MATLAB EXPO

利用人工智能实现模型降阶

--- 加速Simulink模型设计与仿真

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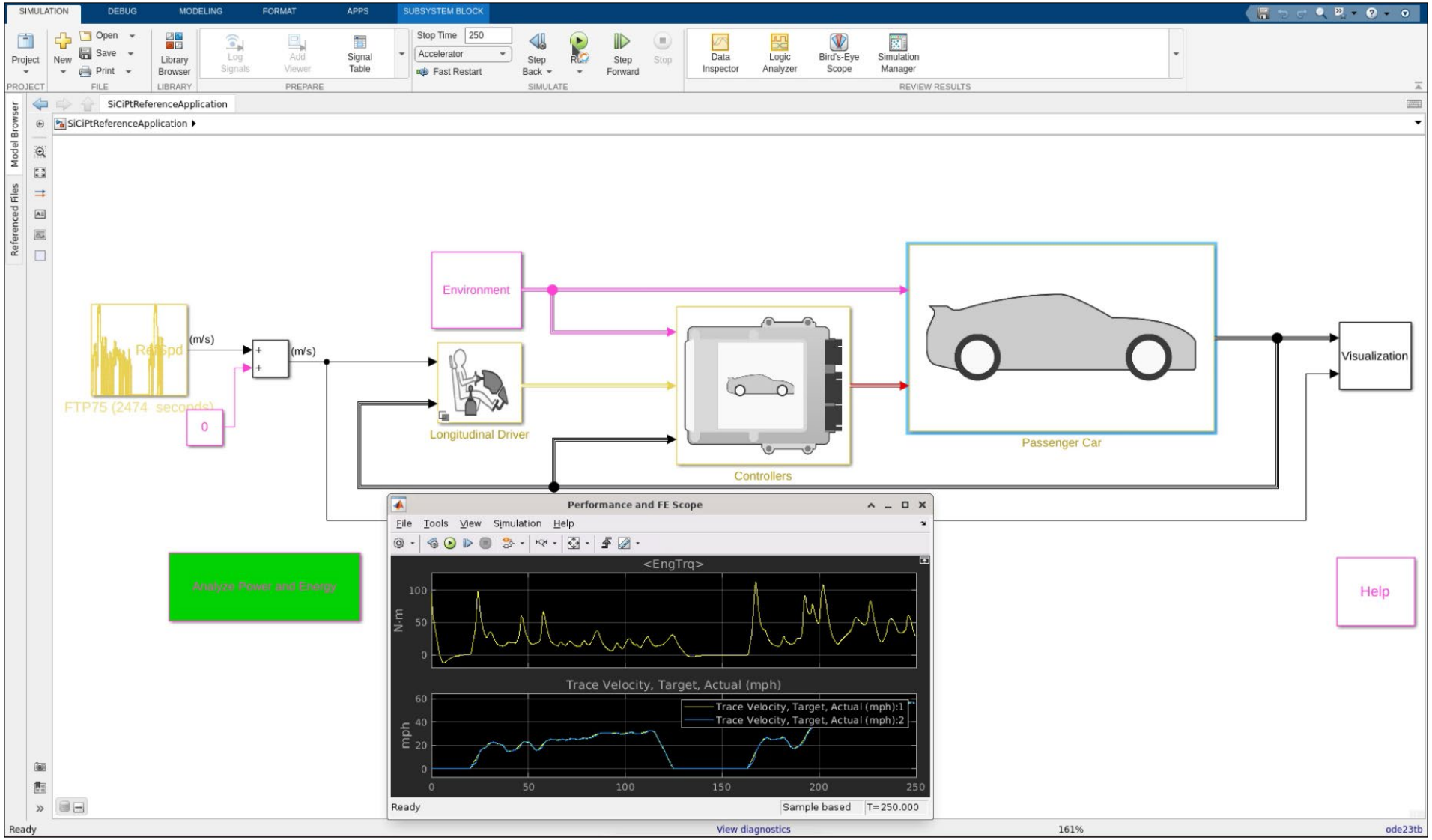
MathWorks®

主要内容

- MATLAB中的数据驱动的模型降阶技术介绍
- MATLAB中数据驱动的模型降阶流程介绍

Simulink模型

系统级仿真



我们面对的挑战

高保真度的模型，例如，来自第三方有限元分析工具的模型，在系统级仿真和 HIL 测试中过于缓慢。

创建一个能在速度、准确度、可解释性等方面产生期望结果的降阶模型 (ROM，Reduced Order Modeling)。

模型降阶(Reduced Order Modeling)

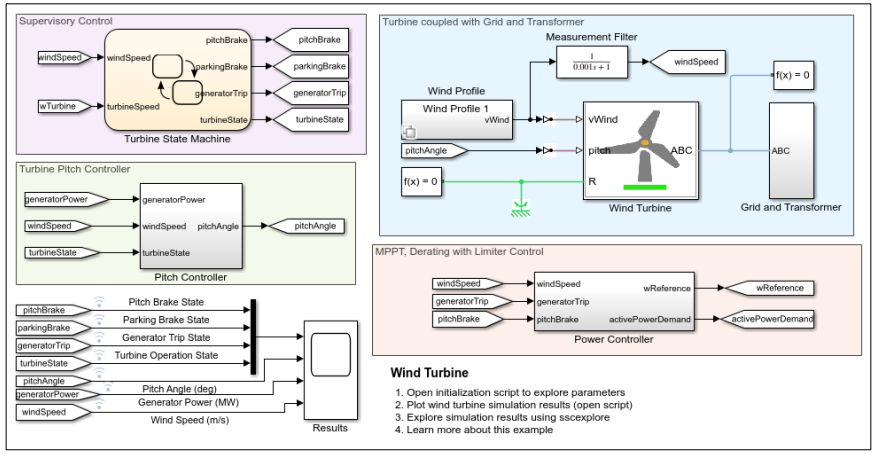
What?

