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Application of 3D Virtual Prototyping Technology to the Integration of Wearable Antennas into Fashion Garments

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Abstract: A very large number of scientific papers have been published in the literature on wearable antennas of several types, structure and functionality. The main focus is always antenna efficiency from an engineering point of view. However, antenna integration into actual, realistic garments is seldom addressed. In this paper, 2D pattern and 3D virtual prototyping technology is utilized to develop regular clothing, available in the market, in which wearable antennas are incorporated in an automated manner, reducing the chances of compromising the garment elegance or comfort. The functionality of various commercial software modules is described, and particular design examples are implemented, proving the efficiency of the procedure and leading the way for more complex configurations.

Keywords: wearable antennas; textennas; garments; pattern software; fashion design software; integration

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1. Introduction

Wearable antennas have been a topic of interest for more than a decade, with applications of a very broad scope, including security, health, sports, communications, glamor, etc. Hundreds of articles have been published in the literature, and a comprehensive review discussing all aspects of wearable antenna applicability is presented in [1]. Actual products based on this particular technology range from biometric insoles and interactive belts to connected T-shirts and Bluetooth jewelry. On the basis of their functionality and structure, wearable antennas may be categorized into two generic types: rigid and flexible. Typical rigid structures are used for off-body radio links, such as in smart watches [2] and life jackets [3], or even on-body configurations, firmly attached to the garment, such as in a military badge [4]. A wider variety of rigid antenna designs may be found in [5]. On the other hand, flexible antennas can easily be worn by a human body, which naturally moves, causing clothing deformation; however, such radiating structures are much more difficult to incorporate to a garment. This particular problem concerning textile antenna (*textenna*) manufacturing is the main focus of [6].

According to [6], textenna manufacturing may be implemented through (1) thin conductive layers attached to dielectric textiles; (2) woven or knitted conductive textile yarns attached or stitched onto the non-conductive textile substrate; (3) conductive textile yarns embroidered on the non-conductive textile substrate; and (4) inkjet and screen printing on non-conductive textile materials. Advantages and disadvantages of all four methods are discussed in [6]. Specifically, the third method (embroidery) is found to be preferable to the rest because computerized embroidery machines already exist in industry; so, it is easier to apply this technique for the mass production of garments with integrated embroidered textennas, allowing repeatable geometries to be made.

The aforementioned discussion raises the question of automated production of a large number of garment copies, where identical flexible antenna configurations are incorporated.

Obviously, suitable design-oriented software is necessary for this task. Moreover, an important factor should be taken into account, which is often neglected by engineers driven by a solely practical mentality: fashion and aesthetic design. Wearable antennas are not only expected to function well, but they should be comfortable and not awkward looking, like that shown in Figure 1. No matter how good a design is, from an electromagnetic point of view, very few people would be willing to carry such a device on their clothes.

Figure 1. A clumsy, wearable patch antenna attached to a shirt with a plastic, transparent sheet; computer simulation based on [6].

In this paper, realistic clothing design procedures are presented, incorporating antenna models to actual garments readily available in the market for sale. To this end, pattern and fashion design software tools are utilized, which are not well known to the engineering community, although much more widespread among design scientists. It is shown how an engineering approach may blend with a fashion designer's insight to produce garments combining elegance and efficiency. In Section 2, a selection of textennas amenable to such a procedure is presented. In Section 3, the operability of specific pattern and fashion design software tools is explained. In Section 4, examples of basic textenna patterns are integrated into actual garments, and the results are demonstrated. Section 5 discusses available options, whereas Section 6 summarizes the article and draws useful conclusions.

2. Challenges and Restrictions of Characteristic Textenna Types to Be Considered for Computer-Aided Garment Design

Several textenna configurations using woven, knitted or sewed conductive sheets/threads have been proposed in the literature. Reviewing all of them lies outside the scope of this paper; the interested reader may refer to [6]. In this section, only representative, simple designs are selected to show the fundamental concept of the applicability of fashion design software to antenna integration into garments.

The first ever compact fabric antenna design for commercial smart clothing was presented in [7]. It is a typical microstrip patch antenna intended for WLAN (wireless local area network) applications at a frequency equal to f = 2.45 GHz. The dimensions of the conductive patch shown in Figure 2 are L = 56 mm, W = 51 mm, whereas the ground plane dimensions are 76 mm and 71 mm, respectively. Conductive parts are made of knitted copper fabric, while the substrate is regular fleece with a relative permittivity equal to ε_r = 1.04, measured at f = 2.45 GHz.

