Automated Driving
with MATLAB® and Simulink®

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2018-04-05
How can you use MATLAB and Simulink to develop automated driving algorithms?

- Perception
- Control
- Planning
Examples of how you can use MATLAB and Simulink to develop automated driving algorithms.

Perception

Control

Planning

Deep learning

Sensor models & model predictive control

Sensor fusion with live data

Path planning
How can you use MATLAB and Simulink to develop perception algorithms?

- Deep learning
- Sensor fusion with live data
- Perception
- Control
- Planning
- Sensor models & model predictive control
- Path planning
Automated Driving System Toolbox introduced:
Ground Truth Labeling App to label video data
Automate labeling lanes with Ground Truth Labeler

Run automation algorithm
Specify attributes and sublabels in Ground Truth Labeler App
Automate labeling pixels with Ground Truth Labeler
Learn how to train a deep learning network using this example

- Train free space detection network using deep learning
  Computer Vision System Toolbox™
Load and plot training images

% Create datastore for images
imds = imageDatastore(imgDir);
I = readimage(imds, 1);
I = histeq(I);
imshow(I)
% Load pixel labels
classes = ['Sky'; 'Building';...
         'Pole'; 'Road'; 'Pavement'; 'Tree';...
         'SignSymbol'; 'Fence'; 'Car';...
         'Pedestrian'; 'Bicyclist'];
pxds = pixelLabelDatastore(...
    labelDir,classes,labelIDs);

% Display labeled image
C = readimage(pxds, 1);
cmap = camvidColorMap;
B = labeloverlay(I,C,'ColorMap',cmap);
imshow(B)
% Visualize label count by class

tbl = countEachLabel(pxls)

frequency = tbl.PixelCount / ...
            sum(tbl.PixelCount);

bar(1:numel(classes),frequency)
xticks(1:numel(classes))
xticklabels(tbl.Name)
xtickangle(45)
ylabel('Frequency')
Create and visualize baseline network

% Create SegNet architecture
lgraph = segnetLayers(...
    imageSize, numClasses,...
    'vgg16');

% Display network structure
plot(lgraph)
title('Complete Layer Graph')

% Display last layers
plot(lgraph); ylim([0 9.5])
title('Last 9 Layers Graph')
Add weighted layer to compensate for imbalanced data set

% Create weighted layer
pxLayer = pixelClassificationLayer(...
    'Name', 'weightedLabels', 'ClassNames', tbl.Name,...
    'ClassWeights', classWeights)
Add weighted layer to compensate for imbalanced data set

% Create weighted layer
pxLayer = pixelClassificationLayer(...
    'Name','weightedLabels', 'ClassNames',tbl.Name,...
    'ClassWeights',classWeights)

% Replace layer
lgraph = removeLayers(lgraph, 'pixelLabels');
lgraph = addLayers(lgraph, pxLayer);
lgraph = connectLayers(lgraph,...
    'softmax', 'weightedLabels');

% Display network structure
plot(lgraph); ylim([0 9.5])
title('Replaced Layers Graph')
Augment images to expand training set

```matlab
augmenter = imageDataAugmenter(...
    'RandXReflection', true,...
    'RandRotation', [-30 30],... % degrees
    'RandXTranslation',[-10 10],... % pixels
    'RandYTranslation',[-10 10]; % pixels

datasource = pixelLabelImageSource(...
    imdsTrain,... % Image datastore
    pxdTrain,... % Pixel datastore
    'DataAugmentation',augmenter)
```
Deep learning on CPU, GPU, multi-GPU and clusters

options = trainingOptions('sgdm', ...
    'InitialLearnRate', 1e-3, ...
    'MaxEpochs', 100, ...
    'MiniBatchSize', 4, ...
    'Shuffle', 'every-epoch', ...
    'VerboseFrequency', 2, ...
    'ExecutionEnvironment', 'auto');

Single CPU
Single CPU
Single GPU
Multiple GPUs
On-prem server with GPUs
Cloud GPUs (AWS, Azure, etc.)

