R3-A.1: Millimeter Wave Whole Body Scanning Radar Hardware for Advanced Imaging Technology (AIT)

Abstract—The second phase of the Advanced Imaging Technology project is divided into hardware research (R3-A.1, this report), and algorithm research (R3-A.2, following 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 lead to faster, more accurate whole body imaging to improve the security screening process, with proved detection capabilities validated by means of measurements carried out with a first mm-wave portal prototype.

I. PARTICIPANTS

<table>
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<th>Faculty/Staff</th>
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| Nigil Lee | BS | NEU | 5/2017 |
| Scott Pitas | BS | NEU | 5/2015 |
| Tiphanie Zeng | BS | NEU | 5/2016 |
| Thurston Brevett | BS | NEU | 5/2018 |
| Michael Woulfe | BS | NEU | 5/2018 |
| Matthew Tivnan | BS | NEU | 5/2017 |
II. PROJECT OVERVIEW AND SIGNIFICANCE

As people enter secure areas, it is important that they be scanned to ensure that 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 X-ray backscatter systems 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 though 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, including 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

Three significant technological advances have been pursued in the past year in the AIT hardware development project: modularized mm-wave radar electronics realization, new elliptical torus reflector design for multistatic broadband blade beam illumination and successful experimentation with low-loss dielectric slabs affixed to the body.

A.1 Modularized mm-wave electronics

The millimeter-wave imaging system was designed around a low-cost, highly-integrated, wide-bandwidth, transceiver chipset as described in [1]. A block diagram of the system is shown in Figure 1, with black lines representing signal lines, red trigger lines, orange clock lines and blue control lines. The transceiver chipset was designed for high-speed, indoor, wireless communication using the unlicensed 60 GHz band. The chipset provides 8 GHz of bandwidth split into 16 separate 500 MHz bands in the range 56.5–64.5 GHz. The entire bandwidth is covered with a baseband input signal in the range 5–550 MHz. Although the transceiver chipset was not intended for use in millimeter-wave imaging, with appropriate modification, it can function as a wideband stepped-frequency radar: i) The transmitter and receiver operate on a common clock; ii) Both the transmitted and received signals are sampled; and iii) A phase coherence mechanism is used to combine the 16 separate 500 MHz bands into 8 GHz of imaging bandwidth. The notable aspect of this novel design (with provisional patent) is that the clock signal – shown in orange – carries relatively low frequency signals, and therefore can use long lengths of standard, flexible cable, thereby allowing the transmitters and receivers to be widely separated for multistatic radar operation. The design, realized with component hardware, was
built, tested and proved to be effective in the previous year.

Progress in the past year has resulted in an RF printed circuit board custom design as seen in Figure 2a and realization, Figure 2b. As shown in Table 1, besides size advantages, the printed circuit version offers significant cost reduction. Since the eventual full mm-wave radar system will require multiple channels for multiple views, it may employ as many as 32 receivers. Reducing the cost per receiver from $23.5K to $160 brings the total receiver cost down from a prohibitive $752K to about $5K (with comparable cost reductions for the transmitters). In addition, the Hittite transceiver chip [2] incorporates an integrated wide-beam antenna (shown in the lower right corner in Figs. 2a and 2b). The PC board will be mounted with the integrated antenna positioned in the feed region of the new torus reflector (discussed in the next section). This will eliminate the need for expensive, heavy and dispersive waveguide, and since the antenna is in the board corner, the boards can be packed closely, overlapping 80% of an adjacent card.

**Figure 1:** Block layout of a single channel of the novel multistatic mm-wave imaging radar.

**Figure 2:** Custom designed PC board with Hittite transceiver chip: a) Multilayer PC layout (left), and b) PC component placement on board (right).

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<tr>
<th>Hybrid</th>
<th>PC prototype</th>
<th>PC production</th>
<th>Notes</th>
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<tr>
<td>RF and mm-wave components</td>
<td>$12,000</td>
<td>$128</td>
<td>$25 Hittite chip with integrated antenna</td>
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<tr>
<td>Supporting electronics: power supply, control</td>
<td>$200 – 500</td>
<td>$90</td>
<td>$10 Low-volume to high-volume cost ratio 10:1</td>
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<td>Mechanical</td>
<td>&gt;$500</td>
<td>$25</td>
<td>$5 Hybrid uses high precision mechanical supports, etc.</td>
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<tr>
<td>Digitizer electronics</td>
<td>$10,000</td>
<td>$1,000</td>
<td>&lt;$100 Use integrated TI digitizer on-board for production</td>
</tr>
<tr>
<td>Cabling</td>
<td>$300 – 500</td>
<td>$50</td>
<td>&lt;$10 Hybrid precision-matched</td>
</tr>
<tr>
<td><strong>Total cost</strong></td>
<td><strong>$23,500</strong></td>
<td><strong>~ $1,275</strong></td>
<td><strong>&lt; $160</strong> <em>Cost driven by digitizer</em></td>
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*Table 1: Cost comparison for original, second generation PC prototype and production version estimates.*
A.2 New elliptical torus reflector design for multistatic broadband blade beam illumination

