MATLAB EXPO

AI用于Simulink模型的降阶方法和应用场景
AI for Simulink Model Reduced Order Modeling and Application Scenarios

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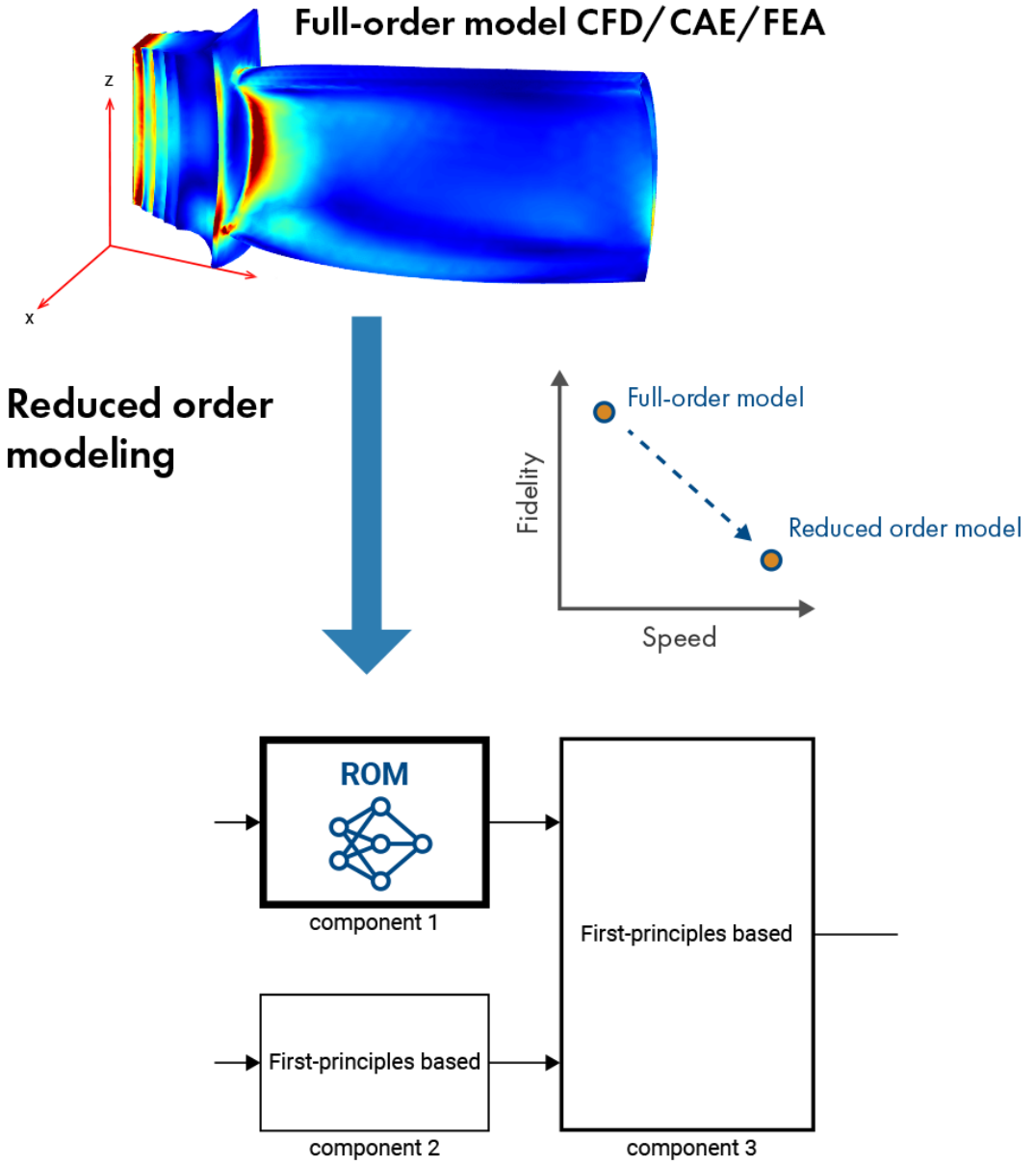
MathWorks

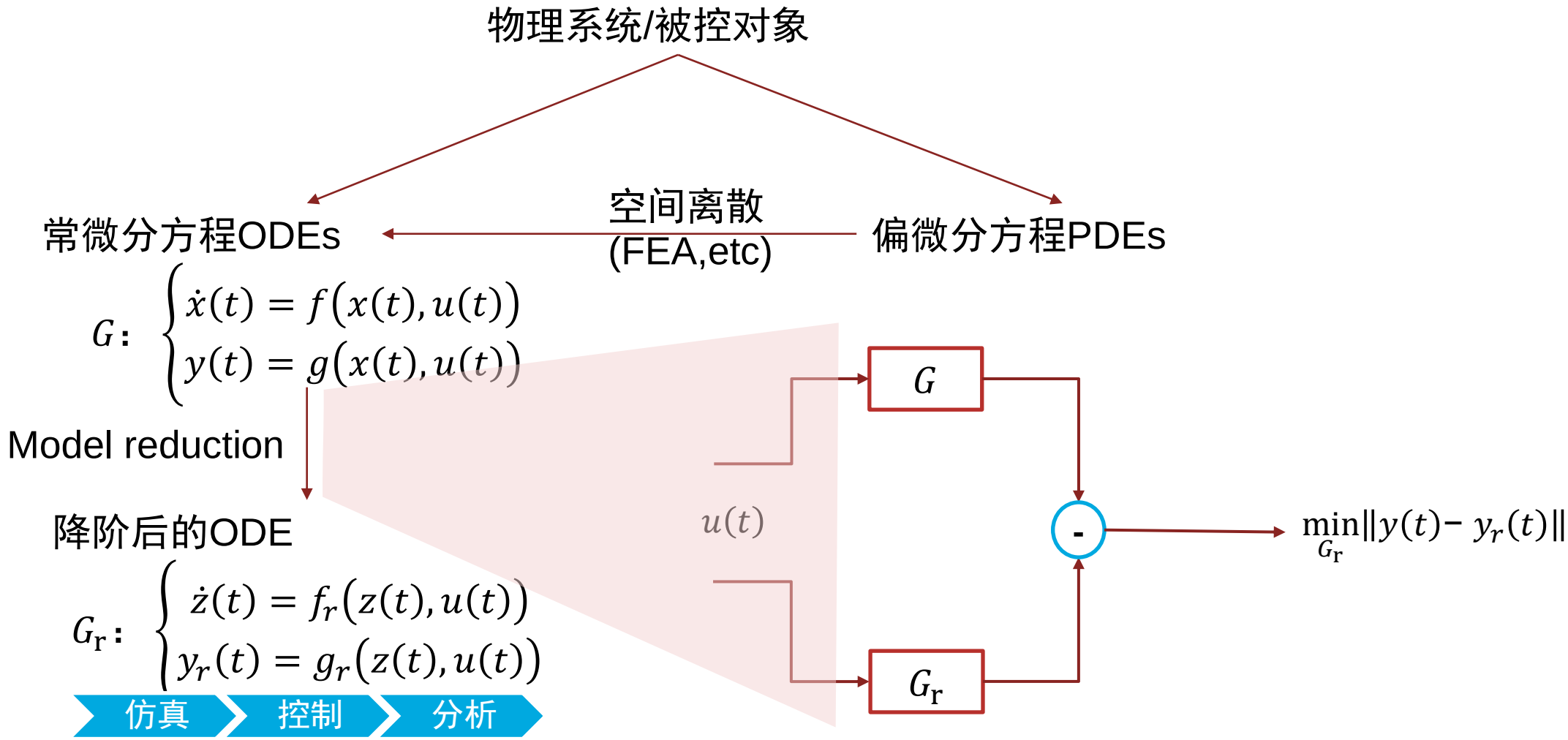
模型降阶

- **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（例如 模型预测控制）



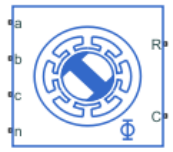
模型降阶：Overview

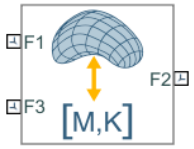


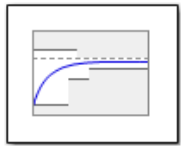
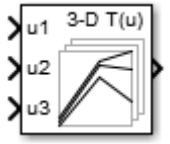
模型降阶

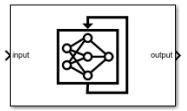
实现方式

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**
    

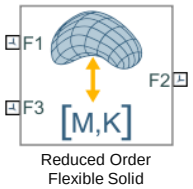
    Simulink, Curve Fitting Toolbox, Model-Based Calibration Toolbox
  - **Dynamic**
    

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

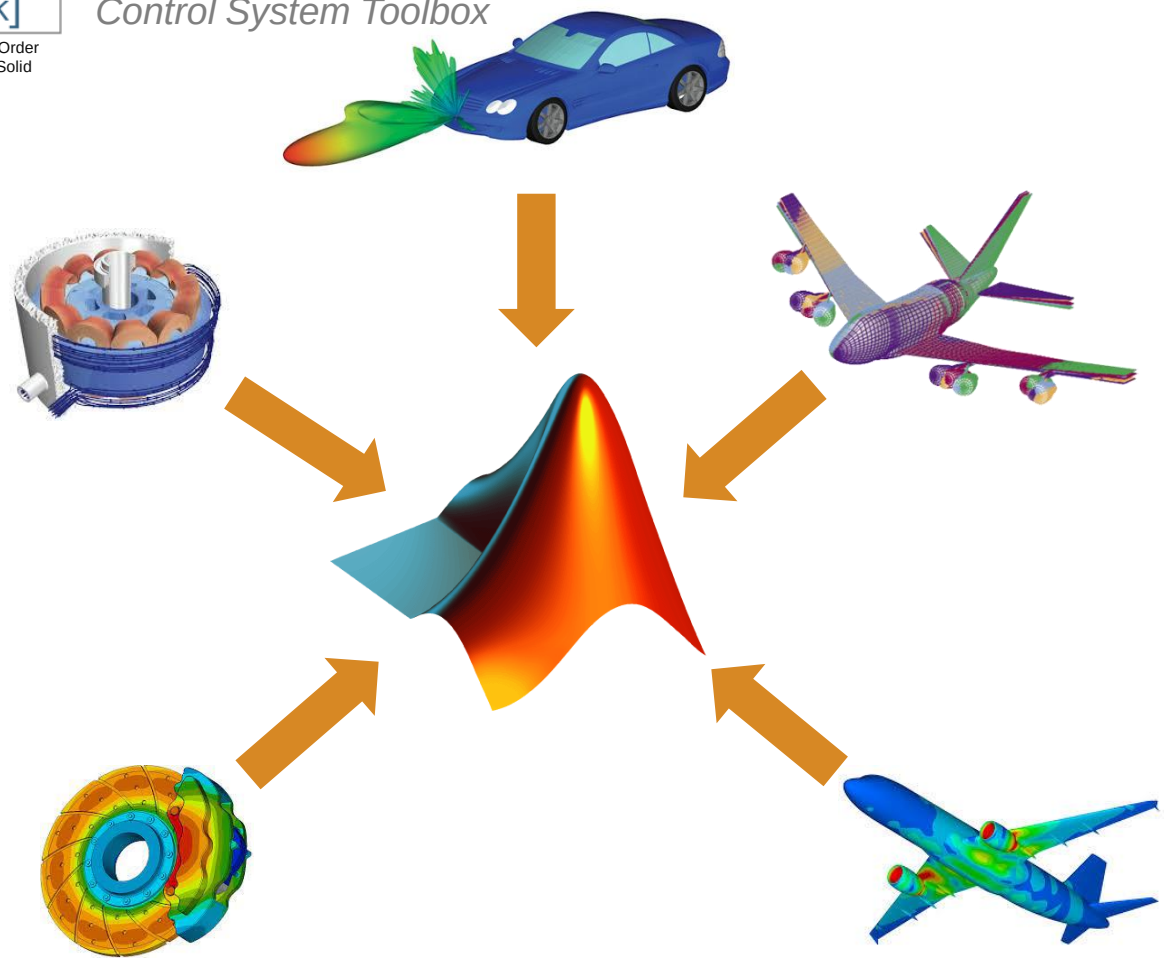
模型降阶

将FEA 和 Simulink/Simscape结合

Model-based



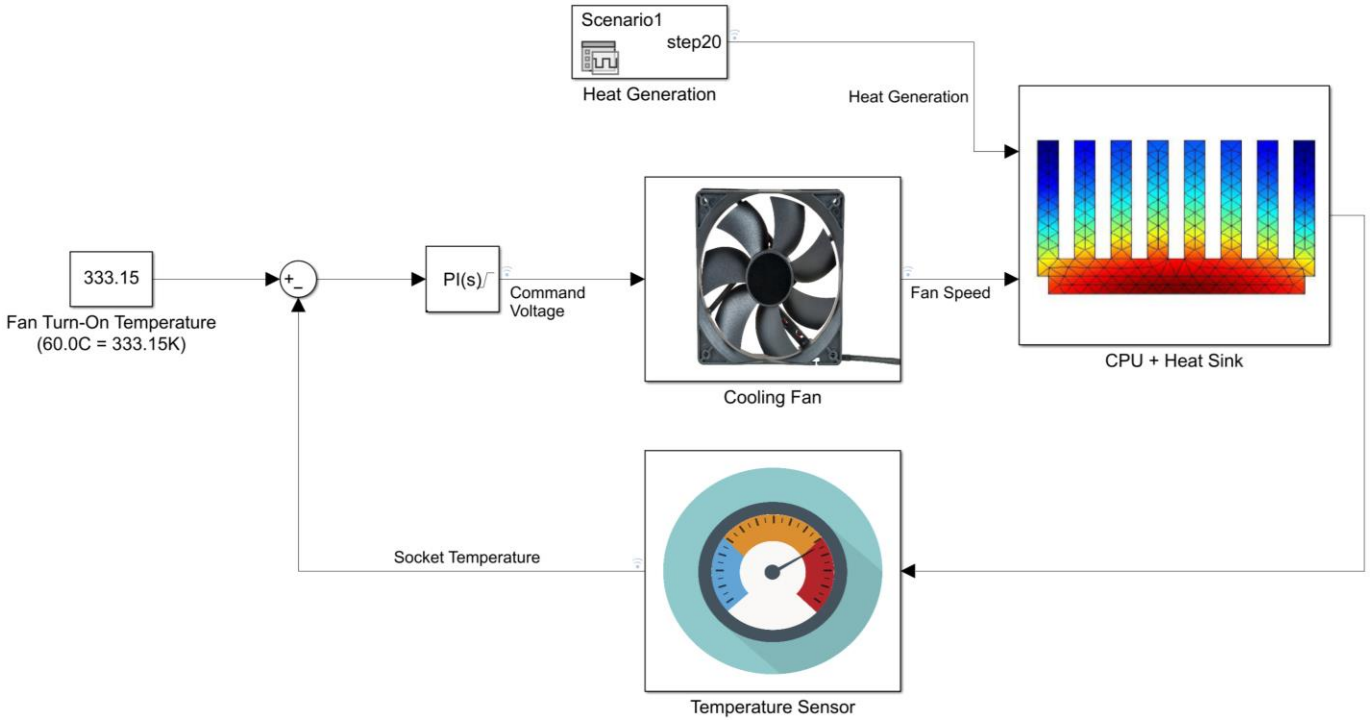
Simulink, Simscape Multibody, Simscape Electrical, Partial Differential Equation Toolbox, Control System Toolbox

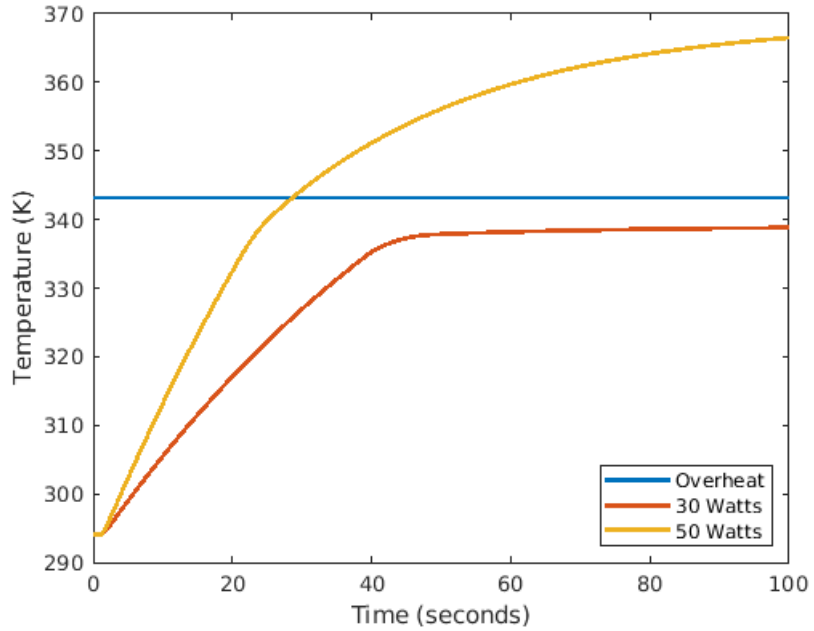


模型降阶

使用瞬态温度模型用于系统设计

给定一个固定的风扇和散热器几何形状 确定CPU的最大安全运行功率





- 100种不同的运行功率，每次仿真100秒, 一个温度场的FEA 几个小时

Model available on MATLAB Central

模型降阶

物理系统/被控对象 $T = f(t, x)$

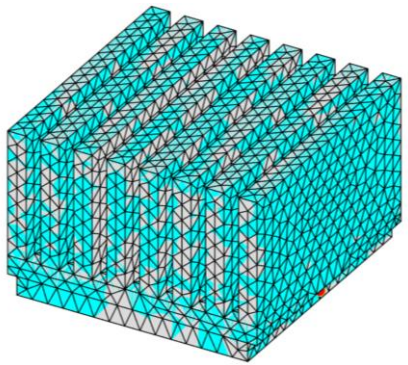
空间离散

常微分方程ODEs

$KT_i = Q$

偏微分方程PDEs

$\rho c_p \frac{\partial T}{\partial t} + \nabla \cdot \mathrm{k}\nabla T = q$

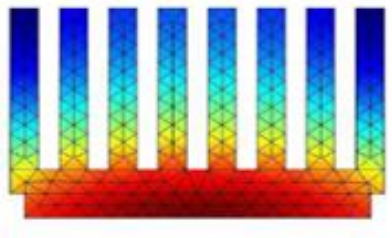


$M\dot{T} + KT = Q$

数值离散解

$$T_h(x) = \sum_i T_i \psi_i(x)$$

$$\sum_i T_i \int_\Omega k\, \nabla\psi_i(x) \cdot \nabla\psi_j(x)\, dV +$$
$$\sum_i \int_{\partial\Omega} (-kT_i\, \nabla\psi_i(x)) \cdot \mathbf{n}\psi_j(x)\, dS =$$
$$\int_\Omega q(\sum_i T_i\psi_i(x))\psi_j(x) dV$$