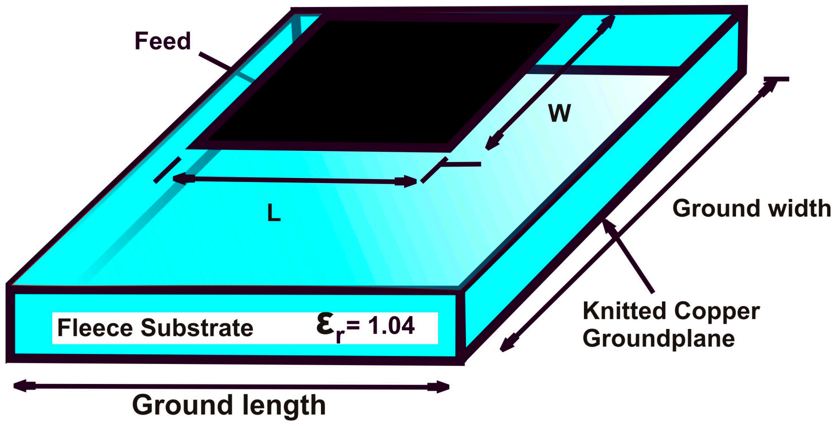


Figure 2. Geometry of the WLAN fabric antenna proposed in [7].

Apart from the antenna itself, additional instrumentation is necessary to facilitate actual radiation. For instance, a miniature feeding network for a patch antenna at f = 2.45 GHz is proposed in [8]. The main purpose is to reduce the length of the coupling aperture and the length of the stub to render the entire antenna structure more flexible and easier to handle. In order to compensate for performance deterioration due to miniaturization, periodic open conducting fingers are loaded to the coupling aperture, and a T-shaped structure is used at the end of the feed line (Figure 3). The substrate is made of nonconductive felt textile with relative permittivity and loss tangent equal to 1.3 and 0.044, respectively. The patch and the ground consist of ShieldIt superconductive textile with an estimated conductivity of 1.18×10^5 S/m, whereas FR-4 with permittivity 4.3 and loss tangent 0.025 is used as the feeding substrate.

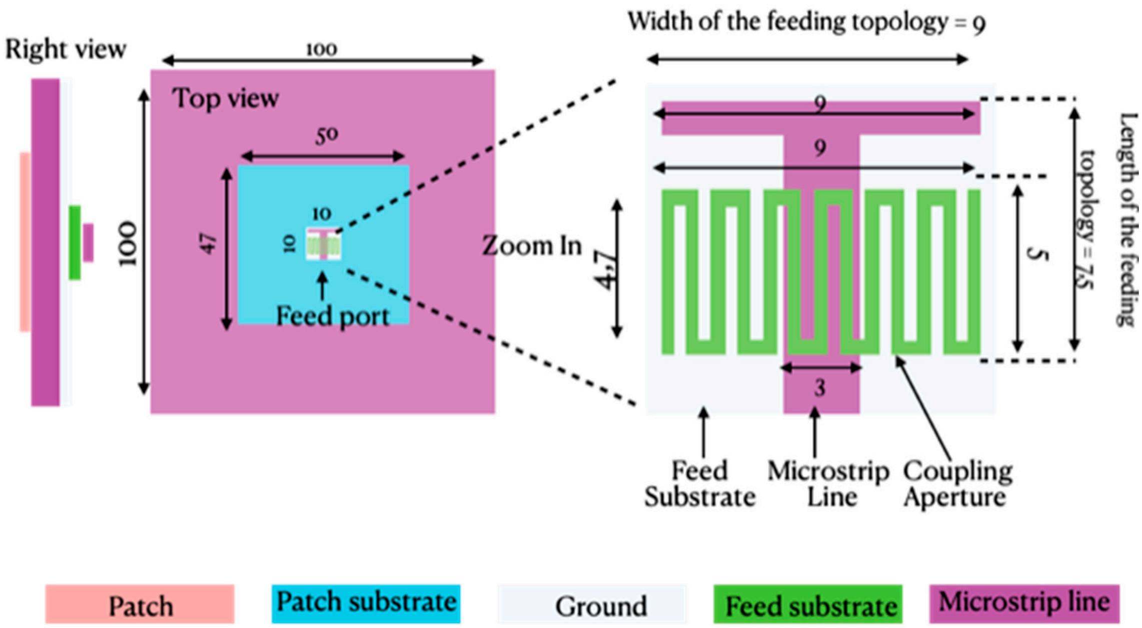


Figure 3. Feeding network of a patch antenna; design based on [8]. (**Left**): complete antenna. (**Right**): miniature feeding network. Dimensions are in mm.

