Review

Embroidery and Related Manufacturing Techniques for Wearable Antennas: Challenges and Opportunities

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Abstract: This paper will review the evolution of wearable textile antennas over the last couple of decades. Particular emphasis will be given to the process of embroidery. This technique is advantageous for the following reasons: (i) bespoke or mass produced designs can be manufactured using digitized embroidery machines; (ii) glue is not required and (iii) the designs are aesthetic and are integrated into clothing rather than being attached to it. The embroidery technique will be compared to alternative manufacturing processes. The challenges facing the industrial and public acceptance of this technology will be assessed. Hence, the key opportunities will be highlighted.

Keywords: wearable antennas; embroidered antennas; wearable technology; inkjet printing; textiles

1. Introduction

Wearable antennas technology has rapidly grown over the last couple of decades. It could be said and assumed that this technology is the future of smart garments and furthermore the future of our daily life. A wearable antenna is meant by definition to be part of the garments worn by humans or

animals. Therefore, the antenna should be flexible or miniaturized so as to not inhibit the movement of the human body. Consumers will demand smaller and more intelligent communications systems which will enhance their quality of life. Smart garments due to the evolution of wearable antennas technology may find their place in our everyday lifestyle. Smart clothes will emerge in various applications including: sports, emergency workers, military, medical and space applications or even in casual daily clothes or in fashion [1].

This paper will be structured as follows. Section 2 will review the dielectric properties of textile substrates. Section 3 will compare different manufacturing techniques with particular emphasis on embroidery. Section 4 will consider particular examples and applications of wearable rigid miniaturized and textile antennas. Section 5 will address the challenges both from a technical point of view and also from the market acceptance point of view. Section 6 will consider some of the opportunities that exist in this area. An extensive (but not complete) list of references will be given at the end of this paper.

2. Substrate Materials for Wearable Antennas

The substrate material selection for a wearable antenna design is of crucial importance. The substrate selection requires a low loss material so as to have better chances of increased antenna efficiency when placed on the body. The work in [2] where a Planar Inverted F-Antenna (PIFA) was fabricated out of a foam sheet spacer as the substrate and copper plated nylon for conductive sections states that a low loss conductive fabric is critical to the performance of a textile antenna. For wearable textile antennas the substrate material is required to be flexible. Textile substrate dielectric properties vary with the choice of material and the frequency. The accurate characterization of the properties of a textile substrate is fundamental before designing a textile antenna. A summary of the properties that various researchers use for antenna design are outlined in Table 1.

Table 1. Substrates' dielectric properties.

Material	Permittivity (ε_r)	Loss Tangent (tanδ)	Frequency (GHz)	Reference
Denim	1.40		2.4 & 5.2	[3]
Denim	1.40		0.9 & 1.8	[4]
Leather	2.95	0.16	0.9 & 1.8	[4]
Denim	1.70		3–12	[5]
Denim	1.80	0.07	2.4 & 5	[6]
Velcro	1.34	0.006	2.4 & 5	[6]
Denim	1.8–2.0	0.014	14–40	[7]
Denim (black)	1.8	0.07	3.3 & 5	[8]
Velcro	1.37		2.4 & 5	[9]
Felt	1.38	0.023		
Fleece	1.17	0.0035		
Moleskin	1.45	0.05		
Panama	2.12	0.018	2.6–3.95	[10]
Silk	1.75	0.012		
Tween	1.69	0.0084		
Perspex	2.57	0.008		
PTFE	2.05	0.0017		

Table 1. *Cont.*

| Material	Permittivity (ε_r)	Loss Tangent (tanδ)	Frequency (GHz)	Reference
Polystyrene foam	1.02	0.00009		
Felt	1.36	0.016		
Fleece	1.2	0.004		
Neoprene rubber	5.2	0.025	2.4	[11]
Silk	1.2	0.054		
Cotton	1.54	0.058		
Leather—different types	1.8–2.4	0.049–0.071		

From the above table it is clear that textiles typically have a low relative permittivity. The work in [12] studied the effect of different textile materials on wearable antenna performance. A patch antenna for Global Positioning System (GPS) operation was designed and five antennas were fabricated [12]; all of them used copper tape for the conductive sections. The different textile materials used for the substrate were: fleece (thickness, t = 4 mm), upholstery fabric (t = 1.1 mm), vellux (t = 5 mm), synthetic felt (t = 4 mm) and cordura (t = 0.5 mm). Non-conductive textile materials have low relative permittivity which reduces the surface waves (for patch antennas) and improves antenna impedance bandwidth. The measured dielectric constant of these textile materials at 1.575 GHz was between 1.1 and 1.7. Therefore, fabric substrate antennas are somewhat larger in physical dimensions than rigid antennas due to the low value of permittivity. Cordura is made by Delcotex, Germany. The name of the fabric is Delinova 200, which is woven from Cordura fibers. Cordura is a polyamide fiber with a nylon and Gore-Tex membrane. Delinova 200 is a textile impregnated with fluorocarbon and coated with polyurethane. Delinova 200—Cordura fabric proved to be an interesting fabric for textile antennas because of its strength, constant thickness and high water resistance properties [1,12].

The effect of using different textile materials as the substrate of a patch antenna was studied in [13]. Four antennas were designed and fabricated. The different textiles that were used for antenna fabrication are: wash cotton, curtain cotton, polyester and polycot. The polyester patch antenna yielded the best antenna performance in terms of gain and efficiency (polyester patch antenna yielded measured gain equal to 9.6 dBi compared to 7.2–7.5 dBi with the other antennas) [13]. The polyester had the lowest loss tangent compared to the other three textiles that were used for antenna fabrication. Additionally, as shown in [14,15] fleece fabric provides sufficient thickness for an adequate bandwidth. The low permittivity of fleece allows design of textile wearable antennas with large gain and high efficiency which claims fleece fabric as a very good candidate for textile substrate material.

