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A Microwave Imaging System for the Detection of Targets Hidden behind Dielectric Walls

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Abstract

In this work, a prototype of microwave imaging system for through-the-wall monitoring is presented. The system can operate remotely, as well as by using antennas directly in contact with the wall. For the remote modality, ad-hoc wide-band antennas have been designed and integrated into an efficient measurement system, able to acquire the scattered-field data. Such measurements are processed by a novel hybrid inversion procedure able to create an image of the inspected scenario. For the proximity modality, a Bessel beam launcher is specifically designed, realized and tested to provide a focused near-field with enhanced penetration capabilities. Preliminary results are provided for assessing the capabilities of the system.

1 Introduction

Through-the-Wall Imaging (TWI) is an important application field in which microwaves play a fundamental role [1]–[4], e.g., for remote surveillance, rescue campaigns, and detection of humans inside buildings. Indeed, electromagnetic waves at microwave frequencies, especially in the range between approximately 300 MHz and 10 GHz, have the unique property of being able to penetrate inside building materials, thus allowing the possibility of an extra-wall detection of the targets hidden in inaccessible regions. However, the propagation of electromagnetic waves is significantly affected by the presence of the wall, which introduce electromagnetic losses and internal reflections that makes the imaging problem more challenging than in other applicative fields in which free-space conditions can be assumed.

Despite in the past years several literature works have been devoted to this problem and significant achievements have been reached, there is still the need of further developments in order to enhance the detection capabilities. In particular, from the points of view of the hardware required to perform the measurements, manual positioning of commercial antennas is often used in apparatuses currently available [5]. Concerning the data processing, two main topics need to be considered. First, effective inversion techniques able to produce images of the hidden scenario, with enhanced resolution and high robustness to noise, are needed. To this end, two ways can be followed. On the one hand, beamforming methods allows to obtain qualitative images of the scenario, but may exhibit limited resolution. On the other hand, inversion techniques based on a rigorous scattering formulation can be adopted to enhance the reconstruction, but they usually require more computational resources. Another important issue is related to the need of having efficient numerical simulators for solving the scattering problem. To this purpose, a forward solver for the scattering by targets placed behind a wall has been proposed [6], [7]. The method provides an analytical-numerical tool, as based on expansions into cylindrical waves, allowing a fast and accurate analysis of a TWI environment. Its numerical data can be useful for a better understanding of the radar retrievals or can be employed to test inversion schemes.

In this paper, a new prototype of imaging system for through-the-wall detection is presented. The system allows two different working modalities, in order to be able to work remotely from the wall or in direct contact with it. For the remote modality the measurement setup is based on a vector network analyzer (VNA) and a set of eight Vivaldi antennas controlled by RF switches. The measured data are processed by using an hybrid procedure, which combines a delay-and-sum beamforming algorithm [8] with a regularization method developed in the framework of the variable-exponent Lebesgue spaces [9], [10]. A different approach is adopted for the detection system based on direct contact. In this modality, the proposed radar employs a Bessel beam launcher as transmitting antenna [11] and a wideband low-profile reflector-enhanced printed antenna for receiving the field scattered from objects located beyond the wall [12]. Since Bessel beams exhibit limited diffractive effects [13], [14], this modality allows to better detect objects close to the considered wall.

The paper is organized as follows. The design of the system is briefly outlined in Section 2. Some results are discussed in Section 3. Finally, conclusions are drawn in Section 4.

2 System description

2.1 Hardware design

Two possible operating modalities have been considered. In the remote modality a VNA measures, in a given number of equally spaced frequency points, the scattering parameter between a transmitting (T) and a receiving (R) Vivaldi antennas selected by two switches. In this manner, an equivalent antenna is achieved whose phase centre is located between T and R. A power amplifier (PA) is inserted in the transmitting channel to increase the Radar range. The proximity system exploits the advantageous limited diffractive effects of Bessel beams, which can be synthesized through specific antenna arrays [15] or launchers [16]. In [13], [15] the feasibility of focusing RF energy and synthesize Bessel and Airy beams in specific spatial regions using antenna arrays has been demonstrated. This technique, although more flexible, is characterized by higher costs and complexities. Therefore, a simple launcher configuration consisting of circular waveguide equipped with an exciter suitable to generate a Bessel beam has been developed [11]. The launcher, working around 8.7 GHz excites a beam orthogonally to the wall on which the antenna is positioned, thereby maximizing the RF energy sent to the target. A printed antenna [12] placed in the neighbouring of the launcher is used to receive the field scattered by the target. Said antenna being able to operate in polarization diversity (by mechanical rotation), can better detect specific characteristics of the scatterers.

