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

I. PARTICIPANTS

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<table>
<thead>
<tr>
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<th>Degree Pursued</th>
<th>Institution</th>
<th>Month/Year of Graduation</th>
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<tbody>
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<td>5/2016</td>
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<td>Thayer Academy</td>
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<td>Anthony Bisulco</td>
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II. PROJECT DESCRIPTION

A. Overview and Significance

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 explosive residues or heat signatures on the outer surface of their clothing, and characterizing explosives using penetrating X-rays [1] [2],
terahertz waves [3, 4, 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 (see Fig. 1).

B. State-of-the-Art and Technical Approach

As recently pointed by the International Air Transport Association (IATA), being able to detect security threats without interrupting the motion of the person under test will be one of the most valuable features of the next generation personnel screening systems [10] (page 14). Current state-of-the-art 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 with 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 special application to detecting and identifying 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, needed to go from a 3D mechanical scanning imaging system (Generation 1 [10]) to a 3D fully electronic scanning imaging system (Generation 3 [11,12]). An intermediate imaging system (Generation 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 Generation 1 and Generation 3 imaging systems.

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>Generation 1</th>
<th>Generation 2</th>
<th>Generation 3</th>
</tr>
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<tr>
<td>System scanning design</td>
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<td>Task-2.1: 50% Completed</td>
<td>Task-3.1: 0% Completed</td>
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<tr>
<td></td>
<td>- Mechanical</td>
<td>- Fully electronic (small targets)</td>
<td>- Fully Electronic</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Hybrid: electronic + mechanical (large targets)</td>
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<tr>
<td>Radar configuration</td>
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<td>Task-2.2: 50% Completed</td>
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<tr>
<td></td>
<td>- 1 Transmitter</td>
<td>- 5 Transmitter</td>
<td></td>
</tr>
<tr>
<td></td>
<td>- 4 Receivers</td>
<td>- 5 Receivers</td>
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</tr>
<tr>
<td></td>
<td>- 2 Switches</td>
<td>- 10 Switches</td>
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<tr>
<td></td>
<td>- 800 Frequencies</td>
<td>- 600 Frequencies</td>
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<tr>
<td></td>
<td>- 70-77GHz Bandwidth</td>
<td>- 70-77GHz Bandwidth</td>
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<td>Radar Calibration</td>
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<tr>
<td></td>
<td>- Transceiver Electromagnetic characterization</td>
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<td>- Transceiver Spatial characterization</td>
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<td>Mechanical Assemblage</td>
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<td>Control Mechanism</td>
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<td>- Arduino-based</td>
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<td>Imaging capabilities</td>
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<tr>
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<td>- 3D coherent</td>
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<td>- Static for small targets</td>
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<tr>
<td></td>
<td>- Static targets</td>
<td>- Dynamic for large targets</td>
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<td>Spatial Codification</td>
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<td>Non Applicable</td>
<td>Task-3.7: 0% Completed</td>
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Table 1: Roadmap towards a fully electronic radar imaging system: from Generation 1 [24] to Generation 3 [25, 26].

During the last year, the following activities were developed for this project: 1) Hardware design and integration of a multistatic imaging system (Tasks- 1.4 and 2.4); 2) Development of control firmware and soft-
ware for the multistatic imaging system (Task-1.5 and 2.5); 3) Calibration algorithm for coherent image formation in multistatic imaging system (Task-1.3); and 4) Experimental imaging results using the multistatic millimeter wave radar system (Task-1.6); 5) Study of a new “on-the-move” system configuration (Task-2.1). This project is intimately related to the ALERT project R3-B.2: Advanced Imaging and Detection of Security Threats using Compressive Sensing; in which the imaging algorithms for this hardware system have been developed. Additionally, many of the technology and techniques developed for this project are commonly used in near-field applications by other ALERT projects, including R3-A.1 and R3-A.2.

C. Major Contributions

A summary of the Year 2 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 1.4 and 2.4)- This year, the main outcomes of these two tasks have been the following:</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Outcome 1.1 – Finish the design and integration of the Gen-1 mm-wave imaging system.</td>
</tr>
<tr>
<td>• Outcome 1.2 – Preliminary design and integration of the Gen-2 mm-wave imaging system using one transmitting and one receiving switch and a micro-controller.</td>
</tr>
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<tr>
<th>C.2- Development the control firmware and software for the multi-bistatic imaging system (Tasks 1.5 and 2.5)- This year, the main outcomes of this task have been the following:</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Outcome 2.1 – LabVIEW, C and microcontroller firmware and software to operate the commutation amongst different receivers of the Gen-1 system.</td>
</tr>
<tr>
<td>• Outcome 2.2 – Preliminary LabVIEW, C and FPGA-based firmware and software to operate the commutation amongst different transmitted and switched receivers of the Gen-2 system.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>C.3- Calibration algorithm for coherent image formation in multiple-bistatic imaging system (Task 1.3)-This year, the main outcomes of the Task 1.3 have been the following:</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Outcome 3.1 – “Sphere-based” 2D calibration algorithm using two receivers in the Gen-1 system.</td>
</tr>
<tr>
<td>• Outcome 3.2 - “Pole-based” 2D calibration algorithm using two receivers in the Gen-1 system.</td>
</tr>
</tbody>
</table>

