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

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II. PROJECT DESCRIPTION

A. Project Overview

We are developing 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. Building on the concepts and analysis of Project R3-A.1—which was terminated during the last project reporting period—we are extending the Blade Beam Reflector from a single illuminating antenna
into a multi-beam Toroidal Reflector, with multiple feeds. Each feed generates a different incident beam with different viewing angles, while still maintaining the blade beam configuration of narrow slit illumination in the vertical direction. Having multiple transmitters provides horizontal resolution and imaging of full 120 degrees of body. Furthermore, the 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.

B. Biennial Review Results and Related Actions to Address

The Biennial Review panels appreciated the innovation and research results of project R3-A.3, and agrees with the claims that it is advancing the state of the art in AIT. The report recognizes that the elliptical toroidal reflector antenna concept provides more signal and gathers more information cost-effectively than conventional systems, and that although bugs have to be worked out, the concept should advance the person-scanning paradigm.

C. State of the Art and Technical Approach

Concealed threat whole-body scanning systems are becoming increasingly prevalent at airports, secure building entrances, and meeting venues. The preferred scanning modality which effectively penetrates clothing but does not produce ionizing radiation is millimeter-wave radar. Portals employ translating transmitters and receivers which illuminate and observe scattered waves from multiple positions to image body surface and any unusual attached objects. Currently employed systems in airports are multi-monostatic, with multiple mm-wave radar transceivers, each using the same antenna for transmission and reception [1, 2]. Well-established Fourier optics theory is used to quickly and effectively process the observed field data and reconstruct body surface profiles. Monostatic imaging is physically limited in imaging, with dihedral artifacts from oppositely-inclined body surfaces, such as the between the legs, between an arm and torso, or between folds of skin which cannot be removed by processing.

Alternatively, multistatic radar sensing avoids the dihedral artifacts because scattered rays are received from many directions simultaneously, rather than only from the spectral direction defined by the surface normal. Multistatic radar is more complicated than monostatic because the receiver electronics are physically displaced from the transmitter, although no transceiver circulators are needed [3-5]. In addition, balancing the compromise between coverage aperture and great numbers of radar antenna elements is challenging. It is important to provide both sufficient element density and array size to yield a high resolution point spread function (PSF), but avoid the financial and computational expenses of dense arrays. One cost-savings approach to a large 2-dimensional array is a reflector that produces a small focal PSF spot at the target position [6]. This prolate spheroidal reflector must be mechanically rotated in two directions to scan across the entire target. If instead the reflector is doubly curved (elliptical in the vertical direction but parabolic in the horizontal direction), it will produce a horizontal focal line on the target [7]. The reflector would only be translated vertically to scan a 2D target, and all processing would be performed on separate 2D slices of data, and stacked to form the reconstructed target surface [8-10]. Reflectors are wideband, inexpensive and lightweight, but to illuminate different regions around the target, multiple reflectors must be used, which presents a problem of careful spacing to avoid overlapping.

D. Major Contributions

A solution to the multiple reflector problem is to smoothly blend several adjacent reflectors into an elliptical toroidal reflecting surface, as depicted in Figure 1 (on the next page). This surface is generated by rotating a vertical ellipse about a vertical axis. For limited illumination, the circular variation in the horizontal direction approximates parabolic curvature. The feed positions pass through the primary ellipse focus on an arc, also
centered on the reflector axis of rotation. The radius of this arc is about half of the reflector radius, but must be numerically optimized for the offset geometry. Multiple feeds on the feed arc can generate non-interacting overlapping illumination patterns on the reflector, which in turn generate separate transmit beams. In addition, the same reflector can be used for received signals with receiving elements placed along the feed arc in-between transmitting elements. The reflector is a sufficiently offset ellipse section, to prevent any feed blockage of the aperture. The ellipse is rotated about the vertical z-axis from \(-\pi/3\) to \(\pi/3\), which can be stated mathematically by merely replacing \(-y\) with the cylindrical radius, as displayed in Figure 1. Figure 2 on the shows a top view, indicating the focal arc and simplified target contour with incident field intensity due to illumination from an open ended waveguide feed at 60 GHz.

