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Textile-Based Flexible Electronics for Wearable Applications: from Antennas to Batteries

Asimina Kiourti
ElectroScience Laboratory, The Ohio State University, Columbus, OH, 43212

Abstract

We present a new class of textile-based electronics for wearable applications that are flexible, robust, and completely unobtrusive to the wearer. Contrary to state-of-the-art flexible electronics, the proposed technology brings forward unprecedented tolerance to mechanical/thermal stresses; enables precision and Radio-Frequency (RF) performance similar to that achieved by rigid copper prototypes; and eliminates the need for rigid/bulky batteries. Specifically, conductive traces (antennas and transmission lines, among others) are realized via automated embroidery of conductive E-threads, while batteries are directly "printed" on fabrics via conductive inks. The proposed technology brings forward transformational opportunities for a very wide range of applications, including healthcare, sports, wireless communications, Radio Frequency Identification, etc.

1. Introduction

Flexibility and robustness are critical properties for electronics that operate in environments subjected to shape deformation, such as wearables. Notably, the wearables market is growing at a phenomenal rate [1-5], indicating an anticipated shipment of over 550 million devices by the year 2021. Example applications for wearables include, but are not limited to, healthcare, sports, child monitoring, defense/emergency, smart homes, Internet of Things, etc.

Previously known processes for fabricating flexible electronics entail the use of conductive inks [6-8], conductive fabrics [9-11], copper tape [12, 13], etc. Though promising results have been demonstrated, these processes are typically prone to failure due to fatigue and wear, are difficult to reproduce at large scale, and are integrated with rigid/bulky batteries for powering. For the first time, the proposed textile-based electronics are flexible, mechanically robust, lightweight, reproducible, and exhibit similar Radio-Frequency (RF) performance to their rigid copper counterparts. Concurrently, shape precision / resolution can be as high as 0.1mm, viz. similar to the state-of-the-art printed circuit boards (PCBs). Colorful versions are also realizable for unobtrusive integration into colorful logos or other esthetic shapes within everyday clothings. Remarkably, these textile-based electronics can be ubiquitously fed by a new class of flexible power-generating fabrics (instead of rigid batteries). The proposed technology has already been validated as part of several applications, including wearable antennas for enhanced Quality of Service (QoS), smart hats for deep brain neurosensing, stretchable and flexible Radio Frequency Identification (RFID), antenna-impregnated fabrics for recumbent height monitoring, wound-detection fabrics, and E-textile Origamis.

2. Fabrication Process

2.1 Flexible Conductive Traces

Fabrication of conductive traces (antennas, transmission lines, etc.) relies on digitization of the desired pattern in a computer simulation platform, and subsequent stitching upon a fabric substrate via electrically conductive threads (E-threads) and an automated embroidery machine (see Fig. 1) [14]. The employed E-threads consist of twisted filament bundles comprised of 7 to 664 metal-coated polymer filaments, each 15μm thick. This structure enables extreme robustness, as attributed to the strong polymer (typically Kevlar) core and twisting, as well as high conductivity, as attributed to the surrounding high-conductivity material (typically silver). There are no limitations as to the employed fabric substrate. In fact, we have already demonstrated successful embroidery on fabrics as thin as organza and as thick as Kevlar.

Figure 1. Flexible antennas fabricated via automated embroidery of conductive E-threads.

2.2 Stretchable and Flexible Prototypes

If stretchability of the prototype is desired, besides flexibility, the underlying non-conductive fabric substrate can be removed (e.g., via melting), and the E-textile embroidered pattern can be embedded into a stretchy polymer (see Fig. 2) [15]. In doing so, the E-threads can stretch along with the polymer. This also preserves the integrity of the threads and protects them from corrosion.

Figure 2. Stretchable and flexible RFID antenna fabricated by embedding the conductive E-thread into stretchy polymer.

2.3 Colorful Prototypes

To realize colorful prototypes, the embroidery process relies on unicolor E-threads in the bobbin of the embroidery machine to stitch the antenna on the back side of the garment [16]. Concurrently, a colorful assistant yarn is threaded through the embroidery needle of the embroidery machine and used to secure or "couch" the E-threads onto the fabric. In doing so, the colorful shape appears in the front side of the garment (see Fig. 3).

