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

Abstract—The second phase of the Advanced Imaging Technology project is divided into algorithm research (R3-A.2, this report), and hardware research (R3-A.1, previous report). The two parts work together to develop an improved multi-modality, portal-based passenger screening system. Millimeter-wave (mm-wave) scanning and X-ray backscatter, supplemented by Kinect surface depth mapping, have been implemented. The 56-64 GHz mm-wave imaging system has produced several hardware and data processing innovations. These include: a second generation Blade Beam reflector transmitting antenna that produces narrow target illumination to allow accurate stacked 2D reconstructions of the 3D surface; a carefully positioned multistatic, array receiving antenna for artifact-free imaging; and a fast data processing technique, based on the Fast Multipole Method (FMM) that produces 2D SAR images from scattered field samples. The specially-built hardware platform facilitates reconfigurable sensor placement in order to develop the multistatic imaging radar system. In addition, a patent-pending algorithm for determining the dielectric constant of weak dielectric objects attached to the body – has been developed under R3-A.2 and tested in this project, and is now ready for transition to industry as part of a proposed DHS Task Order contract. These improvements have resulted in faster, more accurate whole body imaging with the ability to improve the security screening process, with proven detection capabilities validated by means of measurements carried out with a first mm-wave portal prototype.

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II. PROJECT OVERVIEW AND SIGNIFICANCE

As people enter secure areas, it is important that they be scanned to ensure they are not entering with weapons or explosives. In addition to airport departure gates, office buildings, stadiums and arenas must have fast, accurate, non-intrusive means of detecting threats concealed under clothing.

The Whole Body Imaging project is developing an improved multi-modality, portal-based passenger screening system. Millimeter-wave (mm-wave), infrared and low frequency microwave sensing are methods being pursued. The 56-64 GHz mm-wave imaging system includes a patented Blade Beam reflector transmitting antenna that produces narrow target illumination to allow accurate stacked 2D reconstructions of the 3D surface; a multistatic array receiving antenna for artifact-free imaging; and a fast reconstruction algorithm that significantly outperforms conventional Synthetic Aperture Radar processing. The specially-built hardware platform facilitates reconfigurable multi-sensor configurations.

With the X-ray backscatter system becoming less favored by the traveling public, especially in Europe, high resolution human body imaging has fallen to mm-wave imaging and detection. Mm-waves pass through clothing readily, but can identify dangerous objects attached to the body. Current state-of-the-art millimeter wave portal imaging systems are mostly based on monostatic radar. Although these systems are inherently fast, they present some disadvantages, for example reconstruction artifacts, such as dihedral effects, and misrepresenting sudden indentations and protrusions due to the monostatic nature of the collected electric field data, and a lack of quantitative range of depth information display.

For practical 3D human body screening, real-time capabilities are required, so fast methods for geometry reconstruction are needed. The system that has been developed under ALERT support is based on fast multistatic Synthetic Radar Aperture (SAR) imaging and introduces several new contributions to the field of millimeter wave imaging.

III. RESEARCH ACTIVITY

A. State-of-the-art and technical approach and major contribution

Four significant technological advances have been pursued in the past year in the AIT algorithm development project: radon transform image processing, algorithm development for dielectric slabs attached to skin, compressive sensing for portal mm-wave scanners, and multistatic FFT-based reconstruction algorithms.

A.1 Radon transform image processing

The mm-wave AIT radar operates at the limits of the desired resolution. Accurately determining the reconstructed imaged object contours is often challenging because of wide range bins and cross range bins combined with imaging artifacts. A novel approach has been developed to smooth out the image intensity variations and facilitate contour estimation. The important aspect of this image processing procedure is that the length and width of the high intensity region remain the same after processing. The Radon transform is a series of planar projections of data values in specific directions, modeling the effect of multi-view transmission x-ray attenuation. When these projections are filtered and inverted with the Fourier-based inverse Radon transform, the internal structure of the data values is reconstructed. This is the basis of computerized tomography. If filtering is not done, and if too few angular projections are taken, the internal structure is blurred. However, since the transform is based on projections, the external envelope of the high intensity image region is not significantly expanded as it would be with simple low-pass spatial filtering.

