How to simulate and implement a sensor fusion based ADAS feature?

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Application Engineering
Core Products

MATLAB®
The leading environment for technical computing

▪ The industry-standard, high-level programming language for algorithm development, numeric computation, data analysis and visualization

SIMULINK®
The leading environment for modeling, simulating, and implementing dynamic and embedded systems

▪ Applications in controls, signal processing, communications, physical modeling, and other system engineering areas
Develop Automated Driving with MATLAB and Simulink
<table>
<thead>
<tr>
<th>Level</th>
<th>Automation</th>
<th>Technologies</th>
</tr>
</thead>
<tbody>
<tr>
<td>L0</td>
<td>No Automation</td>
<td>ACC, FCW</td>
</tr>
<tr>
<td>L1</td>
<td>Driver Assistance</td>
<td>Lane Keep Assist, Lateral Support, AEB-Vehicle (City/Inter-Urban)</td>
</tr>
<tr>
<td>L2</td>
<td>Partial Automation</td>
<td>Auto Pilot: Traffic Jam Assist, AEB-VRU (Pedestrian), AEB-Vehicle (City/Inter-Urban)</td>
</tr>
<tr>
<td>L3</td>
<td>Conditional Automation</td>
<td>Auto Pilot: Highway, Junction Assist, AEB-VRU (Cyclist)</td>
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<tr>
<td>L4</td>
<td>High Automation</td>
<td>Auto Pilot: Road Train, Automated Parking Valet</td>
</tr>
<tr>
<td>L5</td>
<td>Full Automation</td>
<td>Self-Driving Car, Self-Driving &amp; Human-Driven Car, R2018a, R2018b, R2017a</td>
</tr>
</tbody>
</table>
Examples of how you can use MATLAB and Simulink to develop automated driving algorithms

**Perception**
- Lidar & vision processing, labeling, deep learning
- Vehicle dynamics, 3D virtual testing

**Control**
- Sensor models, model predictive control, regression test automation
- C/C++ code analysis, security standards

**Navigation**
- Path planning
- Data analytics, big data, machine learning
- ISO 26262 Certification
- Vehicle dynamics, 3D virtual testing
Create Occupancy Grid Using Monocular Camera and Semantic...

Estimate free space and create an occupancy grid using semantic segmentation and deep learning. You then use this occupancy grid to...
FCW Algorithm using Sensor Fusion with recorded data

- Video Display
  - VideoReader
  - readFrame
  - imshow

- Video Annotation
  - parabolicLaneBoundary
  - insertLaneBoundary
  - vehicleToImage
  - insertObjectAnnotation

- birdsEyePlot
  - coverageAreaPlotter
  - plotCoverageArea
  - detectionPlotter
  - plotDetection
  - laneBoundaryPlotter
  - plotLaneBoundary
  - trackPlotter
  - plotTrack

- multiObjectTracker
  - objectDetection
  - trackingEKF
  - trackingUKF
  - trackingKF
  - updateTracks
Forward Collision Warning Algorithm using Sensor Fusion

- imu
- radarSensor
- visionSensor
- lane
- findNonClutterRadar
- objectDetection
- multiObjectTracker
- updateTracks
- assessThreat
- findMIO
- FCW
Multi-Object Tracker

Multi-object tracker using a global nearest neighbor (GNN) criterion and Kalman filter

objectDetection

updateTracks

Detects

Tracks

Parameters

AssignmentThreshold
ConfirmationParameters
NumCoastingUpdates
...

FilterInitializationFcn

trackingEKF

State-transition function
Measurement function
StateCovariance
MeasurementNoise
ProcessNoise
...

• Linear Kalman filter
• Extended Kalman filter
• Unscented Kalman filter

Update tracker with new detections
Sensor Fusion by Multi-Object Tracker

Vision detection

Radar detection

Predicted track at time step k

Fused track at time step k

Fused track at time step k-1

Range

Cross-range
Get C Code for Sensor Fusion with MATLAB Coder

Generate C code with `codegen`
A Case Study: Traffic Jam Assist
ACC and Lane Following Control for Traffic Jam Assist
Traffic Jam Assist

- It helps drivers to follow the preceding vehicle automatically with a predefined time interval in a dense traffic condition

... while controlling steering for keeping current lane.