More complicated geometries are presented in [9–11], where large, flexible wearable antennas are proposed for FM receivers (87–108 MHz) as an alternative to tunable small internal antennas. Shown in Figure 4, we chose a flexible third-order Minkowski fractal antenna that was designed to operate with land mobile radio systems at 136 MHz [11]. The work in [12] proposed a dual-band and dual-polarized button antenna for wearable body-centric communication (Figure 5). Button antenna can be easily integrated using copper as its conductive material, which is likely to outperform other more lossy conductive flexible materials in wearables [1].

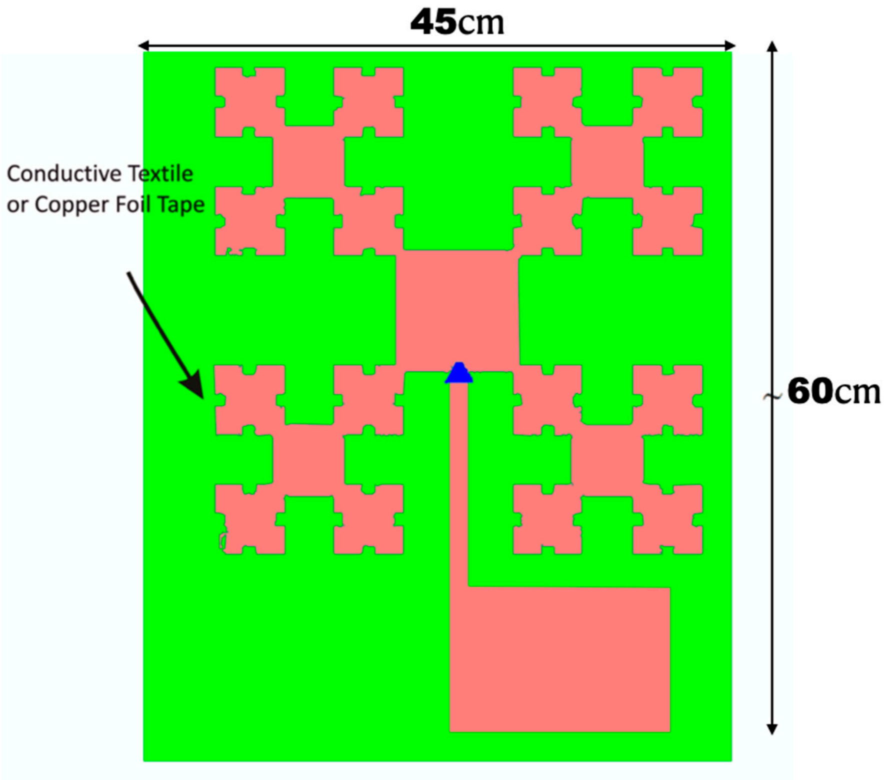


Figure 4. Large, flexible wearable antennas FM receiver (87–108 MHz); design based on [9].

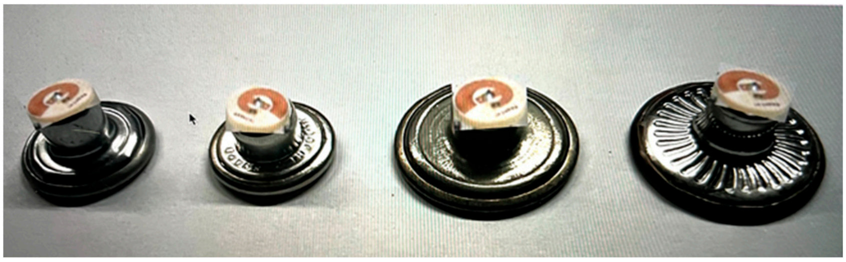


Figure 5. Button antenna; design based on [12].