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<tr>
<th>C.4- Experimental imaging results using the multistatic millimeter wave radar system (Task-1.6)-This year, the main outcomes of this Task 1.6 have been the following:</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Outcome 4.1 – 3D images at 1-2 m range using a modular mm-wave radar system working with multiple receivers, single moving transmitter and switching devices Gen-1 system.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>C.5- Study of a new “On-the-move” system configuration (Task-2.1)-This year, the main outcomes of these Tasks 2.1 and 3.1 have been the following:</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Outcome 5.1 – Study of a new “On-the-move” hardware configuration for real-time imaging.</td>
</tr>
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</table>

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

D.1. Hardware design and integration of a multiple-bistatic imaging system (Tasks 1.4 and 2.4)

In collaboration with our transition partner, HXI Inc., we have designed, integrated and tested a millimeter wave radar system for detecting security threats at mid-ranges. In particular, our current hardware systems (Gen-1 to 3) make use the following elements: a) five HXI # 8302 Transmitter (Tx) Modules (Generation 2); b) five HXI # 8301 Receiver (Rx) Modules (Generation 1 and 2); c) one HXI # 8303 Local Oscillator Module (LOM) (Gen-1 and 2); d) ten HXI # HSWM41203 SP4T 4-way Antenna Switches (Generation 2). The LOM has eight sync outputs, and it permits the use of eight Tx and Rx working in a fully-coherent multistatic mode of operation. Additional transmitting and/or receiving modules can be added by the inclusion of extra amplifiers and power dividers at the LOM outputs.

The Gen-1 imaging system, which has been finished this year, is shown in Figure 2 on the next page. It is composed of four receivers, which are represented by white squares in Figure 2a. The picture of the real system, Figure 2b, also highlights the position of the four receivers; and Figure 2c shows a zoomed image of the millimeter-wave receiver. The transmitter is mechanically scanned in a two dimensional aperture, highlighted in red in Figure 2a, by using two linear actuators. These actuators are the two black rails that are shown in Figure 2b in a cross configuration. Figure 2d shows a zoomed version of the transmitter. Figure 2e shows a basic schematic of the control system used to provide coherent phase reference for all the receivers and the transmitter.
Figure 2: Generation 1 millimeter-wave radar architecture assembled by the company HXI (only one Tx and one Rx Module shown).
The on-going Gen-2 imaging system builds upon the functionality developed for the Gen-1 system in order to increase the number of coherent channels, so that fully electronic imaging can be done for small targets. The 4 coherent channels of the Gen-1 system are increased to 400 in the Gen-2 system by enhancing the hardware with the following elements: 1) the number of transmitters is increased from one to five; 2) the number of receivers is increased from four to five; and 3) a single-pole four-throw (SP4T) switch is added to each transmitter and receiving module. This configuration leads to a 400 coherent channels system, which results from multiplying the 20 transmitting ports (5 transmitters x 4 ports/transmitter) by the 20 receiving ports (5 receivers x 4 ports/transmitter). Figure 3 shows a simplified schematic of the architecture of the Gen-2 radar imaging system, where only two receiving modules and one transmitting module are shown for the sake of simplicity.

The designed on-going Gen-2 system supports two modes of operation: 1) Mode-E, fully electronic static imaging of targets located in small reconstruction regions of about 0.2 meters by 0.2 meters by 0.2 meters; and 2) Mode-EM, hybrid, electronic and mechanical, dynamic SAR imaging of targets located in large image regions of over 1 meter by 2 meters by 1 meter. The Gen-3 system will leverage the Gen-2 architecture to be able to perform 2D imaging of large reconstruction domains. This can be done by exploiting one or several of the following strategies: a) Using a Coded Compressive Reflector Antenna [25, 26], in order to enhance the dispersion of the singular values of the sensing matrix; b) 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 c) Using image compression techniques, like wavelets, curvelets or cosine-based basis, in order to 'sparsify' the representation of the object under test.
Figure 4a shows a 3D model of the Gen-2 millimeter-wave radar system, which is currently under construction. This imaging system is composed of five transmitters and five receivers, each affixed with a 4-port switch. Four of the transmitters and receivers are fixed in place at the corners of the frame, while the transmitter and receiver in the middle of the frame can be either static (Mode-E) or smoothly and precisely moved together (Mode-EM). This movement is controlled by two linear actuators, allowing the transmitter and receiver to move up to 63 cm vertically and 84 cm horizontally. Moving the center transmitter and receiver pair during experiments can synthetically simulate many radar modules in a 2D plane. The fixed transmitters and receivers in the corners of the frame can optionally be moved and re-fixed in two dimensions, allowing changes to be made between experiments.