- 降低模型的计算复杂度或存储需求的技术
- 在可控误差范围内保持结果的准确性

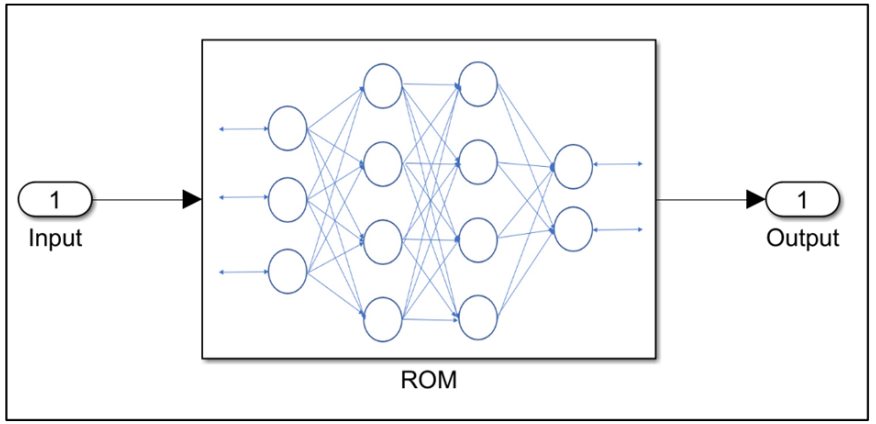
Why?

- 加速桌面系统仿真
- 硬件在环测试（HIL）
- 使能系统级仿真
- 开发虚拟传感器，数字孪生
- 执行控制设计

High-fidelity model



Reduced-Order Model (ROM)



模型降阶(Reduced Order Modeling)

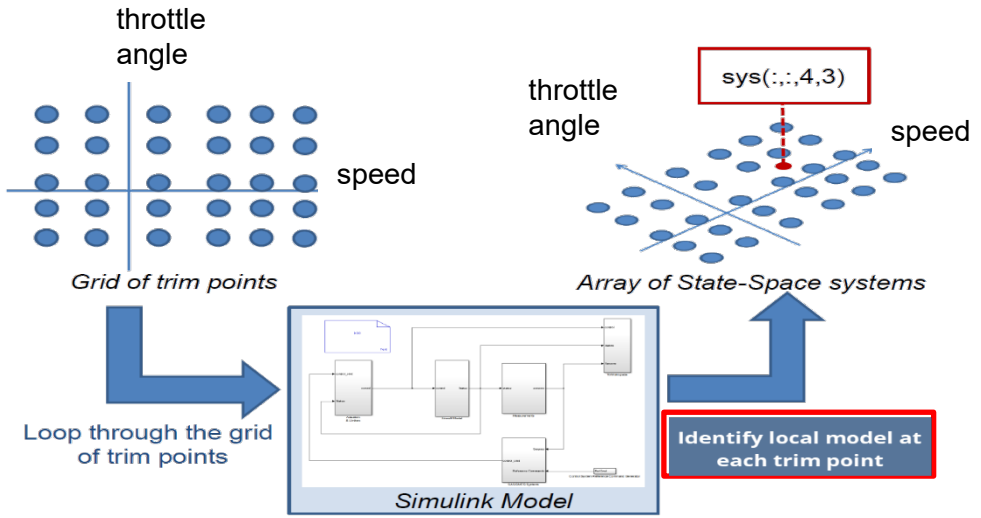
How?

Reduced order model

Model-based

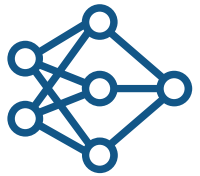
FEA Software → **Simulink**
Simscape Multibody
Control System Toolbox

Linearization



AI-Based Data-driven

Inputs
Engine speed (RPM)
Ignition timing
Throttle position
Wastegate valve



AI model

Outputs
Engine Torque

focus today

第一性原理建模(First principal models)与数据驱动建模(Data driven models)

Data-driven models and first-principles models can co-exist

DATA-DRIVEN MODELS

Statistics, optimization, AI

FIRST-PRINCIPLES MODELS

Physics, math, domain knowledge

Advantages

- 当第一原理模型不可用或难以/不可能找到时，数据驱动的方法是一个选项（可能会成功）
- 可以降低模型复杂度，加快仿真
- 可以充分利用现有的测试和仿真数据
- 不需要太多的领域知识