Although the aforementioned designs are easy to implement from a geometrical point of view, various restrictions should be taken into account prior to computer aided design (CAD) and manufacturing procedures. Corchia et al. [13] discuss several challenges of wearable antennas; among them, major ones are technology invisibility to the user and similar wearability guarantee of conventional clothes. Additionally, according to [14], operations such as washing and ironing are key aspects of antenna robustness. Additional factors were also considered herein that ensure stable antenna characteristics, such as (a) the antenna, combined with the supporting structure must be sufficiently flexible, but not drainable, (b) layouts are to be protected against stress [15] and crumbling [16]. Moreover, the literature suggests that (c) embroidered patch antennas, due to low-cost automatic embroidery machines that operate with conductive yarns, are highly popular [6]. Finally, the selection of the fabric material is also of great importance. A textile fabric may be described as a mixture of fibers, air, and water molecules [17,18]. Hertleer et al. [19] recommend hydrophobic fabrics, with low moisture regain (MR < 3%) as a rule of thumb.

The design process of integrating antennas into clothing will have to cope with all the above. Three-dimensional visualization tools for clothing design can assist in confronting some challenges when designing wearable antennas. According to [13], the robustness of the antenna performance to the operating scenario is one of these. More specifically, close proximity or direct contact with the human body can strongly affect the antenna performance. Thus, as proposed in [13], by adopting an appropriate design approach, this problem can be solved. The use of 3D software visualization has the potential to aid significantly in the development process [20,21]. Three-dimensional software visualization may transform the way that knowledge-gathering activities take place during software engineering phases [22,23].

By using digital prototyping tools, the design of such wearable items can be developed in a very fast and efficient manner, selecting different materials either from the software's fabric library or importing the digital representation of a specific material. This process ensures the design options for the decision-making process are numerous, resources are not wasted since everything is developed in a digital and virtual environment, and the visualization of the digital wearable is very close to the actual physical item when fabricated.

3. Description of Commercial Fashion Design Software Functionality

Below are presented the best-known commercial 3D solutions available, according to [24]. The list is believed to be fully up to date since it is based on recent developments, such as research by [25], the 5th edition of WhichPLM [26] focusing on 3D, a recent Ph.D. thesis on the effective integration of 3D prototype [21], the latest relevant Texprocess exhibition [27], and the 1st 3D Fashion Summit in Greece (2021) [28]. The following 3D systems are described below (in alphabetical order) based on the previous research:

Accumark3D (Gerber) [29]
CLO3D [30]
Modaris 3D (Lectra) [31]
Optitex3D [32]
Style3D [33]
V-Stitcher (Browzwear) [34]
Tukatech [35]

Accumark3D

Accumark3D is a fully integrated 3D tool to Accumark2D CAD system and Ynique-PLM. Like V-Stitcher, Accumark3D uses the powerful opensource simulation engine, Blender, a widely used technology tool in animation, movie, video game and simulation industries. The 3D tool for virtual sampling aims at assisting apparel companies to reduce time and cost of development and sample making. It is also possible to generate 3D renderings, incorporating parametric, fully customizable materials chosen from the 6000+ strong Substance Source library [36].

CLO3D

CLO3D is a commercial solution allowing the creation of the virtual fit process by inputting 2D patterns and virtually sewing them on a 3D digital human model (avatar). According to [37], users can visualize the fit of the garment in 3D at the time of sketching. This platform also encompasses a rich library of more than 900 "digital twins" of physical fabrics to eliminate excess waste [38].

Lectra Modaris 3D

Modaris classic and 3D are used for all stages of pattern development, from initial digitization to 3D virtual prototyping. According to [39], Modaris Pattern Cutting software is Lectra's leading solution which integrates on the same platform with the Modaris 3D Virtual Try-on of 2D garments' patterns. Like the rest of the 3D software tools mentioned in this section, this one also contains industry specific data libraries with more than 300 fabric samples [40].

Optitex3D

Pattern Design Software (PDS) 3D is the the name of Optitex's 3D virtual sample generator, fully integrated with the PDS 2D digital pattern solution The user can develop a new pattern, edit an existing one from the database or import a pattern file from another system in .dxf, .asthma and .aama formats. Similarly, the system provides an ingrate digital fabric library, but the user can measure and simulate new fabric in 3D based on its physical and visual properties.

