AN EFFECTIVE APPROACH TO THE FAST, GPU-BASED, THROUGH-WALL IMAGING

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Abstract

We present an approach for the Through-Wall-Imaging based on a simple model of the scattering problem involving few unknowns, exploiting effectively the a priori information on the scenario and using a global optimization approach, relying on Legendre-Fenchel Transforms, tailored to fast, parallel implementations on Graphic Processing Units (GPUs).

Experimental results are presented against X-band data collected in a realistic scenario made of a wall of Ytong concrete blocks and a metallic cylindrical scatterer.

Keywords: Through-Wall Imaging, GPU, Global Optimization, Legendre-Fenchel Transform, LLT.

1. INTRODUCTION

Seeing through walls is desired when entering rooms or buildings is hazardous and inspecting the interior from outside is needed [1]. Examples are locating people in hostage scenarios, counter-terrorism, and search and rescue following critical events.

Thanks to their potentiality of propagating through building materials, electromagnetic-waves promise to be successfully exploited to retrieve information on the content of closed environments. However, making electromagnetic-wave sensors operational requires hardware and algorithms guaranteeing reliable responses in extremely short runs.

The aim of the paper is to present an approach based on a simple model of the scattering problem involving few unknowns, exploiting effectively a priori information on the scenario and last, but not least, using a global optimization approach [2] tailored to computing systems of the next generation, for the highly parallel, fast and low-cost data processing [3].

The algorithm seeks for the location of the beyond-the-wall items and for the parameters of the building structure, thus simultaneously correcting for the through-the-wall wave propagation.

The approach amounts to the global minimization of a (multimodal) cost functional, taking into account the available a priori knowledge on the scenario and tackling the optimization by applying the Fast Legendre-Fenchel transform to quickly estimate the convex envelope of a properly defined cost function [4].

Concerning the hardware platform, the multithread implementation of the approach has been carried out on a Graphic Processing Unit (GPU) to exploit very favorably the synergy between the high-throughput structure for data-parallel processing of such devices and the high parallel workloads of the proposed solution algorithm, even in the case of constrained optimization.

Experimental results are presented against X-band data collected in a realistic scenario made of a wall of Ytong concrete blocks and a metallic cylindrical scatterer.

2. THE APPROACH

Let us consider the 1D scenario depicted in Fig. 1, made of a dielectric layer of relative permittivity ε_{r2}, conductivity σ and thickness d accounting for the presence of the wall and of an obstacle represented, in this simple model, by a perfectly conducting plate located at a distance l from the wall. The scenario is illuminated by a plane wave, with normal incidence and frequency f varying within a specified band $[f_{min}, f_{max}]$.

This simple setting allows dealing with a reduced number of unknowns, namely, ε_{r2}, σ, d, and l.

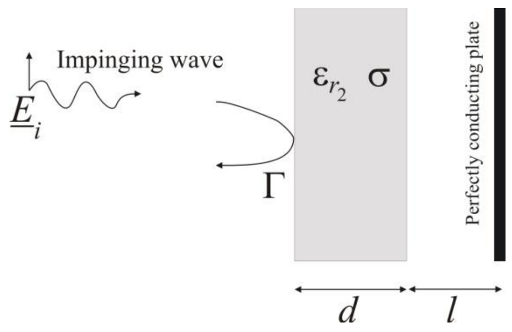

Fig. 1. Geometry of the problem.

The measurement of the reflected plane wave allows evaluating the reflection coefficient $\tilde{\Gamma}$ at the interface boundary for the different considered frequencies f.

The reconstructions of the involved unknowns is performed by minimizing the cost function

$$\Phi(\epsilon_{r2},\sigma,d,l) = \sum_i \left|\tilde{\Gamma}(f_i) - \Gamma(f_i,\varepsilon_{r2},\sigma,d,l)\right|^2. \qquad (1)$$

where i spans the employed frequencies.

3. THE GLOBAL OPTIMIZATION ALGORITHM ON GPU

To guarantee the required reliability for the application of interest, the optimization of functional Φ must be performed in a way to reach its global minimum, avoiding the local ones. Furthermore, the (global) optimization algorithm to be adopted must be also effective in providing the result in short time and be able to fully exploit the parallel features of the employed GPU up to realizing real-time processing.

