R3-B.1: Hardware Design for "Stand-Off" and "On-the-Move" Detection of Security Threats

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

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II. PROJECT DESCRIPTION

A. Project Overview

As the problem of identifying suicide bombers wearing explosives concealed under clothing becomes increasingly important, it becomes essential to detect suspicious individuals at a distance. Systems that employ multiple sensors to determine the presence of explosives on people are being developed. Their functions include observing and following individuals with intelligent video, identifying explosives residues and/or heat signatures on the outer surface of their clothing, and characterizing explosives using penetrating X-rays [1–2], terahertz waves [3–5], neutron analysis [6–7], or nuclear quadrupole resonance (NQR) [8–9]. At present, radar is the only modality that can both penetrate and sense beneath clothing at a distance of 2–50 meters without causing physical harm.

The objective of this project was to develop and evaluate the hardware for an inexpensive, high-resolution radar that can distinguish security threats hidden on individuals at mid-ranges (2–10 meters) using an on-the-move configuration, and at stand-off ranges (10–40 meters) using a van-based configuration (see Figure 1).

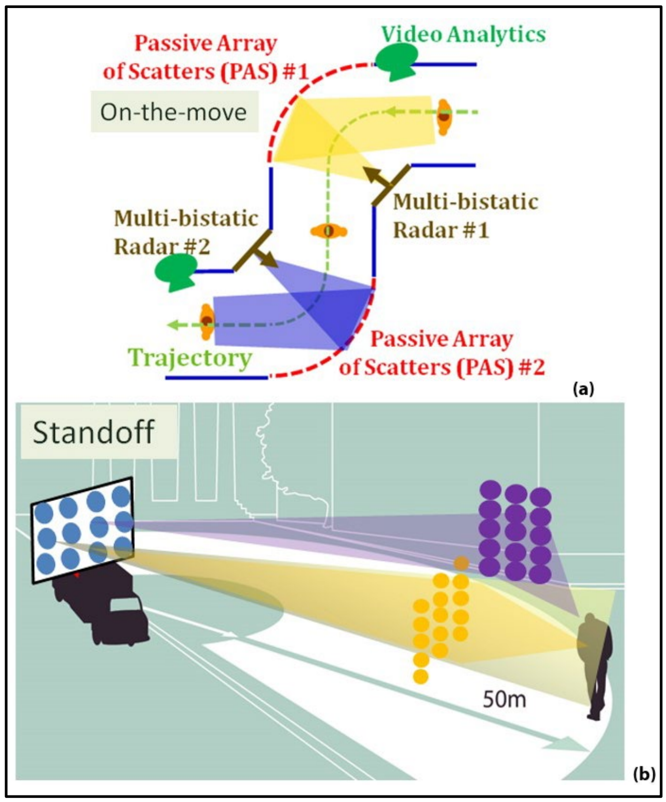

Figure 1: General sketch of the inexpensive, high-resolution radar system used for detecting security threats at (a) mid-ranges using an on-the-move configuration; and (b) stand-off ranges using a van-based configuration.

B. State of the Art and Technical Approach

As pointed out by the International Air Transport Association (IATA), being able to detect security threats without interrupting the motion of the person under scrutiny will be one of the most valuable features of the next-generation personnel screening systems [10]. Current state-of-the-art millimeter-wave (mm-wave) imaging systems for security screening require people to stop and stand in front of the scanning system. Mm-wave generation and acquisition is achieved with a static array of transmitter (Tx) and receiver (Rx) modules [11–12], or movable arrays that create planar [13–14] or cylindrical [15–17] acquisition domains. Most of them are based on monostatic radar and Fourier inversion [11–15]. Monostatic imaging system limitations are mainly related to the appearance of reconstruction dihedral artifacts, as described in [17–19].

The scope of this project was to develop the first inexpensive, high-resolution radar system with a special application to detect and identify potential suicide bombers. Its uniqueness was based on its ability to deploy multistatic configurations [20–23], in which the information from multiple receivers and transmitters are coherently combined by using a common local oscillator. This project had the potential to be the first radar system that is capable of functioning at multiple ranges for both indoor and outdoor scenarios. Unfortunately, limitations on available hardware prevented the realization of the system by the summer of 2020. However, work will continue on the project leveraging non-DHS funding sources with the aim of demonstrating a working system.

Our research program evolved from a 3D imaging mechanical system (Generation 1, Gen-1 [24]) to an intermediate imaging system (Gen-2) capable of imaging small targets in a fully electronic fashion and then to a fully electronic scanning 3D imaging system (Gen-3 [25–26]). The major contributions toward the Gen-3 system are discussed next.

C. Major Contributions

A summary of the Year 7 major contributions follows.

C.1. Hardware Design and Integration of a Multiple-Bistatic Imaging System

- Outcome 1.1: Mechanical assembly of the radar system toward 1,152 multiple-input multiple-output (MIMO) channels
- Outcome 1.2: Design and fabrication of an active phased array and reflect arrays
- Outcome 1.3: Setup of new hardware gantry with four compressive reflector antenna (CRA) arrays

C.2. Calibration Algorithm for Coherent Image Formation in Multiple-Bistatic Imaging System

- Outcome 2: 3D calibration for producing 3D images for the Gen-3 systems

C.3. Imaging Results Using the Multistatic Millimeter Wave Radar System Configuration

- Outcome 3.2: Fully electronic 3D imaging at the 1–2 m range using the modular Gen-3 mm-wave radar system
- Outcome 3.1: Simulation of a system using an array of CRAs

D. Milestones

As we stated in last year's plan, two goals were set for this year:

- Showing preliminary experimental results of real-time imaging using multiple CRAs and HXI's front-end modules.
- Designing a new front end that is more cost-effective and electromagnetically robust than one based on HXI's modules would be.

On one hand, thermal drift and hardware instability of the initial front-end design hindered our ability to achieve the first goal.

On the other hand, important progress was made toward reaching the second goal. Milestones achieved toward reaching the aforementioned goals follow.