The firmness of a textile material substrate can affect the performance of the textile antenna. An embroidered textile antenna (Sierpinski Carpet Antenna) was designed in [16] using fractal antenna technology. Two antennas were fabricated. One antenna was embroidered on denim and the other on felt. The first one showed the best performance—denim fabric has a firm surface compared to felt fabric that has a soft fluffy surface which gives disadvantages to felt—*fluffy* surfaces are easily compressed and the variable thickness affects the antenna properties. Both fabricated antennas are very good candidates for wearable applications. For good antenna performance homogeneity of the textiles is a requirement [10]. The accurate characterization of the textile properties is also a requirement for

good agreement between the antenna design and manufacture [10]. In [17] a novel method to measure the relative permittivity of textile substrates and eventually to design and manufacture a textile patch antenna is described and proposed. Once a patch has been designed by using an estimated value for the dielectric constant and then when the antenna is manufactured, a different resonant frequency occurs which means that the initial estimation was wrong. Then there is a need of tuning the permittivity and using the right value for the design. One method of characterizing the dielectric properties is by using split post dielectric resonators at the respective frequencies as seen in Figure 1. The dielectric properties can be measured for example using a split post dielectric resonator [18]. However, in practice an effective permittivity can be found by comparison with measurements.

Figure 1. (**a**) Q-meter measurement setup measuring a piece of felt by using the 1.9 GHz split post resonator; (**b**) Resonator-Vector Network Analyzer (VNA) setup measuring a piece of felt by using the 1.1 GHz split post resonator.

(**a**)   (**b**)
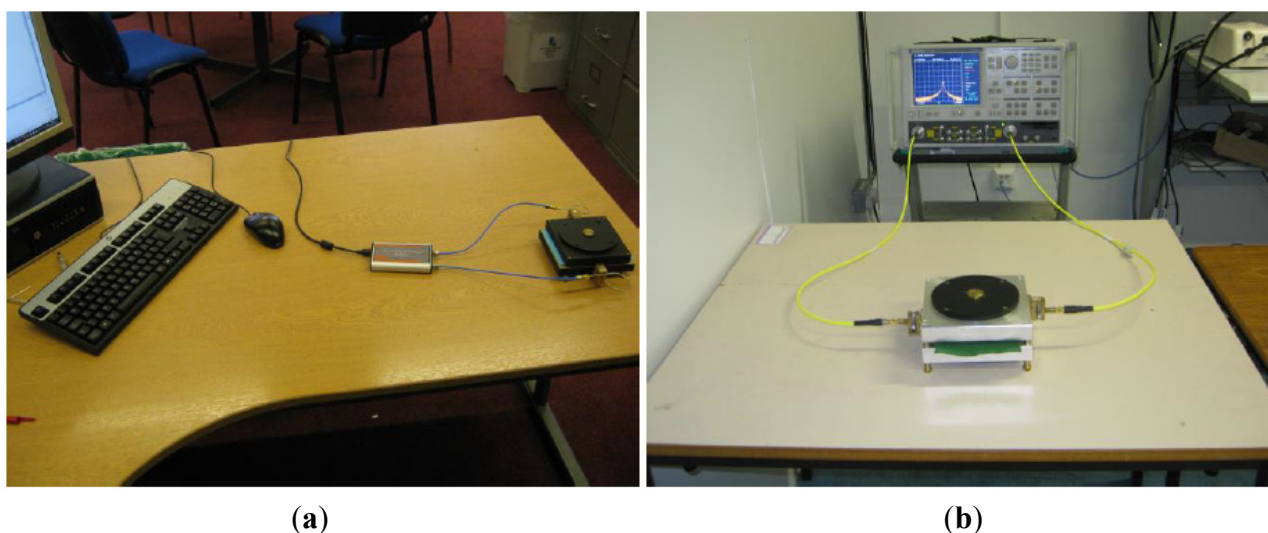
A novel polymer substrate was developed, produced and used as an RF substrate [19]; it is known as Polydimethylxiloxane (PDMS) ($\varepsilon_r = 3$, tan $\delta < 0.02$ from 0–1 GHz). PDMS has a good mechanical flexibility and low loss performance. By adding ceramic powder to the PDMS, the polymer composite is capable of providing tunable permittivity.

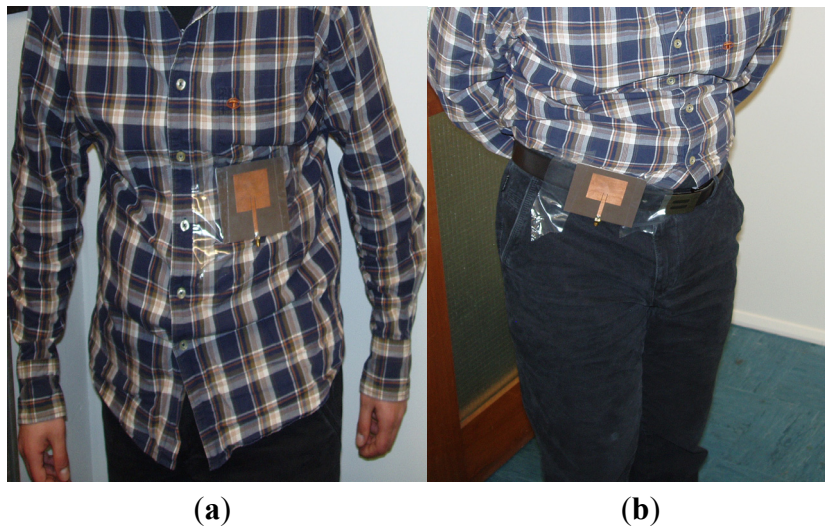## 3. Manufacturing Techniques for Wearable Antennas

The design and moreover the manufacture process of a wearable antenna is of crucial importance in terms of antenna performance and manufacturing time. The manufacture process of wearable antennas should guarantee good agreement with the design and simulation results and should lead to robustness and repeatability of the wearable antenna. This arises from the fact that the wearable antenna is supposed to be embedded on the garments and it will operate under different conditions (movement of the wearer, weather conditions, temperature, bending and crumpling conditions). In addition, washability is a requirement in the case of embroidered textile antennas where the goal is that these antennas should be part of the clothes. Embroidered antennas are a great opportunity to connect wearable antenna technology with the industry of textiles. In this section, the manufacturing techniques used so

far on wearable antennas are described and there are two categories: (1) rigid and (2) flexible (often textile) antennas.

