Embedded Machine Learning:
Enabling Workflows for Edge Devices

Gokhan Atinc
BMW designs, tests and deploys data-driven systems that enhance vehicles’ capabilities using MATLAB and Simulink


> 95% accuracy
MathWorks provides embedded machine learning workflows that integrate nicely with Model-Based Design.

- **MATLAB**
  - Data-driven, smart algorithms capable of running on edge devices

- **SIMULINK**
  - Embedded Machine Learning
    - Data-driven, smart algorithms capable of running on edge devices

- **GPU Coder**
- **MATLAB Coder**
- **Simulink Coder**

- **Software In The Loop**
- **Processor In The Loop**
- **Hardware In The Loop**

**Embedded Systems**
Machine learning algorithms are supported for a variety of embedded systems workflows

Deploy machine learning models in MATLAB & Simulink

Deploy fixed-point machine learning models

In-place modification of deployed models

```
fixdt(1,8,3)
```

1 | 0 | 1 | 1 | 0 | 0 | 1 | 0

Real world value: -9.75
Learner apps provide convenient ways to compare and iterate over different machine learning algorithms.
Classification Learner App demonstration
Models trained with Learner App can be saved for deployment

**Extract Trained Model**

```matlab
ensembleModel =

struct with fields:
    predictFcn: @(x)exportableModel.predictFcn(predictorExtractionFcn(x))
    ClassificationEnsemble: [1x1 classreg.learning.classif.CompactClassificationEnsemble]
    HyperParameterOptimizationResult: [1x1 bayesianOptimization]

About: 'This struct is a trained model exported from Classification Learner R2020a.'
HowToPredict: 'To make predictions on a new predictor column matrix, \( X \), use: \( yhat = c.predictFcn(X) \)'
```

**Save Trained Model for Deployment**

```matlab
saveLearnerForCoder(ensembleModel.ClassificationEnsemble,'DigitImagesRF');
```
Trained models can be used in Simulink

openExample('stats/SystemObjectsForClassificationAndCodeGenerationExample')

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Trained models can be used in Simulink

ECOC System object

Random Forest System object
Trained models can be used in Simulink via System Blocks
Majority of machine learning models are supported for deployment

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<th>Supported Models</th>
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<tr>
<td>• Linear Classification</td>
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<td>• SVM</td>
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<td>• Decision trees and Random Forests</td>
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<td>• Linear Discriminant Analysis</td>
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<td>• k-Nearest Neighbor models</td>
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<td>• Gaussian Process</td>
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<td>• Linear/Generalized Linear Regression</td>
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Deploy machine learning models in MATLAB & Simulink
Native Simulink Library Blocks

Supported Models
- Binary Classification SVM
- Regression SVM

R2020b
Majority of machine learning models are supported for deployment

Supported Models
- Linear Classification
- SVM
- Decision trees and Random Forests
- Linear Discriminant Analysis
- k-Nearest Neighbor models
- Ensemble models
- Naïve Bayes models
- Gaussian Process
- Linear/Generalized Linear Regression

Simulink
- Simulink Library Blocks
- MATLAB System Block
- MATLAB Function Block
- Stateflow

Deploy machine learning models in MATLAB & Simulink
Machine learning algorithms are supported for fixed-point workflows

Deploy machine learning models in MATLAB & Simulink

Deploy fixed-point machine learning models

In-place modification of deployed models

```
fixdt(1,8,3)
```

1 0 1 1 0 0 1 0

Real world value: -9.75
Deploy fixed-point machine learning models

Minimize energy consumption
Reduce cost

fixdt(1,8,3)

1 0 1 1 0 0 1 0

Real world value: -9.75
Fixed-point workflows allow deployment of models with small memory footprint.

Train in MATLAB

- Supervised Learning
  - CLASSIFICATION
  - REGRESSION

Model

Fixed-Point Representation of Model

New Data

Fixed-Point Implementation of Predict

Convert in Fixed-Point Designer

Cost-effective model

Predict on low power embedded device

- fixdt(1,8,3)
  - $\begin{bmatrix} 1 & 0 & 1 & 1 & 0 & 0 & 1 & 0 \end{bmatrix}$
  - Real world value: -9.75
Fixed-point conversion is a trade-off between resource usage optimization and accuracy
Popular machine learning models are supported for fixed-point workflows

**Supported Models**
- Binary SVM
- Decision Trees
- Ensembles of Decision Trees
Machine learning algorithms are supported for in-place modification workflows

**Deploy machine learning models in MATLAB & Simulink**

**Deploy fixed-point machine learning models**

**In-place modification of deployed models**

Machine learning algorithms are supported for in-place modification workflows.

**Deploy machine learning models in MATLAB & Simulink**

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In-place modification of deployed models

Update running model

SIL/HIL Verification of models

OTA Update of models on remote vehicles

C/C++
In-place modification of deployed models allows model updates without code regeneration.
In-place modification workflow is agnostic to communication method, supported in Simulink

Modified version of `openExample('stats/HARDeploymentExample')`
Popular machine learning models are supported for in-place modification workflows

**Supported Models**
- SVM
- Linear Models
- Decision Trees
Machine learning algorithms are supported for a variety of embedded systems workflows.

**Deploy machine learning models in MATLAB & Simulink**

**Deploy fixed-point machine learning models**

**In-place modification of deployed models**

```
fixdt(1,8,3)
```

1 0 1 1 0 0 1 0

Real world value: -9.75
Q & A

Which machine learning algorithms have you previously used in your projects?

A SVM  B Decision Trees
C Ensembles  D Gaussian Process Models
E KNN  F Other

Are you already working on a project that involves deploying a machine learning model to an edge device?

A YES  B NO

If you have questions, please reach out:

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