Feasibility of Computational Methods for Realistic Simulation and Image Reconstruction for Millimeter Wave Whole-Body Imaging

Kathryn Williams, Carey Rappaport, Jose Martinez, Borja Gonzalez Valdes, Yuri Alvarez
Contact: williams.ka@neu.edu

Abstract

Computational methods that are both fast and accurate are required in the design phase for improved millimeter-wave whole-body scanners. These methods are needed to model and understand the interactions of radiation with realistic human body types, weapons, and explosives and to efficiently explore complex hardware sensor designs. Fast and accurate methods are also required in the hardware implementation of millimeter-wave systems to enable real-time image reconstruction in high throughput security areas. Computational algorithms based on ray tracing, Physical Optics, and Finite Difference in the Frequency Domain methods are evaluated for feasibility for both simulation and implementation. Tradeoffs between the accuracy of field solutions and the time and memory required to solve for the solutions are considered in this work.

Relevance

Person-borne weapons and explosives present major threats to security at infrastructures such as airports, government venues, and other highly populated areas. Pat-downs can identify these objects, but are viewed by the public as too physically invasive. Millimeter-wave imaging systems provide an alternative to both metal detectors and pat-downs by using electromagnetic radiation to detect any object underneath an individual's clothing.

Portal-based screening systems are implemented in many facilities to identify anomalous objects hidden underneath a person's clothing. Improvements to these systems can be investigated through modeling and simulation using various computational electromagnetic methods. Systems with greater resolution and more effective imaging algorithms can reduce false alarm rates and allow more automatic computerized detection.

The computational methods investigated in this work provide insight into the limitations of the current tools available for modeling system configurations and for creating imaging algorithms.

Technical Approach

Realistic Scenarios

Realistic human bodies are simulated using cryosection slices of a male human cadaver taken from the Visible Human Project (Figure 1). These 2D images were extended to a 3D surface mesh for use in the 3D computational methods (Figure 2). Body features less than .05mm^2 in size were not included in these models, since the scattering response of these features at a receiver location of .6m is only about 1% of the scattered response from the rest of the body.

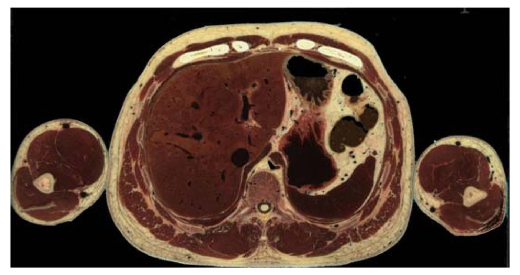
Figure 1. Axial slice from human cadaver

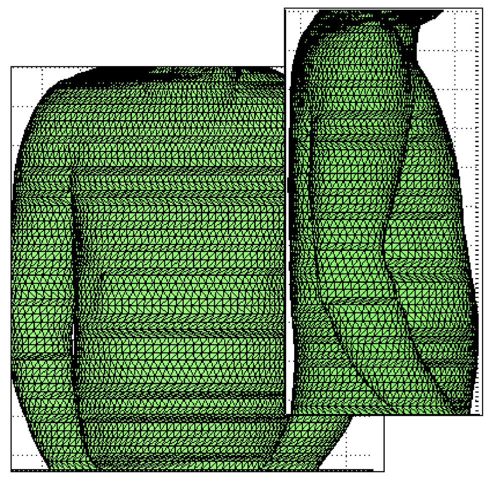
Figure 2. 3D mesh generated from 2D slices

New Algorithms

A ray tracing algorithm is being developed for approximating electromagnetic scattering and for model-based inversion. Conventional full-wave methods used for computing the scattering of electromagnetic waves from objects, such as Finite Difference Frequency Domain (FDFD), provide exact solutions but are too computationally intensive to be used for 3D simulation and inversion. Ray tracing computes reflected rays by applying Snell's law at each triangle in the mesh geometry, traces the rays until they reach a receiving surface, and then adds all ray contributions, including path length phase, impinging on a given small surface patch. Figure 3 shows reflected rays from a human chest, which will be observed on a cylindrical surface. This algorithm is being implemented on NVIDIA GPUs, offering potential for real-time simulation and inversion.