Figure 4b shows an angled view of the 3D model of the Gen2 millimeter-wave radar system. This view clearly shows the depth of the Gen-2 system that allows the center transmitter and receiver to move. Figure 4c shows a zoomed image of the millimeter wave transmitter with a 4-port switch attached. This transmitter
is in the “right-side-up” orientation, and is mounted on the Gen2 frame as such. Figure 4d shows a zoomed image of the millimeter wave receiver with a 4-port switch attached. When mounted on the Gen2 frame, the receiver module is rotated 180 degrees (as shown in Figs. 4a and 4b) to allow for proper location of the antennas in the imaging system.

D.2. Development the control firmware and software for the multi-bistatic imaging system (Tasks 1.5 and 2.5)

The control system associated with multi-channel multistatic systems is extremely complex, and it requires a careful design, implementation and validation.

This year, we have finished the control firmware and software of the Gen-1 imaging system, which allowed collecting data from multiple receivers. The Gen-1 switching system is currently based on an Arduino Mega 2560 microcontroller, a LabVIEW Virtual Instrument (VI), and various routing cables. As an intermediate step towards developing the Gen-2 imaging system, two TI CD74HC4067 multiplexers have been added to the control firmware and software of the Gen-1 system. As a result, two SP4T switches (one connected to a transmitting module and the other to a receiving module) can be used. These multiplexers are used with voltage dividers to create four distinct voltage values indicating the current active port for each one of the two SP4T switches. This Arduino-based system is limited to controlling two HSWM41203-262 WR12 SP4T switches at a time, otherwise delays due to the single-core processor in the Arduino microcontroller would become pronounced and degrade switch transition times.

In the Gen-2 imaging system, an FPGA-based switching system based on an Altera Cyclone V DE1-SoC board has been designed to eliminate the limitation associated with the maximum number of switches. This FPGA-based design is able to drive 10 SP4T switches in parallel; 5 of the switches will be working in transmission mode and the remaining 5 switches will be working in reception mode. An image of the FPGA board that is being used in the on-going Gen-2 imaging system is shown in Figure 5a on the next page.

The DE1-SoC board has two GPIO outputs, each of which provides 36 outputs. Each SP4T switch is controlled via five LVTTL (3.3V) compatible signals. When all ten SP4T switches are connected to the FPGA, 50 out of the 72 available FPGA outputs are used to control the 10 SP4T microwave switching system.

This year, we have started to develop a modular FPGA VHDL code that controls the 10 SP4T switches. This code has been successfully tested in a virtual FPGA environment. This code is composed of three separate modules: a) a master module; b) a slave receiving module; and c) a slave transmitting module. The master module drives to the slave modules; and it acts as a finite state machine. Indeed, the master module controls the timing of events, thus indicating which particular ports of transmitting or/and 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 5 transmitting modules and 5 receiving modules.
Figure 5b shows a VHDL simulation of the switching system, in which each transmitting switch has an enable line to determine if it is actively illuminating the target at a precise point in time. Each port on the active transmitting module is sequenced individually to transmit the FMCW chirp signal, while all of the ports on the receiver modules are also sequenced individually to receive the scattered field.

As briefly indicated before, the VHDL is capable of operating in two modes: 1) Mode-E, fully electronic scanning; and 2) Mode-EM, hybrid electronic/mechanical scanning. For the Mode-EM, the moving Tx module is active and switched between its four ports, while the remaining Rx modules are switched between their corresponding four ports of the SP4T switch. In the Mode-E, there are no moving Rx or Tx modules; and the switching method is the same, except that after the first Tx module switches throughout its four ports, the
second Tx module is enabled, and so forth, until the final Tx module finishes switching throughout all the ports. It is important to mention that in the implemented cycle, only one port of the transmitting ports connected to the multiple transmitters is active at a time.

This year, we have also developed the LabVIEW control VI for the FPGA system, which is shown in Figure 6. The updated LabVIEW VI contains an array field that stores the positions of the SP4T switches relative to a fixed set of gantry center coordinates in the two cross-range and range directions. Currently, the VI and the VHDL code are set to use five switched transmitting modules and five switched receiving modules. Nonetheless, this configuration is modular; and it can be easily adapted to be used with a different number of switched transmitting and receiving modules. The LabVIEW VI also has fields to write the experiment name, data acquisition parameters, and for 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 Tx and Rx modules to create a synthetic aperture, enabling 2D or 3D imaging via SAR methods.