The first phase of this ALERT project conceived and demonstrated the effectiveness of the Blade Beam reflector to illuminate narrow sections of a subject, facilitating efficient high resolution processing of body contours. The second phase has now been building on the lessons learned from Phase 1. In particular, it was determined that the nearfield mm-wave imaging of large convex objects, such as a human torso, is much more dependent on specular ray paths than previously thought. No amount of focusing can overcome the effects of glancing incidence. If representative rays reflect from an object in directions with no receiving antennas, no field will be observed. Armed with this realization, it became clear that a single transmitter, even one with as carefully tailored illumination as the Blade Beam elliptical/parabolic reflector, cannot effectively probe the entire front of a torso. To accomplish this complete imaging requirement, multiple incident directions of transmittance are needed. Either multiple reflectors had to be used, or a new design is necessary.

The current novel reflector design borrows from satellite reflector concepts by blending multiple individual reflector surfaces into a single large section of a torus; circular in the horizontal plane and offset elliptical in the vertical plane. Because of the elliptical vertical profile, the torus reflects rays from the system feed to a second focus at the target object; and with the appropriate choice of offset and circle radius, the rays can be made to be essentially parallel in the horizontal plane (for any given feed position). Thus, this surface piecewise approximates the previously developed Blade Beam surface. Figure 3a shows the torus reflector with the two foci in the plane of symmetry. Figure 3b is a top view of this reflector, indicating in blue the arc of possible feed locations. Note that the feed focus lies in the plane which contains the bottom edge of the torus, while the target focus is in the plane of the ellipse vertex (furthest point to the left), and that the center of rotation is at \((x, y) = (0, 0)\).

![Figure 3: Offset elliptical torus reflector: a) perspective view (left) and b) top view (right).](image)

By circular symmetry, any feed on the feed arc will generate the same set of reflected rays tilted by the angle of the feed from \((0, 0)\) relative to the y-axis. Figure 4a on the next page shows the top view of the reflector numerically illuminated by a feed in the central position, and Figure 4b on the next page shows a perspective view, also indicating the field on the torso target. Only the central section of the reflector is illuminated, but the torso is almost entirely illuminated from side to side, and the illumination is very narrow vertically. Figure 5 on the next page shows the illumination when the feed is positioned on the feed arc at 45 degrees relative to the y-axis. Only the right side of the reflector is illuminated, and the right side of the torso is illuminated by a similar blade beam. Because the rays in this case are inclined 30 deg. in azimuth, most of them will reflect back to the reflector, rather than forward, away from the antenna; fewer specular rays will be missed.
One advantage of using this type of symmetric torus reflector is that it can be used for both transmission and reception. Receiving antenna elements can be interspersed with transmitting elements along the feed arc, each using overlapping sections of the reflector. In effect, the reflector provides multiple independent high gain beams for all radar modules in the transmit and receive arrays. Figure 6 illustrates this effect, as seen from above, for imaging as much of the torso as possible. In this case, five transmitters, located at 0, ±22.5, and ±45 deg, are used in turn, with 151 idea receivers evenly spaced across the ±60 deg. arc. Figure 6a shows the reconstruction when the receivers are pointed to the reflector and, as such, gather more of the scattered waves, while Figure 6b is the image that results when the receiving antenna elements are instead pointing to the torso. Note the much closer agreement to the true torso contour (in green) for the reflector-based receiving scheme. In particular, the imaging correctly reconstructs the contour for all but the final 10% (edges) where the specular rays reflect forward and away from the antenna.

Figure 4: Torus reflector illumination: a) top view (left), b) perspective view also showing illumination of target (right).

Figure 5: Torus reflector illuminated by feed at 45 deg., also showing illumination of target.

Figure 6: Imaging results using 5 transmitters at 0, ±22.5, and ±45 deg. illuminating the torus reflector: a) using the reflector with 151 receiving elements (left), b) using just the 151 receiving element directly (right).
One open area of research is the choice of number and best positions of the receiving and transmitting elements. The resolution of the reconstructed image is proportional to the combination of the point spread function (PSF) of the transmitter and the receiver. If the nulls of one line up with the sidelobes of the other, the image becomes clearer. Array periodicity tends to produce grating lobe artifacts, so non-uniform element distributions are preferable. With these thoughts in mind, it is possible to thin both the transmit and the receive array, as long as elements remain non-uniformly distributed and uncorrelated. Genetic algorithms are being pursued to optimize the element configurations.