To meet these requirements, a global optimization algorithm exploiting the Legendre-Fenchel Transform (LFT), has been used. Indeed, by applying the LFT twice, the convex envelope $\mathcal{C}$ of the functional can be determined and, in principle, the global minimum of Φ can be obtained as the global minimum of $\mathcal{C}$, as referred in [4]. Furthermore, the LFT can be effectively implemented on a GPU.

In the following, the LFT is briefly recalled and the parallel implementation of the LFT-based, global optimization algorithm discussed.

The LFT

Given a function u of $\Re^K$ sampled at the points $\underline{x}_n \epsilon X \subset \Re^K, n = 1,\dots,N$, the discrete LFT evaluated at points $\underline{y}_m \epsilon Y \subset \Re^K$ is defined as

$$u_X^*(\underline{y}_m) = \underbrace{max}_{\underline{x}_n \epsilon X} \left[< \underline{y}_m, \underline{x}_n > - u(\underline{x}_n) \right], \qquad (2)$$

where $<\cdot,\cdot>$ denotes the scalar product in $\Re^K$.

Obviously, when the double LFT is of interest, eq. (2) is applied to $u_X^*(\underline{y}_m)$ instead of $u(\underline{x}_n)$.

As important property of the LFT to be exploited in the parallel implementation, is that, when u is available on a regular grid and u_X^* is required, as well, on a regular grid, the K-dimensional LFT can be evaluated by nesting K 1-dimensional LFTs, just like a standard Fourier Transform. For example, when K=2,

$$u_X^*(\underline{y}_m) = \underbrace{max}_{x_n^1} \{ \mathrm{y}_\mathrm{m}^1 \mathrm{x}_\mathrm{n}^1 + \underbrace{max}_{x_n^2} [\mathrm{y}_\mathrm{m} \mathrm{x}_\mathrm{n}^2 - u(\mathrm{x}_\mathrm{n}^1, \mathrm{x}_\mathrm{n}^2)]\}, \qquad (3)$$

where $\underline{x}_n = (x_n^1, x_n^2)$ and $\underline{y}_m = (y_m^1, y_m^2)$.

Parallel implementation of the LFT

Let us begin observing that, evaluating u over the grid defined by the $\underline{x}_n$'s represents an embarrassingly parallel task to be effectively performed on a GPU by charging individual threads to computing different $u(\underline{x}_n)$ for different values of n.

Concerning the evaluation of the LFT, in the sequential case, the computational burden is linear in N, provided that proper fast procedures, e.g., the Legendre Linear-time Legendre-Fenchel Transform (LLT) transforms [4], are exploited. In the parallel case, the property expressed in eq. (3) can be exploited by evaluating, in parallel, 1-dimensional LLTs corresponding to different values of the output variable $\underline{y}_m$, just as it happens for the parallel implementation of multidimensional FFTs [5].

The optimization algorithm

Once the double LFT is evaluated, the minimum $\underline{M}$ of the convex envelope of Φ can be determined. As it is shown in [6], if $\mathcal{C}(\underline{M}) = \Phi(\underline{M})$ and the gradient $\underline{\nabla}\Phi(\underline{M}) = \underline{0}$, then this represents the global optimizer for Φ.

However, the minima of $\mathcal{C}$ and Φ can differ if the convex envelope is evaluated over an insufficiently fine grid. Accordingly, iterations are employed performing the following steps

1. Define a grid for evaluating Φ;
2. Evaluate $\mathcal{C}$ by a double LFT;
3. Determine $\underline{M}$;
4. Check if $\mathcal{C}(\underline{M}) = \Phi(\underline{M})$ and $\underline{\nabla}\Phi(\underline{M}) = \underline{0}$; if not, then define a finer grid and restart from #2.

4. EXPERIMENTAL RESULTS

We now present results obtained by the above described algorithm against experimental data from X-band (8.2-12.4GHz) measurements performed in the smallest anechoic chamber (7 x 3.1 x 3.3m sized) of the Dipartimento di Ingegneria Biomedica, Elettronica e delle Telecomunicazioni (DIBET), Università di Napoli Federico II.