Challenges

- 需要大量的数据集
- 通常不能：
  - 可解释性
  - 以物理上有意义的方式参数化
- 泛化能力的局限性

Advantages

- 低/高保真模型可以进行参数化行为
- 有清晰的物理意义
- 不需要数据工程

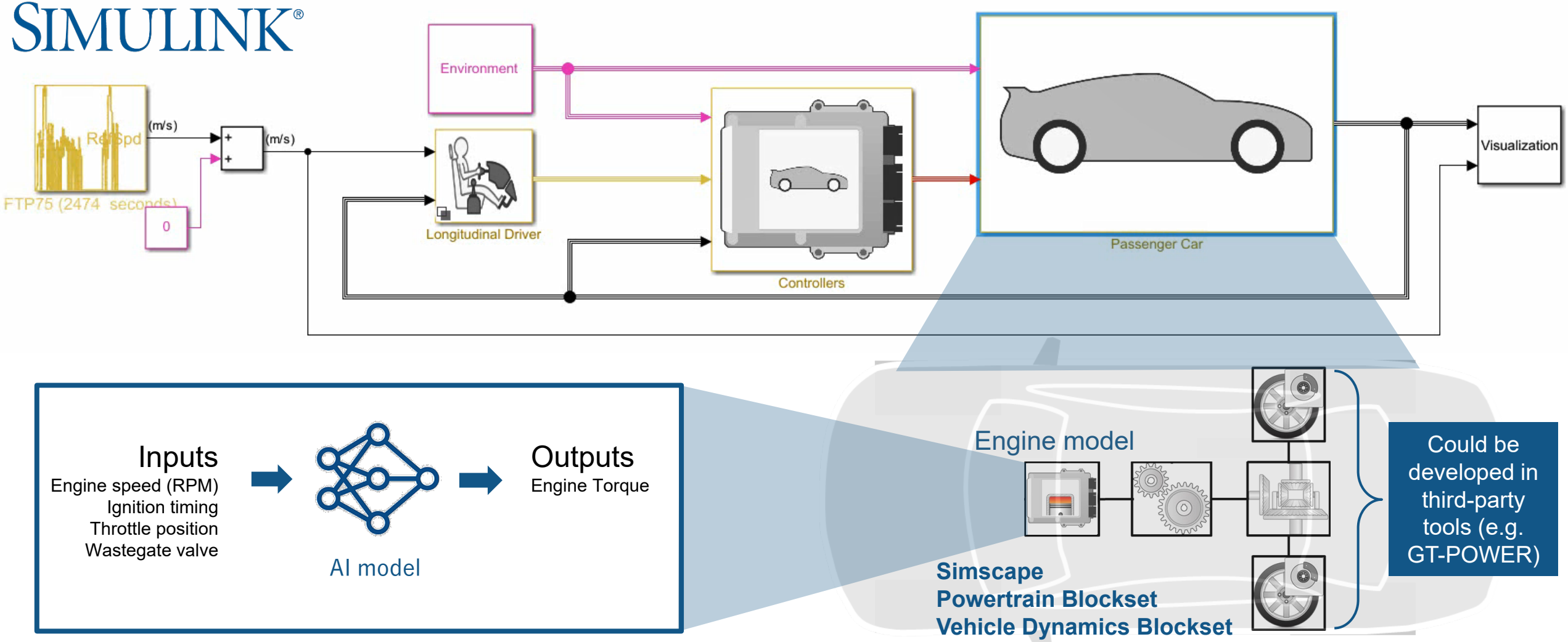
Challenges

- 某些情况下的高复杂度难以建模
- 需要大量的推导时间
- 需要领域专业知识

举例

用基于人工智能的降阶模型取代第一性原理模型

SIMULINK®



Inputs
Engine speed (RPM)
Ignition timing
Throttle position
Wastegate valve

AI model

Outputs
Engine Torque

Engine model

Simscape
Powertrain Blockset
Vehicle Dynamics Blockset

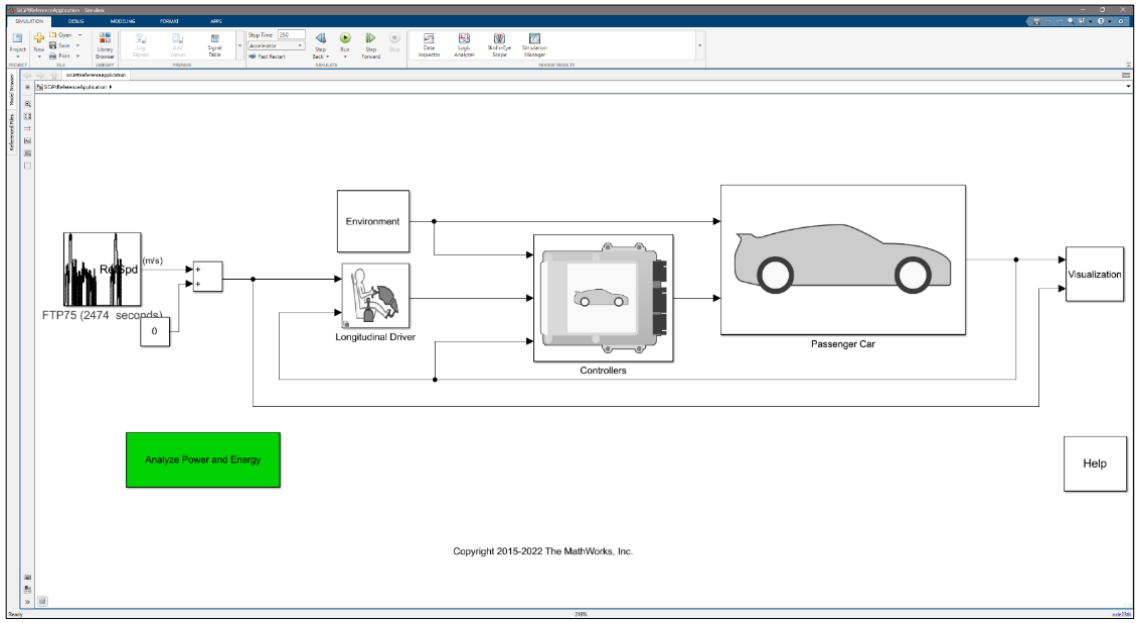
Could be developed in third-party tools (e.g. GT-POWER)