Figure 3. Colorful E-textile antennas fabricated via a hybrid approach that employs colorful threads on the front side and uni-color conductive threads on the back side.

2.4 Textile-Based Batteries

Flexible textile-based batteries can be implemented by depositing alternating regions of silver and zinc dots upon the fabric (see Fig. 4) [17]. When in contact with an aqueous solution (such as sweat, wound fluid, or saline), silver acts as the positive electrode (cathode) which is reduced, while zinc acts as the negative electrode (anode) and is oxidized. In this way, DC voltage and DC micro-currents are generated just by getting the dressing moistened, without the need for any additional circuits or components.

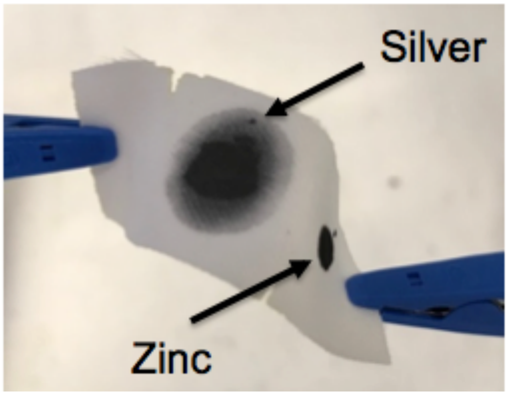

Figure 4. Single battery cell "printed" on fabric via silver- and zinc-based inks that serve as the cathode and anode, respectively.

3. Performance

Geometrical precision as high as 0.1mm can be achieved by employing very thin E-threads and embroidering the pre-determined pattern using very high stitching density [18]. This dense embroidery reduces physical discontinuities and achieves surface conductivity nearly that of copper. Indeed, our E-textiles have shown to exhibit similar RF performance to that of their rigid copper counterparts at frequencies as high as 4 GHz (e.g., see Fig. 5 [16]). Beyond this frequency, losses associated with the E-thread polymer and surface discontinuities start becoming an issue. Mechanical tests for our E-textiles have demonstrated no appreciable changes in performance, even after 300 flexing cycles. Thermal tests have also been performed at +90°C and -85°C, indicating an almost unchanged performance. Last but not least, our E-textile prototypes can withstand repetitive washing and drying cycles without any deterioration in performance.

Regarding the proposed flexible batteries, reproducible results have already been obtained for multiple "printed" cells. Notably, a single cell has been shown to be able to generate power levels of over 80 µW for 4 hours. Scalable voltage and current generation capabilities have also been demonstrated by connecting multiple cells in series and/or in parallel.

4. Applications

4.1 Wearable Antennas for Enhanced QoS

Flexible antennas with large footprints can now be unobtrusively integrated into garments to enhance QoS. As an example, a wearable Wi-Fi repeater has been demonstrated which was shown to extend the Wi-Fi distance range of cell phones and other personal digital assistance (PDA) devices (tablets, laptops, etc.) by more than 2 times.

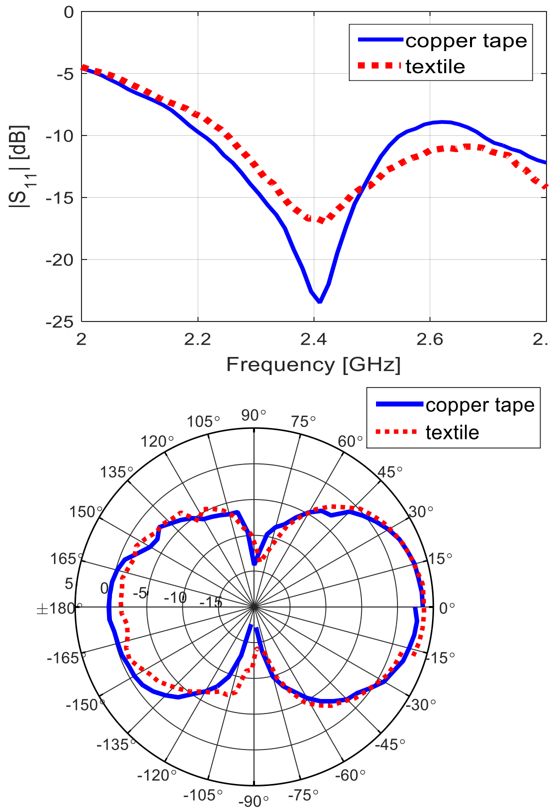

Figure 5. Reflection coefficient (|S11|) and radiation pattern results for a 2.4 GHz textile dipole antenna as compared to its copper tape counterpart.

