High-Resolution Millimeter-Wave Tomography System for Characterization of Low-Permittivity Materials

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Agenda

1. Motivation
2. System Concept
3. Tomographic Reconstruction
4. Measurement Setup
5. Results
6. Conclusion
Microwave Tomography

Industrial Applications

› Detect defects in manufacturing material

› Visualize particle flow in pipes

However: Focus on materials with high dielectric contrast

→ no characterization of gases or light-weight foams
Agenda

Motivation

2. System Concept

Tomographic Reconstruction

Measurement Setup

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System Concept

› Characterize permittivity distribution inside area-under-test (AUT)
› Bi-static fully-integrated radar TRXs → low cost and complexity
› Synchronization for coherency → scalable master-slave operation
› Low-permittivity materials possess low attenuation → no information in amplitude
System Concept

› Evaluate medium-dependent time-of-flight (TOF)

\[ \tau_{m,n} = \int_{p_m}^{p_n} \frac{1}{v(l)} \, dl = \int_{p_m}^{p_n} \frac{\varepsilon_r(l)}{c_0} \, dl \]

› Calibrate with known material

\[ \Delta \tau_{m,n} = \tau_{m,n} - \Delta \tau_{\text{cal},m,n} \]

› Calculate from signal phase \( \varphi \) of FMCW chirp with start frequency \( f_0 \)

\[ \Delta \tau_{m,n} = \frac{\Delta \varphi_{m,n}}{2\pi f_0} \]
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Discretize on grid, linearize by substituting slowness $s = 1/v$

$$\tilde{\tau} = H \cdot s + \omega_\tau$$

- **H**: System matrix
- **$\omega_\tau$**: measurement noise

Higher-order Tikhonov regularization

$$\min_s \{ \|Hs - \tilde{\tau}\|_2^2 + \lambda^2 \|\Gamma s\|_2^2 \}$$

- **$\lambda$**: regularization parameter
- **$\Gamma$**: prior knowledge, boundary conditions

Solve slowness estimate

$$\hat{s} = \left( H^T H + \lambda^2 \Gamma^T \Gamma \right)^{-1} \cdot H^T \tilde{\tau}$$

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Measurement Setup

› Prototype with 2 radar modules and rotary stage → emulate 24 sensors
› AUT with diameter 50 cm
› Variable slave position → 15° steps in range ±30°

› 20 dBi standard gain horn antennas
Instrumentation & DUT Material

- Fully-integrated FMCW TRX by Infineon Technologies
- 1 TX, 3 RX channels active
- Master supplies LO signal

FMCW chirp settings:
- Bandwidth: 1.91 GHz
- Start frequency: 79 GHz
- Sweep Time: 107 µs

Distribution of gases difficult to reproduce in lab setup → focus on light-weight foam

- Extruded polystyrene (XPS) → thermal insulation

Characterization:
- \( \varepsilon_r \approx 1.04 \)

Calculation with Maxwell-Garnett:
- \( \varepsilon_r \approx 1.038 \)
Prototype Implementation

- Absorber
- DUTs
- RX
- TX
- Radar Sensor (Master)
- Radar Sensor (Slave)
- Synchronization
- AUT
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Scenario

Radar Sensor (Master)

Radar Sensor (Slave)

90 mm
70 mm
41 mm
100 mm

XPS
Measurement Procedure
Simulation

› High-level Matlab simulator
  ➔ Gaussian noise
  ➔ no spurious effects
› Discretization: 1 cm

Distribution of intersections:
› Majority in center due to sensor position & antenna beam width
› Best reconstruction in center, uncertainty rises towards outside
Position, orientation in good agreement
Size, permittivity underestimated due to smoothing & non-idealities
Conclusion

› Microwave tomography for gases & foams → reconstruct permittivity distribution from TOF → Tikhonov regularization

› Prototype with 2 sensors & rotary stage → 24 virtual sensors

› Radar TRXs operating at 79 GHz → reduce cost & complexity

› Scenario: 2 XPS cuboids → size, position & permittivity reconstructed
For further questions please contact the speaker via email:
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References