2.2 Data processing

Theoretical and numerical solution to the forward scattering problem has an important role in the processing of synthetic or measured data. An analytical method has been employed for the evaluation of the scattered field in TWI layouts, the Cylindrical Wave Approach (CWA). A 2D simulation layout has been considered, with one or more circular cross-section cylinders placed in a semi-infinite medium, behind a wall. Expansions into cylindrical waves have been employed to deal with the scattered fields by the cylindrical targets, and a rigorous approach has been applied, based on plane-wave spectra, including all the interactions of the scattered fields with the wall boundaries [6], [7]. Numerical solution has been performed to simulate through-wall surveys both in far- and near-field region. The introduction of line-current sources as excitations of the scattering problem has allowed an improved modelling of the field radiated by the transmitting antennas [17]. Simulations of the layout with a multiview scanning of the sources have returned synthetic data used in the modelling of reference cases [18] and in the validation of inversion algorithms in the 'near' modality [19].

An hybrid inversion procedure combining a delay-and-sum beamformer [8] with a novel algorithm able to solve, in a regularized sense, the scattering problem at hand has been designed, too. In particular, assuming a two-dimensional configuration under transverse-magnetic incidence, the following linearized scattering model has been adopted [3]

$$E_s(\mathbf{r}_{RX}^{s,m}) \cong \int_D \gamma(\mathbf{r}') g_{tw}(\mathbf{r}', \mathbf{r}_{TX}^{s}) g_{tw}(\mathbf{r}_{RX}^{s,m}, \mathbf{r}') d\mathbf{r}' \qquad (1)$$

where E_s is the scattered electric field, D is the investigation domain, $\mathbf{r}_{TX}^{s}$ is the position of the s-th transmitting antenna (the total number of transmit locations is S), $\mathbf{r}_{RX}^{s,m}$ is the position of the m-th receiving antenna when the s-th transmitting antenna is used (the total number of receiving locations for every transmitter is M), γ is a function that assumes high values in correspondence to the scatter locations [3], and g_{tw} is the scalar Green's function for the considered three-layer scenario [20].

The functional equation in (1) is solved in a regularized sense by using a variable-exponent Lebesgue-space Landweber scheme, which is able to obtain a solution characterized by the minimum $L^{p(\cdot)}$ norm [9]. Differently from conventional algorithms, the exponent $p(\cdot)$ may assume different values inside D. In particular, such an approach allows to promote the sparsity of the solution in the regions in which the exponent function is close to 1, while keeping good reconstruction of the targets when $p(\cdot)$ is close to 2, as with classical L^2 norm. On such basis, the exponent function is built by exploiting the image provided by a delay-and-sum migration algorithm. As a result, the targets are better localized and artefacts are reduced.

3 Preliminary Experimental Results

3.1 Proximity System

In order to obtain an accurate numerical analysis of the near-field focusing capabilities relevant to Bessel-beam sources in the presence of stratified media, the electromagnetic characterization (dielectric constant as well as loss tangent) of the layers composing the assumed stratification has been performed. A standard coaxial probe (DAK-3.5, SPEAG) is adopted to have a wideband dielectric characterization of the layers, namely plasterboard and wood, which compose the validation wall. Dielectric measurements are performed in the Microwave Laboratory of the University of Calabria. In particular, the probe is connected to a VNA Anritsu VectorStar for the measurement of the reflection coefficient. It is placed in touch with a wall layer of sufficient extension and height, to inhibit multiple reflections, and properly avoiding undesirable airgaps to have accurate measurements. The behavior of the measured dielectric parameters within X-band is shown in Figure 1 [21], while the mean values are reported in Table 1. As expected, almost flat curves vs. frequency are obtained.

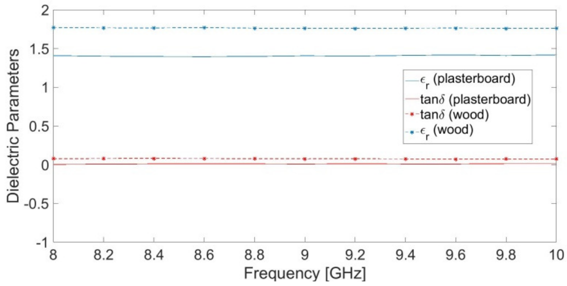

Figure 1. Measured dielectric parameters of wall layers.

Table 1. Mean values of dielectric parameters in Figure 1.

	Dielectric Constant	Loss Tangent
Plasterboard	1.40	0.007
Wood	1.76	0.067

The values of dielectric parameters reported in Table 1 are assumed to simulate the Bessel beam propagation through a stratified wall composed of a 10 mm plasterboard layer and a 20 mm wood layer. The corresponding transmitted field reveals the same focused beam as that obtained from the measurements performed with the designed Bessel-beam launcher, which are reported in Figure 2 [21].

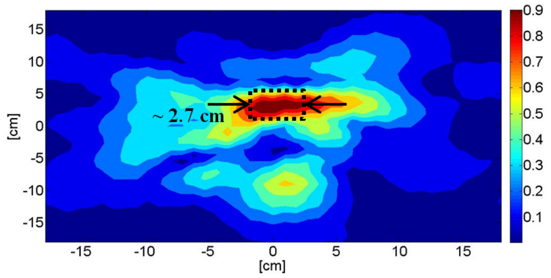

Figure 2. Measured field transmitted behind the wall (normalized values).