D.1. Hardware Design and Integration of a Multiple-Bistatic Imaging System

D.1.a. Mechanical Assembly of the Radar System toward 1,152 MIMO Channels

This year we improved our hardware system, which now possesses the following elements:

- Seven HXI #8302 transmitter (Tx) modules, including one Tx module on the calibration gantry
- Seven HXI #8301 receiver (Rx) modules, including one Rx module for on the calibration gantry
- One HXI #8303 local oscillator module (LOM)
- Fourteen HXI #HSWM41203 single-pole four-throw (SP4T) 4-way antenna switches

The maximum number of available channels in the previous version of the system was 576 (6 transmitter modules × 4 transmitting ports × 6 receiver modules × 4 receiving ports). This configuration enables only the imaging of the front part of the body. To be able to have a fully on-the-move system, the number of coherent channels will need to be doubled. Not only is the electromagnetic stability and thermal drift of HXI's components lacking but also the cost of each transmitting and receiving module is much higher when compared to other alternatives that have reached the market within the last two years. For this reason, this year we not only tried to perform the on-the-move imaging using our current radar components but we also explored more cost-effective and reliable mm-wave radar chips on the market. In pursuit of a system with 1,152 channels, which will afford us ultra-high sensing capacity to image the front and back of a moving person, this year we have tested and validated some off-the-shelf mm-wave mixers (up-converters and down-converters). Those mixers are much more compact and can support much higher output power compared to the current ones. They can provide a better inherent coherence among different Tx/Rx paths, because they are integrated and built in a single printed circuit board (PCB) with one monolithic microwave integrated circuit (MMIC). The latter will reduce the complexity of the calibration procedure when multiple Tx/Rx are used, and it can simplify the use and reliability of the imaging system. Most importantly, those mixers can support user-defined baseband signal input, and as a result of this, we can now perform wave coding by predigital signal processing, including but not limited to the following:

- Binary phase coding of frequency modulated continuous wave (FMCW)
- Orthogonal frequency-division multiplexing of FMCW

These signal processing capabilities resulted in higher signal-to-noise ratio when compared to our previous time-switched MIMO arrays. This year we have also added additional four-way power dividers to the local oscillator (LO), so that additional LO lines are available for the newly introduced mixers. Theoretically, the new augmented LO module has the capability to operate with up to twenty-eight transmitting modules and twenty-eight receiving modules, which is an important increment when compared to the limit of our previous configuration (thirteen transmitting modules and thirteen receiving modules).

D.1.b. Design and Fabrication of an Active Phased Array and Reflect Arrays

Adding active phased arrays in each transmitting and receiving module will also result in a reduction of hardware complexity and imaging speed. This year, we further designed the active phased array. During last year's experiments, we found that our previous phased arrays worked very well for only a limited amount of time. The main reason for this was that the boards were not very stiff, and this made some phase-shift diodes dislodge from the boards. We also observed that our previous substrate combination (RO3003 with RO440F) presented additional manufacturing challenges, since RO4450F showed a reduced peel strength that challenged our foil lamination process.

This year, we have addressed such problems by switching to a RO3003G2 substrate. Specifically, we redesigned our PCB stickup using an RO3003G2 core with FR-4 epoxy underneath, which resulted in enhanced board strength. All the functional units—including the phase shifters, waveguide-to-microstrip transition, antennas, and others—were redesigned under the new stack-up design. Figure 2 shows the S-parameters of two face-to-face waveguide-to-microstrip transitions using new PCB substrates. The return loss was higher than 10 dB after 73.5 GHz. This can be further optimized in the future if this project continues under other DHS funding.