- Partial/conditional automation at level 2/3
  - Speed limit < 60~65 km/h
  - Dense traffic condition in highway

Longitudinal control with ACC with stop & go

Lateral control with lane following
Architecture for ACC and Lane Following Controller

- Radar Detection
- Vision Detection
- Lane Detection

Sensor Fusion and Tracking → Find Lead Car → ACC

Estimate Lane Center → Preview Curvature → Lane Following

Vehicle and Environment
- Acceleration (Longitudinal)

Driving Scenario
- Ego Vehicle Dynamics
- Radar, Vision, Lane Detection Generator
- Steering (Lateral)
- Ego Longitudinal Velocity
Create Test Scenario using Driving Scenario Designer

Test Description
Lead car cut in and out in curved highway (curvature of road = 1/500 m)

Host car
- initial velocity = 20.6 m/s
- HWT (Headway Time) to lead car = 4 sec
- HW (Headway) to lead car = ~80 m
- $v_{set}$ (set velocity for ego car) = 21.5 m/s

Lead Car
- Initially, fast moving car (orange) at 19.4 m/s
- Passing car (yellow) at 19.6 m/s cut in the ego path with HWT = 2.3 s, then cut out

Third Car
- Slow moving car (purple) at 11.1 m/s in the 2nd lane
Simulation with Simulink Model for Traffic Jam Assist

**Test Description**
Lead car cut in and out in curved highway (curvature of road = 1/500 m)

**Host car**
- initial velocity = 20.6m/s
- HWT (Headway Time) to lead car = 4 sec
- HW (Headway) to lead car = ~80 m
- v_set (set velocity for ego car) = 21.5 m/s

**Lead Car**
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Architecture for ACC and Lane Following Controller

- Radar Detection
- Vision Detection
- Lane Detection

- Sensor Fusion and Tracking
- Find Lead Car
- Model Predictive Control (MPC)
- Estimate Lane Center
- Preview Curvature

Vehicle and Environment:
- Driving Scenario
- Ego Vehicle Dynamics
- Ego Longitudinal Velocity
- Radar, Vision, Lane Detection Generator

- Acceleration (Longitudinal)
- Steering (Lateral)
What is model predictive control (MPC)?

- **Multi-variable control** strategy leveraging an internal model to predict plant behavior in the near future

- **Optimizes** for the current timeslot while keeping future timeslots in account

- **Mature** control solution used in industrial applications

- **Gaining popularity in automated driving** applications to improve vehicle responsiveness while maintaining passenger comfort
How can MPC be applied to ACC and lane following control?

**Measuring outputs**
- Relative distance ($D_{relative}$)
- Ego velocity ($V_{ego}$)
- Lateral deviation ($E_{lateral}$)
- Relative yaw angle ($E_{yaw}$)

**Manipulated variables**
- Acceleration ($a$)
- Steering angle ($\delta$)

**References**
- Ego velocity set point ($V_{set}$)
- Target lateral deviation (=0)

**Measured disturbances**
- MIO velocity ($V_{mio}$)
- Previewed road curvature ($\rho$)

**Mathematical formulation**
\[
\text{minimize:} \quad w_1 |V_{ego} - V_{set}|^2 + w_2 |E_{lateral}|^2
\]

**Subject to:**
- $D_{relative} \geq D_{safe}$
- $a_{min} \leq a \leq a_{max}$
- $\delta_{min} \leq \delta \leq \delta_{max}$
# Test scenarios (1/4)

