Near field signal processing for the whole body imaging inversion problem

Jose A. Martinez, Luis Tirado, Fernando Quivira, Galia Gazhi, Kathryn Williams and Carey M. Rappaport
Northeastern University, Boston, MA 02115 Contact Information, jmartine@ece.neu.edu

Abstract

We describe the nearfield signal processing for whole body imaging inversion. 2D stacked slice-based reconstruction is based on illuminating a narrow slice of the body with a specially-designed reflector antenna transmitter, and receiving the scattered millimeter-wave field with a circular arc antenna array. We have developed two inversion algorithms for Frequency Modulated Continuous Wave (FMCW) and Step Frequency radar. In order to test these two algorithms we have used synthetic data created with a) the full wave Finite Difference in Frequency Domain (FDFD) computational model, which provides a very accurate electromagnetic simulation but requires high computational cost, and b) a ray method, based on point spread sources, which is very fast but less precise than FDFD. Our inversion algorithms show outstanding performance in terms of image quality and feature identification.

Relevance

The signal processing algorithms have demonstrated a substantial improvement in the quality of 3D images. The main reason for such a image quality improvement is the use of a multiple bistatic channels, which is different from currently used monostatic systems. Multi-bistatic and multistatic radar eliminates troubling artifacts such as dihedral responses which appear to produce a "tail" between legs. These signal processing techniques can be easily used to fuse the information provided by complimentary X-ray sensors to improve the performance of the system in terms of threat detection and target identification

Technical Approach

Millimeter Wave Radar system configuration.

The system configuration is presented in Fig. 1 and 2. A reflector antenna, which have a parabolic and elliptical profile in the horizontal and vertical plane, respectively, have been used.

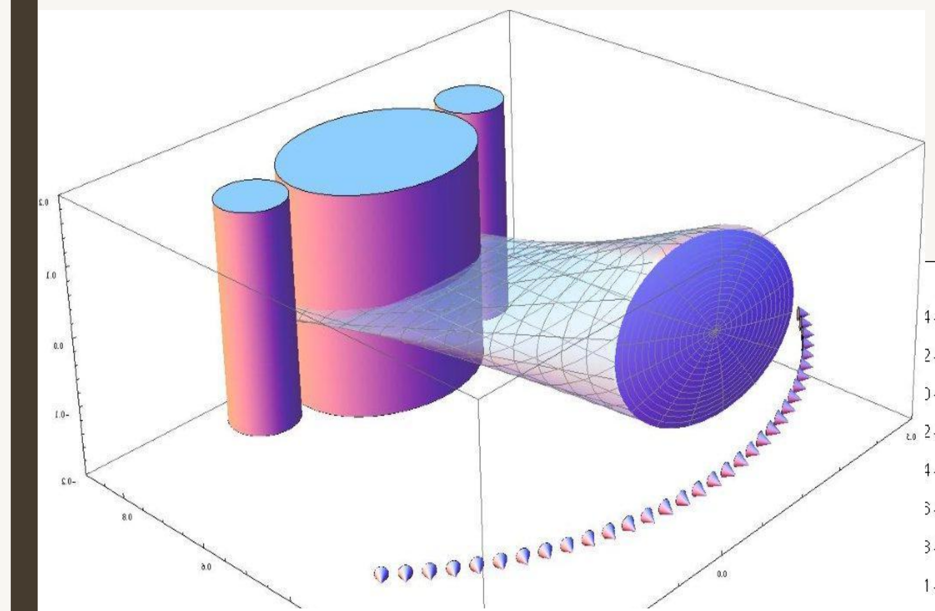

Fig. 1 System configuration based on a reflector antenna an array of receivers.

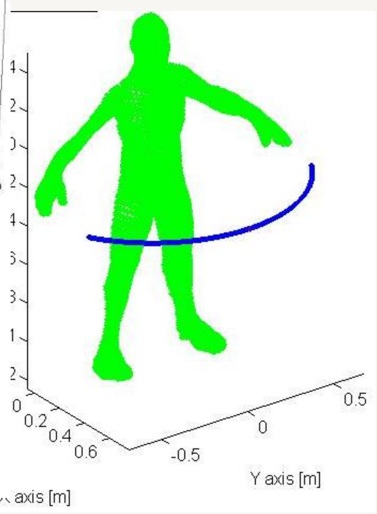

Fig. 2 General view of the person under test .