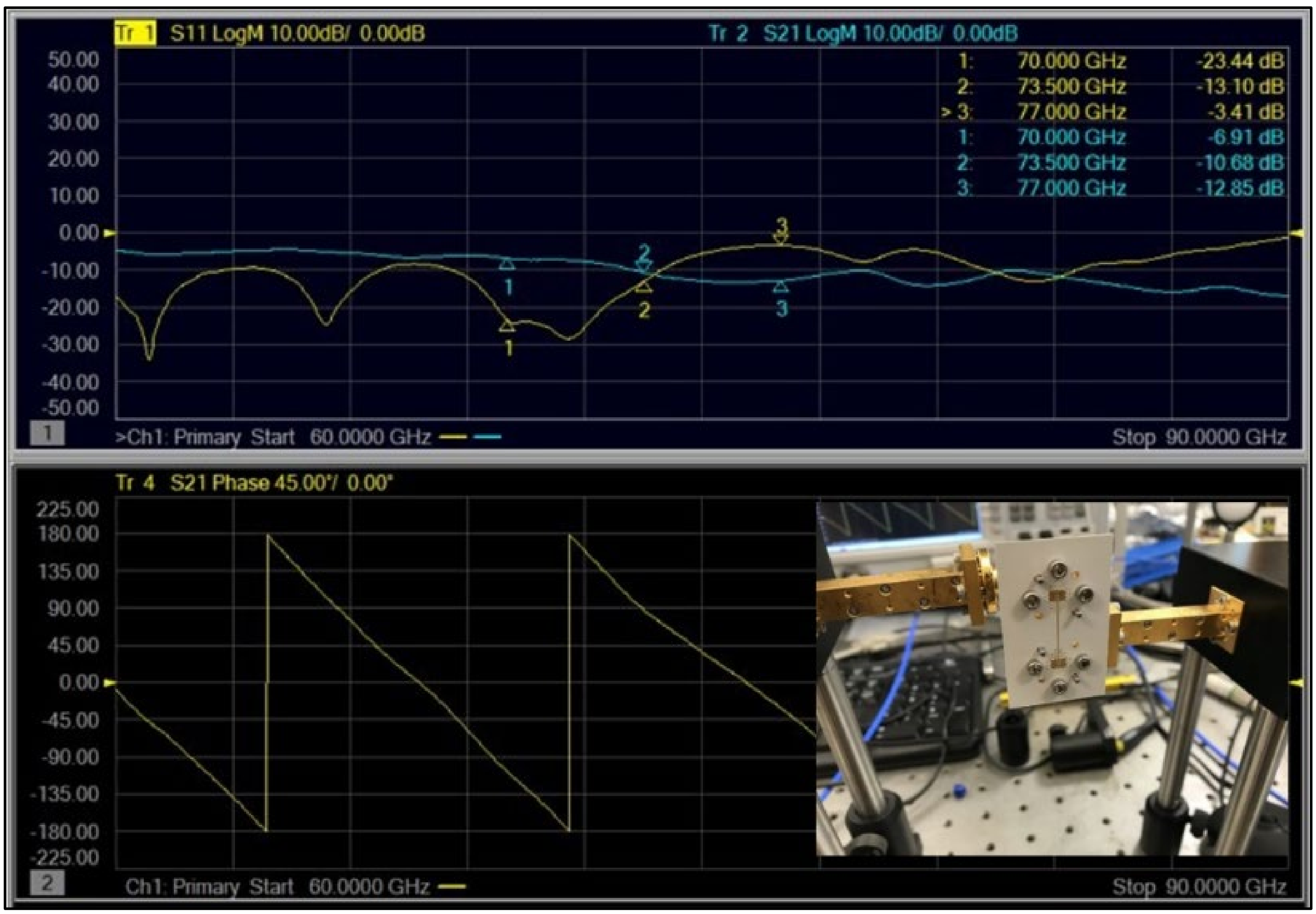

Figure 2: S-parameters of two face-to-face waveguide-to-microstrip transition using new PCB substrates.

This year, we have designed better phase shifters using a 4×4 Butler matrix on microstrip lines. Figure 3 shows the structure of the 4×4 Butler matrix, and Figure 4 shows its ability to steer the beams at 70, 73.5 and 77 GHz, respectively.

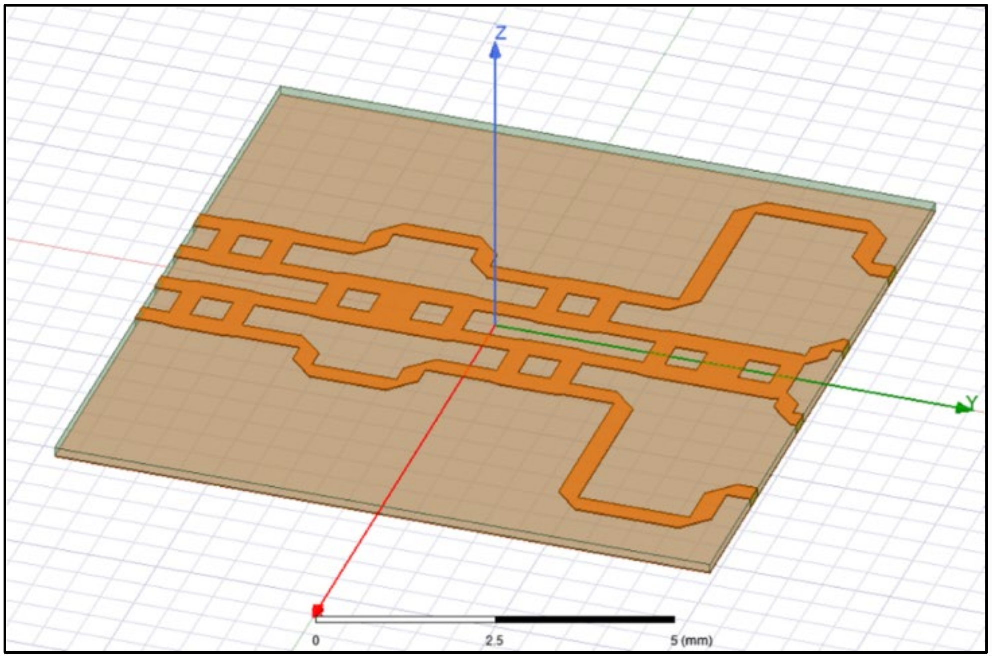

Figure 3: Structure of 4×4 Butler matrix phase shifters.

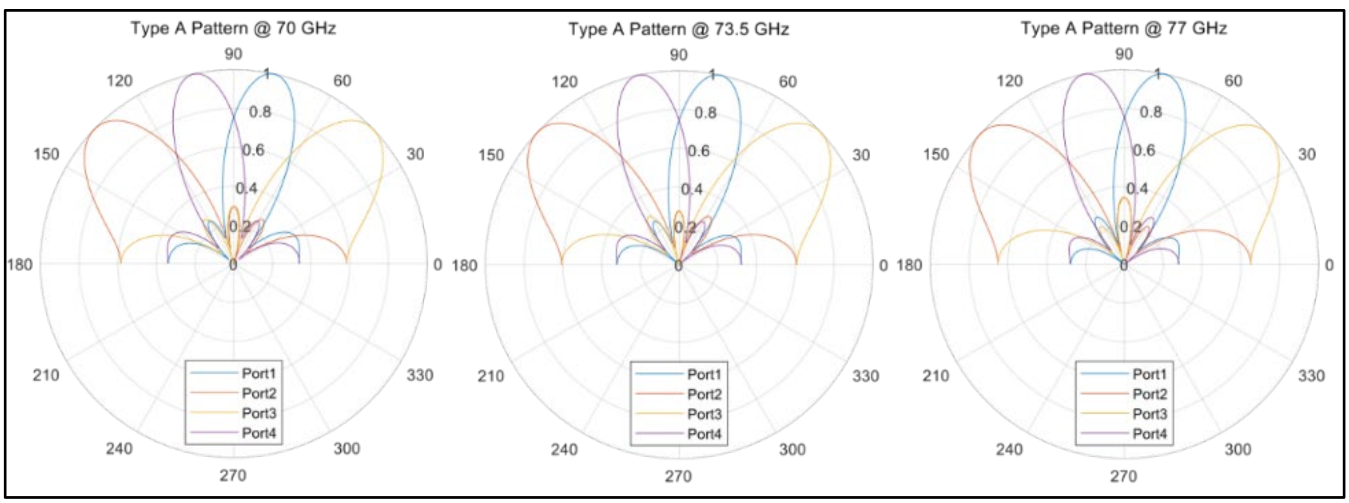

Figure 4: Simulated patterns of 4×4 Butler matrix phase shifters.

