R3-A.3: Multi-Transmitter/Multi-Receiver Blade Beam Torus Reflector for Efficient Advanced Imaging Technology (AIT)

I. PARTICIPANTS

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<tr>
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<th>Month/Year of Graduation</th>
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II. PROJECT DESCRIPTION

A. Project Overview

This project has developed and is continuing to test an advanced millimeter wave (mm-wave) radar whole body (AIT) imaging system using a custom-designed elliptical toroid reflector, which allows multiple overlapping beams for focused wide-angle illumination to speed data acquisition and accurately image strongly inclined body surfaces. For the primary subproject, we have extended the Blade Beam Reflector concept developed previously in Project R3-A.1 [1-3], from a single illuminating antenna into a multi-beam Toroidal Reflector, with multiple feeds both for transmitted and received waves. Each feed generates a different incident beam with different viewing angles, while still maintaining the blade beam configuration of narrow vertical slit illumination in the vertical direction. The entire antenna is translated vertically and the images in each vertical slice are stacked to form a 3D reconstructed body surface.


B.  State of the Art and Technical Approach

Since the toroidal reflector antenna only translates in one dimension, it acquires signals faster and is prone to fewer mechanical alignment, ruggedness, and wear operation than 2D raster scan systems [4, 5]. Having multiple transmitters provides horizontal resolution and imaging of a full 120 degrees of a body. In practice, a second reflector and feed array would be used for the other side of the subject under test. Each reflector can simultaneously be used for receiving the scattered field with high gain, overlapping, high vertical resolution beams for each transmitting or receiving array element. The multistatic transmitting and receiving array configuration sensing avoids dihedral artifacts from body crevices and reduces non-specular drop-outs that are present with existing fielded AIT systems [6-8].

C.  Major Contributions

C.1.  Torus Reflector AIT System

C.1.a.  Configuration Improvements

The toroidal reflector-based system transitioned from a single fixed transmitter (Tx) on the focal arc in conjunction with a swinging arc receiver (Rx) design to a multiple fixed transmitter array and swinging receiver in order to simulate the overall fixed array design.

By Year 6, the goal was to have 7 Tx and 48 Rx in a fixed array, which could operate with all receivers receiving simultaneously with 48 channels, or in a switched configuration with 48 sequentially acquired signals. The former is 48 times faster than the latter, but would require 48 A/D conversion channels—at a considerable cost since this conversion at 500 MHz is expensive. With 7 fixed Tx and a swinging Rx, we can sample 48 discrete receiver positions along the swinging arc and determine the imaging degradation associated with under-sampling the array and imaging improvements with multiple Tx. These measurements can be compared to computational models developed in Project R3-A.2 to both validate the models and optimize the receiver element positions.

In the computationally optimized Tx/Rx array configuration, the intent is to alternate Tx and Rx elements in order to form a rapid scanning multi-static radar with high parallel processing abilities. The overall configuration is illustrated in Figure 1. The challenge has been to fill the toroidal focal arc with both Tx and Rx feed elements so there is a minimum amount of element overlap and blockage. This figure illustrates the arrangement of the Tx and Rx elements over the focal arc. There are four Rx modules on each custom-designed and fabricated RF circuit board, spaced every 17 mm. The seven Tx modules are mounted on thin RF circuit boards, with a minimum amount of blockage or Rx. Figure 1 shows the Tx as blue dots on the green nominal torus focal arc, as well as six four Rx module boards on the arc. Six additional four Rx module boards are also indicated on an arc that is 5 mm smaller that the nominal arc (farther from the reflector). Four individual Rx are blocked by Tx boards and will be inactive.
During Year 5, a miniaturized Generation 4 (Gen4) Transmitter circuit board module design was completed. The first Tx design of the third generation (T-shaped Tx board) was compacted for an easier inclusion in the final array configuration. Dimensions decreased from Gen3 Transmitter (100 x 75 mm) to Gen4 Transmitter (68 x 18 mm), for an equivalent 83% footprint reduction.

Note that the requirements to reduce the transmitter size were multi-fold:

- The Gen1 transmitter was a prototype system, which was unscalable. Gen2 and Gen3 systems consisted of very low-cost FR4 substrate and an integrated chipset and antenna package. In Gen4, there was a change to an off-the-shelf chipset with no antenna and therefore we had to design an ALERT-specific antenna.

