Automotive Radar System Architecture and Evaluation with EEsol solutions

Automotive Radar Seminar
汽車雷達設計與測試研討會

Sep.21-22, 2016, Taiwan
Agenda

- **Automotive Radar Overview**

- **Automotive Radar System Simulation with EEsof Solutions**
  - Waveform generation
  - Signal processing and parameter estimation (Range/Velocity/Angle)
  - Transceiver RF/MW Front-end
  - Array Antennas
  - Verification with connected-solution

- **Summary**
Why we need automotive radar?
Comfort->Passive safety->Active safety->Autonomous Car

The trend from “comfort only” functions to autonomous systems with radar sensing technologies that serve both the comfort and the safety domain.
Automotive Radar Application

- Brake systems
- Emergency brake assist
- Lane change assist
- Lane departure warning system
- Blind spot monitoring
- Collision avoidance in urban traffic
- Occupant safety systems
- Pedestrian protection systems
- Tires and extended mobility systems
- Tire pressure monitoring systems
- Telematics for automatic emergency calls
- ContiGuard®

EBA: Emergency Brake Assist  
BSD: Blind Spot Detection  
LCA: Lane Change Assist  
RCTA: Rear Crossing Traffic Alert

ACC: Adaptive Cruise Control  
LSF: Low Speed Following  
FCW: Forward Collision Warning  
PCS: Pre-Crash Safety  
CMS: Collision Mitigation brake System  
AEB: Autonomous Emergency Braking
Automotive Radar Frequency Allocation

- **24 GHz-ISM (24.05 – 24.25 GHz)**
  - World-wide harmonized
  - Limited output power (range)
  - Narrow bandwidth (range resolution)
  - Established technology
- **24 GHz-UWB (21.65 – 26.65 GHz)**
  - Broadband, low power levels
  - Limited usage (2018) in EU with reduced bandwidth (2.4GHz)
  - High resolution
- **77 GHz-LRR (76 – 77 GHz)**
  - World-wide harmonized
  - Full power mode
  - Small sensors (wavelength is reduced compared to 24 GHz)
- **79 GHz-SRR (77 – 81 GHz)**
  - No world-wide harmonization
  - Large bandwidth, high resolution, small sensors
  - Replacement for 24 GHz-UWB

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Cited from Freescale
Players In the Automotive Radar Market

**Semi-Conductor**
- TRW, Bosch, Delphi, ADC, Continental
- TEMIC, Denso, Hitachi, Honda EleSys, Fujitsu Ten, Mitsubishi, InnoSent, Megamos, Siemens, Tyco Electronics, Valeo, Visteon, Mando, Mobis

**Radar Module**
- Infineon
- Analog Devices
- TriQuint Semiconductor
- Freescale
- Fujitsu

**Vehicles**
- AUDI
- BMW
- Mercedes-Benz
- DAIMLER
- JLR
- OPEL
- PSA
- Renault-Samsung
- VOLVO
- VW
- CHRSLER
- FORD-NA
- GM
- HONDA
- HYUNDAI
- MAZDA
- NISSAN
- TOYOTA

Image by Infineon

Image by Bosch
Automotive Radar Design & Test Challenges

Automotive safety application requirements:
CA(Collision Avoidance), AD(Autonomous Driving) are much higher than ACC(Automatic Cruise Control)
  • Extreme Low False Alarm Rate
  • Extreme Short Delay

Functional test requirements:
  • High cost
  • Unreliable test result
  • Variable environments

Design Consideration:
  • High frequency & Wide bandwidth
  • Low measurement time and computation complexity
    - Ultra short pulse length (xx ns)
    - Wide bandwidth continuous wave(CW)
  • Unambiguous range and velocity measurement with high resolution and accuracy
    - Combined LFM & FSK waveform design technique

Image by TRW Global Electronics
Multiple Topics on Automotive Radar Research Activities

- Design of waveforms for radar systems
- Baseband signal processing and parameter estimation
- Design of transceiver RF/MW Front-end
- Design of array antennas
- Connect simulation software and instruments

(Example 1)

(Example 2)
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Automotive Radar Simulation with EEs sof solutions

**Design Tools**
- **System/DSP**: SystemVue
- **uW/mmW**: ADS
- **Antenna**: ADS/EMPro
SystemVue Platform Brief Introduction

Transition naturally from Design ➔ Test with a single “cockpit”

- Quickly capture “system level” design concepts
- Model implementation-level impairments
- Connect BB, RF, and T&M for rapid validation
- Rapid prototyping with integrated measurement

- SystemVue enables system architects and algorithm developers to innovate the physical layer (PHY) of wireless and aerospace/defense communications systems and provides unique value to RF, DSP, and FPGA/ASIC implementers.
# SystemVue Radar Library
## Models and Reference Design