Style3D

Style3D is a 3D software tool created by Linctex. Fabric management is performed through the Style 3D fabric solution, where existing materials can be scanned to produce photorealistic digital swatches that can be utilized for the same purpose as digitally designed fabrics.

V-Stitcher (Browzwear)

V-Stitcher by Browzwear is the digital tool for 3D fashion development aimed at pattern makers, cutters and technical designers. Lotta solution is suitable for designers, V-Stitcher for pattern makers and manufacturers, and Stylezone is a cloud platform for showcasing 3D designs on web and mobile. Browzwear's Fabric Analyzer (FAB) is part of the expanding digital ecosystem that gives users the ability to determine all physical properties of any fabric, from its thickness to the stretch and bend.

Tuka3D (Tukatech)

Tuka3D is the virtual prototyping making software system from Tukatech. It provides customized virtual fit models and builds life-like virtual clothing samples [41]. What is new in the 2022 version is that it offers an open system that allows designers, brands, retailers and their factories to work efficiently within a virtual process. This means that users of other 3D systems can start their workflow with 266 actual replica avatars from Tukatech's extensive library of over 700 models [42].

4. Application of Commercial Fashion Design Software to Textenna Integration into Garments

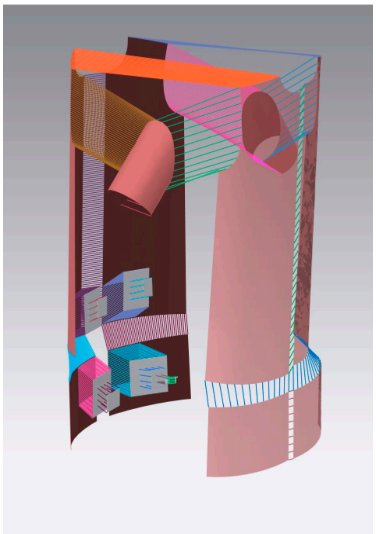
After investigating all the aforementioned 3D software solutions for prototype fashion modeling, the authors used CLO3D and V-Stitcher (Browzwear) to design a small collection of fashion garments that not only satisfy the needs of the wearer, but, most importantly, integrate popular textennas into their initial conceptual design. Moreover, the authors ensured that the integration of the chosen antennas was performed with special care for the characteristics of supporting structure, followed principles of construction and sewing assembly, selected appropriate fabric material (hydrophobic), took into consideration wearability and technology invisibility to the wearer, and lastly applied the selected design textennas to contemporary garment designs that can already be seen in several clothing brands worldwide.

Briefly, the process of the proposed antenna-equipped collection to be developed consisted of the following steps: (a) importing .dxf 2D CAD pattern files, (b) selecting an avatar in the appropriate size of the 2D pattern, (c) drawing/designing the selected antennas' outline in a 2D digital design software tool, (d) importing and tracing the .dxf outline of the antenna in the 3D prototyping tool, (e) virtually stitching the 2D patterns along with the designed antenna, (f) selecting fabrics from the preset library or scanning fabric/material with special scanning tools, (g) placing around the avatar, and finally (h) simulating and correcting the fit. The output file obviously contains implicitly all information related to the fabric mechanical and electromagnetic parameters of the materials involved in the design. Furthermore, it can be extracted in various formats, including .obj, meaning that it may be imported as input to widely used electromagnetic simulation software tools, such as CST EM Studio.

Shown in Figure 6, the patch antenna proposed in [8] was integrated into a dress, complete with its feeding network, including a T-shaped structure at the end of the feed line as shown in Figure 3 Due to the fact that this antenna consists of five layers and the actual miniature feeding network is of very small size, it was decided to be added as an interlining to the actual fabric of the garment. Therefore, it was integrated into the lower part of the proposed short-sleeved A-line dress. The size of the antenna was not adjusted to the pattern size, but the pattern was developed according to the size of the antenna instead. Figure 6A shows the virtual fitted dress without the embedded antenna, Figure 6B shows the dress with one patch antenna sewn internally at the lower part of the dress's hem and Figure 6C shows the possibility of this patch antenna to be placed in an antenna array (for instance, a 2X2 one). Figure 6D–F depicts a proposed style with digital textile design as an all-over print. When a textile all-over print is chosen, the somehow "bulky" look of the embedded antenna almost disappears. Figure 6G shows a closer look of the embedded antenna array; Figure 6H is a view of the inside garment by applying transparency to the back patterns; Figure 6I shows the placement of all the pattern pieces around the avatar with the virtual stitches applied (even on the antenna's five layers); and finally Figure 6J shows the actual construction and virtual sewing of these five layers of the antenna.

