Awareness and Localization of Explosives-Related Threats (ALERT)
A Department of Homeland Security Center of Excellence

“Next steps on standoff and on-the-move detection of security threats.”

Prof. Jose Martinez-Lorenzo

ASPIRE Meeting
April 16th,
Northeastern University,
Boston, MA

This material is based upon work supported by the U.S. Department of Homeland Security under Award 2013-ST-061-ED0001. The views and conclusions contained in this document are those of the authors and should not be interpreted as necessarily representing the official policies, either expressed or implied of the U.S. Department of Homeland Security.
Introduction: Can we detect security threats in crowded environments?

Hardware design for “Stand-off” and “On-the-Move” detection of security threats

Advanced mm-wave imaging and detection of security threats

Conclusions and future plans
Can we detect security threats in crowded environments?

Boston Marathon, April 15, 2013
Can we detect security threats in crowded environments?

- Some potential opportunities:
  - Video analytics → looking for anomalous behaviors of people in the crowd.
  - Mm-wave radar → looking for anomalous objects concealed under-clothing, backpacks, etc...:
    - On-the-move system
    - Van-based standoff system
Hardware design for “Stand-off” and “On-the-Move” Detection of Security Threats

- **Overview and Technical Approach**
  - New low-cost mm-wave imaging for “Standoff” (10-50 m range) and “On-The-Move” (1-3 m walk through) concealed body-worn threat detection

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

- **Potential for Transition**
  - Industrial transition partners: L3 Communication, HXI, Inc.; Smiths Detection
  - Target government customers: TSA, DOJ, CBP, Dept. of State
Hardware design for “Stand-off” and “On-the-Move” Detection of Security Threats

- **Innovative Elements**
  - **Array of Tx/Rx**
    - Rx. – passive array
    - Tx. – mechanically scanned
  - Fully coherent multistatic radar technology
  - Separated transmitters and receivers, using low RF cable connections

**Diagram:**
- **Local Oscillator Module:**
  - Linearized VCO
  - 13.17 - 14.33 GHz
  - 70 - 86 GHz
  - 76 - 77 GHz @ 7 dBm

- **Rx Module:**
  - 100 MHz Ref. Out. @ 0 dBm
  - 50 MHz PWR

- **Tx Module:**
  - 100 MHz Ref. Out.

- **Terminology:**
  - LO (Local Oscillator)
Why is important LO? On-the-move concept

Transmitters and receivers in one-side-wall configuration

Transmitters and receivers in two-side-wall and front-rear configuration

Poor reconstruction

Good reconstruction
Experimental results

3cm separation between plate and rod in Y

Steel Plate

Steel Rod

Rx1
(0.16, -0.24, 1.14)

Rx2
(0.16, -0.24, 1.14)

Transmitter motion (aperture)

x = -0.43 to 0.43, y = 0, z = 0.768

x = -0.0013 to 0.0013
y = 1.4 to 1.4025
z = 0.215 to 1.125

Combined Image
Overview and Technical Approach

- Imaging algorithms for new low-cost mm-wave imaging for “Standoff” (10-50 m range)
- Algorithms for “On-The-Move” (1-3 m walk through) concealed body-worn threat detection, including moving body registration

Innovative Elements

- Less hardware required, since Compressive Sensing and Imaging techniques thins antenna arrays
- Improved quality of the images with faster computation time, using iterative algorithms based in Compressive Sensing
- Coded apertures
Matrix formulation:

\[ b = Ax \]

System is under-determined: \( n \ll m \)
Multiple solutions for \( X \)

\( X \) is sparse:

\[ s := \|x\|_0 \ll m \]

Compressive sensing:

\[ \min \|x\|_0 \quad \text{s.t.} \quad Ax = b \]

Convex problem (LP):

\[ \min \|x\|_1 \quad \text{s.t.} \quad Ax = b \]

Same solution if the RIP condition is satisfied: \( n \times s \) submatrix of \( A \) is an approximate isometry

\[ s \leq O \left( \frac{n}{\log(m)} \right) \]

Nesterov algorithm

Stand-off security system:
new approach 3G, 2D aperture + PAS / MRS

Matrix formulation: $b = Ax$

Sparse array antennas

Sparse array scatterers

$D_v$

$D_h$

$\phi_A < \phi_s$

Increases resolution

3D view

2D top view
Standoff detection using PAS and MRS and 3D Compressive Sensing (CS)

- 2D reconstruction using PAS

- First approach to 3D reconstruction using PRS

- Next step is used Fourier-based imaging combined with Nesterov inversion (CS) to improve the speed of the inversion.
Fourier-based Imaging for Multistatic Radar Systems

- A faster algorithm to implement SAR imaging.
- Multistatic FFT-based formulation, derived from the monostatic case.
- Multidimensional interpolation techniques to map the non-uniform k-space to a regular grid.
- Division of the main subdomain into several sub-domains to reduce phase error

\[
\rho(x, y, z) = \iiint E_{\text{shift, int}}(k'_x, k'_y, k'_z) e^{i k'_x x} e^{i k'_y y} e^{i k'_z z} dk'_x dk'_y dk'_z
\]

\[
\tilde{E}_{\text{scat}} = \iiint E_{\text{scat}}(x, y, z) e^{-j k_x x} e^{-j k_y y} dx dy
\]

- FFT 2D in the cross-range dimension
- Phase error compensation
- Phase shifting
- Interpolation
- IFFT 3D

1 Fourier-based Imaging for Multistatic Radar Systems
Yuri Álvarez, Yolanda Rodríguez-Vaqueiro, Borja Gonzalez-Valdes, Spiros Matzavinós, Carey M. Rappaport, Fernando Las-Heras, and José Angel Martínez-Lorenzo. Submitted to Transactions on Microwave Theory and Techniques on Nov. 2013, in review
Experimental results

- Fourier-based 140 times faster
- Fourier inversion can be improved by using multi-core processors and GPUs
GPU-based simulations: Forward & Inverse

### Forward method (MECA)
- Parallelization on NVIDIA Graphics Processing Units (GPUs)
- Fast simulation of scattered fields for Rx/Tx radar module

### Inverse method (IFMM)
- Move towards real-time image reconstruction via Compute Unified Device Architecture (CUDA) parallel-computing platform on GPUs

---

<table>
<thead>
<tr>
<th>MECA calculation time of scattered fields for human body torso per frequency/transmitter (seconds)</th>
</tr>
</thead>
<tbody>
<tr>
<td>30 cm x 30 cm receiver aperture</td>
</tr>
<tr>
<td>i7-4930K CPU</td>
</tr>
<tr>
<td>185.9</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>IFMM 32 frequencies image reconstruction time for human body torso per slice/transmitter (seconds)</th>
</tr>
</thead>
<tbody>
<tr>
<td>30 cm x 30 cm receiver aperture</td>
</tr>
<tr>
<td>i7-4930K CPU</td>
</tr>
<tr>
<td>420.5</td>
</tr>
</tbody>
</table>
Future Plans: Hardware

- Hardware: integration mm-wave radar system working with multiple transmitters and multiple receivers
- The radar will be fully modular, so that additional modules can be added if needed in different CONOPS
- Development and integration of mm-wave switches for commuting the multiple transmitters/receivers

Future Plans: Algorithms

- Real-time imaging algorithms using multistatic FFT & Compressive Sensing
- Enhanced CS algorithms by using the Nuclear Norm instead of Norm-1 minimization algorithms
- Parallelization of the imaging algorithms using the method of alternating direction of multipliers
- Development of advanced detection features, including clutter reduction, image enhancement, statistical analysis and machine learning