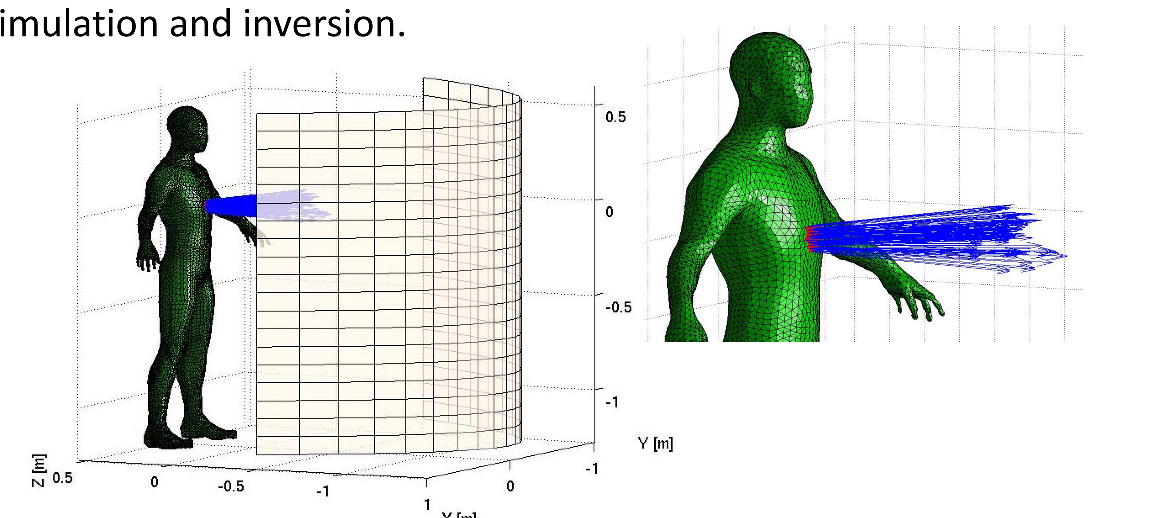
Figure 3. Scattering can be approximated by ray tracing. Here, rays are reflected from a human body geometry.

Comparison of Numerical Algorithms:

Ray tracing, PO (Physical Optics), PO with FMM (Fast Multipole Method), MECA (Modified Equivalent Current Approximation), and FDFD were evaluated for whole-body imaging applications. Table 1 highlights the major differences between these methods.

Table 1. Algorithm Descriptions and Parameters

	Ray Tracing	PO	PO with FMM	MECA	FDFD
Language	C	MATLAB	MATLAB	C	MATLAB
Dimensionality	3D	3D	3D	3D	2D
Electromagnetic Approximations	Reflection only	Does not account for multiple wave interactions	Does not account for multiple wave interactions	Does not account for multiple wave interactions	All wave phenomena
Allowable Material	PEC	PEC	PEC	Any material	Any material
Allowable Observation Points	3D cylinder	3D cylinder or 2D plane	3D cylinder or 2D plane	3D cylinder or 2D plane	2D plane only or 2D arc
Optimizations	Parallel processing on GPU; facet size 2λ	Far-field calculations; facet size 2λ	Far-field calculations; facet size .35λ	Multiple processors; far-field calculations; facet size 2λ	Near-field calculations; domain with spacing λ/10
Other Considerations			Group sizes: 3λ for far-field; 1.5λ for near-field		

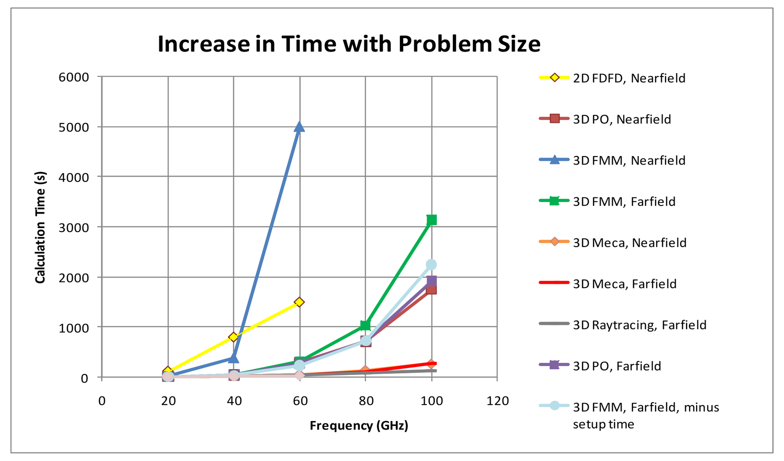

Figure 4. Time requirements in seconds for each method using comparable input parameters. Scattered fields for all methods (except ray tracing) were calculated on both a near-field observation plane and a far-field observation plane. The scattered fields for ray tracing were calculated on a cylinder enclosing the human body.