稳态场景

$\nabla \cdot \mathrm{k}\nabla T = q$

$$\int_\Omega k\, \nabla T \cdot \nabla\varphi dV + \int_{\partial\Omega} (-k\nabla T) \cdot \mathbf{n}\varphi dS = \int_\Omega q\, \varphi dV$$

引入试函数φ 得到 弱形式方程

模型降阶

Solve Finite Element Analysis Workflows with PDE Toolbox

$$\rho c_p \frac{\partial T}{\partial t} + \nabla \cdot \mathrm{k}\nabla T = q \quad \xrightarrow{\text{FEM}} \quad \boldsymbol{M\dot{T} + KT = Q}$$

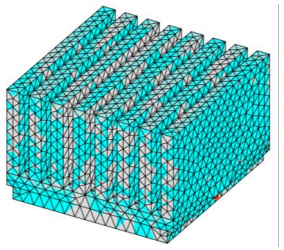
Geometry → Preprocess → Solve → Postprocess

```
heatsink = createpde('thermal','transient');
```

```
geom = importGeometry("heatsink.stl");
```

```
generateMesh(heatsink)
```

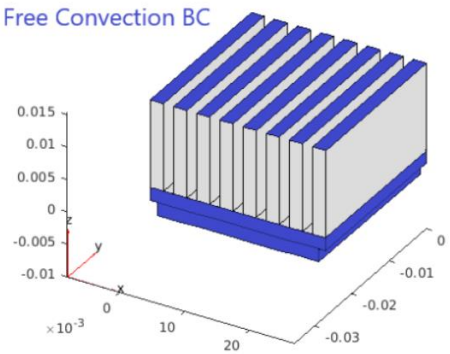
```
ans =
  FEMesh with properties:

            Nodes: [3×24410 double]
         Elements: [10×12840 double]
    MaxElementSize: 0.0017
    MinElementSize: 8.4006e-04
     MeshGradation: 1
    GeometricOrder: '
```



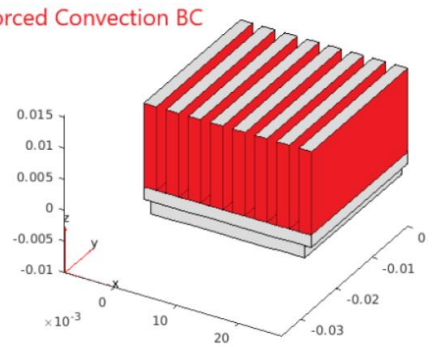
```
% aluminum alloy 6060 T6
mtl = thermalProperties(heatsink,...
    'ThermalConductivity',210, ...
    'MassDensity',2710, ...
    'SpecificHeat',900);
```

```
thermalIC(model,Tambient);
R  = solve(model,0:60:7200);
```

Free Convection BC



Forced Convection BC



```
sysMats = assembleFEMatrices(heatsink)
```

```
sysMats = struct with fields:
    K: [24410×24410 double]
    A: [24410×24410 double]
    F: [24410×1 double]
    Q: [24410×24410 double]
    G: [24410×1 double]
    H: [1×24410 double]
    R: [24410×1 double]
    M: [24410×24410 double]
```

```
freeBC = thermalBC(heatsink,'Face',freeBCfaces,'HeatFlux',1);
forcedBC = thermalBC(heatsink,'Face',forcedBCfaces,'HeatFlux',1);
```

Statistics & ML Toolbox
Deep Learning Toolbox
Model Based Calibration Toolbox

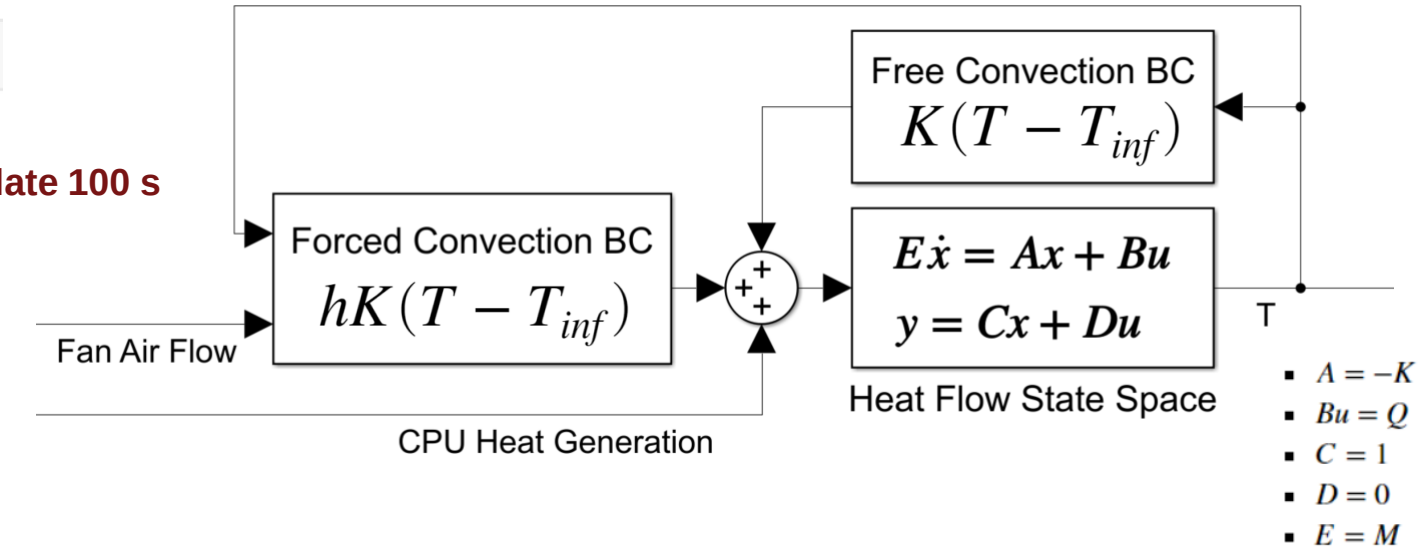
模型降阶

- descriptor state-space block 可以实现在Simulink中使用ODE矩阵
  - 结合其他block来约束 BCs, sources, sinks, etc.

```
sysMats = assembleFEMatrices(heatsink)
```

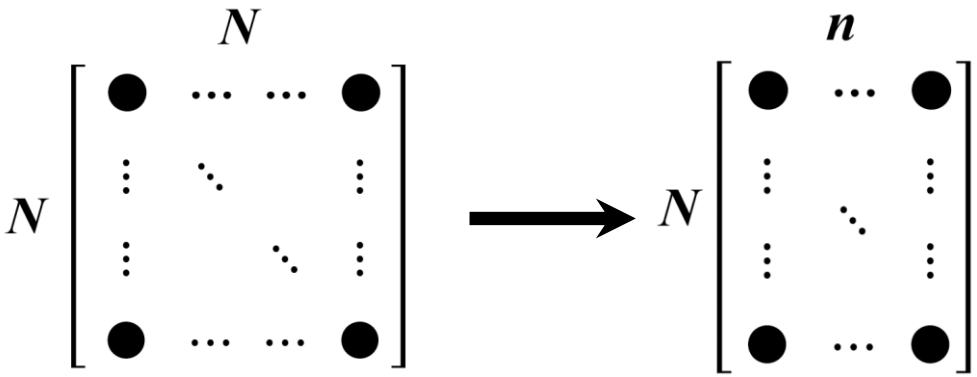
```
sysMats = struct with fields:
    K: [24410×24410 double]
    A: [24410×24410 double]
    F: [24410×1 double]
    Q: [24410×24410 double]
    G: [24410×1 double]
    H: [1×24410 double]
    R: [24410×1 double]
    M: [24410×24410 double]
```

~1 day to simulate 100 s



模型降阶

- 大矩阵变小，保持模型动态特性的同时减少状态数
  - 当前温度传导示例，高频模态会快速衰退
- 找到正交模态空间，保留低频模态
  - 对角化ODE方程$M\dot{T} = Q - KT$，得到变换矩阵**V**
  - 忽略掉对应高频模态（大特征值）的矩阵列向量



$$A_r = V^T AV \qquad B_r = V^T B$$

$$C_r = CV \qquad D_r = D \qquad E_r = V^T \mathrm{EV}$$

$$K, M \in \boldsymbol{R}^{N \times N} \Rightarrow K_r, M_r \in \boldsymbol{R}^{n \times n} \Rightarrow \begin{aligned} E\dot{x} &= Ax + Bu \\ y &= Cx + Du \end{aligned}$$

`eigs()`
`reduce()`
`freqsep()`

Model Reduction 方法

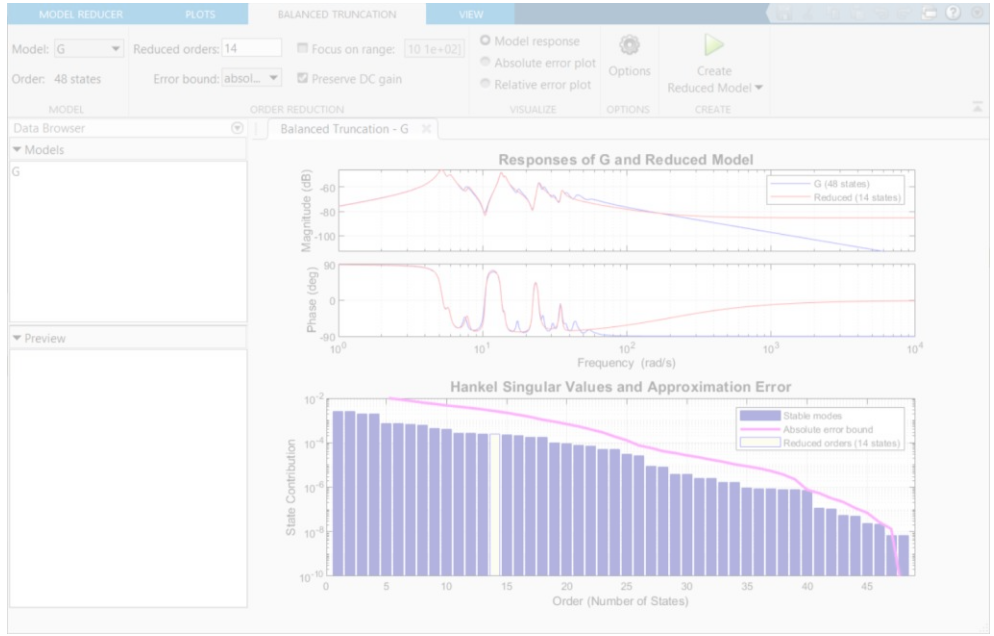
Selection 去掉目标频域范围外的特征 `freqsep()`

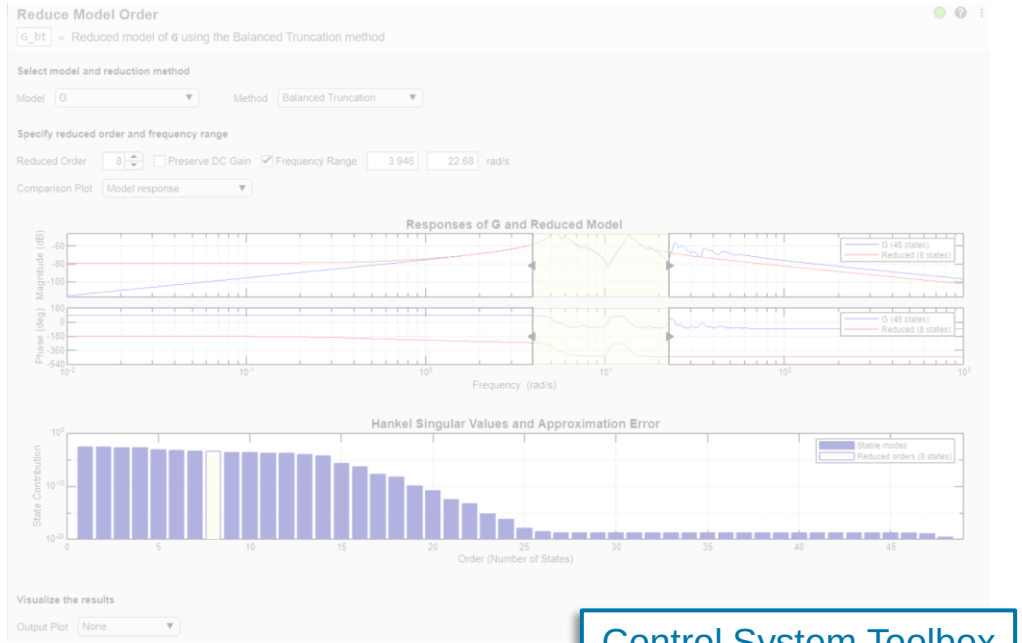
Approximation 找到并移除对目标输出影响小的特征 `balred()`