3.1. Rigid Wearable Antennas

The manufacture process of rigid wearable antennas follows the conventional techniques of printing or constructing antennas for example by using etching. Rigid antennas worn on the body can be miniaturized so as to minimize the inconvenience to the user as conventional antennas are not practical, see Figure 2. These rigid antennas sometimes need to be manufactured in a curved contoured shape so as to meet the wearable requirement [20]. Another difficulty is the small size of these antennas and their complex structure [21].

Figure 2. (**a**) 2.5 GHz patch antenna positioned at the left side of the thorax under the chest; (**b**) 2.5 GHz patch antenna positioned on the trunk.

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

3.2. Flexible Textile Wearable Antennas

Textile antenna manufacturing techniques can be divided into the following categories: (**1**) Thin and uniform metallization layers (*i.e.*, copper or silver tape, foil) attached to the non-conductive textile fabric [22]; (**2**) the use of conductive textile yarns to weave or knit the conductive patterns of the antenna and then attach or stitch them onto the non-conductive textile substrate [22]; (**3**) the use of conductive textile yarns to embroider the conductive patterns of the antenna on the non-conductive textile substrate [22]; (**4**) Inkjet and screen printed printing on non-conductive textile materials.

Before moving into the details of each technique it is important to note that different conductive textile materials (*i.e.*, copper tape, knitted copper, *etc.*) can result in different antenna performance. The effect of different conductive materials on wearable antenna performance is presented in [23]. Six different antennas were fabricated. For all the antennas, the substrate that was used was fleece fabric (thickness = 3.5mm, ε_r = 1.1). The different conductive sections of the antennas were: solid copper tape; knitted copper tape; vertically cut pieces of copper tape; horizontally cut pieces of copper tape; horizontally cut and soldered copper tape; aracon fabric. Conductive tapes and fabrics are both acceptable solutions for the conductive sections [23]. Though, not all copper tape and fabric configurations

are appropriate for textile antennas. The conductive fabric is required to have a good conductivity and needs to have a high density of conducting fibers. A principle derived from this study [23] is that there can be discontinuities in the conducting shape from cutting the copper tape as long as these discontinuities are parallel to the surface current (vertically cut copper tape). When discontinuities are perpendicular to the current flow direction there will be reflections of the electromagnetic fields at the interfaces [23]. Additionally the use of different conductive materials (conducting nylon, embroidered conducting thread, conducting paint) as conductive sections and different constructing methods of a textile spiral antenna were presented in [24].

3.2.1. Thin and Uniform Metallization Conductive Sections

This technique is the fastest when it comes to the manufacture of one or a small number of antennas but when it comes to the mass production of textile antennas it is probably a slower than other techniques due to the manual work which is required. Generally, this technique is reasonable for experimental antenna prototyping but may not be ideal for longer term solutions. It is very easy to attach copper tape or foil on a textile substrate but it is also possible that the copper tape might be detached while bending or even due to environmental conditions (*i.e.*, humidity, heat) (Figure 3).

One solution to avoid having the textile antenna permanently integrated on the garment is to use Velcro connectors [25]. In [25] a wideband wearable textile antenna is presented where the fabricated antenna is integrated on a jacket at the inside side of it by using Velcro. This means that the antenna can be easily physically attached and detached to and from the jacket by using Velcro strips.

Figure 3. Textile patch antenna (substrate: felt, conducting sections: copper tape) with partially detached copper tape due to environmental conditions.

3.2.2. Woven or Knitted Conductive Sheets

This technique requires more time to construct a single antenna but may allow an element of automation for mass production. This can result in a more tolerant and flexible antenna structure compared to using copper tape. We will include woven metallic cloths, in this section. An example of this is Nora Dell which is a textile coated with nickel and silver to from a highly conducting flexible sheet (Figure 4).

Figure 4. Nora Dell conductive cloth.
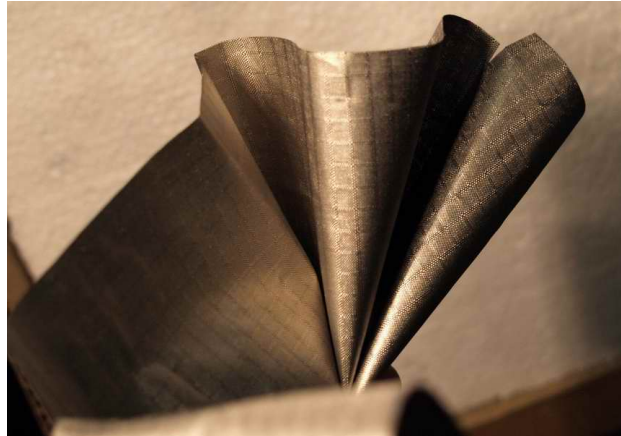
Many papers considering textile antennas using woven or knitted conductive sheets have been published and will be reviewed in this section. The first compact fabric antenna design for commercial smart clothing was presented in [26]. This compact antenna is a patch antenna using fleece fabric as substrate and knitted copper for the conductive sections. In [27] a nickel plated woven textile, which has a high tolerance against oxidation and corrosion, is stable and has a very good conductivity, was attached on a spacer by using ammonia-based textile glue. The textile glue showed negligible influence on the sheet resistance since the plated textile is densely woven [27]. In [15] two antennas manufactured by using two different methods of attaching conductive Flectron onto Fleece fabric were considered. The layers in the first antenna were attached to each other by using a glue stick and the layers have been additionally stitched together using non-conducting threads to enhance the robustness of the antenna. For the second prototype an adhesive sheet which melts when ironing was used to attach the layers together. The first antenna showed better performance in terms of return loss and bandwidth. It can be assumed that the adhesive sheet melting inserts more losses into the antenna compared to the glue stick.

