An exact 2.5D BiCGS-FFT forward solver to model electromagnetic scattering in an active millimeter wave imaging system

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Abstract—**The imaging performance of an active mm-wave imaging system, devoted to the visualization of concealed objects, can be studied using accurate numerical electromagnetic simulations. I present an exact forward solver to calculate the three-dimensional (3D) scattered fields of a two-dimensional (2D) inhomogeneous dielectric object which is illuminated by a given 3D time-harmonic incident field. Since the size of the scattering objects can be very large with respect to the wavelength, a 2.5D configuration is adopted. This reduces the computational cost while it maintains the capability of accurately studying the system performance. The 3D scattered fields are calculated by discretizing a contrast source integral equation with the Method of Moments. The resulting linear system is solved iteratively with a stabilized biconjugate gradient Fast Fourier Transform method.**

Keywords—**Forward solver; millimeter waves; volume integral equation technique**

I. Introduction

Recently, the growth of international terrorism has become an accelerator for the development of active millimeter wave imaging systems. Detecting concealed threats before they can become a danger to people is an important factor in preventing terrorist actions. Metallic weapons can be detected by metal detectors, but those are unable to detect non-metallic threats such as composite guns, ceramic knives and plastic explosives. X-rays could be used since they penetrate clothing and the human body itself, revealing any hidden objects, but the ionizing character constitutes a health risk. Millimeter waves (with a frequency between 30 and 300 GHz or a wavelength between 1 and 10 millimeter) also penetrate clothing but reflect from a person's skin. For short illuminations there is no health risk. Millimeter waves thus are ideal to detect objects that are hidden under clothing.

There is a distinction between passive and active mm-wave imaging systems. Passive systems use the natural radiation of the human body to differ hidden objects from the body itself. The quality of such image depends on the temperature contrast between the human body and the environment. For indoor applications, such as security checkpoints in airports, the temperature contrast is too small to generate useful images. Therefore active systems are developed. Those systems are very similar to a camera with flashlight. The objects are illuminated by a source, yielding a more detailed image.

Different techniques are possible for active millimeter wave imaging. There is a qualitative imaging technique based on an optical approach. It uses lenses for beam and image formation. These lenses produce artifacts in the image that can be reduced using non-coherent illumination and averaging the obtained images. This technique is currently being developed in an IWT-SBO project in which the VUB, UGent, KUL, IMEC and UCL participate [1]. Another, quantitative technique under investigation is derived from microwave imaging principles and is largely based on the exact solution of Maxwell's equations. The goal is then to reconstruct the material parameters of the illuminated object from measurement data and known incident fields. These so-called inverse problems are widely studied in literature [2] and they are non-linear and ill-posed. In both approaches, an exact model of the wave-field propagation and scattering is indispensable to carefully study system performance and imaging capabilities.

Therefore I developed an exact forward solver which simulates electromagnetic scattering of mm-waves from inhomogeneous dielectric objects. The hidden objects are usually several centimeters long, thus covering plenty of wavelengths. Furthermore, the objects have to be discretized using at least ten cells per wavelength in the discretized medium. This leads to a very large number of unknowns when simulating full three-dimensional (3D) objects. Therefore a 2.5D configuration is adopted since it reduces the computational burden while maintaining the capability of accurately studying the system's performance. This 2.5 forward solver can be used to simulate qualitative imaging procedures or can be introduced into a quantitative iterative inversion scheme.

II. Method

The 2D inhomogeneous dielectric object is embedded in free space and has a z-invariant complex permittivity $\epsilon(\mathbf{r}) = \epsilon_r(\mathbf{r})\epsilon_0 = \epsilon'(\mathbf{r}) + j\epsilon''(\mathbf{r})$, with $\epsilon'(\mathbf{r})$ and $\epsilon''(\mathbf{r})$ representing the real and imaginary part of $\epsilon(\mathbf{r})$ and $\mathbf{r} = (x, y)$ the transversal position vector. The imaginary part of the relative complex permittivity $\epsilon_r(\mathbf{r})$ is given by $\epsilon_r''(\mathbf{r}) = \frac{\sigma}{\omega\epsilon_0}$, with ω the angular frequency, ϵ_0 the permittivity of vacuum and σ the electric conductivity. The problem is formulated in the frequency domain and the time dependence $\exp(-j\omega t)$ is omitted. The illumination consists of a given 3D time-harmonic incident field $\mathbf{E}^i(\mathbf{r}, z) = [E_1^i(\mathbf{r}, z), E_2^i(\mathbf{r}, z), E_3^i(\mathbf{r}, z)]$. The 3D scattered field which has to be calculated, is defined as $\mathbf{E}^s(\mathbf{r}, z) = \mathbf{E}(\mathbf{r}, z) - \mathbf{E}^i(\mathbf{r}, z)$, with $\mathbf{E}(\mathbf{r}, z)$ the total field. The problem is formulated in terms of the unknown electric flux density [3] $\mathbf{D}(\mathbf{r}, z) = [D_1(\mathbf{r}, z), D_2(\mathbf{r}, z), D_3(\mathbf{r}, z)]$. When a Fourier transform in the z-direction is applied on the Maxwell