Simplification

Reduce without approximation `minreal()`

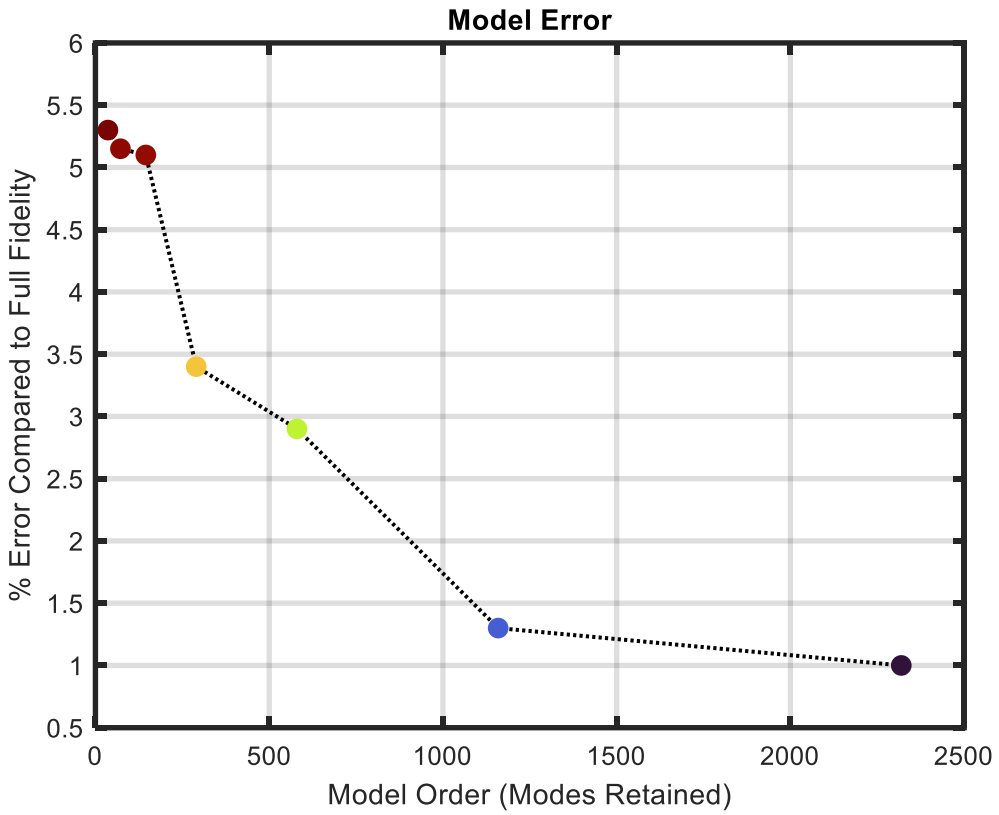
检测并移除对目标输出没有影响的部分 `simnreal()`



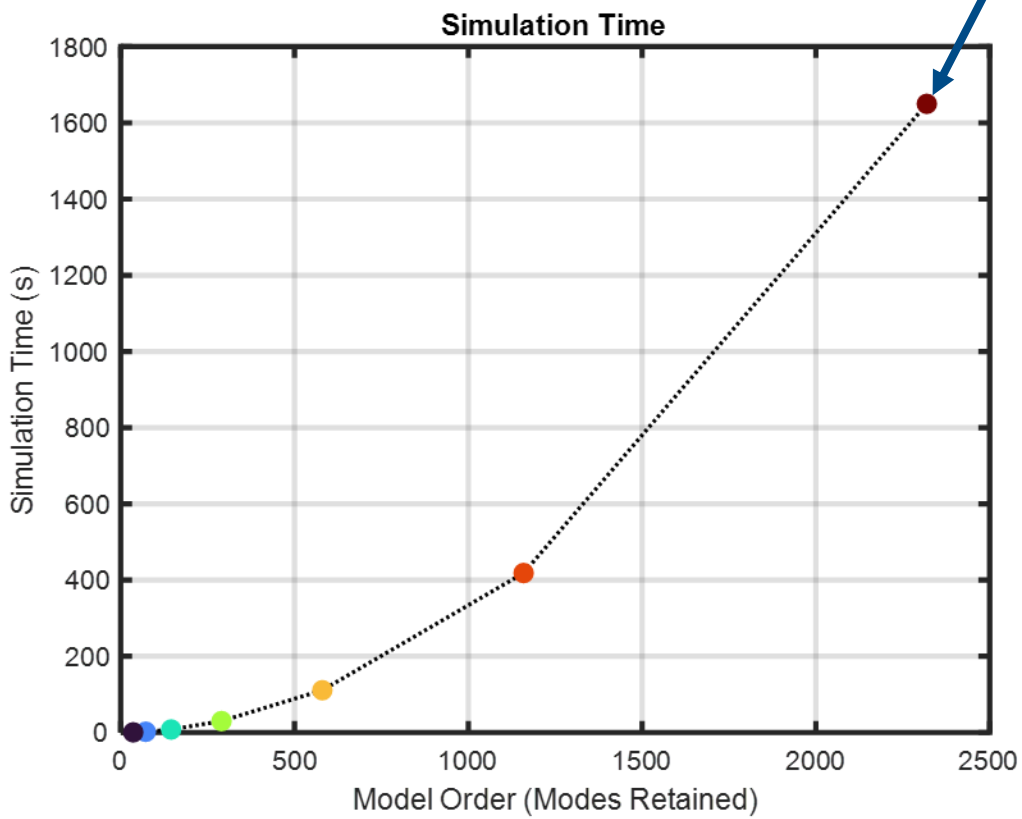


Control System Toolbox

降阶模型的性能



> 50x speed up compared to full fidelity



$K, M \in \boldsymbol{R}^{24{,}410\times 24{,}410}$

1天

$K_r, M_r \in \boldsymbol{R}^{64\times 64}$

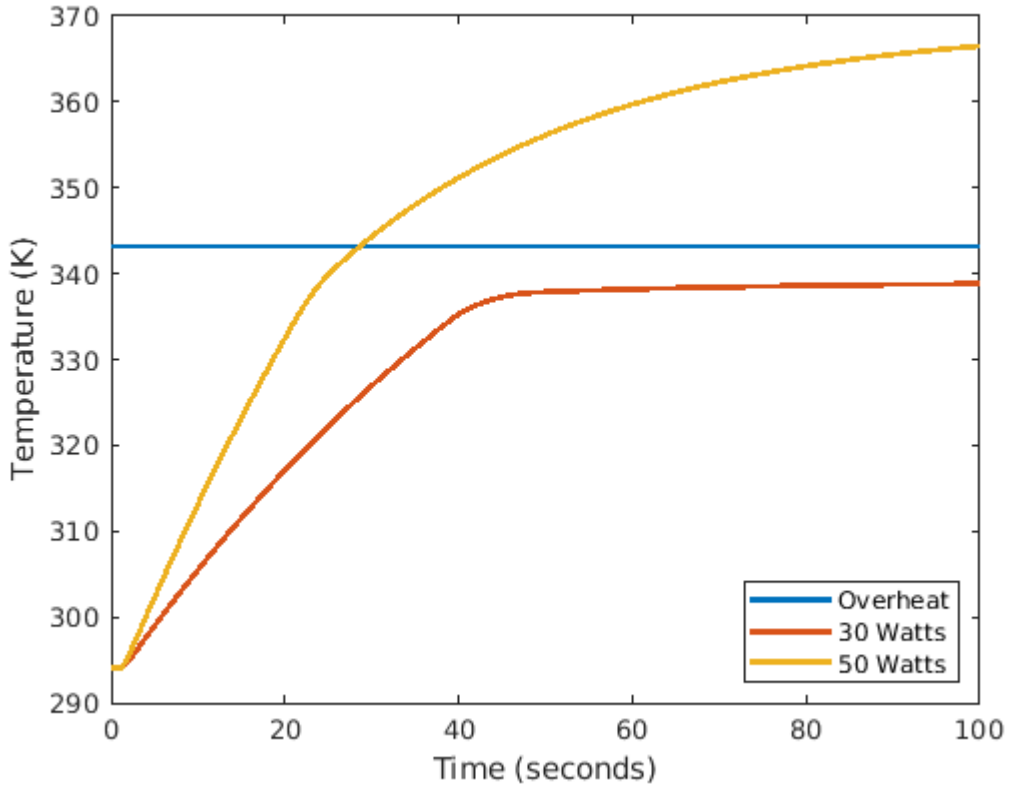
<1 分钟

使用降阶后的模型进行设计优化

```
nSims = 100;
in(1:nSims) = Simulink.SimulationInput(mdl);
for i = 1:nSims
    in(i) = setBlockParameter(in(i),[mdl '/Heat Generation'], ...
                              'ActiveScenario', ['Scenario' num2str(i)]);
end
out = parsim(in,'TransferBaseWorkspaceVariables','on');
openSimulationManager(in,out)
```

```
[08-Jun-2021 16:24:58] Starting Simulink on parallel workers...
[08-Jun-2021 16:25:30] Loading project on parallel workers...
[08-Jun-2021 16:25:30] Configuring simulation cache folder on parallel workers.
[08-Jun-2021 16:25:39] Loading model on parallel workers...
[08-Jun-2021 16:26:16] Transferring base workspace variables used in the model
[08-Jun-2021 16:26:21] Running simulations...
[08-Jun-2021 16:26:56] Completed 1 of 100 simulation runs
[08-Jun-2021 16:26:57] Completed 2 of 100 simulation runs
[08-Jun-2021 16:26:57] Completed 3 of 100 simulation runs
```

```
[08-Jun-2021 16:32:12] Completed 97 of 100 simulation runs
[08-Jun-2021 16:32:15] Completed 98 of 100 simulation runs
[08-Jun-2021 16:32:16] Completed 99 of 100 simulation runs
[08-Jun-2021 16:32:19] Completed 100 of 100 simulation runs
[08-Jun-2021 16:32:19] Cleaning up parallel workers...
```

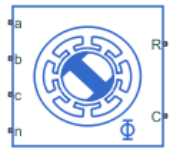


- 设计参数扫描从全保真3个月到降阶后7分钟
- ~5% 错误率的折衷 (c. 1% error换10 小时仿真时间)

模型降阶

实现方式

系统建模

- **Physics-based**
  - 

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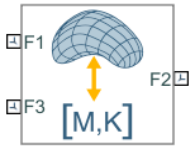
  - 

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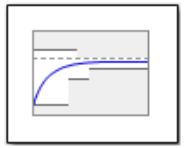
  - 
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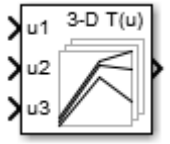
    - 

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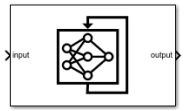
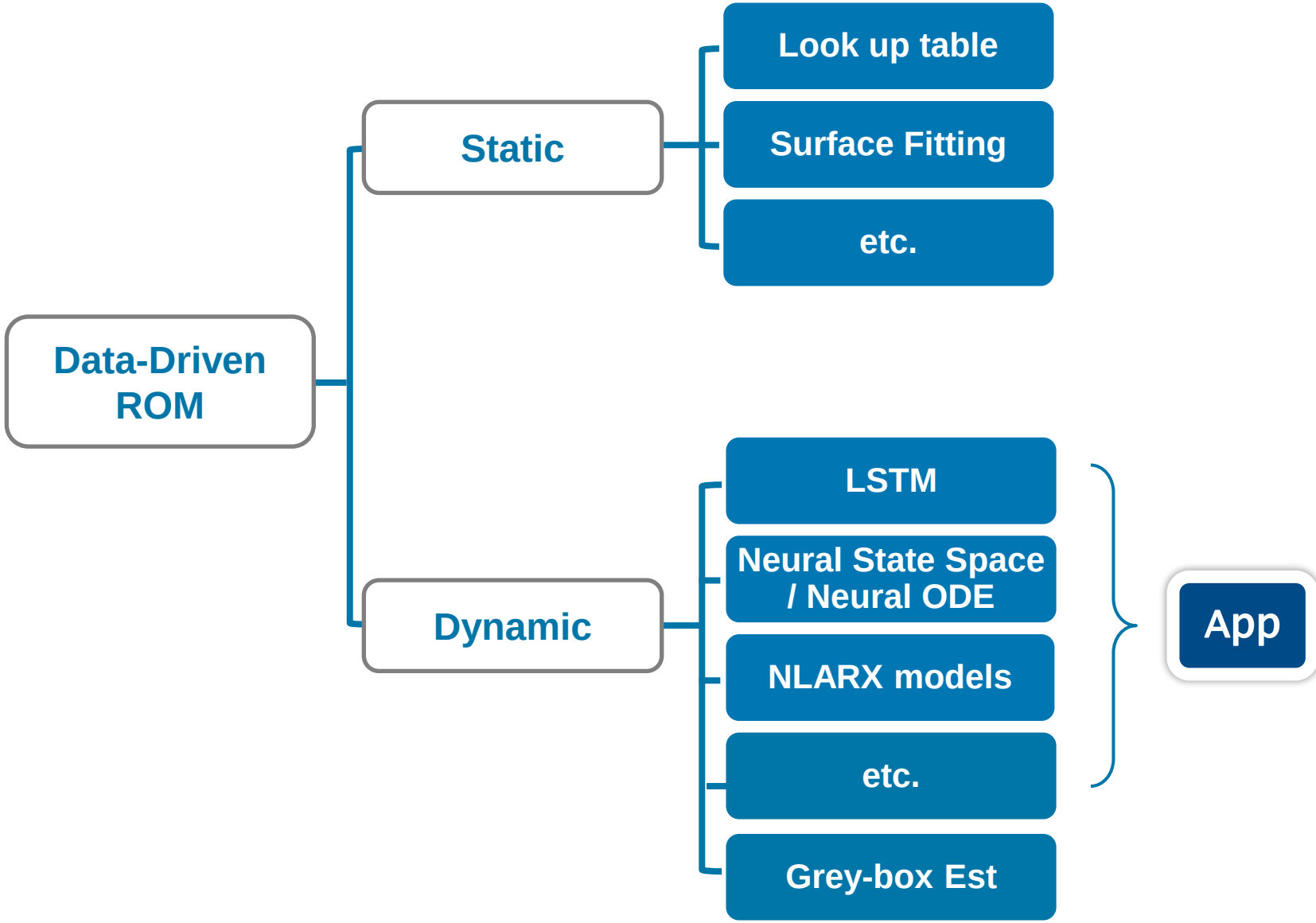
    - 

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

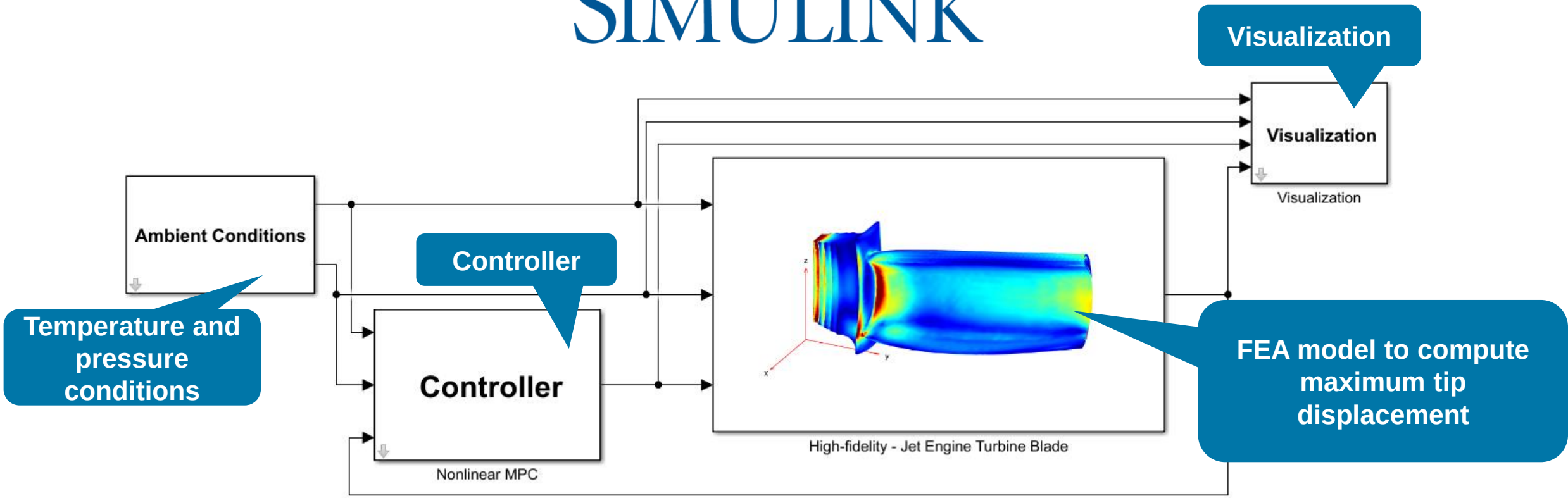
Data-driven ROM



示例概览

用基于AI的降阶模型替代高保真喷气发动机涡轮叶片模型

SIMULINK®



Closed-loop temperature control

示例概览

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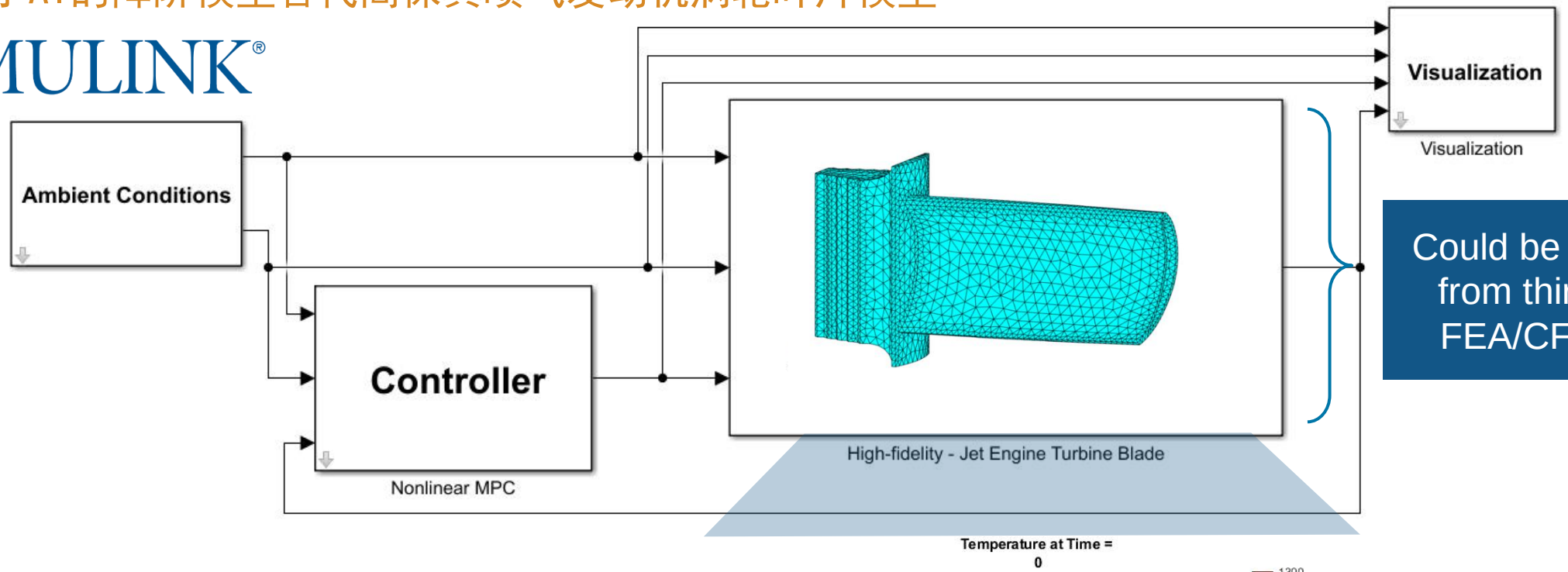
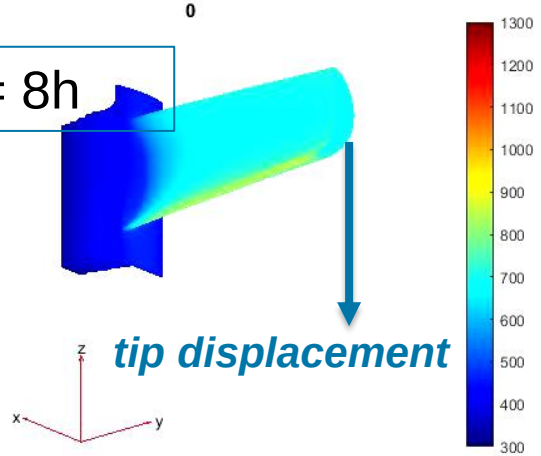
SIMULINK®



