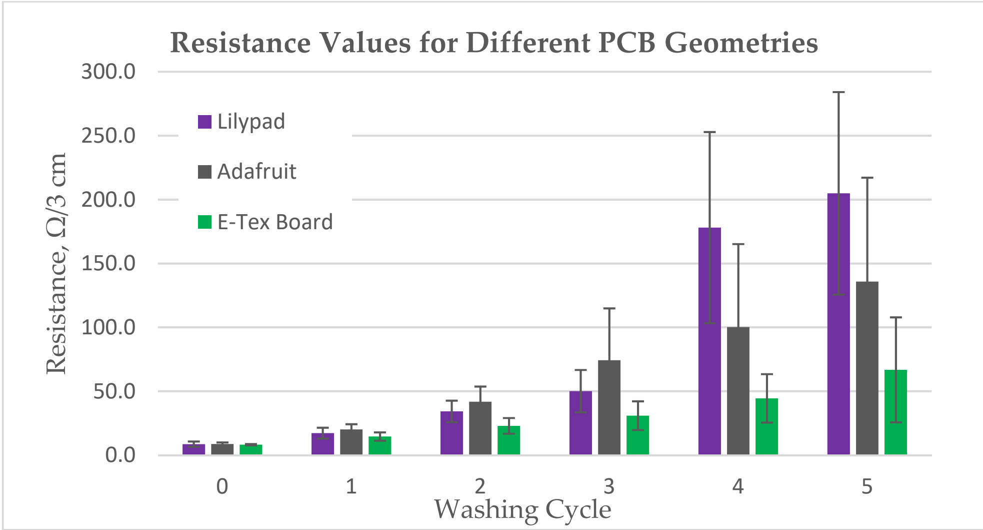
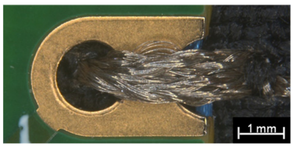
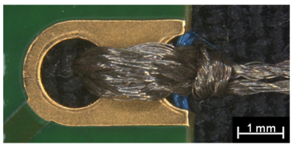


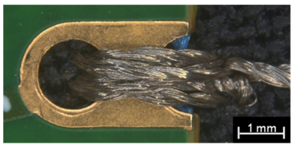
Figure 1. Resistance changes over five washing cycles for three different PCB geometries [1].



Three stitches, parallel, long

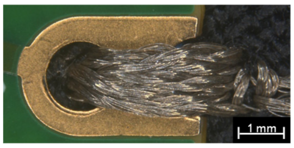


Three stitches, parallel, short

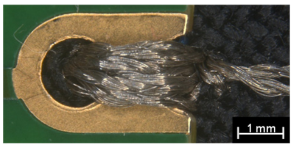


Three stitches, crossed, long

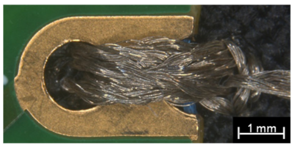
Three stitches, crossed, short



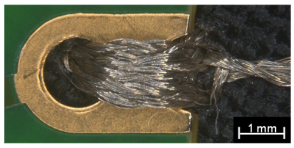
Five stitches, parallel, long



Five stitches, parallel, short



Five stitches, crossed, long



Five stitches, crossed, short

Figure 2. Examined stitch sequence variations with the ZSK E-Tex Board and Madeira HC 40 conductive thread [2].