BLACK BOX GREY BOX **WHITE BOX**

基于AI的模型降阶

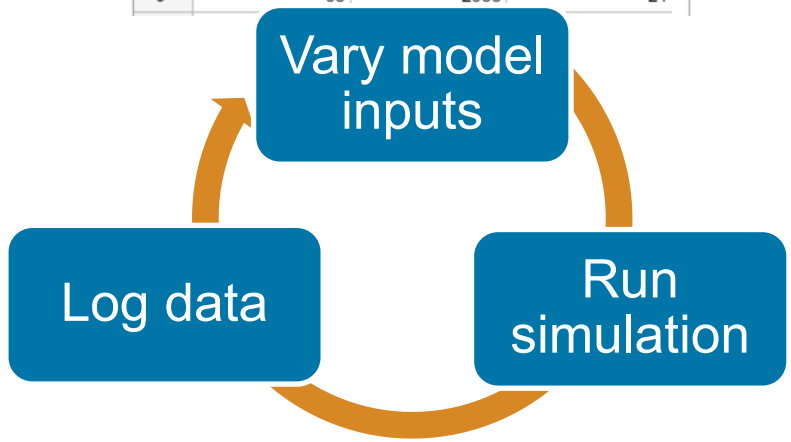
- 生成数据

执行设计实验（DoE）并从Simulink模型生成数据



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



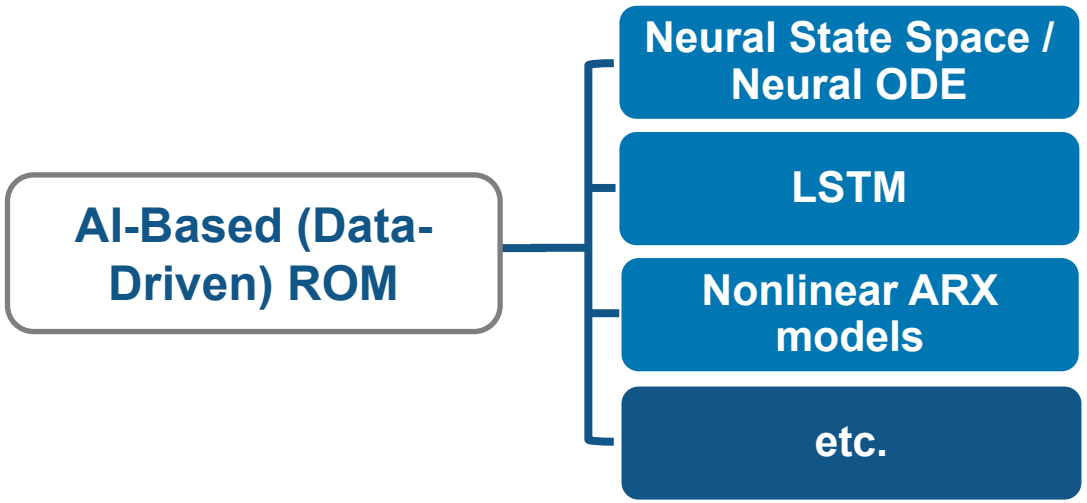
Inputs
Engine speed (RPM)
Ignition timing
Throttle position
Wastegate valve

Output
Engine Torque

Data Preparation | AI Modeling | Simulation & Test | Deployment

基于AI的模型降阶

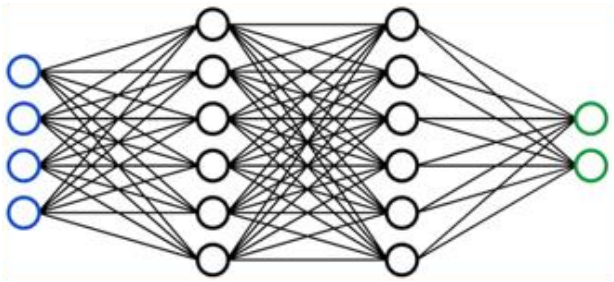
- 动态系统的AI建模



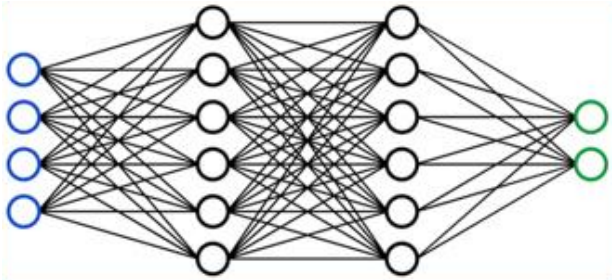
基于AI的模型降阶

- 非线性状态空间建模

$$\begin{cases} \dot{x} = f(x,u) \\ y = g(x,u) \end{cases}$$



State Network (*f*)



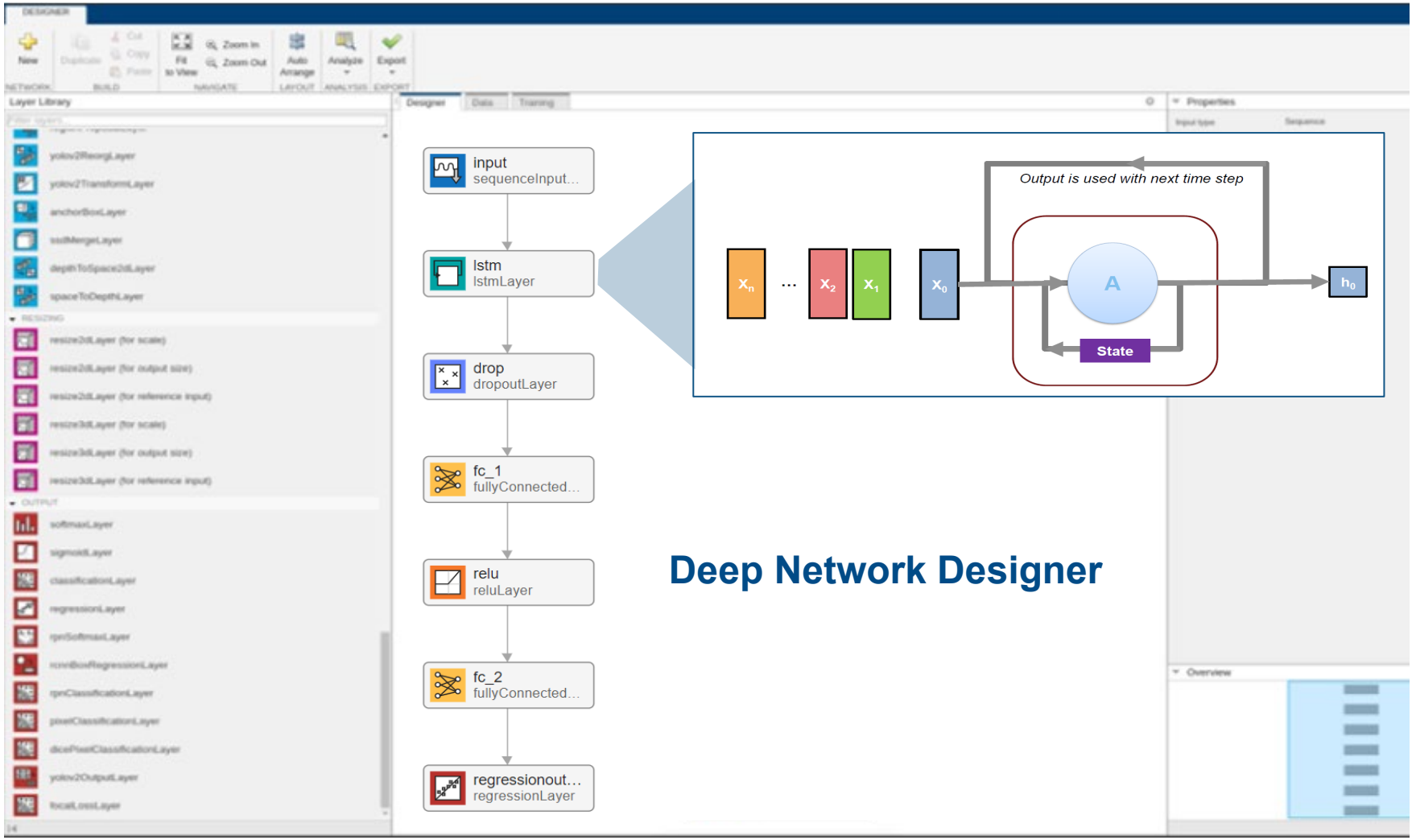
Output Network (*g*)

