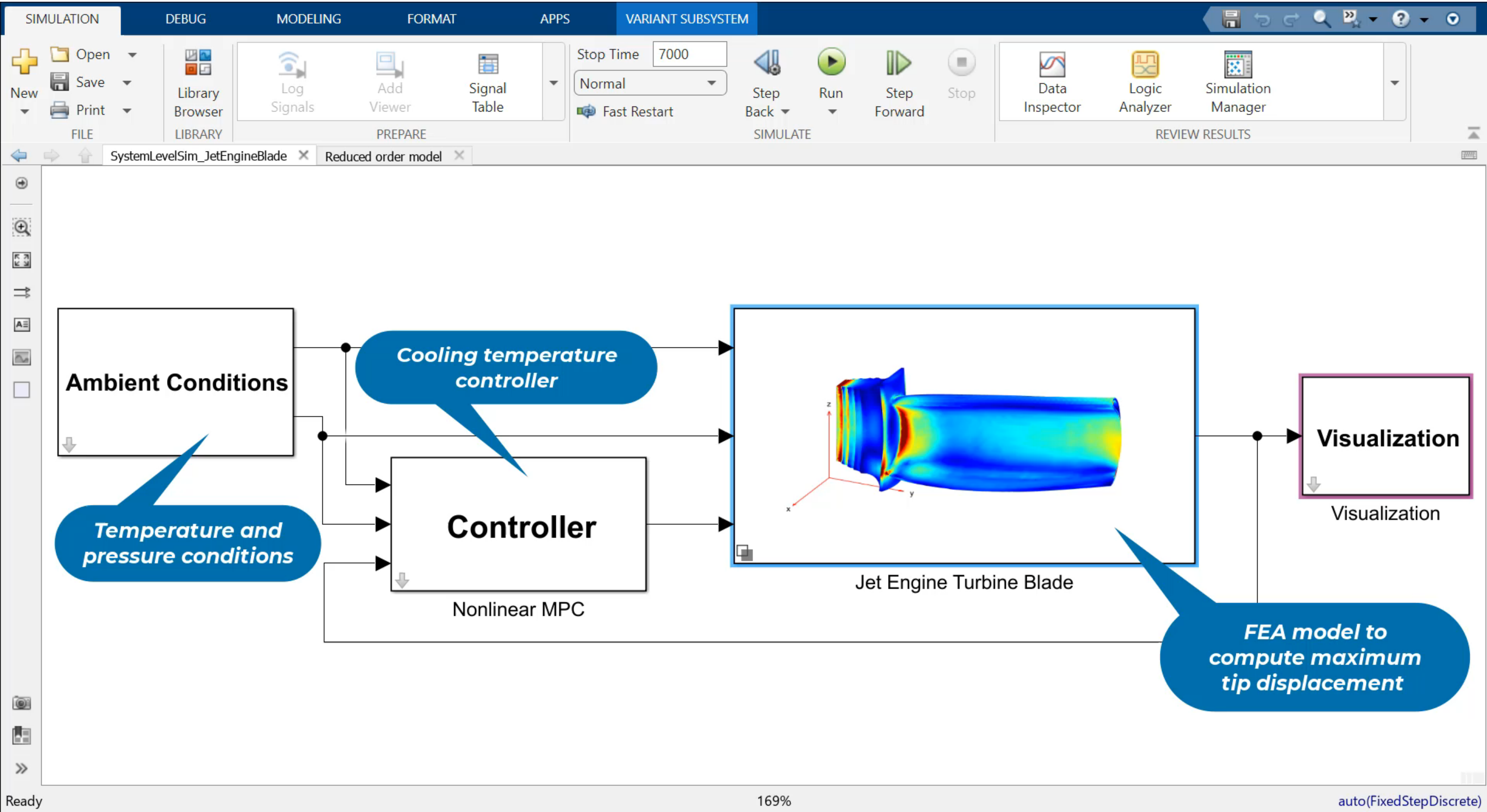
MATLAB EXPO

2024.06.11 | 그랜드 인터컨티넨탈 서울 파르나스

차수축소 모델링 활용방안

김종남, 매스웍스 코리아

MathWorks

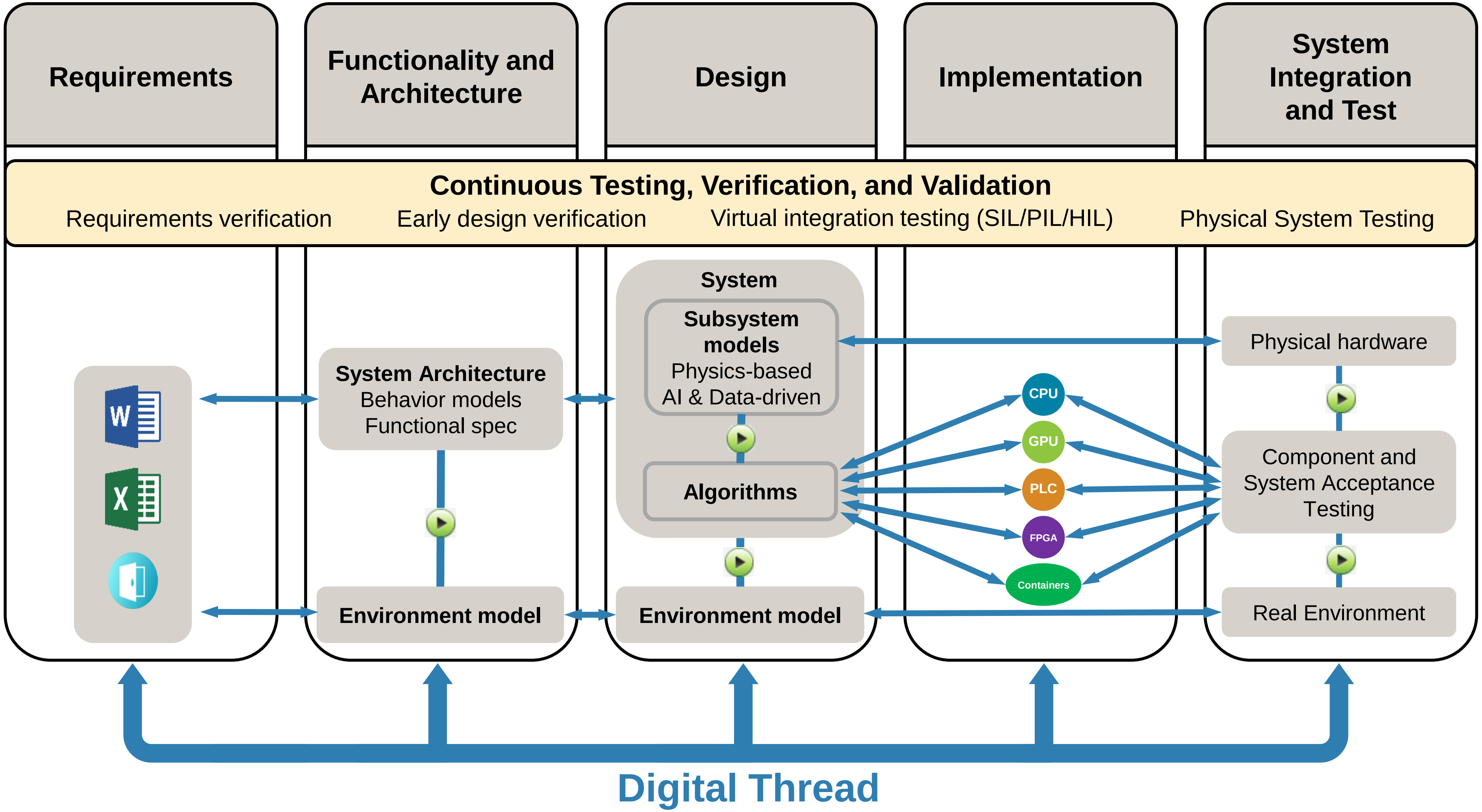

SIMULATION
DEBUG
MODELING
FORMAT
APPS
VARIANT SUBSYSTEM
New
Open
Save
Print
FILE
Library Browser
LIBRARY
Log Signals
Add Viewer
Signal Table
PREPARE
Stop Time
7000
Normal
Fast Restart
Step Back
Run
Step Forward
Stop
SIMULATE
Data Inspector
Logic Analyzer
Simulation Manager
REVIEW RESULTS
SystemLevelSim_JetEngineBlade
Reduced order model
Ambient Conditions
Cooling temperature controller
Temperature and pressure conditions
Controller
Nonlinear MPC
Jet Engine Turbine Blade
Visualization
Visualization
FEA model to compute maximum tip displacement
Ready
169%
auto(FixedStepDiscrete)