This year, we have also used a substrate integrated waveguide (SIW) to provide beam steering. The SIW uses a dielectric substrate with two rows of metallic via-holes, which connect the upper and lower metallic plates. Two SIW designs were carried out this year. The first design is a 2D array that used two 3 dB couplers, as shown in Figure 5. The second design is a 1D array that used a Butler matrix, as shown in Figure 6. The first design can be used with an HXI switch, so that a reduction in grating lobes and better imaging is achieved. The second design can be combined into a cross-shape area array for the new transmitting and receiving modules, so that reduction in granting lobes and better imaging performance is achieved.

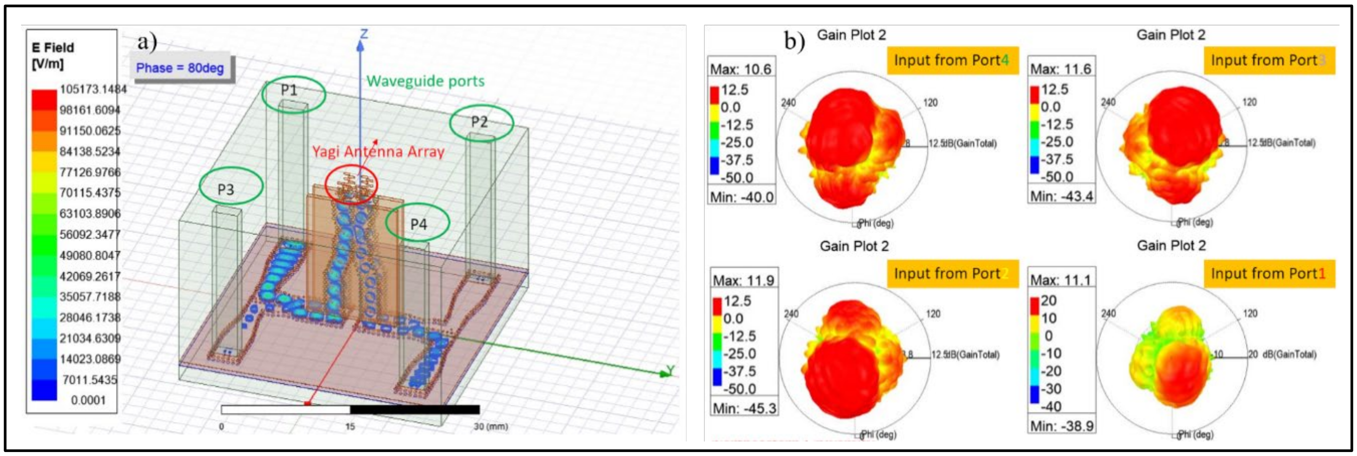

Figure 5: (a) The structure of 2D phased array; (b) simulated pattern.

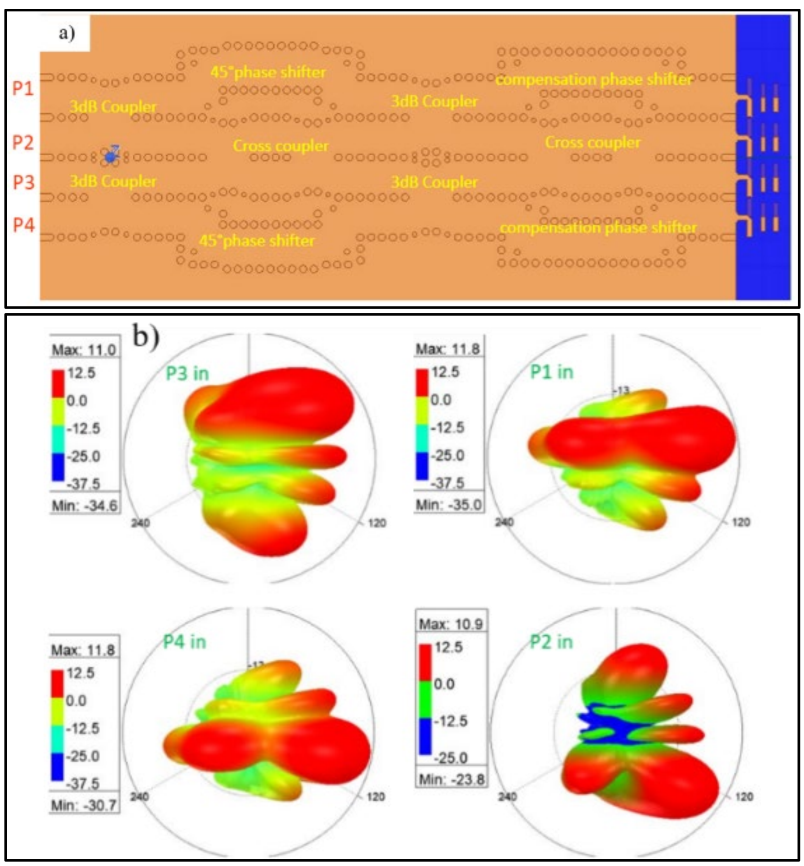

Figure 6: (a) The structure of 1D phased array; (b) simulated pattern.

D.1.c. Setup of New Hardware Gantry with Four CRA Arrays

This year, we have also finalized the new gantry of the CRA imaging system. In Figure 7, the front view of the CRA imaging system is shown in (a), and the back view of the system is shown in (b). The new gantry accommodates four separate arrays of CRAs, which are placed at the four corners of the imaging system. This configuration enables the system to image both front and back of the moving target. Each CRA array supports up to four vertical CRAs, and each one is fed by a MIMO array composed of three transmitting ports and four receiving ports. Each CRA array covers an area of 1.5 meters by 0.5 meters, which enables imaging of human-size targets.

