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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<tbody>
<tr>
<td>Name</td>
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<tr>
<td>Jose Martinez</td>
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<td>Juan Heredia Juesas</td>
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<th>Graduate, Undergraduate and REU Students</th>
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<td>Name</td>
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<tr>
<td>Galia Ghazi</td>
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<td>Chang Liu</td>
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<td>Weite Zhang</td>
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<td>Anthony Bisulco</td>
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<td>Alexis Costales</td>
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<td>Katherine Graham</td>
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<td>Nabil Kebichi</td>
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<td>Alex Zhu</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 which 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 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 to 50 meters.
without causing physical harm. The objective of this project is the hardware development and evaluation of 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 (Fig. 1).

**Figure 1:** General sketch of the inexpensive, high-resolution radar system used for detecting security threats (a) at mid-ranges using an “On-the-Move” configuration, and (b) at standoff-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 Tx/Rx [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.

Table 1 shows a technology development road map, including the steps needed to go from a three-dimensional (3D) mechanical scanning imaging system (Generation 1, Gen-1 [24]) to a 3D fully electronic scanning imaging system (Generation 3, Gen-3 [25,26]). An intermediate imaging system (Gen-2), capable of imaging small targets in a fully electronic fashion and large targets in a hybrid electrical/mechanical fashion, will be used to create a smooth transition between the Gen-1 and Gen-3 imaging systems.

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>Generation 1</th>
<th>Generation 2</th>
<th>Generation 3</th>
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<tr>
<td>System scanning design</td>
<td><strong>Task-1.1: 100% Completed</strong>&lt;br&gt;-Mechanical</td>
<td><strong>Task-2.1: (Y4: 75%, Y5:100%)</strong>&lt;br&gt;-Fully electronic (small targets)&lt;br&gt;-Hybrid: electronic + mechanical (large targets)</td>
<td><strong>Task-3.1: (Y4: 30%, Y5:100%)</strong>&lt;br&gt;-Fully Electronic</td>
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<tr>
<td>Radar configuration</td>
<td><strong>Task-1.2: 100% Completed</strong>&lt;br&gt;-1 Transmitter&lt;br&gt;-4 Receivers&lt;br&gt;-2 Switches&lt;br&gt;-800 Frequencies&lt;br&gt;-70-77GHz Bandwidth</td>
<td><strong>Task-2.2: (Y4: 75%, Y5:100%)</strong>&lt;br&gt;-5 Transmitter&lt;br&gt;-5 Receivers&lt;br&gt;-10 Switches&lt;br&gt;-800 Frequencies&lt;br&gt;-70-77GHz Bandwidth</td>
<td><strong>Task-3.2: (Y4: 10%, Y5:100%)</strong>&lt;br&gt;-5 Transmitter&lt;br&gt;-5 Receivers&lt;br&gt;-10 Switches&lt;br&gt;-800 Frequencies&lt;br&gt;-70-77GHz Bandwidth</td>
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<tr>
<td>Radar Calibration</td>
<td><strong>Task-1.3: 100% Completed</strong>&lt;br&gt;-Transceiver Electromagnetic characterization&lt;br&gt;-Transceiver Spatial characterization</td>
<td><strong>Task-2.3: (Y4: 60%, Y5:100%)</strong>&lt;br&gt;-Transceiver Electromagnetic characterization&lt;br&gt;-Transceiver Spatial characterization</td>
<td><strong>Task-3.3: (Y4: 0%, Y5:50%)</strong>&lt;br&gt;-Transceiver Electromagnetic calibration&lt;br&gt;-Transceiver Spatial characterization</td>
</tr>
<tr>
<td>Mechanical Assemblage</td>
<td><strong>Task-1.4: 100% Completed</strong>&lt;br&gt;-Mechanical gantry</td>
<td><strong>Task-2.4: 100% Completed</strong>&lt;br&gt;-Mechanical gantry</td>
<td><strong>Task-3.4: (Y4: 0%, Y5:50%)</strong>&lt;br&gt;-Mechanical gantry</td>
</tr>
<tr>
<td>Control Mechanism</td>
<td><strong>Task-1.5: 100% Completed</strong>&lt;br&gt;-Micro-controller&lt;br&gt;-Arduino-based</td>
<td><strong>Task-2.5: 100% Completed</strong>&lt;br&gt;-FPGA</td>
<td><strong>Task-3.5: (Y4: 0%, Y5:50%)</strong>&lt;br&gt;-FPGA</td>
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<td>Imaging capabilities</td>
<td><strong>Task-1.6: 100% Completed</strong>&lt;br&gt;-2D coherent&lt;br&gt;-3D Incoherent&lt;br&gt;-Static targets</td>
<td><strong>Task-2.6: (Y3: 50%, Y5:100%)</strong>&lt;br&gt;-3D coherent&lt;br&gt;-Static for small targets&lt;br&gt;-Dynamic for large targets</td>
<td><strong>Task-3.6: (Y4: 0%, Y5:50%)</strong>&lt;br&gt;-3D coherent&lt;br&gt;-Static for small targets&lt;br&gt;-Dynamic for large targets</td>
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<tr>
<td>Spatial Coding</td>
<td>Non Applicable</td>
<td>Non Applicable</td>
<td><strong>Task-3.7: (Y4: 0%, Y5:50%)</strong>&lt;br&gt;-Coded Compressive Reflectors Antenna/ Meta-Antenna</td>
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Table 1: Roadmap towards a fully electronic radar imaging system; from Gen-1 [24] to Gen-3 [25, 26].

