2022 MathWorks
中国汽车年会

数据驱动的动态系统建模-模型降阶之路

刘海伟, MathWorks 中国

MathWorks

Agenda

- 动态系统与数据驱动模型简介
- 基于AI的降阶模型开发与集成
- MathWorks的AI与MBD技术支持

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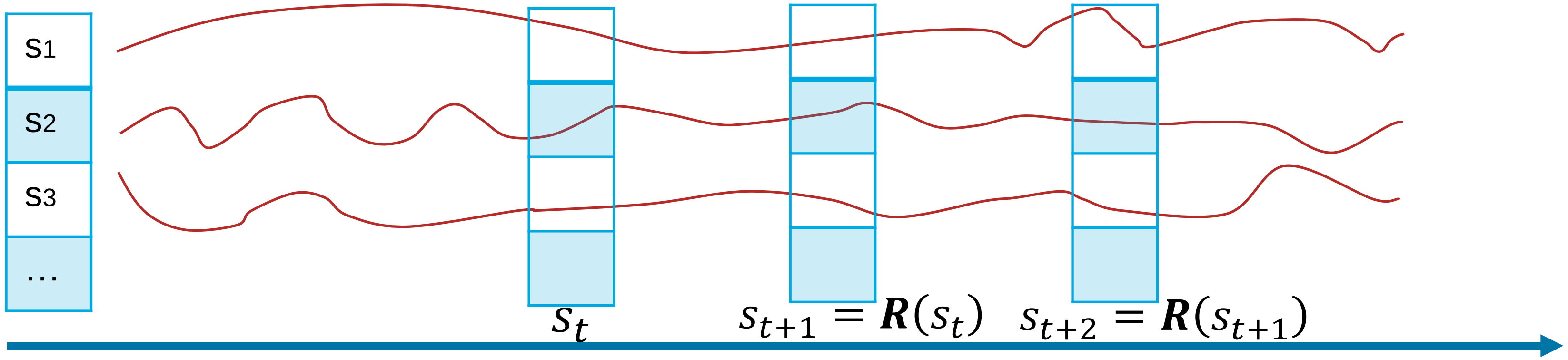
动态系统

状态空间：S

$\boldsymbol{R}: S \times T \rightarrow S$

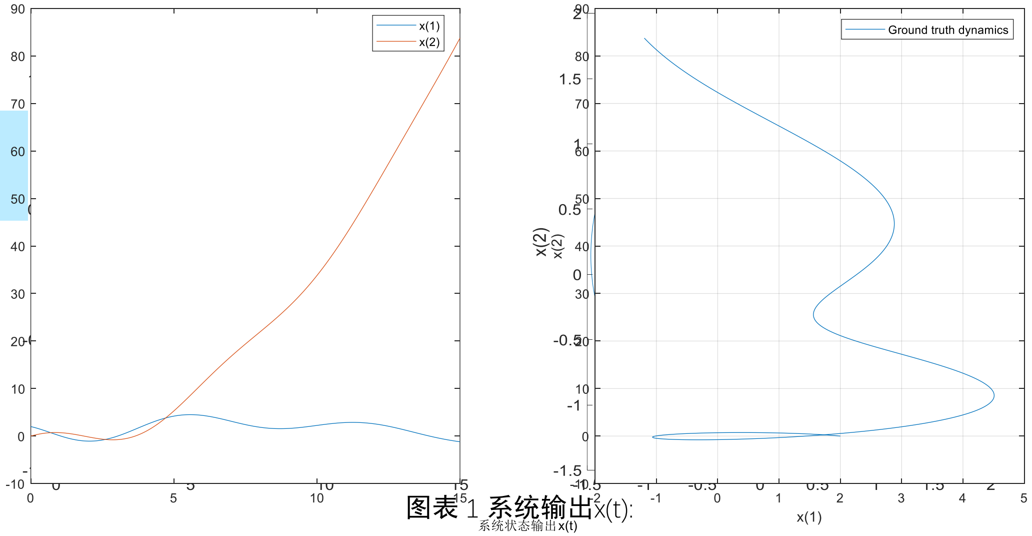


时间集：T

简单的线性系统

$x(t)' = Ax(t) + Bu(t)$

```
x0 = [2; 0];
A = [-0.1 -1; 1 -0.1];
trueModel = @(t,y) A*y + B*controlsignal(t,ft,f);
% 定义系统函数，此处就是一个状态空间方程
numTimeSteps = 2000;
T = 15;
odeOptions = odeset(RelTol=1.e-7);
t = linspace(0, T, numTimeSteps);
[~, xTrain] = ode45(trueModel, t, x0,
odeOptions);
```



图表 1 系统输出x(t):

何为数据驱动的动态系统建模

- 旋转体的状态空间模型　（线性系统）

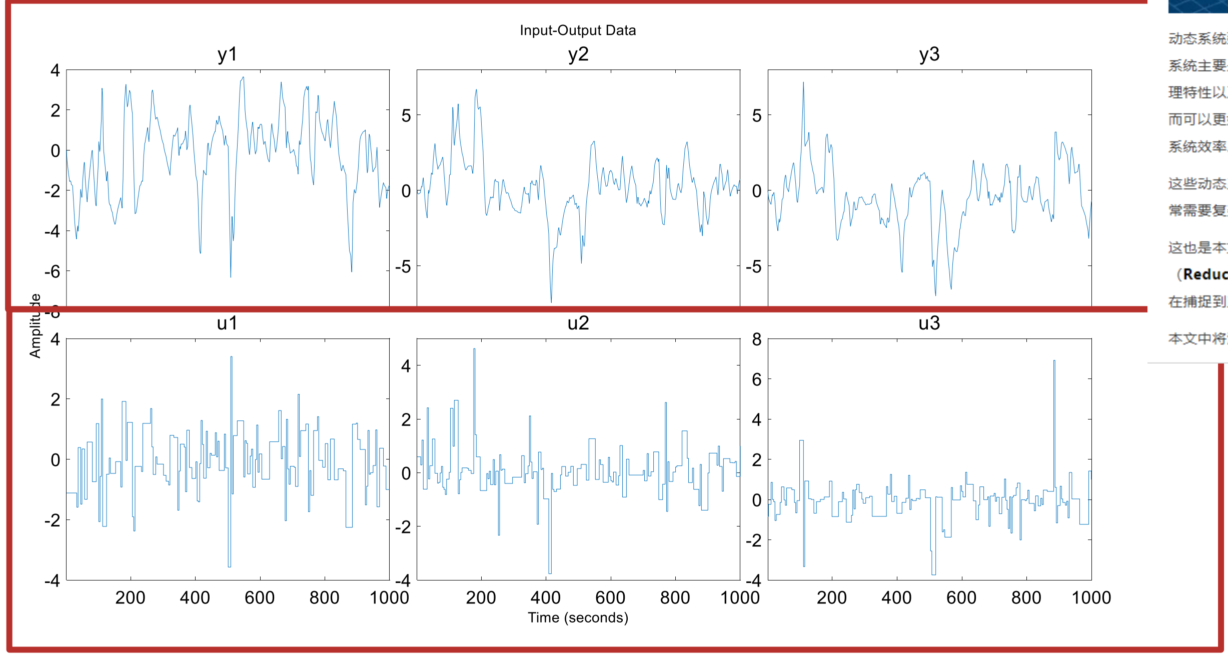
$$\frac{dx}{dt} = Ax + Bu$$
$$y = Cx + Du$$

$$J\frac{d\omega}{dt} + F\omega = T$$
$$y = \omega$$

$\boldsymbol{A} = -J^{-1}F, \boldsymbol{B} = J^{-1},$
$\boldsymbol{C} = I, \quad \boldsymbol{D} = 0$

$$\frac{d\omega}{dt} = -J^{-1}F\omega + J^{-1}$$
$$y = \omega$$

```
sys_mimo = ss(A,B,C,D);
[y,t] = lsim(sys_mimo,u,t);
```



数据驱动的动态系统（Dynamical System）建模(一)：深度学习

Original 刘海伟 MATLAB 2022-04-06 18:00

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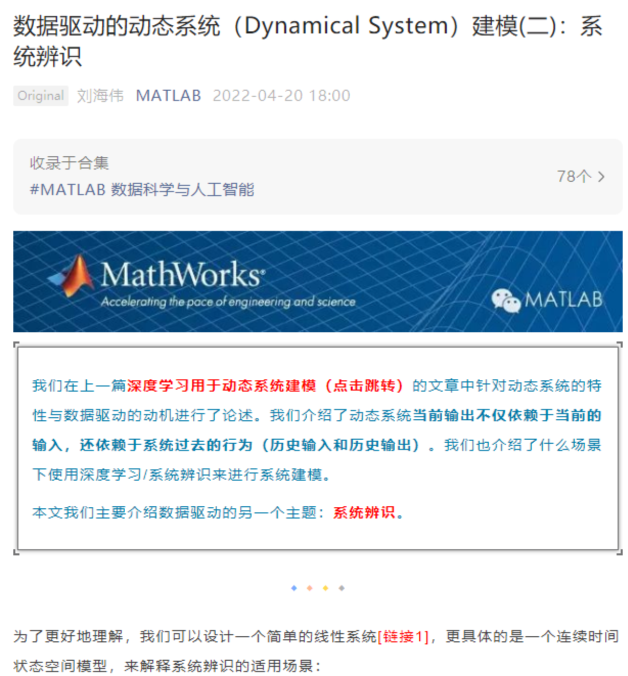
#MATLAB 数据科学与人工智能 78个 >

动态系统建模被各领域广泛应用，例如电动汽车，能源系统，航空航天。我们本文提到动态系统主要是**被控对象**，对被控对象进行建模是因为我们希望了解这个系统（被控对象）的物理特性以及接受一些外部输入（力，扭矩，电流等等）时会有什么样的动态响应，基于此从而可以更好的给出控制输入得到我们期望的系统的输出，以及理解系统的退化或最大化提升系统效率。

这些动态系统的行为是由多物理场复杂的交互作用决定的，因此系统行为和系统响应建模通常需要复杂的第一原理支撑，仿真时也需要大量的计算(例如有限元模型)。

这也是本文的出发点，提供数据驱动（主要介绍**深度学习和系统辨识**）的模型降阶（**Reduced Order Modeling**）提速的方法，通过数据得到具有一定保真度的数据模型，在捕捉到系统**动态特性**的同时也提升**仿真速度**。

本文中将涉及多个 demo，数据以及脚本文件，若您感兴趣进一步获取这些链接，可以在文



数据驱动的动态系统（Dynamical System）建模(二)：系统辨识

Original 刘海伟 MATLAB 2022-04-20 18:00

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#MATLAB 数据科学与人工智能 78个 >

我们在上一篇**深度学习用于动态系统建模（点击跳转）**的文章中针对动态系统的特性与数据驱动的动机进行了论述。我们介绍了动态系统**当前输出不仅依赖于当前的输入，还依赖于系统过去的行为（历史输入和历史输出）**。我们也介绍了什么场景下使用深度学习/系统辨识来进行系统建模。

本文我们主要介绍数据驱动的另一个主题：**系统辨识**。

为了更好地理解，我们可以设计一个简单的线性系统[链接1]，更具体的是一个连续时间状态空间模型，来解释系统辨识的适用场景：

Continental 使用动态神经网络用于估计发动机温度

Classical ECU Functions
Advantages/Disadvantes

Advantages	Disadvantage
Physically motivated	Require development (modelling + coding)
High understanding of whats going on (intermediate signals have typically physical units)	Require methodology development for calibration = training
Enabling "transfer learning" for single HW change	Require tooling for the training (backpropagation)
	Require very special measurements from engine test bench

Continental | Electrification & Data Analytics Internal | 11.04.19 Michael Wutz, © Continental AG

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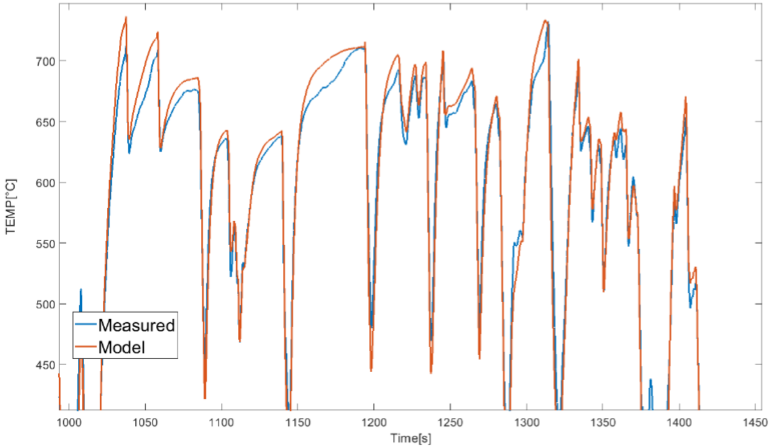
Deep Dynamical Systems
Temperature example 40min of driving (validation)



Continental | Electrification & Data Analytics Internal | 11.04.19 Michael Wutz, © Continental AG

Link to presentation

Renault 使用Deep Learning Networks 来估计 NO_X 排放: LSTM

挑战

Design, simulate, and improve aftertreatment systems to reduce oxides of nitrogen (NO_X) emissions

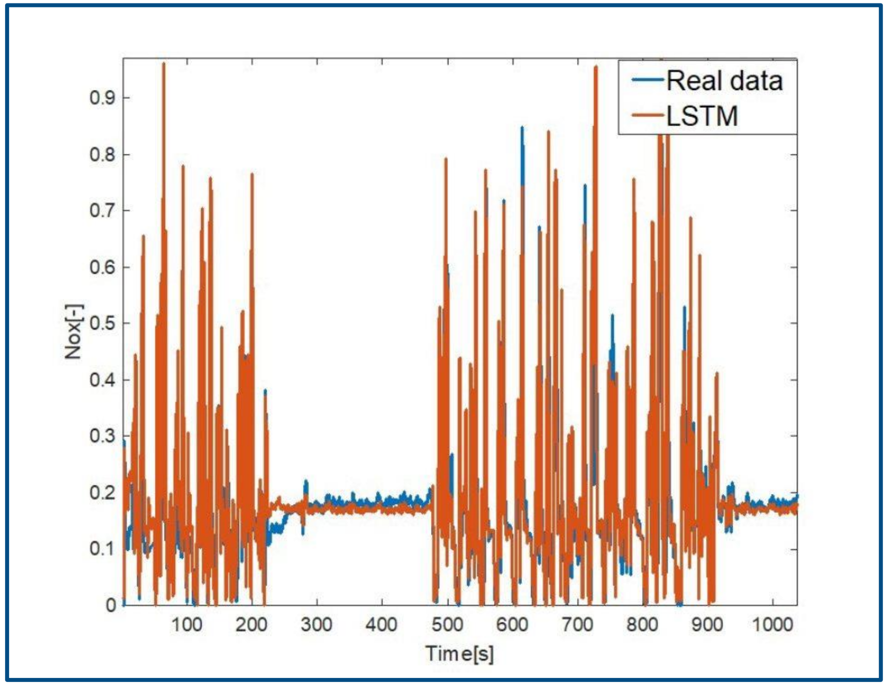
方案

Use MATLAB and Deep Learning Toolbox to model engine-out NO_X emissions using a long short-term memory (LSTM) network

结果

NO_X emissions predicted with close to 90% accuracy

- LSTM network incorporated into aftertreatment simulation model
- Code generated directly from network for ECU deployment



Measured NO_X emissions from an actual engine and modeled NO_X emissions from the LSTM network.

“Even though we are not specialists in deep learning, using MATLAB and Deep Learning Toolbox we were able to create and train a network that predicts NO_X emissions with almost 90% accuracy.”