<table>
<thead>
<tr>
<th>No</th>
<th>Test Name</th>
<th>Test Description</th>
<th>Host car</th>
<th>Lead car</th>
<th>Third car</th>
<th>Spec</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>ACC_01_ISO传动_TargetDiscriminationTest</td>
<td>Target Discrimination Test</td>
<td>initial velocity = 30m/s</td>
<td>constant accel 24m/s → 27m/s @ 2m/s²</td>
<td>24m/s</td>
<td>ISO 15622 ISO 22178</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>HWT = 2.2sec (HW = 66m)</td>
<td>V_end = 27m/s (97.2kph)</td>
<td></td>
<td></td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>v_set = 30m/s</td>
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<td></td>
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<tr>
<td></td>
<td><img src="image1.png" alt="Diagram" /></td>
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<tr>
<td>2</td>
<td>ACC_02_ISO传动_AutoDecelTest</td>
<td>Automatic Deceleration Test</td>
<td>initial velocity = 15m/s</td>
<td>initial velocity = 13.9m/s</td>
<td>none</td>
<td>ISO 22178</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>HWT = 2.2sec (HW = 33m)</td>
<td>decelerates to full stop with 2.5m/s²</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>v_set = 15m/s</td>
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<tr>
<td></td>
<td><img src="image3.png" alt="Diagram" /></td>
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<td><img src="image4.png" alt="Diagram" /></td>
<td></td>
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<tr>
<td>3</td>
<td>ACC_03_ISO传动_AutoRetargetTest</td>
<td>Automatic Retargeting Capability Test</td>
<td>initial velocity = 15m/s</td>
<td>initial velocity = 13.9m/s</td>
<td>constant speed = 2.1m/s</td>
<td>ISO 22178</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>HWT = 2.2sec (HW = 33m)</td>
<td>Lead car changes lane @ HWT=3s to overtake slow moving car</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>v_set = 15m/s</td>
<td></td>
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</tr>
<tr>
<td><img src="image5.png" alt="Diagram" /></td>
<td><img src="image6.png" alt="Diagram" /></td>
<td><img src="image7.png" alt="Diagram" /></td>
<td><img src="image8.png" alt="Diagram" /></td>
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<tr>
<td>No</td>
<td>Test Name</td>
<td>Test Description</td>
<td>Host car</td>
<td>Lead car</td>
<td>Third car</td>
<td>Spec</td>
</tr>
<tr>
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<td>-----------------------------------------------</td>
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<tr>
<td>4</td>
<td>ACC_04_ISO_CurveTest</td>
<td><strong>Curve Capability Test</strong></td>
<td>initial velocity = 31.6m/s</td>
<td>initial velocity = 31.6m/s</td>
<td>none</td>
<td>ISO 15622</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(curvature of test track = 1/500 m)</td>
<td>HWT = 1.5sec</td>
<td>(HW = 47.4m)</td>
<td>ISO 22178</td>
<td></td>
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<tr>
<td></td>
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<td></td>
<td>v_set = 31.6m/s</td>
<td>Drive at a constant speed for 10s, decrease speed by 3.5m/s in 2s, and keep it constant.</td>
<td></td>
<td></td>
</tr>
<tr>
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<td></td>
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<tr>
<td>5</td>
<td>ACC_05_StopnGo</td>
<td><strong>Stop and Go in highway</strong></td>
<td>initial velocity = 27m/s</td>
<td>initial velocity = 27m/s</td>
<td>8 slow moving</td>
<td>Real-world scenario</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>HWT = 1.5sec</td>
<td></td>
<td>cars at 12m/s</td>
<td>in the second lane</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>(HW = 40.5m)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>v_set = 27m/s</td>
<td>Lead car slows down to 15m/s at -3m/s² and stay constant for 7s, then speed up to 25m/s at 2.5m/s²</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**HW**: Headway
**HWT**: Headway time
**v_set**: set velocity for ego car

\[ R \]

\[ +2.5m/s^2 \]

\[ -3m/s^2 \]
<table>
<thead>
<tr>
<th>No</th>
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<th>Third car</th>
<th>Spec</th>
</tr>
</thead>
<tbody>
<tr>
<td>6</td>
<td>LFACC_01_DoubleCurve _DecelTarget</td>
<td><strong>Automatic Deceleration Test</strong>&lt;br&gt;(Similar with ACC_04_ISO _CurveTest)</td>
<td>initial velocity = 22m/s</td>
<td>initial velocity = 22m/s</td>
<td>none</td>
<td>Real-world scenario</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>HWT = 2sec&lt;br&gt;(HW = 44m)</td>
<td>Drive at a constant speed for about 11s, decrease speed by 3.5m/s in 2s (deceleration: (-1.8 \text{ m/s}^2)) and keep it const.</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>(v_{\text{set}} = 22\text{m/s})</td>
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<td></td>
</tr>
<tr>
<td>7</td>
<td>LFACC_02_DoubleCurve _AutoRetarget_TooSlow</td>
<td><strong>Automatic Retargeting Capability Test</strong>&lt;br&gt;(Similar with ACC_03_ISO _AutoRetargetTest)</td>
<td>initial velocity = 15m/s</td>
<td>initial velocity = 13.9m/s</td>
<td>Slow moving car at constant speed = 2.1m/s</td>
<td>~ISO 22178</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>HWT = 2.8sec&lt;br&gt;(HW = 43m)</td>
<td>Lead car changes lane @ HWT=3s to overtake slow moving car</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>(v_{\text{set}} = 15\text{m/s})</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>LFACC_03_DoubleCurve _AutoRetarget</td>
<td><strong>Automatic Retargeting Capability Test</strong>&lt;br&gt;(Similar with ACC_03_ISO _AutoRetargetTest)</td>
<td>initial velocity = 15m/s</td>
<td>initial velocity = 13.9m/s</td>
<td>Slow moving car at constant speed = 10m/s</td>
<td>~ISO 22178</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>HWT = 2.8sec&lt;br&gt;(HW = 43m)</td>
<td>Lead car changes lane @ HWT=3s to overtake slow moving car</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>(v_{\text{set}} = 15\text{m/s})</td>
<td></td>
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<td></td>
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</table>
## Test scenarios (4/4)