The following activities related to the completion of the Gen-2 system and beginning of the Gen-3 system continued to be worked on from Year 4 and were completed in Year 5 for this project: 1) hardware design and integration of a multistatic imaging system (Tasks 2.1, 2.4, 3.1); 2) development of control firmware and software for the multistatic imaging system (Task 2.5); 3) calibration algorithm for coherent image formation in multistatic imaging system (Task 2.3); 4) experimental imaging results using the multistatic mm-wave radar system (Task 2.6); and 5) study of a new “On-the-Move” system configuration (Task 2.1 and 3.1). The additional activities expected to be started in Year 4, but actually began in Year 5 were: 1) hardware design and integration of a multistatic imaging system (Task 3.4); 2) development of control firmware and software
for the multistatic imaging system (Task 3.5); 3) calibration algorithm for coherent image formation in mul-
tistatic imaging system (Task 3.3); and 4) experimental imaging results using the multistatic mm-wave radar
system (Task 3.6, and 3.7). This project is intimately related to ALERT Project R3-B.2, “Advanced Imaging and
Detection of Security Threats using Compressive Sensing,” in which the imaging algorithms for this hard-
ware system have been developed. Additionally, many of the technologies and techniques developed for this
project are commonly used in near-field applications by other ALERT projects, including Projects R3-A.2 and
R3-A.3.

C. Major Contributions

A summary of the Year 4 and Year 5 major contributions can be found in Table 2.

<table>
<thead>
<tr>
<th>C.1- Hardware design and integration of a multiple-bistatic imaging system (Tasks 2.1, 2.4, 3.1, 3.4) - This year, the main outcome of these four tasks has been the following:</th>
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<tr>
<td>o Outcome 1.1 – Mechanical assemblage of the radar system working with 400 channels and enabling Mode-E and Mode-EM data collection.</td>
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<td>o Outcome 1.2 – Design and fabrication of an active patch array and reflect-arrays</td>
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<tr>
<td>C.2- Development of the control firmware and software for the multi-bistatic imaging system (Tasks 2.5 and 3.5) - This year, the main outcomes of these tasks have been the following:</td>
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<tr>
<td>o Outcome 2.1 – 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.</td>
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<td>o Outcome 2.2 – Generation of the first set of static images with the new firmware architecture.</td>
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<tr>
<td>o Outcome 2.3 – Hardware and firmware development to enable 3D calibration.</td>
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<tr>
<td>C.3- Calibration algorithm for coherent image formation in multiple-bistatic imaging system (Task 2.3 and Task 3.3) - This year, the main outcomes of these tasks have been the following:</td>
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<tr>
<td>o Outcome 3.1 – 3D calibration for producing 3D images for the Gen-2 and Gen-3 system.</td>
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<tr>
<td>C.4- Experimental imaging results using the multistatic mm-wave radar system (Task-2.6, Task 3.6, Task 3.7) - This year, the main outcomes of this task have been the following:</td>
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</table>
| o Outcome 4.1 – Fully-electronic 3D imaging at the 1-2 m range using the modular Gen-2 mm-
wave radar system. |
| o Outcome 4.2- Fully-electronic 3D imaging at the 1-2 m range using the modular Gen-3 mm-wave radar system. |
| C.5- Study of a new “On-the-Move” system hardware and configuration (Task-2.1 and Task 3.1) - This year, the main outcomes of these tasks have been the following: |
| o Outcome 5.1 – Fabrication of Metamaterial Absorber (MMA) |
| o Outcome 5.2 – Mechanical design of a system using a Compressive Reflector Antenna (CRA) |

Table 2: Summary of this year’s major contributions.
D. Milestones

D.1. Hardware Design and Integration of a Multiple-bistatic Imaging System (Tasks 2.1, 2.4, 3.1 and 3.4)

D.1.a. Mechanical Assemblage of the Radar System Working with 400 Channels and Enabling Mode-E and Mode-EM Data Collection

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) Five HXI #8302 Transmitter (Tx) Modules; 2) five HXI #8301 Receiver (Rx) Modules; 3) one HXI #8303 Local Oscillator Module (LOM); and 4) ten HXI #HSWM41203 single-pole four-throw (SP4T) 4-way antenna switches. The LOM has eight sync outputs, and it permits the use of eight Tx and Rx modules working in a fully-coherent multistatic mode of operation.

