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

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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 a major threat to security in airports, government venues, and other highly populated or highly secure areas. With the rise of nonmetal threats, including improvised explosives, liquids, plastics, and ceramic weapons, metal detectors are no longer sufficient security measures. 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.

The current state-of-the-art portal-based millimeter-wave scanning technology uses a monostatic radar configuration and a 2D maximum intensity projection for image display, resulting in flat, two dimensional images with little detail at angles except the specular angle. This provides motivation for investigating alternative antenna positions and new reconstruction methods that could result in increased detection of anomalous objects on the body.

The computational methods investigated in this work provide insight into the limitations of the current tools available for modeling system configurations and for creating forward-based inversion methods.

Technical Approach

Comparison of Numerical Algorithms

Ray tracing, PO (Physical Optics), PO with FMM (Fast Multipole Method), MECA (Modified Equivalent Current Approximation), and FDFD (Finite Difference in the Frequency Domain) are evaluated for whole-body imaging applications. Table 1 highlights the major differences between these methods. The terms near-field and far-field are used with respect to the mesh facet size.

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		

Realistic Scenarios

Realistic human bodies were 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 (Figure 2). Body features less than .05mm² 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.

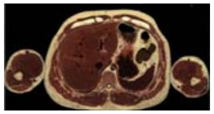

Figure 1. Axial slice from human cadaver

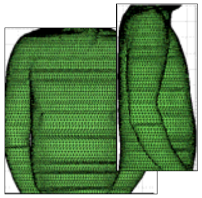

Figure 2. 3D mesh generated from 2D slices

Comparison Results:

Figure 3 shows scattered field results from one slice of the body illuminated with a plane wave at 60Ghz. A 2D slice was simulated in FDFD and a 3D mesh with no variation in height was simulated in PO, FMM, and MECA. The fields at the boundary of the body and air in the PO-based methods are -10dB, due to the inaccuracy of PO scattered field solutions close to surfaces that exhibit currents. The ray patterns are different between FDFD and the PO-based methods since the PO-based methods do not consider mutual coupling between the mesh facets and do not account for multiple bounces of waves between boundaries. Time and memory requirements for each method are shown in Figures 3 and 4.

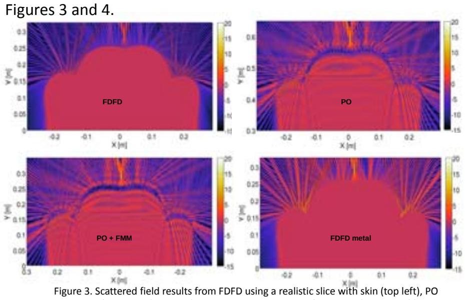

Figure 3. Scattered field results from FDFD using a realistic slice with skin (top left), PO using a surface mesh (top right), PO with FMM using a surface mesh (bottom left), and FDFD using a slice modeled with the electrical parameters of metal (bottom right).

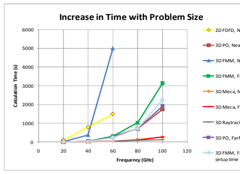

Figure 4. Time requirements in seconds for each method using comparable input parameters. Scattered fields for all methods (except ray tracing) were calculated on both a near-field observation plane and a far-field observation plane. The scattered fields for ray tracing were calculated on a cylinder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

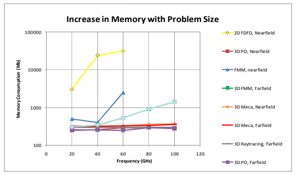

Figure 5. Memory requirements in MB for each method.

Simulating Complex Sensor Configurations

Figure 4 shows the beam from an elliptical parabola reflector. The beam focuses to illuminate a 1cm thick slice of the body at the second ellipse focal point at 0.6m. This proposed configuration was simulated using FDFD and PO. Figure 5 shows the PO simulation, with the reflector, human torso, and observation points. Figure 6 shows the FDFD simulation, which is limited to two dimensions.

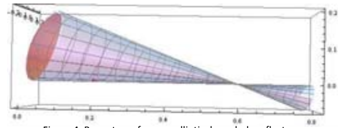

Figure 4. Beam trace from an elliptical parabola reflector

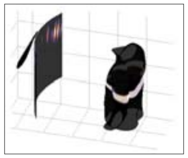

Figure 5. Novel sensor configuration simulated with PO.
88 seconds; 3D result

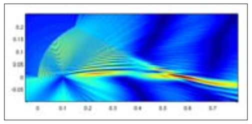

Figure 6. Novel sensor configuration simulated with FDFD.
97 seconds; 2D result

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, forward data was generated by FDFD. Figure 7 shows the results from Generalized Synthetic Aperture Focusing (GSAF) reconstruction. Figure 8 shows the results from a PO/FMM based inversion method, which offers comparable accuracy to GSAF at huge cost savings.

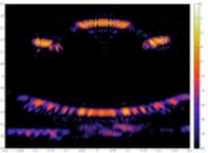

Figure 7. GSAF reconstruction.
FDFD forward synthetic data: 6.6 hours
GSAF inversion: 70 minutes

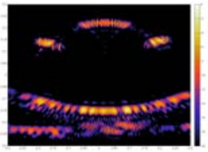

Figure 8. PO/FMM based reconstruction.
FDFD forward synthetic data: 6.6 hours
PO/FMM inversion: 129 seconds

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.

Conclusion and Future Work

Each computational method offers tradeoffs in the solution accuracy and the cost to compute. 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, which may change the fields measured at an observation point. Physical Optics and ray tracing make several approximations to wave behavior, offering limited accuracy in field solutions. However, these methods offer 3D solutions, as well as huge cost savings in terms of the time and memory required to compute the solution. Physical Optics has been demonstrated to quickly simulate novel sensor configurations and to quickly provide accurate reconstructed surfaces when used as an inversion method. Based on the work of this project, the Modified Equivalent Current Approximation extension of Physical Optics with speed optimizations from the Fast Multipole Method has been shown to be most feasible for simulating and reconstructing realistic scenarios.

Future work involves further validating the algorithms with experimental measurement, identifying metrics to determine to within what accuracy a computational method is considered adequate for modeling realistic scenarios, and extending the evaluation to include 2.5D FDFD.

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.

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[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>.

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