Complex Permittivity Characterization of textile materials by means of Surrogate Modelling

Declercq F.*[1], Couckuyt I.[2], Rogier H.[1], and Dhaene T.[2]

[1] Ghent University - INTEC, Belgium, Ghent, 9000
[2] Ghent University - IBBT, Belgium, Ghent, 9000

Introduction

The emergence of body-centric communication systems necessitated the design of wearable antennas constructed from non-conductive and conductive textile materials [1-2]. To effectively design these antennas, accurate knowledge of the electromagnetic properties of the textile materials is necessary. Generally, the extraction of material properties is an inverse problem in which measurements are compared with numerical simulations in order to identify the unknown parameters.

In this paper, we perform electromagnetic characterization of textile materials by means of fitting simulated and measured textile antenna performances. The process is automated by using an optimization method based on kriging surrogate models. More in particular, we apply expected improvement (EI) as implemented in a flexible research platform called the SUrrogate MOdelling (SUMO) Toolbox [3]. Previously, kriging surrogate models were used for EM device optimization, in which the surrogate model is then optimized instead of an expensive simulation [4]. Here, we convert the inverse problem to a forward optimization problem by minimizing an error function between the simulated and measured data. Results of two different textile materials serving as antenna substrate are presented and compared with the results obtained by a direct measurement method in which the electromagnetic properties are determined based on microstrip line measurements [5].

Characterization method: Inverse kriging surrogate modelling

The electromagnetic properties of interest are the permittivity ϵ_r and the loss tangent $\tan\delta$ of the textile substrate. At first, a rough estimation of the electromagnetic properties of the textile materials is made and used in Momentum from Agilent technologies to design a textile antenna exhibiting a sharp single-mode resonance in the vicinity of 2.45 GHz. Together with the patch geometry, the unknown parameters ϵ_r and $\tan\delta$ determine the antenna performance indicators such as resonance frequency and bandwidth, as captured in the curve representing the antenna's reflection coefficient $|S_{11}|$ as a function of frequency. The goal is to identify the material properties of the textile antenna substrate by fitting the simulated and measured reflection coefficient. In Particular, this is an inverse problem which is converted into a forward optimization, by minimizing an error function between the simulated $|S_{11}|$ and measured $|\widetilde{S_{11}}|$. The error function used here is the Mean Squared Error defined by

$$MSE = \frac{1}{n}\sum_{i=1}^{n}(|S_{11}|_i - |\widetilde{S_{11}}|_i)^2, \tag{1}$$

with n the number of frequency points.

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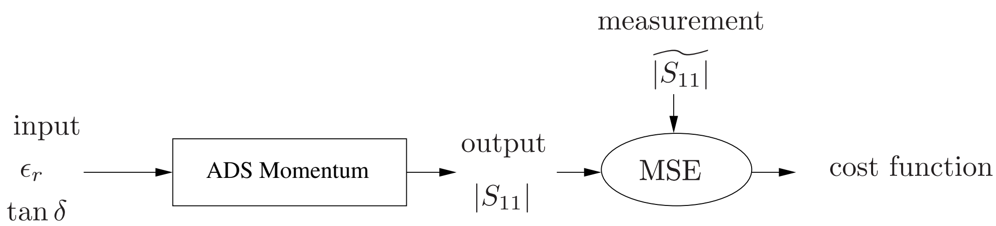


Figure 1: Inverse problem is solved by minimizing the error function MSE

In practice, a simulation model is built in ADS Momentum, as depicted in Figure 1, in which the substrate properties ϵ_r and $\tan\delta$ are unknown parameters limited to a certain range (e.g. ϵ_r =[1.1, 2.5] and $\tan\delta$ =[0.001, 0.005]). Version 6.2 of the SUMO Toolbox is used to solve the inverse problem. A full description of the surrogate modelling process used here is described in [6]. In this paper we limit ourselves to a brief discussion. First, the cost function is created by an initial set of samples generated by an optimal maximum Latin Hypercube Design of 20 points together with four corner points, resulting in a total of 24 points. The expected improvement function is then optimized using the DIRECT algorithm to determine the next sample to evaluate and finding the optimal electromagnetic properties of the substrate yielding a minimal MSE. The optimization is halted when the number of samples exceeds 71. The surrogate model used here is kriging, which is by default an interpolation technique. Since the reflection coefficient measurement is prone to errors, the cost function will be noisy. Therefore, the kriging surrogate model was adapted to a regression technique instead of an interpolation technique.

Results and validation

The proposed procedure was used to characterize two different textile fabrics serving as antenna substrate of a textile antenna. Substrate 1 is an assembly of four layers of plain woven aramid fabric, resulting in an overall substrate thickness of 1.67 mm. Substrate 2 is a nonwoven polypropylene fabric with a thickness of 3.6 mm. For both fabrics, a textile antenna consisting of a textile substrate with the conductive parts implemented in copper foil was designed using an inset feeding technique and measured in the frequency range from 1 GHz – 3 GHz. The conductive layers as well as the textile layers were glued by means of an adhesive sheet. The geometry of the antenna is depicted in Figure 4(b).

