R3-B.1: Hardware Design for “Stand-off” & “On-the-Move” Detection of Security Threats

I. PARTICIPANTS

<table>
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<tr>
<th>Faculty/Staff</th>
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<tr>
<td>Name</td>
<td>Title</td>
</tr>
<tr>
<td>Jose Martinez</td>
<td>PI</td>
</tr>
<tr>
<td>Juan Heredia Juesas</td>
<td>Post-Doc</td>
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Graduate, Undergraduate and REU Students

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<tr>
<th>Name</th>
<th>Degree Pursued</th>
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<th>Month/Year of Graduation</th>
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<tr>
<td>Luis Tirado</td>
<td>PhD</td>
<td>NEU</td>
<td>04/2019</td>
</tr>
<tr>
<td>Weite Zhang</td>
<td>PhD</td>
<td>NEU</td>
<td>12/2022</td>
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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 between 2–50 meters without causing physical harm.

The objective of this project is 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 standoff-ranges (10–40 meters) using a “van-based” configuration (see Fig. 1).
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 outcome of this project would be the first inexpensive, high resolution radar system with a special application to detect and identify potential suicide bombers. Its uniqueness is 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 has the potential to be the first radar system that is capable of functioning at multiple ranges for both indoor and outdoor scenarios.

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; to a fully electronic scanning 3D imaging system (Generation 3, Gen-3 [25–26]). The major contributions toward the Gen-3 system are discussed next.

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) standoff-ranges using a “van-based” configuration.
C. Major Contributions

A summary of the Year 6 major contributions can be found below:

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

- Outcome 1.1: Mechanical assembly of the radar system working with 1024 channels.
- Outcome 1.2: Design and fabrication of an active patch array and reflect-arrays.
- Outcome 1.3: Description of the new hardware gantry.

C.2. Development of the Control Firmware and Software for the Multiple-bistatic Imaging System

- Outcome 2: Finishing the LabVIEW-, C-, and field-programmable gate array (FPGA)-based firmware and software to operate the commutation among different transmitted and switched receivers of the Gen-2 system.

C.3. Calibration Algorithm for Coherent Image Formation in Multiple-bistatic Imaging System

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

C.4. Experimental Imaging Results Using the Multistatic Mm-wave Radar System

- Outcome 4.1: Fully-electronic 3D imaging at the 1-2 m range using the modular Gen-3 mm-wave radar system.
- Outcome 4.2: Fast and distributed Alternating Direction Method of Multipliers (ADMM) algorithms for mm-wave radar imaging.

C.5. Study of a New “On-the-Move” System Hardware and Configuration

- Outcome 5.1: Experimental setup of a system using an array of compressive reflector antennas (CRAs).
- Outcome 5.2: Fabrication and near-field measurement of a Meta Material Absorber (MMA)-based CRA.

D. Milestones

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

D.1.a. Mechanical Assembly of the Radar System Working with 1024 Channels

In collaboration with our transition partner, HXI LLC, we have continued the design, integration, and testing of our mm-wave radar system for detecting security threats at mid-ranges. In particular, our current hardware systems make use of the following elements:

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

The Gen-2 imaging system builds upon the functionality developed for our former Gen-1 system in order to increase the number of coherent channels, so that fully electronic imaging can be done for small targets. The four coherent channels of the Gen-1 system have been increased to 400 in the Gen-2 system by enhancing the hardware with the following elements: 1) The number of transmitters was increased from one to five; 2) The number of receivers was increased from four to five; 3) A SP4T switch was added to each transmitter and receiving module; and 4) LNAs and 4-way power dividers were added to the local oscillator module (LOM) intermediate frequency and multiplier outputs. The addition of the LNAs and power dividers enables concurrently utilizing the five Rx and five Tx modules at the same time. This configuration leads to a 400 coherent channel system, which results from multiplying the 20 transmitting ports (five transmitters x four ports/transmitter) by the 20 receiving ports (five receivers x four ports/transmitter). Figure 2 shows a simplified schematic of the architecture of the Gen-2/Gen-3 radar imaging system, where only two receiving modules and one transmitting module are shown for the sake of simplicity.