In [28] four different methods were used to attach the conductive woven textile on the non-conductive textile were examined: (i) liquid textile adhesive (golden fix); (ii) point wise application of conductive adhesives; (iii) sewing and (iv) adhesive sheets which melt when ironed. The 4th attachment method yielded the best results out of the four methods; it barely affected the substrate (felt) thickness which helped the antenna to maintain the geometrical designed dimensions [28], also described the design of woven and knitted conductive textiles, the material selection criteria and the characterization of the material properties (sheet resistance of the conductive textiles and the permittivity, tangent loss of the non-conductive textile). The effect of various weave patterns of conductive cloths in combination with the non-conductive dielectric substrate is presented in [29,30]. This was studied because not all fabric patterns are symmetric. There are some fabrics with asymmetrical patterns on each side. This means that some conductive fabric patterns have the majority of the conductive threads on one side of the fabric. In these works ([29,30]), the cases where the side of the fabric (conductive) with the majority of the conductive threads was directly attached onto the dielectric non-conductive substrate yielded less dielectric loss and better conductivity compared to the cases where the side of the fabric (conductive) with the minority of the conductive threads was directly attached on the dielectric non-conductive substrate.

In [31] an aperture coupled patch antenna using two different textiles (fleece and felt) for the substrates was proposed, designed and manufactured. Additionally, two different conductive textiles were used for the patch, ground and the microstrip line. For the patch, Shieldit was selected because it has an additional adhesive layer which made it easier to attach the patch to the substrate. For the ground and the microstrip line Flectron was used because of its smoothness and low surface resistivity. The two layer antenna allowed an independent selection of the antenna substrate. Fleece fabric was selected for the antenna substrate because it has permittivity close to 1 and a low loss tangent which is optimal for the radiation efficiency. Felt was selected for the microstrip feed line substrate. Felt has a higher permittivity and by selecting a thinner material the radiation losses are restricted.

A new design of a woven textile antenna covered with a protective cloth (e.g., waterproof, insulation) was presented in [32]. Finally a novel grid microstrip woven antenna design and fabrication method is presented in [33]. The substrate of the antenna was a 3D woven glass fiber fabric and the conductive yarn that used was copper yarn. The conductive yarns were orthogonally woven to produce a grid structure.

3.2.3. Embroidery

The traditional embroidery process creates aesthetic shapes using colored threads on a base textile material. By using specialist conducting threads, antennas can be embroidered onto the base textile. Although the basic principles are the same, the technology has advanced to enable a digital image to be directly embroidered using a computer aided embroidery machine (Figure 5). The conducting threads must exhibit suitable flexibility and strength so as not to be broken by the high tensions required in the embroidery machine.

**Figure 5.** Computer aided embroidery machine at Loughborough University.
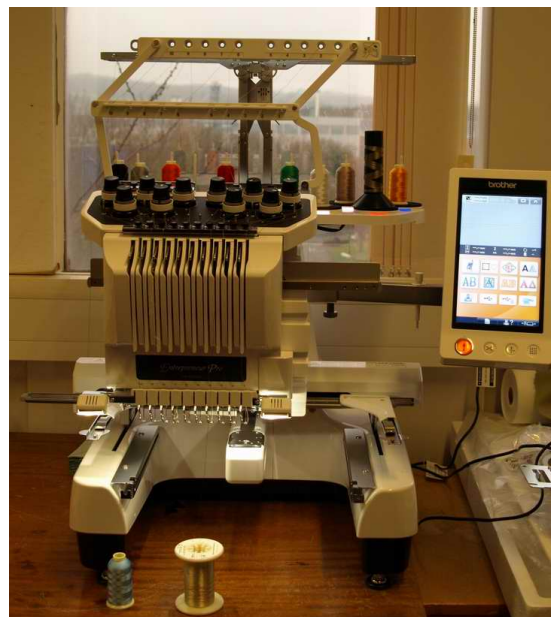
Of great importance before designing and embroidering the antenna is knowledge of the properties (*i.e.*, DC resistance, conductivity) of the conductive yarns to be used [34]. Once the conductive yarns are characterized then it is easier to find techniques to improve the performance of the antenna; for

example using a higher density of stitching. Conductive threads with high resistance yield poor S21 results in transmission line measurements [34]. After the characterization of the conductive yarns and of the textile substrate, the design of the embroidered textile antenna (Figure 6) comes next. The design and simulation method to model wearable antennas composed of embroidered conductive threads is presented in [35]. A detailed simulation method is required to model the directional and discrete nature of the threads [35] (Figure 7).