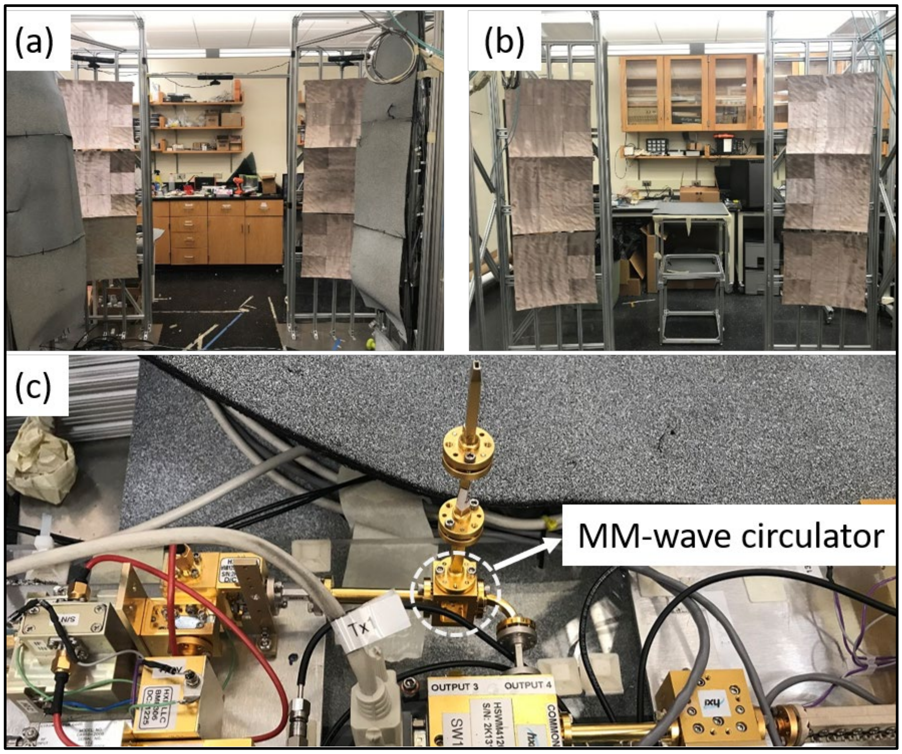

Figure 7: (a) Front view of the CRA imaging system; (b) rear view of the CRA imaging system; and (c) improved calibration configuration of the CRA imaging system.

D.2. Calibration Algorithm for Coherent Image Formation in a Multiple-Bistatic Imaging System

This year, we have advanced the calibration system of the CRA imaging system by using co-located scanning for both the moving transmitter port and the moving receiver port. This is achieved by using a mm-wave circulator, as shown in Figure 7(c). Both the moving transmitter and receiver are connected to the two ports of the circulator and use the common port to transmit and receive the electric fields. In this way, all the calibration fields for any static transmitters and receivers will have the same spatial coordinates, which will improve the accuracy of the calculated sensing matrix. We have also enabled near-field capture of both transmitters and receivers in a single calibration measurement, which can reduce the time for performing a calibration of the imaging system. As shown in Figure 7(c), an SP4T switch is attached to the Tx module to ensure that no power forms when the moving transmitter is coupled into the moving receiver. Although coordinate coherence was achieved, the additional interference between the moving transmitter and receiver modules was observed and had to be removed from the calibration fields to get a reliable sensing matrix. We measured such interferences by using a back-to-back setup, where the moving transmitter and receiver were directly connected, allowing us to enhance the sensing matrix.

D.3. Imaging Results Using the Multistatic Millimeter Wave Radar System Configuration

Preliminary imaging results for a single CRA were presented last year; these results are shown again, for completeness of reported work, in Figure 8 and Figure 9. These results shows that one CRA can image one part of the body relatively well. However, in order to image a human-size target, the coupling between adjacent CRA—each one having a different transmitting and receiving module—must be done.