Could be imported from third-party FEA/CFD tools

~30 seconds per time step for solving FEA models * 5000 = 8h

Not suitable for control design and HIL testing



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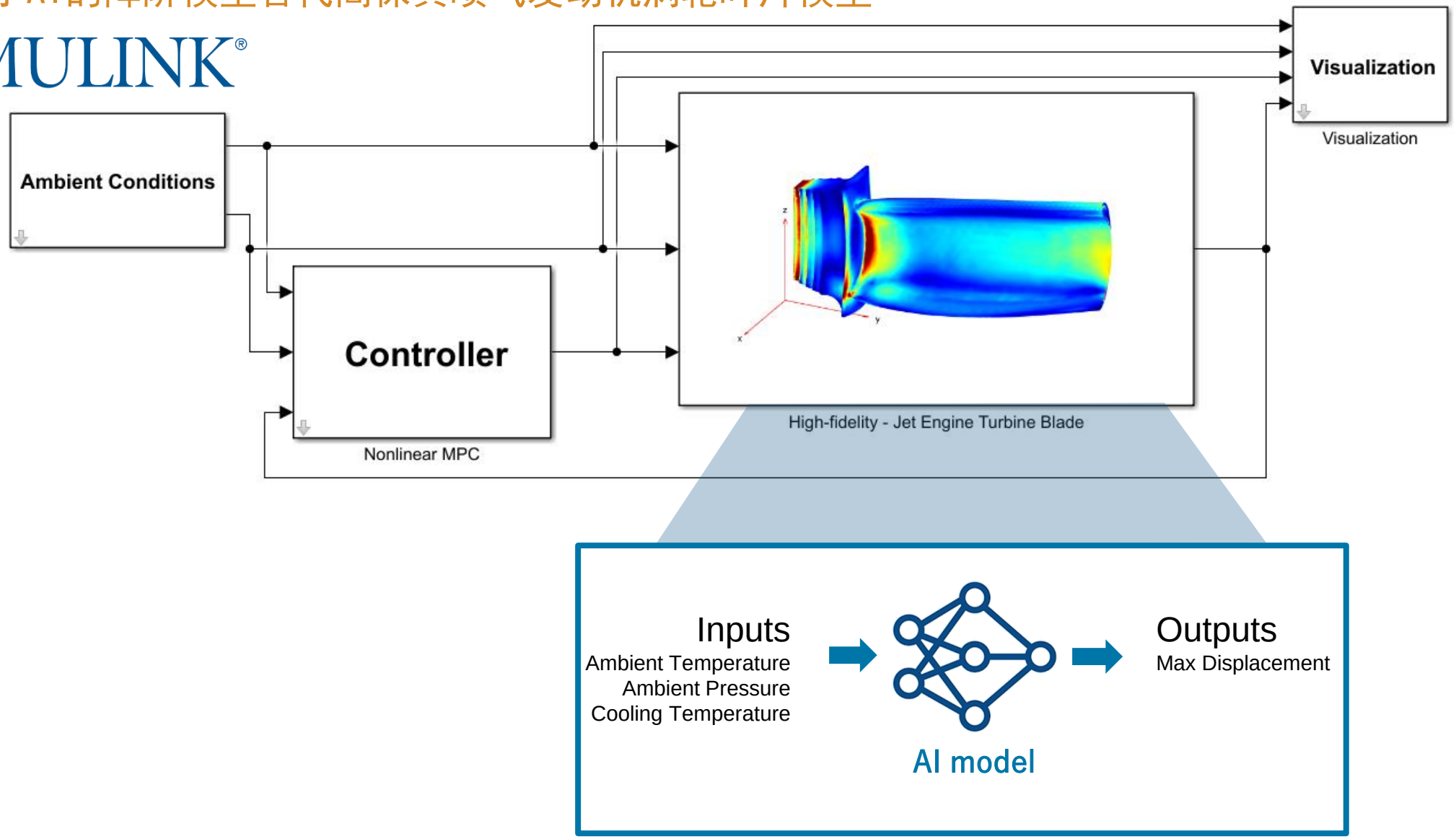
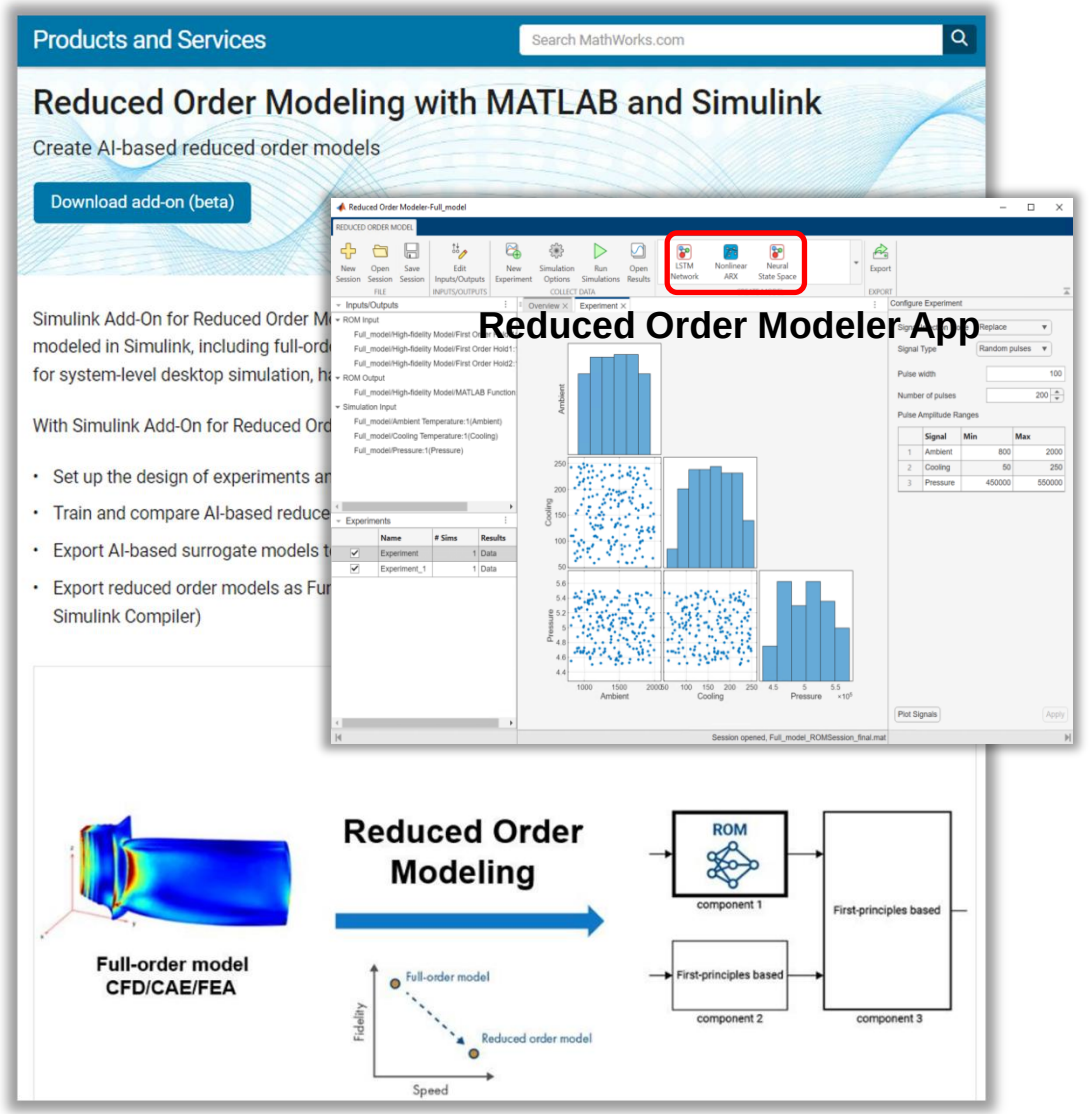


用于模型降阶的Simulink Add-On

创建基于AI的降阶模型(ROM)

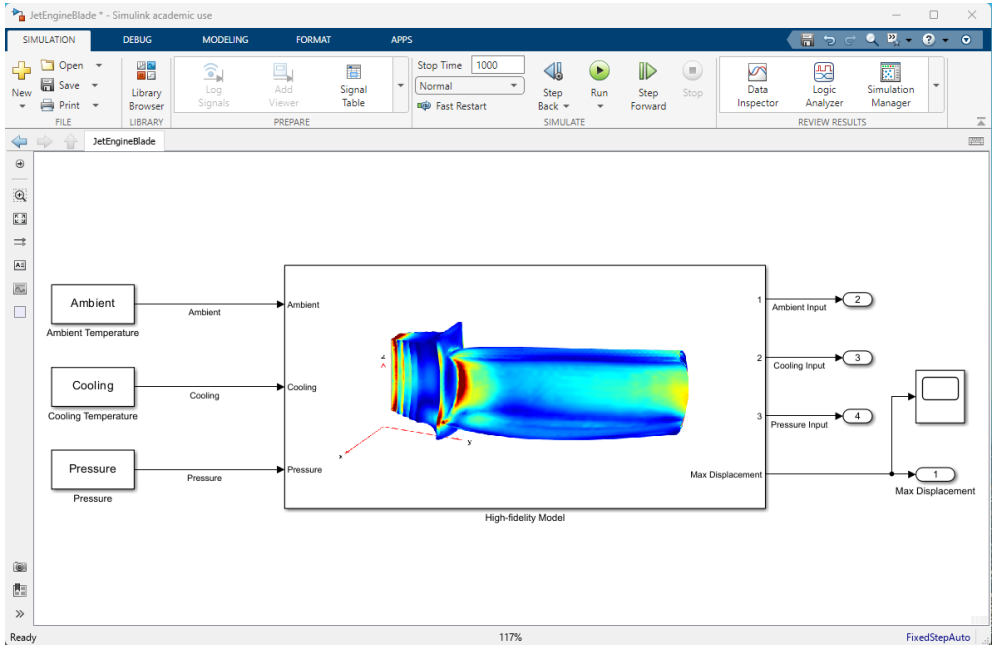
- **Set up Design of Experiments (DoE)**
- **Generate input-output data from full-order, high-fidelity subsystems**
- **Train and compare AI-based reduced order models using preconfigured templates**
- **Export trained reduced order models into Simulink or outside of Simulink through FMUs**



[Reduced Order Modeling with MATLAB and Simulink]

生成训练数据

Physical system

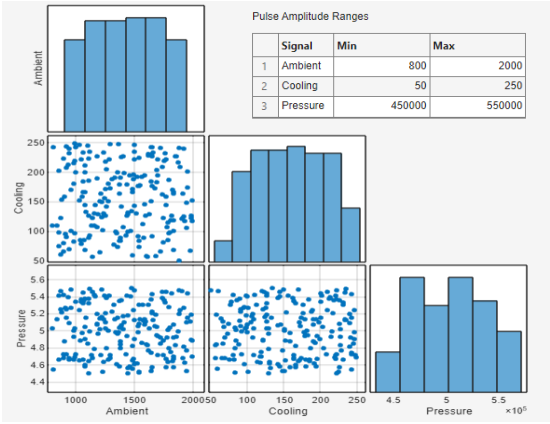


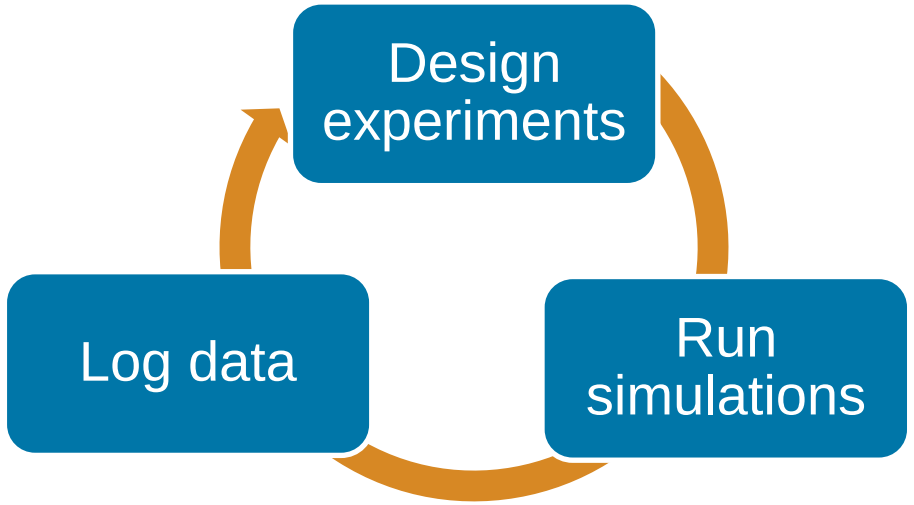
Simulink/Simscape

Data Preparation | AI Modeling | Simulation & Test | Deployment

合成数据生成

Design of Experiments（实验设计）



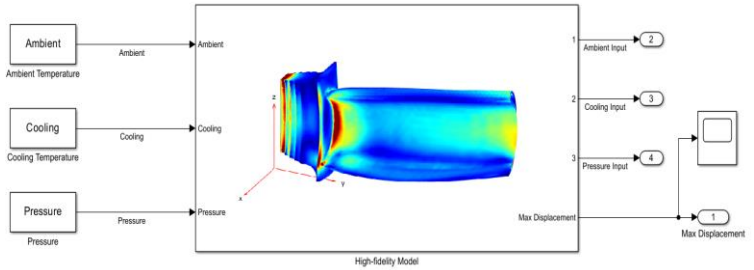


Input features

Ambient Temperature
Ambient Pressure
Cooling Temperature

Response

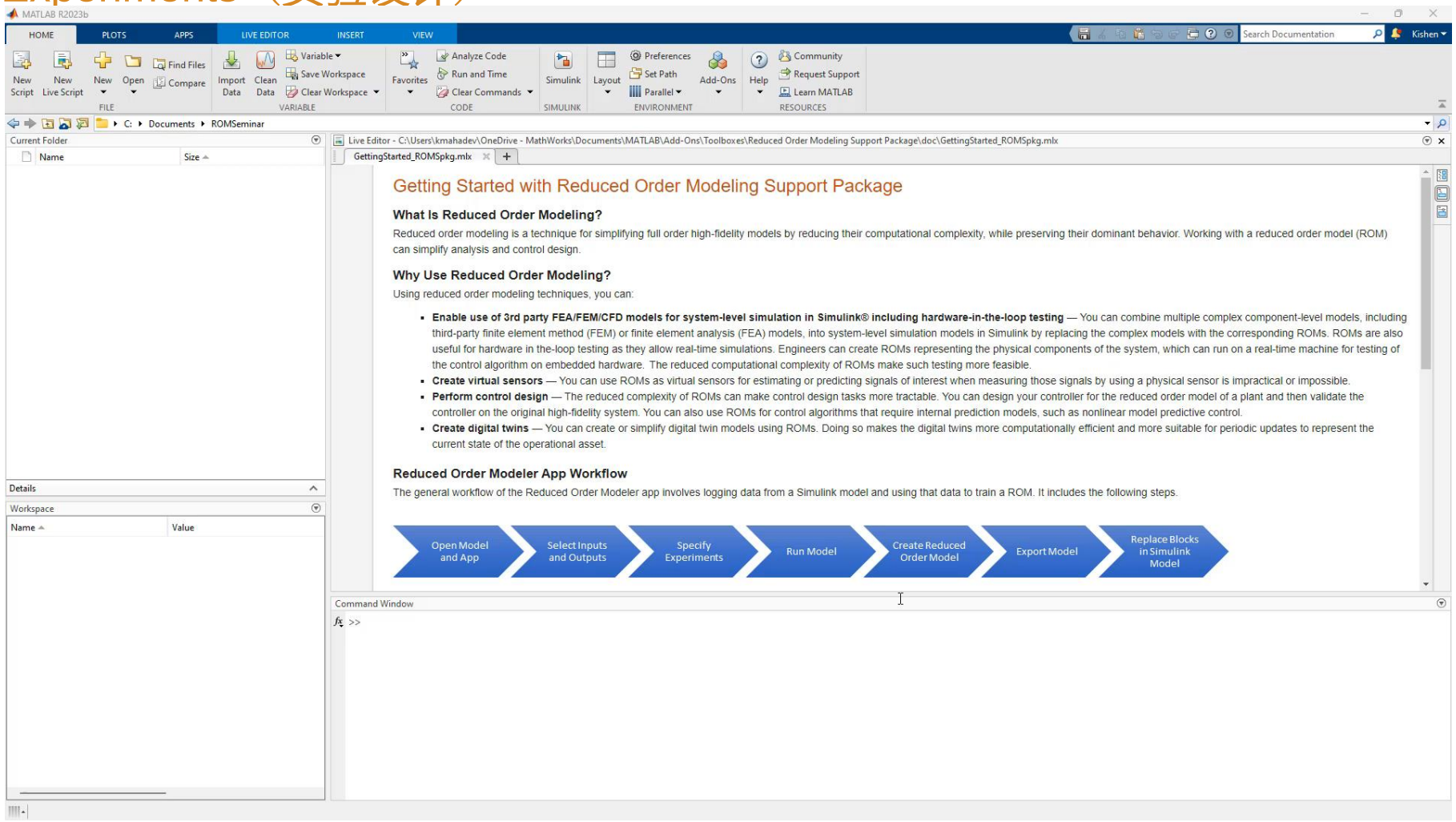
Max Displacement



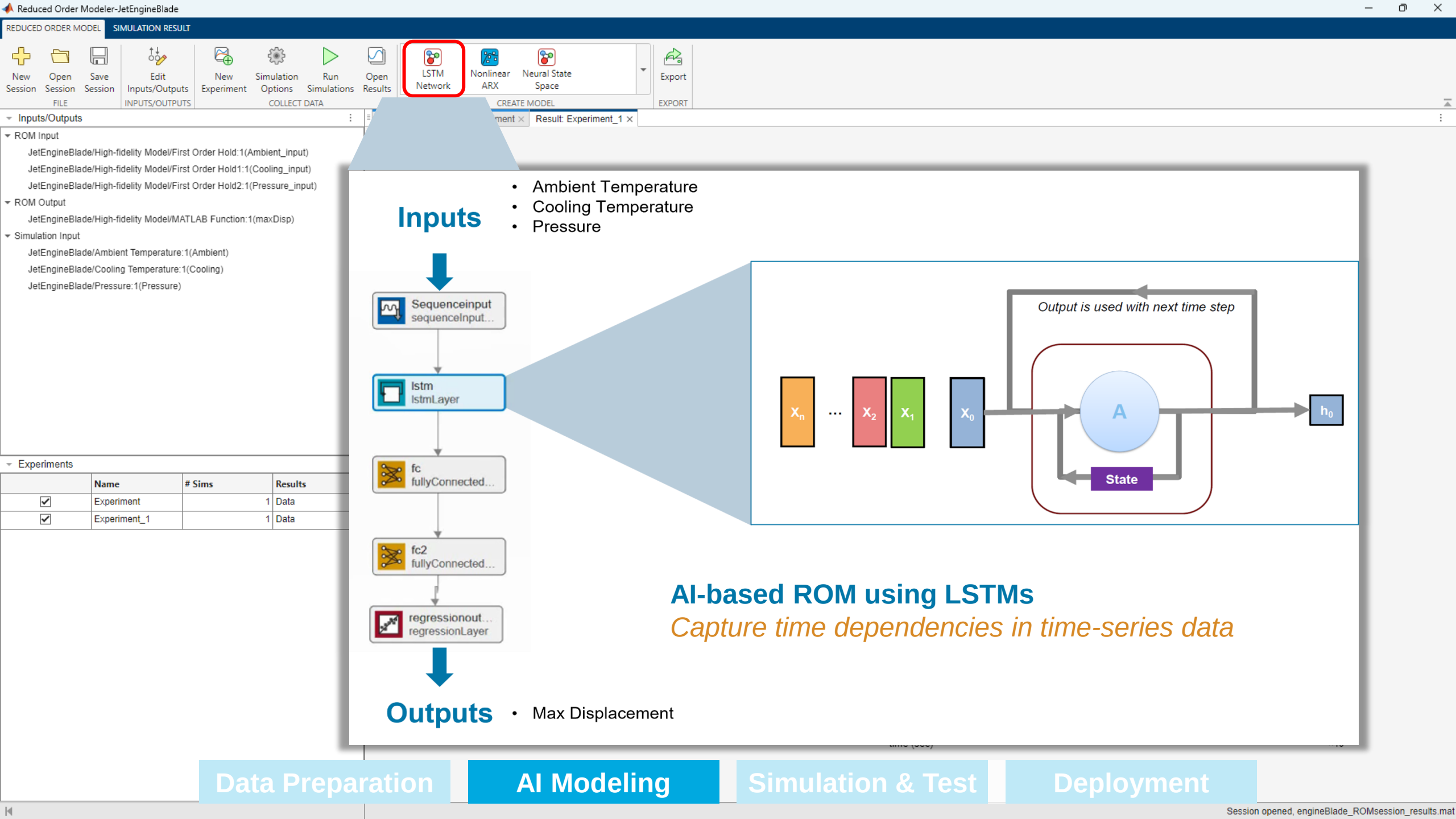
Data Preparation | AI Modeling | Simulation & Test | Deployment