- Nicoleta-Alexandra Stroe, Renault

Link to article

AI驱动的系统建模

Data Preparation

- Data cleansing and preparation
- Human insight
- Simulation-generated data

Modeling & Training

- Model design and tuning
- Hardware accelerated training
- Interoperability

Simulation & Test

- Integration with complex systems
- System simulation
- System verification and validation

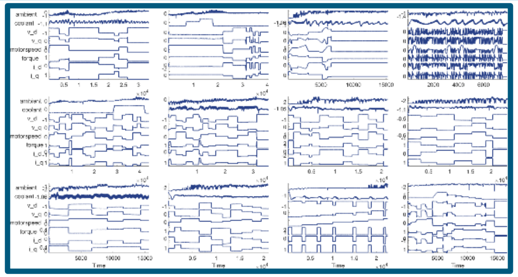
Deployment

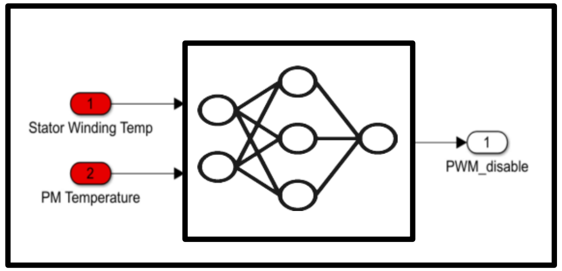
- Embedded devices
- Enterprise systems
- Edge, cloud, desktop

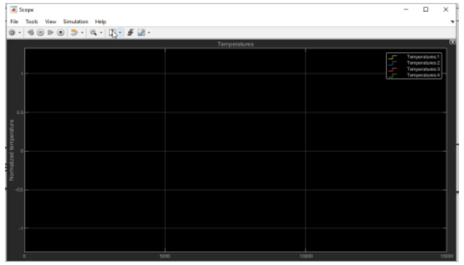
使用AI模型进行动态系统建模

Data Preparation → Modeling & Training → Simulation & Test → Deployment

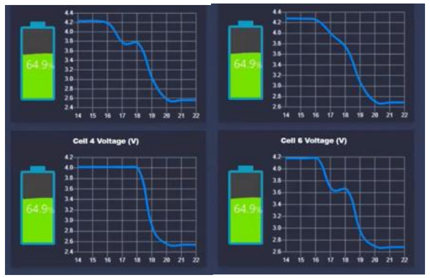
电机温度预测

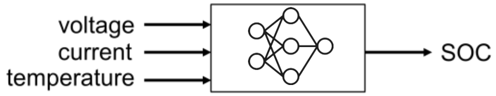


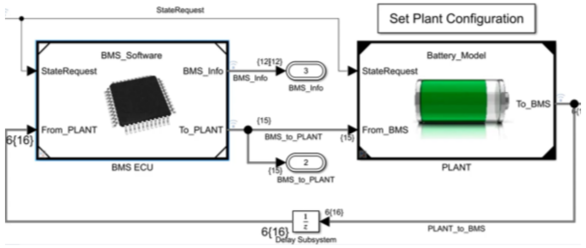




电池SOC估计







MATLAB中AI相关工具箱的发展

2016 - 2019

Toolboxes
- Deep Learning Toolbox
- Text Analytics Toolbox
- Reinforcement Learning
- Predictive Maintenance Toolbox

Code Generation
- GPU Coder
- MATLAB Coder

Apps
- Image Labeler
- Deep Network Designer
- Video Labeler
- Signal Labeler

Interoperability
- TensorFlow-Keras Importer
- ONNX Support

2020 - 2021

Apps
- Experiment Manager
- Lidar Labeler
- Reinforcement Learning Designer

Compression
- Quantization

Code Generation
- Deep Learning HDL Coder

Model-Based Design
- Image Classification & Model Prediction
- Recurrent Neural Networks
- Object Detectors

Interoperability
- TensorFlow Model Importer

2022

Accessibility
- Deep Learning Model Hub

Apps
- Data Cleaner

Compression
- Taylor Pruning

Code Generation
- TensorFlow Lite

Interoperability
- TensorFlow Lite inference for MATLAB and Simulink

Machine Learning
- Drift Detection

500+ examples, covering:
- **Computer Vision, LidarAudio, Signal and Wireless**
- **Computational Finance**
- **Controls**
- **Machine Learning**

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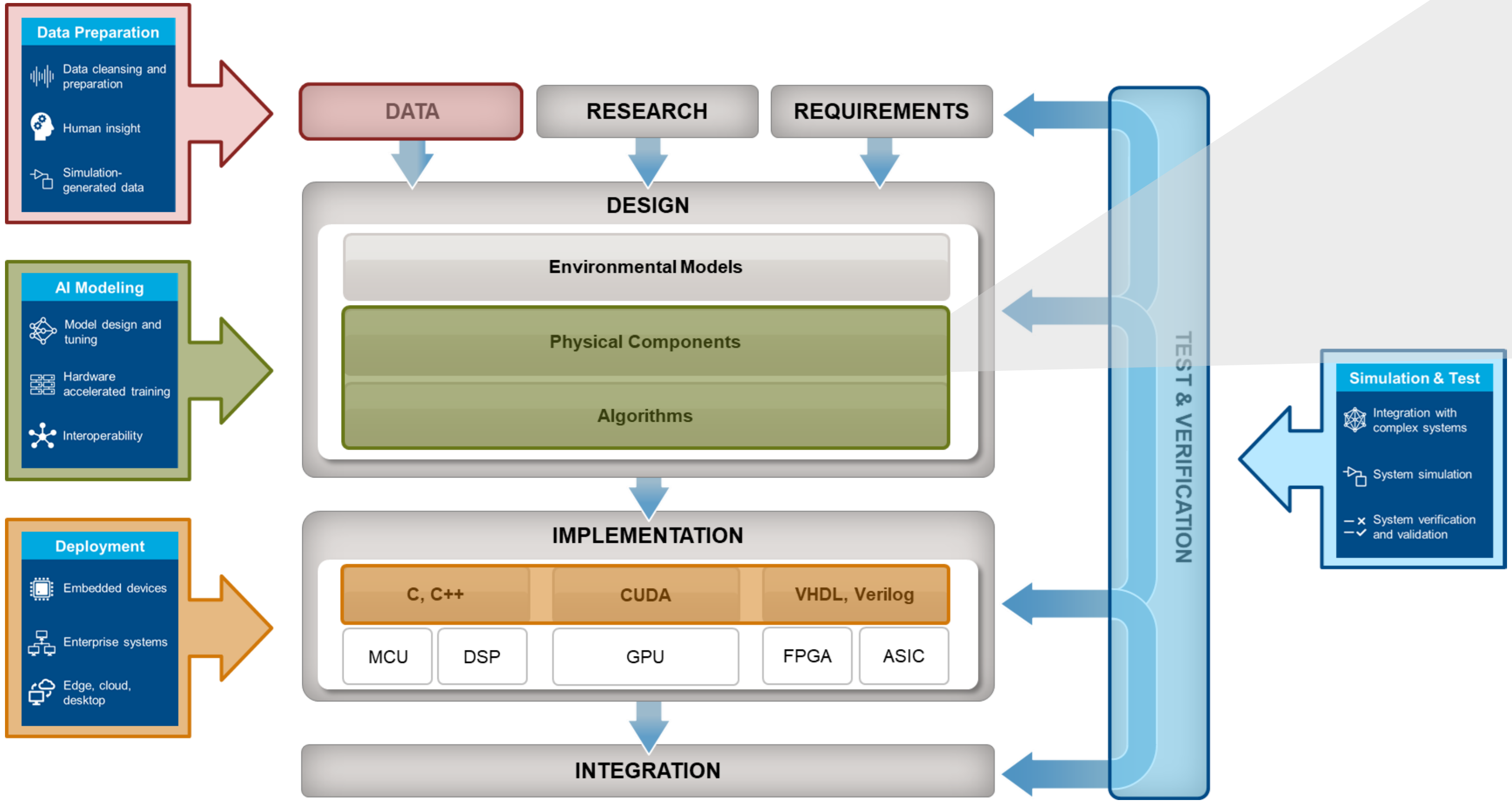
AI用于被控对象建模



AI用于被控对象建模

- 加速桌面与HIL仿真
- 当第一原理模型不能构建时通过数据进行动态系统（被控对象）建模

模型降阶

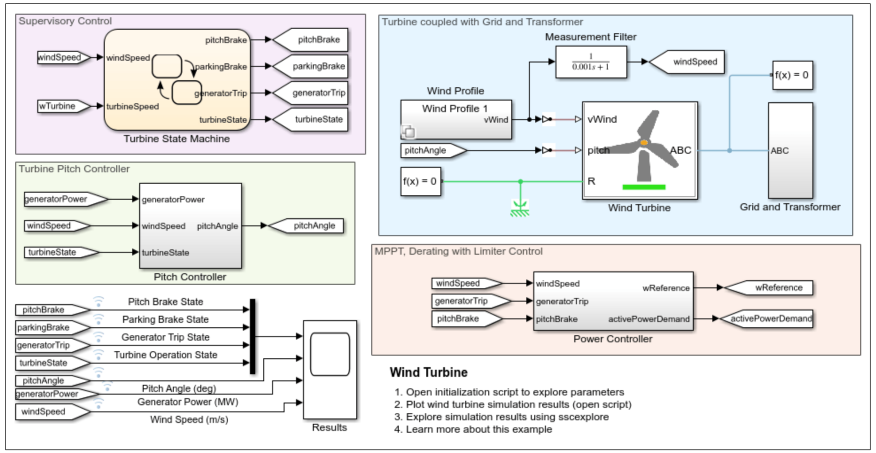
什么是模型降阶？

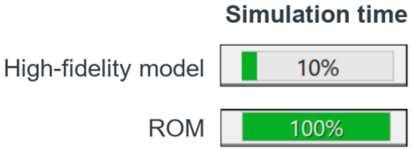
- 减少模型**计算复杂度或存储需求**的一种技术
- 在误差允许的范围内**保持期望的保真度**

为什么进行模型降阶

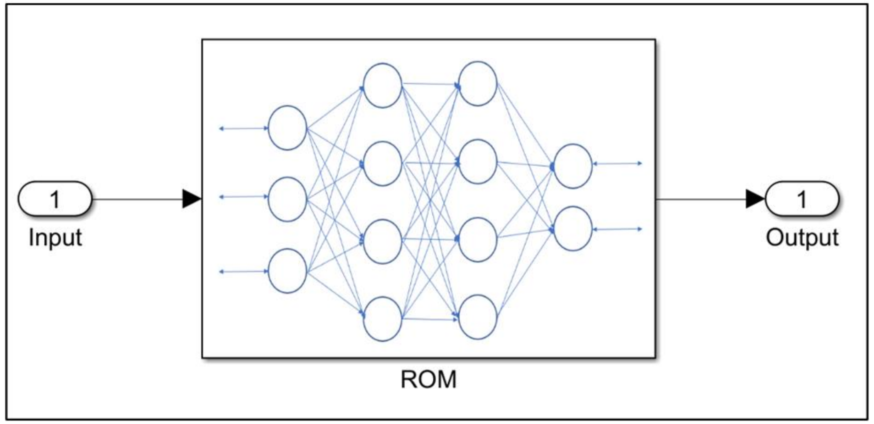
- 加速系统级桌面仿真
- Hardware-in-the-loop testing
- Enable system-level simulation
- 开发虚拟传感器，数字孪生
- 控制设计

High-fidelity model





Reduced-Order Model (ROM)

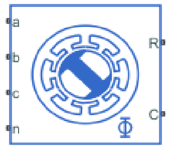


模型降阶

实现方式

Reduced order model

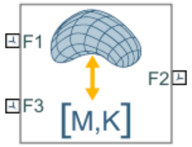
- **Physics-based**



FEM-Parametrized PMSM

Simulink, Simscape products, Simulink Design Optimization

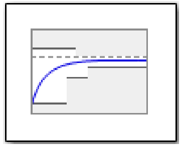
- **Model-based**



Reduced Order Flexible Solid

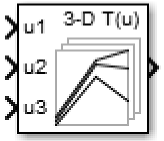
Simulink, Simscape Multibody, Simscape Electrical, Partial Differential Equation Toolbox, Control System Toolbox

- **Linearization**



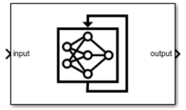
Simulink, Simulink Control Design, Control System Toolbox

- **Data-driven**
  - **Static**



Simulink, Curve Fitting Toolbox, Model-Based Calibration Toolbox

  - **Dynamic**



Simulink, Statistics and Machine Learning Toolbox, Deep Learning Toolbox, System Identification Toolbox

Focus today

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数据驱动（Data-driven） vs. 第一原理建模（first-principles）

数据驱动和第一原理建模可以共存

数据驱动的模型
Statistics, optimization, AI

第一原理模型
Physics, math, domain knowledge

Advantages

- 当第一原理的模型难于构建时可以发挥作用
- 降低复杂度，仿真加速
- 可以利用当前已有的或者测得的数据
- 不需要领域知识

Challenges

- 需要大量的数据
- Are often not
  - 可解释
  - 包含物理意义的参数化
- 在训练数据之外的外插能力较弱

Advantages

- 可以以低/高保真度捕获(全局)可参数化的行为
- 清晰的物理含义（可解释）
- 无需数据工程

Challenges

- 难于获取/推导第一原理
- 需要强大的专业知识与理论背景

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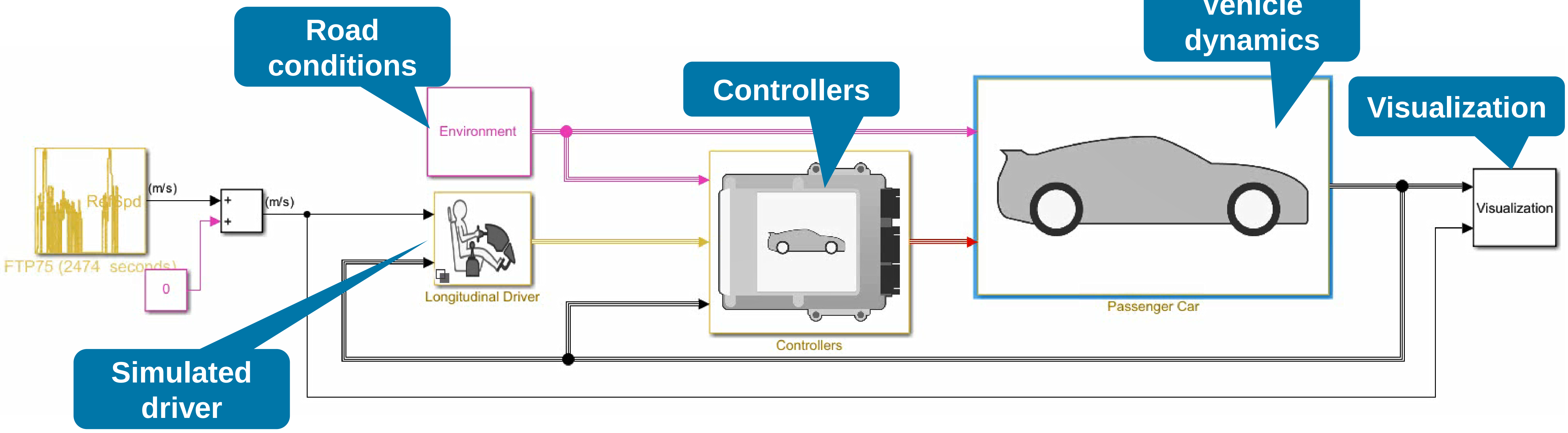
示例概览

使用基于AI的降阶模型替换第一原理发动机模型

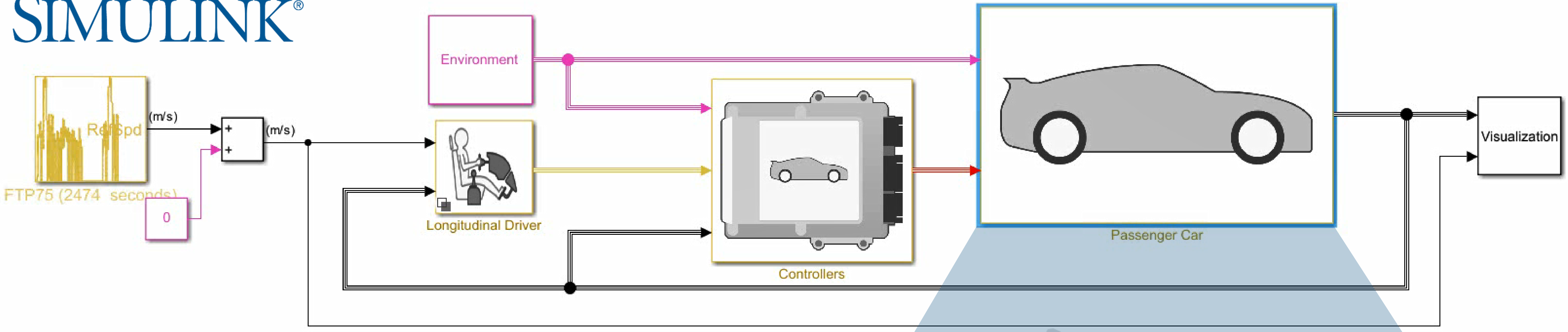


车速的闭环控制

示例概览

使用基于AI的降阶模型替换第一原理发动机模型

SIMULINK®



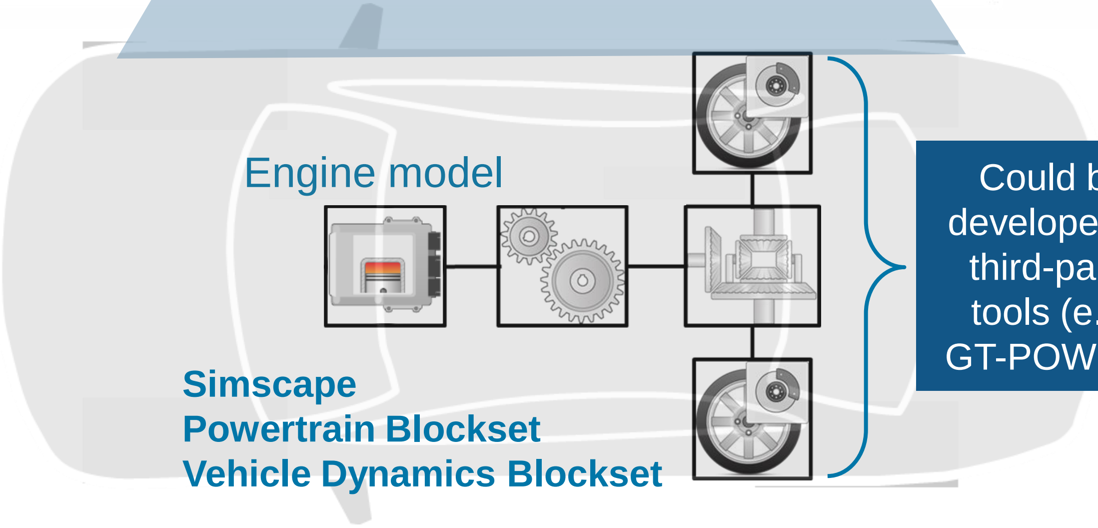
高保真

↓

复杂模型

↓

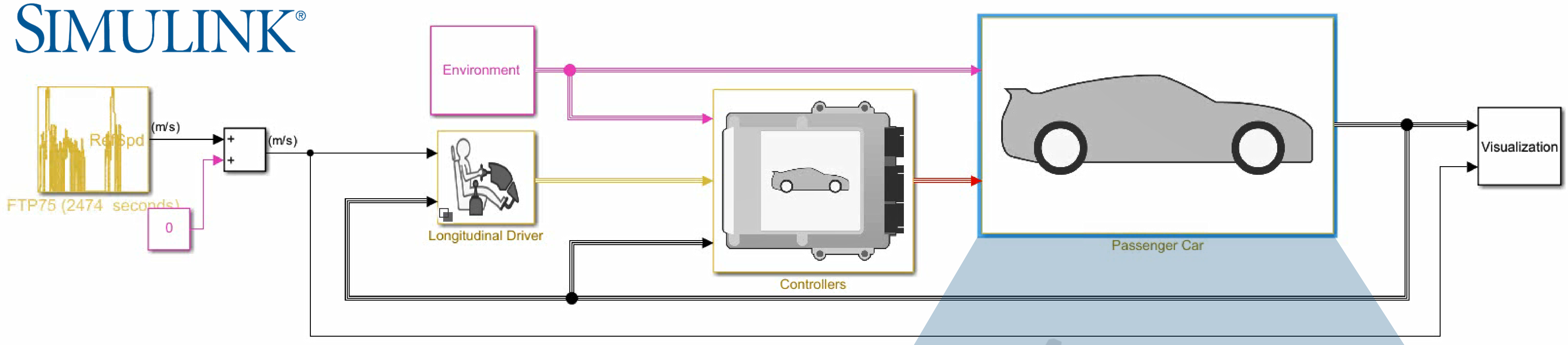
仿真慢



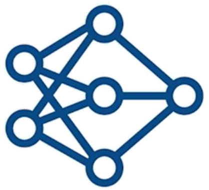
Could be developed in third-party tools (e.g. GT-POWER)