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, tested this year, builds upon the functionality developed for our former Gen-2 system in order to increase the number of coherent channels, so that fully electronic imaging can be done for extended targets. Toward this effort, an additional three Rx modules, three Tx modules, and six SP4T antenna switches are on-order from HXI. As delivered, the LOM has eight sync outputs, and it permits the use of eight Tx and Rx modules working in a fully-coherent multistatic mode of operation. In this year, to utilize additional radar Tx and Rx modules in the Gen-3 system, we have expanded the LOM sync outputs based on the addition of two HXI HLNA220-588 Low Noise Amplifiers (LNAs) and two Pulsar Microwave PS4-14-452/7S four-way SMA Power Dividers. This enables the use of five Tx and five Rx modules concurrently. This setup has been validated via 3D calibration measurements and reflectivity-based imaging of static and moving targets. The architecture is fully expandable, and by using an additional 22 SP4T switches, 14 amplifiers, and 14 four-way power dividers, the system can 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, compared to 400 ports in the Gen-2 system. Mini-Circuits ZX60 series amplifiers can be used in lieu of the HXI provided amplifiers for the expansion towards cost-effectiveness of the system.
The designed Gen-2/Gen-3 system supports two modes of operation: 1) Mode-E—fully electronic static imaging of targets located in small reconstruction regions of about 0.2m x 0.2m x 0.2 m; and 2) Mode-EM—hybrid, electronic and mechanical, dynamic Synthetic Aperture Radar (SAR) imaging of targets located in large image regions of over 1m x 2m x 1m. The Gen-3 system leverages the Gen-2 architecture to be able to perform two-dimensional (2D) imaging of large reconstruction domains. This can be done by exploiting one or several of the following strategies: 1) using a Coded Compressive Reflector Antenna (CRA) [25, 26], in order to enhance the dispersion of the singular values of the sensing matrix; 2) using a higher number of low-cost transmitters and receivers, in order to increase the number of non-zero singular values of the sensing matrix; and 3) using image compression techniques, like wavelets, curvelets, or cosine-based basis, in order to “sparsify” the representation of the object under test.

Figure 3a illustrates the Gen-2/Gen-3 mm-wave radar system modules. The Gen-2 imaging system is composed of five transmitters and five receivers, each affixed with a four-port switch. Four of the transmitters and their associated switches are arranged to create a vertical linear array at a fixed position, while four of the receivers and their associated switches are arranged to create a horizontal linear array at a fixed position. This configuration enables the fully electronic scanning mode (Mode-E). A transmitter and a receiver, and their associated switches, are located on a smoothly and precisely moved plate to enable a combined electronic and mechanical mode of operation (Mode-EM). This movement is controlled by two linear actuators, allowing the transmitter and receiver to move up to 63 cm vertically and 88 cm horizontally. Moving the center transmitter and receiver pair during experiments can synthetically simulate many radar modules in a 2D plane.

Figure 3 shows that our Gen-2/Gen-3 system enables the collection of data in Mode-E and Mode-EM. Note that Mode-EM is very important for understanding the limitations of the imaging system, in terms of the number of points required for imaging and predicting the expected signal to noise ratio (SNR) required for good imaging. As was done last year, the Gen3 system leverages the customized Mode-EM acquisition in or-
der to enable the measurements of the fields in a 2D aperture located in front of the radar. In addition, to reduce phase mismatches between multiple receivers and transmitters, Micro-Coax UFA210A-0-0960-000000 AM low loss phase-matched microwave cable assemblies have been used to replace the previously used Micro-Coax UT-085C-L cable assemblies. These changes were needed in order to perform the 3D calibration, which is described later in this report. Figure 3b and 3c show zoomed images of a mm-wave transmitter and receiver with a four-port switch attached.

Figure 3: (a): Gen-2/Gen-3 mm-wave radar system modules. The transmitting vertical array is shown on the left of the image, while the receiving horizontal array is shown on the right. The 2D movable transmitter and receiver is shown in (b), and (c) shows the zoomed views of the Tx and Rx Modules with four-port switches. Pictures show the replaced powder-blue color Micro-Coax phase-matched microwave cable assemblies.

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

In order to be able to image more than one person with our system, an active Reflect Array (RA) has been designed. RAs are planar printed surfaces that are excited by an electromagnetic incident field and direct the field in a desired direction or point. RAs have the combined technological features and characteristics of parabolic reflectors and electronically scanned phased array antennas, including: low weight, small size, simple feeding system, and low feeding loss [27]. These features make RAs an attractive architecture for both near-
field beam focusing and far-field beam steering applications. Dynamically controlled radiation in the RA can be achieved by the use of electronically tunable reflecting elements, such as PIN diodes [28], varactor diodes [29], and MEMS switches [30]. The family of patch antennas is a good candidate for radiating elements of RAs, due to their low cost, light weight, conformability to the host surface, and ease of manufacturing process [31]. Among the patch antenna configurations, the Aperture-Coupled Patch (ACP) [32] provides the benefit of isolating spurious feed radiation by adopting a common ground plane.

In this section, we present the design and fabrication of a low cost electronically reconfigurable RA, which employs a 2x2 array of ACPs as its radiating elements. Each 2x2 ACP array is electronically controlled by a Single-Pole, Single-Throw (SPST) switch, to adjust the phase of the reflected field.

In the RA design presented below, instead of allocating a switch to every ACP element, each switch controls four ACPs through a micro-strip feeding network, as shown in Figure 4. By this means, the number of switches and cost of the RA are reduced four-fold, while maintaining the same beamwidth as before in both cross-range axes. The length of the open-ended transmission line \( L \) in the feeding network of the array is adjusted such that the phase of the reflected field changes approximately by \( \pi \) when the diode switches from the ON state to the OFF state, and vice versa.

