MATLAB을 활용한 자동차 레이더 개발
서기환
Agenda

▪ Different Usage for Radar Modeling

▪ Radar Design Workflow
  – DSP Design and Simulation
  – RF/Antenna Modeling

▪ High Level Simulation with Probabilistic Model
Agenda

- Radar Modeling with Fidelity Control
  - Radar Design Workflow
    - DSP Design and Simulation
    - RF/Antenna Modeling
  - High Level Simulation with Probabilistic Model
Two Personas using Automotive Radar Sensor Models

**Radar Designers**

- **Radar Sensor**
  - World / Truth
  - Detections
  - Tracks
  - IQ Data
  - ...

**Radar Users**

- **Radar Sensor**
- **Lidar Sensor**
- **Camera Sensor**
- **Ultrasound Sensor**

- **World / Truth**
  - Detections
  - Tracks
Radar Modeling and Simulation

RF/Antenna Modeling DSP Algorithm Modeling

Antenna/Array/RF

Radar Signal Processing

Signal Processing

Waveform Generation

Scheduling and Radar Control

Target Classification

Tracking and Sensor Fusion

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Radar Modeling and Simulation

Probabilistic Model

Radar Sensor

Target Classification

Tracking and Sensor Fusion
# Automotive Radar Sensor Models

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Agenda

- Radar Modeling with Fidelity Control

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Radar Simulation and Modeling Architecture

- Functions for calculations and analysis
- Apps for common workflows
- Parameterized components for system modeling
- Easy path to increased fidelity for antenna and RF design
- Code generation for deployment

\[ P_r = \frac{P_t G_t G_r \lambda^2 \sigma}{(4\pi)^3 R_t^2 R_r^2 L} \]
Radar Model to Simulate High Fidelity Raw Data

Antenna, Antenna arrays
- type of element, # elements, configuration
- • Antenna Toolbox
- • Phased Array System Toolbox

Mixed-Signal
- Continuous & discrete time
  - • Simulink
  - • DSP System Toolbox
  - • Control System Toolbox

Algorithms
- beamforming, beamsteering, MIMO
  - • Phased Array System Toolbox
  - • Communications System Toolbox
  - • DSP System Toolbox

Signal Processing
- • RF Blockset
- • RF Toolbox

Tracking & Sensor Fusion
- • Sensor Fusion and Tracking Toolbox

Waveforms & Resource Scheduling
- • Phased Array System Toolbox
- • Signal Processing Toolbox
- • Wavelet Toolbox

Channel
- interference, clutter, noise

RF Impairments
- frequency dependency, non-linearity, noise, mismatches
Path to Higher Fidelity

- Extend model fidelity over project evolution
- Simple interface to replace off-the-shelf components with custom ones

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<td>Multipath, terrain and ducting effects</td>
<td>Analog-mixed simulation</td>
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DSP Algorithms for Radar Systems

 Beamforming

 Detections

 Direction of Arrival
Antenna Array Design

Design subarray with desired fidelity

Replicate to build array

\[ p = \text{design(patchMicrostrip,66e9)} \]

Assess resulting pattern
Beam Steering

Azimuth Cut (elevation angle = 0.0°)

Elevation Cut (azimuth angle = 0.0°)

Directivity (dBi), Broadside at 0.00 degrees

Aperture Size:
Y axis = 599.585 mm
Z axis = 74.948 mm
Element Spacing:
Δ y = 27.474 mm
Δ z = 37.474 mm
Synthesizing an Array from a Specified Pattern

- Introduce optimization workflow

https://blog.naver.com/matlablove/221205030640
Hybrid Beamforming

- 4 subarrays of 8 patch antennas operating at 66GHz → 4x8 = 32 antennas
- Digital beamforming applied to the 4 subarrays (azimuth steering)
- RF beamforming (phase shifters) applied to the 8 antennas (elevation steering)
RF Front End Modelling using Circuit Envelope

- Direct conversion to IF (5GHz) and superhet up-conversion to mmWave (79GHz)
- Non-linear impairments such as IP2, IP3, P1dB.
- Power dividers (e.g. S-parameters)
- Variable phase-shifters
Radar Waveform Analyzer

- Sample Rate: 90000 Hz
- Waveform: FMCW

**Ambiguity Function**

- Delay $\tau$ (ms) vs. Doppler $f_d$ (kHz)
- Persistence Spectrum: $F_{res} = 10.267$ kHz, $T_{res} = 250$ $\mu$s
Sensor Array Analyzer

Array Characteristics
- Frequency: 79 GHz
- Array Directivity: 18.18 dBi at 9 Az, 0 El
- Array Span: x=0 m to 13.29 mm, y=0 to 5.7 mm
- Number of Elements: 32
- HPBW: 12.61° Az, 42.02° El
- FWHM: 26.94° Az, 17.53° El

Array Cut (elevation angle = 0.0°)

Parameters
- Array Geometry: Uniform Rectangular
- Element Spacing: 0.05 m
- Lattice: Rectangular
- Array Normal: x
- Taper: Rectangular
- Row Taper: None
- Column Taper: Hamming