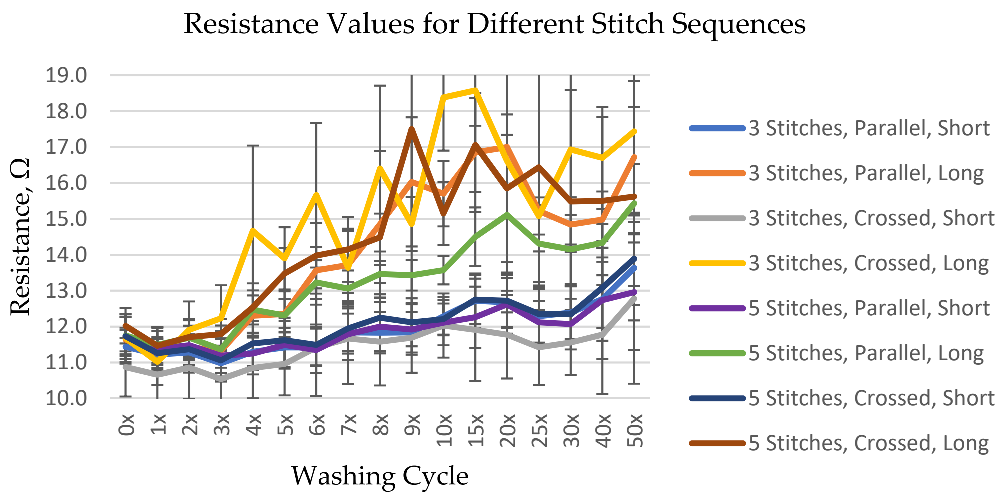


Figure 3. Resistance changes over 50 washing cycles, comparing various stitch sequences using the ZSK E-Tex Board and Madeira HC 40 conductive thread [2].

2.1.2. Embroidered Conductive Traces

(a) Compensation for high yarn resistivity and avoiding conductive thread damage.

Addressing the challenge of a high resistivity in conductive embroidery threads involves innovative solutions. Embroidering multiple passes, resembling a running stitch, acts like parallel resistors, reducing resistivity. Incorporating a conductive bobbin thread reinforces the electrical path, contributing to an increased conductivity. It is crucial to alternate the stitching path with each pass to avoid stitching into the already embroidered thread. Alternatively, conductive traces can be embroidered as filled areas, using the so-called fill stitch, with an underlayer angled to the primary stitch direction. This technique ensures a high material density and sufficient electrical contact between stitches [3].

(b) Enabling Crossing and Insulation of Conductive Traces

Complex e-textiles' designs often feature closely adjacent or intersecting conductive traces. To prevent unintended electrical connections, nonconductive bridges can be added between traces, created by embroidering multiple layers of satin stitch with nonconductive thread. Conductive traces can also be completely covered with nonconductive thread to mechanically protect the thread and match to the design. For applications requiring waterproofing, a seam-sealer tape or polymer coatings can be utilized.

2.2. Mass-Producibility

Achieving mass-producibility is a critical aspect for transitioning e-textile innovations from concepts to market-ready products. This involves addressing two fundamental aspects: automation and scalability.

2.2.1. Automation

Embroidery technology's high degree of automation is a pivotal factor in streamlining the production of e-textiles. Modern embroidery machines boast computerized precision, ensuring consistent quality. A state-of-the-art sequin placement device can be configured to incorporate functional sequins into textiles (Figure 4a). Functional sequins can be equipped with SMD soldered components, such as LEDs or RFID chips. For larger circuit boards, whether rigid or flexible, embroidery machines fitted with the automated ZSK PCB Placement Device can precisely position and secure the PCBs onto the textile (Figure 4b), followed by the embroidery of the electrical connections. This level of automation is particularly advantageous in realizing large-scale production with high reliability and reproducibility.

(**a**) (**b**)

Figure 4. Attachments for automated integration of electronic components: (**a**) ZSK Functional Sequin Device; (**b**) ZSK PCB Placement Device.

2.2.2. Scalability

Embroidery, having served as an industrial production technology for decades, embodies inherent scalability. The introduction of multihead embroidery machines allows for a proportional increase in output per unit time without compromising quality. This scalability is instrumental in extending the same production techniques to the realm of e-textiles, making it feasible to produce them on a large scale. The utilization of established industrial practices ensures that the benefits of embroidery, such as precision, durability, and versatility, are seamlessly extended to the mass production of e-textiles.

3. Conclusions

Embroidery technology, evolving from a historic craft to a cutting-edge innovation, stands as a pivotal force at the crossroads of tradition and technology. Its precision and automation capabilities unlock a myriad of applications, from incorporating electronic components and PCBs to embroidering complete electrical circuits. In the landscape of mass production, automation and scalability can be achieved by embroidery, ensuring precision, consistency, and efficiency.

As technology advances and the demand for smart textiles grows, continued research and innovation in the field of technical embroidery will be essential. With ongoing efforts to refine techniques and materials, we can expect to see even more sophisticated and reliable embroidered e-textiles, opening up new possibilities in wearable technology, healthcare, fashion, and beyond.

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