示例概览

使用基于AI的降阶模型替换第一原理发动机模型

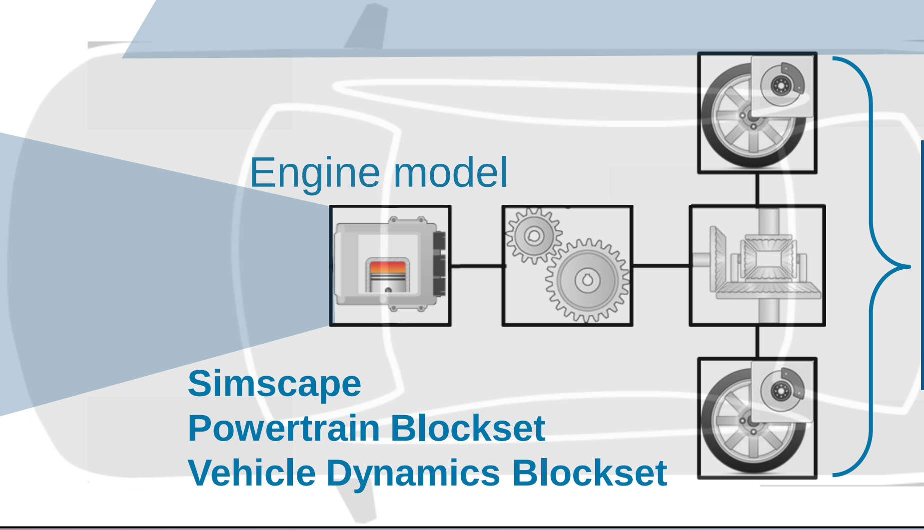


输入量
发动机转速 (RPM)
点火时间
节气门开度
废弃旁通阀



输出量
发动机扭矩

Deep Learning Toolbox

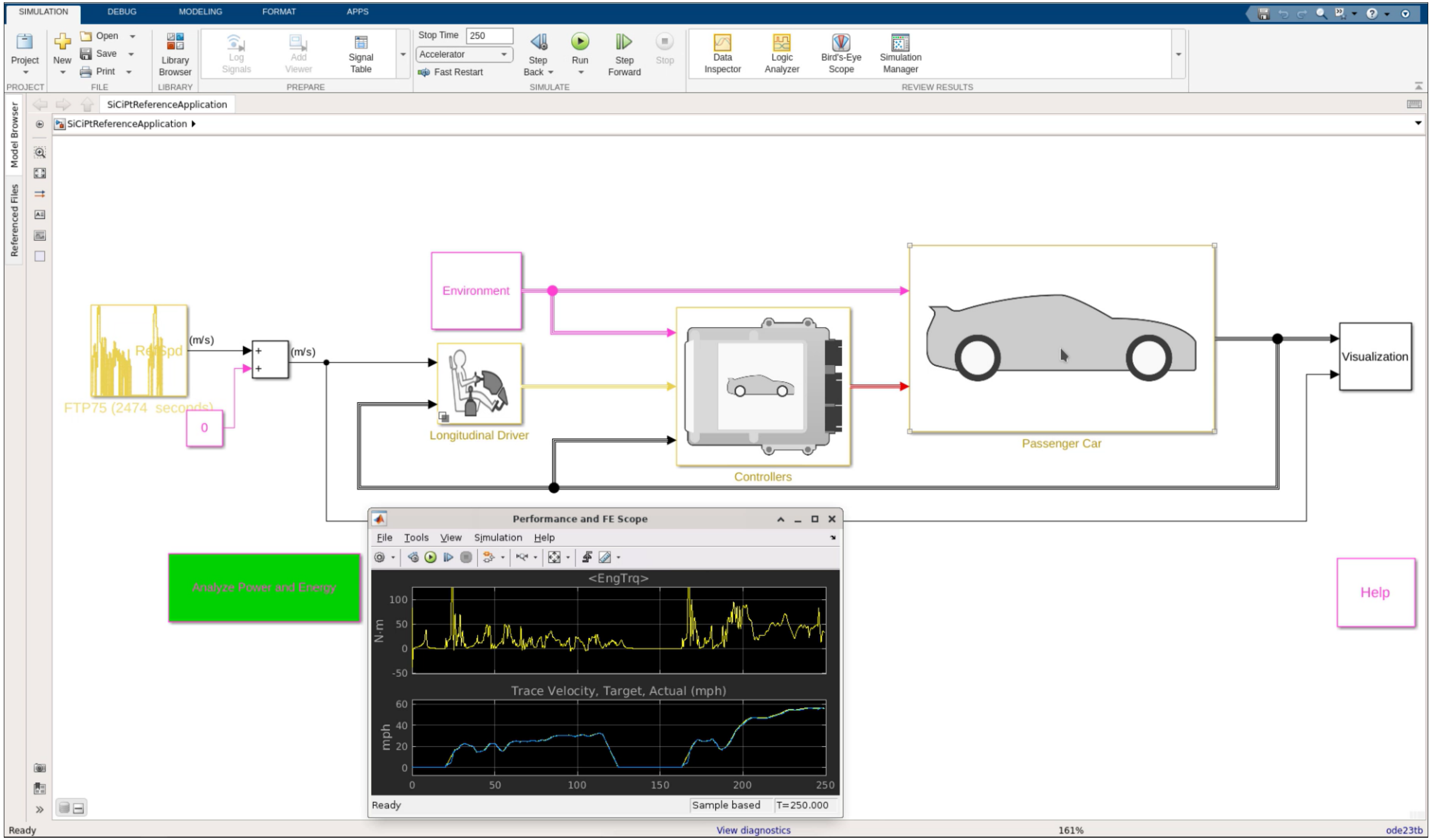


Could be developed in third-party tools (e.g. GT-POWER)

黑盒 ↔ 白盒

示例概览

系统级仿真



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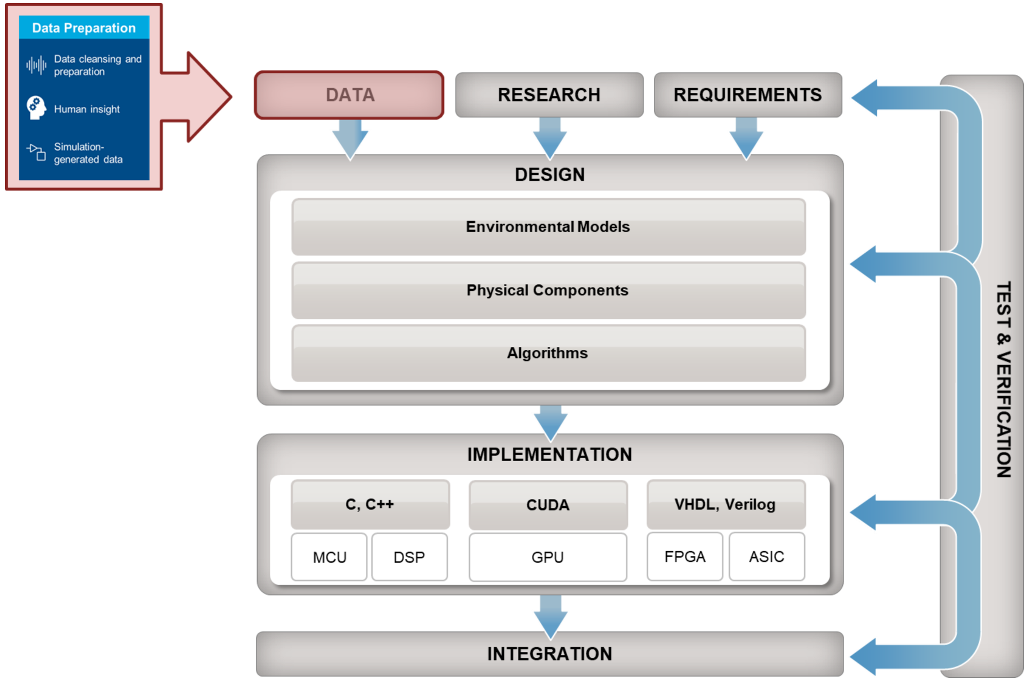
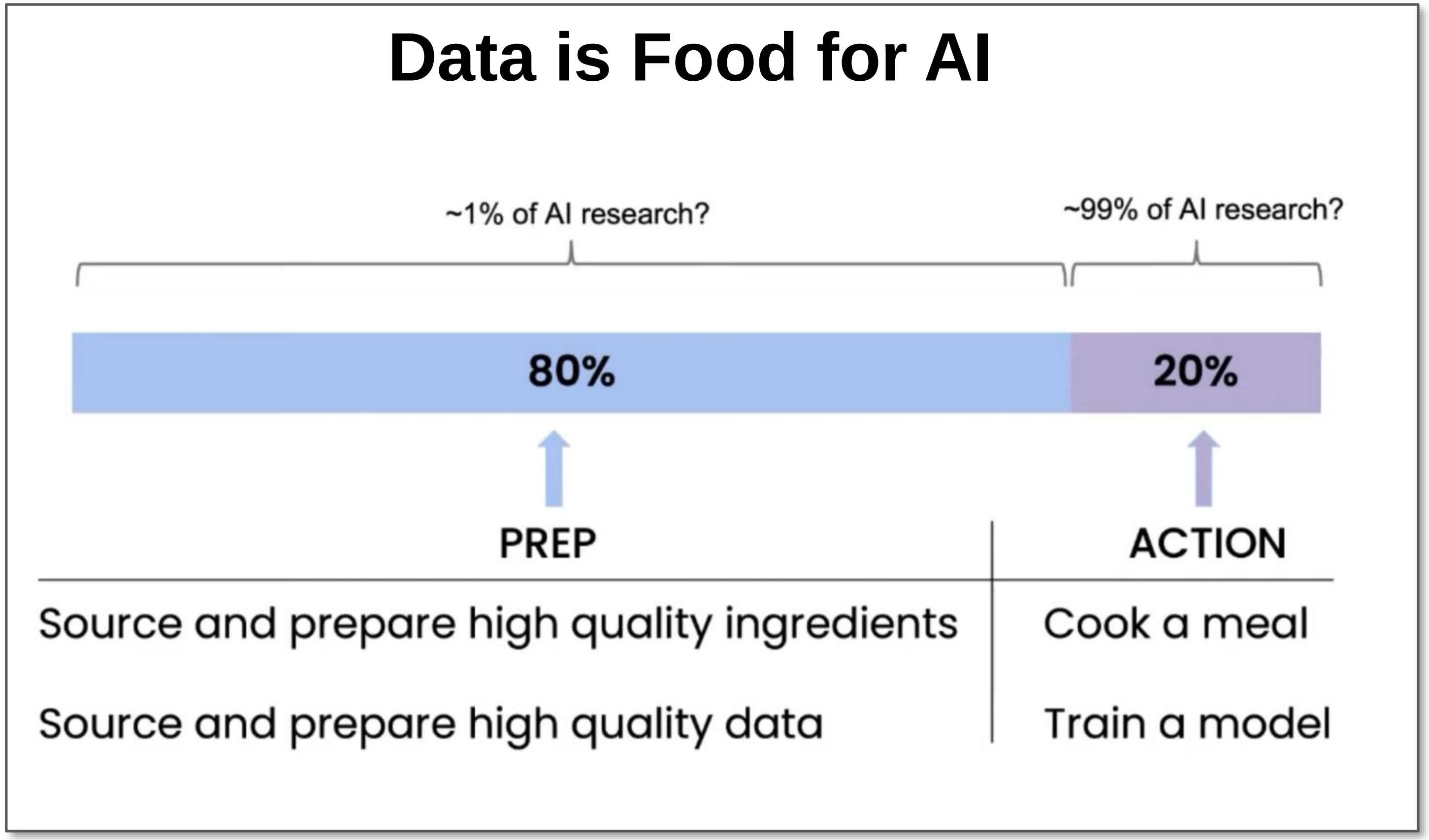
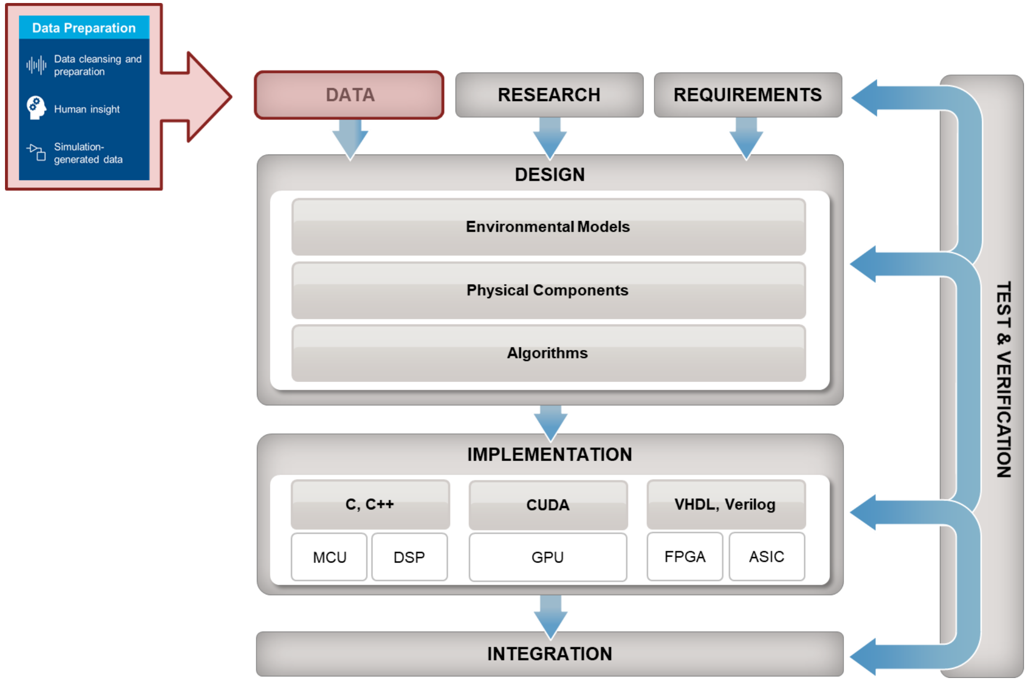
数据准备的时间通常占大部分

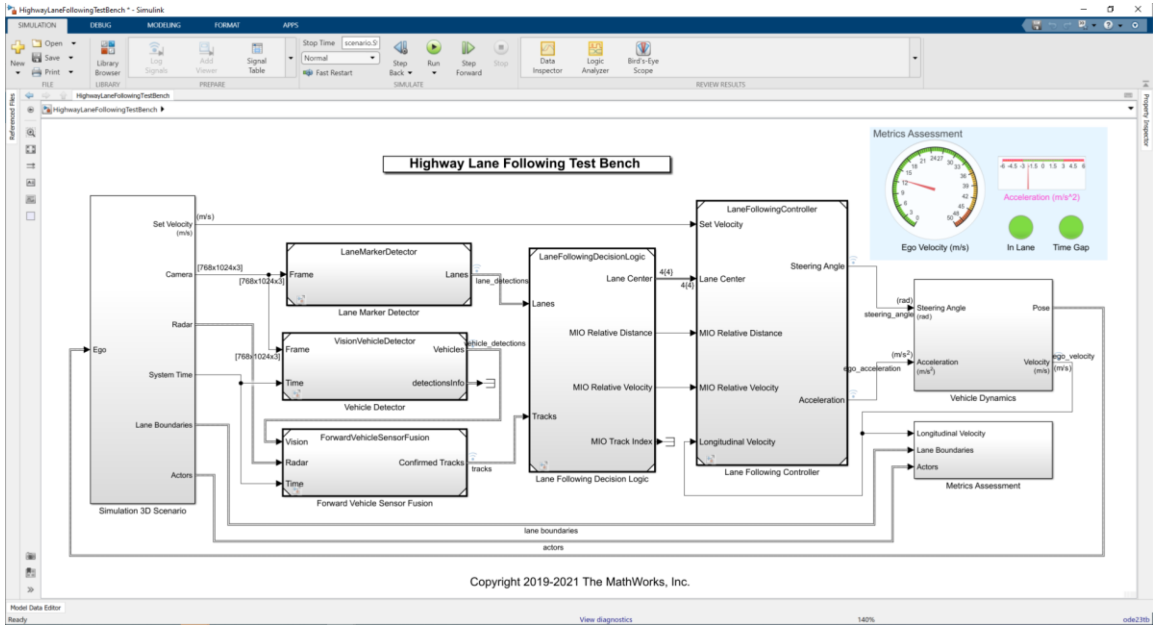




Source: Andrew NG slide from MLOps 2021

生成合成数据用于训练

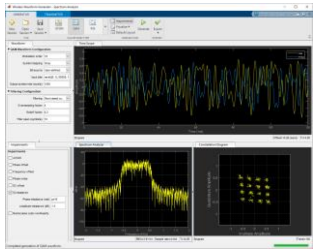




Simulink/Simscape

Other techniques:

GANs



Wireless Waveform Generator

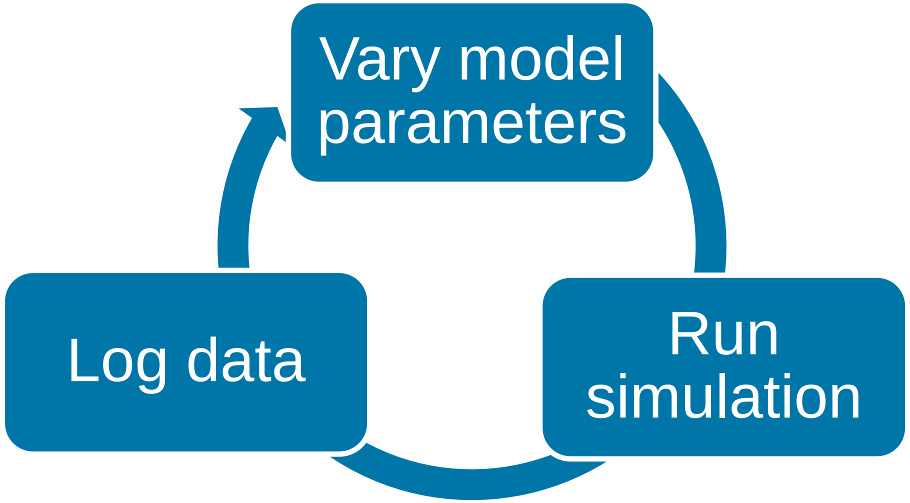
Unreal Engine®

合成数据生成

Design of Experiments

DoE = 512×3 table

	EngTrqReq	EngSpdR...	SpkAdvOfst
1	60	2000	-30
2	128	2500	15
3	94	2750	8
4	111	2875	-19
5	77	2625	-11
6	144	2125	4
7	85	2563	-21
8	119	3313	-28
9	68	2938	21

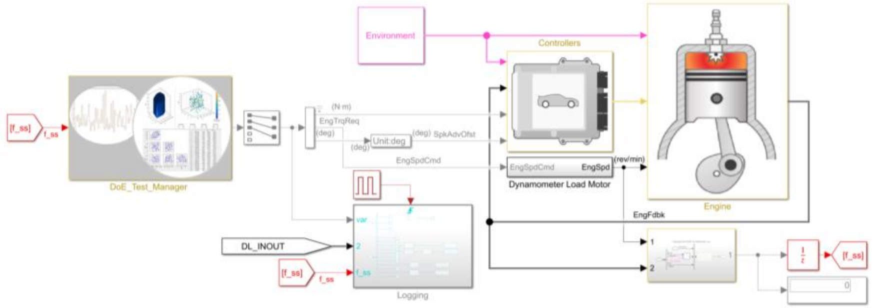


<u>Input features</u>

Engine speed (RPM)
Ignition timing
Throttle position
Wastegate valve

<u>Response</u>

Engine Torque



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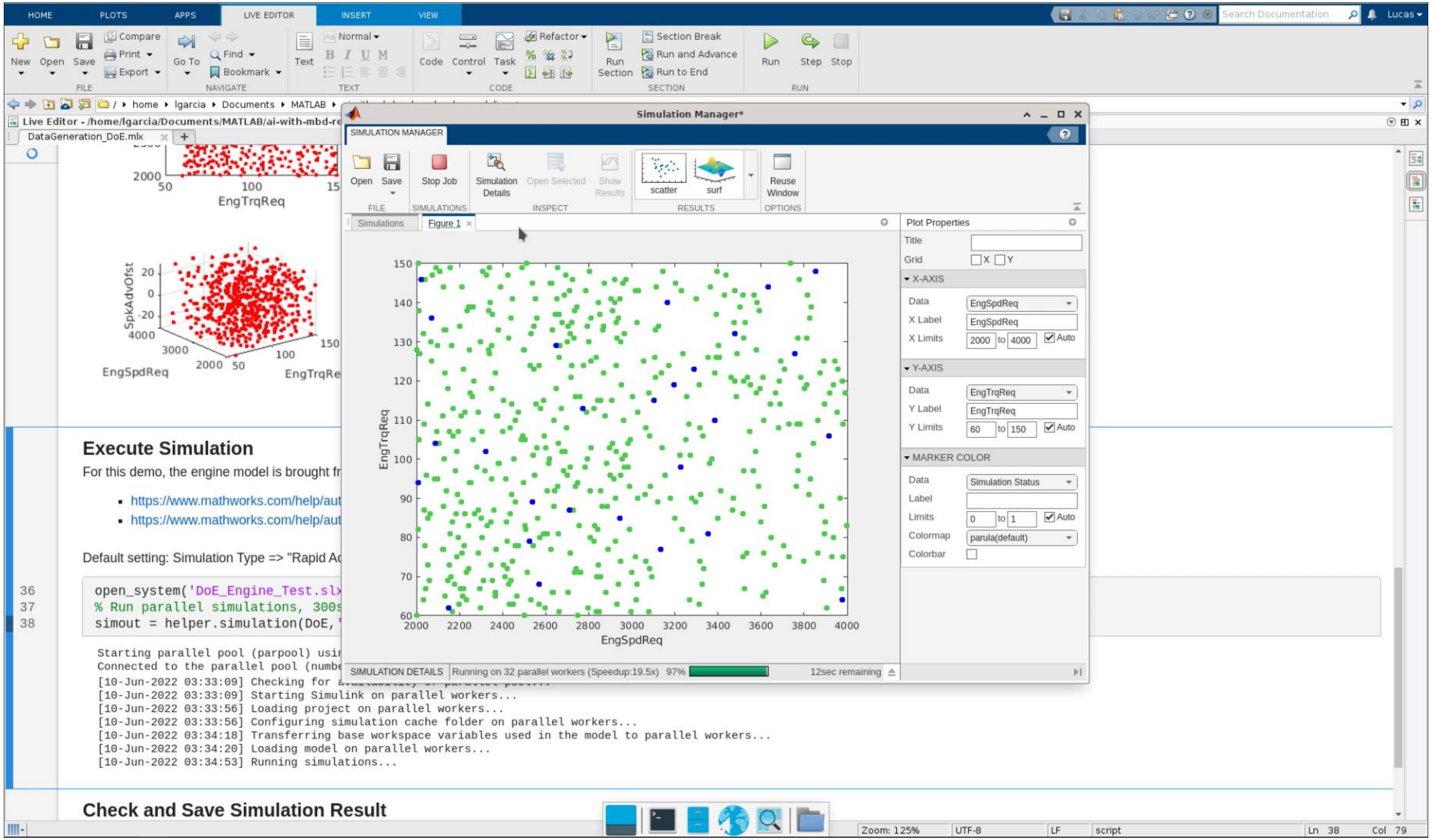
合成数据生成

Design of Experiments



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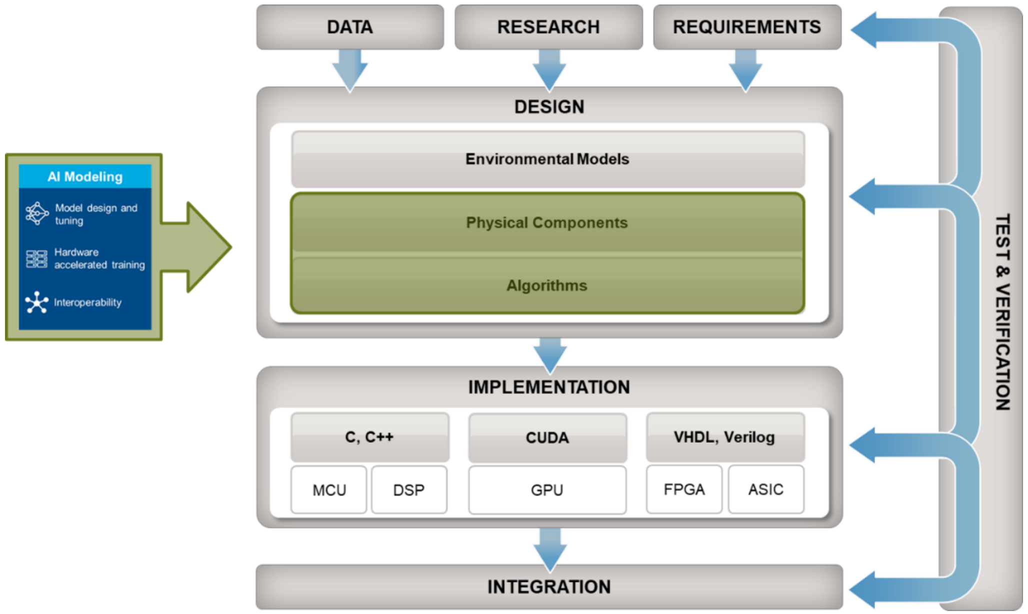
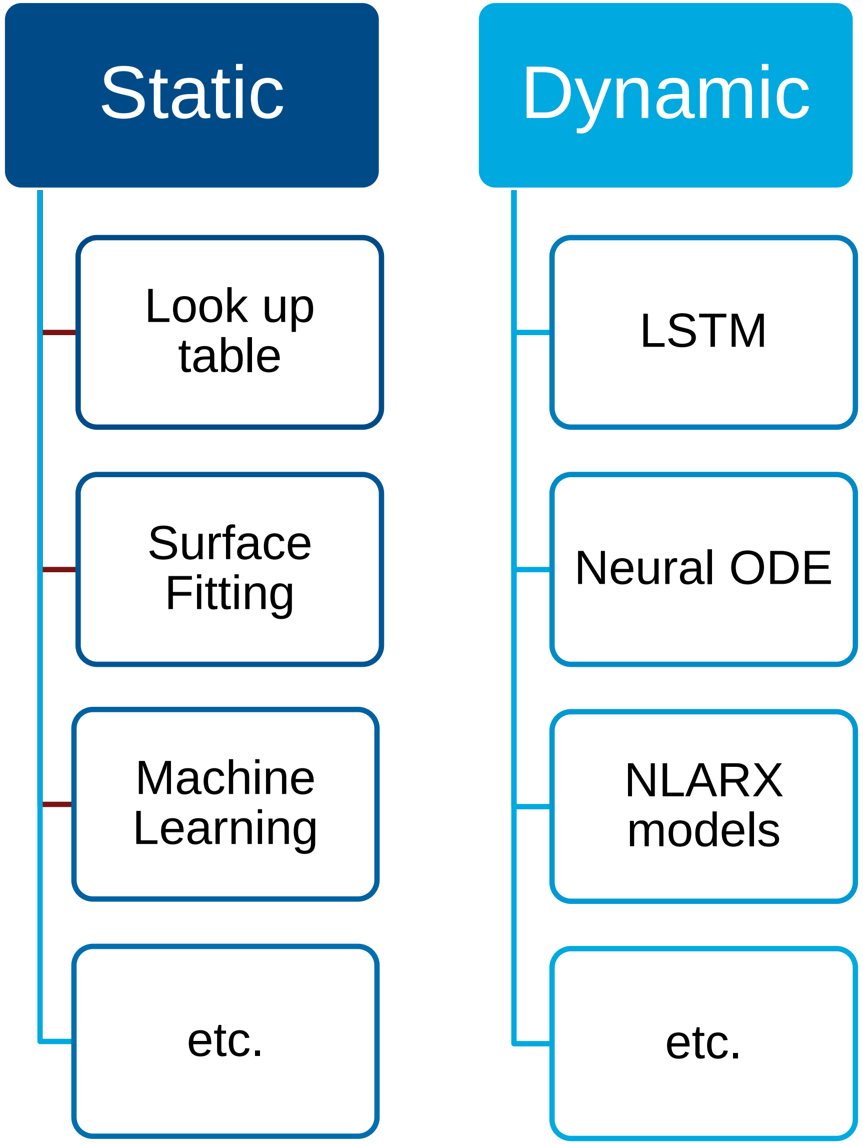
数据驱动的ROM


AI Modeling
Model design and tuning
Hardware accelerated training
Interoperability
DATA
RESEARCH
REQUIREMENTS
DESIGN
Environmental Models
Physical Components
Algorithms
IMPLEMENTATION
C, C++
CUDA
VHDL, Verilog
MCU
DSP
GPU
FPGA
ASIC
INTEGRATION
TEST & VERIFICATION


Static
Look up table
Surface Fitting
Machine Learning
etc.
Dynamic
LSTM
Neural ODE
NLARX models
etc.

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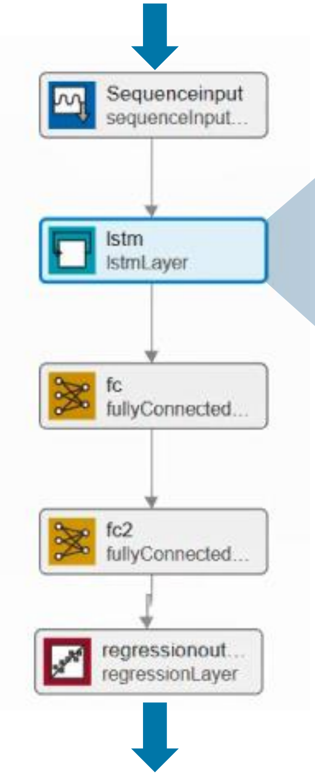
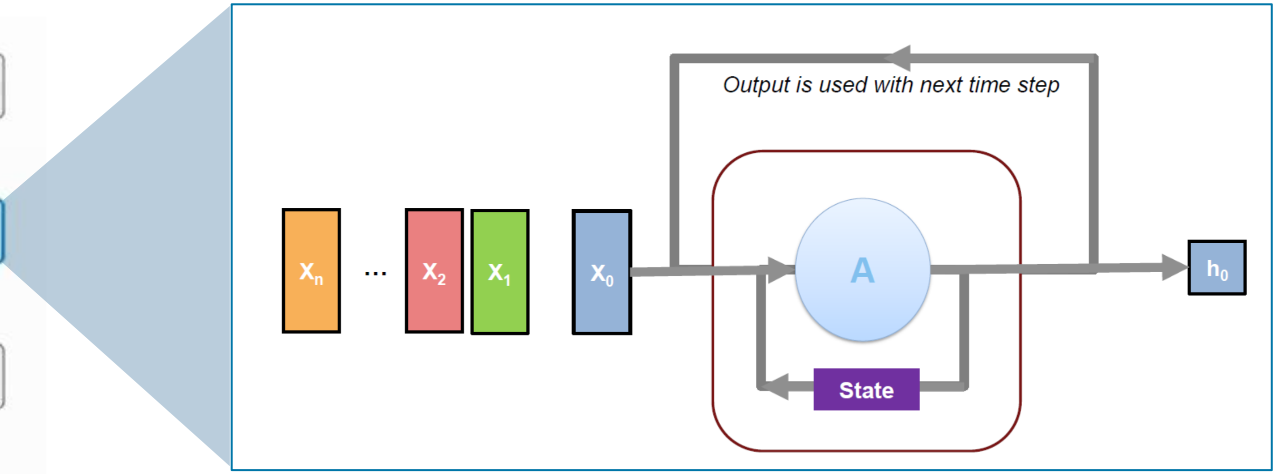
基于AI的ROM：LSTM