合成数据生成

Design of Experiments（实验设计）



Data Preparation | AI Modeling | Simulation & Test | Deployment


Reduced Order Modeler-JetEngineBlade
REDUCED ORDER MODEL
SIMULATION RESULT
New Session
Open Session
Save Session
FILE
Edit Inputs/Outputs
INPUTS/OUTPUTS
New Experiment
Simulation Options
Run Simulations
Open Results
COLLECT DATA
LSTM Network
Nonlinear ARX
Neural State Space
CREATE MODEL
Export
EXPORT
Inputs/Outputs
ROM Input
JetEngineBlade/High-fidelity Model/First Order Hold:1(Ambient_input)
JetEngineBlade/High-fidelity Model/First Order Hold1:1(Cooling_input)
JetEngineBlade/High-fidelity Model/First Order Hold2:1(Pressure_input)
ROM Output
JetEngineBlade/High-fidelity Model/MATLAB Function:1(maxDisp)
Simulation Input
JetEngineBlade/Ambient Temperature:1(Ambient)
JetEngineBlade/Cooling Temperature:1(Cooling)
JetEngineBlade/Pressure:1(Pressure)
Result: Experiment_1
Experiments
Name
Sims
Results
Experiment
1
Data
Experiment_1
1
Data
Inputs
Ambient Temperature
Cooling Temperature
Pressure
Sequenceinput
sequenceInput...
lstm
lstmLayer
fc
fullyConnected...
fc2
fullyConnected...
regressionout...
regressionLayer
Outputs
Max Displacement
Output is used with next time step
x_n
x_2
x_1
x_0
A
State
h_0
AI-based ROM using LSTMs
Capture time dependencies in time-series data
Data Preparation
AI Modeling
Simulation & Test
Deployment
Session opened, engineBlade_ROMsession_results.mat

Reduced Order Modeler-JetEngineBlade

REDUCED ORDER MODEL | SIMULATION RESULT

Simulation Result 1 of 1

Show output only

Show as scatter plot

SIMULATION RESULTS | OPTIONS

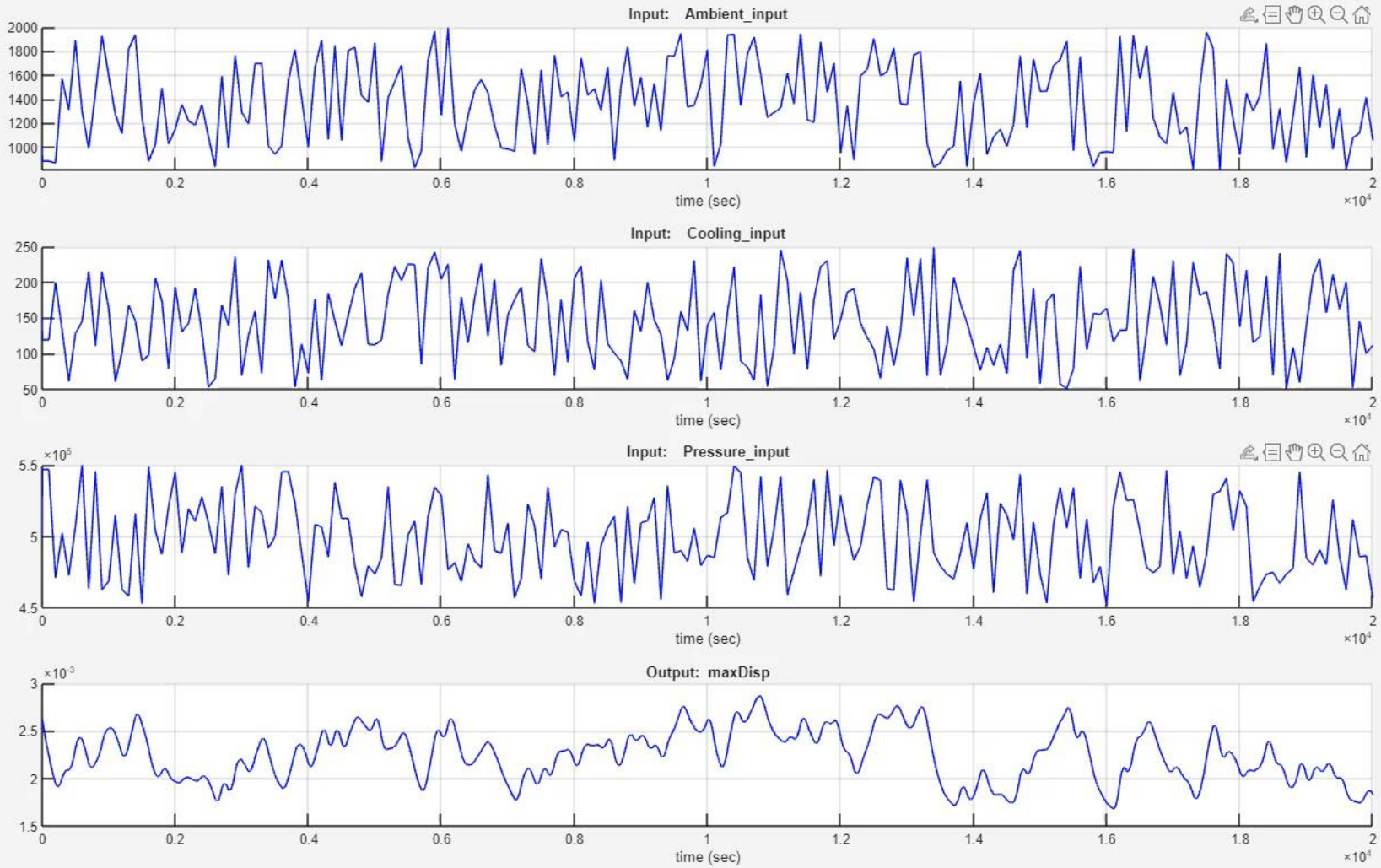
Inputs/Outputs

- ROM Input
  - JetEngineBlade/High-fidelity Model/First Order Hold:1(Ambient_input)
  - JetEngineBlade/High-fidelity Model/First Order Hold1:1(Cooling_input)
  - JetEngineBlade/High-fidelity Model/First Order Hold2:1(Pressure_input)
- ROM Output
  - JetEngineBlade/High-fidelity Model/MATLAB Function:1(maxDisp)
- Simulation Input
  - JetEngineBlade/Ambient Temperature:1(Ambient)
  - JetEngineBlade/Cooling Temperature:1(Cooling)
  - JetEngineBlade/Pressure:1(Pressure)

Experiments

	Name	# Sims	Results
☑	Experiment	1	Data
☑	Experiment_1	1	Data

Overview | Result: Experiment | Result: Experiment_1 | Experiment_1



Session opened, engineBlade_ROMsession_results.mat

Reduced Order Modeler-JetEngineBlade

REDUCED ORDER MODEL | SIMULATION RESULT

New Session | Open Session | Save Session — FILE
Edit Inputs/Outputs — INPUTS/OUTPUTS
New Experiment | Simulation Options | Run Simulations | Open Results — COLLECT DATA
LSTM Network | Nonlinear ARX | Neural State Space
Export — EXPORT

Inputs/Outputs

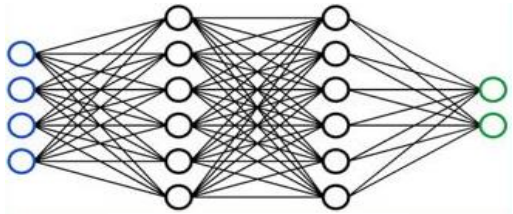
- ROM Input
  - JetEngineBlade/High-fidelity Model/First Order Hold:1(Ambient_input)
  - JetEngineBlade/High-fidelity Model/First Order Hold1:1(Cooling_input)
  - JetEngineBlade/High-fidelity Model/First Order Hold2:1(Pressure_input)
- ROM Output
  - JetEngineBlade/High-fidelity Model/MATLAB Function:1(maxDisp)
- Simulation Input
  - JetEngineBlade/Ambient Temperature:1(Ambient)
  - JetEngineBlade/Cooling Temperature:1(Cooling)
  - JetEngineBlade/Pressure:1(Pressure)

Experiments

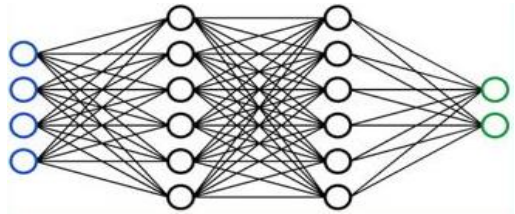
	Name	# Sims	Results
☑	Experiment	1	Data
☑	Experiment_1	1	Data

Overview | Result: Expe | nt_1

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



State Network (*f*)



Output Network (*g*)

AI-based ROM using Neural State Space *(also known as Neural ODE)*

Create Deep Learning-based nonlinear state-space models

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

Session opened, engineBlade_ROMsession_results.mat

Reduced Order Modeler-JetEngineBlade

REDUCED ORDER MODEL | SIMULATION RESULT

New Session | Open Session | Save Session | Edit Inputs/Outputs | New Experiment | Simulation Options | Run Simulations | Open Results | LSTM Network | Nonlinear ARX | Neural State Space | Export

FILE | INPUTS/OUTPUTS | COLLECT DATA | MODEL | EXPORT

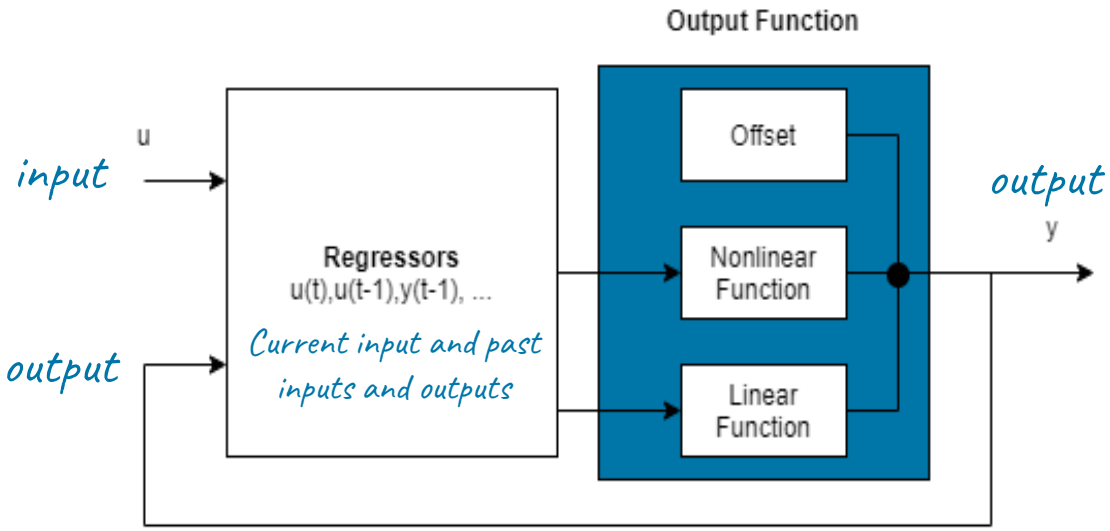
Inputs/Outputs

- ROM Input
  - JetEngineBlade/High-fidelity Model/First Order Hold:1(Ambient_input)
  - JetEngineBlade/High-fidelity Model/First Order Hold1:1(Cooling_input)
  - JetEngineBlade/High-fidelity Model/First Order Hold2:1(Pressure_input)
- ROM Output
  - JetEngineBlade/High-fidelity Model/MATLAB Function:1(maxDisp)
- Simulation Input
  - JetEngineBlade/Ambient Temperature:1(Ambient)
  - JetEngineBlade/Cooling Temperature:1(Cooling)
  - JetEngineBlade/Pressure:1(Pressure)

Experiments

	Name	# Sims	Results
☑	Experiment	1	Data
☑	Experiment_1	1	Data

Overview | esult: Experiment_1



AI-based ROM using Nonlinear ARX

Extend linear models and model nonlinear behavior using flexible nonlinear functions

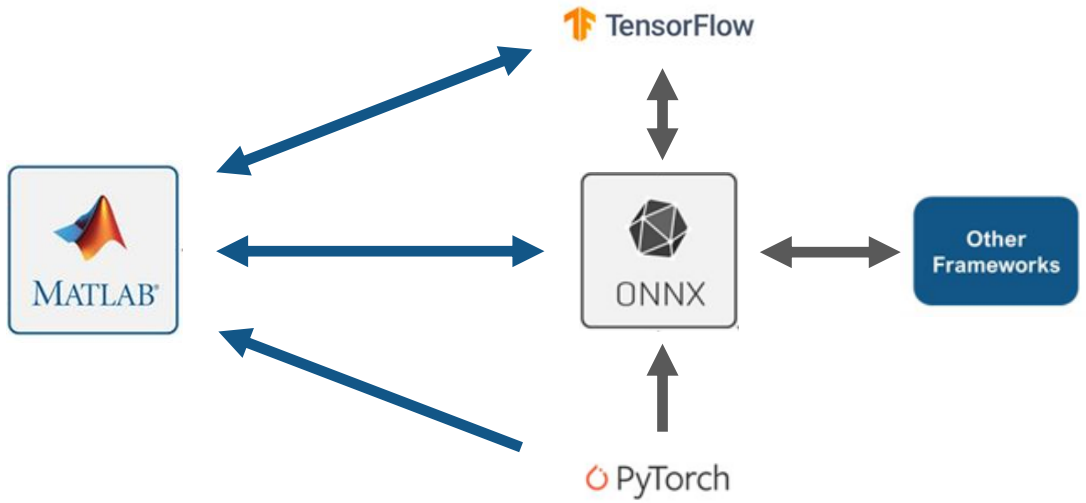
Data Preparation | AI Modeling | Simulation & Test | Deployment

Session opened, engineBlade_ROMsession_results.mat

MATLAB 和其他AI框架互操作

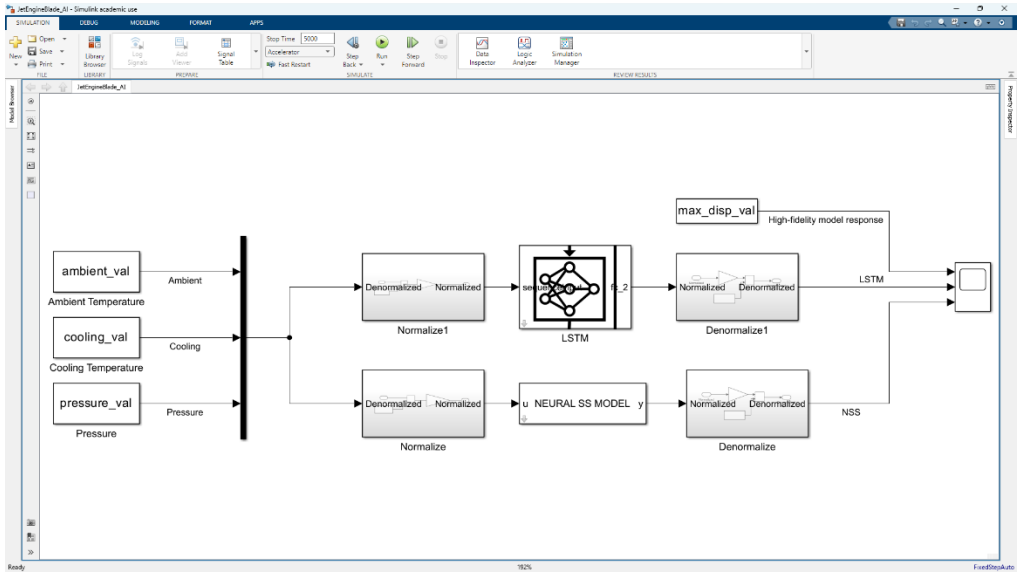
框架互操作性构建了数据科学、工程和生产之间的桥梁

TensorFlow-Keras Import	R2017b
ONNX Converter (Import & Export)	R2018a
TensorFlow Converter (Import)	R2021a
TensorFlow Converter (Export)	R2022b
PyTorch Converter (Import)	R2022b