The basic configuration produces a rectangular beam when projected into the person under test (see Fig. 1). This special type of illumination is ideal for 2D analysis, which is optimal for reducing the computational cost of the inversion algorithm. It is also optimal for working on a multiple bistatic configuration, where an array of receivers are located on a circular arc, since avoids dihedral artifacts.

FMCW signal processing.

We have developed an inversion algorithm based on Frequency Modulated Continuous Wave signal.

The inversion problem can be written in a matrix form as:

$$s_{IF}(n) = \mathbf{A}(n)\rho(n)$$

where $s_{IF}(n)$ is the field measured at the n^{th} receiver, the vector $\rho(n)$ is the unknown reflectivity function, and the matrix $\mathbf{A}(n)$ accounts for the field produced at the n^{th} receiving antenna by each reflectivity point.

The coefficients of the matrix are:

$$A_{l,m} = \exp\left(j\left[2\pi\alpha\tau_m l T_s + 2\pi f_c\,\tau_m - \pi\alpha\tau_m^2\right]\right) \quad (1)$$

where α is the ratio between the radar bandwidth and pulse duration T_s f_c is the central frequency of the radar, and the time of flight τ_m accounts for the time delay of a pulse to travel from the transmitter antenna to a reflection point on de person under test, and then travel to receiving antennas, and l is a time index.

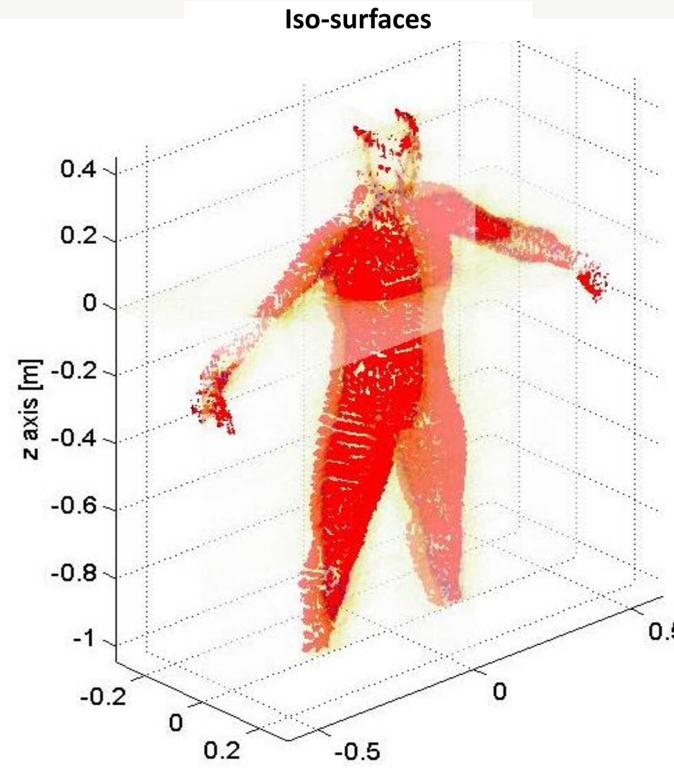

Fig. 3. Reconstructed image at three perpendicular planes and iso-surfaces.

