R3-A.2: Computational Models and Algorithms for Millimeter-Wave Whole Body Scanning for Advanced Imaging Technology

I. PARTICIPANTS INVOLVED FROM JULY 1, 2019 TO JUNE 30, 2020

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II. PROJECT DESCRIPTION

A. *Project Overview*

Active millimeter-wave (mm-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 measured data from the high definition (HD) AIT system developed by PNNL, these approaches consider the differential paths taken by rays that pass through dielectric slabs on the way to the conductive human skin backplane. The current AIT systems provide sufficient information about the scattering to generate the overall shape of a foreign dielectric object, but with appropriate processing they can also calculate how thick the dielectric object is and whether its dielectric constant is consistent with a material of interest. The algorithms conceived of and developed in R3-A.2 are being implemented as fully automatic approaches to classify anomalies, some of which were representative low-dielectric materials. Project R3-A.2 algorithms have shown in laboratory testing to discriminate concealed foreign materials, both single frequency raster scanned focused systems (such as the Smiths Detection eqo[1] system) [12-16] and wideband frequency modulated continuous wave or stepped frequency systems (such as the L3 ProVision[2], PNNL[3]). Armed with this material classification information, security personnel have a much clearer sense of the potential threat, leading to fewer false alarms—and fewer pat-downs at checkpoints. Since even a 10% reduction in false alarms results in tens of millions of dollars in reduced TSA labor costs, as well as faster throughput at security checkpoints and a much happier traveling public, this project has enormous value to the homeland security enterprise.

The goals of the project are to:

- Determine the best means of identifying features of 3D image data that indicate the presence and material characteristics of concealed foreign object on all parts of the body.
- Use the most advanced mm-wave image data available to develop an appropriate algorithm to exploit these features.
- Isolate anomalies and infer their complex dielectric constants.
- Compare this inferred dielectric information with that of potential threats and nuisance objects, and report alarms for potential hazards and pass innocent objects.
- Score the performance of the algorithm relative to know ground truth to establish receiver operating characteristics (ROCs) and show the potential for effectiveness.

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 determine the range of foreign object dielectric constant and rule out innocent materials that would have dielectric constants outside this range.

The technical approach used is to determine the front dielectric slab position and the delayed back slab position, both relative to the nominal body surface position, as shown in the cross-sectional image of a body part. Guided by information about the existence and surface location of an anomaly, as provided by the front end automatic target recognition algorithm, our algorithm determines if the object (a) is essentially lossless with a dielectric constant between 2 and 6, corresponding to high explosive, (b) contains bright reflectivity regions 1.5 times that of nominal skin, indicating a metallic object, or (c) is very lossy with a high dielectric constant, associated with a container filled with water-based liquid. If any of these conditions are met, further screening is necessary. To our knowledge, we are the only research group that is using this method—or any method that incorporates images that protrude or are depressed relative to the body surface.

C. Major Contributions

- Conceived and simulated the imaging response for the elliptical torus reflector "blade beam" reflector antenna. This fully multistatic nearfield imaging radar eliminates dihedral artifacts, provides high gain, can be operated quickly, and is less expensive than currently deployed AIT systems (2015).

[1] https://www.smithsdetection.com/products/eqo/

[2] http://www.sds.l-3com.com/advancedimaging/provision-2.htm

[3] Three-dimensional radar imaging techniques and systems for near-field applications, https://doi.org/10.1117/12.2229235

- Established a fast and robust algorithm for elliptical torus reflector imaging of experimentally measured data (2016).
- Developed an optimized feed distribution for efficiently gathering wide-angle radar signals across the entire 120-degree aperture (2017).
- Identified the source and developed an algorithm to correct for grating lobe artifacts from spatial undersampling of elements in receiver array (2018).
- Combined high resolution 2D multi-view angle “projected” images with the richer 3D raw reflectivity data to generate cross sectional slices and contour lines that indicate the shape of the body part as Figure 1 (2018).