Neural state-space model

基于AI的模型降阶

- LSTM模型

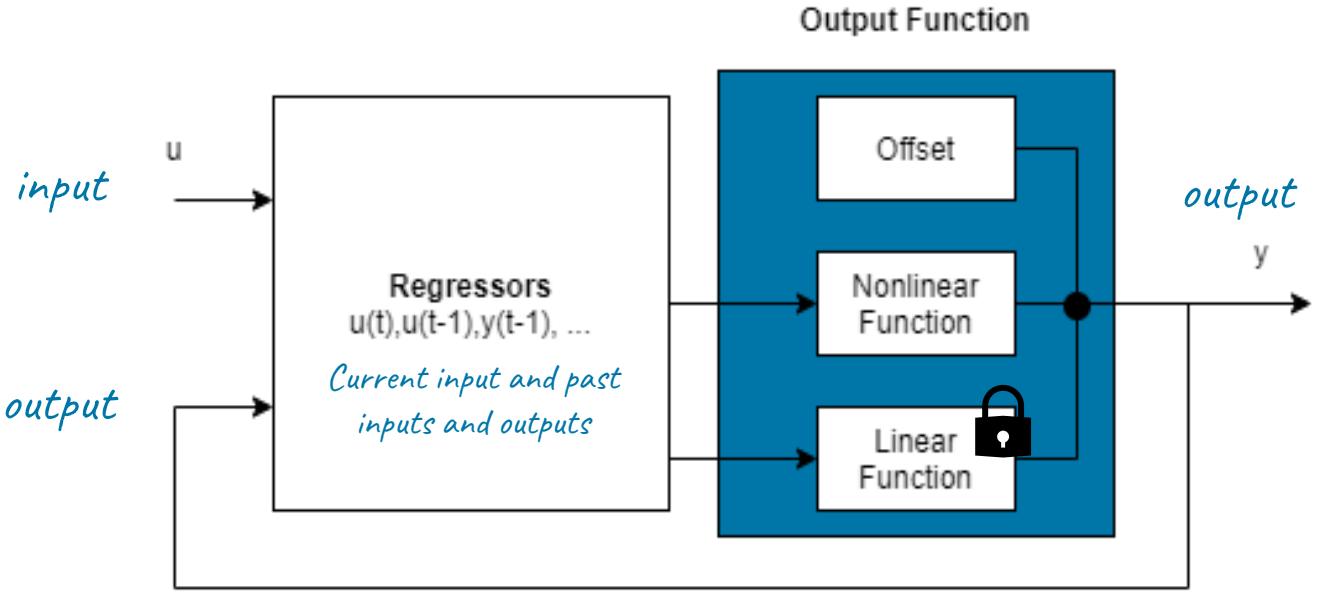
捕获时间上的依赖关系



Data Preparation | AI Modeling | Simulation & Test | Deployment

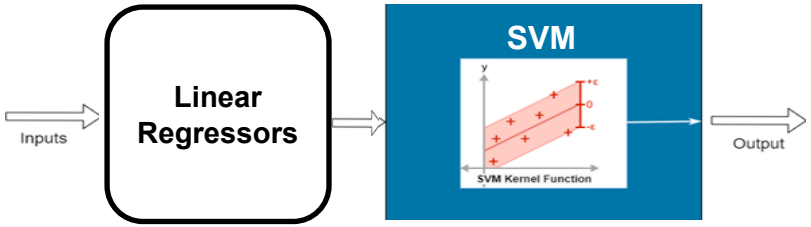
基于AI的模型降阶

- **非线性的带有外生变量的自回归（Nonlinear ARX (NLARX)）**
  - 将线性ARX扩展到非线性情况
  - 灵活选择非线性函数
  - 比深度神经网络更具有可解释性
  - 训练和仿真更快



Extend linear models and model nonlinear behavior using flexible nonlinear functions

Selected configuration



选择适合的模型

	LSTM Long Short-Term Memory Network	Neural SS Neural State Space (Neural ODE)	NLARX SVM Nonlinear ARX Support Vector Machine (SVM)
Training Speed	*●	●	●
Inference Speed	●	●	●
Model Size	●	●	●
Accuracy (RMSE)	●	●	●