To date, we have designed, modeled, fabricated, and tested the novel elliptical torus reflector. This reflector provides high gain, narrow blade beams that allow for stacked 2D processing and reconstruction. This concept is completely new with patents pending.

**Figure 1:** View of offset elliptical torus blade beam reflector surface with focal points and axis of rotation.

**Figure 2:** Top view of illuminated reflector, showing feed arc, torso target shape, and secondary focal line for central beam.
Figure 3 shows the reflector as built. The transmitting and receiving elements are positioned on the focal arc (hidden by the reflector). Unlike typical radar scanners and the previous design of R3-A.1, both transmitters and receivers point towards the reflector. This way, both transmitting and receiving elements benefit from the reflector-generated, well-focused, high gain blade beams, and because of the circular symmetry of the toroidal reflector, overlapping regions of the reflector can be simultaneously illuminated to produce non-interfering beams.

The reflector was fabricated using a computer numerically controlled mill, in four identical sections, each encompassing 30 degrees of circular arc. The sections are carefully aligned and bolted together, with seam error (as well as overall surface roughness) less than 0.2 mm. The entire reflector weighs roughly 35 kg. Additional reflector surfaces with 0.2 surface accuracy can now be cast from this aluminum form. Resin layups can be formed to be both thin and strong, and would weigh a fraction of the aluminum reflector. Thus, the eventual implementation would be lightweight and easy to mount and move.

Last year, using previously fabricated radar modules, we demonstrated and analyzed that the reflector performed as modeled; imaging simple scattering objects, and maintaining symmetric patterns for all feed points on the focal arc. This year, we have refitted the transmitting and receiving elements with new, considerably less expensive radar modules.

These new modules were designed and fabricated as part of the collaboration with Rapiscan, Inc. and the John Adams Innovation Institute. Twelve quad-receivers and 12 single transmitters were built with a total cost comparable to a single waveguide-based transmitter module used in the original system from Project R3-A.1. Unfortunately, with the redesign of the radio frequency (RF) electronics, new problems appeared that needed to be methodically debugged. We uncovered mistakes in the circuit layout, and determined that the digital data path was too noisy. We fixed these problems by modifying components on the digital control part of the board and by adding filters at critical points to decrease noise level. By solving the digital problems, we were able to read the Tx and Rx modules’ registers. Problems remained with the Tx/Rx signal not locking their frequency selection register values to the clock signal. We investigated the clock path and the register values that tune the frequency bands. Eventually, we established the correct register values, which inexplicably...
bly disagreed with the values for the old modules, and the lock problem was solved. We tested the radar link between Tx and Rx modules in free space to evaluate the received signal characteristics and board performance. We found that the measured phase is inconsistent and noisy. Since large phase errors can completely corrupt the reconstruction process, this deficiency had to be corrected. We investigated the source of noise and tried to decrease noise level on the board or in the measured data. After applying other measurement algorithms, and designing and implementing several filters and impedance matching circuits on the clock and baseband signal paths, we found that the source of noise was from a circuit design mistake and poor grounding. Figure 4 presents a sampling of the standard deviation of phase for measurements at different frequencies after fixing poor grounding problem on the boards.

![Figure 4: Samples of the standard deviation of phase (i.e. phase noise) for a typical Tx/Rx pair, as a function of frequency.](chart.png)

We performed numerical simulations to investigate the effect of noise on the final reconstructed image. The results for an elliptical target are shown in Figure 5 (on the next page). Figure 5a is the image for a noiseless system. Figures 5b and 5c are the reconstructions for noisy systems for cases when the standard deviation of phase variation is 0.2 and 0.4 radians respectively. Based on the measurements (Fig. 4), the standard deviation of the phase in the system after modifying the boards is less than 0.2 radians, which based on Figure 5b appears to be an acceptable level of performance, with a reasonably continuous image on the elliptical target with minimal artifacts at points off the ground truth green curve.
We modified and tested all the Tx and Rx boards, examining the digital and analog section of each board, and studying the plot of phase vs. frequency to ensure phase linearity and phase noise level for each of the 14 five-hundred MHz frequency bands.