The evolution plots of the minimum cost function values versus the number of samples for the characterization process of the substrates are depicted in Figure 2. Starting from the initial set of 24 samples, the EI function starts exploring other parts of the design space. However, it quickly locates the global optimum after approximately 30 samples. For substrate 1, the global optimum is found after sample 66 but the sampling continues until the sample budget is exceeded. For the second substrate the optimum is found after sample 54. The kriging surrogate models of the cost functions for the textile antenna constructed on substrate 1 and 2 are depicted in Figure 3(a) and Figure 3(b), respectively. The cost functions have the shape of a valley, since the MSE is more affected by a change in the permittivity then a change in the loss tangent of the substrate. The optimal parameter combination for the textile substrates is presented in Table 1 along with the results obtained from the characterization method presented in [5]. The reflection coefficients of the optimal solution runs and the measurements of the textile antennas are plotted in Figure 4(a). A comparison between the simulated and measured reflection coefficients shows us that a high accuracy is achieved in the extracted electromagnetic properties. To further evaluate the results we extracted the radiation efficiencies e_r of the antennas by means of full 3D radiation pattern measurements in an anechoic chamber with an ORBIT/FR positioning system. A comparison of the simulated radiation efficiencies based on the extracted electromagnetic properties and the measured e_r demonstrates that a high accuracy is achieved. Comparing the simulated e_r based on the electromagnetic properties extracted in [5] with the measured e_r proves that the extracted electromagnetic properties in this paper are even more accurate than the extracted properties in [5].

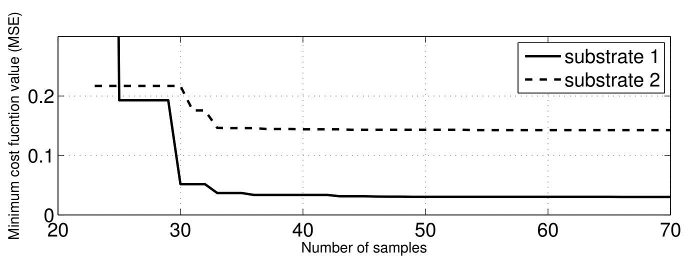
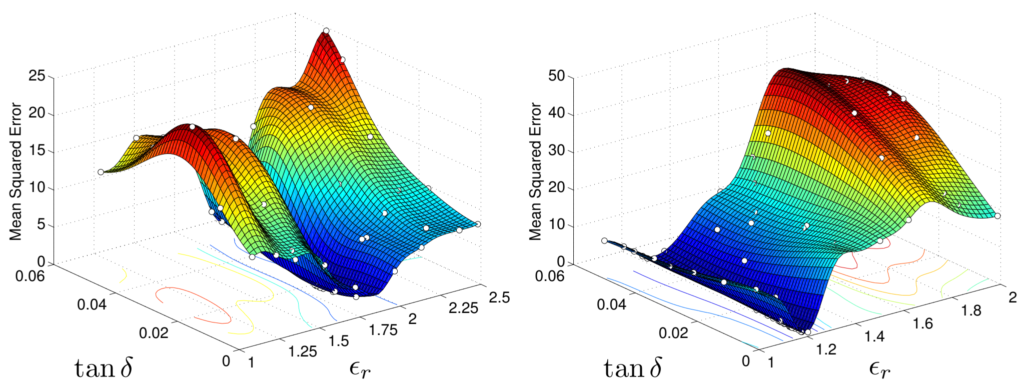


Figure 2: Evolution plots of the minimum cost function values versus the number of samples.



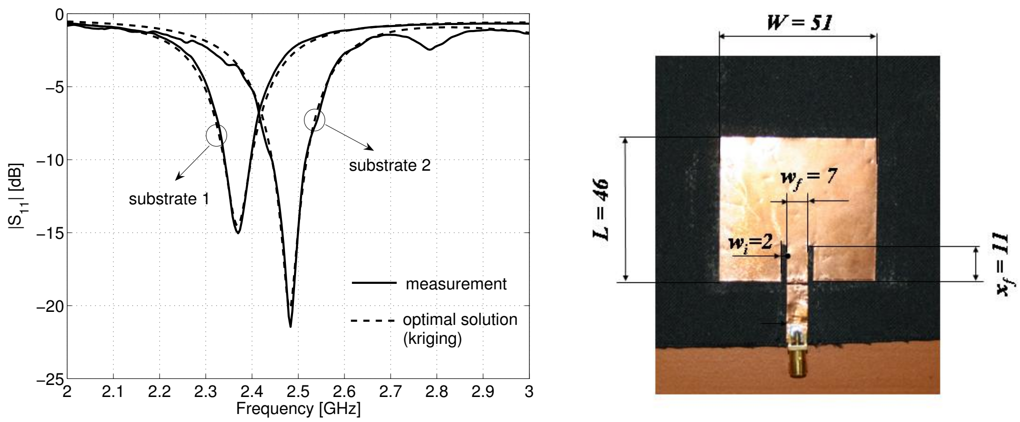
(a) substrate 1

(b) substrate 2

Figure 3: Final kriging surrogate models of the cost functions based on 71 data points.

Table 1: Optimal electromagnetic properties of the textile substrates and validation results.

substrate	kriging		results from [5]		simulated	simulated	measured
	ϵ_r	$\tan\delta$	ϵ_r	$\tan\delta$	e_r (kriging)	e_r [5]	e_r
1	1.84	0.019	1.88	0.015	49%	56%	50%
2	1.21	0.006	1.2	0.025	90%	67%	89%



(a) (b)

Figure 4: (a) Measured $|\widetilde{S_{11}}|$ and optimal simulated $|S_{11}|$ (found by kriging) of both textile antennas. (b) Geometry of the inset fed patch antenna on substrate 1 (dimensions in mm).

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