<table>
<thead>
<tr>
<th>No</th>
<th>Test Name</th>
<th>Test Description</th>
<th>Host car</th>
<th>Lead car</th>
<th>Third car</th>
<th>Spec</th>
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</thead>
<tbody>
<tr>
<td>9</td>
<td>LFACC_04_DoubleCurve_StopnGo</td>
<td><strong>Stop and Go in curved highway</strong>&lt;br&gt;(Similar with ACC_05_StopnGo)</td>
<td>initial velocity = 14m/s</td>
<td>initial velocity = 14m/s</td>
<td>10 slow moving cars at 8m/s in the 3rd lane</td>
<td>Real-world scenario</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>HWT = 3.6sec (HW = 50m)</td>
<td>Lead car slows down to 8m/s at -1.7m/s² and stay constant for 10s, then speed up to 13m/s at 1.3m/s²</td>
<td>3 fast moving cars at 15m/s in the 1st lane</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>v_set = 14m/s</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>LFACC_05_Curve_CutInOut</td>
<td><strong>Lead car cut in and out in curved highway</strong>&lt;br&gt;(curvature of road = 1/500 m)</td>
<td>initial velocity = 20.6m/s</td>
<td>Initially, fast moving car (orange) at 19.4m/s</td>
<td>Slow moving car (purple) at scenario 11.1m/s in the 2nd lane</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>HWT = 4sec (HW = ~80m)</td>
<td>Passing car (yellow) at 19.6m/s cut in the ego path with HWT=2.3s, then cut out</td>
<td></td>
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</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>v_set = 21.5m/s</td>
<td></td>
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</tr>
<tr>
<td>11</td>
<td>LFACC_06_Curve_CutInOut_TooClose</td>
<td><strong>Lead car cut in and out in curved highway</strong>&lt;br&gt;(curvature of road = 1/500 m)</td>
<td>initial velocity = 20.6m/s</td>
<td>Initially, fast moving car (orange) at 19.4m/s</td>
<td>Slow moving car (purple) at scenario 11.1m/s in the 2nd lane</td>
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</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>HWT = 4sec (HW = ~80m)</td>
<td>Passing car (yellow) at 19.6m/s cut in the ego path with HWT=1.5s, then cut out</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>v_set = 21.5m/s</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Representative test scenario**

- HW : Headway
- HWT : Headway time
- v_set : set velocity for ego car

---
Test Manager in Simulink® Test™

- Automate Simulink model testing using test cases with pass-fail criteria
# Test Report with baseline parameter set for 11 test cases

## Summary

<table>
<thead>
<tr>
<th>Name</th>
<th>Outcome</th>
<th>Duration (Seconds)</th>
</tr>
</thead>
<tbody>
<tr>
<td>TestScenarios_Baseline</td>
<td>✅ 8 ✗ 3</td>
<td>565</td>
</tr>
<tr>
<td>ACCTest</td>
<td>✅ 3 ✗ 2</td>
<td>210</td>
</tr>
<tr>
<td>ACC_01 ISO TargetDiscriminationTest</td>
<td>✗</td>
<td>35</td>
</tr>
<tr>
<td>ACC_02 ISO AutoDecelTest</td>
<td>✗</td>
<td>22</td>
</tr>
<tr>
<td>ACC_03 ISO AutoRetargetTest</td>
<td>✗</td>
<td>32</td>
</tr>
<tr>
<td>ACC_04 ISO CurveTest</td>
<td>✅</td>
<td>43</td>
</tr>
<tr>
<td>ACC_05 StopnGo</td>
<td>✅</td>
<td>73</td>
</tr>
<tr>
<td>LFACCTest</td>
<td>✅ 5 ✗ 1</td>
<td>354</td>
</tr>
<tr>
<td>LFACC_01 DoubleDecel_DecelTarget</td>
<td>✅</td>
<td>43</td>
</tr>
<tr>
<td>LFACC_02 DoubleCurve_ AutoRetarget_TooS_low</td>
<td>✗</td>
<td>36</td>
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<tr>
<td>LFACC_03 DoubleCurve_AutoRetarget</td>
<td>✅</td>
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<tr>
<td>LFACC_04 DoubleCurve_StopnGo</td>
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<tr>
<td>LFACC_05 Curve_CutInOut</td>
<td>✅</td>
<td>48</td>
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<tr>
<td>LFACC_06 Curve_CutInOut_TooClose</td>
<td>✅</td>
<td>49</td>
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*Note: Baseline parameter set was tuned based on a single test scenario.*
Baseline vs. Fine-tuned parameters

