ALERT: Awareness and Localization of Explosives-Related Threats

Opportunities and Challenges for Advanced Mm-Wave Radar Whole Body Security Scanning

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Portal-Based Mm-Wave Security Screening (AIT)

- **Goal:** Detect concealed man-made objects under clothing
- **Portal-based broadband mm-wave radar**
  - 26-33 GHz (15-45 GHz)
  - 56-64 GHz
  - 70-77 GHz
  - 91-98 GHz
- **Advantages:**
  - Non-ionizing, eye-safe
  - Reasonable resolution ~ 0.25-2.5 cm
  - Sensitive to metal and low-permittivity explosives
  - Commercially available RF modules
  - Many algorithms for shape reconstruction
- **Disadvantages**
  - Huge amounts of data
  - No chemical information
  - Limited time to acquire / process
  - Poor non-specular focusing / SAR imaging
Monostatic / Multistatic Radar

- Monostatic
  - Multi-monostatic
- Bistatic
  - Multi-bistatic
- Multistatic
Radar Focusing Resolution – Point Spread Function

Aperture width \( d \)

Range resolution:
\[ \sim \frac{c}{2BW} \]

Cross range resolution:
\[ \sim \frac{r \lambda}{d} \]
Imaging with Mm-Wave Radar

- Raster scanned focused point
- Electronically scanned phased array
- Synthetic aperture radar
# AIT Systems

<table>
<thead>
<tr>
<th>Raster scanned focused point</th>
<th>Cost</th>
<th>Perf.</th>
<th>Developer</th>
</tr>
</thead>
<tbody>
<tr>
<td>Moving antenna / mirror</td>
<td>$$</td>
<td>★★★</td>
<td>JPL, PNNL</td>
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<tr>
<td>Electronically scanned reflect-array</td>
<td>$</td>
<td>★</td>
<td>Smiths</td>
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<table>
<thead>
<tr>
<th>Electronically scanned phased array</th>
<th>Cost</th>
<th>Perf.</th>
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</thead>
<tbody>
<tr>
<td>Multi-monostatic</td>
<td>$$$</td>
<td>★★★★</td>
<td></td>
</tr>
<tr>
<td>Multi-bistatic</td>
<td>$$$$</td>
<td>★★★★</td>
<td></td>
</tr>
<tr>
<td>Multistatic</td>
<td>$$$$</td>
<td>★★★★</td>
<td>Rohde &amp; Schwarz</td>
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</table>

<table>
<thead>
<tr>
<th>Synthetic aperture radar</th>
<th>Cost</th>
<th>Perf.</th>
<th>Developer</th>
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<tbody>
<tr>
<td>Moving mast of multiple monostatic</td>
<td>$</td>
<td>★★★</td>
<td>L3</td>
</tr>
<tr>
<td>Moving focusing multistatic system</td>
<td>$</td>
<td>★★★★</td>
<td>NEU</td>
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Monostatic vs. multistatic

Monostatic: Dihedral images to a point

Multistatic: Dihedral images to correct corner scatterer
Portal Provides the Possibility for Full Aperture Sensing

Huge 360 deg. Aperture

• Almost perfect body surface reconstruction
• No motion artifacts

However:
• Very expensive
• Long acquisition time
• Long computation time and massive storage
(200 × 300)² Tx/Rx
10,000 (cm²) body pts.
= 3.6 × 10¹³ focusing calculations
Current State-of-the-Practice Example: L3 ProVision Mm-Wave Imager

- TSA qualified AIT system
- Detects many types of materials based on shape (metallic and non-metallic): liquids, gels, plastics, metals, ceramics
- Uses two linear antenna arrays, scans through 240 degrees
- Quick acquisition, processing
- Mm-wave Limitations
  - Poor non-spectral imaging
  - Limited views
  - No spectroscopic info
  - Poor penetration through wet or metallic clothing
  - No penetration through skin or into body cavities
Current State-of-the-Practice Example: Smiths eqo Mm-Wave Imager

- ECAC Std. 2 qualified AIT system
- CW – 26 GHz
- Detects shape anomalies
- Uses reflect-array with single antenna: 45 deg. view (360 deg. with subject rotation)
- Extremely quick acquisition, processing (> 10 frames/s)
- Mm-wave Limitations
  - Requires subject rotation
NEU AIT Concept for 3D Body Scanning

Computed illumination on torso with foreign objects

Slice illuminated by the beam
Human body
Dielectric object
Incident beam
Scattered field
Incident field
Arcs of receivers
Blade-Beam reflector antenna (transmitter)

R = 0.75 m
R = 1 m

90°
Specially Designed Elliptical Parabolic Reflector Focuses to a Thin Slice on Body

Parabolic in azimuth
- Gives wide beam
- Parallel incident rays

Elliptical in elevation
- Gives tight “Blade Focus”
- Illuminates narrow slice
NEU System Simulated Scanning Protocol
Stacked Reconstruction Approach