This year, we have also expanded the Analog to Digital Converter (ADC) capabilities of the system; so that the 8 ADC channels of the Gen-1 system are expanded to 16 ADC channels in the Gen-2 system. This is done by connecting two GaGe Octopus 8284 PCI-E Digitizer cards in Master/Slave configuration. The implemented Labview VI controls the acquisition of the 16 ADC. Each Rx module has two output channels consisting of an In-Phase signal and a Quadrature signal, so 10 out of 16 available ADC channels are by the five switched receiving modules, leaving room for future expansion if needed.

![Figure 6: LabVIEW VI front panel to control and define parameters in the FPGA-based switching system.](image)

**D.3. Calibration algorithm for coherent image formation in multiple-bistatic imaging system (Task 1.3)**

In order to coherently combine the information from multiple transmitters and receivers, several radar calibration algorithms must be implemented. The aim of the calibration procedure is to correct for the different sources of variability existing in the radar system, which may ultimately lead to poor imaging. The most important sources of variability in the multistatic radar system: 1) The lack of accuracy on the position of the
transmitting and receiving ports, as well as the calibration target; 2) The unknown transfer function of the transmitting, receiving and switching modules; 3) The thermal-drift effect on the amplitude and phase of the transfer function of each transmitting and receiving module.

This year, we have worked on two different calibration algorithms that address the first of the aforementioned variability sources. The first “Sphere-based” calibration algorithm builds upon the 2D algorithm developed last year [27], which used synthetic data to demonstrate the feasibility of using two metallic spheres to correct for the unknown relative position of the transmitting and receiving modules. This year we validated the algorithm with experimental data. The second “Pole-based” calibration algorithm is slightly faster than the “Sphere-based” algorithm, which is suitable for quickly calibrating a deployed system, but its accuracy is reduced when compared to the “Pole-based” algorithm.

D.3.a. Calibration algorithm #1: “Sphere-based” calibration

In the first algorithm, we use two spheres as the calibration target (as shown in Figure 7 on the next page). This algorithm determines the correction needed for the position of each receiver, so that a coherent image can be created. The algorithm extracts the phase of the complex image generated by each receiver, using Inverse Fast Multiple Method (IFMM) [28], in order to find the discrepancy in the center of the calibration spheres for each receiver. This discrepancy is then used to calculate the error in the position of the second receiver $\vec{d}_k = y\hat{y} + x\hat{x}$. Thus, the algorithm is divided in two steps: a) Training step; and 2) Correction step.

In the training step, a series of synthetic experiments (using the configuration shown in Figure 7 on the next page) are used to find the displacement error vectors $\vec{d}_k$ using the misalignment on the images of Sphere 1 (Sp1) and Sphere 2 (Sp2) [29]. If the second receiver (Rx2) is positioned inaccurately with respect the first receiver (Rx1), the center of Sp1 as reconstructed by each receiver will not coincide. Instead, the predicted sphere centers will be displaced by an error vector $q_1\hat{x} + p_1\hat{y}$. For a reasonably close initial guess on the relative position of the two receivers, the corresponding cross-range ($q_1$) and range ($p_1$) components of sphere center displacement can be related to cross-range ($x$) and range ($y$) components of the vector $\vec{d}_k$ through an affine transformation of the form:

$$\begin{align*}
p_1 &= A_1x + B_1y + C_1 \\
q_1 &= D_1x + E_1y + F_1
\end{align*} \tag{1}$$

In the training step, the constants $A_1, B_1, C_1, D_1, E_1, F_1$ are obtained after applying a linear regression algorithm to a full set of at least three synthetic training experiments, each with a different known Rx2 position displacement: $x^k, y^k$, and each yielding an observed sphere center displacement $q_1^k, p_1^k$ for $k=1,2,...,N_k$, where $N_k$ is the number of training experiments. The synthetic training data is generated by a Physical Optics algorithm for predetermined values of $x^k$ and $y^k$, and later is processed with the Inverse Fast Multiple Method (IFMM), in order to extract $q_1^k, p_1^k$.

In the correction step, the obtained parameters of $A_1, B_1, C_1, D_1, E_1, F_1$ are used to estimate the $x^k$ and $y^k$ by using the values $q_1^k, p_1^k$ extracted from the complex images generated from experimental measured (not synthetic) data. Therefore, the displacement vector $q_1\hat{x} + p_1\hat{y}$ is used to obtain the true position of the second receiver; and it is used afterwards in order to coherently generate the image of the multi-bistatic imaging system.