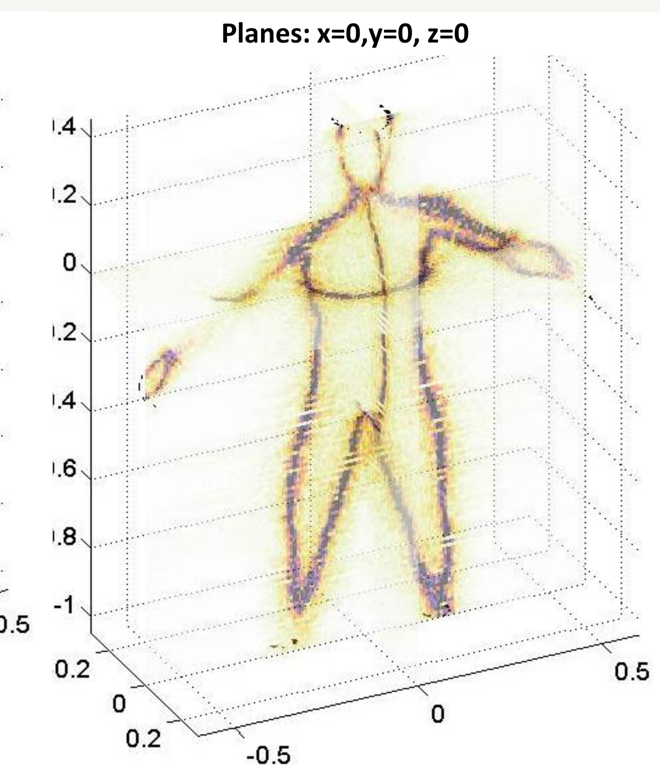

Fig. 4. Reconstructed image at three perpendicular planes.

The reflectivity can be computed as:

$$\rho(n) \approx \mathbf{A}^{\dagger}(n) s_{IF}(n) \quad (2)$$

Where the pseudo inverse matrix $\mathbf{A}^{\dagger}(n)$ can be computed as:

$$\mathbf{A}^{\dagger}(n) = \left(\mathbf{A}^{*}(n)\mathbf{A}(n)\right)^{-1}\mathbf{A}^{*}(n) \quad (3)$$

where * indicates transpose conjugate of the matrix. After combining N_n receivers, the reflectivity function is calculated as:

$$\rho = \frac{1}{N_n}\sum_n \rho(n) = \frac{1}{N_n}\sum_n \mathbf{A}^{\dagger}(n) s_{IF}(n) \quad (4)$$

Fig.3 present the reconstruction of our phantom in terms of iso-surfaces (pixels with same reflectivity value) and Fig. 4 presents the reflectivity in three orthogonal 2D planes. The quality of the reconstructed image is outstanding when compared with the model presented in Fir. 2.

Step Frequency Signal processing.

We have also implemented an inversion algorithm based on Step Frequency signal. The imaging function is defined as:

$$I(\mathbf{r}_u^s) = \sum_{l,n,p} \mathbf{E}(f^l, \mathbf{r}_t^n, \mathbf{r}_r^p)\, a(f^l, \mathbf{r}_t^n, \mathbf{r}_r^p, \mathbf{r}_u^s)\, e^{j\Phi(f^l, \mathbf{r}_t^n, \mathbf{r}_r^p, \mathbf{r}_u^s)} \quad (5)$$

$\mathbf{E}$ is the field measured at the receive antenna, located at $\mathbf{r}_r^p$, when the transmitting antenna, located at the point $\mathbf{r}_t^n$, is transmitting with the l^{th} frequency f^l, the a term is an amplitude factor that can be considered constant in our algorithm, Φ is a phase term that depends on the imaging point $\mathbf{r}_u^s$, and it can be written as:

$$\Phi_B^{FS}(f^l, \mathbf{r}_t^n, \mathbf{r}_r^p, \mathbf{r}_u^s) = \phi_1 + \phi_2$$
$$\phi_1 = k_0^l|\mathbf{r}_u^s - \mathbf{r}_t^n|, \;\; \phi_2 = k_0^l|\mathbf{r}_r^p - \mathbf{r}_u^s| \quad (6)$$

where k_0^l is the free space wave number associated with the l^{th} frequency.

Synthetic data is obtained using FDFD. Fig. 5 presents a cross section of a human body on the scanner (left), and the reconstructed image of the front part of the chest (right).

