Radio-Mechanical Model of Epidermal Antenna Stretching during Human Gestures

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***Abstract*—Recent developments in Materials and Radiofrequency Identification (RFID) technologies are currently stimulating the development of new class of flexible epidermal devices for the wireless remote monitoring of biophysical parameters. The natural movements and gestures of the human body will not only produce mechanical stretching of skin antennas but they could also affect their communication performance. In this contribution we evaluate the degradation of the radiation gain of on-skin UHF antennas in common gestures by a combined mechanical-electromagnetic model. The deformation of the skin is firstly quantified by using a 3D scanner and hence the communication impact is evaluated with reference to a typical 867 MHz thin wire split-ring epidermal antenna. Preliminary numerical simulations and experimentations demonstrated that the behavior of the antenna is modified with a maximum 30% degradation of the read distance for the strain orientation producing the minimum mechanical stiffness.**

***Index Terms*—Epidermal Electronics, Radiofrequency Identification.**

I. Introduction

The current trend of pervasive and personal monitoring of human health and wellness is quickly stimulating the shift of electronics from wearable clothes and accessories to a directly assembly over the skin, according to the paradigm of *Epidermal Electronics* [1]. Flexible bio-compatible and breathable membranes hosting sensors, microchip transponders and antennas can be stuck over the epidermis to collect biophysical parameters with a high comfort for the user. Usually, epidermal devices communicate by backscattering modulation with a remote interrogator through the Radiofrequency Identification (RFID) framework. Among some options (NFC, HF, UHF), the UHF (860-960 MHz) standard [2] potentially enables a superior read distance of $1-2$ m so that a user can be monitored and tracked as he moves within small environments. Achieving a stable and robust communication performance when an antenna is applied onto the skin is still a technology challenge due to the variability of the human body in terms of shape and tissue layerings [3]. Moreover, epidermal devices are continuously subjected to mechanical stress during natural body gestures, like turning the neck and lifting an arm, that could also modify their electromagnetic response. Although antenna bending over textiles is a well studied topic [4], a specific picture of what happens at UHF frequencies with on-skin antennas due to the natural stretchability of the body is instead - to the best of our knowledge - not yet investigated.

This contribution presents some preliminary results of a numerical campaign aimed at quantifying the maximum deformation of human skin in several parts of the body during natural gestures by means of 3D image capture. The reconstruction of simplified bio-mechanical models through the paradigm of the reverse engineering is then applied to the evaluation of the mechanical strain and stress of a typical epidermal antenna. Finally, the numerical estimation of the effects of such deformation on the realized radiation gain w.r.t. the undeformed layout is derived by electromagnetic simulations.

II. Mechanical model

A. Digitalization of body deformation

A professional handheld 3D scanner (Artec Eva) was used to digitalize the stretching of the skin during natural gestures without contact. The method is described with reference to the neck[1]. A grid of spherical plastic markers and a reference cube were applied on the considered skin position to quantify the mutual 3D displacement during motions (Fig. 1).

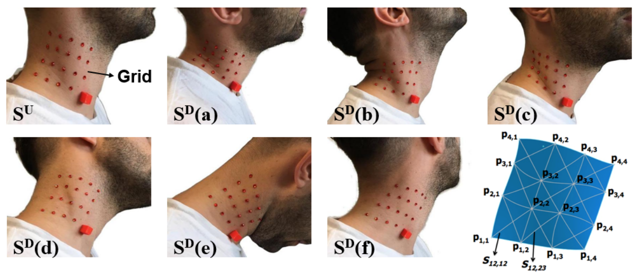

Figure 1. Typical neck movements and the reference grid of plastic markers (with 1.5 cm×1.5 cm spacing) to visually capture the local strain by the 3D optical scanner. At the bottom right, an example of reconstructed surface with markers and splines indexing the portion of the neck.

The 3D NURBS images of the deformed grids were then interpolated by 2D splines over a triangular grid (bottom right of Fig. 1). The relative strain between each marker at the edges of the grid was calculated as $\varepsilon_{ij,hk} = [L(S^D_{ij,hk}) - L(S^U_{ij,hk})]/L(S^U_{ij,hk})$, where $L(S^{U/D}_{ij,hk})$ are the length of the undeformed (U) and deformed (D) spline connecting markers $p_{i,h} - p_{j,k}$. The resulting positive and negative strain is represented in a color map (Fig. 2) over the undeformed mesh showing both the shrinking (blue scale) and stretching (red scale). Gesture $S^D(a)$ mostly generates a shrinking down to a strain of $\varepsilon = -0.3$, while gesture $S^D(d)$ produces a dominant stretching of up to $\varepsilon = 0.3$. This information is then used, in the next paragraph, to reproduce the on-skin antenna deformation in reference conditions.

[1] Results for other body parts, like arm and chest, will be described at the conference.

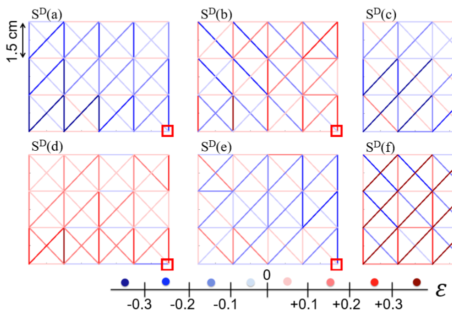

Figure 2. Colormap representation of the (relative) strain undergone by the neck during gestures in Fig. 1.

