R3-B.2: Advanced Imaging and Detection of Security Threats using Compressive Sensing

Abstract—This year, we have focused on the acceleration of two inverse operators, so that they can be used by the Compressive Sensing (CS) imaging algorithms in the future. In particular, the following activities were performed for this project: 1) Development of a multistatic FFT-based formulation for imaging applications; and 2) Acceleration of the multistatic Inverse Fast Multipole Method (I-FMM) using GPUs. Both techniques are inverse methods; the FFT-based is faster than the I-FMM, however the former is less accurate than the latter. For this reason, the FFT can be used as a coarse-scale imaging algorithm and the I-FMM can be used as a fine-scale imaging algorithm.

I. PARTICIPANTS

<table>
<thead>
<tr>
<th>Name</th>
<th>Title</th>
<th>Institution</th>
<th>Email</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jose Martinez</td>
<td>Co-PI</td>
<td>NEU</td>
<td><a href="mailto:jmartine@ece.neu.edu">jmartine@ece.neu.edu</a></td>
</tr>
<tr>
<td>Carey Rappaport</td>
<td>Co-PI</td>
<td>NEU</td>
<td><a href="mailto:rappaport@neu.edu">rappaport@neu.edu</a></td>
</tr>
<tr>
<td>Borja Gonzalez-Valdes</td>
<td>Post-Doc</td>
<td>NEU</td>
<td><a href="mailto:bgonzale@ece.neu.edu">bgonzale@ece.neu.edu</a></td>
</tr>
<tr>
<td>Yuri Alvarez</td>
<td>Visiting Faculty</td>
<td>NEU</td>
<td><a href="mailto:yurilope@gmail.com">yurilope@gmail.com</a></td>
</tr>
<tr>
<td>Richard Moore</td>
<td>Consultant</td>
<td>MGH</td>
<td><a href="mailto:rhmoore@partners.org">rhmoore@partners.org</a></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Name</th>
<th>Degree Pursued</th>
<th>Institution</th>
<th>Intended Year of Graduation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yolanda Rodriguez-Vaqueiro</td>
<td>PhD</td>
<td>NEU</td>
<td>12/2014</td>
</tr>
<tr>
<td>Greg Allan</td>
<td>BS</td>
<td>NEU</td>
<td>4/2016</td>
</tr>
<tr>
<td>Matthew Nickerson</td>
<td>BS</td>
<td>NEU</td>
<td>5/2016</td>
</tr>
<tr>
<td>Galia Ghazi</td>
<td>PhD</td>
<td>NEU</td>
<td>12/2014</td>
</tr>
<tr>
<td>Luis Tirado</td>
<td>PhD</td>
<td>NEU</td>
<td>12/2014</td>
</tr>
<tr>
<td>Imani George</td>
<td>High School</td>
<td>Thayer Academy</td>
<td>2015</td>
</tr>
<tr>
<td>Jenny Dinh</td>
<td>High School</td>
<td>Lowell High School</td>
<td>2015</td>
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II. PROJECT 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 10 to 50 meters without causing physical harm.

The objective of this project is the development of advanced imaging and detection algorithms, based on Compressive Sensing (CS) techniques, which can be used to detect security threats hidden on individuals at
mid-ranges (2-10 meters) and at standoff-ranges (10-40 meters). In particular, the algorithms implemented in this project will be directly used in conjunction with the hardware developed in the ALERT project: R3-B.1- Hardware design for “Stand-off” and “On-the-Move” Detection of Security Threats. Figure 1 shows a schematic of the on the move configuration.

Figure 1: General sketch of proposed the inexpensive, high-resolution radar system being developed for the use of detecting security threats (a) at mid-ranges using an “on-the-move” configuration, and (b) at standoff-ranges using a “van-based” configuration.

