Multistatic 3D Whole Body Millimeter-Wave Wave Imaging for Explosives Detection

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Outline

- State of the art
- Multistatic radar
- Blade beam reflector
- Elliptical toroidal reflector
- Penetrable dielectric imaging
- Experimental results
Mm-Wave Imager: Current State-of-the-Practice – L3 ProVision

- Detects many types of materials based on shape (metallic and non-metallic): liquids, gels, plastics, metals, ceramics

- Limitations
  - “Dead Spots”
  - No chemical info
  - Limited views
  - Poor penetration through leather and metallic clothing
  - No penetration through skin or into body cavities
State of the art

Current mm-wave scanners are based on monostatic radar:

• Presents specular reflection only – no depth encoding

• Uses Fourier inversion – fast, but not best for close imaging.

• Shows shapes of metallic objects, but does not fully consider reverse imaging of weak dielectrics (i.e. explosives).

Monostatic / Multistatic Radar

- **Monostatic**
  - Multi-monostatic

- **Bistatic**
  - Multi-bistatic

- **Multistatic**
Radar Focusing Resolution – Point Spread Function

Range resolution: $\sim \frac{c}{2BW}$

Cross range resolution: $\sim \frac{r \lambda}{d}$

Aperture width $d$
Imaging with Mm-Wave Radar

- Raster scanned focused point
- Electronically scanned phased array
- Synthetic aperture radar
Multi-Monostatic vs. Multistatic
Mm-Wave Radar Imaging Example

**Multi-monostatic SAR image setup**
- Dihedral images to a point

**Multistatic SAR image setup**
- Dihedral images to correct corner scatterer

**Multi-monostatic: Dihedral images to a point**

**Multistatic: Dihedral images to correct corner scatterer**
Detection Regimes

- **Distant targets (10 m to >100 m),**
  - Stand-off detection of hazards
  - Far enough away to minimize threat

- **Mid-range targets (3 to 10m)**
  - Enhanced sensing discrimination
  - Not explicitly surrounding target

- **Intimately near targets (< 3 m)**
  - Non-invasively examined
  - Mostly portal sensors
Full-Wave Modeling of Radar Scattering from Accurate Anatomic Geometries


Threat Case with 9 Pipe Bombs
Snapshot of Waves Interacting with Scatterers
Considerable interference from various scattering points on torso

But variation across torso skin surface is slow

Pipes further confuse scattering
And variation is rapid
Custom designed elliptical torus reflector allows multiple overlapping beams for focused wide-angle illumination to speed data acquisition and image inclined body surfaces.

Multiple transmitters provide horizontal resolution and imaging of full 120 deg. of body.

Multistatic Tx and Rx array sensing avoids dihedral artifacts from body crevices and reduces non-specular drop-outs.
Operational Concept: Stack 2D Slices to Generate 3D Surface – Minimize Hardware, Simplify Calculation
System setup: Specially Designed Elliptical Parabolic Reflector Focuses to a Thin Slice on Body

Parabolic in azimuth
- Gives wide beam
- Parallel incident rays

Elliptical in elevation
- Tight “Blade Focus”
- Illuminates narrow slice
Elliptical Torus Reflector – Surface of Revolution

Allows Multiple Scanned Transmitters

- First focal point (feed)
- Second focal point (target)
- Axis of revolution
Reflector View from Above for Two Feed Positions 0 and 45°

0 degrees

-1
-0.9
-0.8
-0.7
-0.6
-0.5
-0.4
-0.3
-0.2
-0.1

x [m]

y [m]

Tx position

Second Focal Line

Target (0.2x0.4 half elliptical cylinder)

45 degrees

-1
-0.9
-0.8
-0.7
-0.6
-0.5
-0.4
-0.3
-0.2
-0.1

x [m]

y [m]

Tx position

Second Focal Line

Circular Focal Arc

Target

45°
Torus Reflector Configured with Both Transmit and Receive Elements on Focal Arc, Facing Torus
Aluminum Reflector Machined with CNC Milling Machine – 0.0001m Surface Tolerance

- 4 Identical panels
- 8 kg per panel
- Elliptical vertical profile X circular arc horizontal profile

Back view, showing rough cuts for weight reduction
Reflector / Cylinder Target Illumination for Scanned Transmitters --Simulation

Tx Position  Reflector Illumination  Target Illumination
Computed Illumination from Vertically Translating Toroidal Reflector

- Blade beam
- Vertical motion
- Freq. band: 56-63 GHz
- Range resolution: 25mm
Multistatic Imaging with Torus Reflector – 20 deg. Inclined Metal Box, Half Receiver Arc

Image from Measured Data

Image from Modeled Data

Ground Truth in Green

Max reflectivity 5.968910e+00

Max reflectivity 5.631552e+00

Max reflectivity 1.883170e+00
SAR Reconstruction of Mm-Wave Radar Measurements

Original Reconstruction

Radon / Inv. Radon processing

Curved metallic torso surrogate with attached square pipe
Dielectric (Explosive) Slab on Skin Characterization

Waves travel more slowly through dielectric:

- Slab delays response from back surface (skin reflection), making primary image look farther away (L3 Provision, Rohde & Schwarz)
- Slab refracts focused rays, making response appear closer to sensor (Smiths)

Wideband, Time Domain, Impulse

Frequency Domain -- CW

Determine Thickness and Dielectric Constant
Determining Slab Dielectric Constant with Wideband Imaging, Using Depth (Range) Response

Skin: $\varepsilon = 11.9 \varepsilon_0 + j 55.6 / (2 \pi f)$

Object 1
Object 2

$\varepsilon_r = 3$

$\varepsilon_r\text{ Est} = \left(1 + \left(\frac{d_{\text{delay}}}{d_{\text{obj}}}\right)\right)^2$

$\varepsilon_r\text{ Est} = (1 + 3/4)^2 = 49/16$


Penetrable affixed dielectric images as a depression
Metal Torso Simulant with Small Affixed Metal and Explosive Simulant Bars
Hallway Detector Paradox: Single Planar Array Requires Unrealistically Wide Aperture for Reasonable Resolution

- 30 GHz bandwidth,
- 60 GHz center frequency
- 0.5 cm × 0.5 cm resolution
Hallway, “On-the-Move” Person Scanning Concept – Imaging Subject’s Front and Back
Hallway Detector Solution: Dual Planar Arrays (or Apertures) Capture Non-Specular Scattering with Reasonable Resolution
Conclusions

- Extension of Blade Beam Reflector into Elliptical Torus for multiple overlapping high quality beams
- Illumination and receiver focusing on narrow slice for fast computation
- Fabrication, testing, optimization of wideband 60GHz multistatic radar
- Novel reflector antenna, stacked 2D reconstruction, and fast inversion for real time processing
- Minimal artifacts from dihedrals, full depth information and advanced visualization

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