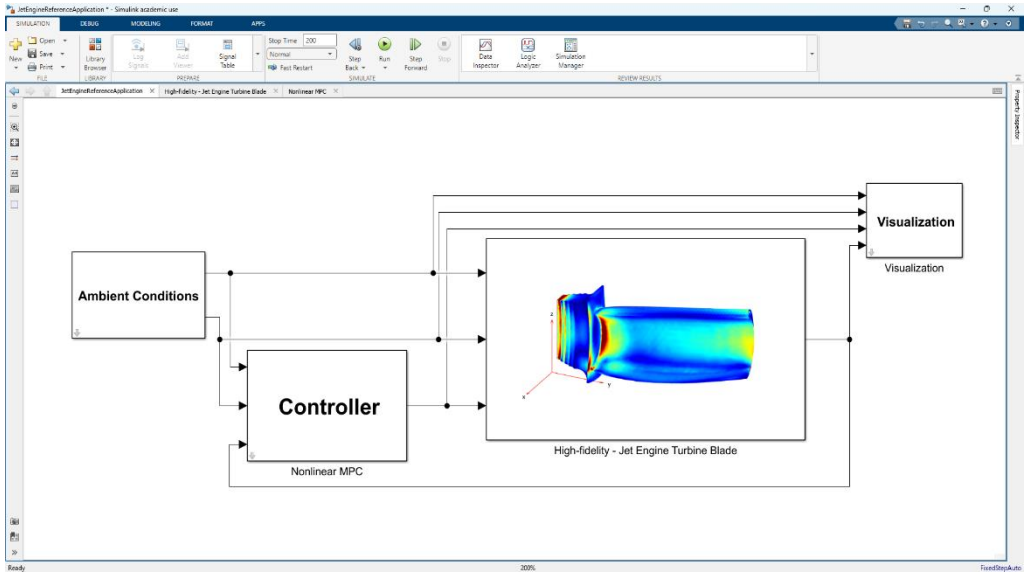


集成AI模型进行系统级仿真和测试

Integration of trained AI model into Simulink

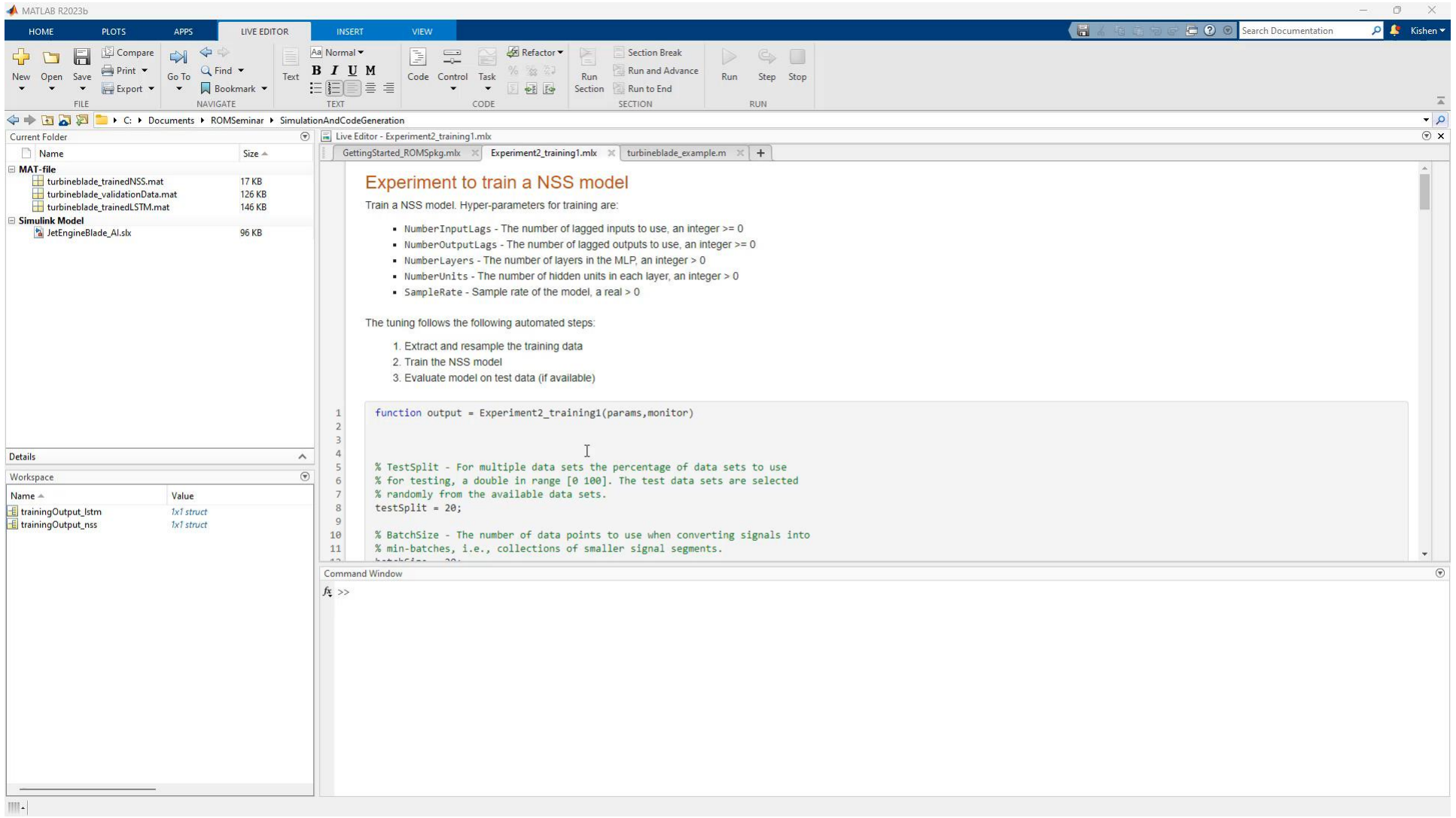


System-level simulation



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

将训练好的AI模型集成到Simulink中



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

将训练好的AI模型集成到Simulink中

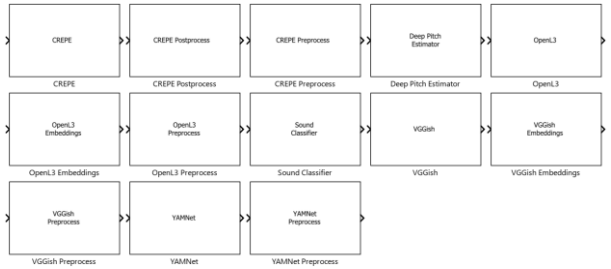
Simulink Profiler

Path	Time Plot (Dark Band = Self Time)	Total Time (s)	Self Time (s)	Number of Calls
JetEngineBlade_AI		17.207	1.807	2014
LSTM		11.465	0.000	0
Scope1		3.895	3.895	1004
Neural State Space Model		0.028	0.000	0
From Workspace1		0.008	0.008	1003
Ambient Temperature		0.002	0.002	1003
Cooling Temperature		0.001	0.001	1003
Pressure		0.001	0.001	1003
Normalize1		0.000	0.000	0
Denormalize1		0.000	0.000	0
Denormalize		0.000	0.000	0
Normalize		0.000	0.000	0

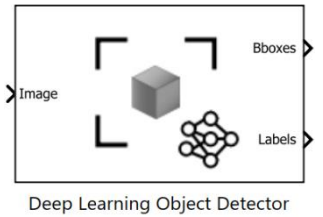
Neural state-space model is approximately 1e6x faster than the FEA model