III. RESEARCH ACTIVITY

A. State-of-the-art and technical approach

The outcome of this project is the development of imaging and detection algorithms required to operate the hardware developed in the R3-B.1 project. In particular, we are interested in the development of CS techniques, which can operate the radar system in quasi-real time. Our previous work demonstrated that CS techniques can be used to detect security threats at standoff distances when a Passive Array of Scatters or Mechanically Reconfigurable Surfaces are used by the imaging system [10]. Unfortunately, CS techniques are iterative methods that require multiple evaluations of forward and inverse operators. The latter requirements are time consuming, and they may limit the applicability of this technology into a real application.

This year, we have focused on the acceleration of two inverse operators, so that they can be used by the CS imaging algorithms in the future. In particular, the following activities were performed for this project: 1) Development of a multistatic FFT-based formulation for imaging applications; and 2) Acceleration of the multistatic Inverse Fast Multipole Method (I-FMM) using GPUs. Both techniques are inverse methods; the FFT-based is faster than the I-FMM, however the former is less accurate than the latter. For this reason, the FFT can be used as a coarse-scale imaging algorithm and the I-FMM can be used as a fine-scale imaging algorithm. This project is closely related to the ALERT project R3-B.1- Hardware design for “Stand-off” and “On-the-Move” Detection of Security Threats; in which a millimeter wave radar prototype has been designed, built and tested. Additionally, many of the technology and techniques developed for this project are commonly used in near-field applications by other ALERT projects, including ALERT Projects R3-A.1 and R3-A.2.

B. Major contributions

B.1 Multistatic FFT-based formulation for imaging applications
B.1.1 General description

A multistatic FFT-based formulation, derived from the monostatic case described in Sheen [11], has been developed [12]. The new method was proved to be faster than traditional SAR imaging techniques. It also reduces the computational cost, due to the use of the efficient FFT algorithm. Additional tasks that are necessary to perform the inversion, like a multidimensional interpolation, are fully parallelizable, thus being well suited to take advantage of multi-core platforms or Graphics Processing Units (GPUs).

B.1.2 Formulation

For the sake of simplicity, a 2D imaging formulation, involving range (z axis) and cross-range (x axis) will be described. The scattered field $E_{\text{scatt}}(f, x)$ acquired in a linear observation domain placed along x axis, for a certain frequency range, $f$, can be represented in the spectral domain $k_x$ by taking the Fourier Transform in the cross-range dimension:

$$
\tilde{E}_{\text{scatt}}(f, k_x) = \int E_{\text{scatt}}(f, x) e^{-j k_x x} dx
$$

with the $k_x$ domain being defined from the aperture size and the sampling rate. Next, the field in the spectral domain is translated to the imaging domain by applying a phaseshift equal to $k_z Z_0$:

$$
\tilde{E}_{\text{trans}}(f, k_x) = \tilde{E}_{\text{scatt}}(f, k_x) e^{+jk_z z_0}
$$

where $Z_0$ is the distance in range from the observation domain, $z$, to the imaging domain, which is assumed to be centered at $(z', x') = (0,0)$. $k_z$ is defined as $k_z = \sqrt{k^2 - k_x^2}$. Next, the incident field is specified. Assuming plane wave illumination:

$$
\tilde{E}_{\text{inc}}(f, k_x) = \tilde{E}_{\text{trans}}(f, k_x) e^{+jk_{inc}(z_{inc}\sin(\alpha) + x_{inc}\cos(\alpha))}
$$

where $k_{inc} = 2\pi f/c$ and $(z_{inc}, x_{inc})$ denoting the position of the transmitter. The incidence angle, $\alpha$, is defined relative to the z-axis. To recover the image centered in the imaging domain $(z', x')$, the spectral domain is re-defined as follows:

$$
k_z' = k_z + k_{z,inc} \\
k_x' = k_x + k_{x,inc}
$$

with $k_{z,inc} = k_{inc} \sin(\alpha)$, $k_{x,inc} = k_{inc} \cos(\alpha)$. Thus, the incident field $\tilde{E}_{\text{inc}}(f, k_x)$ has to be interpolated into a regular grid $k_x' = n \Delta k_x$, $k_z' = m \Delta k_z$. This step is the most time-consuming operation in Fourier-based imaging methods.