This year, we have applied the “Sphere-based” calibration method to the experimental setup shown in Figure 7; and the preliminary results are displayed in Figure 8 on the next page. The proposed calibration algorithm for enhancing the quality of the un-calibrated coherent image, shown in Figure 8b, in terms of the reconstructed maximum amplitude and image signal to noise ratio (ISNR), as shown in Figure 8c.
Figure 7: Setup of the “Calibration-based” algorithm: (a) top view schematic; and (b) picture of the actual experiment [24, 30].

Figure 8: Reconstructed images from the experimental setup: a) the images from Sp1 (bottom), Sp2 (top) using Rx1 and Rx2; b) coherent sum of images from Rx1 and Rx2 before calibration; and c) coherent sum of images from Rx1 and Rx2 after correction. The calibrated images (c) are better than the non-calibrated ones (b) in terms of signal to noise level as well as the amplitude of the recovered reflectivity function.
The “sphere-based” algorithm produced good results when the algorithm was tested on the same type of geometry used for the training. However, its reliability was reduced when it was experimentally tested with other geometric configurations without using spheres. In our opinion, this drawback may be associated with either the intrinsic overfitting of the “Sphere-based” calibration algorithm, or the aforementioned variability on the thermal drift or/and unknown transfer function of the system. For this reason, a second calibration algorithm was also investigated.

D.3.b. Calibration algorithm #2: “Pole-based” calibration

In the second algorithm, we use a metallic pole as the calibration target (as shown in Fig. 9). The proposed calibration is done in two steps. First, the position of receiver one (Rx1) relative to the position of the transmitting array (Tx) is optimized using a Simulated Annealing algorithm [29]. This is done by using a cost function that is tailored to maximize the amplitude of the image of the pole (Point Spread Function) using the receiver one (PSF_Rx1). In the second step, the position of receiver two (Rx2) is optimized relative to the position of the transmitting array (Tx). In this case, the cost function is based on maximizing the summation of the Image of the pole with Rx1 (PSF_Rx1) and image of the pole with Rx2 (PSF_Rx2). In order to simplify the optimization, the position of Rx1 is displaced only in the XY plane (not in elevation; the calibration in elevation will pursued next year).

Figure 9: Setup of the “Calibration-based” algorithm: (a) top view schematic; and (b) picture of the actual experiment.

Figure 10 on the next page shows the results of the calibration algorithm. In particular, Figure 10a shows the ground truth, derived from software simulations of the experimental setup. Figure 10b shows how the null existing in the reconstructed box (top image) is corrected after the calibration algorithm is applied (bottom image). Figure 10c shows the effectiveness of the algorithm in enhancing the amplitude of the PSF of the pole and reducing the ISNR of the image.
D.4. Experimental imaging results using the multistatic millimeter wave radar system (Task-1.6)

This year, we have tested imaging capabilities of the Gen-1 system in several experimental setups. A representative subset of all the experiments include but are not limited to the following: 1) Experimental result #1 - 3D imaging of a calibration target and a pole; 2) Experimental result #2 - 2D imaging of security threats using two receivers of the Gen-1 system and one additional receiver on the side; 3) Experimental result #3 - 3D imaging of security threats using two receivers of the Gen-1 system. A more detailed explanation and justification of these experiments is given in the next subsections.

D.4.a. Experimental result #1: 3D imaging of a calibration target and a pole

Figure 11a on the next page shows a picture of the experimental setup consisting of a calibration target, made of nine small metallic spheres, and a metallic pole. Only two receivers from the Gen-1 system are used in this experiment. The reconstructed images are shown in Figure 11b on the next page for the receiver 1 (Rx1) on the top and for receiver 2 (Rx2) on the bottom. The two images from Rx1 and Rx2 have not been combined coherently, since the calibration algorithm has not been extended to 3D geometries yet. Nonetheless, the amplitude of the reconstructed target seems to be well aligned for both receivers, providing a good starting point for coherent image formation.

Figure 10: Reconstructed image: a) of the box using software simulation and synthetic data; b) of the box before (top) and after (bottom) calibration using measured data; of the pole before (top) and after (bottom) calibration using measured data.

(a) Simulated box

(b) Before

(c) After

Box

Pole

Box

Pole
Experimental result #2: 2D imaging of security threats using two receivers of the Gen-1 system and one additional receiver on the side.

Figure 12a on the next page shows a picture of the experimental setup consisting of threat surrogates on a metallic air duct torso simulant. Two receivers from the Gen-1 system are used in this experiment in addition to a third receiver located on the side. As predicted by our computational algorithms, adding a third receiver to the side of the Gen-1 system will increase the systems’ field of view, thus enhancing its ability to detect security threats. Figure 12b shows a zoomed version of the target (bottom left) and the images reconstructed with each one of the three receivers (top). The magnitude-based combination of the three images (bottom right) shows that in the resulting image the lateral side of the target can now be clearly reconstructed due to the use of the lateral side receiver (see yellow arrow in Figure 12).