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equations [2] and a volume integral equation approach is used, the integral equation over the object domain S takes the following form

$$\begin{bmatrix} E_1^i(\mathbf{r},\beta) \\ E_2^i(\mathbf{r},\beta) \\ E_3^i(\mathbf{r},\beta) \end{bmatrix} = \frac{1}{\epsilon(\mathbf{r})} \begin{bmatrix} D_1(\mathbf{r},\beta) \\ D_2(\mathbf{r},\beta) \\ D_3(\mathbf{r},\beta) \end{bmatrix} - \begin{bmatrix} k_0^2 + \frac{\partial^2}{\partial x^2} & \frac{\partial^2}{\partial x \partial y} & j\beta\frac{\partial}{\partial x} \\ \frac{\partial^2}{\partial x \partial y} & k_0^2 + \frac{\partial^2}{\partial y^2} & j\beta\frac{\partial}{\partial y} \\ j\beta\frac{\partial}{\partial x} & j\beta\frac{\partial}{\partial y} & k_0^2 - \beta^2 \end{bmatrix} \begin{bmatrix} A_1(\mathbf{r},\beta) \\ A_2(\mathbf{r},\beta) \\ A_3(\mathbf{r},\beta) \end{bmatrix}, \quad (1)$$

where $k_0 = \omega\sqrt{\epsilon_0\mu_0}$. The vector potential $\mathbf{A}(\mathbf{r},\beta)$ can be calculated as

$$\mathbf{A}(\mathbf{r},\beta) = \mathcal{F}^{-1}\left[\mathcal{F}[\mathcal{G}(\mathbf{r},\beta)]\,\mathcal{F}[\chi(\mathbf{r})\frac{\mathbf{D}(\mathbf{r},\beta)}{\epsilon(\mathbf{r})}]\right] \quad (2)$$

with $\mathcal{F}$ and $\mathcal{F}^{-1}$ the forward and inverse 2D spatial Fourier transform respectively. The scalar 2D Green's function is given by $G(\mathbf{r},\beta) = \frac{j}{4}H_0^{(1)}(\sqrt{k_0^2-\beta^2}|\mathbf{r}|)$ and the normalized contrast function $\chi(\mathbf{r})$ is defined as $\chi(\mathbf{r}) = \frac{\epsilon(\mathbf{r})-\epsilon_0}{\epsilon(\mathbf{r})}$. This contrast source integral equation (1) is discretized with the Method of Moments (MoM) and solved iteratively with a stabilized biconjugate gradient (BiCGS) method [4] .

III. Results

In order to validate the proposed technique, the results of the 2.5D solver are compared to those of a full 3D solver, developed by Peter Lewyllie [5]. The object is a dielectric cylinder with relative permittivity $\epsilon_r = 2$ and with a radius equal to one wavelength ($\lambda_0 = 1$ mm, $f = 300$ GHz). The 3D cylinder should approximate an infinite cylinder (the 2.5D case), thus the length l has to be as large as possible. But a slight increase in l yields a strong increase in the number of unknowns. Therefore the length l is limited to $l = 100\lambda_0 = 100$ mm. In both simulations, the scattered fields are calculated for 360 points on a circle with a radius of $2\lambda_0 = 2$ mm and the incident field is a TM polarized plane wave with oblique incidence: the propagation vector $\mathbf{k}$ makes an angle of 8 degrees with the horizontal plane. In the simulations with the 2.5D solver the BiCGS iterations are stopped when the relative error drops below 10^{-8}, which happened after 60 iterations. In the 3D case the simulations are stopped earlier: when the relative error drops below $10^{-2.5}$, yielding in 360 iterations. Taking more BiCGS iterations for the 3D case leads to a strong increase in the calculation time, which is now already approximately 16 hours. The 2.5D simulation lasts only 17.65 seconds. The 3D problem consists of more than 5 million unknowns and occupies 2.4Gb of memory while the 2.5D problem has only 12288 unknowns and uses no more than 10.712 Mb of memory. This comparison strongly justifies the choice for a 2.5D solver. The amplitude $||\mathbf{E}^s||$ of the scattered field is presented in Fig. 1. There is a good agreement between both solvers and the differences are a consequence of the finite length of the 3D cylinder and the limited number of BiCGS iterations in the 3D case. The amplitude of the scattered field on the computational grid is presented in Fig. 2.

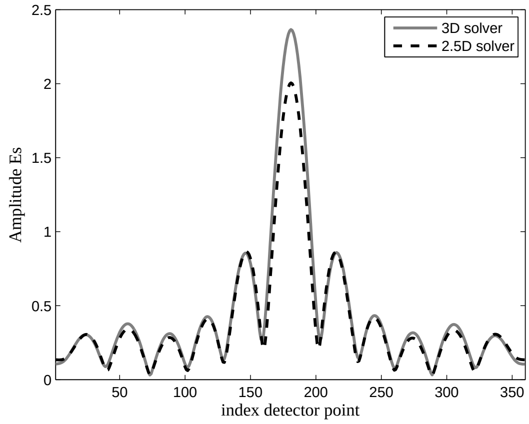

Fig. 1. Amplitude of the total scattered field

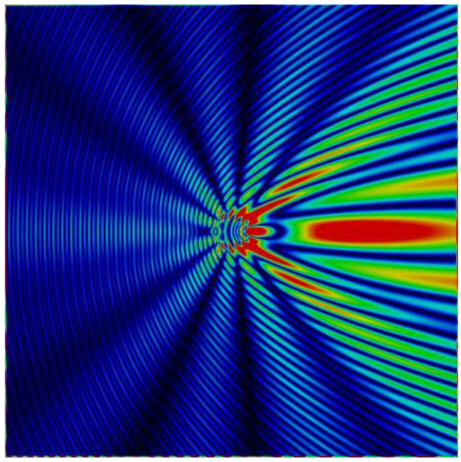

Fig. 2. Amplitude of the total scattered field on the computation grid

IV. Conclusions

A 2.5D BiCGS-FFT solver is developed to simulate the interaction between inhomogeneous dielectric objects and incident mm-waves. The application of FFT's yields a fast and efficient method for solving scattering problems and the 2.5D configuration strongly reduces the number of unknowns. A comparison with a full 3D solver demonstrates the accuracy of the proposed method.

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