Simulink中的AI blocks正在扩展，以包含更多的AI blocks，用于更多的应用程序

Specialized

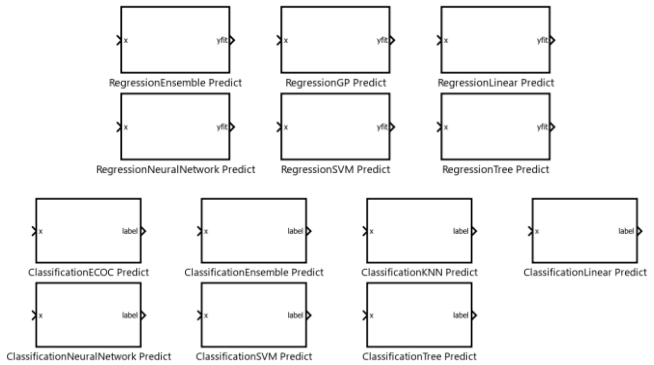


Audio Toolbox

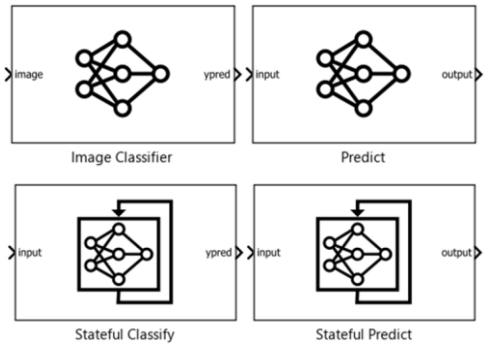


Computer Vision Toolbox

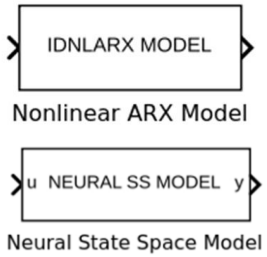
AI Core



Statistics and Machine Learning Toolbox



Deep Learning Toolbox



System Identification Toolbox

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

Deep Learning Toolbox Verification Library

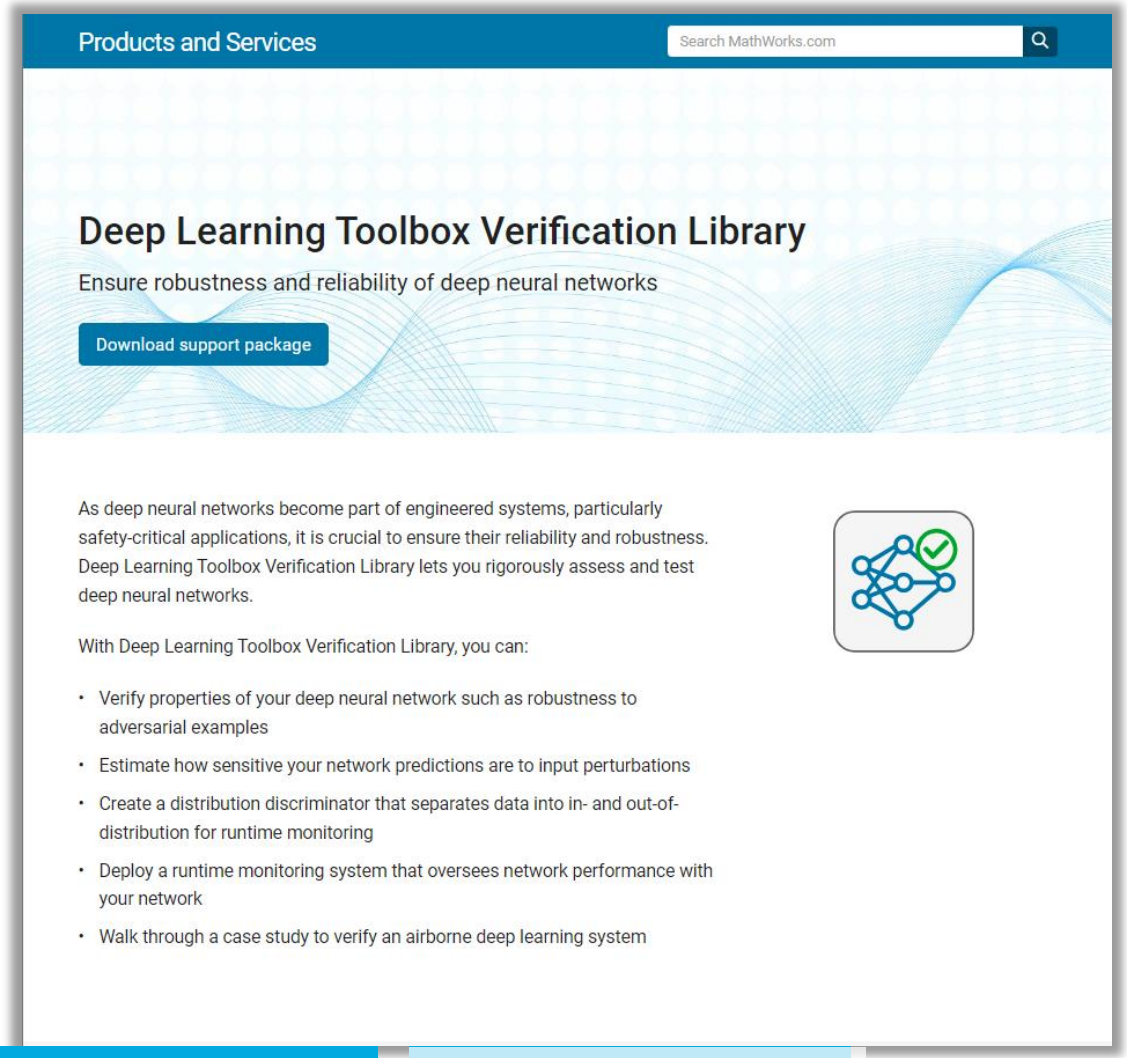
保证深度学习网络的鲁棒和可信

Verify Deep Neural Network Robustness for Classification

Estimate Deep Neural Network Output Bounds for Regression

Build Safe Deep Learning Systems with Runtime Monitoring

Case Study: Verifying an Airborne Deep Learning System

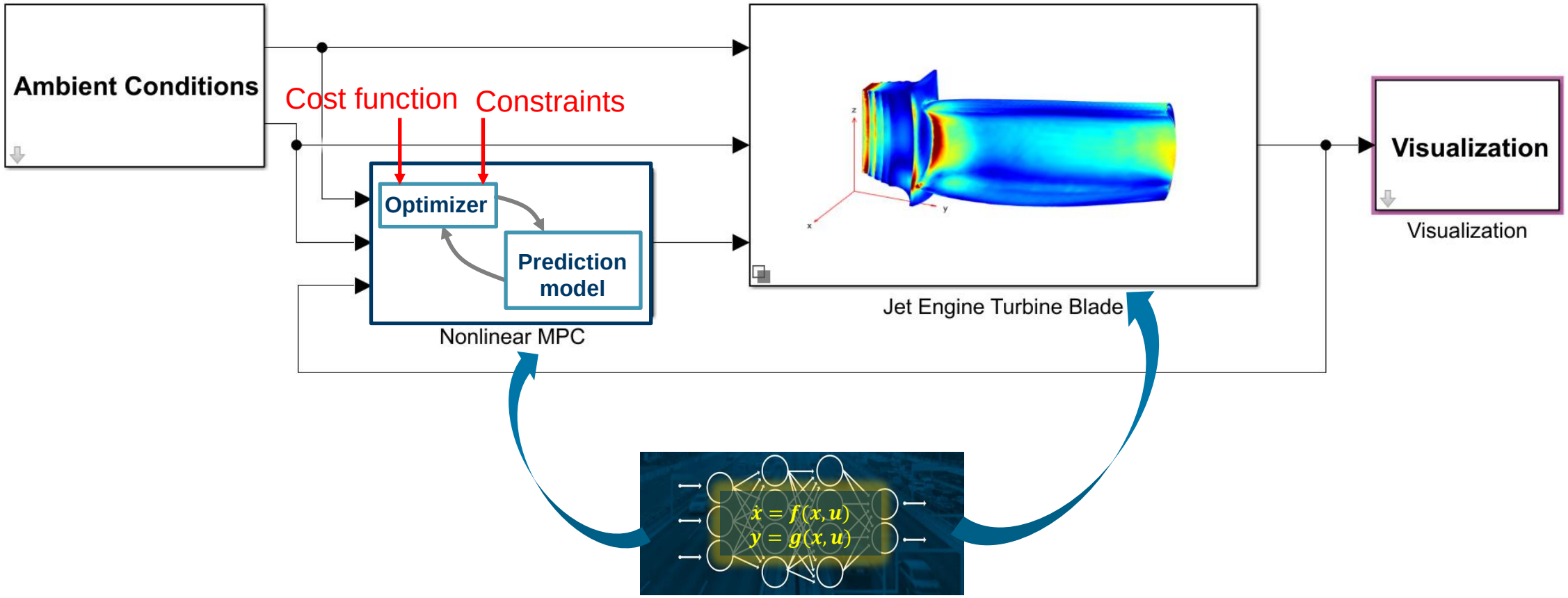


Data Preparation | AI Modeling | Simulation & Test | Deployment

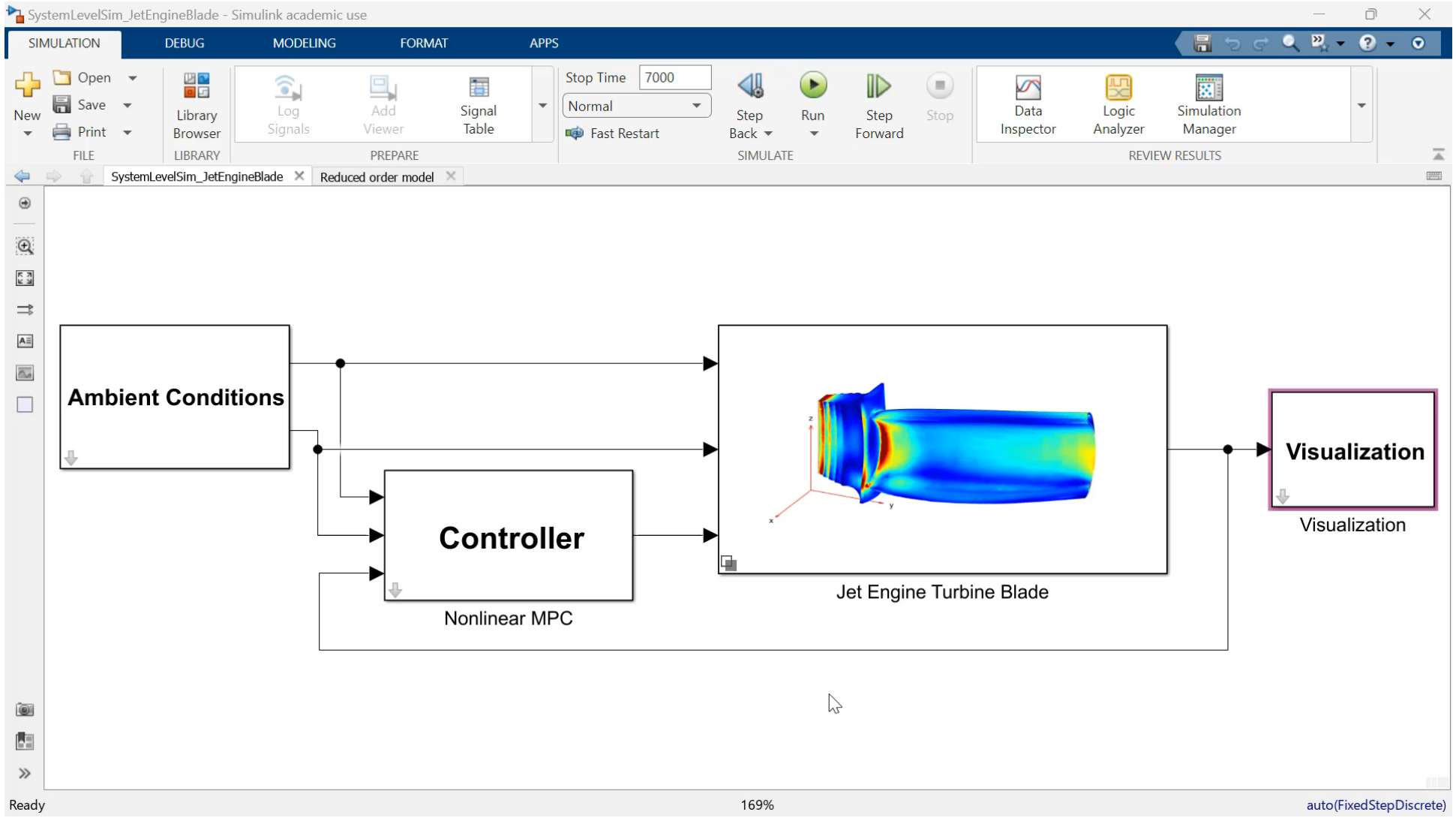
Deep Learning Toolbox Verification Library

构建模型预测控制器 Model Predictive Controller

SIMULINK®

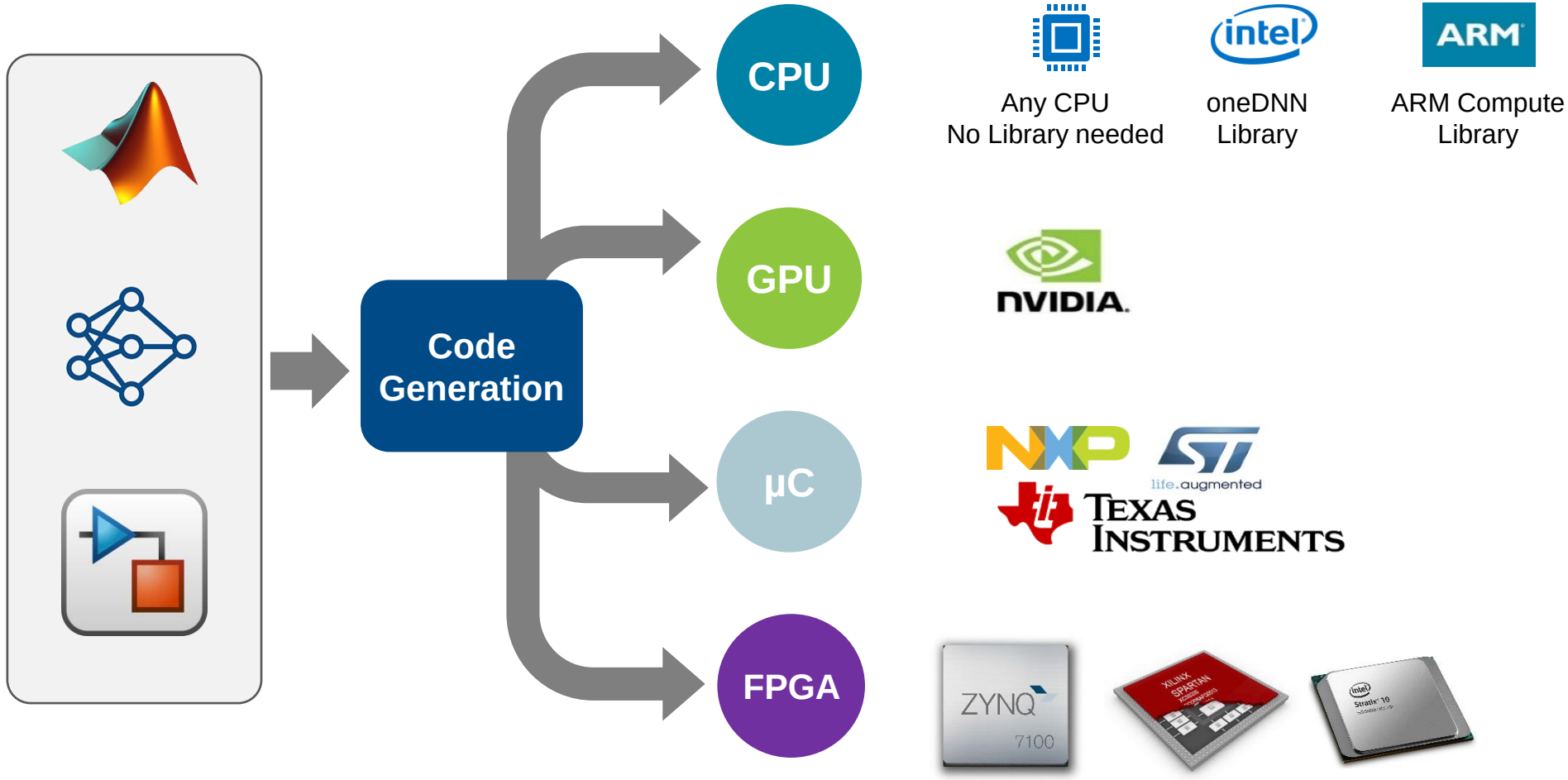


系统级仿真



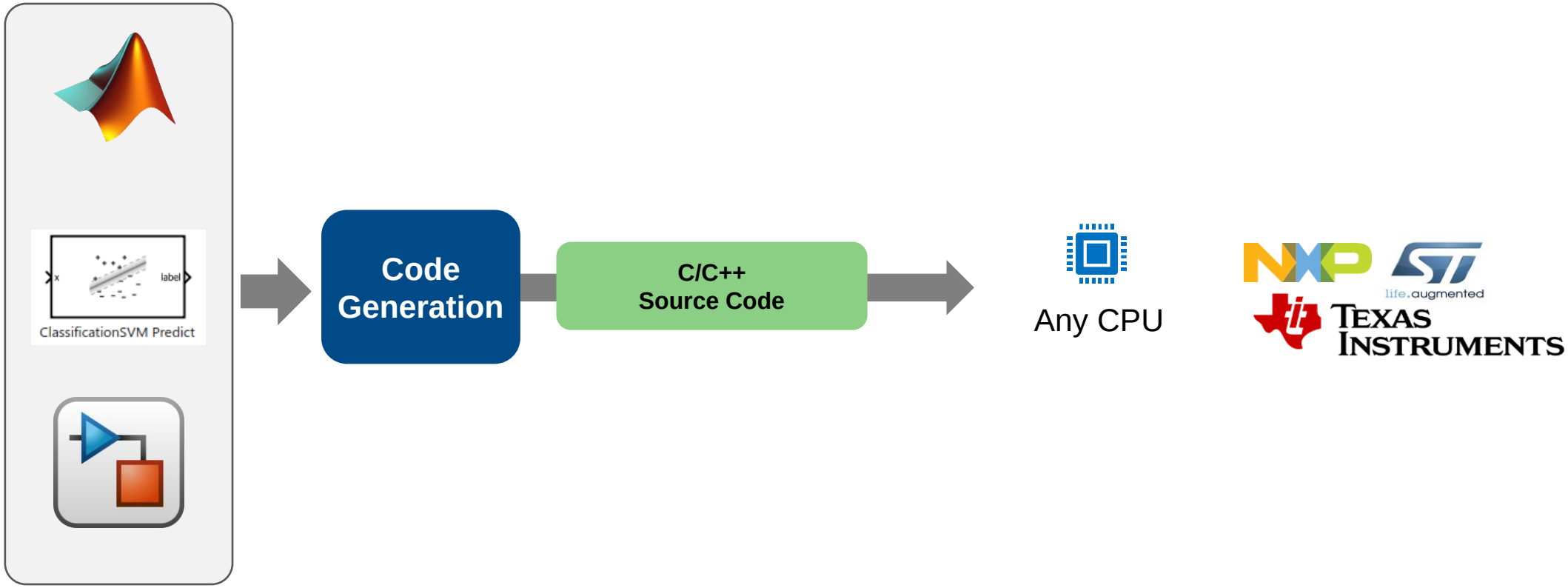
Data Preparation | AI Modeling | **Simulation & Test** | Deployment

Deploy to target with zero coding errors



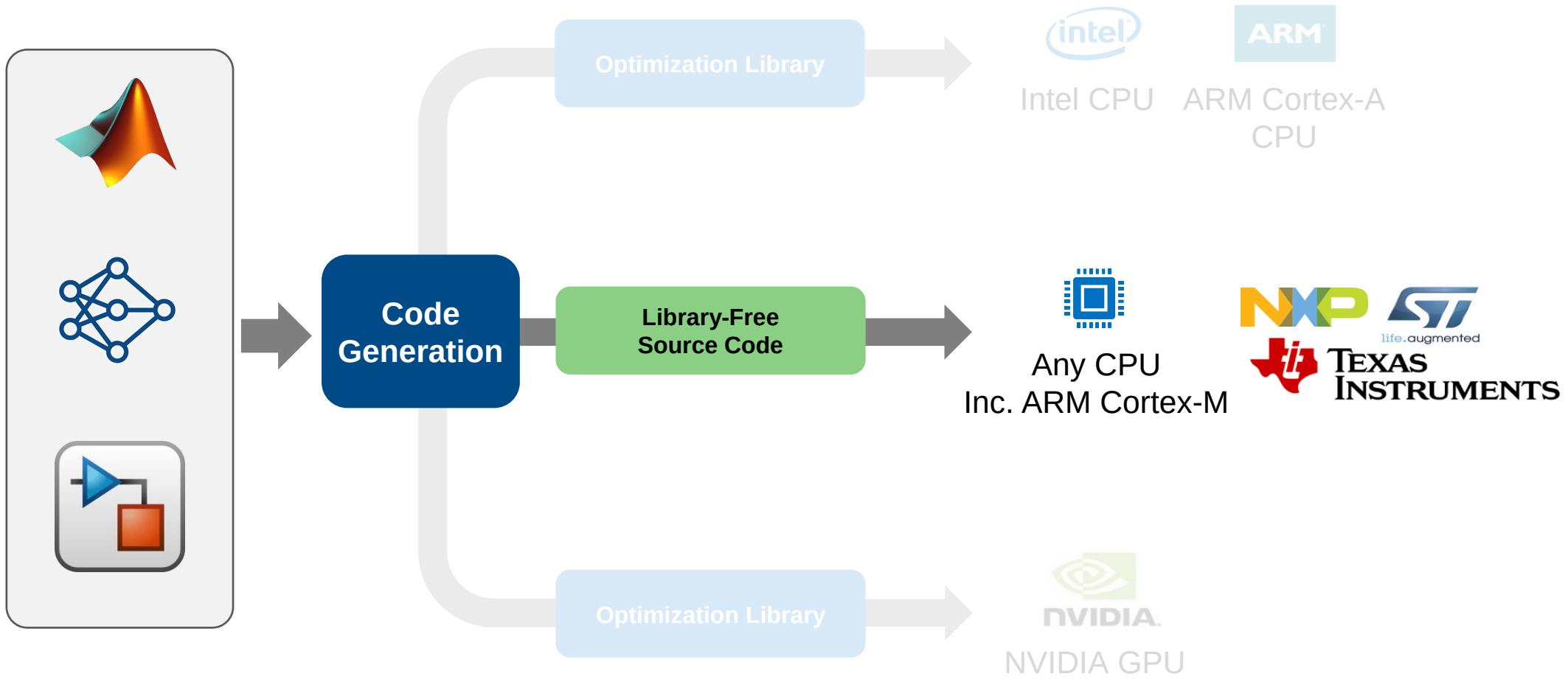
Data Preparation | AI Modeling | Simulation & Test | Deployment

Use Embedded Coder to Generate Code for Machine Learning

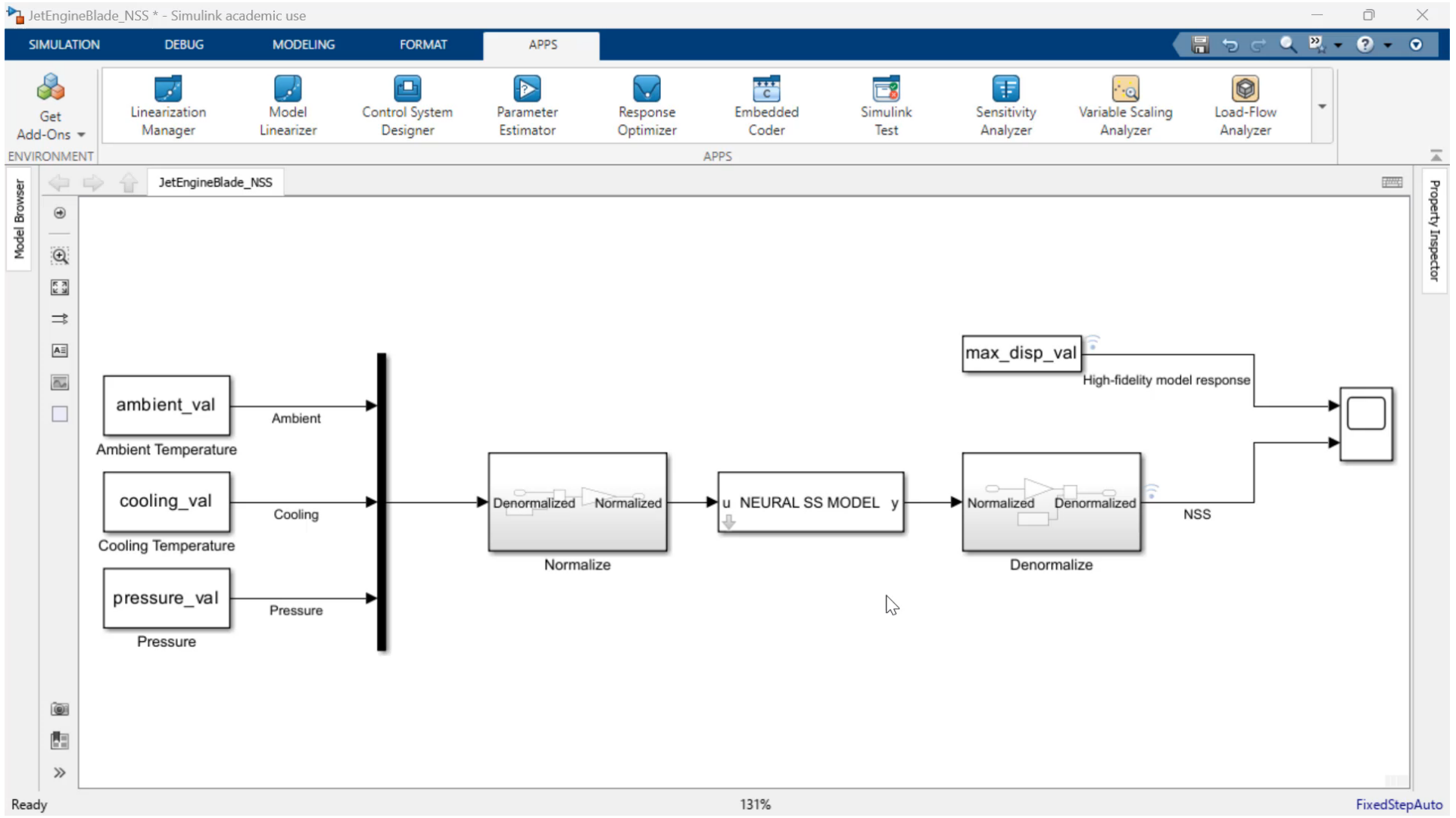


Data Preparation | AI Modeling | Simulation & Test | Deployment

Generate Library-Free C/C++ Code for Deep Learning Networks



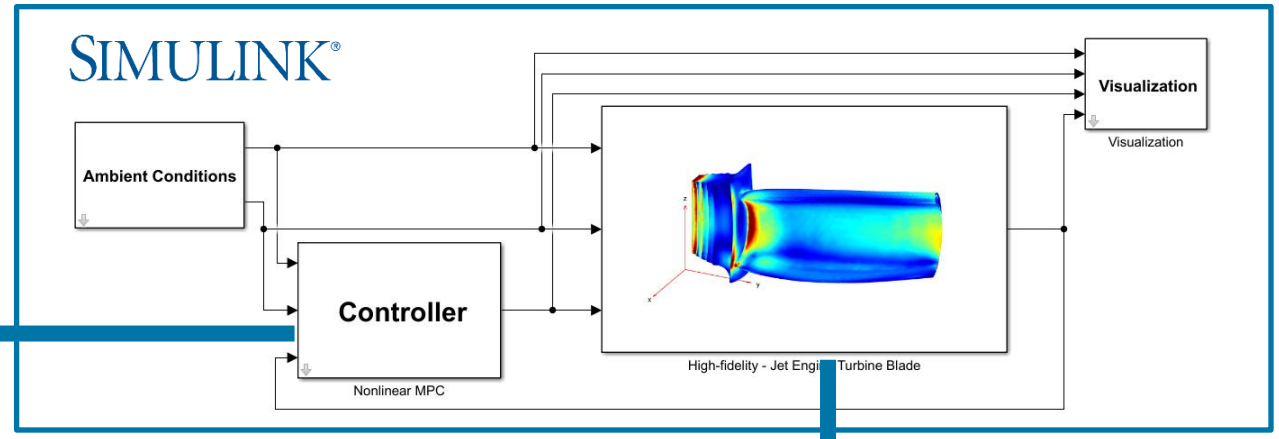
Generate Library-Free C Code for Deep Learning Networks