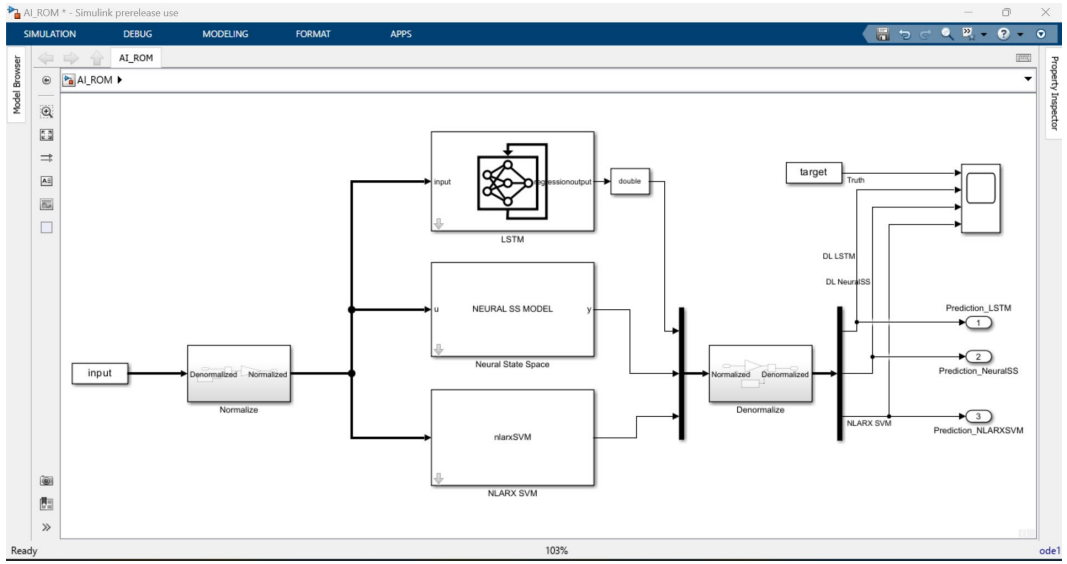
Results are specific to Vehicle Engine ROM example

Better ● Okay ● Worse ●

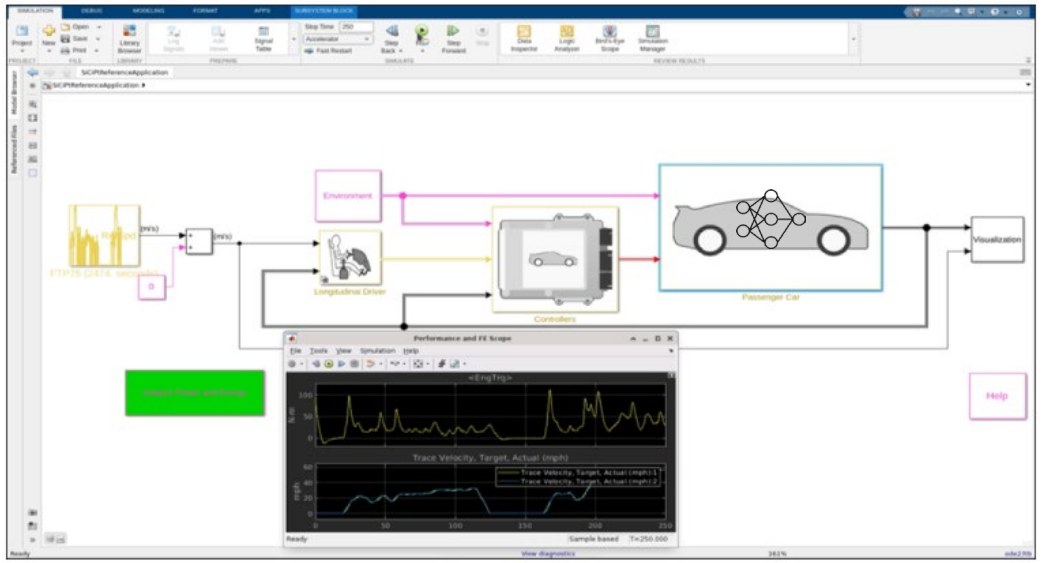
* ● *if trained using a GPU. Testing made with GPU NVIDIA A100*

系统级仿真

Integration of trained AI model into Simulink

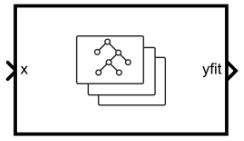


System-level simulation



Data Preparation | AI Modeling | **Simulation & Test** | Deployment

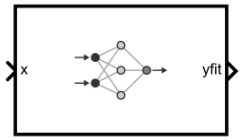
Simulink中的AI相关库逐步进行扩展，包含更多的模型



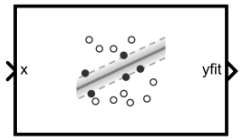
RegressionEnsemble Predict

R2022a

RegressionGP Predict



RegressionNeuralNetwork Predict



RegressionSVM Predict

R2021b

RegressionTree Predict

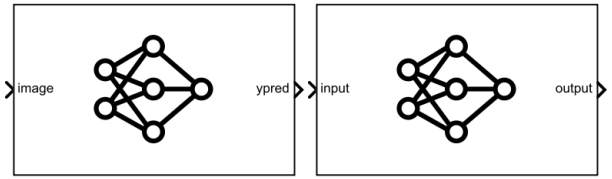
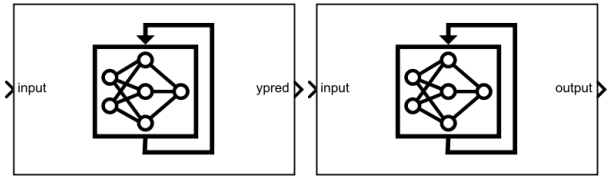