Common challenges

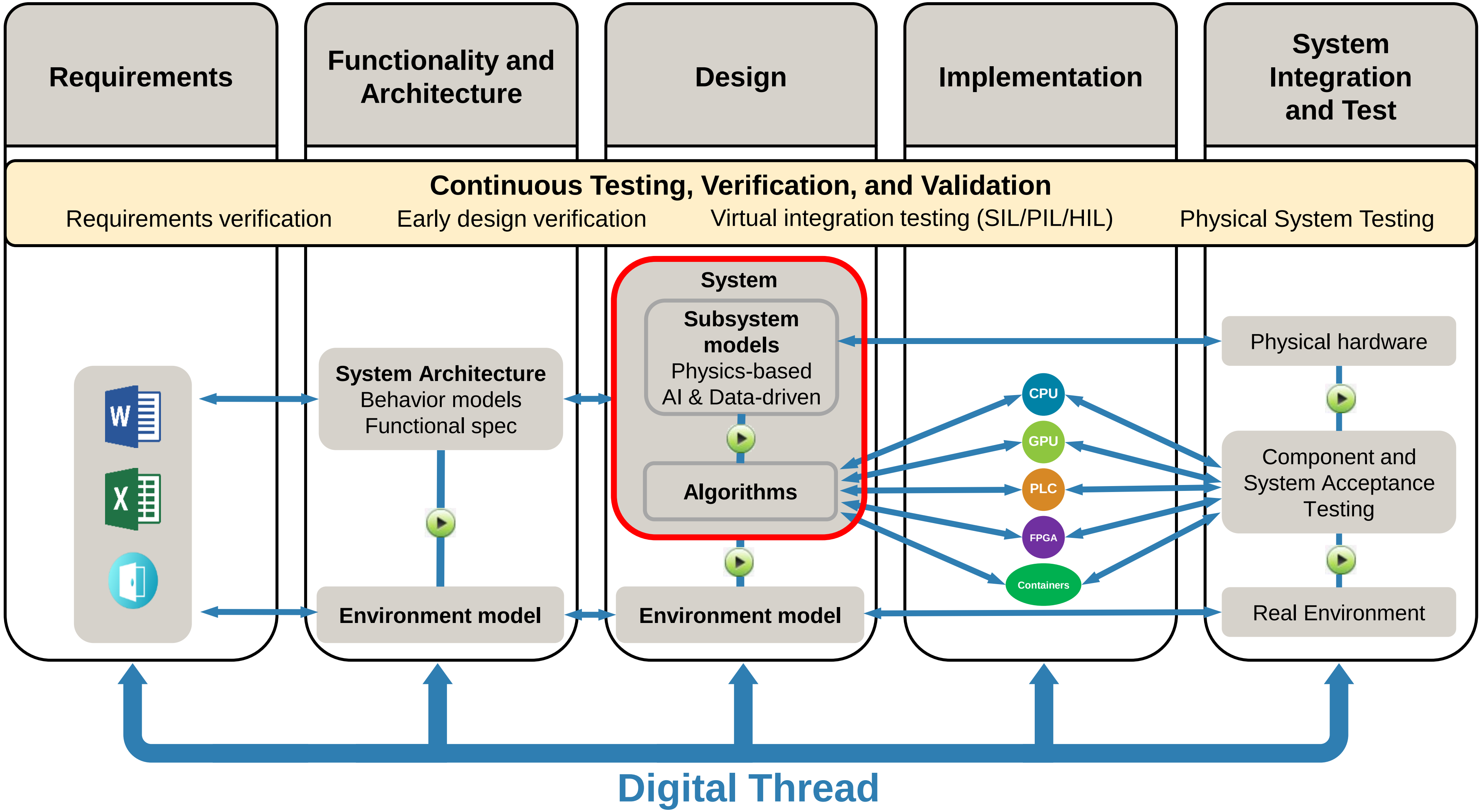
High fidelity models, such as ones from 3rd party FEA/CFD tools, are too slow for system level simulation, control design, and HIL testing.

Creating a ROM that produces desired results in terms of speed, accuracy, interpretability, etc.

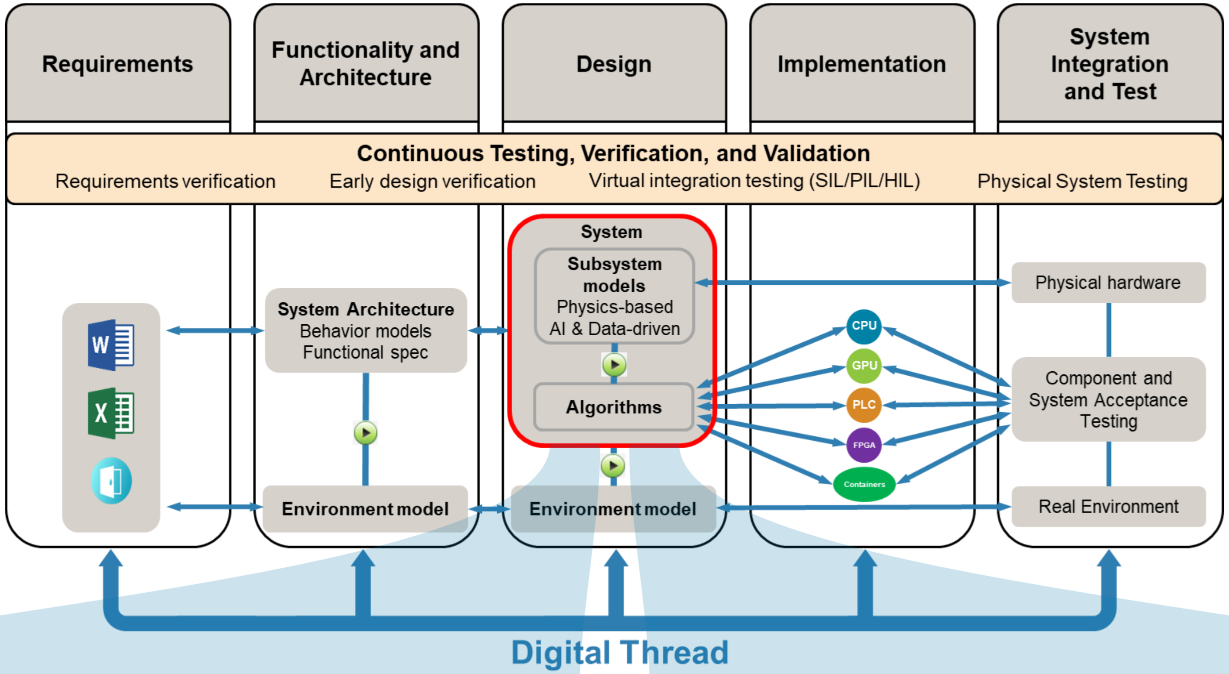
Model-Based Design



Integrating AI into Model-Based Design



Integrate AI models into MBD for system-level simulation and code generation



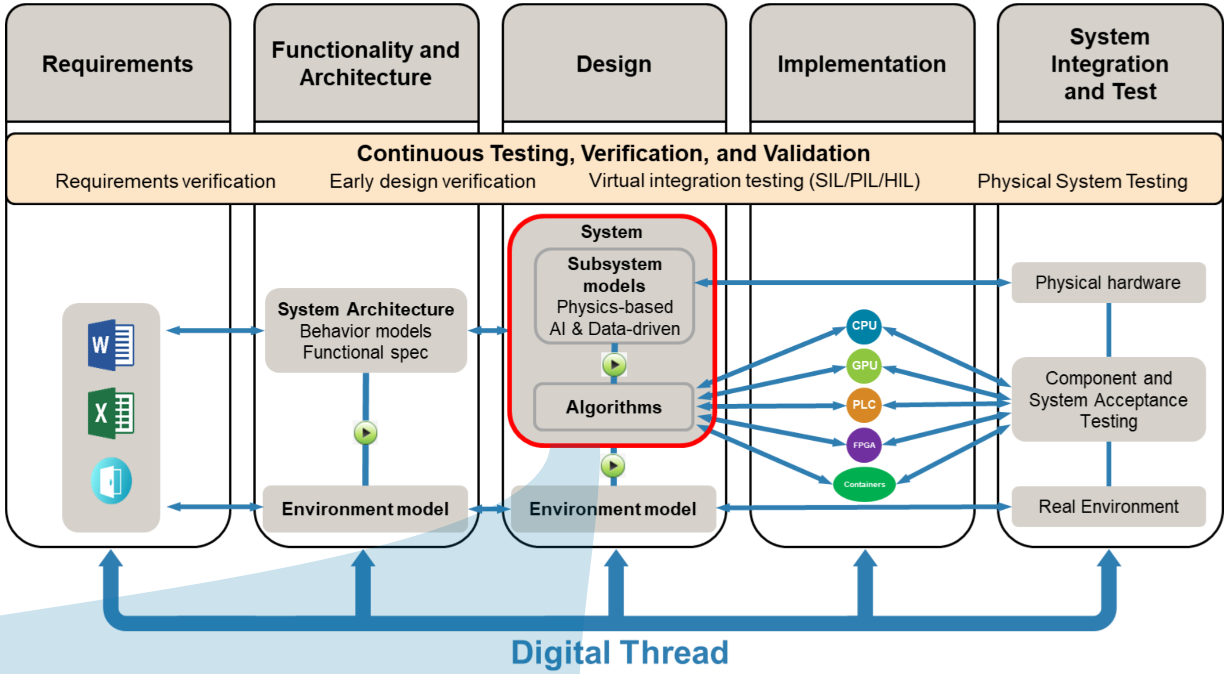
AI for component modeling

- HIL testing and system-level simulation for high-fidelity models
- Modeling component dynamics from data when first-principles models cannot be obtained

AI for algorithm development

- Virtual sensor modeling
- Sensor fusion
- Object detection

Focus today



AI for component modeling

- HIL testing and system-level simulation for high-fidelity models
- Modeling component dynamics from data when first-principles models cannot be obtained