For multistatic systems, the interpolation step becomes even more challenging as the $(f, k_x)$ grid is not equally spaced in $k_x$ for oblique incidence, that is, $k_{x,inc} \neq 0$. The interpolation operation is defined as:

$$
\tilde{E}_{\text{shift, int}}(k_z', k_x') = F \left\{ \tilde{E}_{\text{shift}}(f, k_x), f \rightarrow k_z', k_x \rightarrow k_x' \right\}
$$

$F$ is the interpolation operator (e.g., linear interpolation). Finally, a 2D inverse Fourier Transform is applied to recover the reflectivity $\rho$ in the $z', x'$ domain:

$$
\rho(z', x') = \int \int \tilde{E}_{\text{shift, int}}(k_z', k_x') e^{+jk_z' z'} e^{+jk_x' x'} dk_z' dk_x'
$$

As mentioned before, the multistatic formulation has the drawback of non-uniform grid spacing in $k_x$ for oblique incidence, thus requiring 2D interpolation techniques, which increases the computational complexity. To overcome this limitation, a strategy based on $k$-space partitioning is proposed. The idea is to divide the $(k_z', k_x')$-space domain into several subdomains. The advantage of this interpolation technique is that it can be easily parallelized, as every subdomain can be processed independently. Thus, several threads can be launched in parallel for performing interpolation operations. Interpolation can be done faster by pre-calcu-
lating the interpolation operator $F$. This operator is a function of the geometry and the operating frequency band of the imaging system. Thus, for a given imaging system, operator $F$ can be calculated once, then applied to every new set of measured data.

The FFT algorithm for multistatic radar systems makes two assumptions: i) the imaging domain is centered at the origin of the coordinate system; and ii) the incident field is a plane wave. These assumptions limit the scope of application for point source-like transmitters placed in the near-field region of the imaged object. This approach will introduce a phase error in the recovered image proportional to the distance between the origin of the coordinate system and the point where the image is recovered; i.e., the difference between planar and spherical phasefronts. Thus, only the origin of the coordinate system will have zero phase error. To minimize this error, the imaging domain size is divided into several regions. Imaging is done independently for every region, locally compensating the incident field using a plane wave travelling from the transmitter to the phase center specification.

**B.1.3 Preliminary results from experimental data**

The Fourier-based multistatic imaging algorithm is validated in a three-dimensional (3D) configuration using experimental data collected with the radar system developed in the ALERT Project R3-B.1: Hardware design for “Stand-off” and “On-the-Move” Detection of Security Threats [13,14,15]. A general layout and a photograph of the radar are shown in Figure 2. The working frequency band is from 72 to 74.66 GHz, sampled every 445 MHz. The transmitting antenna is translated within $D_x = 50$ cm, $D_z = 20$ cm domain, placed $Y_{Tx} = -1.1$ m away from the center of the coordinate system, creating a synthetic transmitting aperture. This domain is sampled every 0.5 wavelengths at the highest frequency (4 mm), resulting in 251x101 transmitting positions. Range resolution ($y$-axis) is 56.4 mm, and cross-range resolution is 9 mm ($x$-axis) x 22.9 mm ($z$-axis). The receiver is placed at the position $(x, y, z) = (15, -134, 20)$ cm.

Two metallic objects are chosen as targets (see Fig. 2a). Figure 3 on the next page shows the reflectivity obtained using the Fourier-based approach. This processing takes 52 s of calculation (48 s interpolation tasks, 1 s FFT and IFFT operations, 3 s remaining calculations). This time has been found to be 213 times faster than traditional SAR when applied to the same problem.