The Gen-3 imaging system, which was tested this year, builds upon the functionality developed for our former Gen-2 system by increasing the number of coherent channels so that fully electronic imaging can be done for extended targets. In pursuit of this goal, three additional Rx modules, three additional transmitting Tx modules, and six SP4T antenna switches have been purchased from HXI. The LOM has eight sync outputs so it permits the use of eight Tx and eight Rx modules working in a fully-coherent multistatic mode of operation.

This year, we have also expanded the LOM sync outputs based on four Pulsar Microwave PS4-14-452/7S four-way SMA power dividers. This enables the use of seven Tx and seven Rx modules simultaneously—note that one Tx module and one Rx module are assigned to the field calibration. The architecture is fully expandable. By using an additional twelve four-way power dividers, the system has the potential to operate with up to 64 (16*4) transmitting ports and 64 (16*4) receiving ports, leading to 4,096 coherent ports in the Gen-3 system. Adding a four-way SMA power divider can lead to ~6 dB power loss for each LOM port. However, this power loss can be compensated by removing the 6 dB pads that are connected to the Tx and Rx modules in their original design. This way, we can avoid using low noise amplifiers, thus reducing the noise and enhancing the imaging performance when compared to the previous Gen-3 system. This setup has been validated via 2D calibration measurements.
This year, we started to use CRA arrays in the Gen-3 system to enhance the imaging performance, so the configuration of the Tx and Rx modules have been changed. For each CRA, one Tx and one Rx module are employed, as shown in Figure 3. The center of this 7-port array (three ports from Tx and four ports from Rx) is located at the focal point of the CRA to achieve the best illumination angle for the target detection.

Figure 2: Basic architecture of the Gen-2 radar imaging system.
D.1.b. Design and Fabrication of an Active Patch Array and Reflect Arrays

As discussed in last year’s report, there is an urge to establish fully electronic sensing systems to catch up with real-time imaging speeds. One way of having fully electronic and dynamic beamforming networks is by using active switching components. An ideal switching component essentially holds two states: (i) short circuit and (ii) open circuit. In reality, these two states are roughly acquired by virtue of high-frequency semiconductor control apparatuses, such as field-effect transistors (FETs), Schottky diode, and PIN diode [27–28]. For instance, a PIN diode has the ability to get close to the wanted open circuit and short circuit circumstances at microwave and millimeter-wave frequencies under reverse and forward bias voltages, respectively. Digital phase shifters can be composed by establishing diodes and FETs in transmission line (TL) circuits. In general, TL-based phase shifters are divided into two groups of (i) transmission type and (ii) reflection type. The switched-line phase shifter is essentially a true time delay network in which phase shifting is achieved by switching between two TLs having different electrical lengths.

This year, we have fabricated and sent out for assembly of several boards that enable us to perform fast illumination of the scene. Figures 4a and 4b show the fabricated array with the layout excluding and including the phase shifting elements, respectively.
Figure 5 shows the S-parameters of two face-to-face waveguide-to-microstrip transitions. The insertion loss varied from 4.7 dB to 6.1 dB and return loss was higher than 10 dB throughout the 70–77 GHz bandwidth.

Finally, we measured the return loss and gain of the array without phase shifters (Fig. 6). Return loss happened to be higher than 10 dB, but the array had an average gain of approximately 10 dB throughout the desired bandwidth.
Figure 5: S-parameters of two face-to-face waveguide-to-microstrip transitions.

Figure 6: $S_{11}$ of the array without the phase shifting elements.
D.1.c. Description of the New Hardware Gantry

We designed an improved mechanical gantry for the “On-the-Move” scanning system, which can be transitioned into the field. The new gantry can accommodate four separate arrays of four compressive reflector antennas (CRA), each one of them using sixteen transmitting and sixteen receiving ports. This extended configuration will allow the system to image the front and the back of a subject under test. The gantry is also designed to keep transmitters, receivers, and CRA components within 0.4 mm of alignment deviation despite vibration and outside shock forces originating from the moving subjects.

An improved calibrator device was designed for use with the new gantry. This device moves the transmitter and the receiver calibration probes in a raster fashion. The device was built to be easily moved, and it has mechanical interfaces to enable six different pre-fixed calibration orientations.

The new gantry hosts aluminum base plates to mount the CRA, as well as the mm-wave Multiple-Input Multiple-Output (MIMO) Tx and Rx modules, so they are held securely in their ideal location and isolated from mechanical vibrations. Four of these base plates are positioned as indicated in Figure 7.