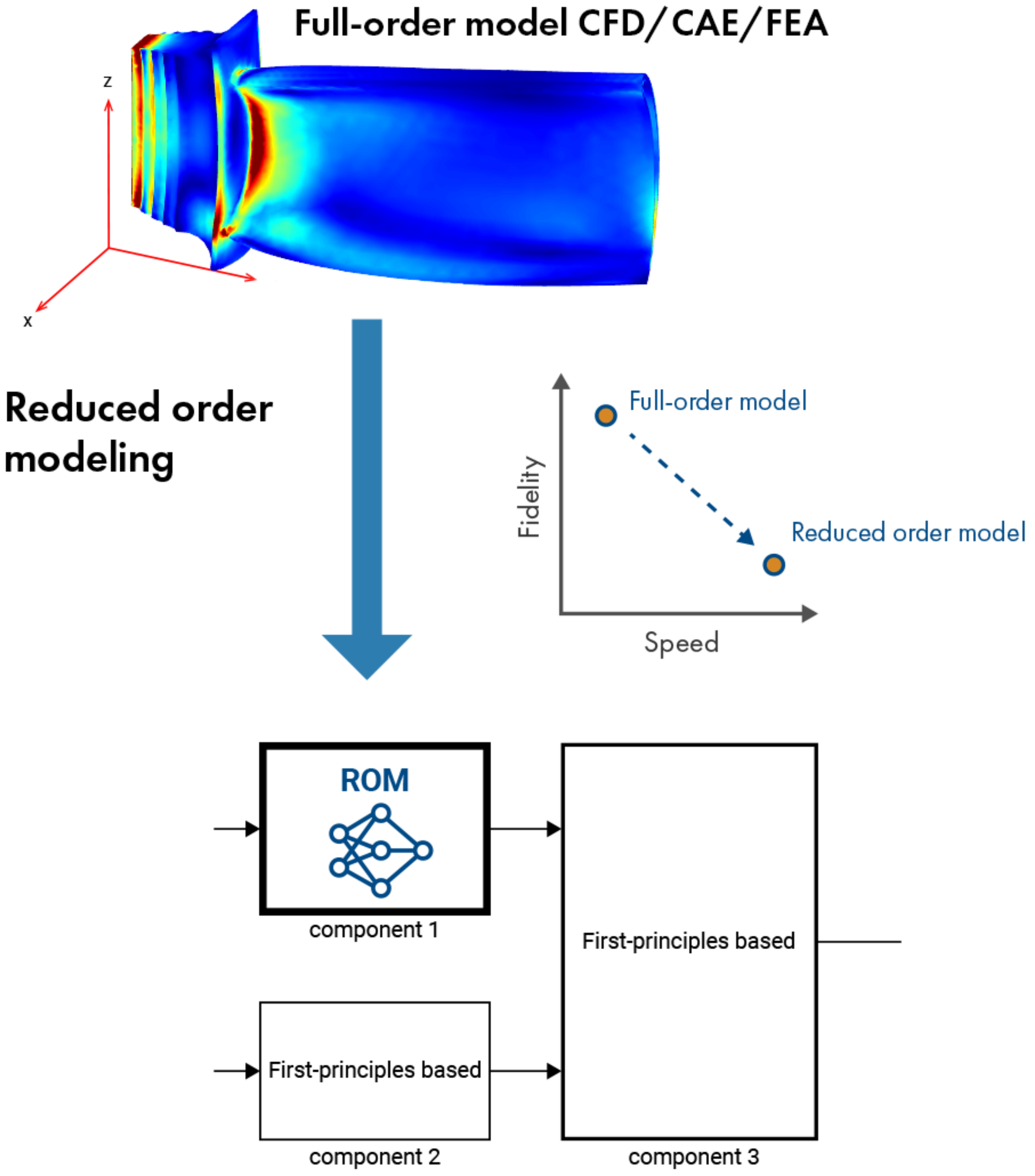
Reduced Order Modeling

What

- Techniques to **reduce the computational complexity** of a computer model
- **Provide reduced, but acceptable fidelity**

Why

- Enable simulation of FEA models in Simulink
- Perform hardware-in-the-loop testing
- Develop virtual sensors, Digital twins
- Enable desktop simulations for orders-of-magnitude longer timescales



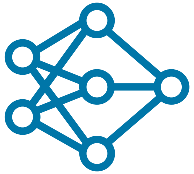
Reduced Order Modeling

How

Reduced order model

AI-Based Data-driven

Inputs
Ambient Temperature
Ambient Pressure
Cooling Temperature

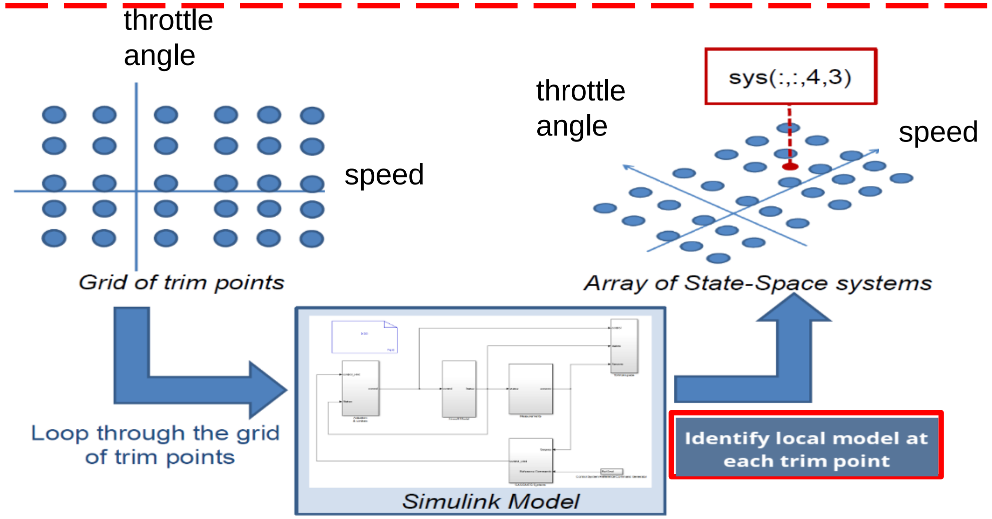


AI model

Outputs
Max Displacement

focus today

Linearization

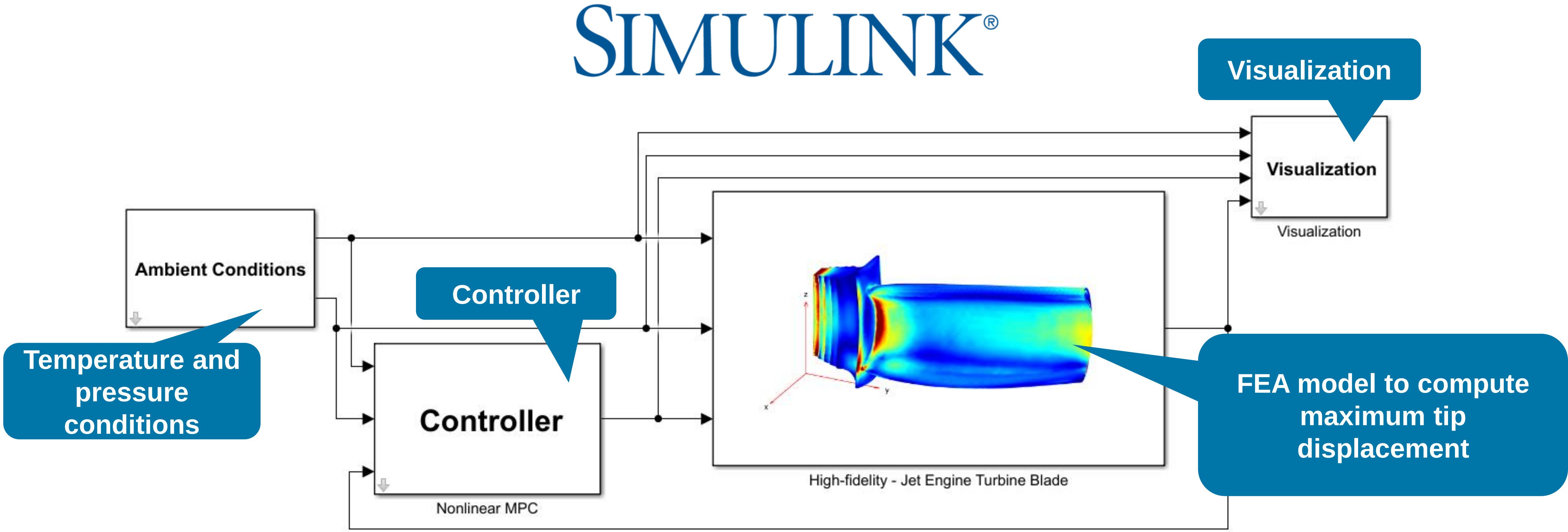


Model-based

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

Example overview

Replacing a high-fidelity jet engine turbine blade model with an AI-based reduced order model