Figure 1 demonstrates the effectiveness of this algorithm. The raw SAR image of a curved slice of a torso that was measured with the mm-wave radar developed in ALERT Project R3-A.1 is shown in Figure 1a. A square metallic box was affixed to the torso section as a discrete anomaly. The torso and box are imaged fairly well,
with alternating 1 cm wide streaks of high intensity reflectivity values ranging from 2 to 5 cm long. As the resolution limit of the radar is about 2 cm, the alternating structure of the image is artificial, and it should be homogenized. As a reference, the true torso and box contours are shown in green. Although the true position of the contour matches the image well, it is challenging to automatically process the image data to estimate this contour. Figure 1b shows the result of performing the Radon transform on the image data of Figure 1a for 23 unevenly spaced angles from 0 to 180 deg., followed by the inverse Radon transform. This process is automatic and very fast, and the results are excellent, with almost the entire interior region blended together without widening or lengthening its periphery. For this processed image, choosing the midpoint of the high intensity region for each column approximates the true contour – including the box – quite well. The Radon transform image processing algorithm provides a fast, non-iterative method for minimizing image artifacts, allowing precise contour estimation.

A.2 Algorithm for dielectric slab characterization

On-going research to simultaneously characterize both the dielectric constant $\varepsilon$ and the thickness $d$ of weak dielectric slabs attached to the body has yielded a new method which will potentially work for multi-monostatic radar systems. Last year, we presented and published a method to determine $d$ and $\varepsilon$ using multistatic radar, considering both the normally reflected rays and the obliquely reflected rays, which requires a receiver symmetrically separated from the transmitter. When using only a single transceiver, as currently employed systems do, only the normals rays can be sensed. Without the second oblique measurement, determination of both $d$ and $\varepsilon$ is problematic.

Figure 1:  a) Raw SAR reconstruction of measured mm-wave radar data for a curved metallic torso surrogate with attached square pipe (left); b) Radon processed image using raw reconstruction (right). Green lines are true contours.
The new approach supplements the observation that the image of the skin reflection through the slab is 
depressed a distance  with the appreciation of the finite bandwidth of the point spread function. Using the same measured data, the bandwidth of observed data can be manipulated to provide a second degree of freedom to generate a second independent equation, and thus a means of solving for both of the unknowns. In particular, if the reconstructed distance separating the reflection from the front and from the back of the dielectric slab is exactly two range bins , then there must be a deep and narrow null midway between them, where the nulls of the PSF of each interface reflection coincide. Thus:

\[
d - d_{echo} = d \sqrt{\epsilon'}
\]

Of course measuring the position of the front interface reflection would provide \( d \) directly, but often this reflection is very weak, and if the PSF from the back reflection destructively interferes with it, it becomes almost undiscernible. Instead, concentrating on the particular bandwidth which produces the deepest null at half a range bin preceding the back reflection (and at half the range to the front face reflection) readily gives the thickness \( d \) using the above equation.

Figure 2 illustrates this algorithm for a 3 cm thick TNT slab (\( \epsilon = 2.9 \), yellow dots) on skin (green dots), illuminated from the top of the figure with 55-65 GHz mm-wave radar (on left) and 55-61 GHz radar (on right). Even though the 10 GHz bandwidth image has higher imaging resolution, the interaction between the PSFs fills their respective nulls to the -15 dB level. The 6 GHz bandwidth case, however, has a range resolution of \( \frac{c}{2BW} = 2.5 \) cm, and since \( d \sqrt{\epsilon'} = 5.1 \), the PSF null from the lower reflection lines up with the null from the upper reflection, producing a clear, deep -30 dB null on the image between ranges -1.7 and +1.2 cm. This null is much easier to identify on SAR images than a low intensity peak, and hence is a strong feature for automatic detection algorithms.

A.3 Compressive sensing for portal mm-wave scanners

One of the limitations of the proposed portal-based system is the minimum number of receivers in the arcs. According to the minimum sampling rate criterion for the proposed system (\( f = 60 - 66 \) GHz, human body having a maximum cross-range size of \( \sim 40 \) cm), the minimum number of receivers on each arc to avoid SAR image aliasing is approximately 150. Reducing the number of receivers and thereby the cost, complexity and
measurement time, without compromising the quality of the reconstructed image, is the purpose of this research. For this goal, Compressed Sensing (CS) techniques, which have been successfully applied in several SAR imaging problems [1] are proposed.