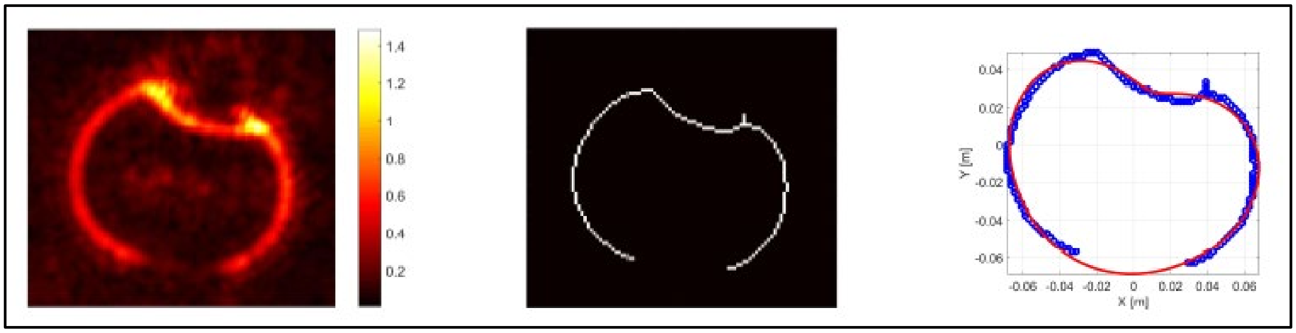

Figure 1: Reflectivity of a cross-section of the lower right thigh contour data of Figure 3 at z = 0.60 m with the depression due to the presence of an affixed slab of petroleum jelly (left), the extracted contour using Canny edge detector filter and morphological processing (middle), and seven-term Fourier series fit to blue contour data (right).

- Exploited the surface curvature and highlighted protruding objects, taking careful consideration of depth dimension (2019).
- Automatically determined the nominal scanned body surface with and without attached foreign objects using high definition advanced imaging technology (HD AIT) measured image data using a Fourier series in circumferential angle. Repeated the series fit after excluding poorly fitting contour points to generate the nominal body contour without the attached anomaly, as shown in Figure 2 (2019).

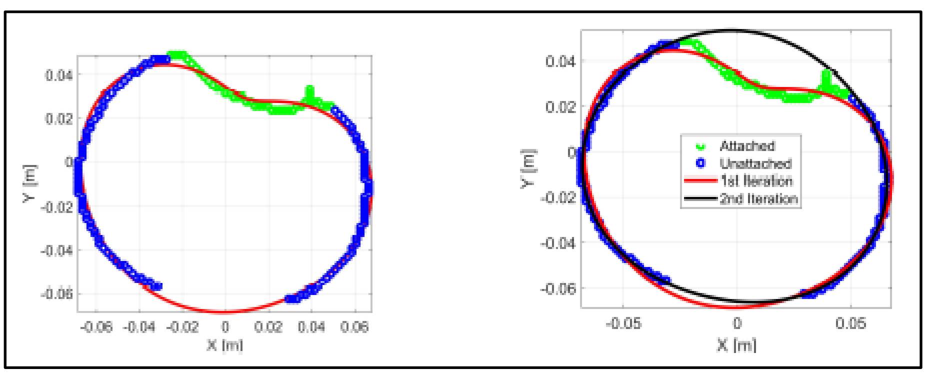

Figure 2: The extracted contour of Figure 1 with points each having a minimum distance from the red fit contour above a threshold value; (left) these thresholded points and all points between them are separated and shown with green color; (right) the second iteration of seven term Fourier series fit shown with black color using only the remaining blue points, and the black contour is used for the estimation of the nominal body surface position to characterize the affixed object.

- Determined the front foreign object reflection and the back (on skin) object reflection, as shown in Figure 3 (2019).