<table>
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<tr>
<th>Source</th>
<th>Basic</th>
<th>Advanced</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>CW Pulse, LFM, NLFM, Binary phase coded (Barker), Poly phase coded (ZCCode, Frank), PolyTime, FSK HP, Arbitrary PRN, FMCW</td>
<td>DDS, UWB, SFR, SAR, Phased Array, MIMO, PBR</td>
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<tr>
<td>RF Behavior</td>
<td>Tx and Rx Front-end, PA, LNA, Filters</td>
<td>DUC, DDC, ADC, DAC, DAC, T/R Modules</td>
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<td>Antenna</td>
<td>Antenna Tx &amp; Rx</td>
<td>Phased Array Antenna, Tx &amp; Rx, Array-Couple</td>
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<tr>
<td>Environments</td>
<td>Clutters, Jamming, Deceptive Jamming, Interference</td>
<td>Moving target, Multi Scattering RCS, STK-Link</td>
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<tr>
<td>EW</td>
<td>Detection, EP, ES, EA</td>
<td>Dynamic Signal generation, Receiver, DOA, DRFM</td>
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<tr>
<td>Signal Processing</td>
<td>Pulse Compression, Detection &amp; Tracking, CFAR, MTI, MTD</td>
<td>Beamforming, Adaptive Phased Array Receiving, STAP, SF Processing, Beam forming, Passive Radar SP</td>
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<tr>
<td>Measurements</td>
<td>Waveform, Spectrum, Group Delay</td>
<td>Antenna Pattern 2D&amp;3D, Imaging Display, Detection Rate, False Alarm Rate, Range &amp; Velocity Estimation, Un-Ambiguity Range &amp; Velocity</td>
</tr>
<tr>
<td>Moving Platform</td>
<td></td>
<td>Moving Platform Tx &amp; Rx</td>
</tr>
<tr>
<td>Systems</td>
<td>CW Pulse, Pulse Doppler, UWB FMCW, SFR, SAR</td>
<td>AESA, MIMO, PBR</td>
</tr>
<tr>
<td>Templates</td>
<td>Almost 100 design templates for reference</td>
<td></td>
</tr>
</tbody>
</table>
FMCW Radar System Architecture in SystemVue

User T/R Module
Could be used

User Algorithm
Could be used

User Algorithm
Could be used

Parameter Estimation

Input parameters
Radial Velocity = 21.0165 m/s
Distance = 586.214 m

Estimated Velocity = 20.9263 m/s
Estimated Range = 588.586 m

Example located at ..\SystemVue2015.01\Examples\Radar\System/FMCW_DSP.wsv
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### Automotive Radar Signal Modulation Types

#### Modulation Types & Waveforms

<table>
<thead>
<tr>
<th>Modulation Type</th>
<th>Waveform/Spectrum (Generated by SystemVue)</th>
<th>Pros.</th>
<th>Cons.</th>
</tr>
</thead>
</table>
| **FMCW**        | ![Waveform Image]                         | - Static & Moving targets  
- Wideband  
- Range accuracy  
- Signal processing | - Multi-target  
- Measurement time for multiple chirps |
| **FSK**         | ![Waveform Image]                         | - Multi-target  
- Cost  
- Measurement time | - Static target  
- Narrowband  
- Accuracy of Range direction |
| **SFCW**        | ![Waveform Image]                         | - Static & Moving target  
- Multi-target  
- Resolution | - Signal processing  
- Cost |
| **FSK+CW**      | ![Waveform Image]                         |       |       |
| **Combined CW** | ![Waveform Image]                         |       |       |

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**Sample Rate Calculation**

- **SampleRate** = 10e+6 Hz
- **DeltaFreq** = 400e3 Hz
- **LowerFreq** = -200e3 Hz
- **Period** = 1e-4 s
- **Amplitude** = 1 V
- **Waveform_type** = Sawtooth

**R16 (RADAR_CW@RADAR Models)**

- **Type** = CW
- **Waveform_type** = Sawtooth
- **Amplitude** = 1 V
- **Period** = 1e-4 s
- **LowerFreq** = -200e3 Hz
- **DeltaFreq** = 400e3 Hz

**R1 (RADAR_StepFreq@RADAR Models)**

- **Type** = StepFreq
- **StepFreqType_Mode** = Positive Hop
- **PRF** = 100e3 Hz
- **DeltaFreq** = 4e6 Hz
- **SampleRate** = 1e9 Hz
- **NumOfStepFreq** = 64

**R2 (RADAR_FSK@RADAR Models)**

- **Type** = FSK
- **FHSequence** = (1x2) [ -200000, 200000 ] Hz
- **PRI** = 2e-4 s
- **TimeIntervals** = (1x2) [ 100e-6, 100e-6 ] s
- **SampleRate** = 10e6 Hz
FMCW (Frequency Modulated Continuous Wave)

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R16 {RADAR_CW@RADAR Models}
Waveform_type=Sawtooth
Amplitude=1 V
Period=1e-4 s
LowerFreq=-200e3 Hz
DeltaFreq=400e3 Hz
SampleRate=10e+6 Hz [fs]

SystemVue
Radar CW waveform generation
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Radar Target Echo

Radar Equation

\[ P_r = \frac{P_i G^2 \lambda^2 \sigma}{(4\pi)^3 R^4 L} \]

Path Loss

Multi-path

Cited from Freescale

SystemVue Target echo Model

Cited from Freescale
Distance (Range) - FMCW

- Traveling Time $t_d = \frac{2R}{c}$ (2: round trip, back and forth)
- Beat frequency $f_b = f_{TX} - f_{Rx} = \frac{2R}{c} \times \frac{B_{sweep}}{T_s}$
- Homodyne receiver extracts the beat frequency

Cited from ATMOS @ TU Delft
Relative Velocity (Range Rate) detection

Moving single target

A moving target induces a Doppler frequency shift

\[ f_d = \frac{2v_r}{\lambda} \]

with the radar wavelength \( \lambda \).