Data Preparation | AI Modeling | Simulation & Test | Deployment

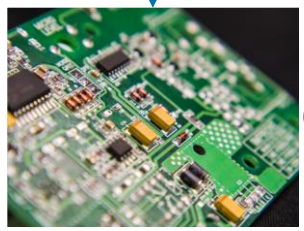
Hardware-in-the-loop 仿真

System-level integration and test



Code generation from algorithm

Code generation from plant model



Target platform

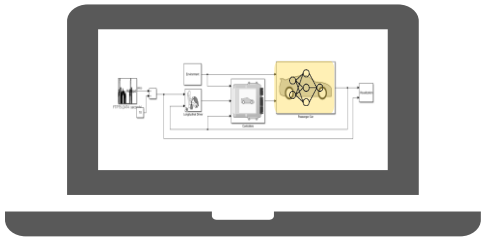
I/O

Real-time computer

Build & download models
Adjust parameters

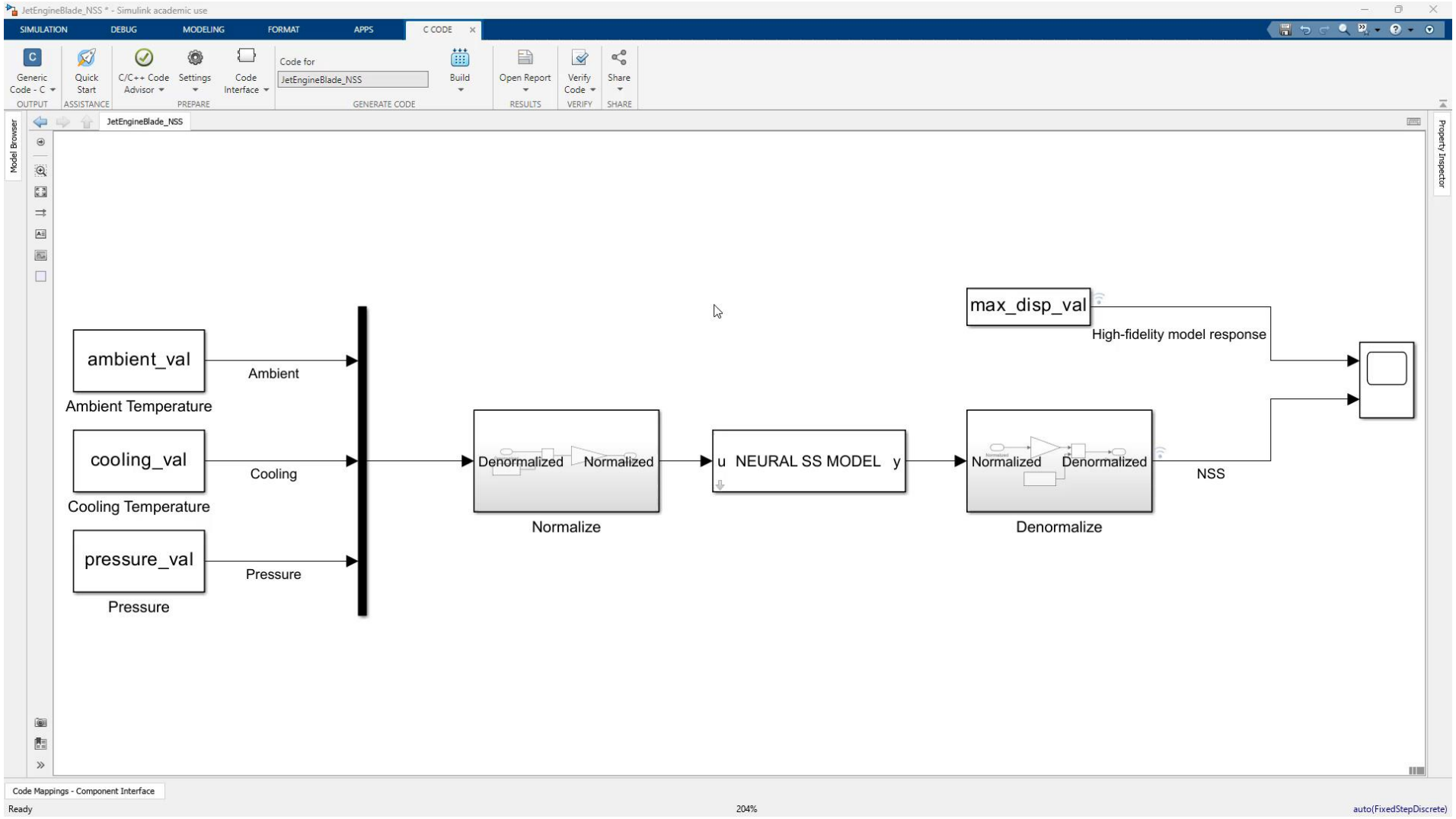
Monitor signals

SIMULINK



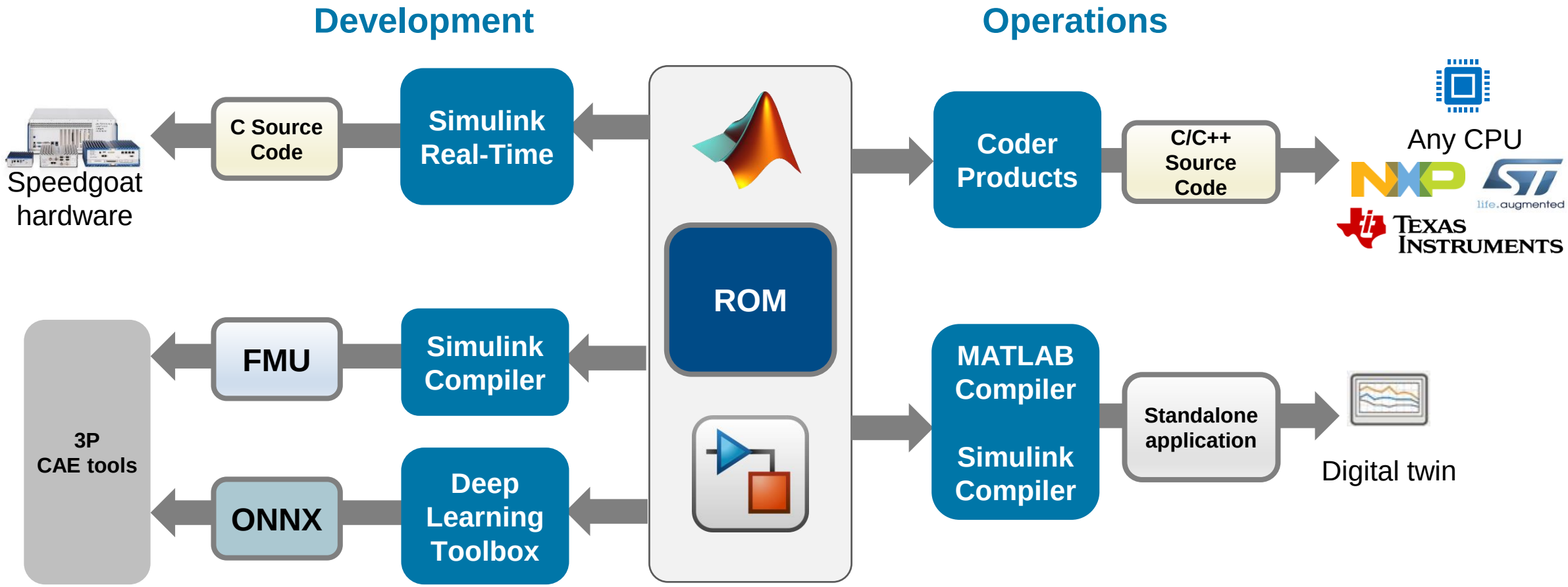
Data Preparation | AI Modeling | Simulation & Test | Deployment

Hardware-in-the-loop 仿真



Data Preparation | AI Modeling | Simulation & Test | Deployment

在其他环境（开发或生产）中使用降阶后的模型



Data Preparation | AI Modeling | Simulation & Test | Deployment

SUBARU利用AI Surrogate Model减少变速器控制系统分析时间

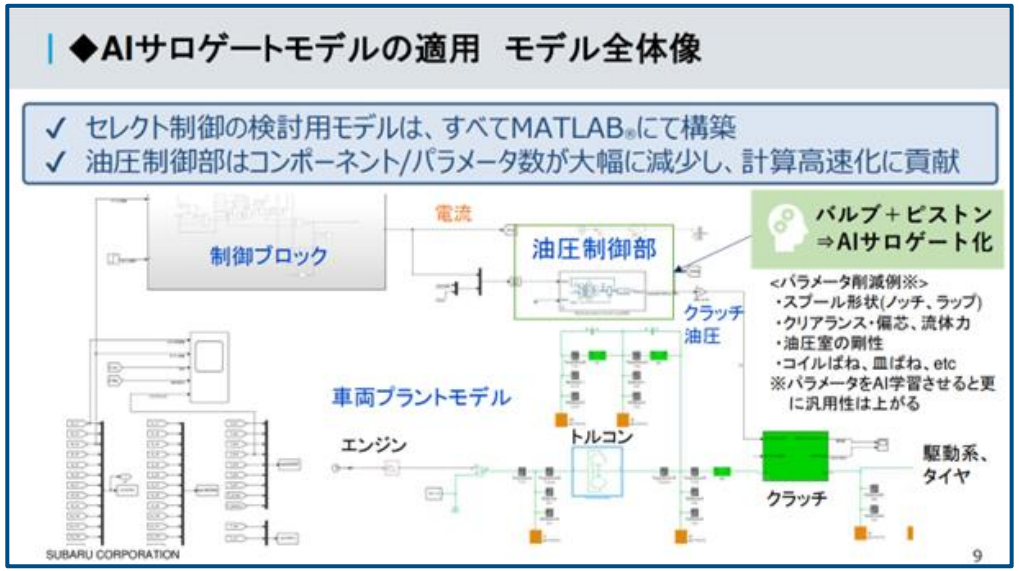
在自动档车辆中，变速器液压控制系统调节液压流体的流量，确保在不同行驶工况下平稳的换挡和高效的动力传递。

方案

- 该 AI 替代模型是通过 MATLAB® 使用神经 ODE 模型构造的。应用这种 AI 替代模型比之前使用第三方一维物理模型进行分析大幅缩短了计算时间。

关键成果

- 与原来的一维模型相比，计算时间减少 99%
- 在 MATLAB 中构造的 AI 替代模型可以重现具有任意电流、油温和源压力读数的波形
- 准确重现波形，即使在模型未经训练的油温范围内也是如此



The AI surrogate model for studying selective control was built completely in MATLAB.

The AI model can now reproduce waveforms at any source pressure, oil temperature, and current. The calculation time can be significantly reduced while ensuring the accuracy of hydraulic waveforms.

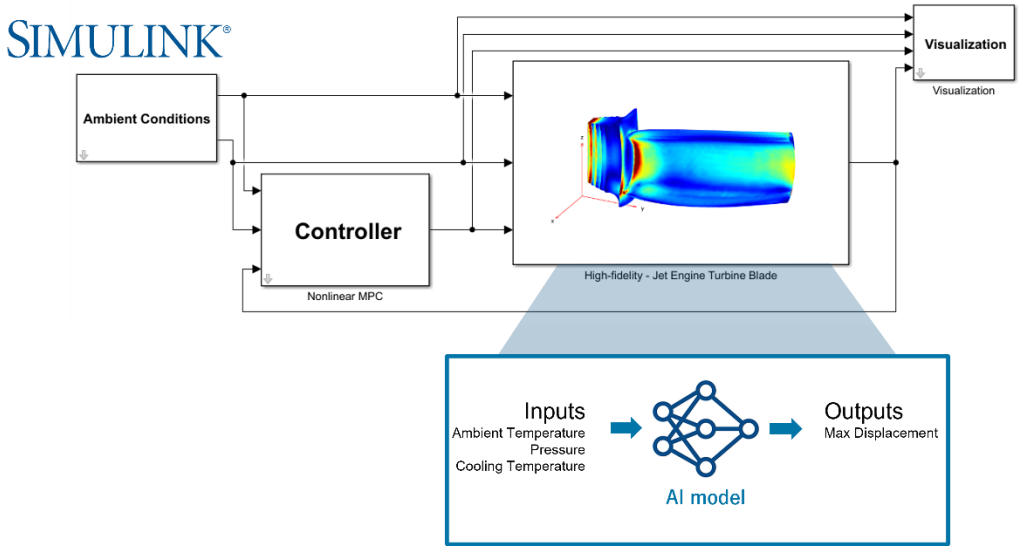
Link to user story

总结

增效	系统级仿真、硬件在环(HIL)测试、非线性控制设计和虚拟传感器建模
探索	MATLAB中不同的ROM的技术来找到效果最好的.

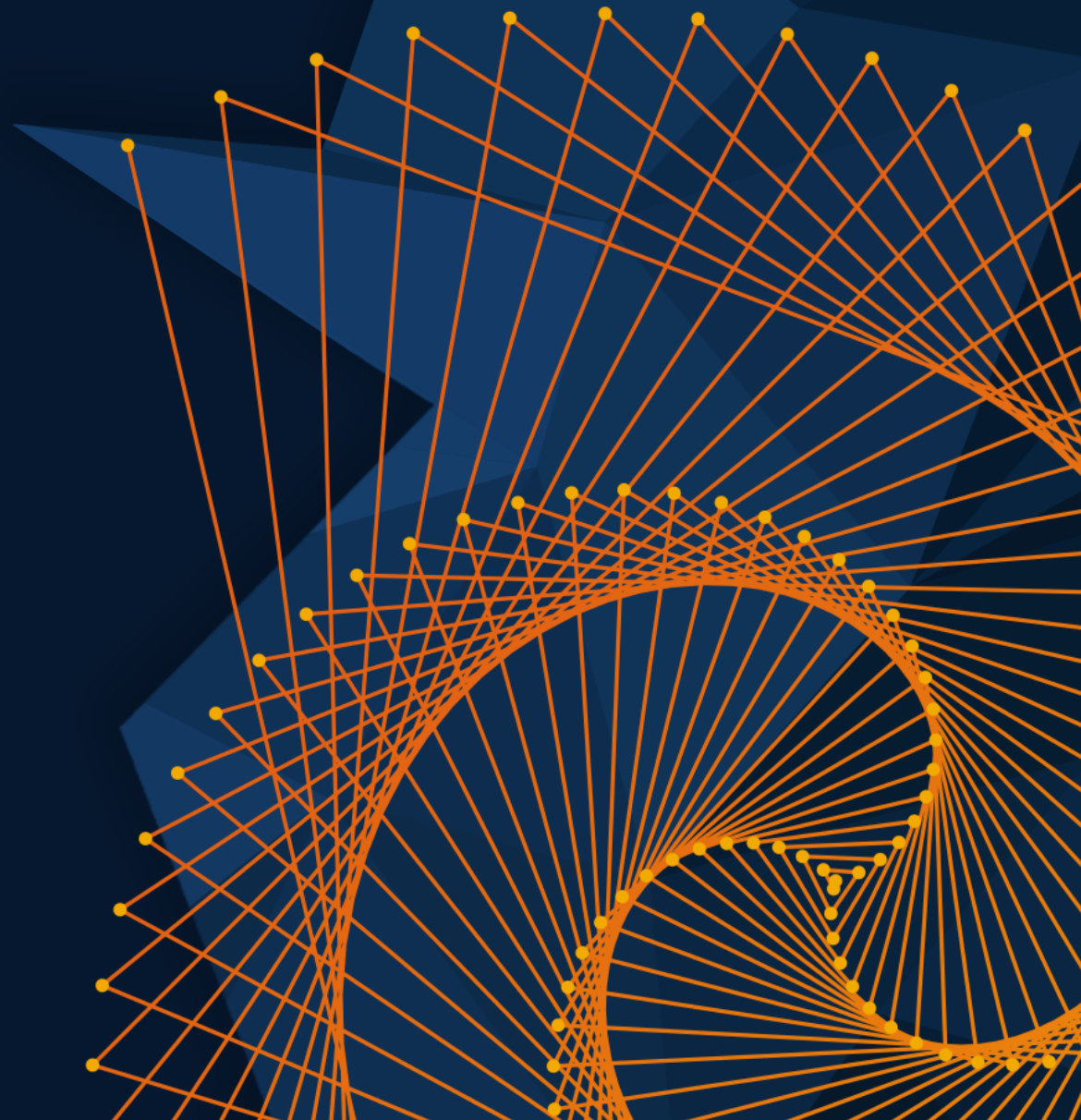
Reduced Order Modeler App

- **Generate synthetic data** from Simulink
- **Train AI Models** to **replace FEA model that computes tip displacement** of a jet engine blade
- **Integrate trained AI model into Simulink** for control design and system-level simulation
- **Generate C code and perform HIL tests**



MATLAB EXPO

Thank you



MathWorks®