Figure 4: (a) Perspective, (b) top, and (c) side view of the 2x2 ACP array used in the reconfigurable RA.
The 2x2 unit-cell has been simulated using the Ansoft High Frequency Structure Simulator (HFSS) software. Periodic boundary conditions are defined along the \(XZ\) and \(YZ\) bounds of the 2x2 array to consider the mutual coupling between adjacent ASP elements. Table 3 shows the assigned values of the design parameters mentioned in Figure 4. The RO3003 laminate with dielectric constant of 3 and thickness of \(h_1=0.254\) mm is used as the top dielectric substrate to support the patches and the RO4450F laminate with dielectric constant of 3.5 and thickness of \(h_2=0.1\) mm is used as the bottom substrate for the feeding network. Figure 5 shows the simulated S-parameters of the 2x2 unit-cell when it is excited by a normal incident plane-wave (port 1). In this simulation, it is considered that the SPST switch works as an ideal short copper strip in the ON state and the open-ended transmission line is connected to a 50 Ω lumped port (port 2). It can be seen from Figure 4 that for the optimized unit-cell, both ports have a return loss better than 15 dB through the operational frequency range of the radar, which is 70-77 GHz. Also, the unit-cell has an insertion loss of less than 2 dB throughout the band. These results demonstrate that the optimized 2x2 unit-cell effectively couples the incident plane wave to the micro-strip port, as well as the SPST switch.

<table>
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<th>PAR.</th>
<th>VAL. [mm]</th>
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<td>(W_p)</td>
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<td>(W_{t2})</td>
<td>0.26</td>
<td>(p_y)</td>
<td>4.08</td>
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<tr>
<td>(L_p)</td>
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<td>(L_{t2})</td>
<td>0.59</td>
<td>(h_1)</td>
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<td>(d_x)</td>
<td>2.04</td>
<td>(h_2)</td>
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<td>0.59</td>
<td>(p_x)</td>
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</table>

Table 3: Optimized parameters of the 2x2 ACP array.

Figure 5: (a) Perspective, (b) top, and (c) side view of the 2x2 ACP array used in the reconfigurable RA.
To evaluate the radiation performance of the RA, we have fabricated 15x15 arrays of the optimized 2x2 unit-cell in two different configurations, as shown in Figure 6. In the first configuration (RA#1), the SPST switch is removed from the feeding line (ideal OFF state) and in the second configuration (RA#2) the SPST switch is replaced by a copper strip (ideal ON state). The length $L$ is adjusted to have about a 180° phase difference for the reflected wave between the OFF and ON state. Figure 7 shows the experimental setup for measuring the magnitude and phase of the reflected field ($S_{11}$) from the surface of the fabricated RA#1 and RA#2. First, a metal plate is mounted on the fixture to calibrate the magnitude and phase of $S_{11}$ with respect to the position of the fixture. Then, the $S_{11}$ of RA#1 and RA#2 are measured and plotted in Figure 8a and 8b, respectively. The results show that the phase difference between RA#1 and RA#2 are 226°, 165°, and 178° for the measurements at 70 GHz, 73.5 GHz, and 77 GHz, respectively. In the future, SPST switches will be incorporated into the RA to enable performing dynamic beam-focusing in the near-field of the radar system.
Figure 8: Magnitude and phase of S11 measured for the (a) RA#1 and (b) RA#2.
As another example of active beam-focusing, we have incorporated the optimized 2x2 array in a linear 2x16 active patch array, to enable beam-focusing in 1D. The schematic of the designed patch array is depicted in Figure 9a. Each 2x2 unit-cell is fed by a SPST absorptive switching network. Based on the ON or OFF state of the switch, the corresponding 2x2 unit-cell may or may not radiate the input electromagnetic wave. This feature enables a unique temporal wave-form coding by adjusting the ON/OFF state for each of the 2x2 unit-cells. Figure 9a and 9b show the top and bottom view of the fabricated PCB for the active patch array, respectively. In the future, flip-chip switching dies will be mounted on the board and near-field temporal wave-field coding of the array will be studied.

Figure 9: (a) Schematic of the multi-layer patch array. (b) Top and (b) bottom view of the fabricated patch array.
D.2. Development of the Control Firmware and Software for the Multi-bistatic Imaging System (Tasks 2.5 and 3.5)

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 & Gen-3 System

The control system associated with multi-channel multistatic systems is extremely complex, and it requires careful design, implementation, and validation. In Year 4, we have expanded the capabilities of the Gen-2 imaging system by integrating two HXI HLNA220-588 Low Noise Amplifiers (LNAs) and two Pulsar Microwave PS4-14-452/7S four-way SMA Power Dividers, which enables the use of five Tx and five Rx modules concurrently. The power output after using the SMA amplifiers and power dividers was verified 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. Following this approach for the remaining LO outputs, the Gen-3 imaging system can be expanded to use 32 (8*4) transmitting ports and 32 (8*4) receiving ports via an additional 6 SP4T switches, 4 amplifiers, and 4 four-way power dividers, resulting in 1,024 coherent ports in the Gen-3 system. The control firmware and software of the Gen-2 imaging system has been updated to allow data collection using up to eight Rx modules by sequencing up to eight transmitters, as shown in Figure 3c. The Gen-2 imaging system includes an FPGA-based switching system based on an Altera Cyclone V DE1-SoC board (see Fig. 10a). It is capable of driving multiple SP4T switches in parallel; this year, the FPGA output signal wiring to the SP4T switches has been cleaned up and modularized to allow for further expandability. Currently, up to eight switches can work in transmission mode and the remaining eight switches work in reception mode. An image of the FPGA board that is used in the Gen-2 and Gen-3 imaging system is shown in Figure 10a.

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 Transistor Logic (LVTTL) (3.3V) signals, and up to 20 HSWM1203-286 SP4T switches can be controlled via three LVTTL signals. When the 22 SP4T waveguide switches are connected to the FPGA, 70 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, 32 switches can be controlled using 106 of the 150 available FPGA outputs.