- In order to obtain best performance of the ALERT antenna for each Tx and RX, a higher performance Rogers 4350B substrate was required. To maintain the relatively low cost, a smaller circuit board has been implemented. The design characteristics of the antenna are shown in Figure 2, with the resulting computed radiation pattern illustrated in Figure 3.

- The scalability of the 100 x 75 mm Gen4 transmitter for physical layout in the large array shown in Figure 1 is not sustainable since transmitters need to be placed as close as possible, with a target inter-element spacing of 17 mm. This could not be achieved without complex mechanical compromises and overlap mounting.
A comparison of the Gen3 and Gen4 TX RF circuit boards are shown in Figure 4. Note that the Gen4 board requires additional low frequency supporting circuitry connected through a ribbon cable. The active portion of the Gen4 board is six times narrower, allowing for much easier placement in front of the receiver array with minimal blockage.
Considering the miniaturized size of the new board, the quality of the assembly of the circuit boards was inspected carefully in order to ensure reliability for the large array system. As the number of elements in the array increases, the intent is to have higher quality components with less failure probability in order to ensure reliability and longevity of the overall system. A number of inspection and verification activities on the Gen4 transmitter are shown in Figure 5.

Figure 4: The Gen4 final transmitter design (right) is six times smaller than the Gen3 transmitter design (left).

Figure 5: Improving reliability of transmitter chipset via reflow and microscope inspection.

Figure 6 shows the toroidal reflector with three Tx boards mounted on the feed focal arc that are facing the reflector and between the reflector and the swinging Rx arc. The orange Tx board holders are inclined at the precise angle to face the mid-plane of the toroidal reflector (indicated by the horizontal line drawn on the reflector). As such, the reflected beams will have maximum intensity along the focal line lying on the horizontal plane, which illuminates the target at the secondary focal arc. This secondary focal arc has a radius of 15 cm, lying about 10 cm above the white circular target platform to the right.


C.1.b. Imaging Results

Using two Gen3 Transmitters and a single rotating Gen2 Receiver, along with the SAR algorithm developed in Project R3-A.2, a number of targets were imaged as seen in Figure 7. Each of these images represents a 2D horizontal slice of the middle of the respective targets (as seen from above). Note the y-axis represents range and x-axis represents cross-range, with illumination coming from below.

The image of the metal corner bracket (Fig. 7a) indicates the unique effectiveness of our multistatic imaging. Valleys are particularly challenging to image accurately because rays reflect from first one face, then the perpendicular one, returning exactly in the direction they were incident from. The resulting response for monostatic radar scanners (such as the L3 Provision) is not a corner, but instead a strong isolated point at the position of the corner vertex. Clearly, our multistatic scanner avoids this deficiency, showing both faces of the corner bracket.

Figures 7b and 7c show imaging results for a metal channel and a paraffin explosive simulant block mounted on a metal box. The image of the metal anomaly protrudes, as expected, while the weak dielectric block slows incident waves down, and presents an image with the anomaly appearing as a depression in the box surface.
Stacking 2D images of different reconstructed slices will result in a 3D surface reconstruction of the target. Figure 8 shows 3D surface reconstruction of a complex target simulating a torso with a dielectric and metal bar present. The images are plotted based on the range position of the maximum reflectivity for each.

Figure 7: Reconstructed images for various targets based on measured data. The overlaid light blue line represents the ground truth of the target.

Stacking 2D images of different reconstructed slices will result in a 3D surface reconstruction of the target. Figure 8 shows 3D surface reconstruction of a complex target simulating a torso with a dielectric and metal bar present. The images are plotted based on the range position of the maximum reflectivity for each.
cross-range point. The color scale represents range, lighter being closer to the front of the target, and darker towards the back. Please note that a depression forms wherever the dielectric is placed on the metal plate.

Figure 8: Metal torso simulant with white dielectric explosive simulant bar and metal bar (top left); 2D slice (top right); and two different views of the 3D reconstructed image (bottom).

C.1.c. Receiver Board Design (Gen3)

As illustrated in Table 1, Year 5 was spent completing manufacturing of the Gen4 transmitter (also shown in Figure 4), as well as the design of the Gen3 Receiver. The target is that the Gen4 Tx and Gen3 Rx will be the final hardware iterations, bringing the system design to a pre-industrialization beta-level prototype phase.
The advantages of the Gen4 Tx and Gen3 Rx starts from the underlying components (HMC6300 and HMC6301 vs. the earlier predecessors HMC6000LP711E and HMC6001LP711E, respectively), which have been covered in project reports from previous years. The Gen3 Rx has the same footprint as the Gen4 Tx (68 x 18 mm) which make both easy to integrate together in the reflector-array shown in Figure 1. The top side of the Gen3 receiver is illustrated in Figure 9. The design maintains the same polarization as the Gen4 transmitter when aligned with the long sides parallel. The 3D view of the receiver is shown in Figure 10.