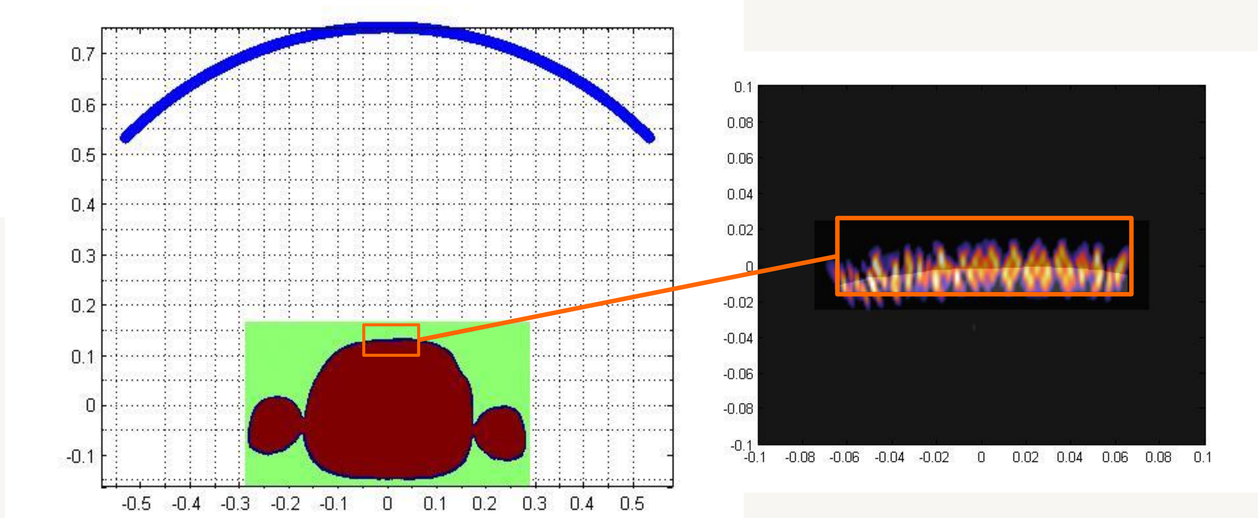

Fig. 5. Reconstructed image at three perpendicular planes and iso-surfaces.

GPU implementation of the inversion algothirms

# array columns	# array rows	CPU code (sec) forward	CPU code (sec) inverse	GPU code (sec) forward	GPU code (sec) inverse
4	2	10.93	350.81	0.65	27.65
8	4	39.37	1197.30	2.70	109.80
16	8	143.26	4539.80	10.95	437.62
32	16	562.66	18107.26	43.57	1742.33
46	26	1625.07	41702.07	102.36	4082.68

Opportunities for Transition to Customer

The inversion algorithms presented in this poster are an important component of the hybrid X-ray/MMW radar whole body imaging system which being developed under of ALERT funding. This system will be able to substantially improve the image quality of current X-ray or MMW systems, and the transition to TSA agents can be quickly implemented.

Accomplishments Through Current Year

During the current year we have developed two types of inversion algorithms: 1) a Frequency Modulated Continuous Wave (FMCW) signal processing , and; 2) a Step Frequency signal processing. The fist algorithm has also been implemented on a GPU, which improves the computational cost by one order of magnitude.

Future Work

We will continue working in improving the quality and speed of our inversion algorithms by means of:

1) Development of a fast forward model, based on fast Physical Optics, which will makes a model based inversion possible.

2) Development of a super resolution algorithm based on the Iterative Field Matrix approach.

3) Development of a new mathematical formulation which express the inversion problem in terms of multipole expansions.

Publications Acknowledging DHS Support

1. Fernandes, J., et al. "FMCW SAR imaging of body worn explosives from FDFD modeled scattered field data," *PIERS*, Cambridge, MA, July 2010, pp. 350.
2. Fernandes, J., et al. "Simulation results for standoff detection of suicide bombers at millimeter-wave frequencies using a full wave numerical analysis," *Homeland Security Summit*, Washington, DC, March, 2010,.
3. Martinez-Lorenzo, J., et al. "SAR imaging of suicide bombers wearing concealed dielectric structures," *IEEE Homeland Security Technology*, Waltham MA, Nov 2010.
4. Fernandes, J., et al. "A comparison of experimental and simulated millimeter wave imaging system for standoff detection of person-borne improvised explosive devices," *IEEE Homeland Security Technology*, Waltham MA, Nov 2010.

Other References

1. Curlander J. C., McDonough R. N., Synthetic Aperture Radar: Systems and Signal Processing, John Wiley Sons, Inc., USA, 1991.
2. Carrara W. G., Goodman R. S., Majewski R. M., Spotlight Synthetic Aperture Radar: Signal Processing Algorithms, Artech House, Inc., USA, 1995..

This material is based upon work supported by the U.S. Department of Homeland Security under Award Number 2008-ST-061-ED0001. The views and conclusions contained in this document are those of the authors and should not be interpreted as necessarily representing the official policies, either expressed or implied of the U.S. Department of Homeland Security.