This year, development was renewed for the modular FPGA VHSCIC Hardware Description Language (VHDL) code for the DE1-SoC board, expanding it to control 16 SP4T waveguide switches, up to a maximum of 22 switches. In addition to the existing version of the code that was previously developed, a new FPGA code has been finalized and validated with a single Tx and Rx SP4T switch, in which the scattered field data can be collected in only 168 microseconds. In this ‘fast-clock’ version of the code, a 10 MHz clock rate is used to control the faster switching frequency for the microwave switching system, as compared to the previous 3.05 KHz clock rate. This updated FPGA code has been tested on-board with a logic analyzer for various configurations, and was successfully used to control one Tx switch and one Rx waveguide switch using HXI’s Model 8300 Radar Front End (RFE) to arrive at the fully-electronic 3D imaging experimental imaging results shown in this report on Section D.4.c.

A block diagram of the amplifiers and SP4T switches integrated in the RFE is shown in Figure 11. Additional power dividers and amplifiers can be added in the same manner to enable the use of up to 16 Rx and 16 Tx modules.

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; it acts as a finite state machine. Indeed, 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, with three Rx and three Tx modules on-order from HXI.

Figure 10b depicts a logic analyzer output of the switching system, in which each transmitting switch is sequenced individually to actively illuminate the target at a precise point in time. The switching cycle for the previously designed “slow-clock” VHDL code and the newly developed “fast-clock” code is described for one transmitting module and five receiving modules in Table 4. The difference between the two codes is the switching frequency speed—the “slow-clock” code is based on a 3.05 KHz clock rate derived from the radar pulse repetition interval (PRI), while the “fast-clock” code is based on a faster 10 MHz clock rate. Figure 4b clearly shows that each port on the active transmitting module is sequenced individually to transmit the Frequency-Modulated Continuous-Wave (FMCW) chirp signal, while all of the ports on the receiver modules are also sequenced individually to receive the scattered field.

This year, a 0.5m x 0.5m Coded Compressive Reflector Antenna (CRA) was manufactured and integrated with the HXI RFE. A transmitter and receiver module pair illuminate the center of the CRA, and it illuminates a target volume of interest at a distance of 1.5m. For the case of the CRA, WR-12 waveguide terminations are not required as used previously to restrict a single transmitter from actively radiating at a time. Both the “slow-
clock” and “fast-clock” FPGA codes have been verified with the CRA configurations. Experimental imaging results utilizing the CRA are shown in Section D.4.c.

Figure 11: Block diagram showing the LOM port expansion of the Gen-2/Gen-3 mm-wave radar system. Two Pulsar Microwave PS4-14-452/75 four-way SMA Power Dividers and two HXI HLNA220-588 Low Noise Amplifiers are used to provide the necessary outputs for up to five receivers and five transmitters, fully expandable up to 16 receivers and 16 transmitters. Diagram is shown with a configuration of five transmitters and five receivers corresponding to the Gen-2 configuration.

Table 4: Pseudo-code of the switching cycle for one transmitter (Tx1) and multiple receivers (Rx1, Rx2, Rx3, Rx4, and Rx5) connected to multiple SP4T switches.
The VHDL code is capable of operating in two modes: 1) Mode-E; and 2) Mode-EM. For Mode-EM, the moving transmitting module is active and switched between its four ports, while the remaining receiving modules are switched between their corresponding four ports of the SP4T switch. In fact, Mode-EM is the basis for capturing the calibration data that is used to compute the sensing matrix of the system. This is described further in Section D.3. In Mode-E, there are no moving receiving or transmitting modules. The switching method is the same except that after the first transmitting module switches throughout its four ports, the second transmitting module is enabled, and so forth, until the final transmitting module finishes switching throughout all the ports. To detect the start of the FPGA switching cycle, a single LVTTL state-line is used for the “slow-clock” version of the code. This state line is high when the first transmitter in the sequence becomes active, and it is acquired along with the measurement data in order to detect the clock cycles in which the respective transmitters are active. The “fast-clock” code version of the code is synced to the LOM clock output, thus no additional synchronization signal is needed to be sampled in this case.

The LabVIEW Virtual Instrument's (VI) back-end control flow has been updated this year in order to add a MATLAB-based radar-triggering and data capture 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 front-end Graphical User Interface (GUI) and digitizer channel configuration is also being updated to enable the capture of data from up to eight Rx modules. The VI GUI is shown in Figure 12. As designed, the LabVIEW VI contains an array of controls that store the positions and orientation of the SP4T switches relative to a fixed set of gantry center coordinates in cross-range, range, and elevation directions. The VI is adaptable to modular configurations with different numbers of switched transmitting and receiving modules. The LabVIEW VI also has fields to write the experiment name, data acquisition parameters, and in the case of the moving Rx and Tx module, the distance moved by the linear actuator carrying the modules. The VI controls the linear actuators that move the transmitting and receiving modules to create a synthetic aperture, and it acquires the received data via two GaGe Octopus 8284 PCI-E Digitizer cards in master/slave configuration, enabling 2D or 3D imaging via SAR or Compres-
sive Sensing (CS) methods. A MATLAB-based processing code loads the data saved by the LabVIEW VI and reconstructs images based on the selected configuration parameters.

D.2.b. **Generation of the First Set of Static Images with the New Firmware Architecture**

With the updated FPGA code, LabVIEW VI, and MATLAB code, we have tested the imaging capabilities of the Gen-2 and Gen-3 system in several experimental setups. One of these setups is the static coherent imaging setup which employs the sensing matrix computed with the calibration data described in the next section.