Figure 6. Embroidered patch antenna.
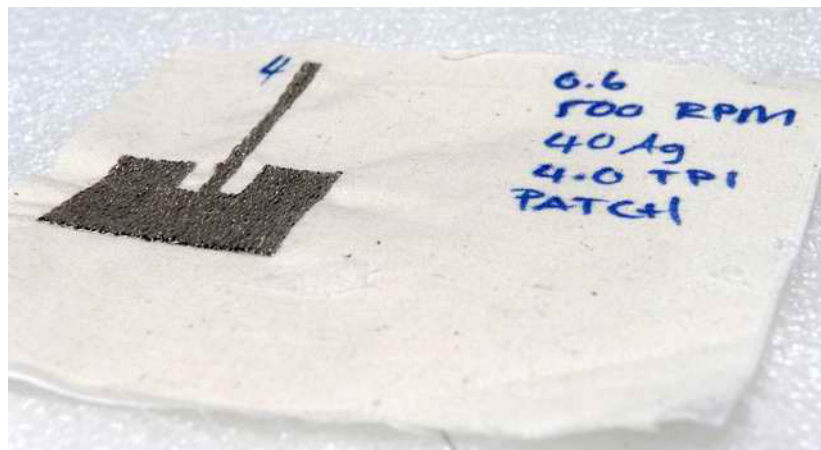
Figure 7. Embroidered patch antenna magnified to observe the air gap between the conductive threads.
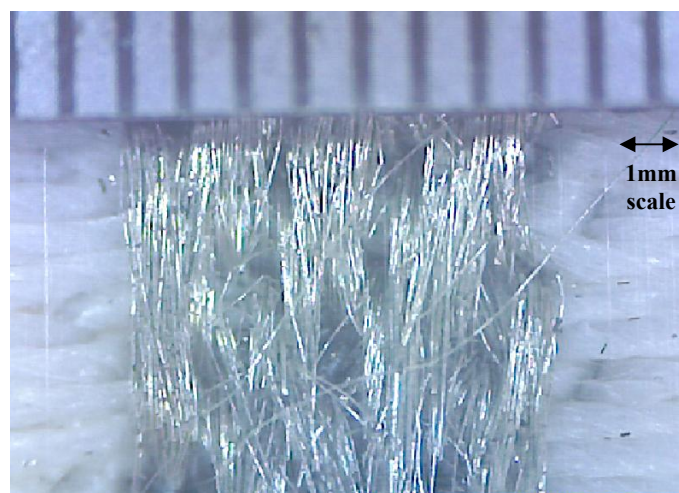
The challenges of fabricating embroidered antennas are outlined in [36]. Such challenges include: selecting the most suitable conductive thread in terms of conductivity; strength; flexibility and the assessment of the behavior of the conductive threads when they are stitched to form an approximately continuous object so as to improve the efficiency of the patch antenna [36]. The effect of the stitch direction and stitch density on the performance of the antenna has been extensively studied and described in [37]. The understanding of the current flow on a designed patch antenna is a fundamental requirement to choose the stitch direction (Figure 8). Higher antenna efficiencies can be obtained by ensuring the principle current flow is parallel to the stitch direction. This can lead to further challenges when the design is required to also work at higher modes where the current is in the perpendicular direction and for more complicated designs where the current flows in different directions.

Figure 8. Simulated surface current of two different stitch direction patch antennas.
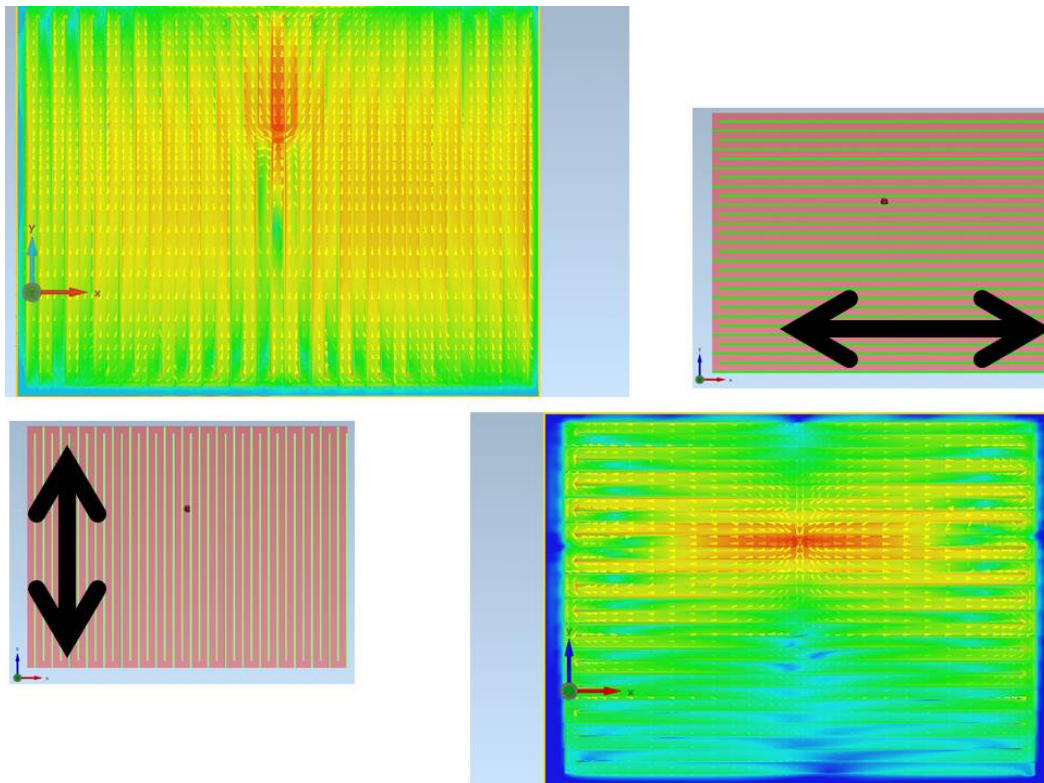
The effect on antenna performance caused from different stitching geometries is studied and presented in [38]. The effect of the stitch spacing on the gain and directivity was examined. Generally, the closer the stitching spacing, the higher the antenna efficiency will be. However, this comes at the expense of reduced flexibility and increased length of thread which directly leads to higher manufacturing costs.