Element - Cosine Antenna
- Cosine Power: 11 dB
- Propagation Speed (m/s): 30000000000
- Signal Frequencies (Hz): 700 MHz
Radar Equation Calculator, RF Budget Analyzer

![Radar Equation Calculator interface](image1)

![RF Budget Analyzer interface](image2)

**Radar Equation Calculator**

- **Calculation Type:** Target Range
- **Radar Specifications**
  - **Wavelength:** 2.45 GHz
  - **Peak Transmit Power:** 60 kW
  - **SNR:** 30 dB
- **System Parameters**
  - **Available Input Power:** 20 dBm
  - **Noise Figure:** 1.3 dB

**RF Budget Analyzer**

- **System Parameters**
  - **Input Frequency:** 8 GHz
  - **Available Input Power:** 20 dBm
  - **Noise Figure:** 1.3 dB
Model FMCW RADARs at mmWave Frequencies
Model FMCW Radar – RF Front-End

**FMCW Radar Range, Speed, and Angle Estimation**

![Diagram of FMCW Radar System]

**Transmitter**

- Amplify and transmit the signal. Transmitter can either maintain coherence between pulses or insert phase noise.
- Parameters:
  - Peak power (W): paramFMCWRSRppow
  - Gain (dB): paramFMCWRSRtxGain
  - Loss factor (dB): 0

- Simulate using: Interpreted execution

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**Radar and Channel and Target**

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Model FMCW Radar – Transmit Array Antenna

FMCW Radar Range, Speed, and Angle
Model FMCW Radar – Signal Processing
Visualizing Radar and Target Trajectory
Automated Driving Simulation with IQ-level Radar Signal

Without ground reflection
Simulating Micro-Doppler Signatures

Micro-Doppler for Pedestrian

Bicycle
Pedestrian Micro-Doppler with and without Parked Vehicle

Micro-Doppler for pedestrian (only)  
Micro-Doppler for pedestrian and parked vehicle
Pedestrian and Bicyclist Classification Using Deep Learning
Pedestrian and Bicyclist Classification Using Deep Learning
Increasing Angular Resolution with MIMO Radars (Virtual Array)

Two options: Increase number of receive elements or perform signal processing
Simulation

Non-MIMO

MIMO

Live Data

MIMO

non-MIMO
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Virtual Driving Scenarios with Radar Sensor

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<th>Scenes</th>
<th>Cuboid</th>
<th>3D Simulation</th>
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<tr>
<td></td>
<td>![Cuboid Image]</td>
<td>![3D Simulation Image]</td>
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<tr>
<th>Testing</th>
<th>Controls, sensor fusion, planning</th>
<th>Controls, sensor fusion, planning, perception</th>
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<th>Driving Scenario Designer App Programmatic API (drivingScenario)</th>
<th>Unreal Engine Editor</th>
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<tr>
<th>Sensing</th>
<th>Probabilistic radar (detection list) Probabilistic vision (detection list) Probabilistic lane (detection list)</th>
<th>Probabilistic radar (detection list) Monocular camera (image, labels, depth) Fisheye camera (image) Lidar (point cloud)</th>
</tr>
</thead>
</table>
Synthesize Radar Sensor Data

Simulate Radar Sensors in 3D Environment
- Extract the center locations
- Use center location for road creation using driving scenario
- Define multiple moving vehicles
- Export trajectories from app
- Configure multiple probabilistic radar models
- Calculate confirmed track

*Automated Driving Toolbox™*
Design trackers

- Multi-object tracker
- Global Nearest Neighbor (GNN) tracker
- Joint Probabilistic Data Association (JPDA) tracker
- Track-Oriented Multi-Hypothesis Tracker (TOMHT)
- Probability Hypothesis Density (PHD) tracker

- Linear, extended, and unscented Kalman filters
- Particle, Gaussian-sum, and Interacting Multiple Model (IMM) filters

From various sensors at various update rates

Automated Driving Toolbox™
Sensor Fusion and Tracking Toolbox™

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Design Multi-Object Trackers

**Extended Object Tracking**
- Design multi-object tracker
- Design extended object trackers
- Evaluate tracking metrics
- Evaluate error metrics
- Evaluate desktop execution time

*Sensor Fusion and Tracking Toolbox™*
*Automated Driving Toolbox™*
Design track level fusion systems

Vehicle 1
- Detections
  - Multi-Object Tracker
  - Track Fuser
  - Tracks

Vehicle 2
- Detections
  - Multi-Object Tracker
  - Track Fuser
  - Tracks
Track-Level Fusion

Track-to-Track Fusion for Automotive Safety Applications

Parked vehicles observed by vehicle 1
Pedestrian observed by vehicle 1

Occluded vehicle fused from vehicle 1
Occluded pedestrian fused from vehicle 1

Rumor control: the fused track is dropped by vehicle 1 because vehicle 2 is coasting and there is no update by vehicle 1 sensors

Sensor Fusion and Tracking Toolbox™
Automated Driving Toolbox™

Track-Level Fusion
Key Takeaways

- Choose the Right Modeling Method
  - You can control the fidelity

- Start Your First Radar Design with Various Apps

- High Level Simulation with Probabilistic Model
  - Tracking
  - Control
Thank You!