![Figure 7: Improved Gantry Model, 4 MIMO substructures with superstructure](image)

See the built prototype in Figure 8. The L-shaped structures were mounted to two separate 15 cm by 20 cm plates. The first is mounted to the CRA substructure, and the second is mounted to an adjoined MIMO tower using 3D printed adapter plates (Figure 9). In doing so, the MIMO plates can be easily moved and tuned when first installed. Most importantly, this keeps the MIMO units rigidly connected to the CRA units, making them less likely to fall out of alignment.
Figure 8: Improved gantry prototype.

Figure 9: MIMO substructure.
Connecting these components is a 2-inch by 2-inch 80/20 superstructure that serves as an impact barrier. A user that bumps the outside structure will not cause enough movement in the MIMOs or CRAs as to throw them out of focus. The superstructure also serves the purpose of keeping the four base plates at the correct position such that calibrator positioning guides can be implemented, to be discussed in the following section.

The vibration and shock resistance for the unit has been evaluated through dial indicator tests and improved throughout testing. See Figure 11 below for the vibrational response to a maximum force of 5.8 lbf to the outer structure. Additional trussed supports have been added throughout the structure to improve rigidity.

![Figure 10: Substructure prototype.](image)

![Vibrational Response to Superstructure Impact](image)

**Figure 10: Substructure prototype.**

**Figure 11: MIMO substructure vibrational response to superstructure impact.**
The new calibration device (Fig. 12) is designed to be easily and accurately positioned within the gantry and locked down for calibration. The calibrator must raster an area of 36-inches by 80-inches with a resolution of 2 mm and a linear speed of 120 mm/s. The calibration device will need to interface with the gantry to be accurately positioned in six calibration locations. While the distance between the CRAs and calibrator is not critical, it is important for the calibrator to be oriented normal to the CRA’s surface. The calibrator should not require user input for any of the calibration positions once the raster sequence is initiated. In the event of an unexpected power down, a counterweight system (Fig. 12) keeps the transmitter and receiver module from dropping down the vertical power screw.

![Counterweight System](image1)

**Figure 12: Calibrator and counterweight systems.**

Figure 13 depicts the raster sequences the calibration device will perform on each CRA unit. The dashed lines represent the MIMO’s movement.

![Raster Pattern](image2)

**Figure 13: Raster pattern of calibrator MIMO.**
To assist with correct placement of the calibrator device, a rail in the gantry will guide the calibrator into the six calibration locations, as illustrated in Figure 14. Note that all positions are perpendicular to the wave reflected from the center of the CRA units, as shown by the dashed red lines.

![Figure 14: Calibration positions with respect to critical components from top-down view.](image)

A critical aspect for the calibrator is its ability to interface with the gantry. A crossbeam of 1-inch by 1-inch 80/20 struts linked by a 3D-printed structure is mounted at the very center of the superstructure to act as a guide for calibrator positioning. A screw-like component at the center of the calibrator slides into the T-slots of the crossbeam structure, and adjustable rubber bumpers align the calibrator with one or more CRA beam forms. Figures 15, 16, and 17 show the calibrator alignment from three different viewpoints. For clarity, the calibrator is rendered in red for Figures 15 and 17.
Figure 15: CAD model of calibrator alignment.

Figure 16: Alignment on prototype.
D.2. Development of the Control Firmware and Software for the Multiple-bistatic Imaging

D.2.a. Finishing the LabVIEW-, C-, and FPGA-based Firmware and Software to Operate the Commutation among Different Transmitted and Switched Receivers of the Gen-2 and Gen-3 System