<table>
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<tr>
<th>Feature</th>
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<td>4 x 6 mm</td>
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<td>$20-110 (qty dep)</td>
<td>$30-150 (qty dep)</td>
<td>$20-110 (qty dep)</td>
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</table>

Table 1: High-level specifications of the transmit/receive components.

Figure 9: Receiver design (68 x 18 mm) with key features labeled.
Due to the complexity and reduced footprint of the new Gen3 transmitter component, the board design illustrated in Figure 9 has a 75% increase in stack-up complexity, as shown in Figure 11.

In the Year 4 Project Report, we discussed the main- and daughterboard concept for setting up the multi-transmit-multi-receive system. Each of the Tx and Rx daughterboards shown in Figure 4 (Tx) and Figure 9 (Rx) are connected to a main board supporting up to four transmitters or receivers; the main board contains basic support components and circuitry to power up and transmit information to the computer system that creates the imaging. As previously maintained, this implementation reduces the prototyping cost by up to 80% while maintaining the reliability and reducing the risk. An equivalent motherboard-daughterboard concept is illustrated in Figure 12.
C.1.d. Overall System Configuration

The proposal for the arrangement of the Tx and Rx configuration is shown in Figure 13. With the alternating Tx and Rx, the spacing between the Tx and Rx antenna phase centers is maintained at an optimum of approximately 17 mm. The same spacing is achieved if either multiple Tx or multiple Rx are arranged sequentially next to each other, and this ensures full flexibility for multiple Tx and multiple Rx configured side by side while maintaining the design spacing.

Figure 13: Tx-Rx configuration arrangement, aligning antennas (yellow patches), but keeping cable connections on opposite sides to minimize blockage and entanglement.

In Figure 14, the system block diagram of the entire configuration is shown. Transmitters and receivers are linked together via a common clock. Optionally, a high frequency IF can add additional flexibility in the system configuration at the expense of additional circuitry. Note that the AWG (waveform generator) and digitizer are inside the PC that is also used for imaging. The Cytec switches are used for switching one Tx and one Rx at any one time for combining each multi-static signal path (transmitter m to receiver n).
In order to support the required antenna for the Gen3 circuit board, an on-board antenna was designed. The patch antenna, which is most appropriate for this configuration, requires a 56.5 – 64GHz bandwidth, which is approximately 11% fractional bandwidth. With typical patch designs having 2-5% bandwidth and a gain of approximately 8 dB, the requirement was to increase the bandwidth. This can be achieved via:

- Low permittivity substrate(s) – compatible with the daughterboard concept since lower permittivity substrates are typically more expensive;
- Increased height of the substrate;
- Noncontact feeding methods (difficult fabrication, hence out of scope of our investigation); and
- Multi-resonator stack configuration (create large thickness prototype, hence considered out of scope for our designs).

As the Rx has a single-ended input for the antenna, the best configuration was to use a balun to convert a differential patch to the single-ended Rx input as shown in Figure 15.

Differential patch advantages included:

- Reduced noise
- Reduced feed line radiation which is important for the antenna
- Thinner feed lines compatible with the chipset input
The S11 input matching parameter to the antenna graph is illustrated in Figure 16. A -10 dB matching is shown for 55 – 65 GHz, which is a good metric for a robust antenna design.

The antenna patterns for 57, 60, 65 GHz are illustrated in Figure 17. They are uniform across the operating bandwidth of the antenna, which will result in even performance across the entire frequency set of the system. The approximate ±25 deg. E- and H-plane beam width fills the toroidal reflector efficiently with a minimum amount of wave spill-over.

Figure 15: Differential patch to single-ended Rx design.