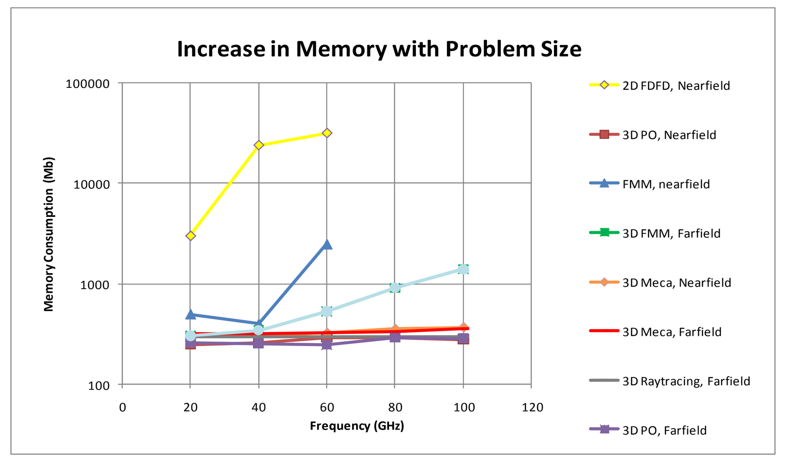

Figure 5. Memory requirements in MB for each method.

Feasibility for Image Reconstruction

Forward models can be used to develop model-based inversion methods, which can produce significantly improved images than the current state-of-the-art. In this work, synthetic forward data was generated by FDFD. Figure 6 shows the results from Generalized Synthetic Aperture Focusing (GSAF) reconstruction. Figure 7 shows the results from a PO/FMM based inversion method, which offers comparable accuracy to GSAF at huge cost savings.

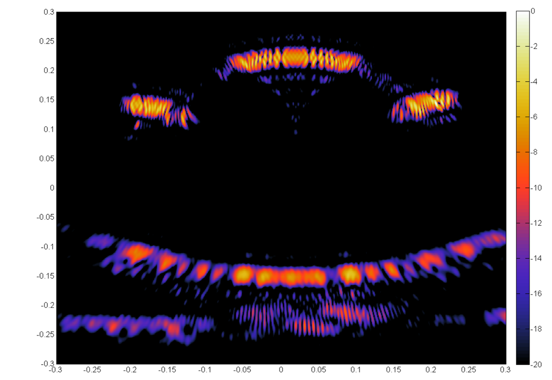
Figure 6. GSAF reconstruction.
FDFD forward synthetic data: 6.6 hours
GSAF inversion: 70 minutes

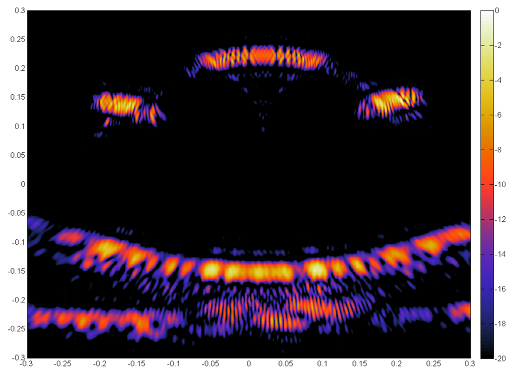
Figure 7. PO/FMM based reconstruction.
FDFD forward synthetic data: 6.6 hours
PO/FMM inversion: 129 seconds

2D Stacked Reconstruction

The images in Figure 6 and 7 show 2D reconstructions. 2D reconstructions can be stacked to obtain a 3D image of the entire body, as show in Figure 8.