The control system associated with multi-channel multistatic systems is extremely complex, and it requires careful design, implementation, and validation. To continue the Local Oscillator Module (LOM) expansion efforts for the Gen-3 system at a reduced cost and enable the simultaneous connection of eight Rx modules and eight Tx modules to the LOM, four additional Mini-Circuits ZX60-24-S+ amplifiers were purchased and integrated alongside the previous four Pulsar Microwave PS4-14-452/7S power dividers and two HXI HLNA220-588 Low Noise Amplifiers (LNAs). The power output after using the new amplifiers and power dividers were verified again using a Keysight U2022XA USB Wideband Power Sensor in order to select the fixed attenuators necessary to drive the transmitter and receiver modules at the correct power levels. In this configuration, the imaging system can use 32 (8*4) transmitting ports and 32 (8*4) receiving ports via an additional 6 SP4T switches, resulting in 1,024 coherent ports in the Gen-3 system. The control firmware and software system was finalized to allow data collection using up to eight Rx modules by sequencing up to eight transmitters. The imaging system includes an FPGA-based switching system based on an Altera Cyclone V DE1-SoC board (see Fig. 18). It is capable of driving multiple SP4T switches in parallel; this year, the FPGA output signal wiring to the SP4T switches has been expanded and re-wired to accommodate up to eight Tx and eight Rx modules. An image of the FPGA board along with the newly re-wired connections using compact DB-15 terminal breakout boards is shown in Figure 18.

![Figure 17: Result position (Position 3) from top-down view.](image-url)
The DE1-SoC board has two general-purpose input/output (GPIO) headers, each of which provides 36 outputs or inputs. Two HSWM41203-262 SP4T switches are controlled via five Low Voltage Transistor Logic (LVTTL) (3.3V) signals, and the remaining 14 HSWM1203-286 SP4T switches are controlled via three LVTTL signals. When the 16 SP4T waveguide switches are connected to the FPGA, 52 out of the 72 available FPGA outputs are used to control the microwave switching system. For future expandability of up to 32 radar modules, a cost-effective Telesto MAX10 FPGA Module based on the Intel/Altera 10M50DAF484 FPGA chip can be used. This board uses the same software programming tools that were used to develop for the DE1-SoC FPGA board, making it easy to transition the code. For the MAX10 FPGA, up to 32 switches could be controlled using 106 of the 150 available FPGA outputs.

This year, the modular FPGA VHSIC Hardware Description Language (VHDL) codes for the DE1-SoC board were tested and validated to control the full set of 16 SP4T waveguide switches, with up to a maximum of 22 switches. The “fast-clock” version of the code, where a 10 MHz clock rate is used to enable scattered field data to be collected in only 168 microseconds, has been validated with the repaired switches received, which were from HXI.

An updated block diagram showing the addition of the Mini-Circuits amplifiers, in addition to the previously used HXI LNAs and four-way power dividers as in the RFE is shown in Figure 19. For simplicity, this diagram only shows two Mini-Circuits amplifiers connected to the system. A picture of the current LOM expansion configuration is shown in Figure 20.

Figure 18: Upgraded Cyclone V DE1-SoC FPGA wiring connections for the microwave switching system. The designations for the Tx and Rx switch connections are shown. Up to eight Tx and eight Rx modules are currently wired.
Figure 19: Block diagram showing the LOM port expansion of the Gen-3 mm-wave radar system. Six pulsar microwave PS4-14-452/7S four-way SMA Power Dividers, two HXI HLNA220-588 LNAs, and four Mini-Circuits ZX60-24-S+ amplifiers provide the necessary outputs for up to eight receivers and eight transmitters. This diagram is shown with only five Rx modules, five Tx modules, and one split point for the Mini-Circuits amplifiers for simplicity.
The FPGA code that controls the SP4T switches is composed of three separate modules: 1) a master module; 2) a slave receiving module; and 3) a slave transmitting module. The master module drives to the slave modules, acting as a finite state machine. The master module controls the timing of events, thus indicating which particular ports of transmitting and/or receiving switches are active at a given instant. The VHDL code has been written to be easily expandable to any number of connected transmitting and receiving modules. Currently, the code has been set to perform a switching pattern using up to eight transmitting modules and eight receiving modules, which includes the last three Tx and three Rx modules received from HXI.

The LabVIEW Virtual Instrument’s (VI) front end and back end control flow has been updated this year in order to allow collection of measurements using one or multiple compressive reflector antennas (CRAs) with the “slow-clock” or “fast-clock” microwave switching codes. The updates retain the MATLAB-based radar-triggering and data capturing of synchronized skeletal data of up to six human bodies to the mm-wave radar data via the Kinect for Xbox 360 (v1) sensor. The updated VI Graphical User Interface (GUI) is shown in Figure 21. The VI is adaptable to modular configurations with different numbers of switched Tx and Rx modules utilizing one of multiple CRAs. For static imaging with CRAs, the VI allows the user to select a previously computed sensing matrix and other experimental parameters such as filtering and frequency selection. A MATLAB-based processing code loads the scattered fields saved by the LabVIEW VI and uses it...
to create a 2D or 3D reconstructed image, depending on the sensing matrix selected by the user. As with previous versions, the LabVIEW VI has fields to write the experiment name and data acquisition parameters. In the case of a calibration measurement, it controls the linear actuators carrying the moving Tx and Rx modules, and records the distance moved in both vertical and horizontal dimensions. The VI acquires the received data via two GaGe Octopus 8284 PCI-E Digitizer cards in master/slave configuration, enabling 2D or 3D imaging via Compressive Sensing (CS) methods for the Gen-3 system.