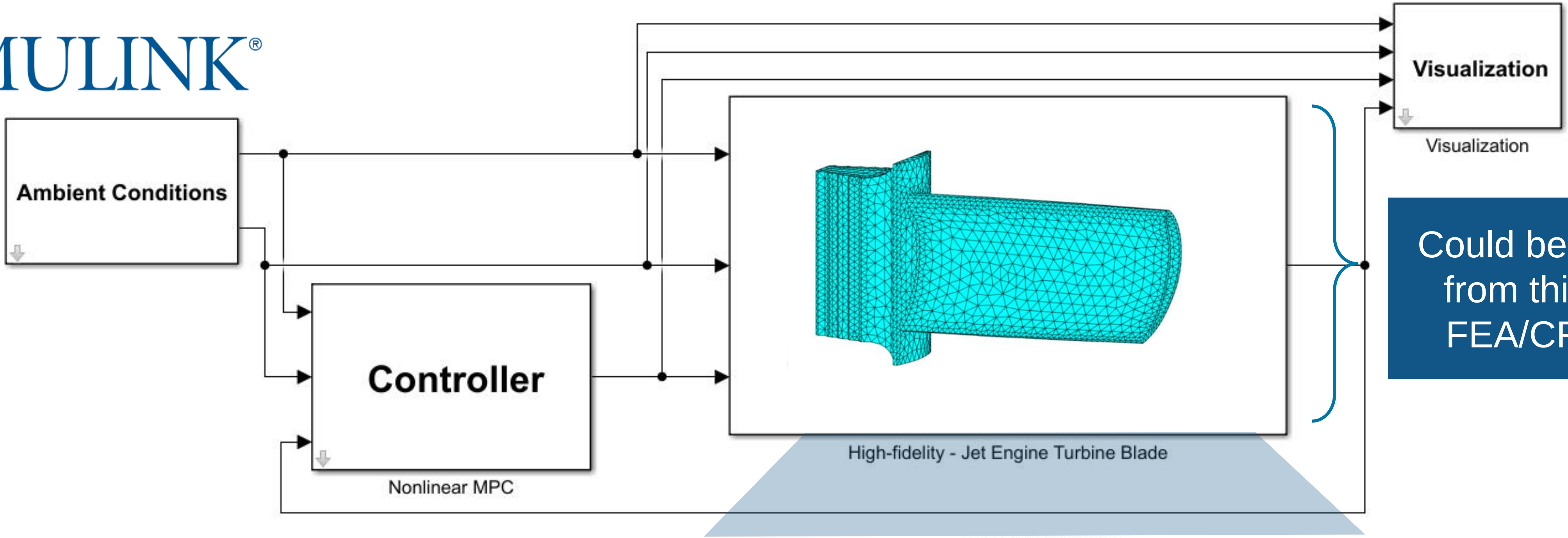


Closed-loop temperature control

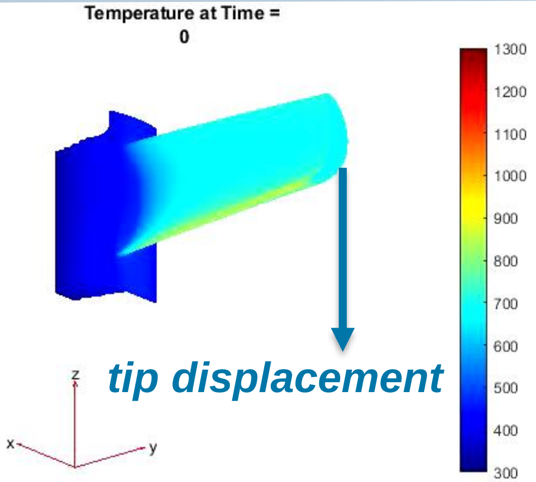
Example overview

Replacing a high-fidelity jet engine turbine blade model with an AI-based reduced order model

SIMULINK®



Could be imported from third-party FEA/CFD tools

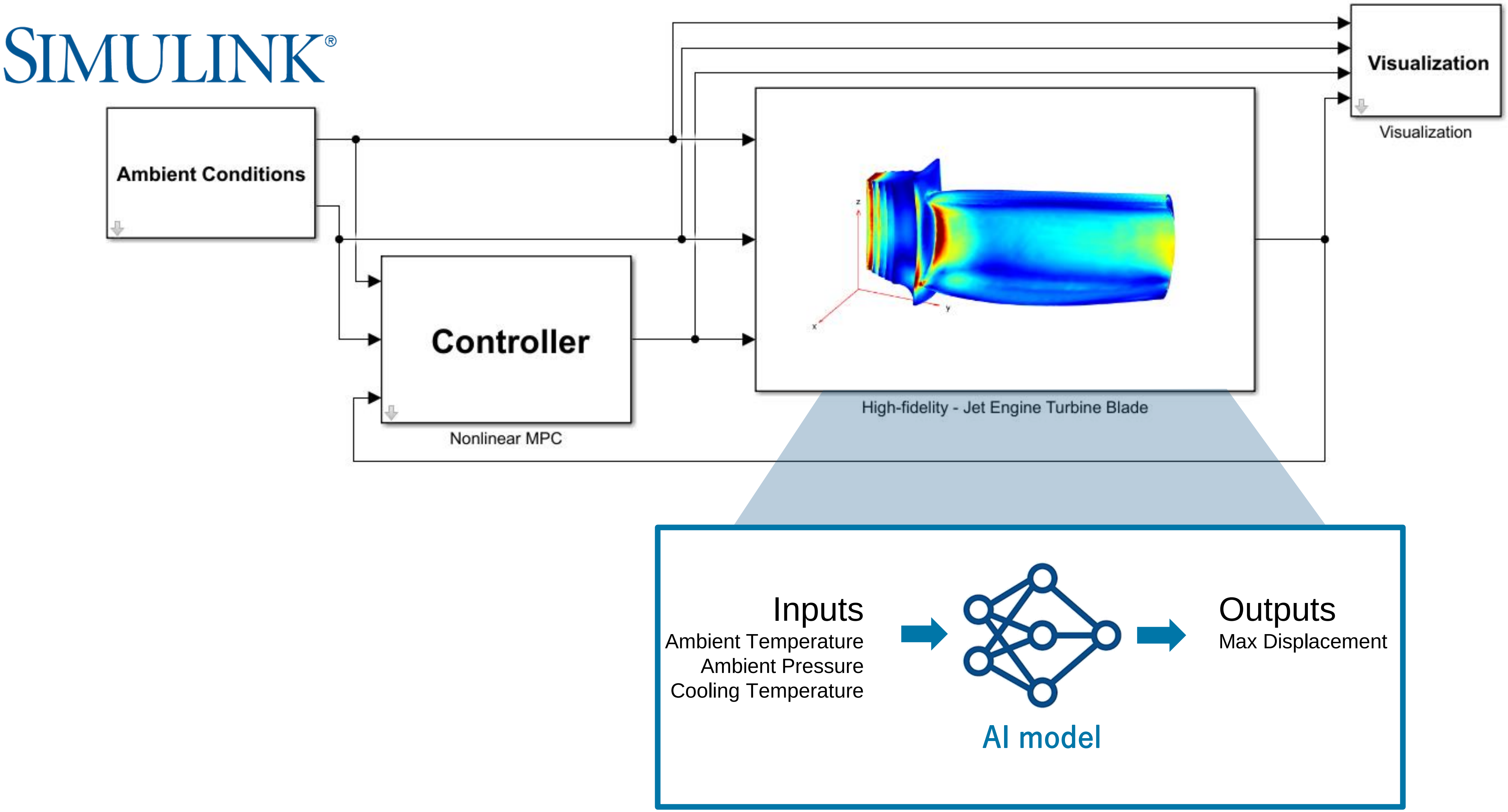


~30 seconds per time step for solving FEA models

Not suitable for control design and HIL testing

Example overview

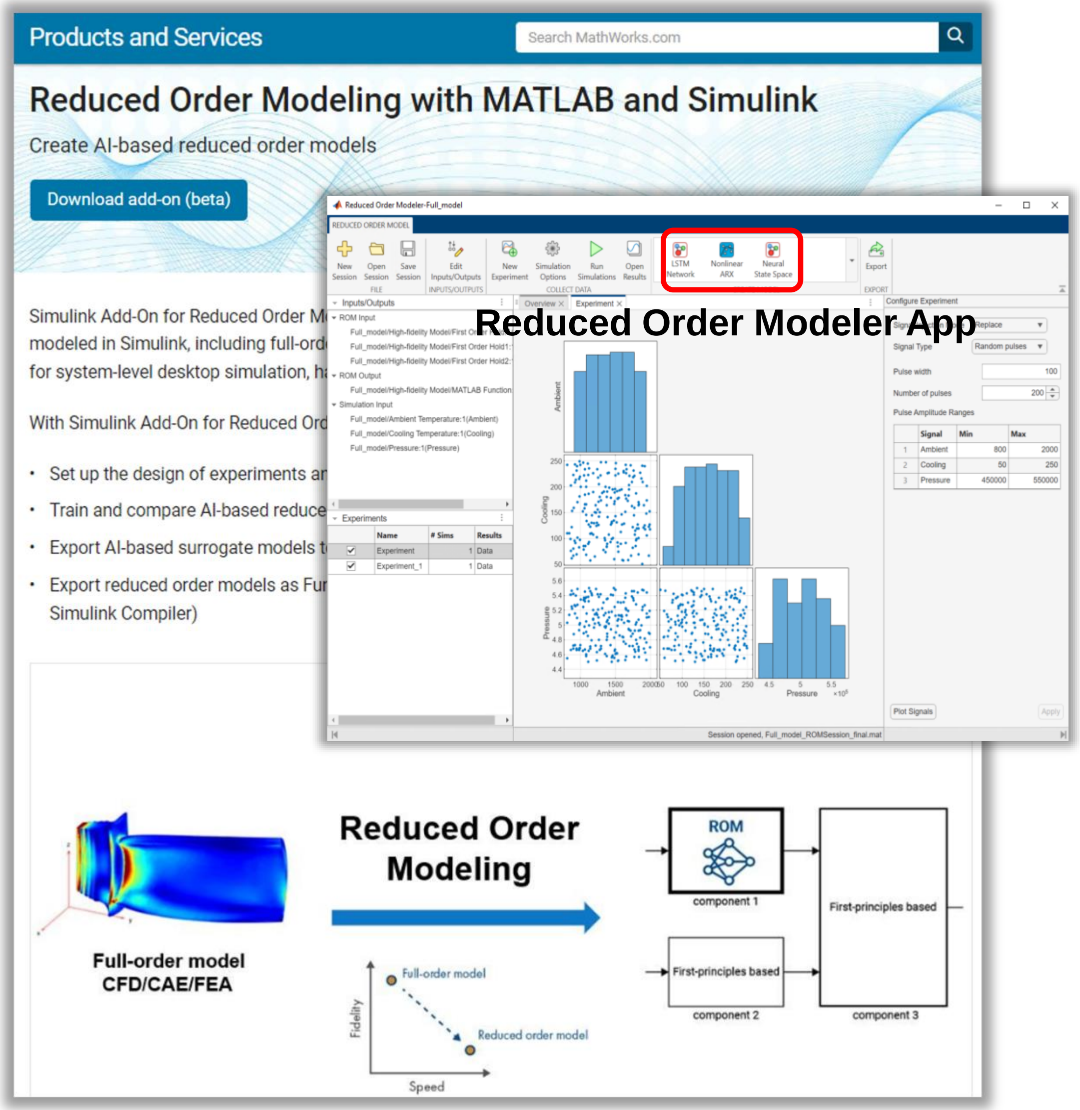
Replacing a high-fidelity jet engine turbine blade model with an AI-based reduced order model



