R3-A.2: Computational Models & Algorithms for Millimeter Wave Whole Body Scanning for Advanced Imaging Technology (AIT)

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II. PROJECT DESCRIPTION

A. Project Overview

Active millimeter wave radar Advanced Imaging Technology (AIT) is the best available imaging technology for detecting objects concealed on the human body at security checkpoints [1-5]. An important need for AIT person screening is to reduce false alarms due to innocent foreign objects worn under clothing [6]. While currently deployed mm-wave nearfield radar systems, such as the L3 ProVision scanner can adequately detect and image concealed foreign objects, with current processing, they are incapable of ruling out filled beverage containers, medical devices, money belts, or other commonly worn items. The resulting alarms necessitate pat-downs, slow the progress of the traveling public, require significant manpower dedicated to alarm resolution, and detract from the overall passenger experience.

Project R3-A.2 has been investigating new approaches to processing mm-wave nearfield radar data to determine the dielectric constant and thickness of electromagnetically penetrable slabs [7-11]. Using available hardware measurements, these approaches consider the differential paths taken by rays that pass through dielectric slabs on the way to the conductive human skin backplane. Indeed, the current AIT systems provide sufficient information about the scattering to generate the overall shape of a foreign dielectric object, but with appropriate processing, can also calculate how thick the dielectric object is and whether its dielectric constant is consistent with a material of interest. The recent DHS S&T/TSA Passenger Screening Algorithm Kaggle Challenge sought automatic approaches to detect anomalies, some of which were representative low-dielectric materials. Project R3-A.2 algorithms have shown in laboratory testing, the ability to perform material discrimination calculations for both single frequency, raster scanned focused...
systems (such as the Smith’s Detection eqo\textsuperscript{1} system) and wideband frequency modulated continuous wave (FMCW) or stepped frequency systems (such as the L3 ProVision\textsuperscript{2}, PNNL\textsuperscript{3}).

With the first goal of automatically determining the nominal scanned body surface without and with attached foreign objects, Project R3-A.2 has been dedicating effort to combine the excellent high-resolution 2D multi-view angle “projected” images with the richer 3D raw reflectivity data from the Kaggle Prize Dataset. The reconstructed images from the projected data are almost photographic in quality. The brightness corresponds to the reflectivity of the surface material (brightest for metal) and the orientation of portions of the scattering surface (brightest for surface portions parallel to the imaging plane). This gives an excellent sense of surface curvature, and highlights protruding objects, but ignores the depth dimension.

Our approach to determining the nominal body surface has been to work slice by slice. First, the axial slices are parallel to the ground, and then, the volumetric distribution of pixel intensities are reduced to the most likely 1D contour in each 2D slice. These contours can give clear indications of anomalies, as shown for Prize Data in Figure 1 for two axial slices.

![Reflection](attachment:figure1.png)

**Figure 1: Surface contours for an axial slice through the torso generated from 3D volumetric data at two heights. Contour interruption on right slice image indicates obscuration by anomaly.**

B. *State-of-the-Art and Technical Approach*

The current effort is to establish a new paradigm for foreign object material characterization, so that explosive threats can be more reliably detected. While currently imaged objects, such as firearms and knives can be recognized by shape, explosive volumes can take on any shape and thickness. We endeavor to

\textsuperscript{1}https://www.smithsdetection.com/products/eqo/
\textsuperscript{2}http://www.sds.l-3com.com/advancedimaging/provision-2.htm
\textsuperscript{3}Three-dimensional radar imaging techniques and systems for near-field applications, https://doi.org/10.1117/12.2229235
determine the range of foreign object dielectric constants, and rule out innocent materials that would have dielectric constants outside this range.

The high resolution 2D multi-view “maximum intensity” images that are conventionally used for anomaly detection have quite recognizable features. At the appropriate viewing angle, the maximum intensity 2D image is excellent for visualizing the size and shape of a foreign object. This approach is much clearer and understandable than sets of multiple angle projected body images or the 3D volumetric reflectivity data, but it has limited use for determining the nominal body surfaces and anomaly composition or thickness, as shown in Figure 2. Since the strongest backscattering occurs in body surfaces that are mostly perpendicular to the incident wave direction, the edges of the body vanish.

![Image of body surface with low dielectric constant foreign objects on upper arm, as rendered by max intensity reconstruction. Note the clear delineation of object boundaries, but poor body edge reconstruction.](image)

*Figure 2: Body surface with low dielectric constant foreign objects on upper arm, as rendered by max intensity reconstruction. Note the clear delineation of object boundaries, but poor body edge reconstruction.*

To combine the detailed surface view with the body volume and foreign object depth information, R3-A.2 focused on identifying the contours most likely to correspond to the surfaces. Using morphological tools available in the MATLAB software platform, the pixels associated with the body contours in a given slice are selected and sharpened. Canny edge detectors plus opening and closing operators are used to eliminate noise and establish clear, smooth surface representation, as shown in Figure 3.
Stacking the identified contours approximates the volumetric 2D body surface. Unlike with maximum intensity views, this processing approach retains depth information, which is essential in characterizing material attached to the body surface.