**Figure 21: LabVIEW VI front panel to control and define parameters in the FPGA-based switching system.**

D.3. Calibration Algorithm for Coherent Image Formation in Multiple-bistatic Imaging System

We have extended our 3D calibration algorithm to work with the Gen-2 and Gen-3 systems, which measures the electric field in a 2D aperture in front of the radar system in order to create the sensing matrix in the target region. The results of this imaging can be seen in the Section D.4.a.

This year, we further improved the calibration setup to enable two-polarization field measurement in a 2D aperture, which achieves a more accurate calibration of the transmitted and received (reciprocity) electric fields. Figure 22 shows the assembled calibration scanner with four probe ports. Both the Tx and Rx modules have the ability to capture the electric field in x- and z-directions. The two-polarization measurement allows the sensing matrix to be calculated more accurately so that the imaging performance can be further improved.
D.4. Imaging Results Using the Multistatic Millimeter Wave Radar System Configuration

This year, we have enhanced the imaging capabilities of our system so that the “On-the-Move” human body experiment from our performance shown last year (see Fig. 23 and Fig. 24) can be executed in real-time for multiple CRAs. Specifically, we have worked on a new ADMM formulation that enables column division of the sensing matrix, so that the imaging can be performed even faster.

Figure 22: Two-polarization calibration setup.

Figure 23: Mm-wave images for the “On-the-Move” human body experiment with a metal box under clothing.
D.4.a. Fast and Distributed ADMM Algorithms for Mm-wave Radar Imaging

Several simulations have been carried out in the past by applying the Norm-1 regularized consensus-based Alternating Direction Method of Multipliers (ADMM) algorithm for mm-wave imaging applications. In order to find a solution for the linearized imaging problem of Equation 1a, these simulations proved that you could use the optimization problem in 1b, where the sensing matrix $H$ and the vector of measurements $g$ are divided into smaller submatrices by rows (Fig. 25a). This solves the problem in a distributed fashion and reaches a consensus of smaller sub-problems to obtain the final imaging $u$ (Fig. 25b).

\begin{align}
\text{a) } \quad & \quad Hu = g \\
\text{b) } \quad & \quad \text{minimize } \frac{1}{2} \sum_{i=1}^{M} ||H_i u^i - g_i||_2^2 + \lambda ||v||_1 \\
& \quad \text{s.t. } \quad u^i = v
\end{align}

FIGURE 24: Video and 3D Kinect-based stereo camera images of the “On-the Move” human body experiment.

FIGURE 25: a) Division of the matrix equation system by rows; and b) architecture of the consensus-based ADMM.
This methodology highly accelerates the imaging process in respect to other traditional algorithms for compressive sensing like Nesterov’s Algorithm (NESTA) [25, 29]. The combination of this technique with the high-sensing capacity capabilities of the compressive antenna-based imaging systems allows the imaging of sparse targets in real time. This imaging technique has also been applied to experimental tests as shown in previous years’ reports; however, this technique has the disadvantage of a large communication overhead.

At each step of the algorithm, a replica of the whole imaging domain needs to be transmitted from and received by each of the computational nodes of the architecture, as shown in Figure 25b. Since the imaging domain can be very large, the communications among the computational nodes can be slow. To overcome this problem, a sectioning-based ADMM algorithm has been developed [30-31], in which the sensing matrix is divided into submatrices by columns, as shown in Figure 26, leading to the optimization problem shown in Equation 2.

\[
\text{minimize } 1/2 \left\| \sum_{j=1}^{N} H_j u_j - g \right\|_2^2 + \lambda \sum_{j=1}^{N} \| v_j \|_1
\]

s.t. \quad u_j = v_j

This alternative approach divides the imaging domain into small regions, which are optimized independently. In this case, only a small amount of information needs to be transmitted from and received by each computational node. This information is the size of the number of measurements, which usually is much smaller than the number of pixels in the imaging domain.