Image Classifier

Predict



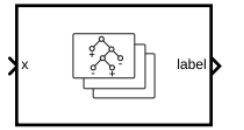
Stateful Classify

Stateful Predict

Deep Learning Toolbox

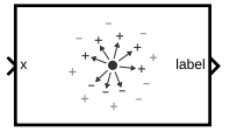
Audio Toolbox

R2022b



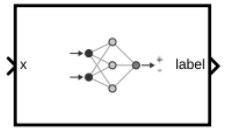
ClassificationEnsemble Predict

R2022b

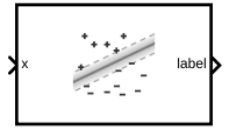


ClassificationKNN Predict

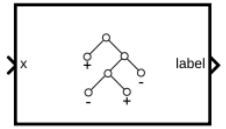
R2021b



ClassificationNeuralNetwork Predict



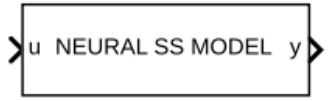
ClassificationSVM Predict



ClassificationTree Predict

Statistics and Machine Learning Toolbox

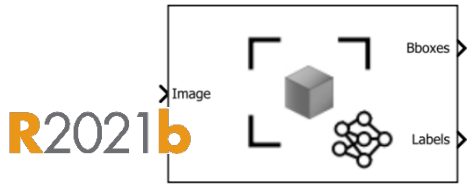
R2022b



Neural State Space Model

Nonlinear ARX Model

System Identification Toolbox

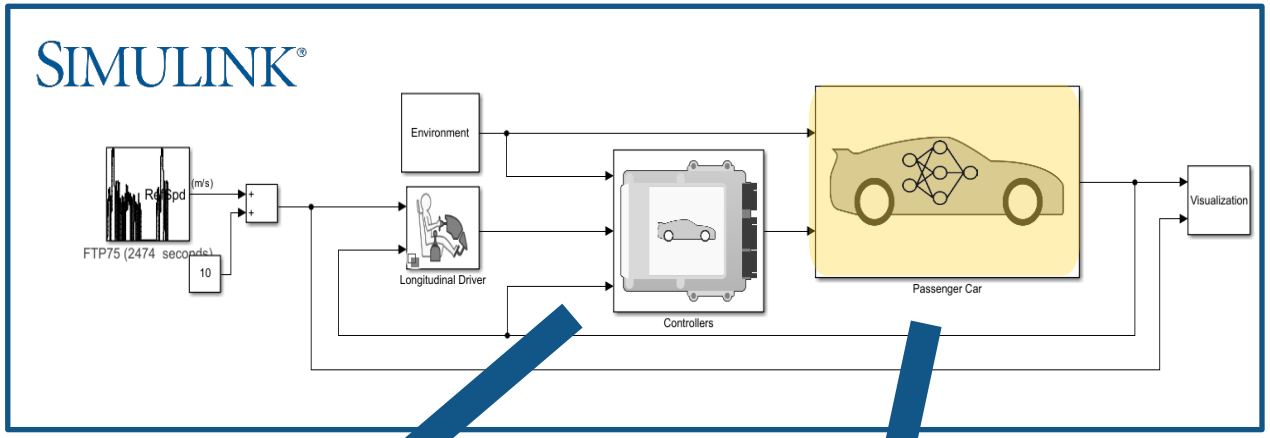


Deep Learning Object Detector

Computer Vision Toolbox

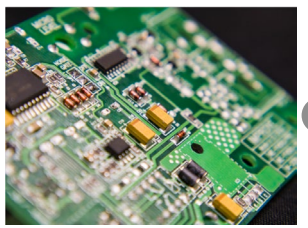
Data Preparation | AI Modeling | Simulation & Test | Deployment