It is now possible to show small differences between contours and use this information to measure the degree of deformation due to a foreign object. For example, the left arm contours of Figure 2 (with and without the object) can be registered to account for the differing positions for the repeated scan. Figure 4 shows a simple registration by eye of the two left arm contours. The depression deformation at the position of a silicon slab is about $\frac{1}{4}$ of the arm width.

Figure 3: Contour cleaning using Canny filtering to identify and enhance sharp boundaries, and opening and closing operations to ensure connected, constant width contours.
To establish the dielectric constant, additional information is required. In particular, the scattering from the front surface of the dielectric slab must be identified and its distance from the nominal body surface must be computed. Returning to the arm slice reconstruction, the scattering from the front slab surface is observable if the sensitivity of the intensity scale is increased with the highest intensity values clipped. Figure 5 shows the slice through the 3D reconstructed left arm in Figure 2 in detail, with the maximum intensity at about $\frac{1}{3}$ of the maximum value and values above 0.3 clipped as black. Note the secondary maxima in the vicinity of the slab in the 8:00 - 10:30 positions. These spots of maxima are highlighted and identified on Figure 5.

**Figure 4:** Left arm slice contours for two scans with foreign object (black) registered with arm contour without object (white), showing the apparent depression of arm surface at the position of the foreign object at 8:00 – 10:30 positions.

**Figure 5:** Left arm detail with foreign object. The color intensity is thresholded at about $\frac{1}{3}$ of the full intensity, to enhance weaker secondary maxima, especially in the region just outside the foreign object slab that extends from clock positions 8:00 – 10:30.
Progress has also been made on a second, related topic: an automatic characterizing algorithm for weak dielectric slabs. We have made measurements and reconstructed images with our own experimental multistatic AIT detector using the geometry shown in Figure 6 for an explosive simulant on a flat metal plate.

![Diagram of measurement geometry](image)

**Figure 6:** Measurement geometry for 60 GHz multistatic imaging of a 2.5 cm thick paraffin and TiO explosive simulant ($\varepsilon' = 2.9$) slab attached to a perfectly conducting finite metal sheet.

The original reconstructed image for this geometry is shown in Figure 7. This data has been Radon/Inverse Radon transformed to fill in discontinuity artifacts without widening the response in range or cross-range. The tilted metal sheet is easily recognized, corresponding to the tilted streak of strong response. The interruption in the middle of the streak is the dielectric object. With the radar illuminating from below, the interruption appears to depress the sheet response, indicative of a weak dielectric. The goal is to automatically determine the thickness and dielectric constant of the dielectric bar.

![Reconstructed image](image)

**Figure 7:** Reconstructed image of tilted finite metal sheet with weak dielectric bar attached. Note the gap in the center of the tilted streak, corresponding to the presence of a foreign object.

First, the nominal surface is found. Figure 8 shows the 50% of max thresholded response (to eliminate the lowest-level noise and clutter), with a red line best fit, corresponding to the metal surface.
The nominal response for a metal sheet is a sinc function projected outwards on both sides, normal to the metal surface [17, 18]. Figure 9(a) is modeled based on the predicted position of the metal sheet, scaled by the original reflectivity at those points. When this modeled response is subtracted from the original reconstruction, the cleaned result is shown in Figure 9(b).

The remaining response in Figure 9b is due solely to the dielectric bar and the metal behind it. Note that this response has been thresholded to above 30% of the original maximum reflectivity intensity, resulting in the totally black regions. By taking the position-weighted average of the remaining signal in the vicinity of the nominal metal sheet (shown again with a red line), the net surface depression is computed and displayed as a green star.
Finally, the response from the back of the dielectric slab, which appears to be a depression in the nominal metal surface, is used to enhance the image. Assuming again that the scattering from the metal behind the dielectric slab has an ideal response that corresponds to a sinc function, we scale sinc functions extending perpendicular to the metal surface by the peak scattering intensity at the position of the green star. This ideal scaled response is now subtracted. The result after thresholding to 20% of the original intensity is shown in Figure 10. The white star indicates the average position of the remaining response, which corresponds to the front surface of the dielectric bar.

![Dielectric Response](image)

**Figure 10:** Original reconstruction with modeled metal sinc function and dielectric sinc function removed and thresholded to 20%. The remaining reflectivity response position-weighted average—corresponding to the dielectric front surface—is indicated by the white star.