As an example, the imaging configuration of Figure 27a is composed by a CRA with six Tx and six Rx in a plus shape at the focal point, using 12 different frequencies, for a total of 432 measurements. An imaging domain containing 4 metallic targets is discretized into 30,000 pixels. The imaging result applying the sectioning-based ADMM imaging algorithm is shown in Figure 27b. The imaging is performed in 1s when dividing the sensing matrix into 4 submatrices by columns. The quality and time of imaging is comparable with that of the consensus-based ADMM; however, the amount of information exchanged among the computational nodes is reduced by 97.1%.
D.5. Study of a New “On-the-Move” System Hardware and Configuration

In order to transition into a fully electronic scanning system, we continued to investigate new hardware components that will enable the Gen-3 system to provide real-time imaging for “On-the-Move” configurations [43-50]. Specifically, we have investigated how metamaterials can be added in front of or in the surface of the “Compressive Reflector” in order to enhance the sensing capacity of the system (see the report for Project R3-B.2 in order to see additional results of this new configuration). The fabrication of the hardware is reported in this report. Moreover, the mechanical design of the Gen-3 system using a Compressive Reflector Antenna (CRA) was studied this year. The details about these contributions are described in the following subsections.

D.5.a. Experimental Setup of a System Using an Array of Compressive Reflector Antennas (CRAs)

This year, we have developed a new mechanical configuration that enables the Gen-3 system to use multiple arrays of CRAs, as described in Section D.1.c.

Figure 28 illustrates the Gen-3 mm-wave radar system using six CRAs. Each CRA is illuminated by one Tx module and one Rx module. All of the modules are affixed with four-port switches. The LOM is located on the top to coherently feed into all of the Tx and Rx modules. The calibration scanner on the center gantry captures the radiation fields from all six CRAs. The calibration scanner has a movement range of 210 cm vertically and 88 cm horizontally, enabling full body imaging using different combinations of those CRAs.
To validate the newly-built CRA-based imaging system, we carried out a simple calibration using CRA #4 and CRA #5. Figure 29 illustrates the measured electric field on the 2D aperture (70 cm x 120 cm), where Tx3 and Tx4 correspond to the feeding antennas for CRA #5 and CRA #4, respectively. Note that only one frequency is plotted in this figure to show the effectiveness of the imaging system without loss of generality.
D.5.b. Fabrication and Near-field Measurement of a MMA-based CRA

In addition to the spatial diversity introduced by the CRAs, spectral diversity is introduced by designing a new type of MMA-based CRA. Instead of coating the regular CRA with a metal layer, the nine pieces of MMA are placed on the back of the CRA while its front surface is still dielectric. Figure 30 shows the fabricated MMA-based CRA with nine pieces of MMA circle patches on the back.
Typical measured radiation fields at two different frequencies are given in Figure 31 to show the spectral diversity. The radiation pattern changes when the operation frequency varies, which differs a lot from the radiation patterns of regular CRAs.

**Figure 30: Fabricated MMA-based CRA.**

**Figure 31: 2D calibration fields of MMA-based CRAs.**
E. Future Plans

Over the course of the next year, we will obtain experimental imaging results using the multistatic mm-wave radar system. We will focus on completion of the following tasks to obtain the expected outcomes, resulting in our final Gen-3 real time imaging system:

1. The number of transmitter and receiver modules will be increased, such that targets of about 1.6 by 0.4 meters in the cross ranges can be imaged using 16 transmitting and 16 receiving ports.
2. The FPGA switching time will be increased in frequency, such that all the radar returns can be collected in 168 microseconds, thus enabling imaging of targets moving at 1 meter per second.
3. Imaging with multiple compressive reflector antennas at the same time will be possible.
4. Using active reflect arrays or phased arrays to be able to image multiple people at the same time will be possible.

III. RELEVANCE AND TRANSITION

A. Relevance of Research to the Department of Homeland Security (DHS) Enterprise

The following features will be of special relevance to the DHS enterprise:

- Non-invasive, minimally-disruptive "On-the-Move" scanning with quality imaging and high throughput; fast data collection in less than 10ms.
- Full body imaging with interrupted forward movement during mm-wave pedestrian surveillance; in multi-view.
- A small number of non-uniform sparse array of Tx/Rx radar modules will minimize the cost of On-the-Move; five transmitters, five receivers, and 10 switches.