Compressed Sensing (CS) [6-10] is a relatively novel signal processing theory, which states that sparse signals can be recovered using far fewer samples or measurements than that required by the Nyquist sampling criterion. The Nesterov algorithm [9], provided as a Matlab toolbox, limits the calculation time (60s in a conventional laptop with matrix size N = 100×100). The choice of this algorithm is based upon superior results when compared to other norm-1 minimization techniques.

The physical basis for the sparsity that is exploited by the CS SAR imaging comes from the fact that the incident field does not penetrate appreciably nor scatter from points inside the human body, so for a 2D slice, only a narrow layer, corresponding to the body surface where electric currents are induced, will be recovered. Thus, the resulting 2D image will be sparse. CS is successful in reducing the amount of samples needed for good inversion results in most SAR imaging systems. Usually, CS images are generated with just 25-30% of the samples required by the Nyquist sampling criterion. In this section, an application example of the CS techniques for the proposed personnel screening system is presented.

For an initial configuration, a 90º-arc with 150 receiving positions placed at z = 0 m is considered. As a test case, two metallic objects are affixed to a human body torso. The forward problem is simulated with physical optics (PO), assuming that the human body behaves as a good conductor in the 60.6-66 GHz frequency band, sampled at 600 MHz frequency steps (F = 10). A Signal-to-Noise ratio of 30 dB is considered, by adding white Gaussian noise to the simulated scattered field. The reconstruction slice is (x, y) = (0.3, 0.3) m, centered at (x, y) = (0, 0.15) m, with z = 0 m.

The results for traditional SAR imaging using the algorithm described in [10] are plotted in Figure 3a for a densely packed array. Both the human body torso and the anomaly (both in green) at the chosen slice are recovered. Next, the number of receivers is reduced to 40 (reduction of 73%). The contour is partially recovered in Figure 3b, but the imaging aliasing artifacts make precise determination impossible. When the CS algorithm is applied to 40 non-uniformly distributed receivers, Figure 3c, the results are stunningly good, matching the green line better than the dense array.

![Figure 3: Reconstruction of synthetic torso with object (true contour: green line): a) Standard densely sampled receiving array with 150 elements, b) under-sampled array with 40 uniformly spaced elements along the same overall size array, and c) 40 element optimally positioned array with Compressive Sensing processing.](image)

A.4 Multistatic FFT-based reconstruction algorithms

Fourier-based methods for monostatic and bistatic setups have been widely used for high-accuracy radar imaging. However, the multistatic configuration has several characteristics that make Fourier processing more
challenging: i) a non-uniform grid in k-space, which requires multidimensional interpolation methods, and
ii) image distortion when the incident spherical wave is approximated by a plane wave. This sub-project
derived the first ever Fourier-based imaging method for multistatic systems. Multistatic FFT-based imaging
requires using multidimensional interpolation techniques, which map the data in the k-space from a non-
uniform grid into a uniform one. To overcome the issue of computational cost, the k-space is split into several
regions where multidimensional interpolation is applied. The details of the method – which is applicable to
both standoff and portal mm-wave radar imaging systems – is described in Project Report R3-B.2.

A 3D AIT portal-type simulation using the Physical Optics code [12], [13] as a forward scattering model is
described in the following section. The problem setup is depicted in Figure 4. The working frequency band
is from 60 to 66 GHz (the same as in [14]), with 600 MHz-steps. The scattered field observation domain is
120x90 cm, discretized every 25 mm (0.55 l at 66 GHz), yielding 481x361 acquisition points. The transmitter
is placed 5 cm ahead of the observation domain, for better observation of the incident field compensation
distortion. Range resolution (z-axis) is 25 mm, and cross-range resolution is 15 mm (x-axis) x 19 mm (y-axis).
Again, no windowing function is considered. The object under test is a 44x44x4.4 l metallic object curved
about the y-axis, with several holes, the smallest being 1x1 cm. It was chosen so that most of the scattered
power falls on the observation domain.