(A) (B) (C) (D) (E) (F) (G) (H)

Figure 6. *Cont.*


(I)

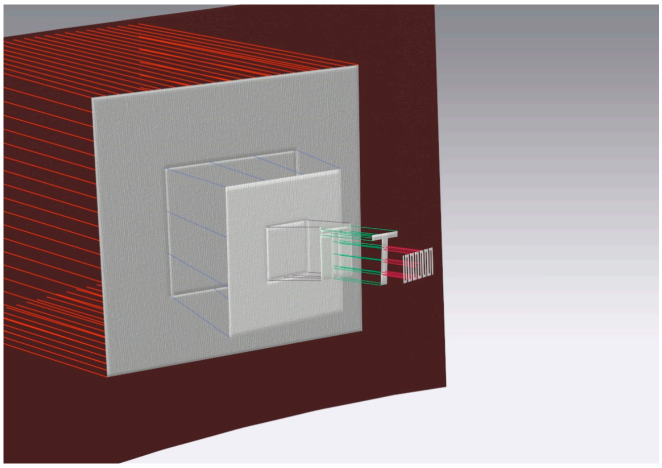

(J)

Figure 6. The patch antenna shown in Figure 3 [8] integrated in the lower part of the proposed short-sleeved A-line dress. Subfigure content is explained in the text.

Of course, placement of the antennas at that particular position of the dress is only indicative of the capabilities of the prototyping technology utilized. Depending on the actual radiation requirements, the antennas may be equally incorporated to any location, provided that there is enough space, for example, on the chest or the back, where deformation due to crumpling would be minimal.

The second garment is a women's bomber jacket. In this style, we integrated the flexible third-order Minkowski fractal antenna shown in Figure 4. Due to its large size, an appropriate pattern piece that accommodates the layout is the back of a garment. Figure 7A shows an antenna design integrated as an embroidered piece on top of the already virtually sewn jacket. Figure 7B shows the rendered design from five different angles, all in 3D virtual visualization software. In Figure 7C, a textile all-over print is applied, drawn from the 3D's software material library. The pattern piece of the antenna was colored with one of the textile's print pigments.

The third garment is a men's sleeveless zip jumper. Again, the integration involves the antenna shown in Figure 4. The back pattern piece of a menswear's jacket is large enough to host it. In Figure 8, the worn jacket is shown from five different angles and is followed by a similarly colored tracksuit trouser pant in a design that creates a smooth aesthetic combination of top and bottom garments.

The fourth garment is a denim-styled jacket with pockets positioned on the bust and metallic buttons as front fastening. In Figure 9, the patterns of the jacket in 2D are presented on the left, and the same pattern pieces positioned around the 3D avatar on the right. The lines/threads that connect the pattern pieces together are the virtual visualization of seams. After this preparation, the user "dresses" the avatar in the chosen body position. In this fashion garment, the antenna is hidden behind the metallic button; therefore, it ensures the invisibility to the wearer of the garment (as proposed in the work of Zhang et al. [12]). In V-Stitcher's interface, as can be seen in Figure 10, buttons can be easily imported as digital images with maps included and the user can insert/change several physical parameters (i.e., transparency, sheen, metallic hue, and diffusion) in order to create a 3D virtual vision of actual trims and other materials.

Figure 7. A third-order Minkowski fractal antenna integrated into a women's bomber jacket.

Figure 8. A third-order Minkowski fractal antenna integrated in a men's sleeveless zip jumper.