从时间序列数据中学习时间上的依赖

Inputs

Engine speed (RPM)
Ignition timing
Throttle position
Wastegate valve





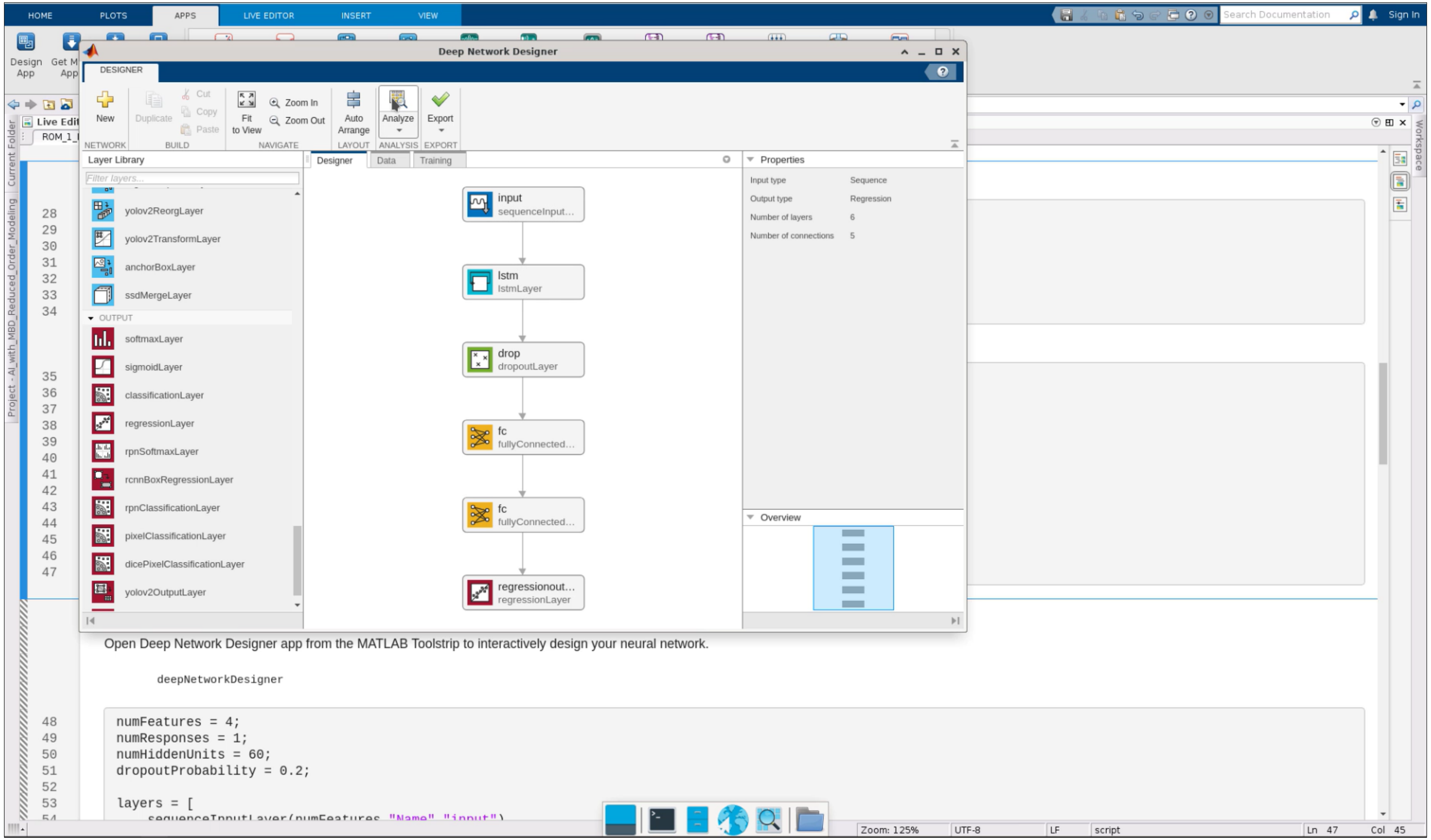
LSTMs carry a memory cell (state) throughout

Outputs

Engine Torque

基于AI的ROM：LSTM

从时间序列数据中学习时间上的依赖



基于AI的ROM：Neural ODEs

使用神经网络学习系统动态特性

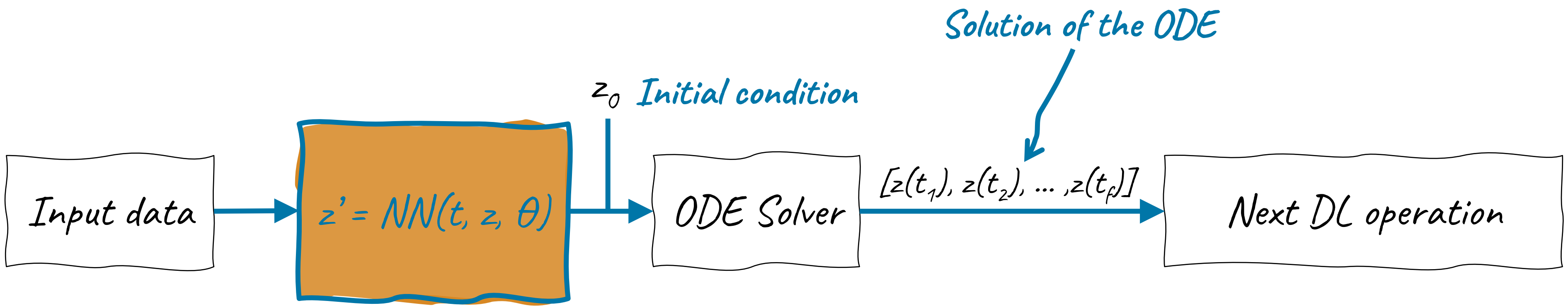
Ordinary Differential Equations (ODEs)

$$\begin{cases} z' = f(t,z), & t \in (t_0, t_f) \\ z(t_0) = z_0 \end{cases}$$

- Model phenomena in many domains: physics, finance, biology, chemistry, …
- In real-world applications, ODEs are solved with numerical integration techniques, approximating $z(t)$

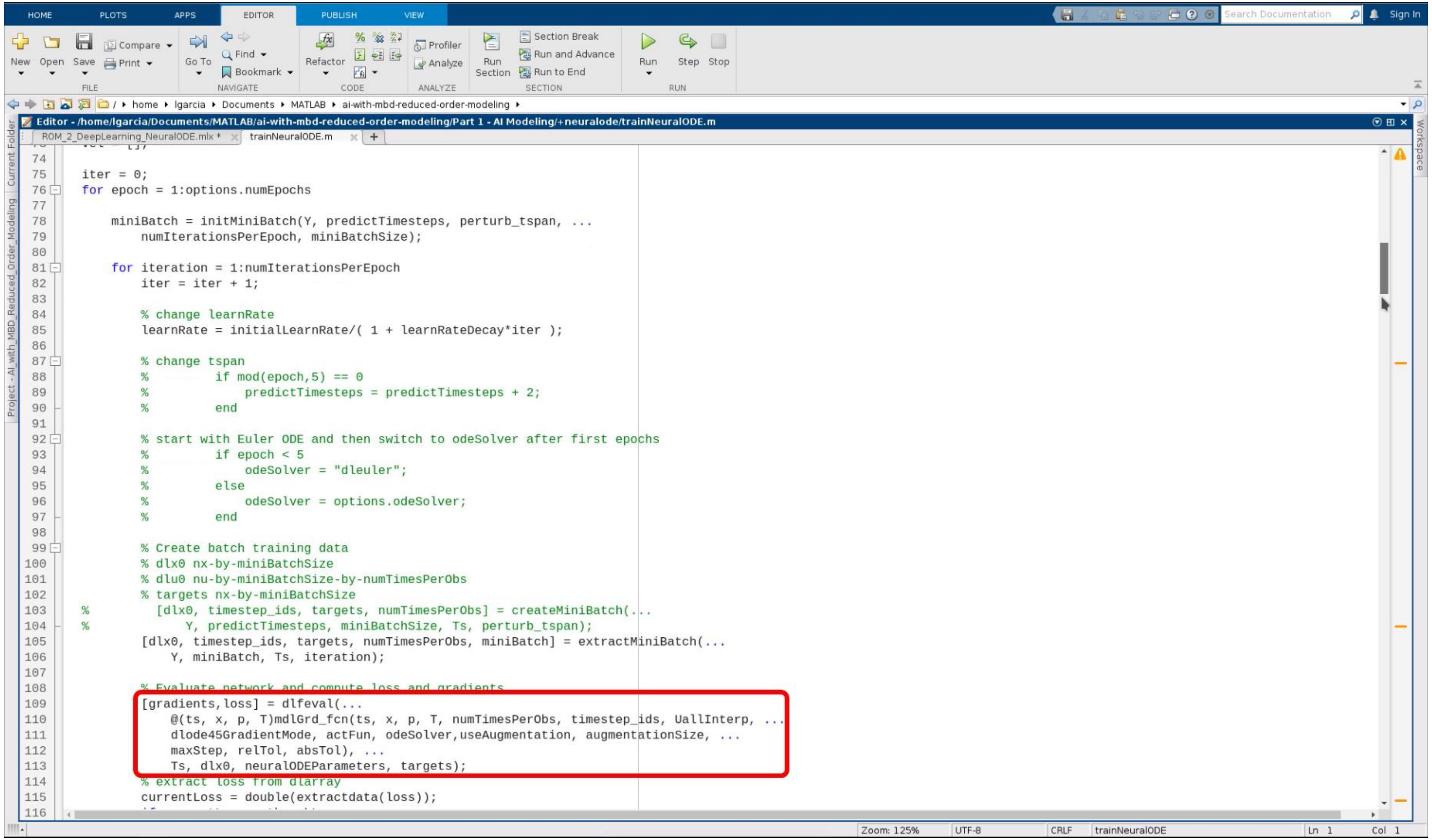
Neural ODEs

- Solving an ODE from first principles may be challenging / not always possible
- Train a neural network from data to represent the function $f(t,z)$
- Solve the ODE using the trained network $NN(t,z,\theta)$ instead of $f(t,z)$



基于AI的ROM：Neural ODEs

使用神经网络学习系统动态特性



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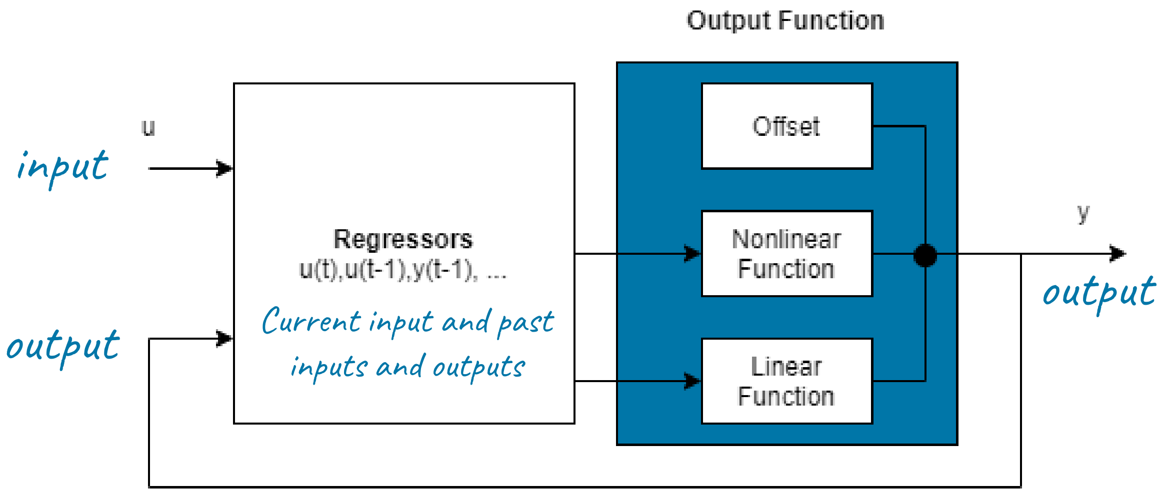
基于AI的ROM：Nonlinear ARX

使用Sigmoid-based Nonlinear ARX Model进行代理模型创建

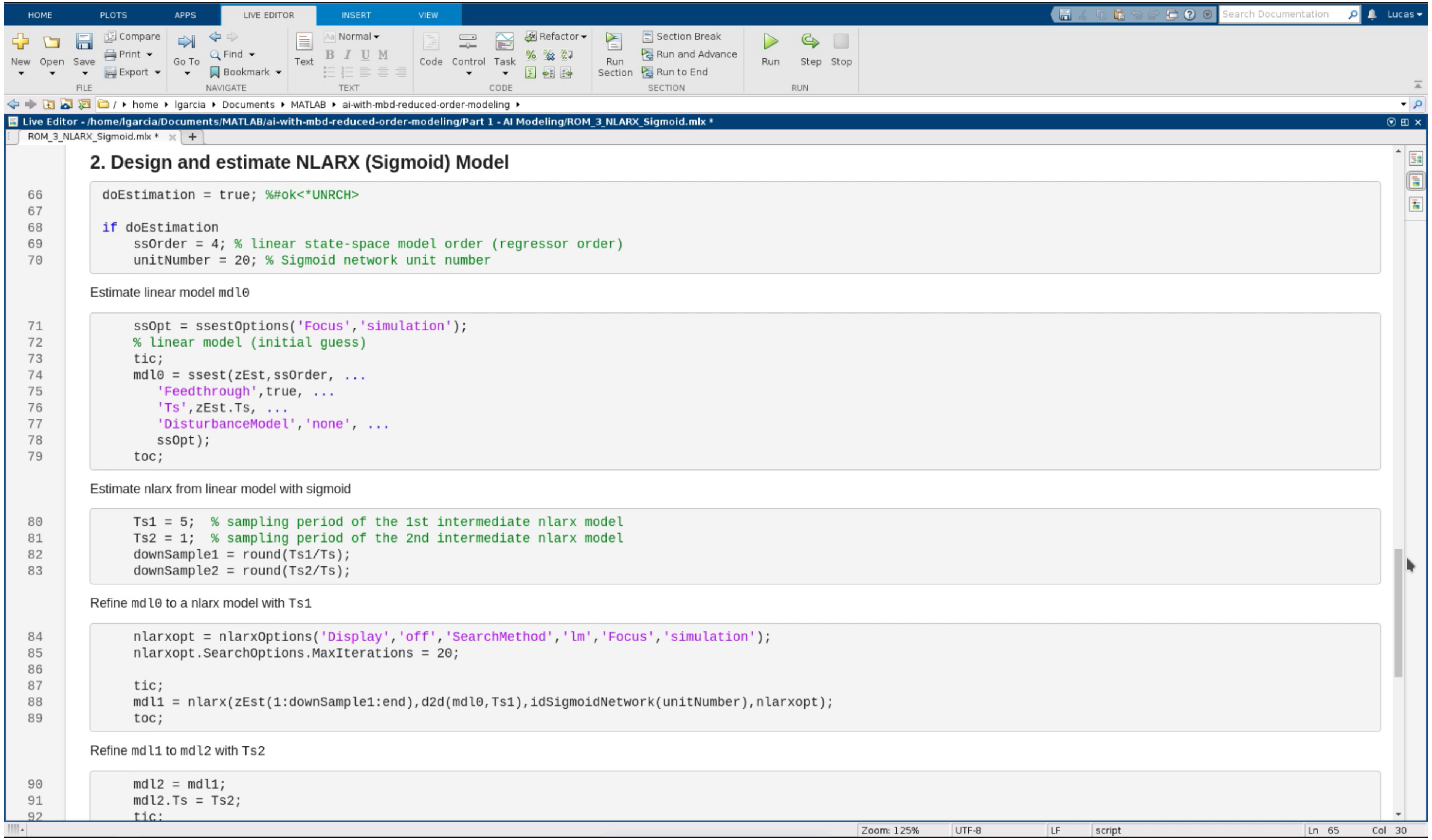
Nonlinear ARX (NLARX)

- Extends linear ARX to the nonlinear case
- Flexible choice of nonlinear functions
- May be more interpretable than Deep Learning models
- Potentially faster training and simulation



基于AI的ROM：Nonlinear ARX

使用Sigmoid-based Nonlinear ARX Model进行代理模型创建



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基于AI的ROM：Nonlinear ARX

使用SVM-based Nonlinear ARX Model进行代理模型创建

2. Design and estimate NLARX (SVM) Model

```
doEstimation = true; %#ok<*UNRCH>

if doEstimation

    Kernel = 'gaussian';

    % Parameters obtained using Experiment Manager:
    BoxConstraint = 8.9381;
    EpsilonMargin = 0.0002;

    isNormalization = false;
    Ts1 = 1;
    downsample = Ts1/Ts;

    % nlarx and options
    focus = 'prediction';
    nlarxopt = nlarxOptions('Display','off','SearchMethod','lm','Focus',focus);
    nlarxopt.Normalize = false;

    linReg = linearRegressor({'EngineTorque',...
        'ThrottlePosition','WastegateValve','EngineSpeed','SparkTiming'},...
        {1:3,0:1,0:1,0:4,0:1});

    svm = idSupportVectorMachine(Kernel);
    svm.BoxConstraint = BoxConstraint;
    svm.EpsilonMargin = EpsilonMargin;

    tic;
    nlarxSVM = nlarx(zEst(1:downsample:end),linReg,svm,nlarxopt);
    toc;
    nlarxSVM.Ts = Ts;
else
    load(fullfile(projectPath,"models","nlarxSVM.mat"))
end
```

3. Test the Model

Now, evaluate the model's performance on the test data set.