Figure 16: S11 input matching of single-ended balun-loaded differential patch.
C.2. Walk Through Hallway On-the-Move Scanner Configuration

In support of the APEX Screening at Speed effort, we studied the feasibility of cooperating dual-sided hallway mm-wave array detection. Of particular concern is how to illuminate and sense scattered field from the full 360 degree extent of a subject, without requiring the subject to stop, turn, or alter their gait. The conventional two-sided multi-monostatic (or even limited multi-bistatic) scanning wall array systems cannot image the front or back of a subject as they walk between the walls because incident rays from these parts of the body reflect specularly away from the transmitters. In order to capture these rays, they must be received on the opposite wall. There must be transmitters on both walls, and independent receivers on both walls of the hallway. This requires a full multistatic configuration with considerably more cabling and processing than conventional multi-monostatic systems; however, it is the only way to accurately image body surfaces that are 90 degrees away from the transmitting wall.

An analysis was conducted to determine the available sensing performance for planar array antennas and co-operating transmitters/receivers on both sides of the hallway. By modeling the human subject as a circle—as seen from above—the sensing performance can be approximated by the fraction of the nominal illumination field of view that returns to the receivers on the same hallway side as the transmitters, along with that fraction that is picked up by receivers on the other wall. Simplistically, this fraction corresponds to angular extent from one edge of the array to the subject surface and then back to the other edge of the array, with the proviso that the surface reflection point must be the one for which the surface normal is the angle bisector of the two array edge rays. Figure 18 shows these points and rays for the nominal 0 degree position on the right side wall; for 45 degrees if the subject is further back from the array (blue); and for 65 degrees relative to the perpendicular for the greatest distance between subject and antenna array (red). In each case, the array is 1 m wide, the subject is 0.15 m in radius, and 0.85 m from the right wall. Note that the radial normals each bisect the edge ray angles. About half the angular field of view is available for the 45 degree position on the right side wall; for 45 degrees if the subject is further back from the array (blue); and for 65 degrees relative to the perpendicular for the greatest distance between subject and antenna array (red). In each case, the array is 1 m wide, the subject is 0.15 m in radius, and 0.85 m from the right wall. Note that the radial normals each bisect the edge ray angles. About half the angular field of view is available for the 45 degree position for the same physical size array, whereas for the 65 degree case, the subtended angle is about $\frac{1}{5}$ the angle at the subject as the 0 degree case. We can thus expect $\frac{1}{5}$ the resolution for this sensed portion of the subject. Performance falls off quickly for greater angles.
To image the subject’s front and back, rays must be reflected from the subject and extended to the other side. This situation is demonstrated in Figure 19. In this case, the limiting factor is less the projection from a tangent line onto the circle, and more a matter of extreme specular reflection. The black rays indicate the relative position of the full array aperture for which the reflection from the front subject surface (at 90 degrees from perpendicular) can be received on the full array on the left wall, with one edge having extreme glancing incidence, while the other edge reflects at the same angle as incident. A 50% smaller portion of the aperture is reflected for 80 degrees, with the first edge ray at glancing incidence to the subject circle. Finally, the green ray shows the limit of zero width aperture capturing only the extreme glancing ray. Here, it is assumed that the arrays are symmetrically positioned on each side, which is why the green case allows only a single glancing incident ray from the trailing edge of the right scanner array to intersect the leading edge of the left scanner array.

Figure 18: Reduction of field of view (and sensing performance) as distance from sensor array increases.

Figure 19: Ray paths for full array aperture specular reflection to opposite side wall (black); half aperture reflection (red); and zero aperture reflection (green).
Combining the angular extent measures for both same wall responses and opposite wall responses yields Figure 20. The leftmost curve plots the relative response of the same wall receivers for three positions with corresponding dot colors to Figure 18: black for nominal perpendicular illumination; blue for 45 degrees (0.78 radian), and 50% illumination and reception; and red for 65 deg. (1.13 radian), and 20% illumination and reception.

The rightmost curve plots the opposite wall response for three angles corresponding to the same color-coded values in Figure 19: black for 90 degrees and 100% aperture illumination; red for 65 degrees and 50% illumination; and green for the limit of zero illumination. In practice, one would choose the curve with the greatest illumination with a cross over between same and opposite walls at about 65 degrees. Of course, the precise values for illumination efficiency depend on the size of the subject and their distance from the walls, as well as the subject’s particular non-ideal shape.