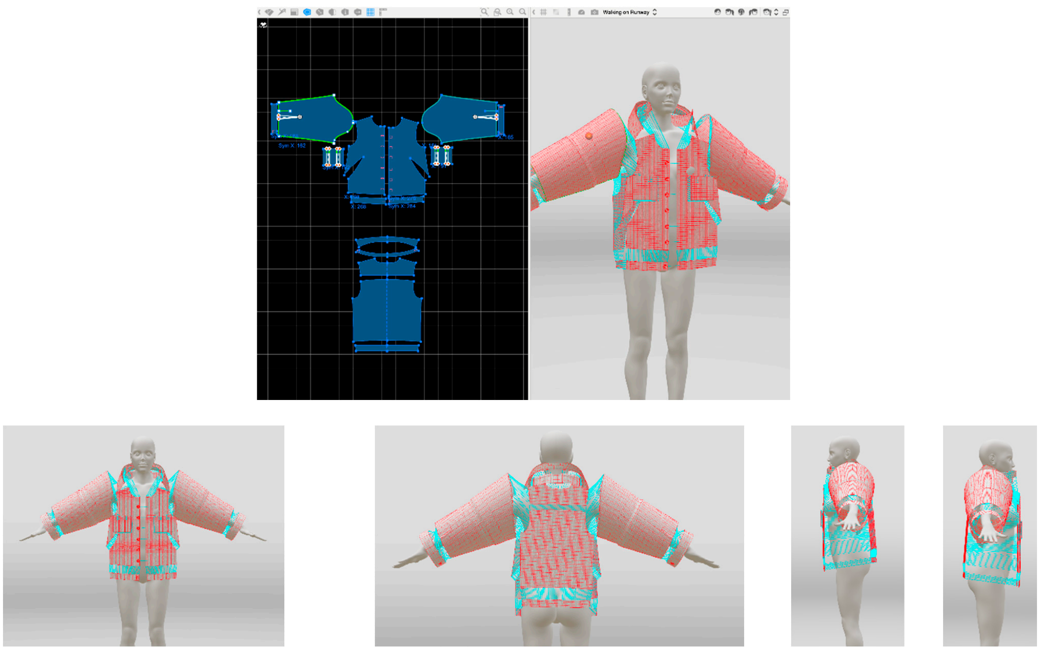


Figure 9. A denim-styled jacket with pockets positioned on the bust and metallic buttons as front fastening.

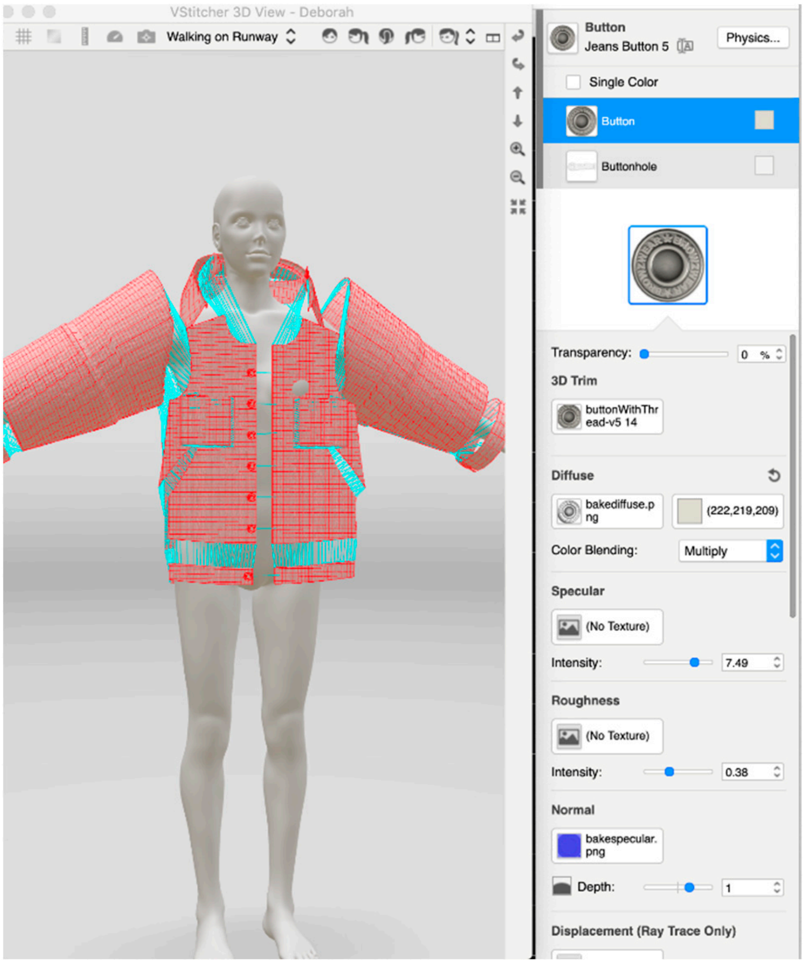


Figure 10. Buttons imported in the garment of Figure 10 as digital images.