B. Stretching of Epidermal Antennas

The reference skin antenna is here a typical split-ring[2] [5] of 3 cm×3 cm external size (Fig. 3.a). The layout is assumed to be placed onto a rectangular 6 cm×4.5 cm ×0.08 mm slab (elastic module $E = 10^6$ Pa, Poisson coefficient $\upsilon = 0.45$) emulating the human tissue. To reproduce the worst case of deformation, the antenna, typically fabricated by an inkjet-printed conductor or by means of a thin copper wire, is assumed in all the mechanical analysis to be made of the same material of the skin substrate. Body deformation is accordingly fully converted into antenna deformation.

By using a mechanical FEM solver (DS-Solidworks Simulation), the antenna layout was subjected to $\triangle l = 10$ mm linear elongation (derived from the maximum strain evaluated in previous section) along several angular directions $\phi_n = n \cdot \pi/6$. Deformations of the split-ring antenna (Fig. 3.b) are thus predicted to be used for the next electromagnetic analysis. The corresponding stiffness (Fig. 3.b), *i.e.* the ratio between the applied strength and the relative elongation, is calculated as $K^D(\phi) = (\sum_{i=1}^{n} R_{v1,i}(\phi) - \sum_{j=1}^{n} R_{v2,j})/\triangle l$, where $R_{v1,i}$ and $R_{v2,i}$ are the constraint reactions of the whole system and of the skin-substrate without the antenna, respectively. The directions of maximum stiffness are $\phi = \{0°, 180°\}$ and even if the absolute values are modest ($K^{D,max} = 0.1$ N/m), it is anyway possible to identify the configurations of weaker resilience of the strained antenna to be accounted for fatigue considerations.

III. Electromagnetic Evaluation of Stretched On-Skin Antennas

The electromagnetic modeling of deformed antennas, now assumed to be made of thin (0.08 mm radius) insulated copper wires, as in the real life, are performed at 867 MHz by CST Microwave Studio, Time-Domain Solver (based on FDTD method). Antennas are placed over a 20 cm×20 cm multi-layered model of human body: 60 mm of muscle (relative permittivity $\varepsilon_r = 55.1$ and electrical conductivity $\sigma = 0.9$ S/m), 10 mm of fat ($\varepsilon_r = 5.5$, $\sigma = 0.05$ S/m) and 1 mm of skin (same parameters of the muscle). For reference, let's denote with G_{τ_0} the realized gain[3] of the unstretched antenna, assumed as perfectly matched to the microchip impedance. Mechanical strain is expected to produce a change of the realized gain G_τ, and accordingly a reduced read distance. Electromagnetic response (currents over stretched antennas and gain variation $\Delta G = G_{\tau,dB} - G_{\tau_0,dB}$ for applied elongation along ϕ_n angles) are superimposed to the stiffness data-set in Fig. 3.b. The resulting maximum electromagnetic degradation w.r.t. the undeformed antenna is of nearly 3 dB for a strain applied along the $\phi = \{120°, 300°\}$ directions, that means a reduction of the read distance of about 30%. It is worth noticing that electromagnetic and mechanical reactions to strain are opposite as the maximum stiffness (0 dB in the normalized polar plot) of the stretched epidermal antenna (higher sensitivity to fatigue) occurs for those strain directions the antenna gain is less modified ($\Delta G \sim 0$ dB).

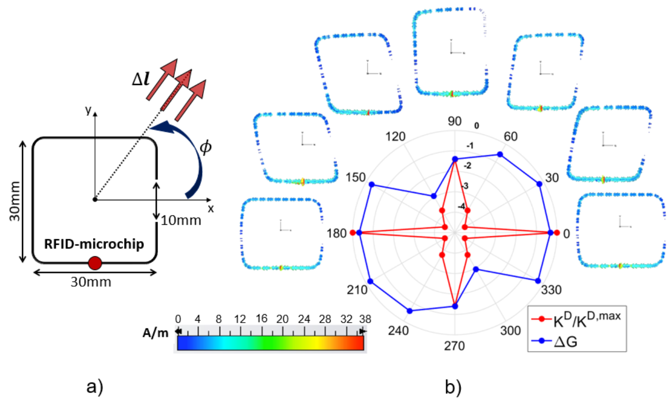

Figure 3. a) Split-ring epidermal antenna. b) Combined mechanic (deformation and normalized stiffness $K^D/K^{D,max}$ ($K^{D,max} = 0.1$ N/m) in dB) and electromagnetic responses (currents and reduction of antenna gain $\Delta G = G_{\tau,dB} - G_{\tau_0,dB}$ at 867 MHz) for 1 cm applied stretching along directions $\phi_n = n \cdot \pi/6$. High ΔG and high K^D correspond to lower electromagnetic degradation and greater stiffness, respectively.

IV. Conclusions

The proposed radio-mechanical modeling procedure permitted to evaluate the combined performance degradation of on-skin antennas due to the natural deformation of the human body. Results revealed that epidermal antennas subjected to the natural human stretching may undergo up to 3 dB communication degradation. Further reduction is moreover expected by accounting for shrinking and bending as it will be shown at the symposium together with the experimental results. The achieved deformation map can suggest how to properly orient the skin antenna onto the specific part of the body to achieve the best trade-off between mechanical stress and communication issues.

Acknowledgments

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[2]Results for loop and meander line dipoles will be presented at the conference.

[3]The product between the gain and the power transmission coefficient [6], taking into account both the mismatch of the antenna input impedance w.r.t. the microchip and the reduced harvested power.

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