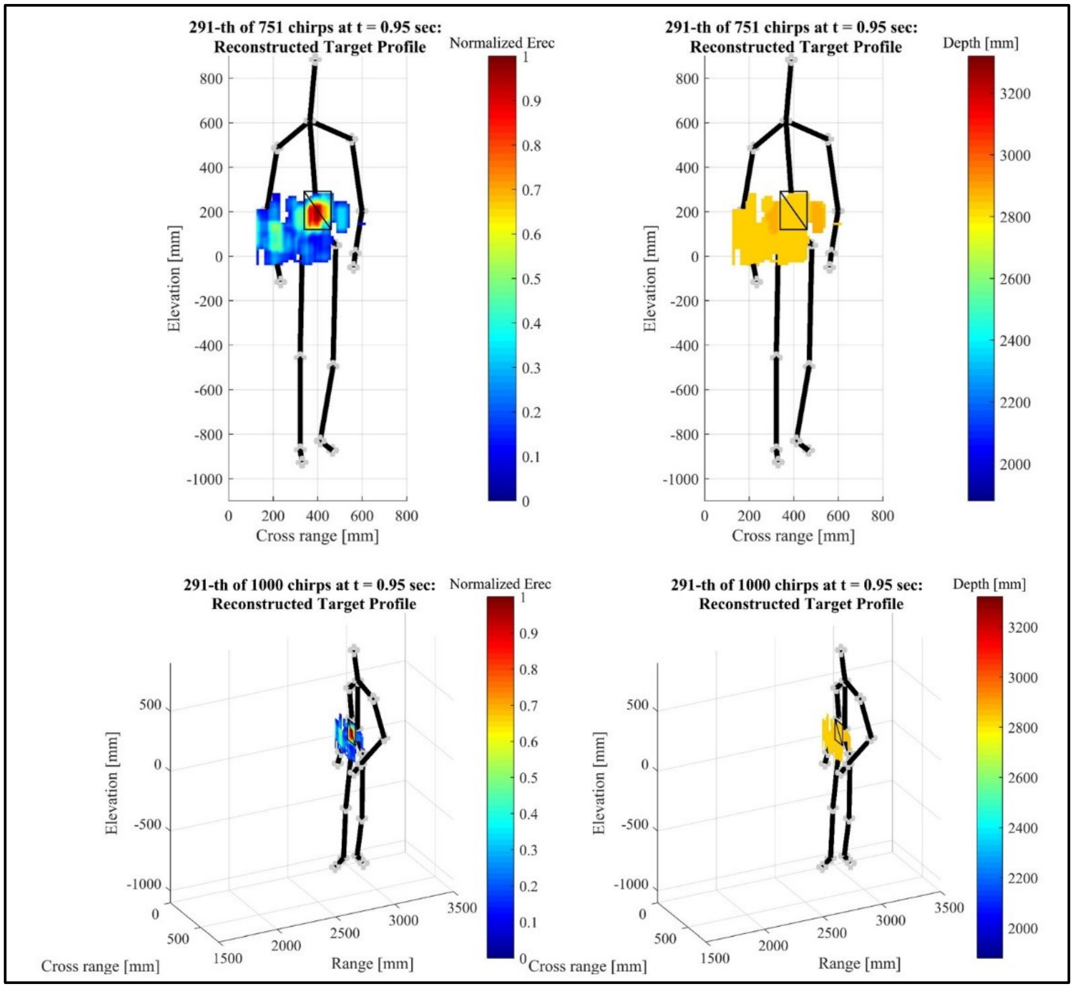

Figure 8: Mm-wave images for the on-the-move human body experiment with a metal box under clothing.

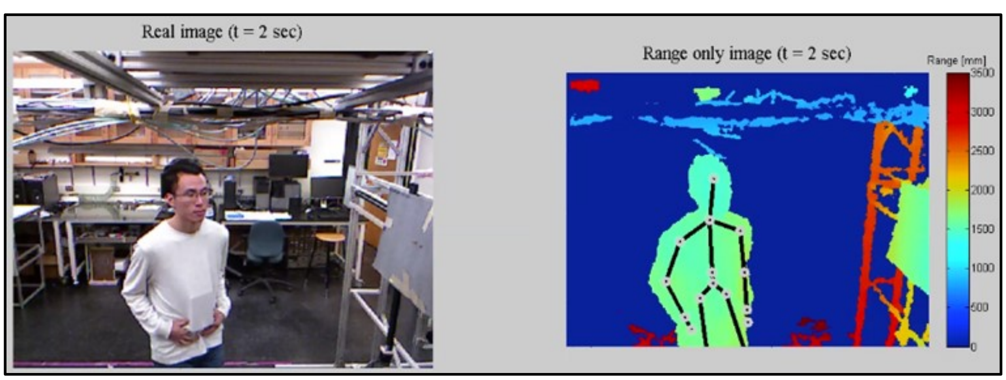

Figure 9: Video and 3D Kinect-based stereo camera images of the on-the move human body experiment.

This year, we aimed at coherently coupling several CRAs to image a human-size target. Our first approach consisted of performing the imaging using the numerically computed sensing matrix and measured electromagnetic fields. This approach was used for three different cases: imaging with the left-middle CRA, imaging with the right-middle CRA, and imaging with the coupling between the left-middle CRA and right-middle CRA. Corresponding imaging results can be seen in Figure 10, where a metallic box is used as a target.

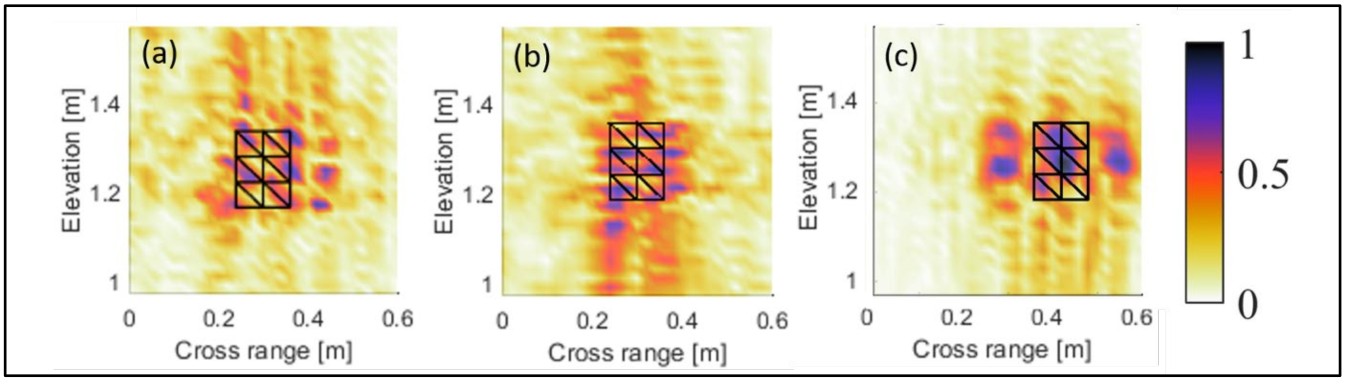

Figure 10: Results from experimental imaging of a metallic box; (a) left-middle CRA, (b) right-middle CRA, and (c) coupling between the left-middle CRA and right-middle CRA.

Our efforts to perform the imaging using multiple reflectors working in a coherent fashion has not been successful when using HXI's front-end modules. We have observed an important thermal drift that causes the measured transfer functions for the transmitting and receiving modules to be unreliable. Using the new low-cost modules has the potential to overcome this limitation. We will continue down this road by using funding from Professor Martinez's current National Science Foundation Faculty CAREER award.

D.4. Study of a New On-the-Move System Hardware and Configuration

D.4.a. Simulation of a System Using an Array of Compressive Reflector Antennas

This year, we also developed simulation models for the Gen-3 mm-wave radar system. In the simulation, we used four CRAs to perform the imaging of different targets. Figure 11 shows the imaging results when the target is a horizontal T-shaped metallic object. HXI's mm-wave switches restrict our ability to place the transmitting and receiving ports in an optimal location, thus making the reconstruction not as accurate as we would like. For this reason, the phased arrays described above—which provide better inter-element spacing—were designed, and their imaging results are presented in the next subsection.