The effect of the type of stitching on the dipole antenna performance is described and demonstrated in [39]; where dipole tag-antennas embroidered with different thread densities and two different stitch patterns were considered. The embroidering aspects of Ultra High Frequency (UHF) Radio-Frequency Identification (RFID) antenna were presented in [40]. Professor Volakis and his colleagues have contributed to the field of embroidered antennas and RF electronics [41–48]. Throughout these publications novel conformal embroidered antennas and novel embroidered sensors for medical applications are presented. Novel embroidered microstrip lines were developed and the fabrication procedure of e-fiber transmission lines was proposed. An ultra-wideband embroidered textile antenna is presented in [49]. Due to the usage of conducting thread, the antenna is flexible; can facilitate washing and can be an attractive solution for a wearable device.

3.2.4. Inkjet and Screen Printed Antennas

Inkjet and screen printing [50] can also be used to create conducting sections of wearable antennas. However, the substrates are generally paper or Kapton while textiles are not ideal printing substrates. As the name suggests screen printing requires a mask to be made for each design and therefore is less practical for different individual designs [51,52]. RF transmission lines have been previously screen printed onto a cotton substrate [53].

Inkjet printing does not require a mask and designs can be created within minutes of receiving the computer file containing the geometry and hence enables great manufacturing flexibility. Typically, silver nanoparticles in solution are used to make thin conducting lines which are approximately 1 μm thick. Therefore, printing on rough surfaces such as textiles is very challenging. In addition textiles are porous materials which make it more challenging to create continuous conducting lines [54]. Other challenges of inkjet printing on textiles include achieving a continuous conducting track with a high conductivity; robustness to stretching and inherent movement and resilience to high temperatures required to remove the non-conducting solvent from the ink.

These challenges can be overcome by first screen printing an interface layer onto fabrics. This process is outlined in [55]. The inherent surface roughness of the cotton fabric is reduced by using screen printed interface layer and enables the printing of antennas with reasonable efficiencies with only one or two layers of ink. This process has been applied to dipoles [55] and patch antennas [56].

Antenna performance can be improved by printing multiple layers but this increases material costs and manufacturing time and reduces the resolution of the lines. As the ink layer is thin, skin depth issues must be considered. This is likely to limit the applicability of inkjet printing on fabrics to higher frequencies.

3.3. Comparison of Embroidery with Other Techniques

Embroidery is advantageous compared to the others because embroidery machines already exist in industry; so it is easier to apply this technique for mass production of garments with integrated embroidered textile antennas. As the currents in embroidered antennas prefer to flow along threads rather than from thread to thread, embroidery may naturally lend itself to linear antennas such as dipoles or spirals. These types of structures can be very hard to fabricate using copper tape or Nora Dell cloths. The design of spirals or dipoles as opposed to patch antennas will also reduce the length of thread required and hence the cost of the antennas. Embroidery uses specialized thread which contains silver which is expensive. Note, the same is true for inkjet printing and Nora Dell. Therefore, the level of wastage of using manufacturing techniques will strongly affect the manufacturing costs.

Embroidery allows repeatable geometries to be made via the computerized embroidery machines. As no mask is required, embroidery can also make one-off bespoke items. Repeatable structures as a Frequency Selective Surface (FSS) structure (Figure 9) can be embroidered by copying the original shape [57]. Fractal antenna technology [16] to design wearable textile antennas could result in attractive and compact designs, however, the accuracy of embroidery is limited to approximately one millimeter. This can be partially overcome by the use of computer aided embroidery. Additionally with embroidery the use of glue is not always a requirement to attach the textile layers together [58]. This can enhance the washability of the garment with the integrated antenna.

Figure 9. Embroidery machine creating FSS structure.

4. Specific Examples and Applications of Wearable Antenna Designs

A large number of wearable antennas have already been proposed for many different applications including miniaturized rigid and flexible textile antennas. Examples of rigid miniaturized antennas are outlined in the first half of this section. A shorted spiral-like patch antenna operating at 430 MHz suitable for military Radio Frequency (RF) Communications was presented in [21]. This antenna was etched on FR4. The use of an electromagnetic bandgap (EBG) structure makes this antenna suitable for wearable applications by reducing the power radiated towards the wearer. The overall size of this antenna is 11.4 cm × 7.6 cm, which is small compared to the wavelength at the resonant frequency. In [20] a dipole and a spiral antenna for military wearable applications (100–500 MHz) were proposed. These antennas are unobtrusive and low profile. In [59] three antennas: (a) $\lambda_g/4$ antenna with ground shield; (b) a dipole V antenna and (c) a square dipole antenna were made out of copper with a glass—epoxy substrate ($\varepsilon_r = 4.8$) and proposed for operation 868 MHz, for medical tele-monitoring applications. These antennas would be more suitable for a patient to wear if they were textile which will make them more flexible and comfortable. In [60] Salonen presented a dual band (900 MHz & 2.4 GHz) Planar Inverted F-Antenna (PIFA) antenna for wearable applications suitable for the Global System for Mobile Communications (GSM) and for short range Bluetooth bands. The antenna was designed as a PIFA so as to radiate away from the human body. A dual mode antenna for on/off-body communications (10 MHz/2.45 GHz) was proposed in [61]. This antenna consists of an L-shaped slit loaded for the 2.45 GHz band (off-body link) connected with an electrode which is mounted on the body and is suitable for the 10 MHz (on-body) link. In [62] a four arm spiral slot patch antenna for radio telemetry capsules was proposed for operation at 915 MHz. In terms of miniaturization a reduced ground plane shorted patch antenna for on-body communications at 2.45 GHz was proposed by Scanlon *et al*. [63] with a miniaturized (~$\lambda/5$) ground plane. A monopole antenna mounted vertically on the body radiates the same way (parallel radiation towards body surface) as this shorted patch [63]. However, this shorted patch proved to be more suitable for the on-body link because it is compact. In [64] a miniaturized diversity antenna dedicated to wireless body area network was proposed. The antenna was printed on FR4. The combination of a PIFA and a top-loaded monopole

yielded distinct patterns. The strong isolation observed between the broadside and the end-fire radiation of the antenna is a significant feature which limits the correlation between the received signals. Other miniaturized wearable antenna designs are detailed in [65–67].