Figure 11: Experimental result#1: Calibration target using nine small spheres and a metallic pole (left); and 3D reconstructed images from the first and second receiver of the Gen-1 system.
Figure 12: Experimental result #2: (a) experimental setup showing the three receivers; (b) zoomed version of the target (bottom left), reconstructed images from each one of the three receivers (top), and magnitude-based combination of the three images showing the enhanced reconstruction of the target.
D.4.c. Experimental result #3: - 3D imaging of security threats using two receivers

Figure 13a shows a picture of the experimental setup consisting of security threats on a metallic air duct. Only two receivers from the Gen-1 system are used in this experiment. The reconstructed images are shown in Figure 13b for the receiver 1 (Rx1) on the top and for receiver 2 (Rx2) on the bottom. The two images from Rx1 and Rx2 have not been combined coherently, since the calibration algorithm has not been extended to 3D geometries yet. Nonetheless, the amplitude of the reconstructed target seems to be well aligned for both receivers, providing a good starting point for coherent image formation. The colorbar of the reconstructed images codes for depth. Therefore, it is possible to see the expected protrusion for the metallic targets (dark red) and the expected depression for the dielectric targets (light orange/yellow) [31]. It is important to note that the algorithm described in [31] can now be used to infer the relative dielectric constant of the dielectric explosive (i.e. Relative dielectric constant of TNT is around 2.3).

![Experimental result #3](image)

Figure 13: Experimental result #3: (a) zoomed version of the target region containing a metallic object and a weak dielectric object, simulating TNT explosive; (b) reconstructed images from the first (top) and second (bottom) receivers, showing the characteristic protrusion of the metallic threat and the characteristic depression of the weak dielectric threat.

D.5. Study of a new “On-the-move” system configuration (Task-2.1)

In order to transition to a fully electronic scanning system, we continued to investigate a new hardware configuration capable of providing real-time imaging for “On-the-move” configurations.
This year, we extended the 2D “On-the-move” configuration presented last year to 3D configurations. The on-the-move active mm-wave system is composed by multiple synchronized transmitters and receivers placed along two walls. The subject under test continuously moves in front of the walls. Figure 14 presents the layout of the system and a person under test in three different positions as moving inside the hallway scanner. Two additional transmitters in front and behind the subject are also used to ensure information from all the possible angles is collected.

As the subject moves inside the system, the transmitters are sequentially activated and the electromagnetic field, which is then scattered by the person, is collected by all the receivers at the same time. Fast electronic switching allows for the quick activation of all the transmitters and the data collection. In this way, information from multiple relative positions of the person from the scanner can be collected.

**D.5.a. 3D configuration of the “On-the-move” imaging system**

The layout of the proposed on-the-move 3D system is presented in Figure 15 on the next page. The configuration is composed of multiple synchronized transmitters and receivers. Lateral receiving apertures of size (X,Z) = (1,2) m, are placed at Y0 =0.75 m. The dimensions of these panels are chosen to provide an approximated cross-range resolution of 1 cm the z-axis and 2 cm in the x-axis. For this preliminary setup, Nyquist sampling requirements are considered for the receiving panels, thus acquiring the field in 201 x 401 receiving positions per panel. Subsampling techniques can be efficiently applied in this setup to reduce the number of receivers, although this analysis is beyond the scope of this contribution. 15 GHz bandwidth, from 15 to 30 GHz, is chosen, similarly to the UWB imaging system described in [32]. This bandwidth provides an approximate range resolution of 1 cm, although, for nearfield radar imaging, besides the frequency and aperture size, the final system lateral and range resolution are given by Eqs. (2) and (3) of [33].
Three arcs of transmitters, each having 20 elements evenly spaced along x and z axes, are considered, centered at $x = +1$, 0, and -1 m, respectively. For the sake of simplicity, only the ones at +1 and 0 m, depicted in Figure 15 will be considered to obtain the results in this section. Some of the transmitters are placed on top and below the body to ensure the areas with larger curvature (as the top of the chest and shoulders) are reconstructed.

A Physical Optics (PO) code [34], [35] in combination with a visibility algorithm [36] has been used to predict the parts of the body model in Figure 16 on the next page that are illuminated by every transmitter. Also, PO provides the amount of scattered field collected on the panels. Thus, it is possible to evaluate if a certain layout of transmitters is capable of illuminating the entire person after crossing the hallway, and to estimate the field scattered by the illuminated areas on the receiving panels. For these simulations the human body is assumed to behave as a Perfect Electric Conductor (PEC) in the 15 to 30 GHz frequency band.