Figure 11 shows the original with predictions of depression distance \( d = 2.7 \) cm and front surface protrusion \( d' = 2.4 \) cm. The dielectric constant formula is: 
\[
\varepsilon' = \left( \frac{d'}{d} + 1 \right)^2 = 3.56,
\]
which is within 25% of the true value [19-20]. We will next be applying this algorithm to the Prize Data, which has been made available to us, through a Task Order contract. Although the Prize Data is multi-bistatic, we anticipate similar good performance for this simpler design.
C. **Major Contributions**

- Elliptical torus reflector physical optics forward model for wave focusing analysis (2014)
- Axisymmetric finite difference frequency domain computational method derivation and validation (2015)
- Adjoint operator inversion method for elliptical torus reflector (2016)
- Hallway multistatic mm-wave concealed object scanning concept and patent application (2017)
- Transmitter/receiver position optimization for elliptical torus reflector AIT scanner (2017)
- Virtual source model for continuous wave (CW), raster scanned focused spot mm-wave nearfield imaging (2017)
- Inversion method using virtual source model for CW, raster scanned focused spot mm-wave nearfield imaging, reported in conference paper IV.B.1 [14-16] (2018)
- Characterization of dielectric slabs using CW, raster scanned focused spot mm-wave nearfield imaging, reported in conference paper IV.B.1 (2018)
- Acquisition, analysis, and validation of Kaggle Prize Data for high-resolution AIT (2019)

![Figure 11: Original reconstruction with ground truth metal sheet line (red), depressed metal-covered dielectric (upper white line), and dielectric front surface (lower white line).](image)
D. **Milestones**

**D.1. Year 6 Milestones**

- We completed the dielectric characterization algorithm for CW raster scanned AIT systems, such as the Smiths eeo scanner.
- We tested our wideband dielectric characterization algorithm using measured experimental data collected by the PNNL 30 GHz bandwidth AIT system. This data was used for the Kaggle AT Challenge, which ended in December 2017. We have obtained ground truth information on the foreign objects attached to human subjects, and we are testing the accuracy of our predictions of their material composition.

**D.2. Year 7 Milestones**

- We expect to reach our final objective of developing a platform-independent set of algorithms for all fielded AIT scanners that will rule out innocent dielectric objects.

**D.3. Programmatic Risks**

- Insufficient reconstructed image fidelity, leading to inconclusive characterization;
- Inability to apply the algorithm to strongly curved body surfaces;
- Challenges with determining nominal body surfaces when objects are affixed to skin; and
- Spoofing of concealed objects by tapering and blending object boundaries.

**E. Future Plans/Project Completion (Year 7)**

The next year will require perfecting algorithms for application of our algorithms to general body surface cases, error trapping, and developing a general format for transferability of algorithms to any given AIT platform. Since the largest threats to the project is poor reconstruction data, the best mitigation approach is to provide recommendations to AIT scanner developers of ways to improve their scanning and reconstruction paradigms. Successful completion of the project would be a software package that could easily be adopted to any given scanner that improves its effectiveness by ruling out typical non-threat foreign objects.

**III. RELEVANCE AND TRANSITION**

**A. Relevance of Research to the Department of Homeland Security (DHS) Enterprise**

The algorithms developed in this project are specifically tuned to existing scanning focused beam mm-wave portal systems. They have provided greater characterization of concealed threats, thereby reducing the probability of false alarms.

**B. Potential for Transition**

Our algorithms apply to all AIT scanning systems and they can potentially be implemented on any system, improving results by ruling-out concealed innocent foreign objects.
C. Data and/or IP Acquisition Strategy

We have provisional patents for both CW raster scanned and wideband mm-wave radar characterization algorithms. All existing and planned AIT systems will benefit from the threat characterization that our algorithms afford.

D. Transition Pathway

Our previous DHS task order involved collaboration with Smiths Detection PLC on the AIT dielectric “material-on-skin” characterization algorithm. Our effective partnership includes semi-monthly international telephone meetings with chief scientists at Smiths Detection, and free exchange of measured data and modeled responses. This concept, which was described in previous project reports, has been validated as part of a two-year DHS Task Order, which concluded in September 2018. The science and implementation of the algorithm have been transferred to Smiths Detection and DHS. We have generated and submitted a white paper to Smiths Detection to suggest a path forward for collaboration with ALERT for modeling and target reconstruction for wideband mm-wave portal scanning. Going forward, the analogous characterization algorithm for wideband mm-wave scanners will be developed for Kaggle Prize data, but will be platform-independent. This last effort will be completed in September 2020.

E. Customer Connections

Biweekly telephone meetings discussing the CW raster scanned eqo-based system have been held with Christopher Gregory, Claudius Volz, Christoph Weiskopf, Martin Hartik, and Michael Jenning of Smiths Detection (Edgewood, MD, USA and Wiesbaden, Germany). In the past 6 months and the coming year, we will be having biweekly telephone meetings with DHS representative Brian Lewis, and monthly meetings with John Fortune.

IV. PROJECT ACCOMPLISHMENTS AND DOCUMENTATION

A. Education and Workforce Development Activities

1. Student Internship, Job, and/or Research Opportunities:

B. Peer Reviewed Conference Proceedings


C. Other Presentations

1. Seminars

V. REFERENCES