'auto'
'auto'
'multi-gpu'
'parallel'
'parallel'
Train network and view progress

```
[net, info] = trainNetwork(datasource, lgraph, options);
```
% Plot actual results
I = read(imdsTest);
actual = semanticseg(I, net);

B = labeloverlay(I, ...
    actual,...
    'Colormap', cmap,...
    'Transparency', 0.4);
imshow(B)
pixelLabelColorbar(cmap, classes);
title('Actual')
Visually compare actual with original labeled results

% Plot expected results
% using original labels
expected = read(pxdstest);
E = labeloverlay(I,...
    expected,...
    'Colormap', cmap,...
    'Transparency',0.4);
imshow(E)
title('Expected');
Visually compare actual with original labeled results

% Plot differences
imshowpair(...
   uint8(actual),...
   uint8(expected));
title('Difference');
Assess similarity using intersection-over-union (IoU) metric

\[ \text{iou} = \text{jaccard}(\text{actual}, \ldots, \text{expected}); \]

table(classes, iou)

\[
\begin{array}{|c|c|}
\hline
\text{classes} & \text{iou} \\
\hline
"Sky" & 0.92659 \\
"Building" & 0.7987 \\
"Pole" & 0.16978 \\
"Road" & 0.95177 \\
"Pavement" & 0.41877 \\
"Tree" & 0.43401 \\
"SignSymbol" & 0.32509 \\
"Fence" & 0.492 \\
"Car" & 0.068756 \\
"Pedestrian" & 0 \\
"Bicyclist" & 0 \\
\hline
\end{array}
\]
Evaluate trained network statistics

pxdsResults = ...
    semanticseg(...
        imdsTest, net, ...
        'WriteLocation', tempdir, ...
        'Verbose', false);

metrics = ...
    evaluateSemanticSegmentation(...
        pxdsResults, pxdsTest, ...
        'Verbose', false);

metrics.ClassMetrics
Distribution of labels in data affects intersection-over-union (IoU)

Underrepresented classes such as Pedestrian and Bicyclist are not segmented as well as classes such as Sky and Road.
Generate CUDA Code for Embedded Deployment

```matlab
% Save network to MAT file
save('SegNet.mat', 'net')

function out = segnet_predict(in) %#codegen
persistent mynet;
if isempty(mynet)
    mynet = coder.loadDeepLearningNetwork('SegNet.mat');
end
out = predict(mynet,in);

% Generate CUDA code
cfg = coder.config('lib');
cfg.TargetLang = 'C++';
codegen -config cfg segnet_predict -args
{ones(360,480,3,'uint8')} -report
```
Free Space Detection Using Semantic Segmentation
Learn more about developing deep learning perception algorithms with these examples

- **Train free space detection network** using deep learning
  *Computer Vision System Toolbox™*

- **Generate CUDA® code** to execute directed acyclic graph network on an NVIDIA GPU
  *GPU Coder™*

- **Add semantic segmentation automation algorithm** to Ground Truth Labeler App
  *Automated Driving System Toolbox™*
Learn about developing lidar perception algorithms with these examples

- **Read Velodyne files**
  - `velodyneFileReader` Automated Driving System Toolbox™

- **Register point clouds with Normal Distributions Transform**
  - `pcregisterndt` Computer Vision System Toolbox™

- **Segment lidar point cloud**
  - `segmentLidarData` Automated Driving System Toolbox™

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Display Point Clouds from Velodyne PCAP File

Align Two Point Clouds Using NDT Algorithm

Cluster Organized Lidar Point Cloud
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Automated Driving System Toolbox introduced:
Multi-object tracker to develop sensor fusion algorithms

- Assigns detections to tracks
- Creates new tracks
- Updates existing tracks
- Removes old tracks
- Predicts and updates state of track
- Supports linear, extended, and unscented Kalman filters
Automated Driving System Toolbox introduced examples to:
Develop sensor fusion algorithms with recorded data

- Design multi-object tracker based on logged vehicle data
- Generate C/C++ code from algorithm which includes a multi-object tracker
How can I test my sensor fusion algorithm with live data?
Test forward collision warning algorithm with live data from vehicle

FCW application

- Read sensor data stream and video stream
- Vision Object
- Radar Object
- Lane
- Vehicle Speed
- Yaw Rate
- Video frame

FCW algorithm

Visualization

TCP/IP

CAN FD

Radar

Camera

IMU
Test forward collision warning algorithm with live data from “surrogate” vehicle
Send and live CAN FD and TCP/IP data
Receive live CAN FD and TCP/IP data
Generate C/C++ code for algorithm
Stream live CAN FD and TCP/IP data into compiled algorithm code

Algorithm uses 1’s of msec in software-in-the-loop mode
Learn about developing sensor fusion algorithms with live data using this example

- **Stream CAN FD** data to prototype algorithms on your laptop

*Vehicle Network Toolbox™*
How can you use MATLAB and Simulink to develop control algorithms?