Introducing Simulink Add-On for Reduced Order Modeling

Create AI-based reduced order models (ROM)

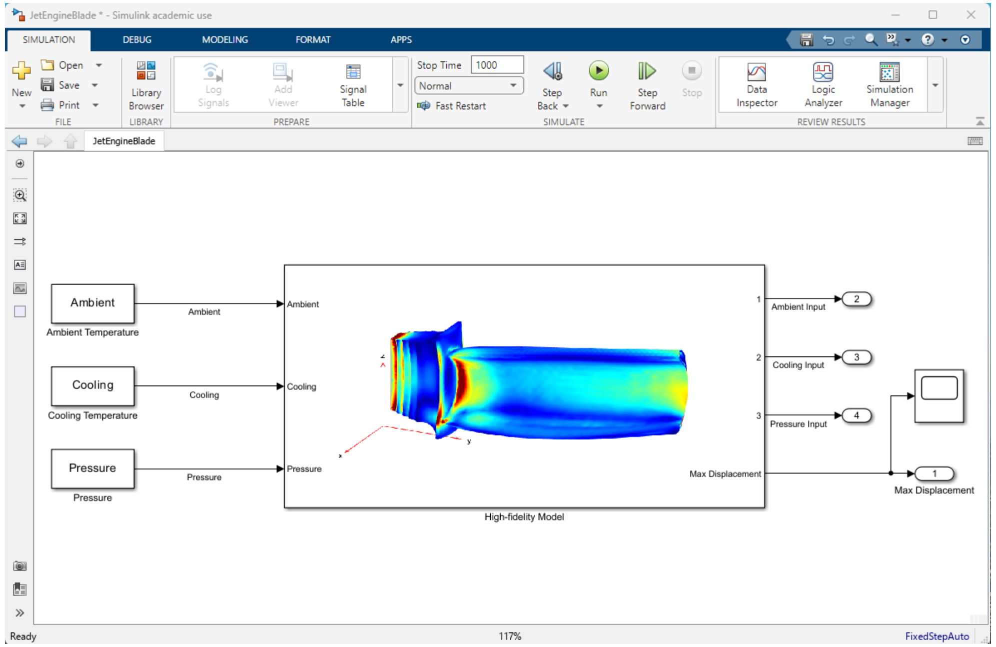
- **Set up Design of Experiments (DoE)**
- **Generate input-output data from full-order, high-fidelity subsystems**
- **Train and compare AI-based reduced order models using preconfigured templates**
- **Export trained reduced order models into Simulink or outside of Simulink through FMUs**



Reduced Order Modeling with MATLAB and Simulink

Generate data for training

Physical system

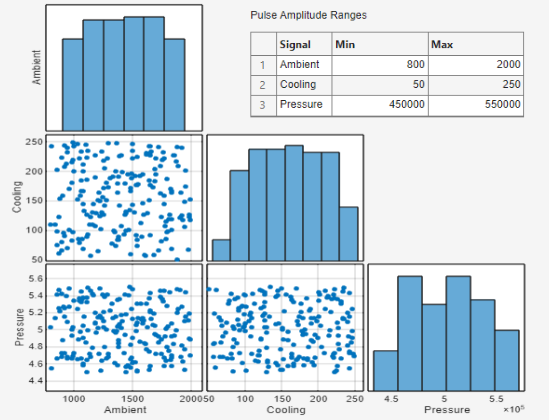


Simulink/Simscape

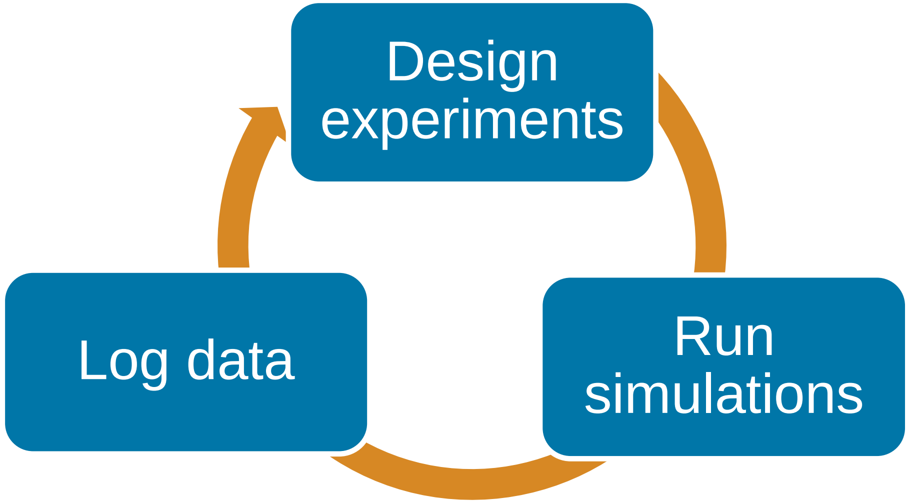
Data Preparation | AI Modeling | Simulation & Test | Deployment