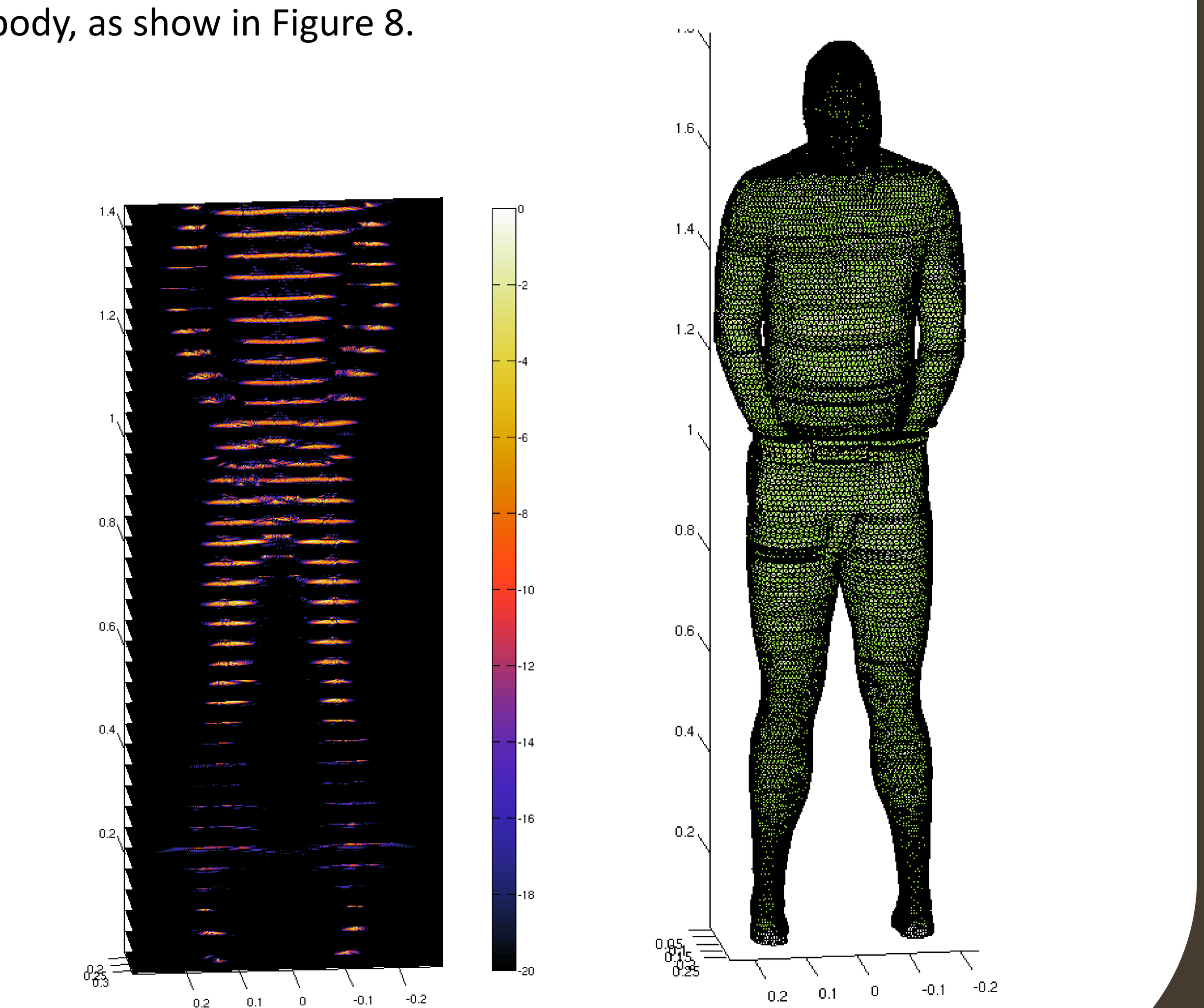
Figure 8. 2D reconstructions are stacked to render an image of the entire body.

Opportunities for Transition to Customer

The analysis presented in this work evaluates the limitations of current modeling tools and provides a foundation for choosing the best method for simulation and inversion given a specific scenario. It is a step toward developing improved hardware and reconstruction techniques to be used in the millimeter-wave radar system being developed under ALERT funding. Accurate reconstructed images will increase the probability of detection of anomalous objects at security sites.

Conclusions and Future Work

A ray tracing algorithm has been developed for 3D simulation of the scattering from human bodies. The tradeoffs between accuracy of field solutions and cost to compute field solutions were evaluated for each in-house computational tool. Although Finite Difference in the Frequency Domain directly solves fundamental electromagnetic equations, it is only valid for 2D simulations and does not account for interference between various regions of the body in the height dimension. However, a 3D image can be created by stacking 2D simulations. Physical Optics and ray tracing make several approximations to wave behavior, offering limited accuracy in field solutions. However, these methods offer full 3D solutions, as well as huge cost savings in terms of the time and memory required to compute the solutions. Physical Optics has been demonstrated to quickly simulate novel sensor configurations and to quickly provide accurate reconstructed surfaces when used as an inversion method.

Future work involves further validating the algorithms with experimental data and extending the evaluation to include 2.5D FDFD. The ray tracing algorithm will be tested on more complex geometries and the algorithm's limitations and accuracy will be determined. Future work also includes developing a hybrid FDFD-Physical Optics approach to render more accurate 3D reconstructions.

Publications Acknowledging DHS Support

[1] K. Williams, C. Rappaport, A. Morgenthaler, J. Martinez, R. Obermeier, F. Quivira, "Computational Modeling of Close-In Millimeter Wave Radar for the Detection of Concealed Threats," presented at the Gordon Research Conference, Italy, June 2011.

References

[2] Meana, J. G., J. A. Martinez-Lorenzo, F. Las-Heras, and C. Rappaport. "Wave Scattering by Dielectric and Lossy Materials Using the Modified Equivalent Current Approximation (MECA)." *IEEE Transactions on Antennas and Propagation* 58.11 (2010). Print.
[3] Sheen, D. M., D. L. McMaken, and T. E. Hall. "Three-dimensional Millimeter-Wave Imaging for Concealed Weapon Detection." *IEEE Transactions on Microwave Theory and Techniques* 49.9 (2001). Print.
[4] "The National Library of Medicine's Visible Human Project." *National Library of Medicine - National Institutes of Health*. Web. July 2011. <http://www.nlm.nih.gov/research/visible/visible_human.html>.

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.