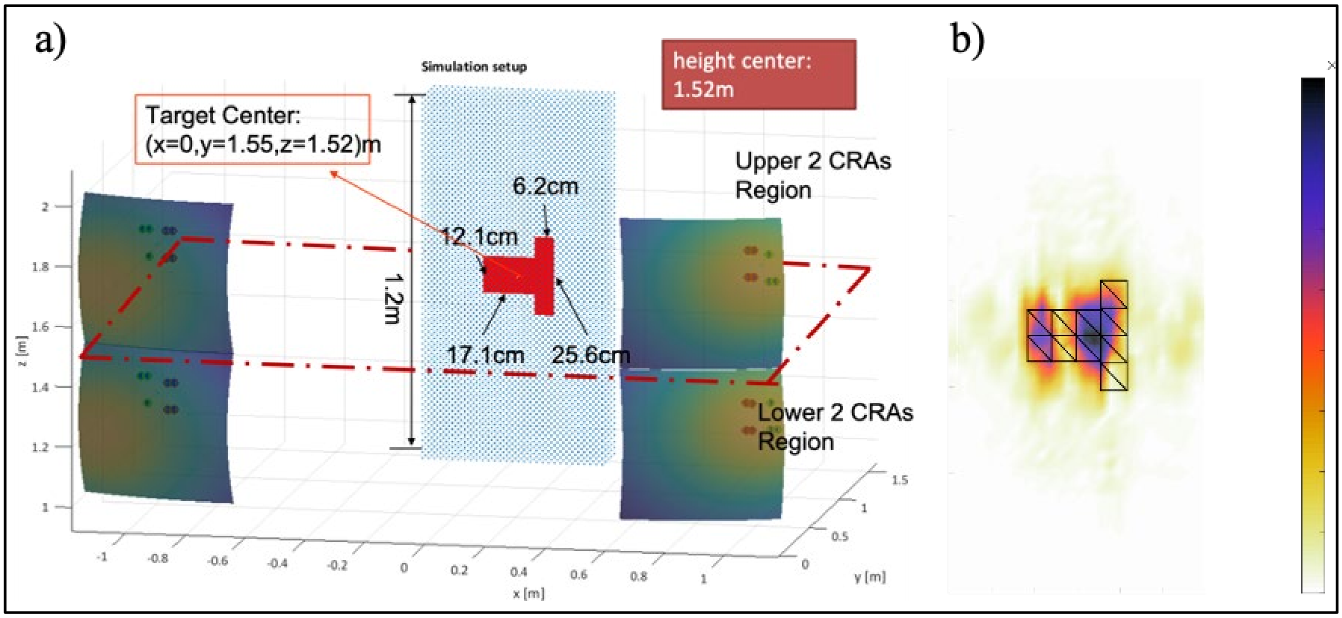

Figure 11: Simulation of four CRAs with a metallic box; (a) simulation setup; (b) corresponding imaging results.

D.4.b. Simulation of a System Using CRA with Active Phased Array

The imaging performance of the CRA system using the active phased arrays was also assessed this year. For the phased array antennas, we designed a plus-shaped antenna configuration with vertically placed Rx antennas and horizontally placed Tx antennas. Figure 12 shows the imaging results of a reversed T-shaped target using the antenna from our phased array. The distance between each antenna element is about two times of the wavelength associated with the center frequency. This result shows that the CRA system with active phased arrays successfully reconstructs the target profile. The active phased array has a good potential to decrease the volume and complexity of our Gen-3 system, where the bulky mm-wave front end of HXI's modules can be replaced with a PCB-based mm-wave front end.

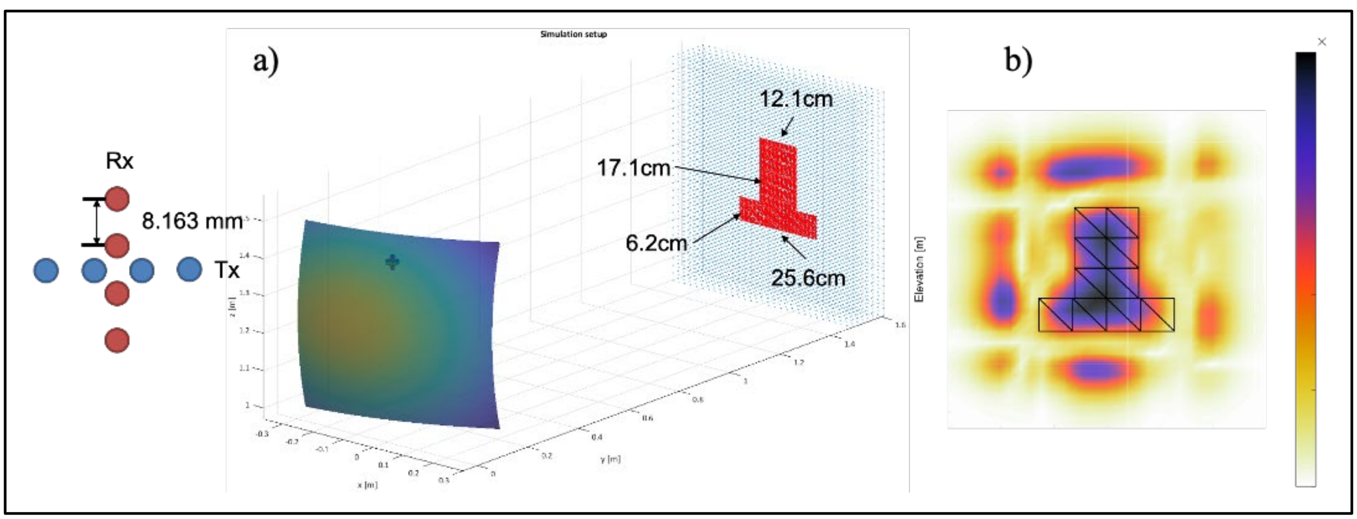

Figure 12: (a) Imaging setup using a plus-shaped array with a reversed T-shaped target; (b) imaging results.