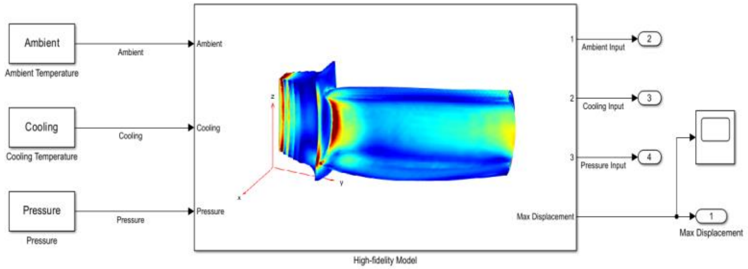
Synthetic Data Generation

Design of Experiments



	Signal	Min	Max
1	Ambient	800	2000
2	Cooling	50	250
3	Pressure	450000	550000





<u>Input features</u>

Ambient Temperature
Ambient Pressure
Cooling Temperature

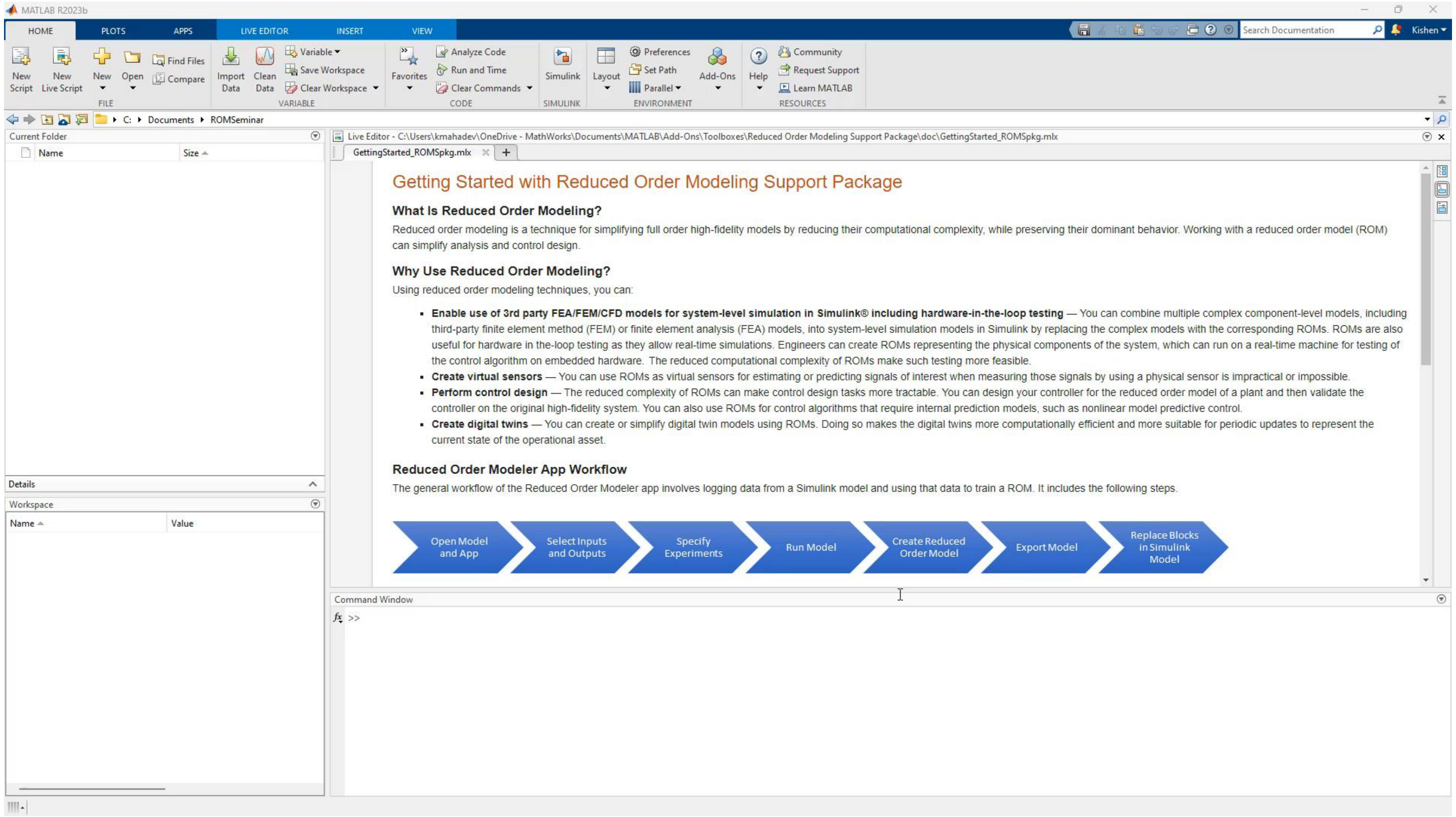
<u>Response</u>

Max Displacement