![Figure 2: (a) Layout of the measurement setup, and (b) Photo of the measurement setup with synthetic transmitting aperture and metallic OUT. Measured field amplitude (from -30 to 0 dB) is shown with partial transparency. Note that this multistatic radar system has a moving transmitter and stationary receiver.](image-url)
B.2 A GPU implementation of the inverse fast multipole method for multi-bistatic imaging applications

B.2.1 General description

In order to make real-time image reconstruction possible, a parallel implementation of the Inverse Fast Multipole Method (IFMM) [16] on NVIDIA Compute Unified Device Architecture (CUDA) [17] Graphics Processing Units (GPUs) has been implemented.

The IFMM algorithm is an inverse scattering technique used to reconstruct the support and constitutive parameters of the object under test (OUT) from the acquired scattered field. The algorithm is based on back-propagating the scattered fields from the observation domain into the reconstruction domain. The algorithm uses the scattered field $E_m^{(q)}$ to recover the currents $j_n^{(p)}$ in a cubic subdomain $\Delta V_n$ via the following operators:

a. aggregation:

$$iA_{m_{obs}n_{source}}^p = C_0 \cdot \sum_{q=1}^{3} \sum_{m=1}^{M_{obs}} K_{m_{obs}n_{source}}^{(p,q)} e^{+jk_0\left(\tilde{r}_{m_{obs}} - \tilde{C}_{m_{obs}}\right)} \hat{k}_{m_{obs}n_{source}} \cdot E_m^{(q)}$$  \hspace{1cm} (1)

b. translation:

$$iT_{m_{obs}n_{source}}^p = iA_{m_{obs}n_{source}}^p \cdot 4 \pi k_0 |\tilde{C}_{m_{obs}} - \tilde{C}_{n_{source}}| e^{+jk_0|\tilde{C}_{m_{obs}} - \tilde{C}_{n_{source}}|}$$  \hspace{1cm} (2)

c. disaggregation:

$$j_n^{(p)} = \sum_{m_{obs}=1}^{M_{obs}} e^{+jk_0(\tilde{C}_{n_{source}} - \tilde{r}_n^{(p)})} \hat{k}_{m_{obs}n_{source}} \cdot iT_{m_{obs}n_{source}}^p \cdot \Delta V_n$$  \hspace{1cm} (3)

where $|\tilde{C}_{m_{obs}} - \tilde{C}_{n_{source}}|$ is the distance from the center of the $m_{obs}$-th observation group $\tilde{C}_{m_{obs}}$ to the center of the $n_{source}$-th source group $\tilde{C}_{n_{source}}$. The $k^{(p)}$ dyadic term and other quantities in (1-3) are defined and described in [2]. A visual depiction of the IFMM algorithm operators is shown in Figure 4 on the next page.
B.2.2 IFMM CUDA implementation

Whereas the existing C IFMM code relies on nested loops to perform the aggregation, translation and disaggregation steps, the CUDA implementation exploits GPU parallelism. It computes the aggregation and translation steps via a kernel with 2D thread blocks spanning $N_{\text{source}} \times M_{\text{obs}}$, where each block performs computations for the elements on each observation group. Disaggregation is performed via a separate 1D thread block kernel spanning the number of source points, each block performing $M_{\text{obs}}$ computations.

B.2.3 Millimeter wave radar system configuration/data and results

The developed radar system built upon the Radar Front End (RFE) Model 8300 developed by HXI [15] operates in the 70—77 GHz frequency band. A sketch of the experimental geometry used is shown in Figure 5. Scattered field data was collected by two receivers, indicated by Rx1 and Rx2 in Figure 5, while a transmitter is moved by a linear actuator over a straight line. A GaGe Octopus 8284 CompuScope digitizer board was used to capture the data. The object under test (OUT), shown in Figure 6a on the next page, is a 91.5cm long steel rod of 2.5cm in diameter, located in front of a metallic plate.