3.2 Remote System

Some of the imaging results obtained with the developed prototype in remote operation are discussed in this Section. The system has been validated by using the setup shown in Figure 3. Measurement have been performed in a hall of the Enea-Casaccia research center. The array of Vivaldi antennas has been located 2 m away from a brick wall 1.2 m high, 1.8 wide and 0.25 m tick, as shown in Figure 3. The return loss of a single Vivaldi antenna is shown in Figure 4, while the radiation diagram at 2.5 GHz is reported in Figure 5. As it can be observed the antenna is well matched (-10 dB) between 1 and 8 GHz. The measurement setup allows to synthesize a monostatic array of $S = 16$ elements with spacing $d = 3.75$ cm. A frequency stepped strategy has been adopted for collecting the scattered-field data. In particular, the frequency has been varied from 1 GHz to 3 GHz with a step of 4 MHz, resulting in 501 frequency samples. The relative permittivity of walls has been measured by waveguide measurements elaborated by means of the Keysight 85071E Materials Measurement Software [22]. It has been found that wall permittivity ranges from 3.5-j0.03 for dried material, to 7.5-j0.5 for material with a 5% gravimetric moisture content.

The considered target is a metallic plate with sides 36×42 cm, which has been located at a distance of 1 m from the wall and 60 cm from the floor. The inversion procedure sketched in the previous Section has been applied with the following parameters: Maximum number of iterations, 100; threshold on the relative variation of the residual, 0.01; range of the norm parameter, [1.4, 2.0]. An example of the obtained results is shown in Figure 6. As it can be observed, the developed system is able to effectively locate the target hidden behind the wall. Moreover, even if the system has been tested in a quite complex area, the obtained image is almost free of artifacts. Finally, it is worth noting that the sizes in the range and cross-range directions are estimated with quite good accuracy, too.

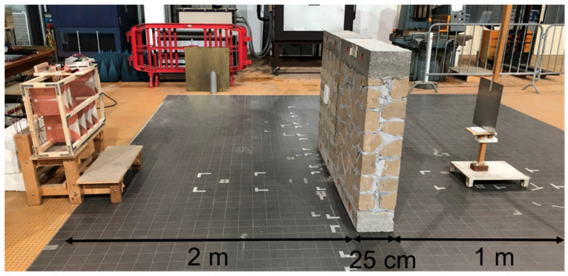

Figure 3. Measurement setup used for validating the developed TWI system.

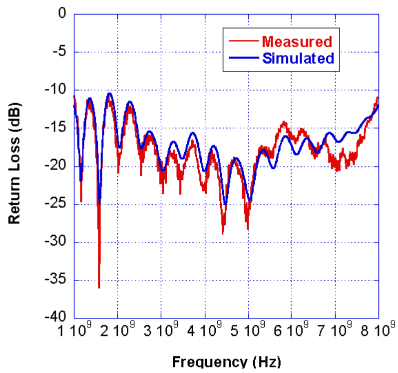

Figure 4. Comparison between the simulated and measured Vivaldi antenna return loss.

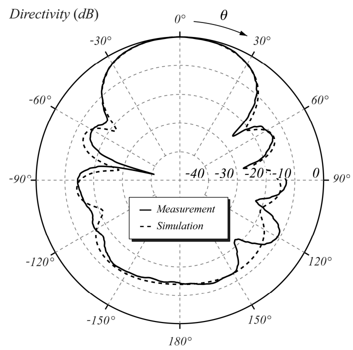

Figure 5. E-plane radiation pattern of the Vivaldi antenna. Frequency $f = 2.5$ GHz.

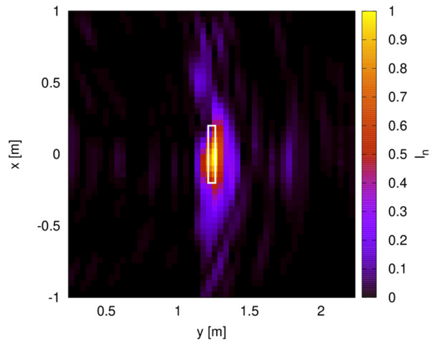

Figure 6. Reconstructed image of the inspected scenario.

4 Conclusions

A prototype of through-the-wall imaging system has been presented in this paper. The measurements are obtained by means of a remote and a direct contact detection system. The remote system employs a switchable array of Vivaldi antennas, while a novel Bessel beam launcher has been used for direct contact. Validation measurements are presented for both configuration modalities, thus assessing the through-the-wall capabilities of the proposed system. The scattered-field data has been processed by a novel hybrid inversion procedure, combining a delay-and-sum beamforming scheme with a variable-exponent Lebesgue-space regularization procedure. The system has been validated in a realistic scenario, showing very good detection capabilities.

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