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

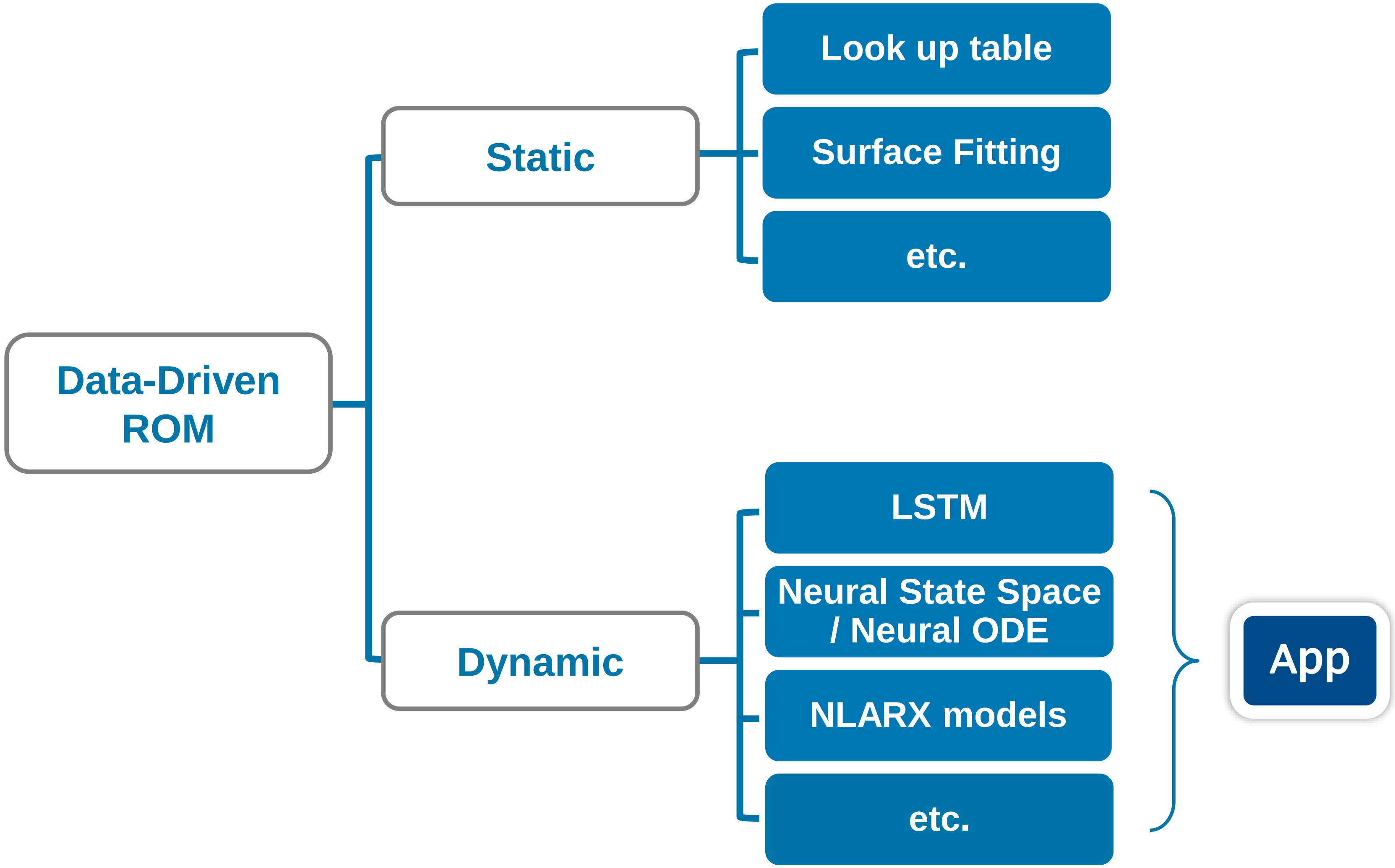
Synthetic Data Generation

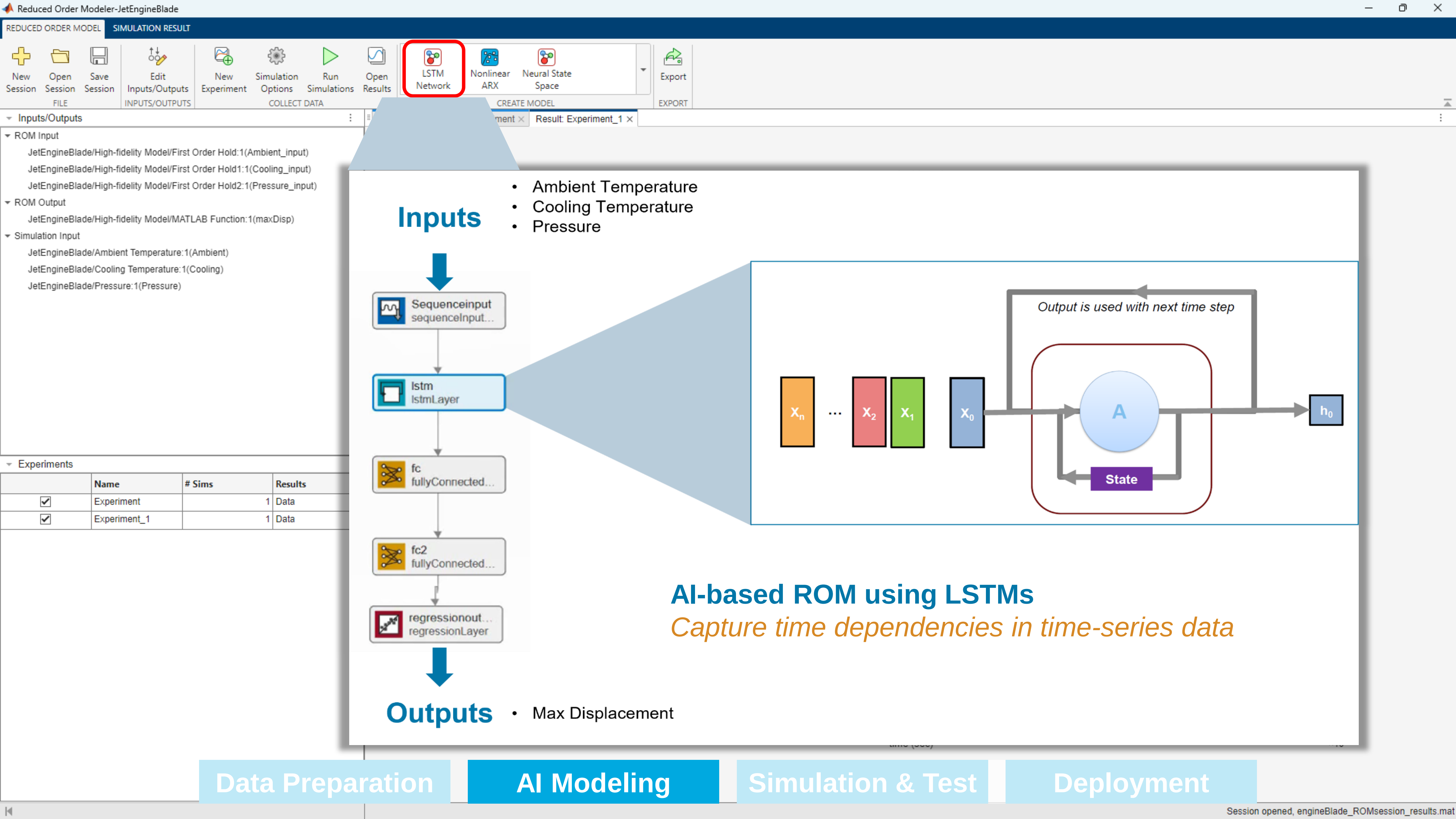
Design of Experiments

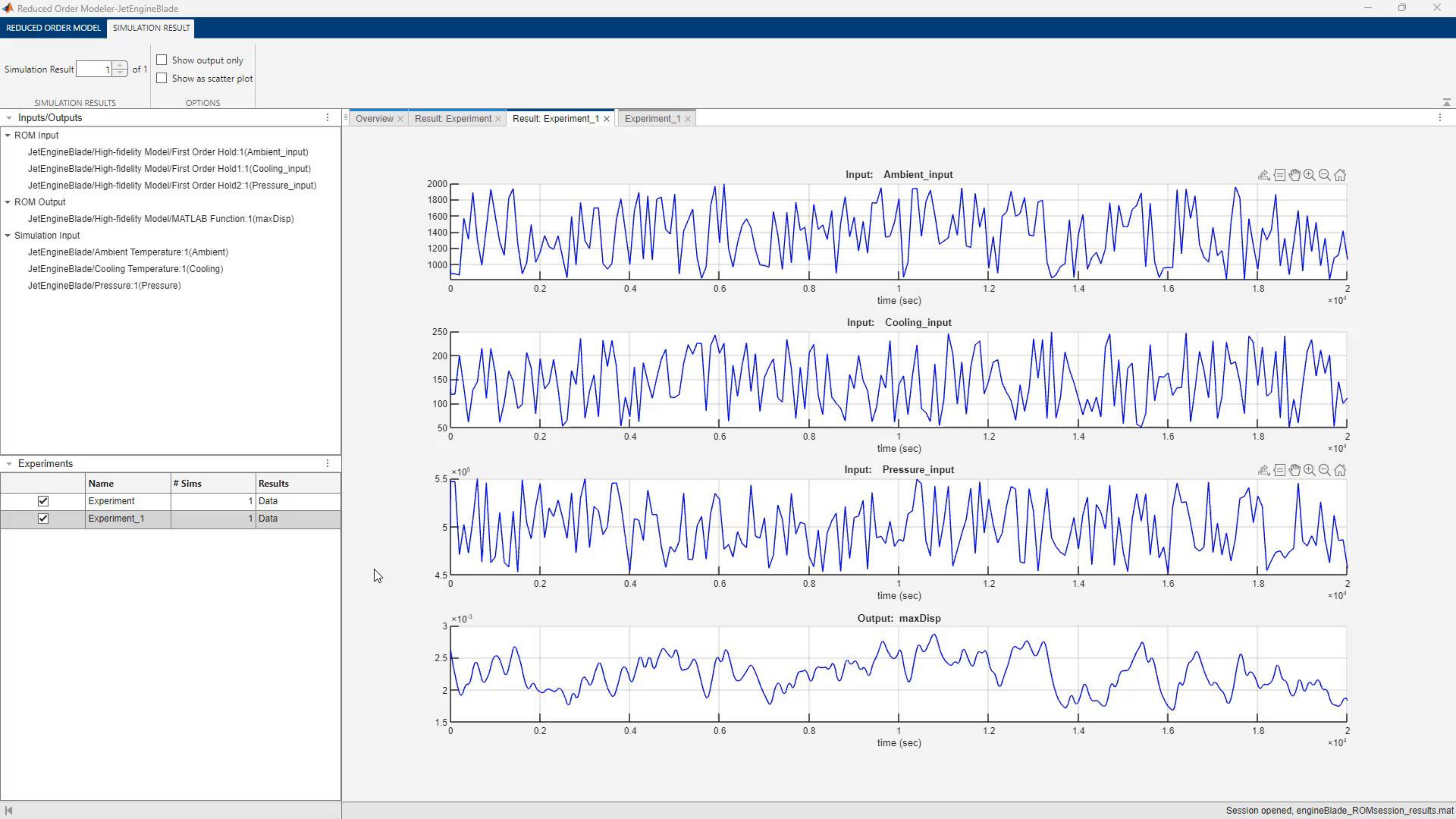


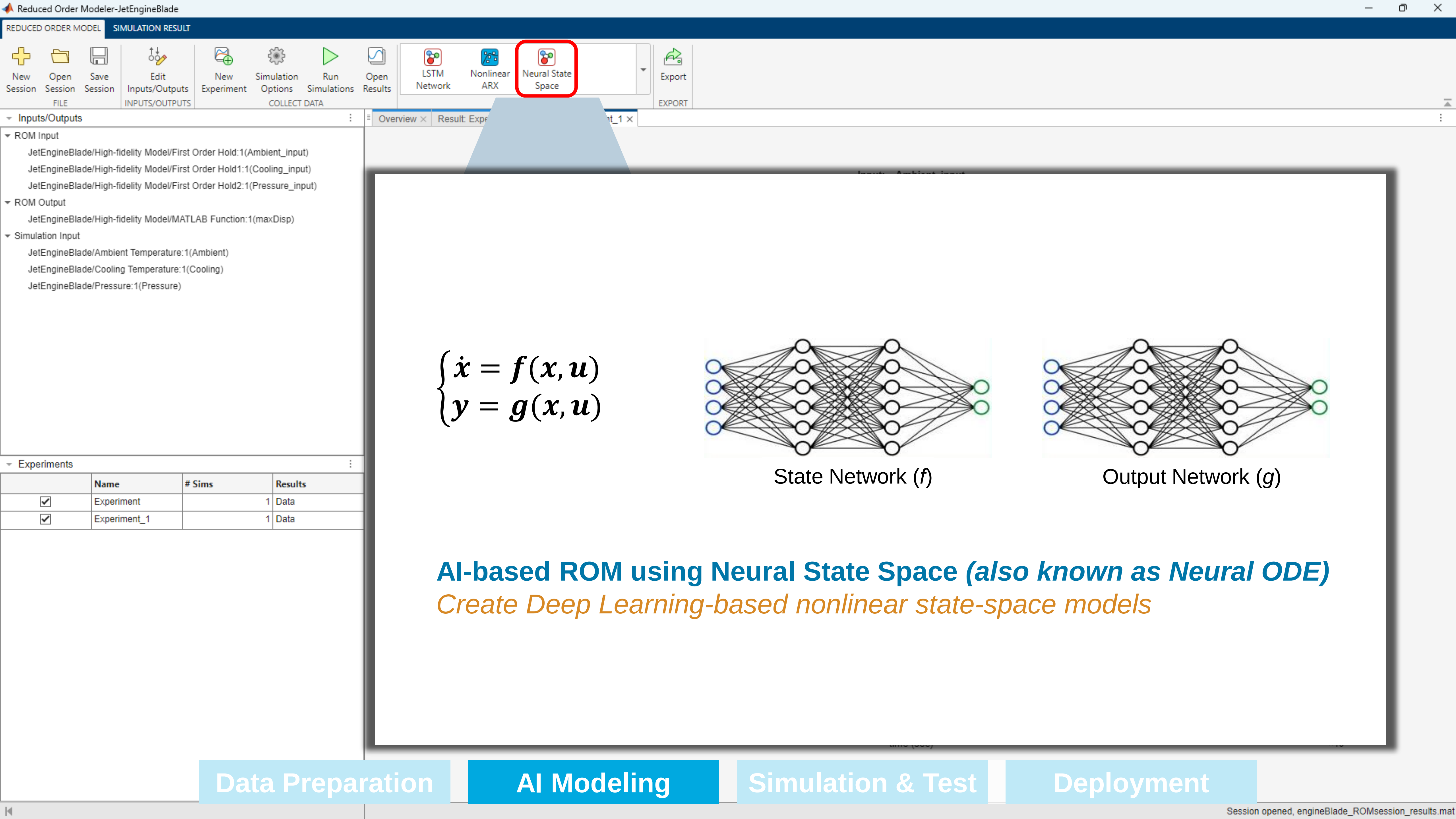
Data Preparation | AI Modeling | Simulation & Test | Deployment