4.2 Smart Hats for Deep Brain Neurosensing

Textile-based spiral antennas have been demonstrated for ubiquitous integration into hats and reading of deep brain neuropotentials. The technology relies on fully-passive microwave backscattering that employs the smart hat as an interrogator to retrieve neural signals collected by a batteryless brain implant [19]. Expectedly, this brings forward unique opportunities for patients with epilepsy, tremor, Parkinson's, etc.

4.3 Stretchable and Flexible RFIDs

A broadband textile-based UHF RFID tag antenna has also been demonstrated. Its wide bandwidth makes the tag less susceptible to objects and materials in the vicinity, while E-threads introduce elasticity, flexibility, and mechanical strength. Experimental results showed that the designed tag achieves much better performance compared with commercially available tags.

4.4 Antenna-Impregnated Fabrics for Recumbent Height Monitoring

Contrary to conventional infantometer and stadiometer technologies that restrict height monitoring to sporadic intervals, this technology brings forward regular height monitoring with minimum impact to the individual's activity. The operation principle lies on a series of dipole antennas placed at known distances, some of which are "blocked" by the overlying human subject. As such, these fabrics can be integrated into baby cribs, bed sheets or rollable mats to provide early detection/monitoring of Turner syndrome, Crohn's disease, short stature, Celiac disease, and growth hormone deficiency, among others.

4.5 Wound Detection Fabrics

A batteryless epidermal sensor was demonstrated that identifies open wounds underneath its surface. Operation lies in an electrochemical fabric with printed battery cells that generate power when exposed to the wound fluid electrolyte. Multiple cells can be inter-connected via E-threads to boost the generated power levels and turn on an LED, for example.

4.6 E-Textile Origami Antennas

This research studies E-textile-based reconfigurable antenna arrays that conform to adaptable topologies by Origami-inspired tessellations. The E-textiles leverage embroidered conductive threads along frameworks established on origami tessellations to permit large compliance at folding edges as needed while retaining the desired electromagnetic wave propagation characteristics. These findings may motivate future concepts for reconfigurable antennas established upon physical deformation processes.

5. Conclusion

We presented a new class of textile-based flexible electronics that rely on E-thread embroidery and "printed" battery cells for operation. For the first time, the proposed electronics are extremely robust, eliminate rigid/bulky components (including batteries) and are completely ubiquitous to the wearer. Overall, the proposed E-textiles are very attractive to the rapidly growing flexible electronics industry and are offering unprecedented opportunities for applications that include, but are not limited to, healthcare, defense/emergency, automotive, smart cities, and the Internet of Things.

6. References

1. D. Metcalf, S.T.J. Milliard, M. Gomez, and M. Schwartz, "Wearables and the Internet of Things for Health: Wearable Interconnected Devices Promise More Efficient and Comprehensive Health Care," *IEEE Pulse*, **7**, 5, September 2016, pp. 35-39.

2. S. Rao, N. Llombart, E. Moradi, K. Koski, T. Bjorninen, L. Sydanheimo, J.M. Rabaey, J.M. Carbena, Y. Rahmat-Samii, and L. Ukkonen, "Miniature Implantable and Wearable On-Body Antennas: Towards the Era of Wireless Body-Centric Systems," *IEEE*

Antennas and Propagation Magazine, **56**, 1, February 2014, pp. 271-291.

3. P. Nepa and H. Rogier, “Wearable Antennas for Off-Body Radio Links at VHF and UHF Bands: Challenges, the State of the Art, and Future Trends below 1 GHz,” *IEEE Antennas and Propagation Magazine*, **57**, 5, October 2015, pp. 30-52.

4. J. Trajkovikj and A. Skrivervik, “Diminishing SAR for Wearable UHF Antennas,” *IEEE Antennas and Wireless Propagation Letters*, **14**, November 2014, pp. 1530-1533.