(1) 2D imaging (one slice)

(2) Stacked 2D images (slices)

(3) 3D surface generation

(4) ATR algorithm and results display
- Lab prototype AIT system
- 56-63 GHz
- Detects shape anomalies
- Uses blade beam and 120 deg. receiver arc
- Second transmitter necessary for more than +/- 30 deg. field of view
- Quick acquisition, processing
- Mm-wave Limitations
Importance of Large Aperture

- Electrically large aperture provides narrow beam and high resolution (wave effect)
- As center frequency increases, for same physical aperture, resolution increases
- As distance to target increases, resolution decreases
- For given aperture, higher frequency demands more elements, more closely spaced
  - Grating lobes for uniform sparse aperture
  - Non-uniform element spacing avoids lobes
Importance of Specular Sensing

- At high frequencies, waves behave like rays
- Rays reflect from piecewise planar boundaries specularly
- Extreme focusing or ultra large bandwidth cannot compensate for specular reflection
- If reflected rays leave subject away from source, the detector must be on the other side of the subject from the source
- Ray analysis is often overlooked, but crucial for effective design
With Single Plane Wave Illumination, Receiving Array Must be Oversized (NEU)

Only front surface (normals < 22.5 deg.) imaged

Even with 2/3 of a circle, not all of forward surface imaged
With Multi-Monostatic, Either Aperture Shrinks or Specular Rays Miss Receiver (L3)

Reduced usable aperture at edges:
Reduced resolution at extremes
For Planar Apertures, Specular Reflection at Edge Points Limits Imaging (Smiths, R&S)

• Only scattering points with normals pointing to array can be imaged.
• Extreme points have aperture reduced to single element

• Even with four independent multistatic planar arrays, only ~50% of the subject can be imaged
Planar Array Requires Wider Aperture for Comparable Resolution – Typical BW Case

- 6 GHz bandwidth,
- 60 GHz center frequency
- 1.0 cm X 2.5 cm resolution

Array Position in Wavelengths ($\lambda = 0.5$ cm)
Effect of 83% Element Thinning (Compression) and Optimization

Full 151 element array

Evenly spaced 26 elements

Optimally spaced 26 elements
CS-SAR imaging.
150 receivers per arc.

Calculation time:
60 s (5 s per slice)

CS-SAR imaging.
40 receivers per arc.

Calculation time:
240 s (20 s per slice)

CS-SAR provides accurate mesh reconstruction with 73% fewer samples (i.e. receivers) than SAR.
Considerations for Fusing Technologies with Mm-Wave Sensing

- Compensate for deficiencies of mm-wave sensing
  - Low resolution
  - No skin penetration
  - Limited material identification
  - Heavy computation burden
- Establish minimum desired sensing requirements
  - Resolution
  - Material classification
- Consider completely orthogonal sensor
  - No joint inversion – simple union of sensor info
- Consider front-end fusion – joint inversion
  - Initial guess
  - Regions of particular interest
Whole Body Imaging Sensors with Multimodal Fusion Potential

- **Mm-Wave**
  - Penetrates clothing
  - Distinguishes body-worn objects other than flesh (i.e. metal, explosives, water, plastic)

- **X-ray Backscatter**
  - Penetrates all concealing layers
  - Dual energy distinguishes foreign materials
  - Ionizing radiation but very low dosage

- **THz**
  - Spectroscopic responses for explosives characterization
  - Penetrates thin clothing

- **IR Thermography**
  - Shows unusual heat patterns on body

- **NQR**
  - Non-localizing, but unique explosive discrimination
  - Penetrates throughout body
Research Personnel

Prof. Carey Rappaport
Prof. Jose A. Martinez-Lorenzo
Prof. Yuri Lopez

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Nigil Lee ‘17
Tiphannie Zeng BS’16
Thurston Brevett BS’18
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Michael Woulfe BS’18

-- also --
Katy Du BS’16, Matt Tivnan BS’17, Alex Piers BS’17, Emma Kaeli ‘18

<table>
<thead>
<tr>
<th>Faculty Involved</th>
<th>3</th>
</tr>
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<tbody>
<tr>
<td>Post-doctoral fellows</td>
<td>1</td>
</tr>
<tr>
<td>Graduate Students</td>
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<tr>
<td>Undergraduate Students</td>
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<td>Papers Published/Accepted</td>
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<td>Presentations by Students</td>
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<tr>
<td>Patents</td>
<td>5</td>
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</tbody>
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Grad Student Team:
Conclusions

- Mm-wave nearfield imaging is effective but can be improved
- Bandwidth is important – range resolution
- Aperture is important – cross range resolution
- Illumination direction is important – spectral reflection

**MUST CONSIDER BOTH WAVES AND RAYS**

- Multistatic sensing is important
  - Multiple rays scattering from same target point
  - Opportunity to observe non-specular rays
- Array thinning is useful and efficient
- Multi-modal fusion with mm-waves radar offers advantages