B. Potential for Transition

Several companies (i.e. HXI LLC, Smiths Detection, Rapiscan, and Smiths Detection) have been collaborating 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 extended targets at speed. The following steps will be taken to ensure its transition to the market:

1) Professor Martinez has already hired a new Gordon Engineering Leadership student: Matt Skopin, whose challenge project will consist on making a deployable prototype to image security threats at speed. Matt will be in charge of making sure that the prototype is mechanically and electronically robust so it can be tested in the field.

2) Matt Skopin will work with our new startup company: Boston Intelligent Systems and Technologies LLC, created by Professor Martinez, to make sure that our prototype can be transitioned to a large manufacturing company, such as Rapiscan, which will be in charge of licensing our intellectual property (IP) in this case.

3) Matt Skopin will also work with Rapiscan to make sure that our prototype meets with DHS performance metrics.
4) Matt Skopin will also make sure that our prototype will be 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.

It is important to note that Matt Skopin already worked as a Capstone Student during Summer 2018 and Spring 2019 in Professor Martinez’s SICA-Lab. Matt was charged with developing a prototype of our mm-wave system that can be deployable in the field.

C. Data and/or IP Acquisition Strategy

- The hardware and algorithmic design, integration, and validation performed under this project will continue to generate IP;
- The hardware will also be used to create benchmark datasets that may be used by industry stakeholders in order to assess the performance of their reconstruction and imaging algorithms;
- A new patent was awarded this year (May 21, 2019) based on the work partially done in this project: U.S. Patent 10,295,664, “On the move millimeter wave interrogation system with a hallway of multiple transmitters and receivers.”
- A patent was awarded in Year 4 (February 21, 2017) based on the work partially done in this project: U.S. Patent 9,575,045, "Signal Processing Methods and Systems for Explosives Detection and Identification Using Electromagnetic Radiation.”

D. Transition Pathway

HXI LLC has been collaborating with our Project R3-B.1 research team. Together, HXI and ALERT have designed, fabricated, integrated, and validated the radar system. We expect that after the assembling the first Gen-3 prototype, HXI will license our IP and transition the technology to the mm-wave imaging market. Additionally, new low-cost miniaturized modules are being developed by HXI for the next generation mm-wave system; some of these components will be tested by the Project R3-B.1 PI.

The PI has also established a working relationship with Smiths Detection and L3 Communications, which bodes well for future collaboration and transition.

E. Customer Connections

E.1. Customer Names and Program Offices:

- HXI LLC: Mr. Earle Stewart
- Smiths Detection: Dr. Kris Roe
- L3 Communications: Dr. Simon Pongratz

New proposals related to the topic of this research will be submitted to other federal funding agencies.

E.2. Frequency of Contact and Level of Involvement in Project:

- The PI has weekly meetings with HXI for the project.
- Smiths Detection and L3 Communications had three to four meetings with the PI last year.
IV. PROJECT ACCOMPLISHMENTS AND DOCUMENTATION

A. Education and Workforce Development Activities

1. Course, Seminar, and/or Workshop Development
   a. Professor Martinez-Lorenzo was invited to give a talk entitled “High Capacity and Efficiency Optimization of Compressive Antennas for Imaging Applications” at the Special Session “Inverse Problems: Theory, Techniques, and Applications” of the European Conference on Antennas and Propagation, London, UK (April 2018). This talk covered several results generated by Projects R3-B.1 and R3-B.2.

2. Student Internship, Job, and/or Research Opportunities
   a. Graduate students Chang Liu, Ali Molaei, Luis Tirado, and Weite Zhang play an important role in our research project. They will continue to assist in the development of new hardware design and integration for the mm-wave radar system.
   b. Our undergraduate students Anthony Bisulco, Christopher Gehrke, Katherine Graham, and Joseph Von Holten, will continue to work on Projects R3-B.1 and R3-B.2.

3. 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 NU’s laboratories 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 Professor Martinez’s lab learning about sensing and imaging.

4. 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


C. Peer Reviewed Conference Proceedings


Pending

V. REFERENCES