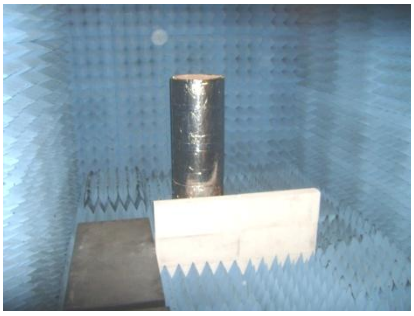

Fig. 2. The wall and the hidden scatterer.

The setup is made of a transmitting (Tx) – receiving (Rx) system, the wall and the hidden object (see Fig.

2). As Tx antenna, a pyramidal horn sufficiently spaced from the wall so to meet local plane wave conditions has been considered. The wall is composed of 12 Ytong bricks (62.5 x 25 x 10 cm) and the hidden object consists of a metallic cylinder with radius of 20cm. The Tx-Rx system is moved on a planar grid parallel to the wall surface and, for each position, multifrequency data are acquired and an optimization is performed.

The algorithm has been implemented in NVidia CUDA programming language [3] and run on an NVIDIA GeForce GTX 260 graphic card.

Fig. 3 shows the strong reduction (three orders of magnitude) in the processing time experienced when passing from a sequential to a parallel evaluation of the functional Φ at the considered sampling grid.

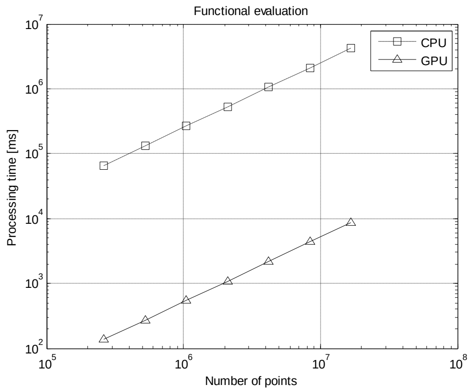

Fig. 3. Computation times for the functional evaluation in the sequential and parallel cases.

Furthermore, Fig. 4 depicts the improvement in computation time achieved when adopting parallel LLT's and compared to sequential ones.

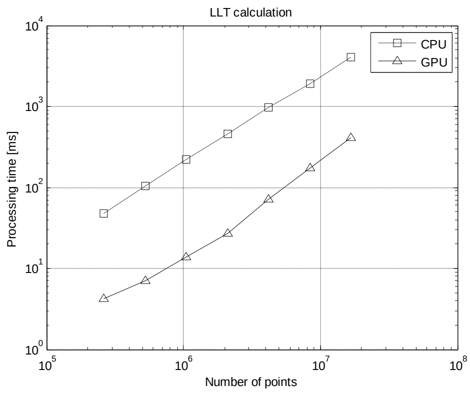

Fig. 4. Computation times for the LLT evaluation in the sequential and parallel cases.

Finally, Fig. 5 shows the result of the different optimizations performed to reconstruct the hidden metallic cylinder. The image shows the different scatterer-wall distances l recovered for the different positions occupied by the horn antenna on the mentioned scanning grid.

5. CONCLUSIONS AND FUTURE DEVELOPMENTS

A Through-Wall-Imaging approach has been presented.

The approach is based on a 1D model of the electromagnetic scattering to involve few parameters and on efficient and effective implementation of an LFT optimization algorithm on a GPU. The strong improvement in the processing time, as compared to a sequential implementation, has been proven and the effectiveness of the algorithm has been shown by experimental results.

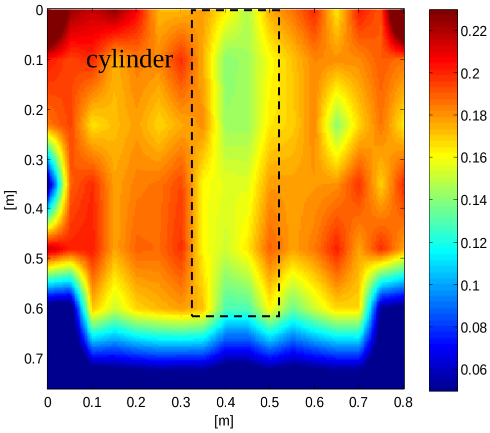

Fig. 5. Through-Wall-Imaging of the hidden cylinder.

As future developments, we foresee accounting for the full plane wave spectrum of the involved antennas, so to remove the limitation of far-field measurements, extensions to the 2D case (if necessary) and the implementation of a portable setup.

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