A.3 Experiments with dielectric slabs

The previous ALERT algorithm research in characterizing weak dielectric slabs affixed to the body has been tested and validated in the past year with the mm-wave hardware in the AIT lab. We use a flat metal plate as a skin simulant and a specifically formulated paraffin-TiO₂, TNT surrogate for the multistatic 56-63 GHz imaging experiment. Figure 7 shows a photograph of the paraffin block taped to the metallic backing, positioned on a microwave-transparent Styrofoam stand. Horizontal slices were measured every 0.5 cm and each reconstructed separately. Figure 8a on the next page shows the raw reconstruction of slice 17, approximately halfway down from the top of the plate. The plate is well-imaged with high intensity corresponding closely to the true 12 cm width of the plate, and the central portion of the image indicating retardation of the signal at the position of the explosive simulant. This retardation is characteristic of a weak dielectric slab, due to the reduced propagation velocity in the dielectric causing an increase in the time for the wave to reflect from the conducting surface behind it. This image is noisy, and a simple processing approach has been developed to clarify it. Figure 8b on the next page is the result of applying a poor, under-sampled and unfiltered Radon/inverse Radon transform to the data in Figure 8a. This processing has the effect of smearing out details within the high intensity region without widening the perimeter of the region. Now, applying a thresholding and column-by-column peak detection provides the estimated contour of the slice, as shown in Figure 9 on the next page. The 2.3cm depression (increased range) in the center of the reconstructed plate corresponds almost exactly to the expected value of the 3.4cm thick slice of material with dielectric constant 2.9, as given by the formula:

\[ D_{\text{depress}} = D_{\text{thick}} \left( \sqrt{\varepsilon_{\text{TNT}}} - 1 \right) \]

This process was repeated for all the slices of the plate, then registered and stacked. The resulting surface image is given in Figure 10 on the next page. This reconstruction shows the shape, size, and position of the explosive simulant, and its depth characterizes its dielectric constant.

![Figure 7: Experimental setup of paraffin block diagonally mounted on a metal plate.](image-url)
Figure 8: a) Raw SAR single slice reconstruction of the flat metal plate with paraffin block (left), b) Radon/inverse Radon processed image with smeared peaks within high-intensity region (right).

Figure 9: Contour detection of paraffin block on metal slice with threshold and column peak processing.

Figure 10: Stacked slices of paraffin block on metal slice using contour detection.
B. Future plans

B.1 Modularized mm-wave electronics

The new PC board is being assembled, and will be tested in the coming months. First, the receiver module will be built and swapped into the existing flexible radar hardware mounting platform to verify that it performs as well as the current hybrid component-based module. Then, the transmitter module will replace the current transmitter. And finally, multiple modules will be mounted in the new torus reflector feed region to test the sparse fixed feed array. Once the electronics are shown to be operational, multiple units will be built and incorporated into the full radar imaging system.

B.2 Elliptical torus reflector

The new reflector concept has been optimized for human target implementation, and modeled to validate its expected performance. On-going work involves optimizing the number and positions of transmitters and feeds, fabricating the reflector surface, precisely mounting the reflector and feeds and conducting a full set of experiments with a variety of inanimate and human targets to test its effectiveness. Eventually the goal is to transition the entire multistatic system to industrial mm-wave security scanner vendors for product development and widespread installation. To fabricate the reflector, we are engaging with several machine shops with CNC milling machines to cut the high tolerance surface. As the entire reflector is almost 2m wide, we anticipate fabricating four identical surface sections to be bolted together. High precision alignment will be necessary to join the sections and maintain a 0.01cm tolerance. A preliminary drawing of the four joined sections is shown in Figure 11.

B.3 Dielectric slab experiments

Continuing research in this subproject will be to perform experiments with different materials and substrates: curved torso-like metal surfaces, real human body surfaces, non-planar slabs, slightly conductive materials, such as rubber and wood. In addition, we will examine multistatic non-specular scattering as a means of providing additional information to determine both the thickness and dielectric constant. Experiments will be conducted to support new algorithm development in R3-A.2, which will use the low intensity signal pattern preceding the retarded signal as added information about the slab thickness.

IV. EDUCATION & WORKFORCE DEVELOPMENT ACTIVITY

A. Student internships

1. Two DHS Research Experiences for Undergraduates students (including two minority students) during 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 reduce detection errors and decrease false positive results.
- Newly designed radar modules using RF printed circuit radar electronics have lowered the cost of implementation by almost two orders of magnitude, allowing for significant cost reduction while simultaneously improving performance.
- Higher resolution coupled with new feature detection will allow more automatic threat detection, less human inspector involvement, and greater passenger comfort.
- A well-conceived experiment is essential to validate models, inversion principles, and the concept of operation.
- Infrastructure has been fabricated to be modular, expandable, and scalable, so it can be used as a platform for a variety of readily fused co-registered security screening modalities.
- Accurate computer-controlled motion allows rapid data collection and validation for multiple trials with large parameter variation.
- Future advancements in mm-wave hardware will be readily implemented and tested on the flexible hardware platform.

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
   a. Carey Rappaport, Overview of ALERT, 2/10/14, Passport Systems Collaboration
   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. Technology Transfers/Patents

1. Patent Applications Filed (Including Provisional Patents)

E. Software developed

1. Multistatic FFT based SAR processing.

F. Requests for assistance or advice

1. From DHS
a. Assisted Johns Hopkins University Applied Physics Laboratory working with Jason Hull and Bill Garrett from TSA to help develop a technology maturity roadmap for the Passenger Screening Program.

VII. REFERENCES


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