5. A. Paraskevopoulos, A. Tsolis, J. Vardaxoglou, and A. Alexandridis, “Cylindrical Near-Field Assessment of Wearable Antennas for Body-Centric Communications,” *IET Microwaves, Antennas, and Propagation*, **11**, 6, May 2017, pp. 761-769.

6. T. Leng, X. Huang, K. Chang, J. Chen, M.A. Abdalla, and Z. Hu, “Graphene Nanoflakes Printed Flexible Meandered-Line Dipole Antenna on Paper Substrate for Low-Cost RFID and Sensing Applications,” *IEEE Antennas and Wireless Propagation Letters*, **15**, January 2016, pp. 1565-1568.

7. H. Saghlatoon, T. Bjorninen, L. Sydanheimo, M. Tentzeris, and L. Ukkonen, “Inkjet-Printed Wideband Planar Monopole Antenna on Cardboard for RF Energy-Harvesting Applications,” *IEEE Antennas and Wireless Propagation Letters*, **14**, October 2014, pp. 325-328.

8. S. Genovesi, F. Costa, F. Fanciulli, and A. Monorchio, “Wearable Inkjet-Printed Wideband Antenna by Using Miniaturized AMC for Sub-GHz Applications,” *IEEE Antennas and Wireless Propagation Letters*, **15**, January 2016, pp. 1927-1930.

9. M. Mantash, A.C. Tarot, S. Collardey, and K. Mahdjoubi, “Design Methodology for Wearable Antenna on Artificial Magnetic Conductor Using Stretch Conductive Fabric,” *IET Electronics Letters*, **52**, 2, January 2016, pp. 95-96.

10. S. Manzari, C. Occhiuzzi, and G. Marrocco, “Feasibility of Body-Centric Systems Using Passive Textile RFID Tags,” *IEEE Antennas and Propagation Magazine*, **54**, 4, August 2012, pp. 49-62.

11. S. Yan, V. Volskiy, and G. Vandenbosch, “Compact Dual-Band Textile PIFA for 433MHz/2.4GHz ISM Bands,” *IEEE Antennas and Wireless Propagation Letters*, **16**, July 2017, pp. 2436-2439.

12. A. Tsolis, W. Whittow, A. Alexandridis, and J. Vardaxoglou, “Embroidery and Related Manufacturing Techniques for Wearable Antennas: Challenges and Opportunities,” *MDPI Electronics*, **3**, 2, May 2014, pp. 314-338.

13. B.S. Abirami and E.F. Sundarsingh, “EBG-Backed Flexible Printed Yagi-Uda Antenna for On-Body Communication,” *IEEE Transactions on Antennas and Propagation*, **65**, 7, July 2017, pp. 3762-3765.

14. A. Kiourti and J.L. Volakis, “High-Geometrical-Accuracy Embroidery Process for Textile Antennas with Fine Details,” *IEEE Antennas and Wireless Propagation Letters*, **14**, October 2014, pp. 1474-1477.

15. A. Kiourti and J.L. Volakis, “Stretchable and Flexible E-Fiber Wire Antennas Embedded in Polymer,” *IEEE Antennas and Wireless Propagation Letters*, **13**, July 2014, pp. 1381-1384.

16. A. Kiourti and J.L. Volakis, “Colorful Textile Antennas Integrated into Embroidered Logos,” *MDPI Journal of Sensor and Actuator Networks*, **4**, 4, August 2015, pp. 371-377.

17. R. Vilkhu, B. DeLong, P.D. Ghatak, S. Mathew-Steiner, C. Sen, and A. Kiourti, “Power Harvesting for Wearable Electronics Using Fabric Electrochemistry,” in Proc. *IEEE International Antennas and Propagation Symposium*, 2017.

18. A. Kiourti and J.L. Volakis, “Fabrication of Textile Antennas and Circuits with 0.1mm Precision,” *IEEE Antennas and Wireless Propagation Letters*, **15**, May 2015, pp. 151-153.

19. A. Kiourti, C. Lee, J. Chae, and J.L. Volakis, “A Wireless Fully-Passive Neural Recording Device for Unobtrusive Neuropotential Monitoring,” *IEEE Transactions on Biomedical Engineering*, **63**, 1, January 2016, pp. 131-137.