As an example, Figures 16a and 16b on the next page show the body of the human illuminated by two different transmitters, as well as the field received on the lateral panels. Note that, even for a single position of the person in the hallway, different areas of the body are illuminated. This layout increases the amount of information thanks to the spatial diversity of the multistatic illumination.
Figure 16: (a) Examples of human body illumination using one transmitter (highlighted in green) and scattered field when the body model is centered in 0.25 m (top) and 0.75 m (bottom); (b) Examples of human body illumination using one transmitter (highlighted in green) and scattered field when the body model is centered in 0.25 m (top) and 0.75 m (bottom).
Regarding the inverse method used to create images in this system, and due to the large computational cost for the imaging when the backpropagation is implemented in 3D, the Fourier-based technique for multistatic imaging [37] has been used (see the R3B.2 report for more detail). The efficient use of Fast Fourier Transforms (FFT) enables the generation of images for 3D whole body imaging in almost real time and using conventional hardware.

As an application example to show the performance of the proposed configuration, a target consisting of a person carrying a concealed weapon in the belt has been considered. For the sake of clarity, only two positions are analyzed: a person standing at \( x = 0.25 \) m and at \( x = 0.75 \) m. In this example, the goal is to clearly illustrate the different nature of the multistatic information collected on each position, rather than a rigorous reconstruction of the whole body. For every position, transmitter, and receiving panel, the amount of data to be processed is the following: 201 x 401 spatial samples x 121 frequency samples (= 9.75x106 scattered field samples), which also determines the number of imaging points in the case of Fourier-based imaging [37]. A workstation with 32 cores at 2.1 GHz and 128 GB RAM was used for data processing. Overall calculation time for every transmitter was 30 s (1200 s total for the 40 used transmitters). The processing has been done using a sequential Matlab code and has not been optimized for real time imaging yet.

The imaging results are depicted in Figure 17, corresponding to a person located at \( x = 0.25 \) m and \( x = 0.75 \) m respectively. Reflectivity points above -25 dB with respect to the maximum are coded in depth according to x-axis, allowing the recovery of the human body profile and potential concealed weapons. Comparison of Figures 17a and b provides a clear example of the On-The-Move Imaging concept effectiveness. In the case of Figure 17a (person placed at \( x = 0.25 \) m) the human sides and some areas of the chest are imaged by the system. In Figure 17b (person placed at \( x = 0.75 \) m) the top of the chest and the shoulders are recovered. In the final system multiple images as the two presented examples can be created and analyzed at video rate to detect any possible threats. Algorithms for mesh generation and automatic thread detection, such as the one used in [38], can be applied.

Figure 17: Recovered human body and concealed object geometry from backpropagation imaging for a person located at (a) \( x = 0.25 \) m and (b) at \( x = 0.75 \) m.
E. Future Plans

- Hardware design and integration of a multiple-bistatic imaging system - For the next few years, the follow-on tasks and expected outcomes are the following:
  - Tasks 2.1 and 2.4 – Finish the hardware design and integration of the Gen-2 system. Expected outcomes: a) Fully coherent mm-wave system working with 400 channels; and b) Mechanical assemblage of the radar system allowing Mode-E and Mode-EM data collection.

- Development of the control firmware and software for the multi-bistatic imaging system - For the next few years, the follow-on tasks and expected outcomes are the following:
  - Tasks 2.5 – Finish the FPGA-base firmware of the Gen-2 system. Expected outcome: a) fully coherent mm-wave system working with 400 channels using an FPGA.

- Calibration algorithm for coherent image formation in multiple-bistatic imaging system - For the next few years, the follow-on tasks and expected outcomes are the following:
  - Tasks 1.3 – Characterize the transfer function and the thermal-drift effect for all the transmitters and receivers in the Gen-1 system. Expected outcome: 2D calibration algorithm accounting for the variability associated with the thermal-drift and transfer functions.
  - Tasks 2.3 – Characterize the transfer function and the thermal-drift effect for all the transmitters, receivers, and switches in the Gen-2 system. Expected outcome: 3D calibration algorithm accounting for the variability associated with the thermal-drift and transfer functions.

- Experimental imaging results using the multistatic millimeter wave radar system - For the next year, the follow-on tasks and expected outcomes are the following:
  - Tasks 2.6 – Generating coherent 3D images for the Gen-2 system. Expected outcome: a) 3D coherent mm-wave system.

- Study of a new “On-the-move” system configuration - For the next year, the follow-on tasks and expected outcomes are the following:
  - Tasks 2.1 and 3.1 – Investigate the same “On-the-move” hardware configuration and imaging methodology for the Gen-2 and Gen-3 system. Expected outcome: a) 3D coherent mm-wave system.