We developed a field programmable gate array (FPGA) program to use the solid state switches to improve

Figure 5: Modeled reconstructed surface contour images for idealized torso for different phase variations: (a) 0 phase noise; (b) 0.2 radians phase standard deviation; and (c) 0.4 radians phase deviation.
the timing between trigger signal commands to read/write to registers. We are merging this code with the main FPGA control program to use more than one receiver antenna at a time. The same FPGA program with a different pattern for the solid state switches can be used for the John Adams Innovation Institute (JAII) system as well.

We are also using other new RF hardware leveraged through JAII, such as an arbitrary waveform generator and digitizer. This involved developing LabVIEW interfaces to control the new hardware. By modifying the current AIT system high level LabVIEW control with a LabVIEW interface for the new digitizer, we will have everything needed to do completely independent measurements on the JAII system.

After fixing the boards and modifying the FPGA and LabVIEW control codes, we did measurements in free space and on the toroidal reflector system to investigate the performance of the system and its components. Initial measurements indicated that to produce a linear unwrapped phase across the full 57 – 64.5 GHz band, the number of frequencies in each pulse needed to be increased. That is, the phase difference between neighboring frequencies must be low enough to avoid under-sampling of the unwrapping algorithm. Although it is clear that the final image is generated based on wrapped phase, it is important to plot the phase vs. frequency behavior of the radar and evaluate the performance of the modules. We also found and solved some problems in the “stitching algorithm,” which calibrates each 550 MHz sub-band by equating the phase of the overlapping frequency at the bottom of the subsequent sub-band with the top of the preceding sub-band. The receiver boards had lock problems in some frequency bands that were solved by slightly retuning the register values. By solving these problems, we have linear and consistent phase vs. frequency plots for a constant position of modules. One of these plots is presented in Figure 6.

Using the repaired Tx and Rx boards and modified FPGA and LabVIEW programs, we mounted the radar modules at the precisely calibrated reflector focal positions. These positions were optimized by electronic calibration, making small vertical and horizontal adjustments for best focusing and beam pattern uniformity. Measurements were taken using one transmitter positioned at the center of the first focal arc (0 degrees; labeled Tx position in Fig. 2) and one receiver moving on half of the arc (from ~12 to 52 degrees). Figure 7 (continued on the next page) presents imaging results. A photograph of the target on the image domain is on the left and the measurement result is on the right. For each case: a flat metal surface; the surface with a single, and then two metal channels; the channels by themselves; and finally a thin, 5 mm diameter metal
rod, the radar image accurately reconstructs the size, cross-sectional shape, and position of all features in the target region.

Figure 7: Five metal test target configurations and corresponding image reconstructions using the reflector and inexpensive RF radar modules.
One challenge that we have addressed is the limited physical space available for the radiating RF hardware elements. These have to fit next to one another along the focal arc. The imaging quality is best if the array avoids periodicity, so a non-uniform spacing between elements is desirable. This means that the antenna positions must be as flexible as possible, which in turn demands that the supporting RF board be as narrow as possible. While the quad-receiver boards are designed for close to minimum separation between antennas, the transmitter board was considerably wider than it needed to be. Figure 8 shows a specification drawing of the redesigned transmitter module circuit board with a narrow “tongue” protruding from the rest of the board with the transmitter RF chip and the integrated broad-beam antenna. With this narrow transmitter configuration, the transmitting and receiving antennas can be positioned as closely as possible to each other for the best spatial sampling to fit the most elements into the focal arc array.