The simulations were conducted on a workstation with a 3.4 GHz Intel® Core™ i7-4930K CPU, and an NVIDIA Quadro K6000 GPU [17]. The reconstruction is carried out with the C-based and CUDA-based IFMM codes. Figure 6b on the next page presents the 2D images, for the $z=0.768$m plane, of the OUT when the field measured by the first receiver, by the second receiver, and when both receivers are used for the imaging. The IFMM CUDA code, which generates exactly the same image as the C-based version, takes 3.75s for two reconstructions, which is a considerable speedup of 46 times compared to 173.96s for the IFMM C code.

The simulations performed with measured data confirm the mm-wave radar testbed is able to discern a metallic threat 2 cm in front of another object. This is sufficient to detect, for example, a 1 inch-diameter pipe-bomb concealed underneath clothing.

The integration of the GPU-accelerated IFMM algorithm along with Modified Equivalent Current Approxima-
tion (MECA) fast forward solver [18] enables faster, iterative model-based imaging. This effort will reduce the number of transmitters and receivers in the imaging system, thus reducing its cost.

C. Future plans

1. Develop a forward operator of the FFT-based algorithm, which can be combined with the inverse operator and CS techniques, for real time imaging and detection of security threats.
2. Develop a CS code based on GPU for real time imaging and detection of security threats.
3. Study the acceleration of the imaging algorithms by using schemes like the Alternating Direction Method of Multipliers (ADMM), which are suitable to be implemented in GPUs.
4. Study the optimal parameters (number of frequencies, number of antennas, number of scatters in PAS and MRS) for the Compressive Sensing imaging algorithm.

IV. EDUCATION & WORKFORCE DEVELOPMENT ACTIVITY

Graduate student Yolanda Rodriguez-Vaqueiro will continue to play an important role in this research project. She will assist in developing new imaging and detection algorithms using CS techniques for the millimeter wave radar system. Undergraduate student Gregory Allan is an active participant in the research group. Indeed, the work he developed for this project helped him to be awarded with one of the prestigious Goldwater Scholarships. 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 of 2014. 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.
V. RELEVANCE AND TRANSITION

A. Relevance of your research to the DHS enterprise

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

1. Imaging for high throughput, non-invasive, minimal disruption scanning.
2. Full body coverage for imaging without interrupting forward steady pedestrian movement.
3. Affordable, with minimum number of non-uniform sparse array of Tx/Rx radar modules.

B. Anticipated end-user technology transfer

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

VI. LEVERAGING OF RESOURCES

New proposals related to the topic of this research will be submitted to other federal funding agencies. The work developed under this project has played an important role in receiving additional funding from other agencies, including DARPA and the United States Army.

VII. PROJECT DOCUMENTATION AND DELIVERABLES

A. Peer reviewed journal articles


Pending-


B. Peer reviewed conference proceedings


C. Other presentations

1. Seminars
   a. Jose Martinez, “Novel signal processing algorithms for the next generation of AIT systems,” 8/14/2013, DHS AIT Industry Day
   d. Jose Martinez, “Next steps on standoff and on-the-move detection of security threats,” 4/16/2014, ASPIRE workshop
   e. Jose Martinez, R3-B: Stand-off Person Screening Systems, 2/19/2014, DHS-ALERT site visit

2. Poster sessions
   a. Borja Gonzalez-Valdes, Jose Angel, Martinez, Carey M. Rappaport, Fernando Las-Heras, “Automatic SAR Processing for Profile Reconstruction and Recognition of Dielectric Objects on the Human Body Surface,” 10/14/13 ADSA09
   e. Yolanda Rodriguez-Vaqueiro and Jose Angel Martinez-Lorenzo. Compressive Sensing techniques applied to standoff detection of security threats using Passive Reflecting Surfaces, 4/10/14, RISE

D. Transferred technology/patents


VIII. REFERENCES


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