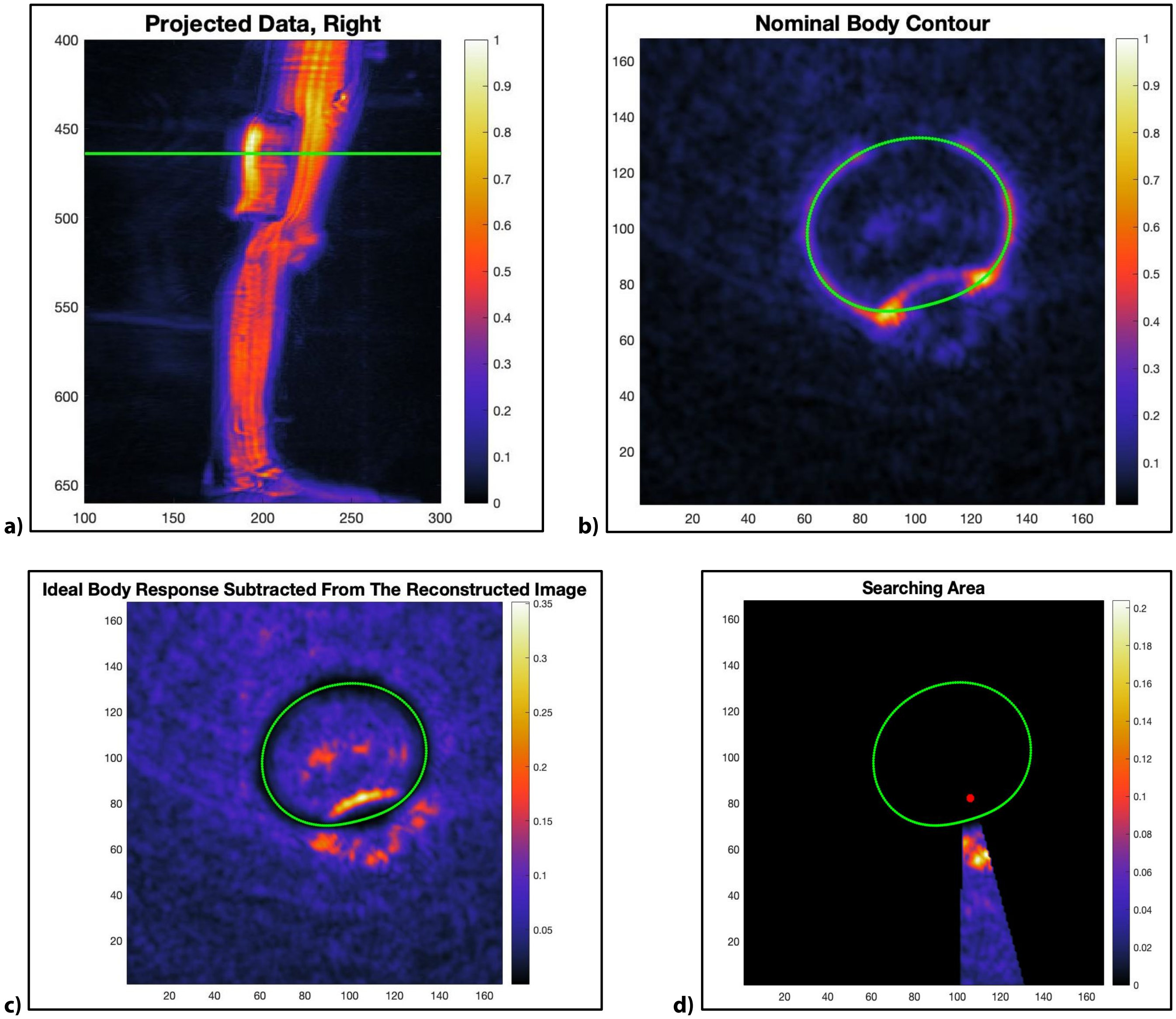

Figure 3: (a) Petroleum jelly attached to the lower right thigh; (b) green curve shows nominal body contour generated with a seven-term Fourier series in φ; (c) back surface of the dielectric displaced *d'* from nominal contour. By subtracting the ideal body response from the data, the displaced body pixels become dominant and can be found by thresholding the image; (d) front surface of dielectric extending *d* from nominal contour with red dot showing depressed body displacement.