<table>
<thead>
<tr>
<th>Parameter Name</th>
<th>Description</th>
<th>Baseline</th>
<th>Fine-tuned</th>
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<tbody>
<tr>
<td>assigThresh</td>
<td>Detection assignment threshold for multiObjectTracker</td>
<td>50</td>
<td>20</td>
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<tr>
<td>time_gap</td>
<td>ACC time gap (sec)</td>
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<td>ACC safe distance margin (m)</td>
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<tr>
<td>min_ac</td>
<td>Minimum acceleration (m/s^2)</td>
<td>-3.0</td>
<td>-3.5</td>
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</tbody>
</table>
Test Report with fine-tuned parameter set for 11 test cases

<table>
<thead>
<tr>
<th>Name</th>
<th>Outcome</th>
<th>Duration (Seconds)</th>
</tr>
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<tbody>
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<tr>
<td>ACCTest</td>
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Report Generated by Test Manager

Title: ACCAndLaneFollowing Fine-tuned
Author: Seo-Wook Park
Date: 26-Apr-2018 13:53:39

Test Environment

Platform: PCWIN64
MATLAB: (R2018a)
Extended Object Tracking
Sensor Fusion and Tracking Toolbox

Design and simulate multisensor tracking and navigation systems

Download a free trial
**Point object vs. Extended object**

- **Point object**
  - Assume “small object”
  - Single detection per object per scan
  - Need clustering the detections in pre-processing

- **Extended object**
  - High resolution sensors generate multiple detections per object per scan
  - Benefits of Extended Object Tracking
    - No clustering needed
    - Less false alarm rate
    - Additional information such as object dimensions and orientation
      - Free space estimation for obstacle avoidance
Point Object Tracker

Automated Driving System Toolbox™

- Assigns detections to tracks
- Creates new tracks
- Updates existing tracks
- Removes old tracks

- Predicts and updates state of track
- Linear, extended, and unscented Kalman filters

- Time
- Measurement
- Measurement Noise
...

- Time
- State
- State Covariance
- Track ID
- Age
- Is Confirmed
- Is Coasted
...

multiObjectTracker

Track Manager

Tracking Filter

Tracks

Detections
Sensor Fusion Using Synthetic Radar and Vision Data

Generate a scenario, simulate sensor detections, and use sensor fusion to track simulated vehicles.

Open Script
Point Object Tracker

Automated Driving System Toolbox™
Extended Object Tracker

- No clustering needed
- Additional info: shape, orientation
- Consistent tracks
- Less false positives
Point Object Tracker

Track back of leading vehicle

False track due to imperfect clustering

Track front of preceding vehicle
Extended Object Tracker

- No false track
- No clustering needed
- Additional info: shape, orientation
- Consistent tracks
- Reduced false positives

Track rear axel of leading vehicle

Track rear axel of preceding vehicle
Learn more about
Extended Object Tracking

- How to track extended objects?
- Create driving scenario
- Use the example of “Sensor fusion using synthetic radar and vision data”
- Compare Point Object Tracker vs. Extended Object Tracker
Tracking Performance Analysis

trackAssignmentMetrics

- Analyze and compare performance of multi-object tracking systems
- Compares tracks from a multi-object tracking system against known truth by automatic assignment of tracks to the known truths at each track update.

trackErrorMetrics

- Get error metrics for tracks
Scan the QR code on the right,
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Know more about automated driving & MathWorks online resources!