Figure 8: Novel transmitter RF circuit board module with greatly reduced width to accommodate tight packing on toroidal reflector focal arc. These cards will be mounted facing downward, as shown, while the receiving boards will face upwards to minimize blocking of the antennas by the boards. The 60 GHz transmitting chip has an integrated antenna (at bottom).
**E. Milestones**

Although the RF electronics hardware has been tested for individual operation, the array of module elements must be incorporated into the torus reflector geometry. Getting the electronics to work as part of the overall system is critical and of highest priority.

The current low cost RF hardware has been successfully tested and optimized (as anticipated) by June 30, 2016.

Following the full RF electronic circuit configuration, there will be numerous tests of 2D imaging to determine capabilities and limitations of the full radar system. This will naturally extend to multiple height 2D imaging and stacking for 3D imaging.

We will apply improved computational models and algorithms on the data generated with the working system to accelerate the imaging process, and determine practical bottlenecks which slow the process. This information will provide feedback for spiral development and improvement of reconstruction algorithms to be addressed by Project R3-A.2.

The major milestones for Year 4 are to: 1) Build a highly accurate positioning structure that allows fine antenna element positioning for all elements in the array; 2) Optimize reflector illumination; 3) Build compact mm-wave printed circuit boards that fit the required tight packaging requirements; 4) Establish a calibration protocol to minimize phase noise; and 4) Experimentally validate the fixed multistatic imaging concept.

The biggest impediment to this project has been the trade-off between cost and development time. We are minimizing the overall budget by trying to adapt commercial off-the-shelf (COTS) hardware, and using untrained students rather than professional full-time technicians to fabricate, assemble, and test hardware. Smart students learn quickly and, once they get up to speed, become quickly effective. One possible threat is the possibility that the sole manufacturer of the 60 GHz transmitter and receiver chips may discontinue the product line. If this occurs, it will be a major setback in the timeline. Although the reflector concept remains viable, the prototype would have to be retooled with different chips and associated signal hardware, along with new antenna element design and fabrication. This would lead to an 18-month delay and over $100,000 in extra costs.

**F. Future Plans**

For the next phase of our research, we will use the results of computational studies conducted in Project R3-A.2 to build an optimal sparse, fixed receiver feed array with interspersed transmitters along the focal arc. This will avoid the use of a rotating receiver arm and speed the measurement process. One important aspect of this major reconfiguration is the coupling between adjacent elements. Initial computational studies have indicated that the coupling is low, but steps may have to be taken to further isolate elements with absorbing material.

We anticipate that the full sparse array will be fabricated and fully tested by repositioning by December 30, 2016. The sparse array support structure will be built and fitted with RF boards by March 2017. Measurements and reconstruction (with the help of Project R3-A.2) will be completed by summer 2017. Full, automatic 3D imaging, with material characterization, will be completed by December 2017.

The measurement campaign that follows this reconfiguration will be as extensive as the first two years of Project R3-A.1, with many cases to consider: flat tilted targets, horizontally varying targets, metal and dielectric targets on metallic backgrounds, curved targets, targets with rapid surface variation, 3D targets, and finally human targets. We have obtained IRB approval for human subjects, but we will not use humans until the radar acquisition time is fast enough to avoid motion artifacts.
III. RELEVANCE AND TRANSITION

A. Relevance of Research to the DHS Enterprise

1. The custom developed AIT hardware developed in the R3-A3 project provides faster, more accurate imaging, increasing resolution, improving detection and reducing false alarms. The concept and implementation of stacking 2D imaging (stacked image slices) reduces hardware requirement by a factor of 100 (for 1 cm resolution), computation by a factor of 10,000, and providing near real-time processing.

2. Commercial Off-The-Shelf (COTS) communication modules repurposed used in the R3-A3 project, as AIT screening radar saves money (radar module cost savings from $12,000 to $150), allows for general security use and makes the R3-A3 project results more likely to transition to our commercialization partners.