D.2.c. **Hardware and Firmware Development to Enable 3D Calibration**

This year, we have also updated and revised the LabVIEW control VI for the FPGA system and the MATLAB-based data processing code to incorporate the measurement of the electric field with the 2D scanner placed in front of the radar system. The LabVIEW code has been updated to load compiled FPGA code for two separate data collections which are needed to create the sensing matrix in the target region: 1) sequenced transmitting from the four static Tx modules, while receiving in a 2D aperture with the moving Rx module; and 2) transmitting from the single moving Tx module, while receiving in the same 2D aperture with the four static Rx modules. The data collection for both calibration measurements scans a 2D region in elevation and cross-range of 74 cm × 88 cm, respectively, spanning past the extent of the static Rx/Tx apertures in the Gen2 gantry. The MATLAB data processing code has been updated to account for the orientation of the moving Rx/Tx apertures on the 2D scanner and processing of static measurements. A combination of MATLAB scripts and compiled C MATLAB executable (MEX) code was developed to process the calibration measurements, and calculate the sensing matrix used to image extended targets. Mode-E (static) measurements of extended targets are taken with the updated LabVIEW code, utilizing up to four static transmitters (12 transmitting ports) and four static receivers (12 receiving ports).

D.3. **Calibration Algorithm for Coherent Image Formation in Multiple-bistatic Imaging System (Tasks 2.3 and 3.3)**

This year 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.

D.4. **Experimental Imaging Results Using the Multistatic Millimeter Wave Radar System (Tasks 2.6 and 3.6)**

This year, we have continued to test the imaging capabilities of the Gen-2 and Gen-3 system in several experimental setups. Representations of all the experiments are the 3D fully-electronic images at the 1-2 m range using the modular Gen-2 and Gen-3 mm-wave radar system.

D.4.a. **Fully-electronic 3D Imaging at the 1-2 m Range Using the Modular Gen-2 Mm-wave Radar System**

Last year’s experimental results were in 2D. In order to realize a full 3D reconstruction of a static target, a new experimental framework has been devised. Figure 13a (on the next page) shows the experiment model for the 3D imaging. The Region of Interest (RoI) has a size of 450 mm in x-axis (cross-range), 300 mm in y-axis (depth), and 900 mm in z-axis (elevation). The center of the reconstruction domain is located at [190, 1400, 1010] mm. The pixel resolutions are 16 mm, 8 mm, and 30 mm in the x-, y-, z-axis, respectively. Figure 13b shows the static metallic plate under detection with a size of 302 mm × 457 mm.

The reconstruction algorithm used in this experiment is based on Tikhonov regularization, which is often used in ill-posed inverse scattering problems. It is given by:

\[
\mathbf{r} = (\mathbf{H}^T\mathbf{H} + \Gamma^T\Gamma)^{-1}\mathbf{H}^T\mathbf{y},
\]
where \( \mathbf{g} \) is the measured vector having 4320 elements (9 Tx apertures \( \times \) 12 Rx apertures \( \times \) 40 frequencies); \( \mathbf{r} \) is the reflectivity vector; \( \Gamma \) is the Tikhonov matrix chosen as a multiple of the identity matrix, \( \alpha \mathbf{I} \), and \( \alpha \) is the regularization parameter. To further mitigate the spatial noise, a 2D cross-section averaging is applied to \( \mathbf{r} \). The averaging processing for the \( y_0 \)-th cross-section reconstruction plane can be expressed as

\[
\mathbf{r}_{\text{av}}(x_0,y_0,z_0) = \sum_{n_x = -\frac{N}{2}}^{\frac{N}{2}} \sum_{n_z = -\frac{N}{2}}^{\frac{N}{2}} \frac{\mathbf{r}(x_0 + n_x,y_0 + n_z,z_0)}{(N + 1)^2},
\]

where the length of the 2D averaging process is \( N + 1 \) in each dimension, \( N \) being an even number.

Figure 13c shows the experimental reconstructed images of the plate with 5-pixel 2D averaging (\( N = 5 \)). Figure 13d is the recorded image by an X-box One Kinect Sensor for fusing of the static mm-wave and stereo-camera Kinect images. As can be seen, the profile of the metallic plate as well as its location is well imaged and similar to that recorded by the Kinect Sensor, which verifies the effectiveness of the 3D imaging ability of the established radar system.
D.4.b. Fully-electronic 3D Imaging at the 1-2 m Range Using the Modular Gen-3 Mm-wave Radar System

This year, we have realized the first experimental results of our 3D millimeter-wave Compressive-Reflector-Antenna imaging system. The addition of a CRA to the HXI RFE-based imaging system improves the system sensing capacity by adding spatial and spectral diversity.

The CRA is 3D-printed and coated with a metallic spray to easily introduce pseudo-random scatterers on the surface of a traditional reflector antenna (TRA). The CRA performs a pseudo-random coding of the incident wavefront, thus adding spatial diversity in the imaging region and enabling the effective use of compressive sensing (CS) and imaging techniques. The CRA is fed with a multiple-input-multiple-output (MIMO) radar, which consists of four transmitting and four receiving apertures. Consequently, the mechanical scanning parts and phase shifters which are necessary in conventional physical or synthetic aperture arrays, are not needed in this system.