The beat frequency is not only related to the range of the target, but also to its relative radial velocity with respect to the radar.

\[ v_r = \frac{c \cdot f_d}{2 \cdot f_c} \]

Cited from ATMOS @ TU Delft
Range Frequency and Doppler Frequency Discrimination

Moving Target

Beat frequency components due to range and Doppler frequency shift:

\[
 f_b = \frac{B_{\text{sweep}}}{T_s} \cdot \frac{2R}{c} \\
 f_d = \frac{2v_r}{\lambda}
\]

that are superimposed as

\[
 f_{bu} = f_b - f_d \\
 f_{bd} = f_b + f_d
\]

so range and radial velocity can be obtained as

\[
 R = \frac{cT_s}{4B_{\text{sweep}}} (f_{bd} + f_{bu}) \\
 v_r = \frac{\lambda}{4} (f_{bd} - f_{bu})
\]

Identify the target (pairing) process is high load for MPU

Cited from ATMOS @ TU Delft
Detection Algorithm Design

Range & Velocity Estimation

Custom detection algorithm can be applied in simulation mode

Range & velocity estimation algorithm is created by using MATLAB_Script model (.m)

Example:

..\SystemVue2015.01\Examples\Radar\System\FMCW_DSP.wsv
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Automotive Radar Transceiver Chipset

Example

FRDxX1050x 77GHz Radar Transceiver Chipset

Differentiating Points

- Highly integrated 77GHz automotive radar chipset supports up to 4Tx and 16 Rx channel configurations for 2D, 3D, DBF, and SAR automotive radar applications
- Supports slow and fast modulation to 10 MHz / 100 ns
- Fully integrated PLL and chirp generator programmed via SPI along with Tx power level, channel activation, & state machine control
- Designed for integration with a multitude of microprocessors including the Freescale MPC567xK

Cited from Freescale
Co-Simulation Make System Design Simple

- System design is critical to the overall success of developing a MMIC/mmMIC/SiP/SOC/Module solution
- Co-simulation at all physical levels
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Planar Antenna Array Simulation in ADS/EMPro

Momentum/FEM/FDTD

Antenna simulation results: E-Field, Gain, Radiation Efficiency, Radiated Power, Directivity, S-Param, … etc.

77GHz Antenna array
64mm x 55mm (HxW)

Phased Array Radar Modeling

WG feeder also can be modeled and simulated

Antenna Pattern can be exported to UAN file and imported to SystemVue for System Co-Simulation
Antenna Pattern From EMPro/ HFSS
Microstrip Dipole Antenna
Beamforming at SystemVue

SystemVue Schematic

Calculate weights based on beamforming direction

Add element pattern

3D plot

Specify the beamforming direction.

Specify the beamforming direction.
Beamforming (8x8)

3D plot
System-Level Simulation
Antenna Pattern and Beamforming
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- Summary
• Diagnose and solve cross-domain problems early in R&D
• Reduce excess design margin in both baseband/DSP and RF transceiver architectures
• Create an accelerated model-based design methodology that sits above traditional RF and baseband hardware design flows, and connects to them, making them more powerful.
Basic Waveform Generation – Target Return signals

SystemVue

Clutter, or noise, or Interference

DOWNLOAD
FROM SystemVue

BB Pattern Generator
BB Arb. Waveform Gen
RF Signal Generator

FMCW Transmission Signal

Received Target Return Signal
Advanced Measurements – Receiver Test

VSA89601B

MTD
up ramp & down ramp

Input parameters
Radial Velocity= 27.8392 m/s
Distance= 320 m

Estimated Velocity= 28.1554 m/s
Estimated Range= 317.8711 m

Verify custom algorithm
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Summary

– Briefly introduced the automotive radar status and applications. And then mainly analyzed the automotive radar system, especially the FMCW architecture. Finally proposed Keysight EEs of solutions for automotive radar system simulation.

– SystemVue and its Radar design library are very fit for automotive radar system architecture and evaluation. SystemVue can generate various automotive radar signals and download them to Keysight signal generators, implement signal processing and algorithm verification, and complete co-simulation of baseband and RF/MW chain with antennas.

– ADS is used for RF/MW circuit and system simulation with high accuracy and speed, and can be invoked by SystemVue for co-simulation.

– EMPro is used for antenna design and 3D EM simulation, and can export the antenna pattern file to SystemVue for beamforming and System-level simulation.