Smart clothes evolution will eventually result in the establishment of textile antennas in widespread use. This may mean that clothes and wearable textile antennas or electronics will be designed as one piece. Examples of wearable textile antennas are outlined in the second half of this section. A textile antenna suitable for fire fighters jackets was presented in [68]. The substrate shell of jacket is made of aramid fabric which is fireproof. In [69,70] a flexible dual band PIFA was proposed for commercial smart clothing. An inexpensive textile patch antenna for off-body wireless sensor communications for monitoring patients at the 915 MHz Industrial, Scientific and Medical (ISM) radio band is presented in [71]. Zelt was used for the conducting parts and felt for the substrate of this antenna. The cost per square meter of Zelt and Felt is equal to $20 [71]. With 1 square meter of these two materials we can fabricate about 5–6 such antennas. A dual band E-shaped patch textile antenna made from felt and copper tape is presented by Salonen in [72]. This antenna operates at 1850 MHz (BW = 100 MHz) and 2450 MHz (BW = 110 MHz). The wearer with this antenna can access GSM1900 and Wi-Fi communication links. Additionally a dual-band wearable textile antenna for the same communication links was proposed in [73]. A novel circularly polarized textile antenna for personal satellite communications is proposed in [74]. Two textile antennas using Nora Dell for conducting sections and Nomex for the substrate are designed in [75]. The two antennas are proposed to be integrated in an extravehicular suit (astronaut suit) for space network applications. A complementary-8 shape e-textile antenna element can be used as part of a body worn communication and navigation antenna system that supports many different bands, including those used by both 802.11 and 802.16 bands. A system of six complementary-8 shape e-textile antennas shifted by 90 degrees can be used for polarization diversity and omnidirectional coverage most of the observable sphere surrounding the astronaut. This is an important requirement for the astronaut communication and navigation. In [76] a fabric equiangular spiral antenna using Nora Dell for the conductive sections is fabricated and presented. The earliest wearable active textile receiving antenna in the 2.45 GHz ISM band was proposed in [77,78]. A low noise amplifier (LNA) is fabricated on a hybrid textile fabric and positioned directly underneath a wearable patch antenna. In [79] a dual band coplanar waveguide feed patch antenna was designed. Zelt is used for the conductive parts of the antenna and felt for the substrate. The use of an EBG substrate under the patch antenna improves the gain and reduces the back radiation by at least 13dB making the antenna suitable for wearable applications and more tolerant to the effects of the lossy human body in terms of antenna efficiency. Additionally, the improvement on antenna performance by the use of an EBG is presented in [80] where the effect of bending the textile patch antenna is fully examined. It is hypothesized that the EBG structure which inevitably adds an extra height to the patch antenna could be hidden into clothing. Another triangular textile patch antenna over an EBG structure is presented in [81]. In [82] the on-body improvement performance of a dual-band wearable textile by using an EBG structure was presented. Two novel Ultra Wide Band (UWB) textile antenna designs were proposed in [83]. The conducting parts of the antennas were made with Shieldit and the substrate is a thick felt. These antennas are fed by a coplanar waveguide. Because of the lack of a ground plane between the antenna and the human body the placement of the antennas on the body degraded the S11 at most locations. The dielectric coupling between the antennas and the body introduced a down shift

of the resonant frequencies. The coupling with the lossy body is expected to degrade the efficiency and the gain of these antennas. Therefore, the use of an EBG structure as previously referred will improve the performance of the coplanar waveguide feed textile antennas. The process of designing a printed textile monopole antenna is presented in [84] which is lightweight and has a very simple structure to fabricate. One disadvantage of a printed monopole is that due to its short partial ground plane its performance is highly affected and degraded by the presence of the human body. This last point renders the printed textile monopole a moderate candidate for wearable applications. A broadband waveguide slot antenna is proposed where denim was used as the substrate filling the waveguide—this proposed waveguide slot antenna is cheap to manufacture [8]. A novel wearable substrate integrated waveguide (SIW) antenna fabricated entirely from textile materials is presented in [85]. The SIW-on-textile integration results in an antenna exhibiting high robustness against bending, low influence of the human body and high front-to-back ratio. In addition this antenna is light weight, flexible and low cost, thus making this antenna well suited for on-body use. Additionally a new wearable textile antenna based on a half-mode substrate integrated cavity was proposed in [86].

Various embroidered textile antennas have been proposed for different applications. A low frequency (COSPAS/SARSAT satellite beacon—406 MHz) embroidered spiral antenna is proposed in [87]. An embroidered wearable multi-resonant folded dipole antenna for FM reception was fabricated in [88]. Also a UWB embroidered antenna design where stainless steel thread was used for the conductive thread is presented in [89]. GSM and Wi-Fi embroidered textile antennas were fabricated onto regular fabrics using an automated embroidery procedure with high density stitching [90]. The proposed antennas offer user-comfort and flexibility.

A distributed body-worn transceiver system for mobile communications with the use of electro-textile antennas was proposed in [91]. Two major features causing the popularity increase for the distributed body-worn system are: (1) the high efficiency of the electro-textile antennas that can be seamlessly embedded into human clothing and (2) significant system diversity gain due to spacing among antennas distributed on the body.

5. Challenges of Wearable Textile Antennas

Once the wearable textile antenna is manufactured then the step of characterizing it is the next in line. Characterize how the wearable textile antenna operates in Free Space and when mounted on a human body. This section addresses some of the challenges of measuring wearable antennas. Initially it is useful to measure the antenna performance (gain, impedance matching (S11), directivity, efficiency, *etc.*) in free space [92–94]. Then the wearable textile antenna will generally operate under the movement of human body, some specific deformations on the antenna such as bending (on cylinder or on a human arm) [13,95–98] and crumpling [99,100] must be considered. The antenna should be measured under different environmental conditions such as high humidity to represent perspiration or exposure to water [101,102]. Additionally, the embroidered textile antennas are supposed to be part of the garment. So testing the durability of the antenna in terms of performance after washing is required [103]. Also the repeatability in terms of performance of a specific textile antenna should always be examined [104].