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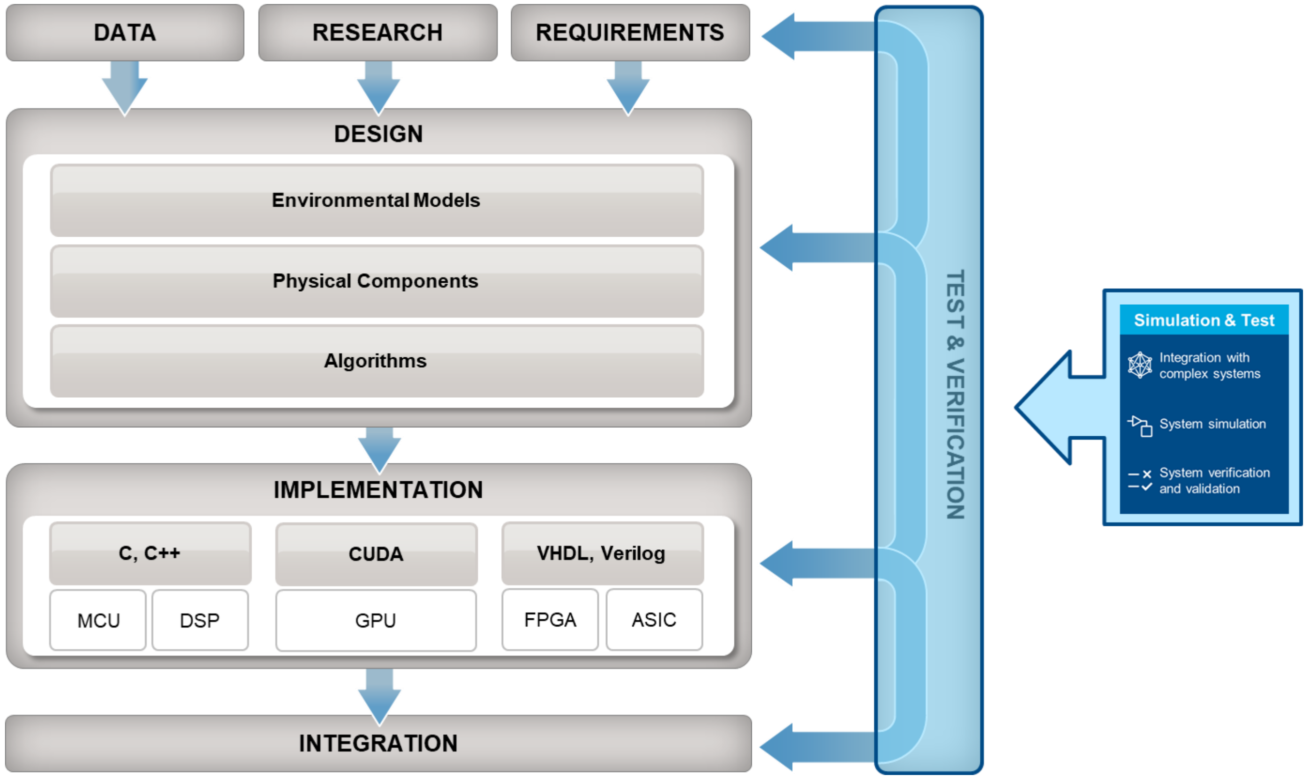
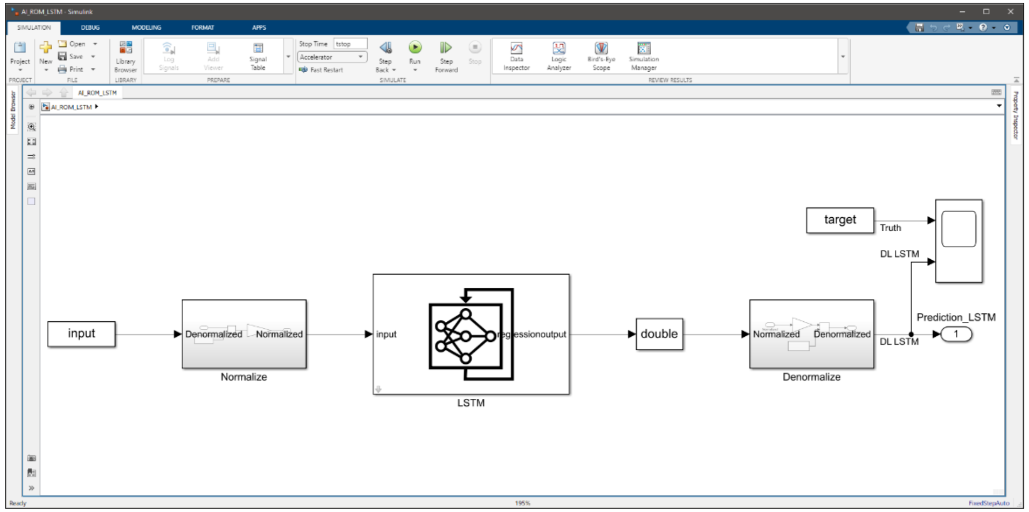
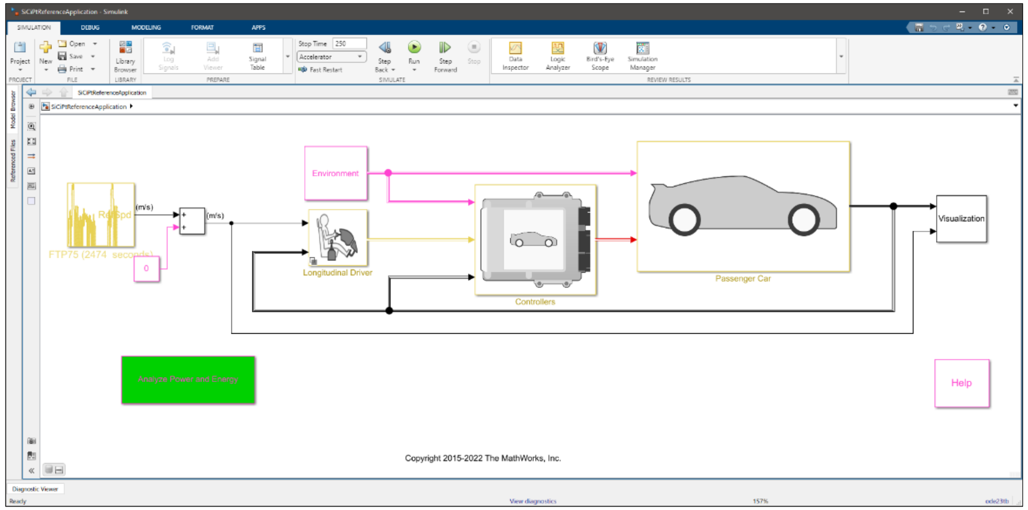
将AI模型集成进行系统级仿真与测试



Integration of trained AI model into Simulink

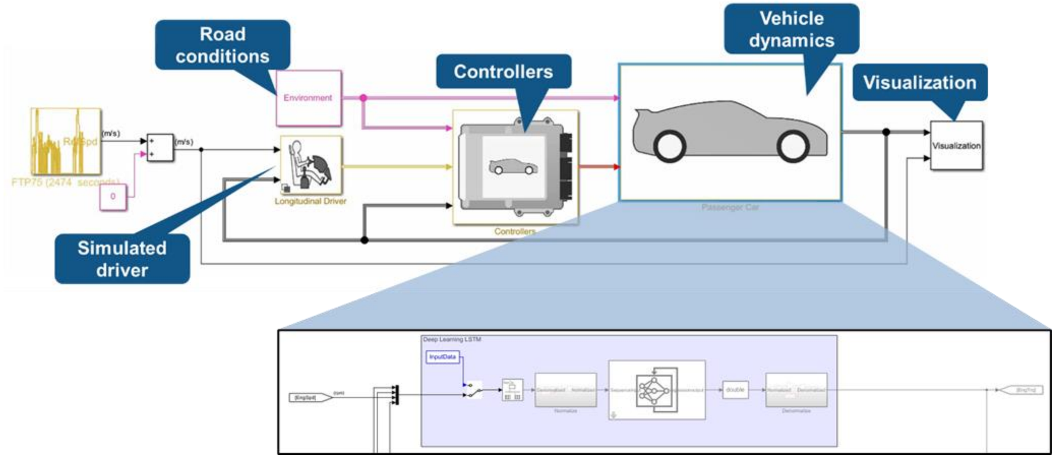


System-level simulation

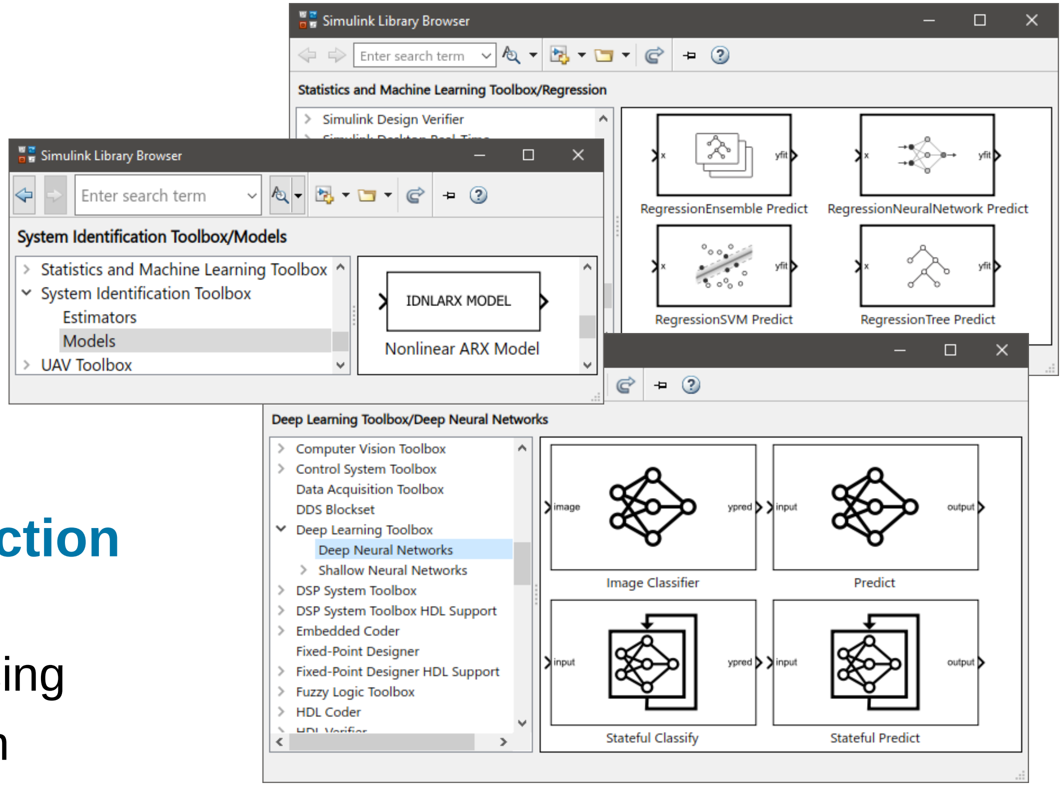


在Simulink的系统模型中集成AI模型

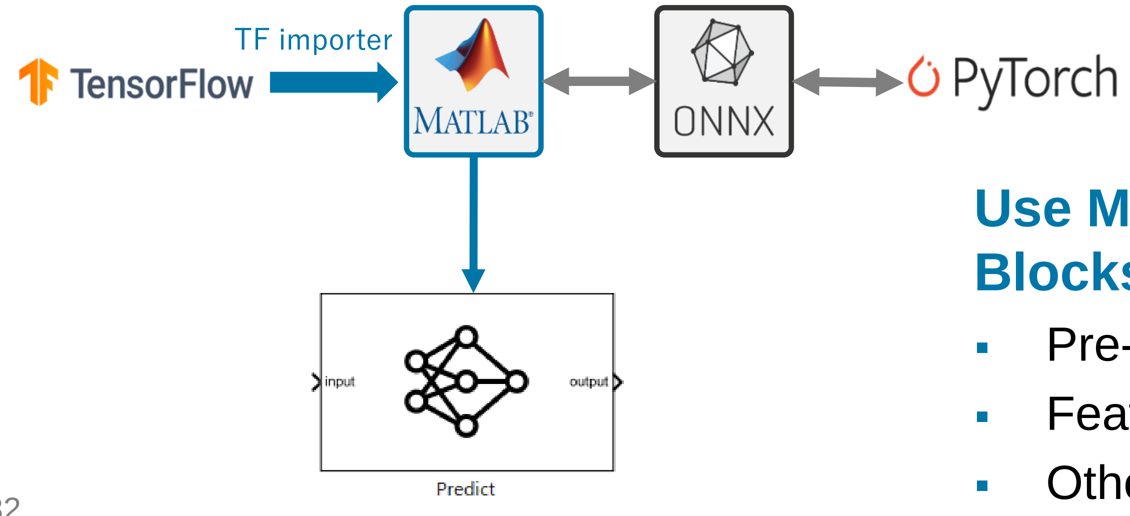
将AI模型集成其他算法用于系统级仿真与测试



Use **Statistics and Machine Learning Toolbox System Identification Toolbox** and **Deep Learning Toolbox block libraries** to bring AI models into Simulink



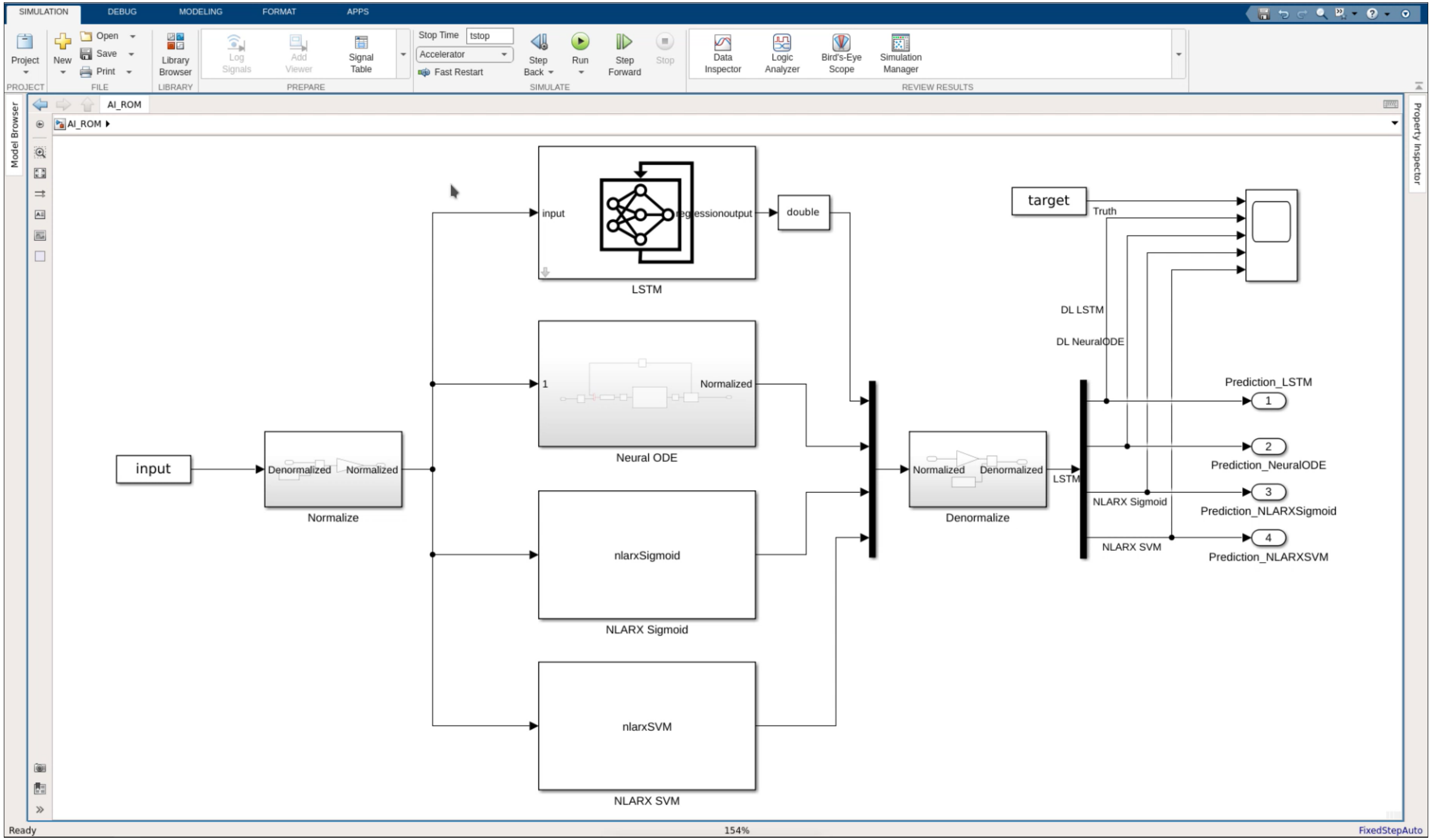
和其他框架互操作



Use MATLAB Function Blocks for:

- Pre-/Post-processing
- Feature Extraction
- Other models

训练好的AI模型集成到Simulink



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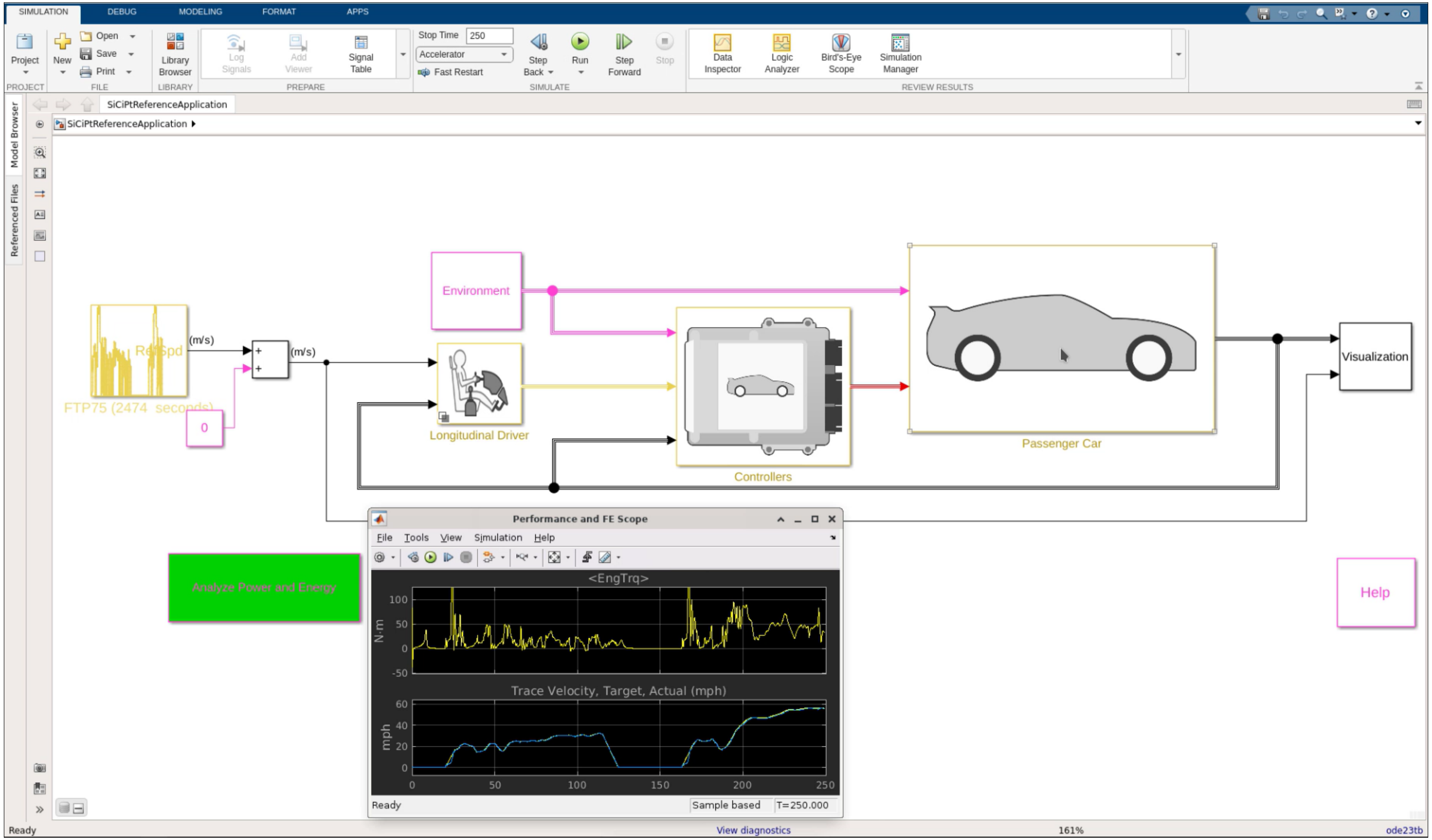
训练好的AI模型集成到Simulink

Simulink Profiler

Path	Time Plot (Dark Band = Self Time)	Total Time (s)	Self Time (s)	Number of Calls
AI_ROM		37.952	35.394	142587
Neural ODE		1.441	0.000	0
LSTM		0.798	0.000	0
NLARX Sigmoid		0.148	0.000	0
From Workspace1		0.086	0.086	23794
Demux		0.057	0.057	95184
Prediction_LSTM		0.019	0.019	23793
Prediction_NeuralODE		0.003	0.003	23793
Prediction_NLARXSigmoid		0.003	0.003	23793
Prediction_NLARXSVM		0.003	0.003	23793
Normalize		0.000	0.000	0
Cast To Double		0.000	0.000	3
NLARX SVM		0.000	0.000	0
Denormalize		0.000	0.000	0

系统级仿真


SIMULATION
DEBUG
MODELING
FORMAT
APPS
Stop Time 250
Accelerator
Fast Restart
Step Back
Run
Step Forward
Stop
Data Inspector
Logic Analyzer
Bird's-Eye Scope
Simulation Manager
SiCiPtReferenceApplication
Environment
Longitudinal Driver
Controllers
Passenger Car
Visualization
FTP75 (2474 seconds)
Analyze Power and Energy
Help
Performance and FE Scope
<EngTrq>
N·m
Trace Velocity, Target, Actual (mph)
mph
Ready
Sample based
T=250.000
View diagnostics
161%
ode23tb

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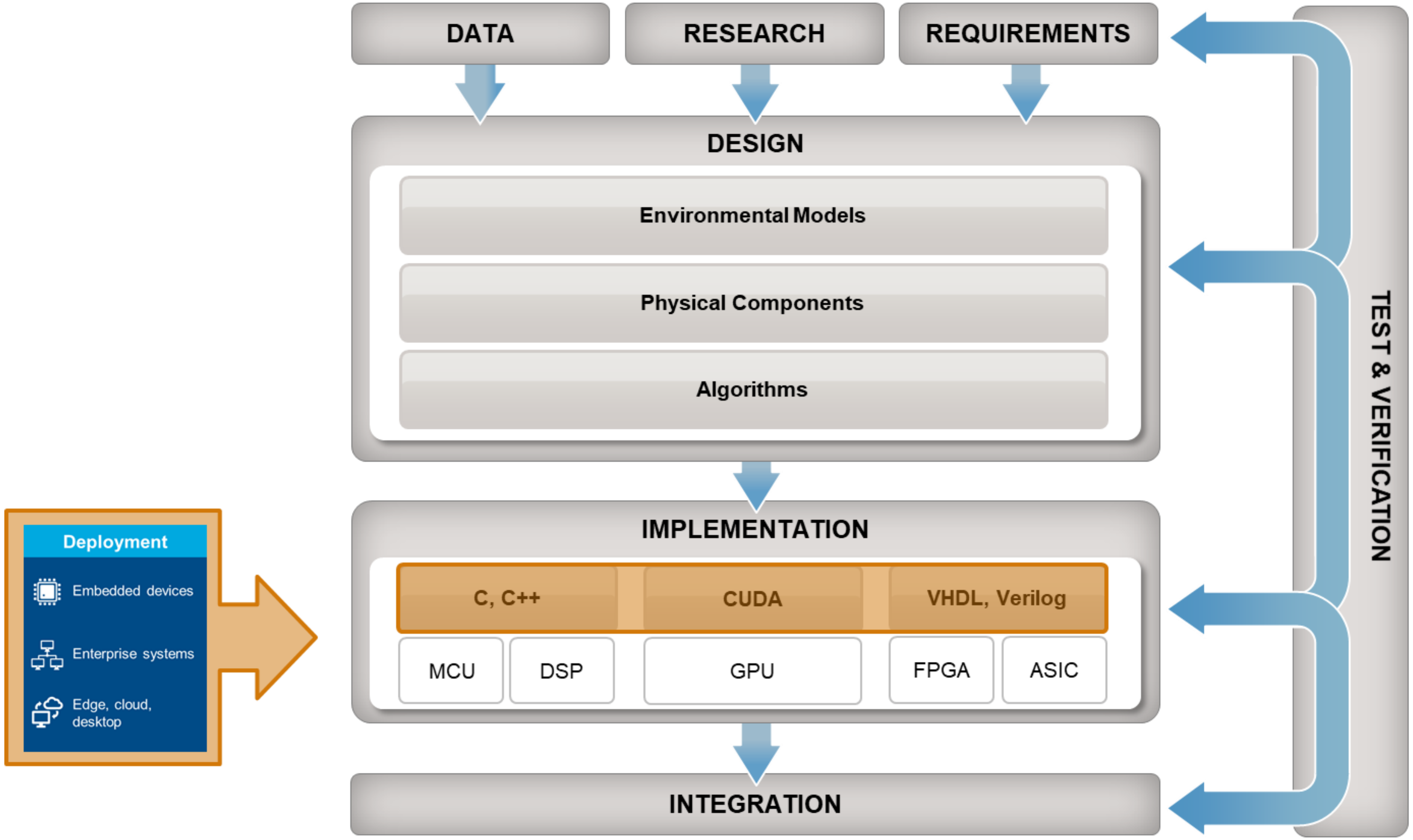
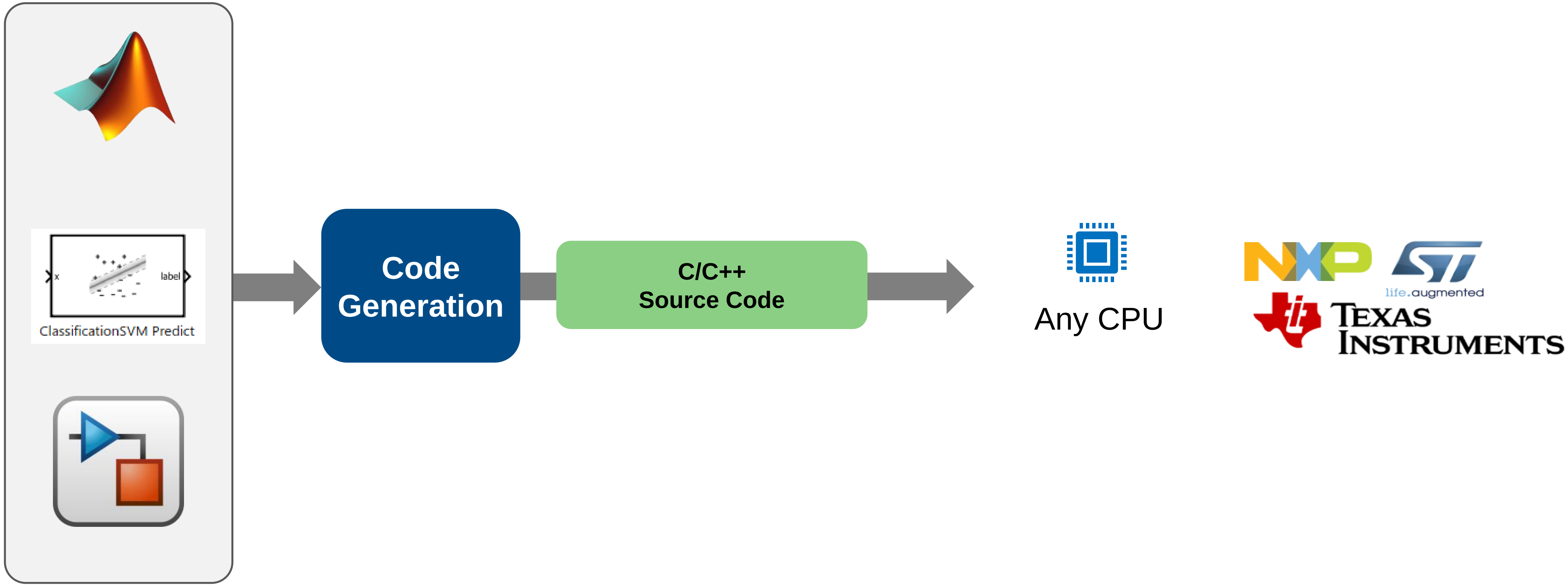
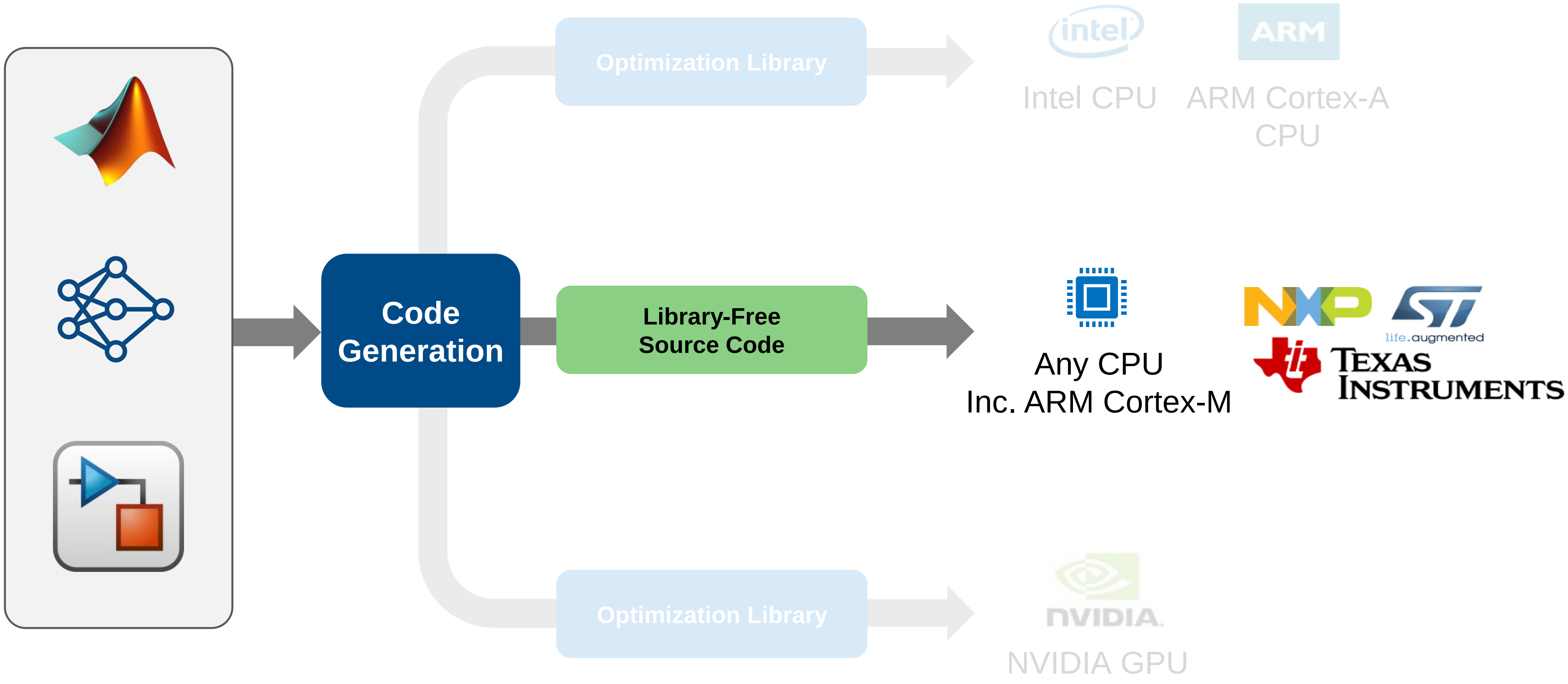
自动代码生成部署到硬件