3. The multistatic radar configuration practiced in R3-A3 project extends imaging performance by giving multiple views of each body surface pixel and helps eliminate dihedral artifacts.

B. Potential for Transition

We continue our collaborative relationship, established last year, with Rapiscan Laboratories, Inc. using funding from the John Adams Innovation Institute to work with the radar system developed in Project R3-A.3 to test the feasibility of the On-The-Move sensing system discussed in Project R3-B.1. As a first step for full 360 degrees whole body imaging with a fixed set of multistatic 60 GHz arrays, we are considering a 2D cross section geometry. Unlike the Blade Beam reflector system which produces 2D illumination of a 3D object, this transition project is considering only a 2D human body cross section, contained within a pair of parallel plates. The received signals will be reconstructed to form a slice image of the object placed between the transmitters and receivers. This work forms a 2D experimental proof-of-concept study which will be expanded following the project's conclusion into fully 3D image reconstruction for full size personnel screening.

The effort is focused on designing the sensor, simulating the RF mm-wave reflections for various geometries of the transmitters (Tx) and receivers (Rx) and determining the layout of the transmitters and receivers for the sensor, as shown in Figure 9 (on the next page). From this layout, we developed a block diagram of the hardware components that will comprise the sensor, ordered parts; fabricated 12 transmitter boards and 12 quad-receiver boards; fabricated the parallel plate guide with slots and slides for the boards; and began testing components. The hardware has been debugged, and experiments have shown the essential aspect of guiding waves predominantly in the TEM mode between the top and bottom plates of the parallel plate waveguide. Radar signals propagate in straight lines between the plates, without dispersing, attenuating, or reflecting from sides or circuit boards. We are now ready to conduct imaging experiments using algorithms developed as part of Project R3-A.2 to quickly reconstruct 2D target objects.

The same hardware will be applicable to the elliptical torus Blade Beam, so there is an effective dual-use strategy for this experiment.
C. Data and/or IP Acquisition Strategy

Disclosures of the patentable innovation have been submitted. Some of the innovation is being treated as “trade secrets.”

D. Transition Pathway

The AIT Dielectric Characterization Task Order was funded by DHS to enable collaboration with industry to validate the ability to assess material properties using mm-wave radar. In particular, the PI is meeting with Smiths Detection via weekly telephone research conferences. We have developed algorithms suitable for the Smiths multistatic CW mm-wave hardware platform that will improve the characterization of non-metallic foreign objects concealed under clothing.

The collaboration with Rapiscan is ongoing and strong. As potential end-users of Project R3-A.3 technology, and partners in the development of these concepts, they are already in the process of transitioning for an end-user. The next steps for Rapiscan are to decide on a commercialization strategy for further concept development and eventual implementation as a product.

E. Customer Connections

- Smiths Detection: Claudius Volz, Christoph Weiskopf, Christopher Gregory, Kris Roe.

IV. PROJECT ACCOMPLISHMENTS AND DOCUMENTATION

A. Education and Workforce Development Activities

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

   a. Research Experience for Undergraduates (REU) students: Kurt Jaisle and Jacob Messner of Northeastern University (2015); and Spencer Pozder and Justin Xia of Northeastern University (2016).
b. Undergraduate students currently participating in this project: Thurston Brevett, Michael Woulfe, Alastair Abrahan, Aayush Parekh, and Selean Ridley.

2. Interactions and Outreach to K-12, Community College, and/or Minority Serving Institution Students or Faculty
   a. NSF Young Scholars Program (YSP): Michelle Lim and Alex Teodorescu (2016).

B. Peer Reviewed Journal Articles


C. Peer Reviewed Conference Proceedings


D. Other Presentations

1. Seminars

E. Technology Transfer/Patents

1. Patent Applications Filed (Including Provisional Patents)
   a. “Modular Super heterodyne Stepped Frequency Radar System for Imaging,” Carey Rappaport,
V. REFERENCES