D. Milestones

- We completed most of the planned measurements and reconstructions in Year 5. This represents the culmination of almost seven years of effort: identifying ways of improving the general AIT portal concept, reducing imaging artifacts, speeding up data acquisition and image reconstruction, and improving the materials characterization of concealed foreign objects.
- Working in the retooling delay, we have implemented low-cost RF hardware and successfully tested and optimized its performance. The sparse array support structure has been designed, built, and fitted with RF boards. Measurements and reconstruction (with the help of Project R3-A.2) are ongoing.
For the parallel plate 2D hallway experiment, we have reassembled the hardware with an improved graphite-based lubricant, which will promote easier sliding of the torso and arm cross section sheet through the “hallway” mockup. RF hardware is working and will be attached by September 30, 2018. Experiments will begin immediately thereafter, continuing for 6 to 12 months, to test the full 360 degree reconstruction capability of the wideband mm-wave concept.

E. Future Plans (Year 6)

- The full sparse array will be fabricated and fully tested for repositioning by October 2018. Fully automatic 3D imaging with material characterization will be pursued during the summer and fall of 2019.
- Operational control software and self-contained reconstruction code will have to be developed to minimize operator intervention. The current form of the system requires numerous instructions from an operator. These must be streamlined with appropriate engineering, preferably with help from system vendors with experience in these aspects.
- Before the AIT portal system can be released for field testing and possible certification, it must be configured for operation with minimal operator involvement. Error trapping and automatic correction must be implemented, and unusual body shapes and sizes, along with difficult object cases must be tested and evaluated.
- The extension of the 2D On-the-Move hallway scanner to a full 3D version must wait until the next funding period, should it become available. It is a major project to develop this extension: conceiving the best radar module layout, optimizing 3D reconstruction algorithms, testing the system with computational simulation, purchasing radar and signal acquisition hardware, developing means of stitching together reconstructions from various poses, validation with phantoms, and eventual testing on walking humans.

III. RELEVANCE AND TRANSITION

A. Relevance of Research to the DHS Enterprise

- The multistatic radar configuration employed in Project R3-A.3 extends imaging performance by giving multiple views of each body surface pixel and helps eliminate dihedral artifacts. Reducing false alarms, improving resolution, providing material characterization, reducing scan time, and lowering costs are all important aspects of value to the Homeland Security Enterprise (HSE).
- The On-the-Move hallway scanner is one of the most challenging security innovations. It requires extensive modeling and algorithm development, but appears to be within reach in the foreseeable future. Our two dimensional proof of principle experiment will demonstrate the physical realizability of 360 degree image reconstruction with minimal disruption to subject motion: a substantial improvement over all current threat detection systems.

B. Potential for Transition and Transition Pathway

- The new technology is of interest to the Transportation Security Administration (TSA), which has offered to test a prototype at the Transportation Security Laboratory (TSL), hopefully after Year 6. Should tests prove successful and the scanner is shown to be superior, we will offer to partner with existing AIT manufacturers, such as L-3 Communication and Smiths Detection, Inc., or companies that are exploring entering the AIT market, such as Rapiscan Systems or Morpho Technology.
- We are developing a joint project with Smiths Detection, Inc. on adapting a new product line using wideband radar as a means of implementing an On-the-Move sensing system. Using a cooperating two-sided nearfield radar imaging configuration will allow imaging of not only the sides of a subject walking by the
scanning antenna, but also their front and back.

C. Data and/or IP Acquisition Strategy

The multistatic Blade Beam reflector concept, the radar realization of the 60 GHz radio chips, and the raster-scanned focused spot hallway scanner are protected by pending patents.

D. Customer Connections

Biweekly telephone meetings are held with Claudius Volz, Christoph Weiskopf, Christopher Gregory, and Kris Roe at Smiths Detection, Inc. (Edgewood, MD, USA and Wiesbaden, Germany).

IV. PROJECT ACCOMPLISHMENTS AND DOCUMENTATION

A. Education and Workforce Development Activities

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

   a. Three ALERT Research Experience for Undergraduates (REU) students conducted research as part of Project R3-A.3: Jacob Londa, Nikhil Phatak, Dan Castle, Anthony, Englert, and Samuel Kebadu.


B. Peer Reviewed Conference Proceedings


C. Other Presentations

1. Seminars


   e. Rappaport, C. “Advanced Millimeter-Wave Radar Concealed Threat Person Scanning System – or, How to Design an Airport Scanner that is so Accurate that We Won’t Need Humans to Look at Images.” Ronald E. Hatcher Science on Saturday Lecture Series, Princeton Plasma Physics Laboratory, February 10, 2018.
D. Student Theses or Dissertations Produced from This Project

E. Technology Transfer/Patents
   1. Patent Applications Filed (Including Provisional Patents)

V. REFERENCES
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