- Used the imaged positions of these reflections to determine the dielectric constant and loss factor of the foreign object (2019).
- Configured the material characterization algorithm to automatically choose the appropriate cross-section slices, find the nominal body contour, isolate the anomaly response, determine its complex dielectric constant, and indicate the potential threat level for all parts of the body (2020).

D. Milestones

- All research milestones were met, and new milestones were established. These are (i) automatic application of the material characterization algorithm goes beyond the intended goal of R3-A.2, as it became part of an associated task order; (ii) support of the receiver/transmitter positioning error compensation effort shown in R3-A.3; and (iii) analysis of the effectiveness of the dual frequency combined point spread function concept applied to the elliptical torus reflector AIT system described in R3-A.3.
- The greatest hinderance for the project has been the unavailability of real measured image data for important common anomalies on the body. Requests have been made, and there is indication that new measurements at government laboratories are forthcoming, which, once received, will be used in the ongoing research under the task order "Maturation and Validation of Dielectric Characterization Algorithms" led by Professor Rappaport, which will continue until April 2021.

E. Final Results at Project Completion (Year 7)

The material characterization algorithm yields excellent results in predicting the complex permittivity for lossless materials, such as high explosives. In an example case study, the response from a bag of petroleum jelly is shown in Figure 3. The conventional projected image, shown in Figure 3a, clearly indicates an anomaly on the thigh (at the height of the green line), but it does not provide any guidance in identifying its material composition. The cross section with computed nominal body contour, shown in Figure 3b, shows weak responses due to the anomaly. Removing the strong body contour reflectivity and rescaling in intensity brings out the depressed anomaly back-surface/skin image, and an even weaker front-surface response, Figure 3c. Enhancing just the responses that are outside the body contour and in the vicinity of the back-surface response, shown in Figure 3d, highlights the front-surface response. Using the distances of the average back-surface response from the nominal contour *d*' and the average front-surface response from the body contour *d* (or object thickness), provides dielectric information that is within 3% of its ground truth of 2.15. This is done entirely automatically, with no operator intervention, which proves the automated algorithm works very well. Other tests have yielded similar results for dielectric materials of interest [17-20].

For typically found benign objects such as paper, leather, rubber, and alcohol, the loss tends to be larger than for threats. The back-surface response is either considerably lower than the front-surface response, or indistinguishable from the background entirely. This constitutes the distinguishing feature for these items. Containers filled with water-based liquids have very strong dielectric constants that display as strong deformations to the nominal body contour.

This method can be used to separate threats from benign objects in the security screening of people, thus reducing the number of body pat-downs needed.

III. RELEVANCE AND TRANSITION

A. Relevance of Research to the DHS Enterprise

The algorithms developed in this project are specifically tuned to existing wideband mm-wave portal systems. They have provided greater characterization of concealed threats, thereby reducing the probability of false alarms and thereby increasing efficiency and reducing wait time and labor.

B. *Status of Transition at Project End*

Algorithmic research is continuing in the form of the task order Maturation and Validation of Dielectric Characterization Algorithms until April 2021.

C. *Transition Pathway and Future Opportunities*

The characterization algorithm for wideband mm-wave scanners has been developed for Kaggle Prize data, but it is being configured to be platform independent. As such, AIT scanner vendors will be able to add our material characterization algorithm to their processing suite. Since the algorithm is flexible and fast, and well-supported by the Department of Homeland Security (DHS), it is likely that it will be accepted by the vendors.

D. *Customer Connections*

In the past twelve months and in the coming year, we have been having and will have biweekly telephone meetings with DHS representative Brian Lewis and monthly meetings with DHS's John Fortune as part of our Materials Characterization task order.