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Automated Driving System Toolbox introduced examples to:

- Synthesize detections to test sensor fusion algorithms
- Synthesize radar detections with probabilistic impairments
- Synthesize vision detections with probabilistic impairments
- Synthesize scenario to test multi-object tracker
Simulate closed loop system with radar/vision detections, sensor fusion, and model-predictive control
Synthesize detections to test sensor fusion and model-predictive controller
How can MPC be applied to lane keeping control?

References
1. For $E_{\text{lateral}}\ (0)$
2. For $E_{\text{yaw}}\ (0)$

Measured disturbance
1. Previewed curvature

minimize: $|E_{\text{lateral}}|^2 + |E_{\text{yaw}}|^2$
subject to: $u_{\text{min}} \leq u \leq u_{\text{max}}$

Measured outputs
1. Lateral deviation ($E_{\text{lateral}}$)
2. Relative yaw angle ($E_{\text{yaw}}$)

Manipulated variable
1. Steering angle ($u$)

MPC controller

Optimizer

Ego vehicle model

Ego vehicle

Ego vehicle model
Vision Detection Generator models lane detection sensor

![Vision Detection Generator block diagram](image)

**Block Parameters: Vision Detection Generator**

- **Vision Detection Generator**
  - Sensor simulation block used to generate vision detections from simulated actor poses.
  - Detections are generated at intervals of the sensor's update interval. A statistical model generates measurement noise, true detections, and false positives. The random numbers used by the statistical model are controlled by the random number generator settings on the Measurements tab.

**Source code**

- **Parameters**
  - **Unique Identifier of sensor:** 1
  - **Types of detections generated by sensor:**
    - Lanes and objects
  - **Required interval between sensor updates (s):**
  - **Required interval between lane detection updates (s):**
    - Lanes and occlusion
  - **Sensor's (x,y) position (m):** [1.9, 0]
  - **Sensor's height (m):** 1.1
  - **Yaw angle of sensor mounted on ego vehicle (deg):** 0
  - **Pitch angle of sensor mounted on ego vehicle (deg):** 1
  - **Roll angle of sensor mounted on ego vehicle (deg):** 0
Create highway double curve with drivingScenario

- Driver waypoints simulate distraction at curvature changes
Simulate distracted driver
Simulate lane keep assist at distraction events
Compare distracted and assisted results

- Detect lane departure and maintain lane during distraction
Detect departure based on lateral offset to lane boundary
Simulate lane following by increasing minimum safe distance
Explore lane following results

- Vehicle stays within lane boundaries
Graphically edit scenarios with Driving Scenario Designer
Explore what is required to follow high curvature paths

Follows curvy lanes at slower speed with wider field of view
Learn about synthesizing sensor detections to develop control algorithms with these examples

- Simulate and generate C++ for model-predictive control and sensor fusion algorithms
- Simulate and generate C++ for model-predictive control with lane detections
- Edit roads, cuboid actors, and sensors with Driving Scenario Designer App
  drivingScenarioDesigner
Learn about modeling vehicle dynamics to develop control algorithms with these examples

- **Simulate vehicle dynamics** for closed loop design
  Vehicle Dynamics Blockset™

- **Co-simulate with Unreal Engine** and to set actor positions get camera image
  Vehicle Dynamics Blockset™
How can you use MATLAB and Simulink to develop planning algorithms?

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Planning
Robotics System Toolbox introduced: Connectivity with the ROS ecosystem

- Communicate via ROS to integrate with externally authored ROS components
- Communication with Gazebo to visualize and simulated system
- Follow path for differential drive robot with ROS based simulator
We are investing in design and simulation of path planning for automobiles
Learn about developing path planning algorithms with these examples

- **Plan path** for automobile given pre-defined map
  Automated Driving System Toolbox™

- **Plot map tiles** using World Street Map (Esri)
  Automated Driving System Toolbox™

- **Simulate V2X communication** to assess channel throughput
  LTE System Toolbox™
Examples of how you can use MATLAB and Simulink to develop automated driving algorithms

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MathWorks can help you customize MATLAB and Simulink for your automated driving application

- Web based ground truth labeling
  - Consulting project with Caterpillar
  - 2017 MathWorks Automotive Conference

- Lidar ground truth labeling
  - Joint presentation with Autoliv
  - 2018 MathWorks Automotive Conference (May 2\textsuperscript{nd}, Plymouth MI)

- Lidar sensor model for Unreal Engine
  - Joint paper with Ford
  - SAE Paper 2017-01-0107
How can we help you can use MATLAB and Simulink to develop automated driving algorithms?