III. EDUCATION AND WORKFORCE DEVELOPMENT ACTIVITY

A. Course, Seminar or Workshop Development

- Prof. Martinez-Lorenzo has been involved in several ADSA workshops. A more important contribution was done for the ADSA12, for which Prof. Martinez served as a plenary speaker with a talk entitled “Millimeter-Wave Sensing and Imaging.” During this talk, several stakeholders learned about the R3B projects.

- Prof. Martinez also convened a session at the 2015 the European Conference on Antennas and Propagation 2014 on “Wave-based sensing and imaging for security applications”.

B. Student Internships, Jobs or Research Opportunities

- Graduate students Galia Ghazi and Luis Tirado play an important role in our research project. They assist in developing new hardware design and integration for the millimeter wave radar system.

- Our undergraduate students Matt Nickerson, Mothit Bhardwaj, Anthony Bisulco, Chenyang Liu and Luigi Annesse, have continued the work started by Nigil Lee, Siddharth Velu, Thurston Brevett and Shaan Patel.
in this project. They will continue to be pillars of this project.

- Chenyang Liu and Luigi Annesse joined the group as participants in the ALERT and Gordon-CenSSIS Scholars Program.
- Moreover, Mohit Bhardwaj and Chenyang Liu have been involved in the center as REU students during 2014 and 2015 summers respectively.

C. Interactions and Outreach to K-12, Community College, Minority Serving Institution Students or Faculty

- Two high school students, Imani George – Thayer Academy, Class of 2015 and Jenny Dinh – Lowell High School, Class of 2015, joined the group over the summer 2014 as a part of the Young Scholars Program at NEU. During 2015 summer, two additional high school students will be joining the group.
- The lead PI participated in the several Building Bridges Program, in which high school students visit NEU’s laboratories to have a hands-on research experience in order to engage them in STEM education.
- The lead PI has also participated in the recruitment of undergraduate research students at the 2014 Society of Hispanic Professional Engineers (SHPE) Conference.

D. Other outcomes that relate to educational improvement or workforce development

Populating the research group with undergraduates brings homeland security technologies to undergraduate engineering students, and it establishes a pipeline to train and provide a rich pool of talented new graduate student researchers.

IV. RELEVANCE AND TRANSITION

A. Relevance of Research to the DHS Enterprise

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

- The non-invasive, minimal disruption on-the-move scanning with quality imaging and high throughput.
- Full body (360 degree) imaging with interrupted forward movement during millimeter wave pedestrian surveillance.
- A small number of non-uniform sparse array of Tx/Rx radar modules will minimize the cost of on-the-move.

B. Potential for Transition

The features of on-the-move have attracted the attention of several industrial and government organizations.

- Industrial transition partners: HXI, Inc.; L3 Communication; Rapiscan; Smiths Detection.
- Target government customers: TSA, DOJ, CBP, Dept. of State.

C. Data and/or IP Acquisition Strategy

The hardware design, integration, and validation performed under this project will continue to generate IP. In the past, several provisional patents have been submitted to NEU’s 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.
D. Transition Pathway

HXI Inc. has been collaborating with our research team in the R3-B.1 project. 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 millimeter wave system; some of these components will be tested by the R3-B.1 PIs.

The PIs have also established a working relationship with Smiths Detection Systems and L3, 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 – Dr. Simon Pongratz
- DHS – Dr. Michael Shepard

Frequency of Contact & Level of Involvement in Project:

- The PIs have weekly meetings with HXI for the project.
- The companies Smiths Detection Systems and L3 had 3 to 4 meetings with the PIs last year.
- Dr. Shepard has also visited ALERT during the last year.

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

V. PROJECT DOCUMENTATION

A. Peer Reviewed Journal Articles


Pending:


B. Peer Reviewed Conference Proceedings


C. Other Presentations

1. Seminars
   a. Jose Martinez, Stand-off Person Screening Systems, 11/19/2014, DHS
   b. Jose Martinez, R3-B: Stand-off Person Screening Systems, 3/10/2015, DHS-ALERT site visit.
   c. Jose Martinez, Millimeter-wave imaging, 3/3/2015, NEU-U.S. Secret Services
   e. Jose Martinez, Research at the SICA-Lab, 5/14/2015, NEU-Keysight
   f. Jose Martinez, Millimeter-Wave Sensing and Imaging, 5/13/2015, ADSA12 Workshop
   g. Jose Martinez, HXI-NEU radar system design, integration and validation, 6/8/2015, HXI Inc.
2. Poster Sessions

3. Interviews and/or News Articles

D. Student Theses or Dissertations

E. Technology Transfer/Patents
1. Full patent application
2. International filing

VI. REFERENCES

[8] H. Itozaki and G. Ota, “International journal on smart sensing and intelligent system,” Nuclear quad-


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