As shown in Figure 14, the CRA surface is designed with an offset length of $L_{\text{off}}$ to minimize the blockage of the reflected field from the TRA and to enhance the radiation efficiency. The coating of the TRA surface with metallic applique scatterers results in a CRA that performs the spatial coding of the fields reflected from its surface. The metallic applique scatterers can be described by a pseudo-random perturbation function in $\Delta h(x,z)$ in the $y$-axis. A geometrical model of the CRA is plotted in the right part of Figure 14a, where the sup-
port of the $\Delta h(x,z)$ function has been discretized into a tessellated mesh of $N_\Omega$ triangular faces. The averaged side length of the triangular facets is $d_0$; and the distortion for each vertex is drawn from an uniform random distribution $U(-\Delta h_m, +\Delta h_m)$, $\Delta h_m$ being the maximum allowed distortion. All the parameters of the designed CRA are shown in Table 5, where $\lambda_0$ is the wavelength corresponding to the center frequency $f_c$ of the radar operating bandwidth $B$.

<table>
<thead>
<tr>
<th>Name</th>
<th>Value</th>
<th>Name</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$D0$</td>
<td>500 mm</td>
<td>$\Delta h_m$</td>
<td>0.8 mm</td>
</tr>
<tr>
<td>$L_{off}$</td>
<td>350 mm</td>
<td>$\lambda_0$</td>
<td>4.1 mm</td>
</tr>
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<td>500 mm</td>
<td>$B$</td>
<td>5 GHz</td>
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<tr>
<td>$d_0$</td>
<td>16.4 mm</td>
<td>$f_c$</td>
<td>73.5 GHz</td>
</tr>
</tbody>
</table>

Table 5: Design parameters of the CRA.

The calibration setup for the CRA imaging system is shown in Figure 15. Two WR-12 tapered waveguides were used with the moving transmitter and receiver, which were mounted on the scanning platform 900 mm away in range from the center of the CRA. The field was collected in an aperture of 880 mm in the x-axis (cross-range) and 640 mm in the z-axis (elevation), and sampled at half wavelength discretization steps in both dimensions. The magnitude and phase of the measured fields for one of the MIMO transmitters are plotted for three different frequencies in Figure 16.
The experimental setup of the CRA imaging system is shown in Figure 17. For the forward path (illustrated with a red dashed line), the four switch ports are successively activated for transmitting the radar signal to the CRA. The incident wavefront is then pseudo-randomly coded to achieve spatially and spectrally diverse measurements. Then, the wave reaches the RoI, containing a T-shaped target placed at its center. The same reasoning applies for the backward path that is plotted in the green dashed line, where all four receiving ports are active and simultaneously receive the radar signals. A total of 30 frequencies are used in the experiment, which are uniformly selected in the operation bandwidth, so that a total of 480 measurements (30 frequencies × 4 Tx apertures × 4 Rx apertures) are recorded. The dimensions of the RoI are 600 mm, 420 mm, and 900 mm in cross-range, range, and elevation, respectively. The pixel resolution is selected to be 6 mm, 30 mm, and 6 mm in the x−, y−, and z−axis, respectively.

Figure 17: Experimental setup for CRA imaging. The forward and backward paths are illustrated in the red and green dashed lines, respectively. A T-shaped metallic target is located 1.5 m away from the center of the CRA. The arrangement and dimensions of the Tx/Rx arrays are shown in the subplot.

Figure 18: (a) Normalized magnitude of the received electric field, |Erec|, on 2D planes at different ranges; (b) maximum |Erec| along range; and (c) reconstructed target profile with a display threshold of |Erec| ≥ 0.5. The 2D averaging process with a length of N = 7 pixels is applied.
Figure 18a shows the 3D imaging results of the T-shaped metallic target, where only three out of fifteen imaged frames in the RoI are shown. 3D reconstructed images are given in Figures 18b and 18c, where a 7-pixel 2D averaging processing is applied. The maximum magnitude of the received electric field $|E_{\text{rec}}|$ is plotted in Figure 18b. The reconstructed target profile is shown in Figure 18c, where a display threshold of $|E_{\text{rec}}| \geq 0.5$ is applied. As can be seen, the reflectivity of the RoI is successfully reconstructed, and the target is imaged, which shows a reasonable T-shaped profile with similar dimensions compared to those of the actual target.

D.5. Study of a New “On-the-Move” System Hardware and Configuration (Tasks 2.1 and 3.1)

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 [37-44]. 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. Fabrication of Metamaterial Absorber (MMA)

Metamaterials are of special interest in high capacity imaging applications. Specifically, the frequency dispersive response of metamaterials may be used to perform spectral coding that ultimately will improve the sensing capacity of the imaging system (see the report for Project R3-B.2 for a detailed explanation on sensing capacity).

![Figure 19](image)

In the following section, the design, fabrication, and experimental validation of a meander-line metamaterial absorber (MMA) is described. The schematic of the suggested meander-line MMA structure is shown in Figure 19. The unit cell contains a supportive substrate with a meander-line pattern on top layer and a metal coating on the bottom layer. A polyimide film (DuPont Kapton VN) is used as the supportive substrate with a relative permittivity of 3 and a thickness of 200nm. The selected substrate is thin and flexible, making it...
easy for tailoring the surface of the parabolic reflector. It should be noted that a thin layer of chromium is coated on the substrate (Fig. 19a) which is a necessary adhesion layer between the substrate and the gold. A full-wave finite-element based commercial software (HFSS) is utilized to design the metamaterial unit cell. The parameters for the designed meander-line are as follows: \( p_x = 570 \); \( p_y = 500 \); \( l = 332 \); \( w = 54 \); \( g = 43 \), all in [\( \mu m \)].