IV. PROJECT ACCOMPLISHMENTS AND DOCUMENTATION

A. *Education and Workforce Development Activities*

1. Student Internship, Job, and/or Research Opportunities
   a. Guanying Sun is pursuing research for her dissertation based on this project.
   b. Mahshid Asri completed her master's thesis based on this project.
   c. Elizabeth Wig completed her master's thesis based on this project.
   d. Femi Lampty has been a paid undergraduate researcher working on this project.
   e. Allison Care has been a volunteer researcher working on this project.

B. *Peer Reviewed Journal Articles*

Pending –

1. Sadeghi, M., Tajdini, M.M., Wig, E., & Rappaport, C. "Single Frequency Fast Dielectric Characterization of Concealed Body-Worn Explosive Threats." *IEEE Transactions on Antennas and Propagation*, accepted for publication.

C. *Peer Reviewed Conference Proceedings*

1. Asri, M., & Rappaport, C. "Automatic Permittivity Characterization of a Weak Dielectric Attached to Human Body Based on Using Wideband Radar Image Processing." *2019 IEEE International Symposium on Antennas and Propagation*, Atlanta, GA, July 2019.
2. Morgenthaler, A., & Rappaport, C. "Modeling Focused CW Mm-Wave Scattering of a Penetrable Dielectric Slab Affixed to a Human Body." *2019 IEEE International Symposium on Antennas and Propagation*, Atlanta, GA, July 2019.

3. Tajdini, M., & Rappaport, C. "Focused CW Mm-Wave Characterization of Lossy Penetrable Dielectric Slab Affixed to Human Body." *2019 IEEE International Symposium on Antennas and Propagation*, Atlanta, GA, July 2019.
4. Asri, M., Tajdini, M.M., Wig, E., & Rappaport, C. "Automatic Permittivity and Thickness Characterization of Body-Borne Weak Dielectric Threats Using Wideband Radar." *European Conference on Antennas and Propagation*, Copenhagen, Denmark, March 2020.
5. Sun, G., Nemati, M., & Rappaport, C. "Improving the Reconstruction Image Quality of Multiple Small Discrete Targets Using the Phase Coherence Method." *European Conference on Antennas and Propagation*, Copenhagen, Denmark, March 2020.
6. Tajdini, M.M., Jaisle, K., & Rappaport, C. "Image Radar Determining the Nominal Body Contour for Characterization of Concealed Person-Worn Explosives**.**" *European Conference on Antennas and Propagation*, Copenhagen, Denmark, March 2020.

D. Other Presentations

1. Rappaport, C. "Multistatic 3D Whole Body Millimeter-Wave Imaging for Explosives Detection." *IEEE Distinguished Lecture*, University of Lund, Lund, Sweden, 5 March 5 2019.
2. Rappaport, C. "Multistatic 3D Whole Body Millimeter-Wave Imaging for Explosives Detection." *IEEE Distinguished Lecture*, Qualcomm, San Diego, 6 December 2019.

E. Student Theses or Dissertations Produced from This Project

1. Asri, M. "Automatic Characterization of Low-Loss Low-Permittivity Body-Born Threats Using Wideband Millimeter-Wave Radar." MS Thesis, ECE, Northeastern University, April 2020.
2. Wig, E. "Mathematical Models for Dielectrics on the Human Body Using Millimeter-Wave Security Scanners." MS Thesis, ECE, Northeastern University, April 2020.

F. Technology Transfer/Patents

1. Patents Awarded
    a. Martinez Lorenzo, J., & Rappaport, C. "Characterization of Dielectric Slabs Attached to the Body Using Focused Millimeter Waves." #10,416,094, 17 September 2019.

Year 6 Patent Not Previously Reported –

a. Gonzales Valdes, B., Martinez Lorenzo, J., & Rappaport, C. "On the Move Millimeter Wave Interrogation System with a Hallway of Multiple Transmitters and Receivers." #10,295,664, 21 May 2019.

V. REFERENCES

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