Fourier results for reflectivity when 4x4 phase center specification are considered are in Figure 4b. The RMS
error between conventional SAR processing and FFT is -25 dB when 16 phase centers are considered. Fouri-
er-based imaging for the 16 phase center specification takes 9000 s. This compares to SAR backpropagation
for the same geometry, which requires 252000 s, 28 times slower. Large calculation times (both for Fourier
and SAR) are due to: i) the use of single-core calculation; ii) the hardware itself (laptop); iii) the electrically
large problem-under-test; and iv) the use of a Matlab®-based implementation.

The Fourier-based method overcomes two of the main limitations that Fourier processing has for this ra-
dar configuration: i) non-uniform grid in k-space, requiring multidimensional interpolation methods; and
ii) image distortion when approximating spherical wave-like OUT illumination with plane waves. The first
drawback is solved by using k-space partitioning, applying interpolation on every domain. The second takes
advantage of using multiple incident plane waves, each referred to a phase center specification within the imaging domain. Both solutions are fully parallelizable, thus allowing calculation time savings; multi-core computers and GPU hardware are suitable for this purpose.

B. Future plans

B.1 Radon transform image processing

The plan is to test and refine the algorithm for different materials and shapes, and to automate for stacked contour to generate images with smooth, regular surfaces.

B.2 Algorithm for dielectric slab characterization

The plan is to test for robustness for different thicknesses and dielectric materials, consider slightly conductive material and extend the algorithm for non-planar layers of material. This will involve determining the piecewise specular rays combined with the reflections form inclined front surfaces.

B.3 Compressive sensing for portal mm-wave scanners

Continuing research in this subproject will be to apply CS principles to the elliptical torus reflector described in Project Report R3-A.1 to reduce the number of transmitting and receiving elements without degrading image quality. Since the required image feature is always the body and anomaly contour, the sparsity constraint is maintained when the mm-waves are reflect from the torus surface. It is anticipated that combining optimum non-uniform element spacing with CS processing could lead to a reduction of 75%, with perhaps as few as 16 transmitting and 16 receiving elements being needed to accurately image most of the front surface of a torso.

B.4 Multistatic FFT-based reconstruction algorithms

The next phase of this research will be primarily to convert the existing SAR processing for most of the AIT imaging experiments to FFT-based processing, and verify that the 1-1/2 order of magnitude speed up applies for general imaging geometries. In addition, performance limitations will be studied, and extensions with custom formulation for particular classes of problems will be explored.

IV. EDUCATION & WORKFORCE DEVELOPMENT ACTIVITY

A. Student internships

1. Two DHS Research Experiences for Undergraduates students (including two minority students) during the summer.
2. Three DHS Career Development Grant master degree research assistant students.
3. Two volunteer undergraduate internships.

B. Interactions and outreach to K-12

1. One NSF Young Scholar Program high school student working on mm-wave anomaly detection.
V. RELEVANCE AND TRANSITION

A. Relevance of your research to the DHS enterprise

Passenger screening is an essential part of the DHS/TSA mission and this research is relevant for the following reasons:

- An improved technology platform and associated algorithms reduces detection errors and decreases false positive results.
- Higher resolution coupled with new feature detection will allow more automatic threat detection, less human inspector involvement, and greater passenger comfort.
- Accurate computer-controlled motion allows rapid data collection and validation for multiple trials with large parameter variation.

B. Anticipated end-user technology transfer

AIT manufacturers, such as L3 Communications, Inc., Smiths, as well as portal scanner suppliers, such as Rapiscan, have expressed interest in our technology. The challenge will be to establish the value of upgrading their individual approaches with our novel approach.

VI. PROJECT DOCUMENTATION AND DELIVERABLES

A. Peer reviewed journal articles


Pending-


B. Peer reviewed conference proceedings


C. Other presentations

1. Seminars
   b. Carey Rappaport, “Improved Mm-Wave Whole Body AIT Threat Discrimination,” 2/12/14, Lincoln Lab visit to AIT Lab.

2. Poster sessions
   a. Thurston Brevette, Michael Woulfe, Borja Gonzalez, Jose Martinez, Carey Rappaport, “Advanced imaging technologies for whole body imaging applied to security related threats,” 4/10/14, Northeastern University Research Innovation and Scholarship Expo.

D. Transferred technology/patents

1. Patent Applications Filed (Including Provisional Patents)

E. Software developed

1. Multistatic FFT based SAR processing.

VII. REFERENCES