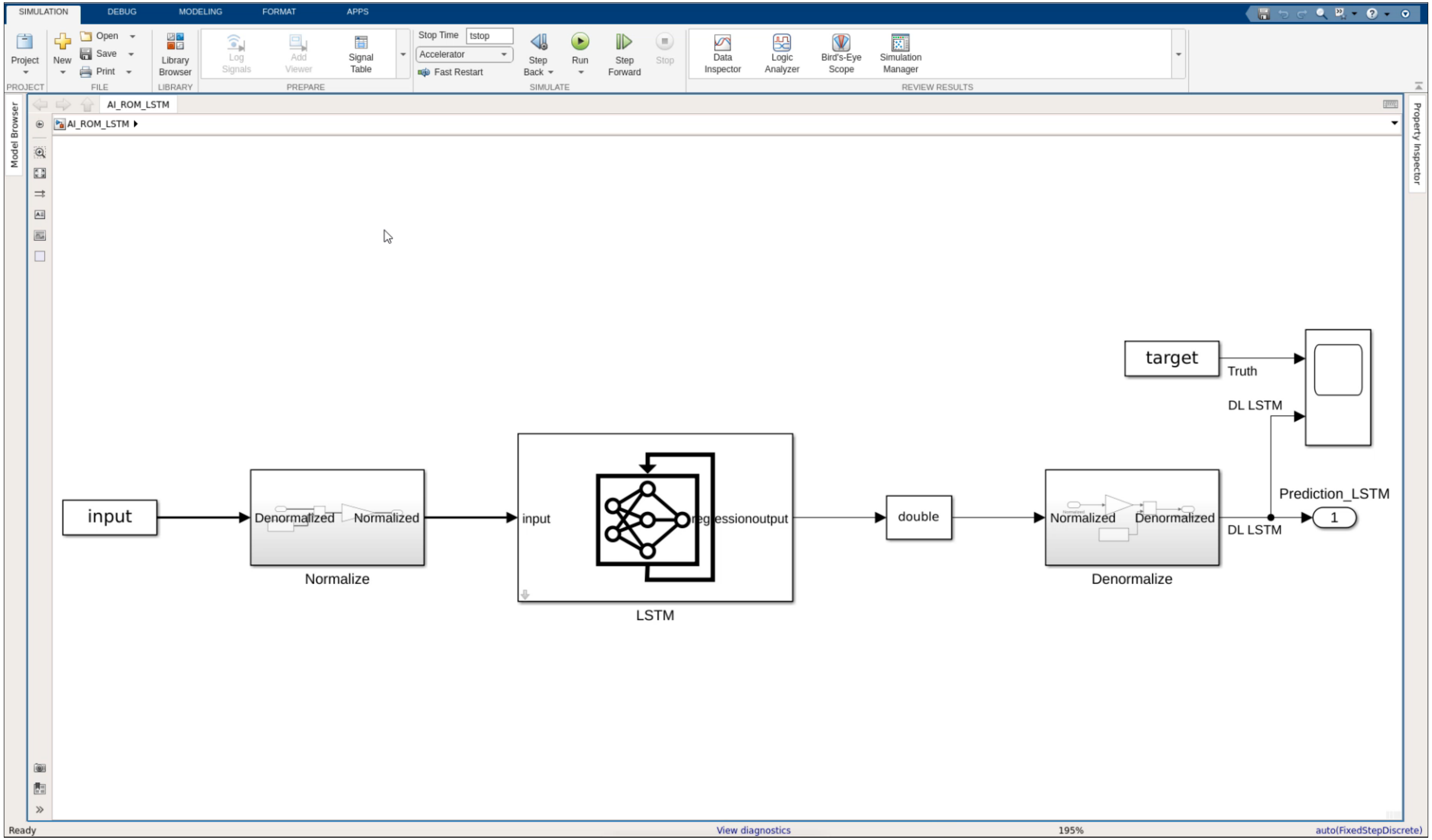
使用 Embedded Coder 生成机器学习代码



生成深度学习 Library-Free 的 C 代码

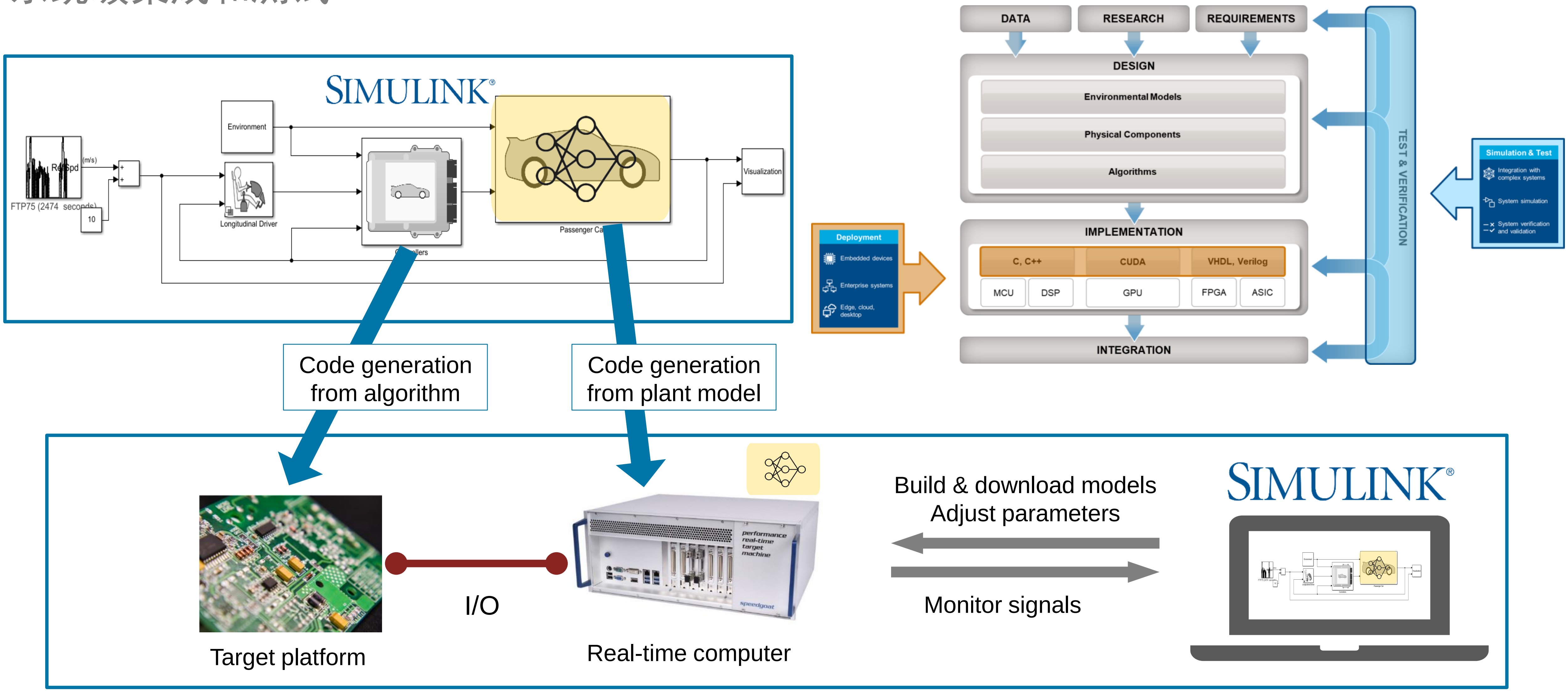


生成深度学习 Library-Free 的 C 代码



Hardware-in-the-loop simulation

系统级集成和测试



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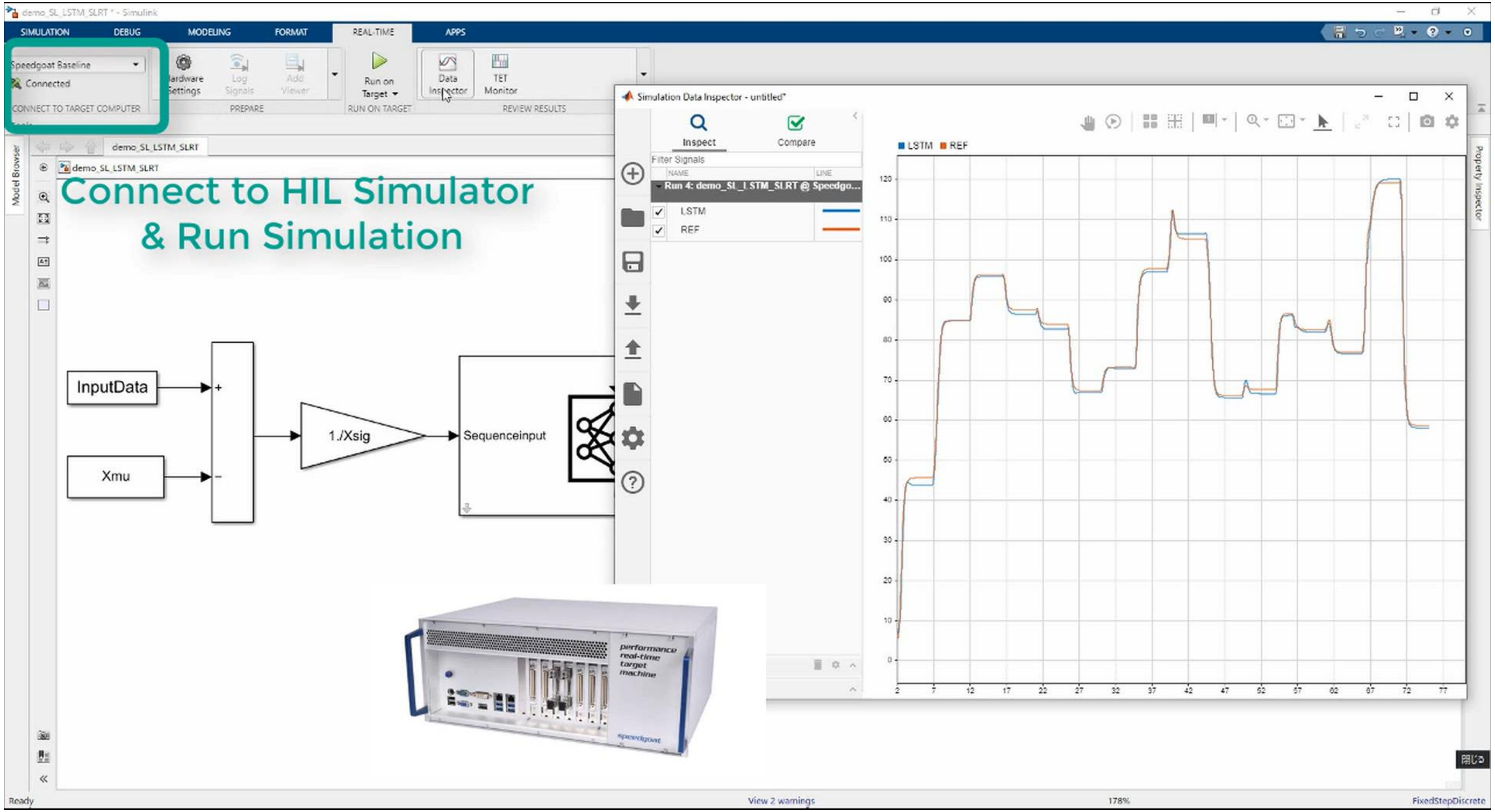
Hardware-in-the-loop simulation



选择系统匹配的AI模型

	LSTM Long Short-Term Memory Network	**Neural ODE** Neural Ordinary Differential Equation	**NLARX Sig** Nonlinear ARX Sigmoid	**NLARX SVM** Nonlinear ARX Support Vector Machine
Training Speed	🟢*	🔴	🟡	🟢
Interpretability	🔴	🔴	🟡	🔴
Inference Speed	🟡	🟡	🟢	🟢
Model Size	🟡	🟢	🟢	🔴
Accuracy (RSME)	🟢	🟢	🟢	🟠

Results are specific to Vehicle Engine ROM example

** Trained using GPU NVIDIA A100*

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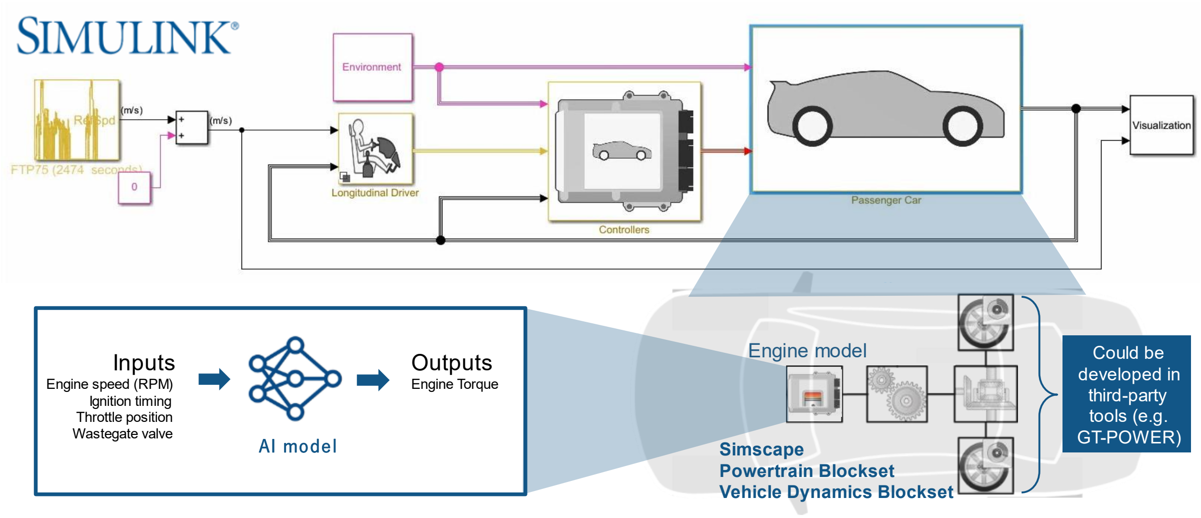
总结

使用基于AI的代理模型替换第一原理的发动机模型

第一原理模型和数据模型可并存

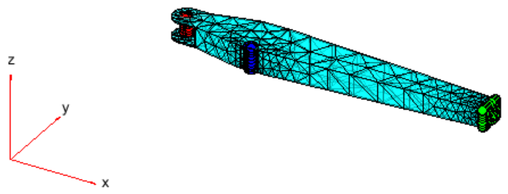
Data-driven models **First-principles models**



- 预处理Simulink合成数据
- 训练好的机器学习/深度学习/系统辨识模型来部分替换复杂的车辆发动机动态系统
- 将训练好的模型集成到Simulink，结合第一原理模型用于系统级仿真
- Generated C code and performed HIL tests

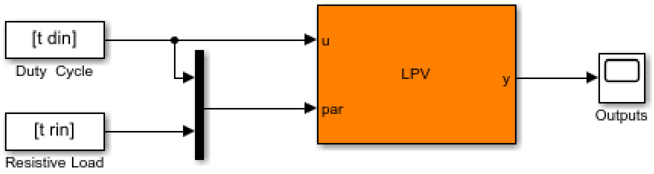
其他的参考示例

Model an Excavator Dipper Arm as a Flexible Body



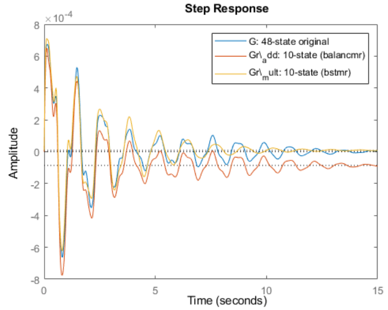
Simscape Multibody,
Partial Differential Equation Toolbox
[Link]

LPV Approximation of Boost Converter Model



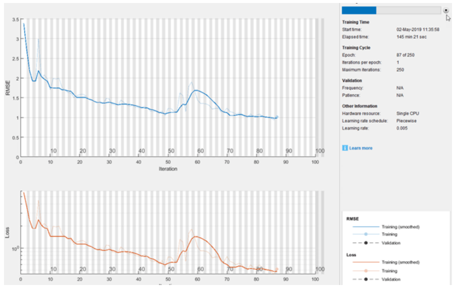
Simscape Electrical,
Simulink Control Design
[Link]

Simplifying Higher-Order Plant Models



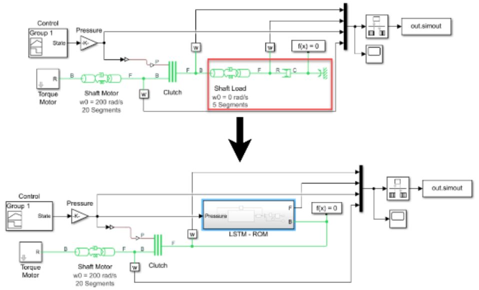
Robust Control Toolbox
[Link]

Generate a Deep Learning SI Engine Model



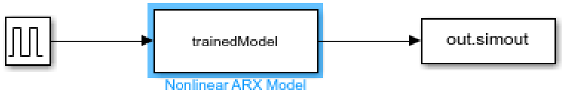
Deep Learning Toolbox,
Statistics and Machine Learning Toolbox
[Link]

Physical System Modeling Using LSTM Network in Simulink



Simulink, Simscape,
Deep Learning Toolbox
[Link]

Surrogate Modeling Using Gaussian Process-Based NLARX Model



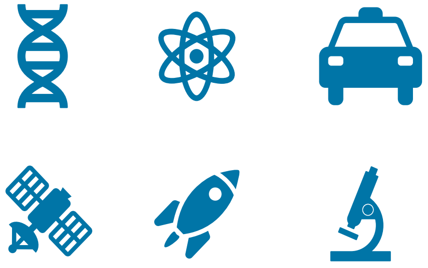
Simulink, Simscape, System Identification Toolbox,
Statistics and Machine Learning Toolbox
[Link]

Agenda

- 动态系统与数据驱动模型简介
- 基于AI的降阶模型开发与集成
- MathWorks的AI与MBD技术支持

MathWorks Provides Capabilities to Develop and Use AI Models

Verticals



WLAN Toolbox

Automated Driving Toolbox

5G Toolbox

Powertrain Blockset

Computer Vision Toolbox

Lidar Toolbox

Wavelet Toolbox

Robotics System Toolbox

Audio Toolbox

Signal Processing Toolbox

Communications Toolbox

MACHINE LEARNING

- K-Means
- Gaussian Processes
- Logistic Regression
- Decision Trees
- Support Vector Machines
- Random Forests
- Feedforward Neural Networks
- Generalized Additive Models
- PCA
- NARX Networks
- Linear Regression
- Naive Bayes
- Autoencoders

DEEP LEARNING

- CNNs
- Transformers
- LSTMs
- Neural ODEs
- TCN
- VAE
- GANs

Statistics and Machine Learning Toolbox

Deep Learning Toolbox

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MathWorks Engineering Support

Training

Guided Evaluations

Onsite Workshops

Consulting

Technical Support

免费入门MATLAB AI

无需下载，无需安装，只需要浏览器…

Deep Learning Onramp

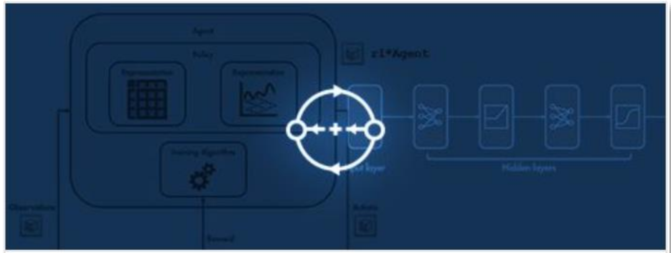
Get started quickly using deep learning methods to perform image recognition.

Details and launch

Machine Learning Onramp

An interactive introduction to practical machine learning methods for classification problems.

Details and launch



Reinforcement Learning Onramp

An interactive introduction to reinforcement learning methods for control problems.

Details and launch

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其他资源

深度学习入门之旅(2小时免费上机操作):
https://www.mathworks.com/learn/tutorials/deep-learning-onramp.html
Deep Learning Workshop（3小时上手实践）
需要的话欢迎联系我们
Deep Learning 培训（16小时深度课程，线上或线下）
https://ww2.mathworks.cn/learn/training/deep-learning-with-matlab.html
使用MATLAB进行深度学习教学（课程开发支持，欢迎联系我们）
https://www.mathworks.com/academia/courseware/teaching-deep-learning-with-matlab.html
MATLAB自带示例（可以直接在MATLAB中运行）
https://ww2.mathworks.cn/help/deeplearning/examples.html
Github MATLAB深度学习资源
https://github.com/matlab-deep-learning/
MATLAB微信公众号
数据驱动的动态系统建模（一）：深度学习
数据驱动的动态系统建模（二）：系统辨识

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Thank you

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