硬件在环仿真



Code generation from controller

Code generation from ROM model



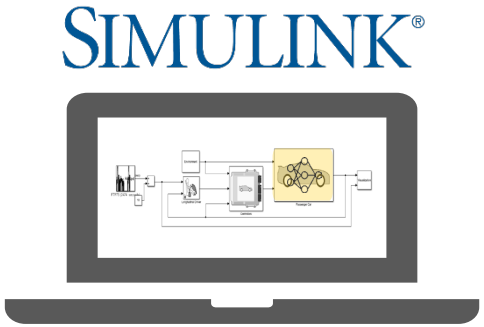
Target platform

I/O

Real-time computer

Build & download models
Adjust parameters

Monitor signals



Data Preparation | AI Modeling | Simulation & Test | Deployment

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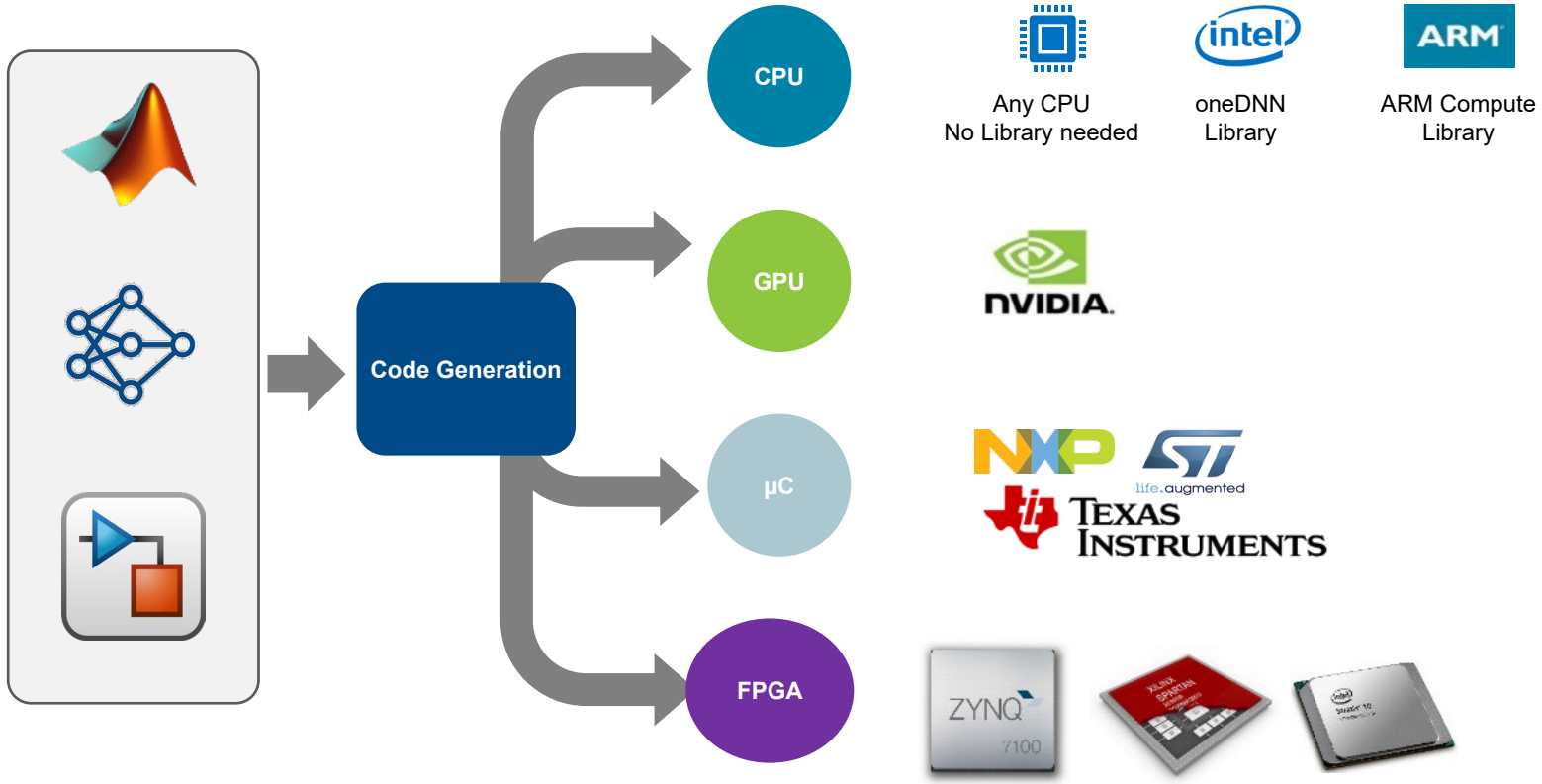
硬件在环仿真

- 代码生成



Data Preparation | AI Modeling | Simulation & Test | Deployment

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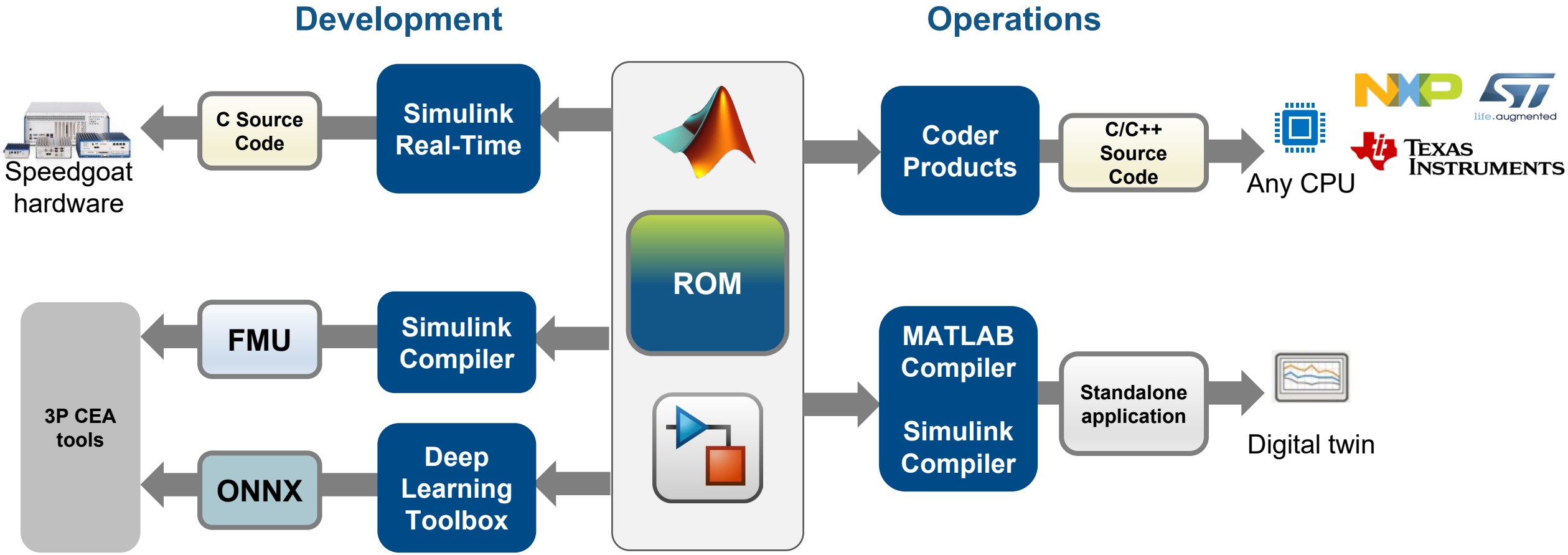
降阶模型的应用和部署


Development
Operations
Speedgoat hardware
C Source Code
Simulink Real-Time
ROM
Coder Products
C/C++ Source Code
Any CPU
NXP
life.augmented
Texas Instruments
3P CEA tools
FMU
Simulink Compiler
ONNX
Deep Learning Toolbox
MATLAB Compiler
Simulink Compiler
Standalone application
Digital twin

总结

赋能	使用高保真度模型进行HIL测试和系统级仿真；探索MATLAB中的各种ROM技术加快HIL测试和系统级仿真。
探索	在MATLAB中探索不同的ROM技术，以找到最佳方法。

MATLAB EXPO

谢谢