Measurements on a real human body [105,106] or with a human phantom [107–109] should take place. The antenna on-body or on-phantom should be measured in terms of S11, near-field, far-field [110–112]. The antenna-body interactions need to be fully characterized. Measurements can take place in an anechoic chamber or in a real environment (outdoors [113] and indoors). Measurements are the final and the most important step to characterize an antenna system. All practical applications rely on measurements results rather than purely simulations.

Measurements of wearable antennas are particularly challenging. The conductivity of the flexible materials is often lower than copper. Dielectric properties of the substrate are generally not well known and can vary from different suppliers or even different batches of the same supplier. As the permittivity is related to the density of fibers it can even change within the same substrate. The thickness of the substrate may changes depending on the method of attaching the different elements which is often an arbitrary non-repeatable process such as adding the same amount of glue across the substrate. The point where the connector meets the antennas is critical in all antenna designs. However, in wearable antennas, this sensitive point depends on the position and orientation of the antenna. These parameters increase the difficulty of wearable textile antenna measurements and make it a real research challenge.

Additionally, when antennas are placed in close proximity to the human body, the specific absorption rate (SAR) must comply with International Commission on Non-Ionizing Radiation Protection (ICNIRP) and IEEE limits [114]. This means that the body can only be exposed to limited levels of electromagnetic fields. There is still public concern about possible health issues and EM radiation. Hence, while the majority of people are happy using mobile phones a new type of antenna embedded in clothing is likely to cause some level of public debate. Wearable antennas are clearly close to the body and the SAR must be considered via simulations and measurements. The emitted power of a device is related to the communication distance. Therefore, Bluetooth wearable devices that connect to a mobile phone will use low power levels and hence have very low SAR values. Whereas devices communicating with mobile phone base stations or even satellites will transmit more power and hence have higher SAR values.

The connection between the wearable antenna and the electronics is arguably the greater weakness in wearable electronics. The majorities of published papers do not consider this and use an SMA connector and a coaxial cable. Having a rigid connector negates some of the advantages of having a textile antenna. Recently, RF measurements have demonstrated the feasibility of using Hook and Loop as an RF connection mechanism at the low GHz frequency range [115]. This has the advantage that the antenna can be disconnected from the electronics and/or clothing to allow washing or for the electronics to be placed in a different item of clothing. However, considerable work is needed to find the optimal solution to this challenge.

Finally, manufacturing costs are still a challenge for wearable antennas. The specialized threads for embroidery typically cost $1.50 per meter and although prices will decrease, the silver content means that costs may not decrease until other alternative materials can be found. As a rough guidelines embroidered antennas operating at 2.4 GHz (~6 cm × 4.5 cm) can contain 5 m of thread. The cost of Nora Dell and inkjet inks are also dependent on the cost of the silver raw materials.

6. Future Opportunities

Futurists and antenna designers have been discussing the idea of wearable technology for nearly two decades. Generally, the integration of wearable technology into main stream society has been slower than expected. This was due to a combination of the technology not being ready and insufficient market pull.

Current technology is driven by the need for data and connectivity. There were one billion smart phones sold in 2013 [116]. This is evidence that people not only want technology, but they will spend money if it enhances their quality of life. Sensors that communicate voice, video, physiological environmental and location data will become increasingly ubiquitous. It is predicted that there will be 50 billion devices connected to the internet by 2020 [117].

The feeling that wearable technology is on the cusp of going mainstream was exemplified by the level of interest at the Consumer Electronics Show in Las Vegas in 2013 where wearable technology was one of the main talking points [118]. There are now many devices on the market integrated into wrist bands that monitor the calories a person burns per day. The market for wearable technology is estimated to be worth more than $5 Billion by 2016 [119] and this market includes medical, fashion, sports, military and emergency services [32]. Other estimates have this value as high as $19B by 2018 [120]. 400 million smart watches are expected to be sold by 2020 [121]. Intelligent glasses with a small screen in front of the eye [122] are now available. Major industrial companies are moving into the wearable technology area [123].

Currently, two thirds of hospital beds in the UK are occupied by people over 65. Furthermore, it is predicted that 10 million people alive in the UK today will live to the age of one hundred [124]. These numbers indicate that the current medical care of the ageing population is not financially sustainable without technological assistance. Telemedicine and remote monitoring can allow patients to be monitored in their own homes or with less medical supervision which will give more comfort to the patients. An example of this is electrocardiography (ECG) systems which monitor heart rate of patients by using antennas integrated into plasters [125]. There are also big opportunities for both recreational and professional athletes.

The requirement for wireless connectivity means that every device may have at least one antenna. Currently the electronics and battery are rigid items and therefore a rigid antenna can also be included without inconvenience, especially at 2.4 GHz where PIFAs are small. Many observers believe that the next step will be for this technology to become truly wearable and be integrated directly into clothing where textile antennas will be required. Electronics is continuing to shrink in size and emerging technologies may allow the textiles themselves to harvest energy [126]. RFID tags in clothing are a current suitable candidate for fabric antennas as no battery is required and the RFID chip is very small so the use of flexible antennas will improve user comfort. Ongoing research into flexible batteries and flexible electronics will further drive the desirability for flexible antennas.

Textile wearable antennas have the advantage that they can be integrated directly into clothing; are aesthetic and do not need to be handheld which allows the technology to exist without the user consciously being involved. By making antennas out of textiles, the size limitations become the torso size and not just the size of the device. This relaxation of the size constraints can increase the gain and bandwidth. This has particular relevance to lower frequencies where the wavelengths are larger.

Author Contributions

Conflicts of Interest

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