5. Discussion

As already mentioned, the literature emphasizes the great importance of fabric material selection when integrating textennas into garments. Three-dimensional virtual prototyping technology tools, such as the ones used for this study, offer a full library of fabric materials with all their physical characteristics being fully parametric. The fabrics, as shown on the lefthand side of Figure 11, are categorized based on their fiber origin (i.e., natural fibers, polymer fibers, and synthetic). Virtual prototyping tools for typical garment visualization do not include woven fabrics with inserted metallic yarns or with plasma coating in their default libraries. Understandably enough, electromagnetic properties of the various fabrics are not explicitly shown in the menu since prototyping software was not originally intended for electromagnetic simulations. However, the user can create new libraries, especially for highly conductive materials, or for dielectrics with specific permittivity, after importing them via specialized hardware tools involving material scanning technologies or applications with embedded AI technologies. Examples of these devices are xTex by Vizoo [43] for scanning physically based samples of up to A4 paper size, and Scanatic™ Nuno Fabric Scanner [44] as a more affordable solution for a speedy material scanning. For the jacket in Figure 9, featuring an antenna integrated in the metallic buttons, authors used hydrophobic fabric (100% polyester). The result of the final visualization (render) of the denim-style womenswear jacket with embedded antenna behind the metallic buttons can be seen in various posture positions in Figure 12.

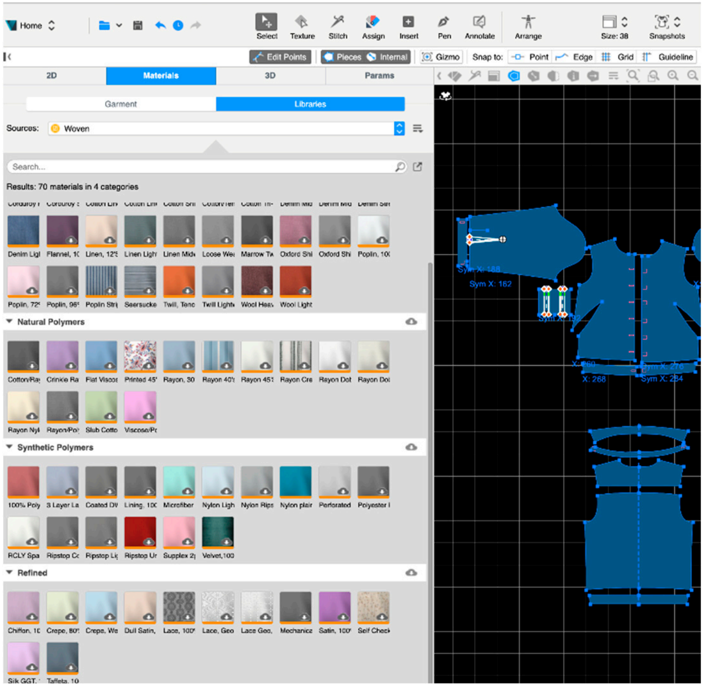


Figure 11. Fabric selection library, expandable by the user according to antenna design needs.

Figure 12. Final visualization (render) of the denim-style womenswear jacket with embedded antenna behind the metallic buttons (Figures 10 and 11) seen in various posture positions.

6. Conclusions

In this paper, the integration of wearable antennas into actual, comfortable and handsome clothes was discussed. Pure engineering design naturally focuses on electromagnetic efficiency of the antenna but often neglects the aesthetic dimension of a garment. A selection of commercially available software modules was presented, whose main functionality is fashion and pattern design. It was demonstrated how textennas are possible to incorporate into the fabric of various types of garments, by utilizing these software modules, without altering the antenna parameters, yet maintaining the elegance and reproducibility of the garment. Several antenna types already proposed and tested in the literature were selected and incorporated into actual clothes worn by human-like avatars. Even miniaturized feeding networks were possible to include in the design. The output files may be imported to commercial electromagnetic simulation packages for overall antenna performance evaluation. The prototyping procedure is important since it embeds often unattractive antenna structures into pleasant-looking clothes and offers an opportunity for antenna simulation in the presence of real-life garments. Finally, this procedure offers unlimited design options and minimizes resources waste since the entire development is completely digital, taking place in a virtual environment.

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