For fabricating the MMA array, gold sputtering followed by a lift-off process is used to pattern the top layer. For the bottom layer, only a gold sputtering process is performed. Figure 20 shows the fabricated meander-line MMA array with 400x magnification. Based on the simulation, 20/200nm of Cr/Au was targeted. Based on the post-deposition measurement; however, the actual deposition is estimated to be slightly less (18/185nm Cr/Au). A vector network analyzer (N5242A PNA-X) synchronized with E-band mm-wave extenders (WR12-VNAX) is used to measure the reflection coefficient of the meander line MMA. A Teflon plano-convex lens is located in front of the horn antenna to collimate the electromagnetic beam, as shown in Figure 21. The next step is to obtain the semi-analytic model for the MMA's reflection response. A Drude-Lorentz model \([45-47]\) with an equivalent bulk magneto-dielectric medium is utilized to characterize the MMA. In Figure 22, a comparison between the measurement and the semi-analytical model for the magnitude square and phase of the reflection coefficient is plotted. A plane-wave with normal incidence angle is applied for both the measurement and the semi-analytic model.
This year, we have developed a new mechanical configuration that enables the Gen-3 system to use multiple arrays of compressive reflector antennas (CRAs). As shown in Figure 23a, the new assembly is composed of four units, each one dedicated to a single transmitter or receiver. Each unit mainly contains an 80/20 structure and 3D-printed parts. Each CRA is mounted on a specially designed holder, and the holder is attached to a vertical beam (see Fig. 23b). Since each transmitter has four ports, four CRAs are required to be deployed symmetrically in the design. The reflection plate, which is used to reflect the signal from the transmitters to the CRAs (see Fig. 23c) is attached to its holder by using an adhesive polymer, and the holder is mounted on a horizontal beam. Finally, each unit is mounted to the main structure of the MIMO (Multiple Input Multiple Output) radar system.

One advantage of this design is that it enables the CRAs to move in all directions. Moreover, the reflection plate can also be moved toward or away from the transmitters freely without any change of the main structure of the MIMO array. Meanwhile, different incidence and reflection angles can also be obtained by making 3D-printed holders of different angles. In this sense, multiple coupling situations can be studied to achieve the best imaging performance. It is important to note that this mobile design will also enable the ability to mount larger CRAs; this will only require adjusting the position of the reflection plate.

Figure 22: (a) Magnitude square and (b) phase of the reflection coefficient for the meander-line MMA.

D.5.b. Mechanical Design of a System Using a Compressive Reflector Antenna (CRA)
Based on the proposed mechanical design in Figure 23, we have developed the architecture of the CRA-array mm-wave radar imaging system. Figure 24 shows the current configuration of the imaging system with 6 identical CRAs, which is the basic setup for high-sensing-capacity on-the-move imaging. The detailed parameters for the design of each CRA have been given previously in Table 5.

![Figure 23: Proposed CRA mechanical design, including: (a) front view of the whole system, (b) detailed design of the fixing part, and (c) signal pathway while working.](image)

![Figure 24: Experimental setup for “On-the-Move” imaging.](image)
In addition to the spatial diversity introduced by the CRAs, the data acquisition time in the current system for the commutation of the transmitters and receivers is reduced to a great extent, as the port-to-port switching time is only 0.1μs. Thus, the system is able to reconstruct an image frame in 328 μs, which is suitable for on-the-move imaging of a human body with a normal walking speed (0.6~1m/s).

As can be seen in Figures 25 and 26, the mm-wave radar successfully reconstructed the object under clothing. By combining all the received chirp signals, a video can be created by the imaging system to show an on-the-move human body with potential threat objects.

**Figure 25:** Mm-wave images for the “On-the-Move” human body experiment with a metal box under clothing.

**Figure 26:** Video and 3D Kinect-based stereo camera images of the “On-the-Move” human body experiment.
**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 DHS Enterprise**

The following features will be of special relevance to the Department of Homeland Security (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 + 10 switches.

**B. Potential for Transition**

The features of “On-the-Move” have attracted the attention of several industrial and government organizations.

- Target government customers: Transportation Security Administration (TSA), the U.S. Department of Justice (DOJ), Customs and Border Protection (CBP), and the Department of State.

**C. Data and/or IP Acquisition Strategy**

The hardware and algorithmic design, integration, and validation performed under this project will continue to generate IP. In the past, several provisional patents have been submitted to Northeastern University’s (NEU) IP office, and our connection with different transition partners will facilitate its transition into industry. Moreover, 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/imaging algorithms. Moreover, 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 Inc. 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

Customer Names & Program Offices:
- HXI – Mr. Earle Stewart
- Smith’s Detection Systems – Dr. Kris Roe
- L3 Communications – Dr. Simon Pongratz

Frequency of Contact & Level of Involvement in Project:
- The PI has weekly meetings with HXI for the project.
- The companies Smiths Detection and L3 Communications had three to four meetings with the PI last year.

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. Course, Seminar, and/or Workshop Development
   a. Prof. 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 6 weeks in Prof. 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:


D. Other Presentations

1. Seminars
   c. Martinez-Lorenzo, J.A. “Imaging at Speed.” NU Meeting with Transportation Security Administration Administrator David Pekoske, Northeastern University, Boston, MA, 18 May 2018.

2. Poster Sessions


3. Interviews and/or News Articles

V. REFERENCES