E. Final Results at Project Completion (Year 7)

This project has achieved important milestones during the seven years of funding. These include, but are not limited to, the following:

1. Design from scratch of a mm-wave system to enable on-the-move imaging
2. Development of the mm-wave imaging algorithms
3. Mechanical design of the imaging system
4. Design and fabrication of arrays of CRAs

At the beginning of the project, we settled with HXI's front-end modules, which were probably the only option of functional modules working at 70–77 GHz. This choice, as well as its hardware limitation legacy experienced during the lifetime of the project, has hindered our ability to achieve coherence between multiple transceiver modules. After realizing this over the last year, we have shifted to address this problem by using different front-end modules that are smaller, provide digital signal processing, are more energy efficient, and are thermally stable. Though this project has concluded in the ALERT COE portfolio, we will continue to pursue this goal using the PI's NSF CAREER award. In addition, new funding will be sought from DHS and potentially other sources as well.

III. RELEVANCE AND TRANSITION

A. Relevance of Research to the DHS Enterprise

The following features of this project were of special relevance to the Department of Homeland Security enterprise:

- Noninvasive, minimally disruptive on-the-move scanning with quality imaging and high throughput; fast data collection, in less than 10 ms.
- Full body imaging with interrupted forward movement during mm-wave pedestrian surveillance; in multiview.
- A small number of nonuniform sparse arrays of Tx/Rx radar modules will minimize the cost of on-the-move; seven transmitters, seven receivers, and fourteen switches.

B. Status of Transition at Project End

Several companies (HXI, Smiths Detection, and Rapiscan) have collaborated with our research team on the tasks performed for the R3-B.1 project. This collaboration has played a pivotal role in the design, fabrication, integration, and validation of our radar system. Our Gen-3 prototype has the potential to be the first system capable of imaging moving targets at speed. The following steps will be taken to enable its transition to the market.

1. Professor Martinez hired a new Gordon Engineering Leadership student, Matt Skopin, who worked toward creating a deployable prototype to image security threats at speed. Matt has been in charge of making sure that the prototype is mechanically and electronically robust so it can be tested in the field.
2. Our prototype is modular and adaptable, so that fundamental research contributions developed at Professor Martinez's SICA lab (i.e., low cost mm-wave phased arrays and silicon-based chips) can be incorporated into our prototype without changing the architecture of the system.

C. Transition Pathway and Future Opportunities

Several companies (HXI, Smiths Detection, and Rapiscan) have been collaborating with our research team on the tasks performed for the R3-B.1 project. However, the PI has started a new spin-off, MatrixSpace, with Gregory Waters (CEO, greg.waters@matrixspace.com; former CEO of Integrated Device Technology), who is currently developing much lower cost mm-wave chips that can be used to increase resolution and performance of the system. This should be a viable solution to address the unreliable behavior of the current modules.

Transition goal #1: Exploring the use of MatrixSpace's mm-wave modules, which have lower cost, reduced drift, and enhanced reliability when compared to those of HXI. In pursue of this goal, we have already engaged in a conversation with MatrixSpace's Greg Waters, and we will explore the possibility of doing a joint demonstration by May 2021, the end of the no-cost extension period for ALERT funding.

D. Customer Connections

- HXI: Mr. Earle Stewart
- Smiths Detection: Dr. Kris Roe
- L3 Communications: Dr. Simon Pongratz
- MatrixSpace: Gregory Waters
- New proposals related to the topic of this research will be submitted to other federal funding agencies.

IV. PROJECT ACCOMPLISHMENTS AND DOCUMENTATION

A. Education and Workforce Development Activities

1. Interactions and Outreach to K–12, Community College, and/or Minority Serving Institution Students or Faculty
    a. The PI participated in the Building Bridges Program, which provides opportunities for high school students to visit the laboratories at Northeastern University and gain hands-on research experience, in order to engage them in STEM education.
    b. The PI participated in the Young Scholars Program at Northeastern University, in which two high school students spent six weeks in his lab learning about sensing and imaging.
2. Other Outcomes that Relate to Educational Improvement or Workforce Development
    a. Populating the research group with undergraduates brings homeland security technologies to undergraduate engineering students and establishes a pipeline to train and provide a rich pool of talented new graduate student researchers.

B. Peer Reviewed Journal Articles

Pending –

1. Heredia-Juesas, J., Molaei, A., Tirado, L., & Martinez-Lorenzo, J.A. "Consensus and Sectioning-Based ADMM with Norm-1 Regularization for Imaging with a Compressive Reflector Antenna." *IEEE Transactions on Antennas and Propagation*, under review. arXiv preprint:1811.05571.
2. Molaei, A., Tirado, L., Bisulco, A., Gehrke, C., Zhu, A., & Martinez-Lorenzo, J.A. "3D Printed Conical Horn Antenna Equipped with Orbital Angular Momentum Lenses for High-Capacity Millimeter-Wave

Applications." *IEEE Antennas and Wireless Propagation Letters*, under review.

C. Peer Reviewed Conference Proceedings

1. Heredia-Juesas, J., Tirado, L., Molaei, A., & Martinez-Lorenzo, J.A. "ADMM Based Consensus and Sectioning Norm-1 Regularized Algorithm for Imaging with a CRA." *2019 IEEE International Symposium on Antennas and Propagation and USNC-URSI Radio Science Meeting (AP-S/URSI 2019)*, Atlanta, GA, 7-12 July 2019.

D. Technology Transfer/Patents

1. Patents Awarded
   a. Martinez-Lorenzo, J. "Compressive coded antenna/meta-antenna." United States Patent 10,698,101, 30 June 2020.
   b. Martinez-Lorenzo, J., et al. "Ultrasonic-based system for detection of metallic security threats containers on cargo." United States Patent 10,477,785, 19 November 2019.
   c. Rappaport, C., & Martinez-Lorenzo, J. "Characterization of dielectric slabs attached to the body using focused millimeter waves." United States Patent 10,416,094. 17 September 2019.
2. Licenses Issued
   a. MatrixSpace is licensing the patent on the compressive reflector antenna.
3. Spin-Off Companies Started
   a. MatrixSpace

V. REFERENCES

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