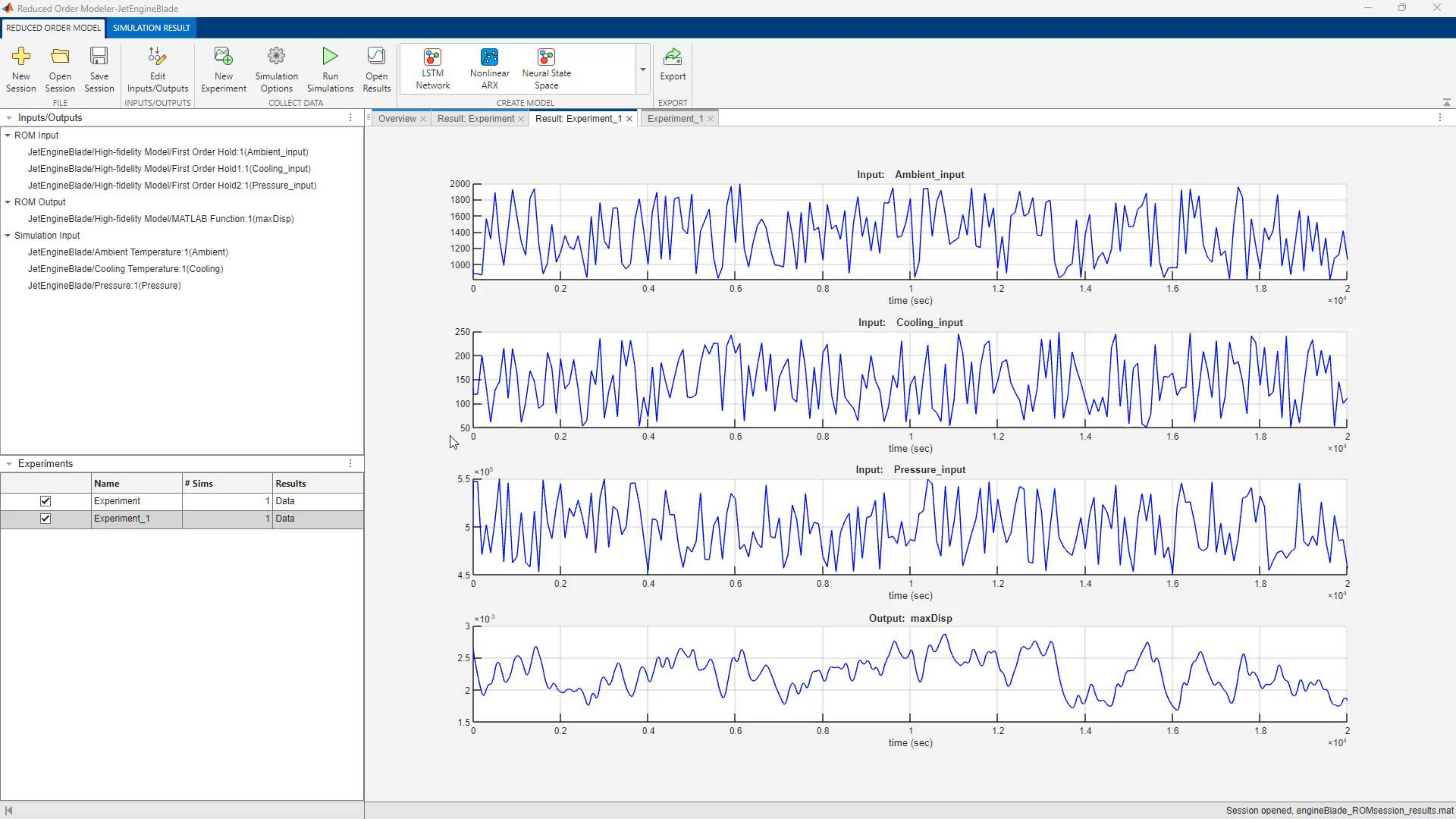
Data-driven ROM




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)
Experiments
Name
Sims
Results
Experiment
1
Data
Experiment_1
1
Data
Result: Experiment_1
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
Xn
...
X2
X1
X0
A
State
h0
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
Input: Ambient_input
Input: Cooling_input
Input: Pressure_input
Output: maxDisp
time (sec)
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
$\begin{cases} \dot{x} = f(x,u) \\ y = g(x,u) \end{cases}$
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
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FILE
Edit Inputs/Outputs
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New Experiment
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JetEngineBlade/High-fidelity Model/First Order Hold1:1(Cooling_input)
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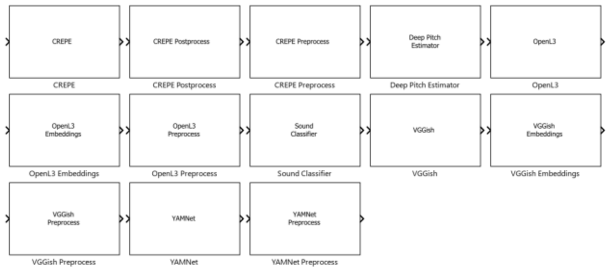
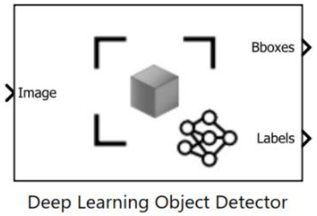
ROM Output
JetEngineBlade/High-fidelity Model/MATLAB Function:1(maxDisp)
Simulation Input
JetEngineBlade/Ambient Temperature:1(Ambient)
JetEngineBlade/Cooling Temperature:1(Cooling)
JetEngineBlade/Pressure:1(Pressure)
Experiments
Name
Sims
Results
Experiment
1
Data
Experiment_1
1
Data
Overview
Result: Experiment
Result: Experiment_1
Experiment_1
Input: Ambient_input
Input: Cooling_input
Input: Pressure_input
Output: maxDisp
time (sec)
Session opened, engineBlade_ROMsession_results.mat

AI libraries in Simulink are expanding to include more AI blocks for more applications

Specialized

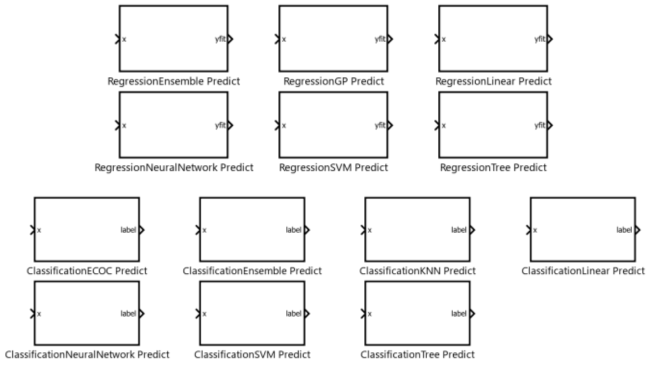


Audio Toolbox

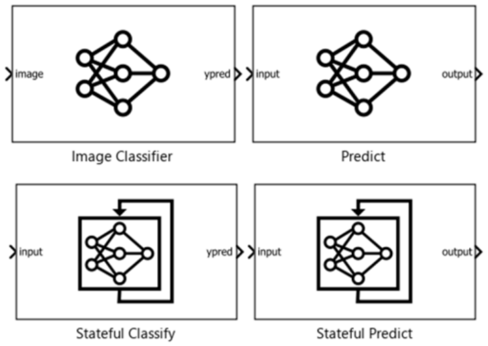


Computer Vision Toolbox

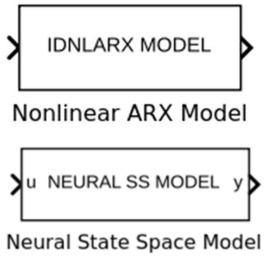
AI Core



Statistics and Machine Learning Toolbox



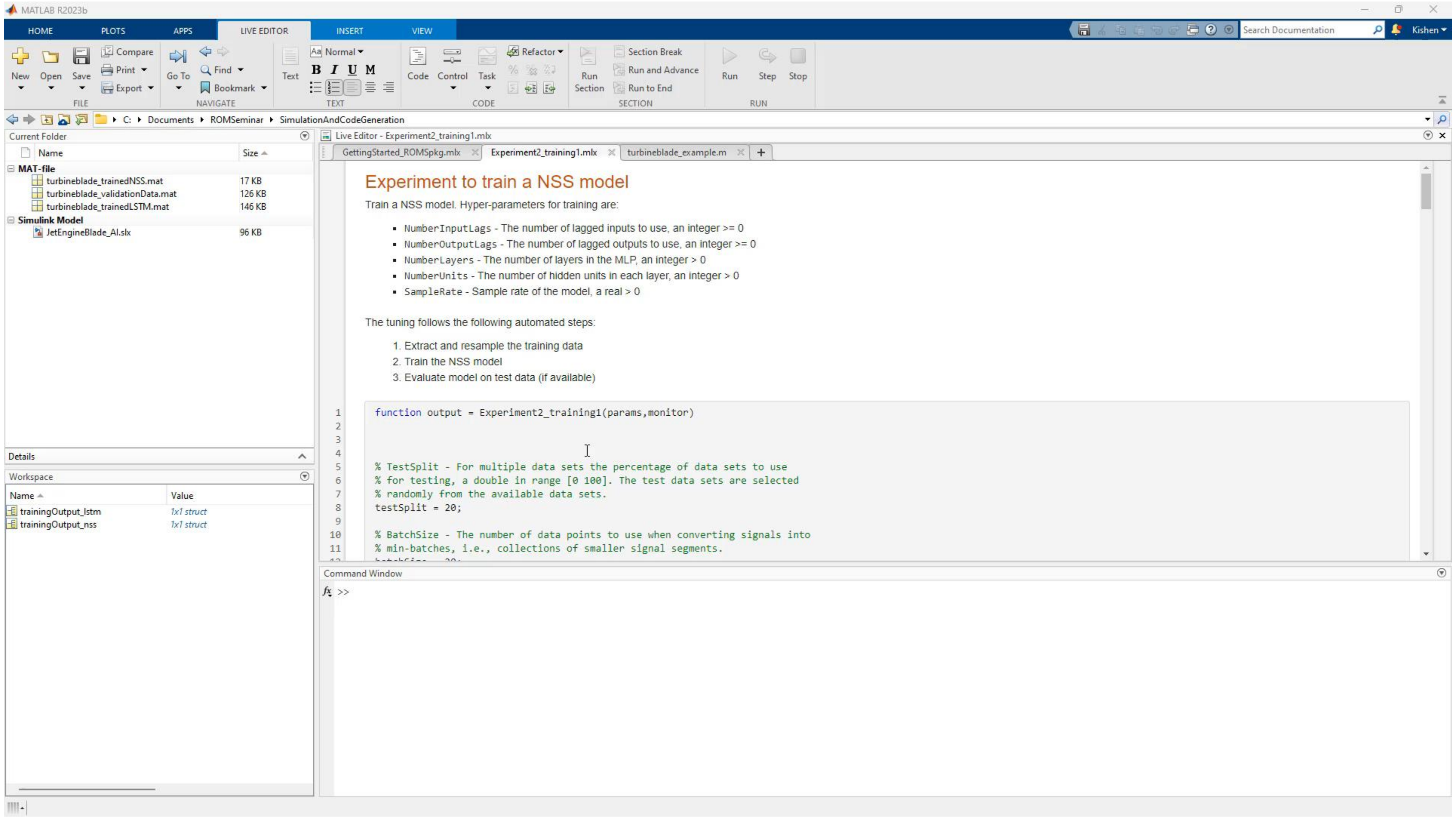
Deep Learning Toolbox



System Identification Toolbox

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

Integration of trained AI models into Simulink



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

MathWorks

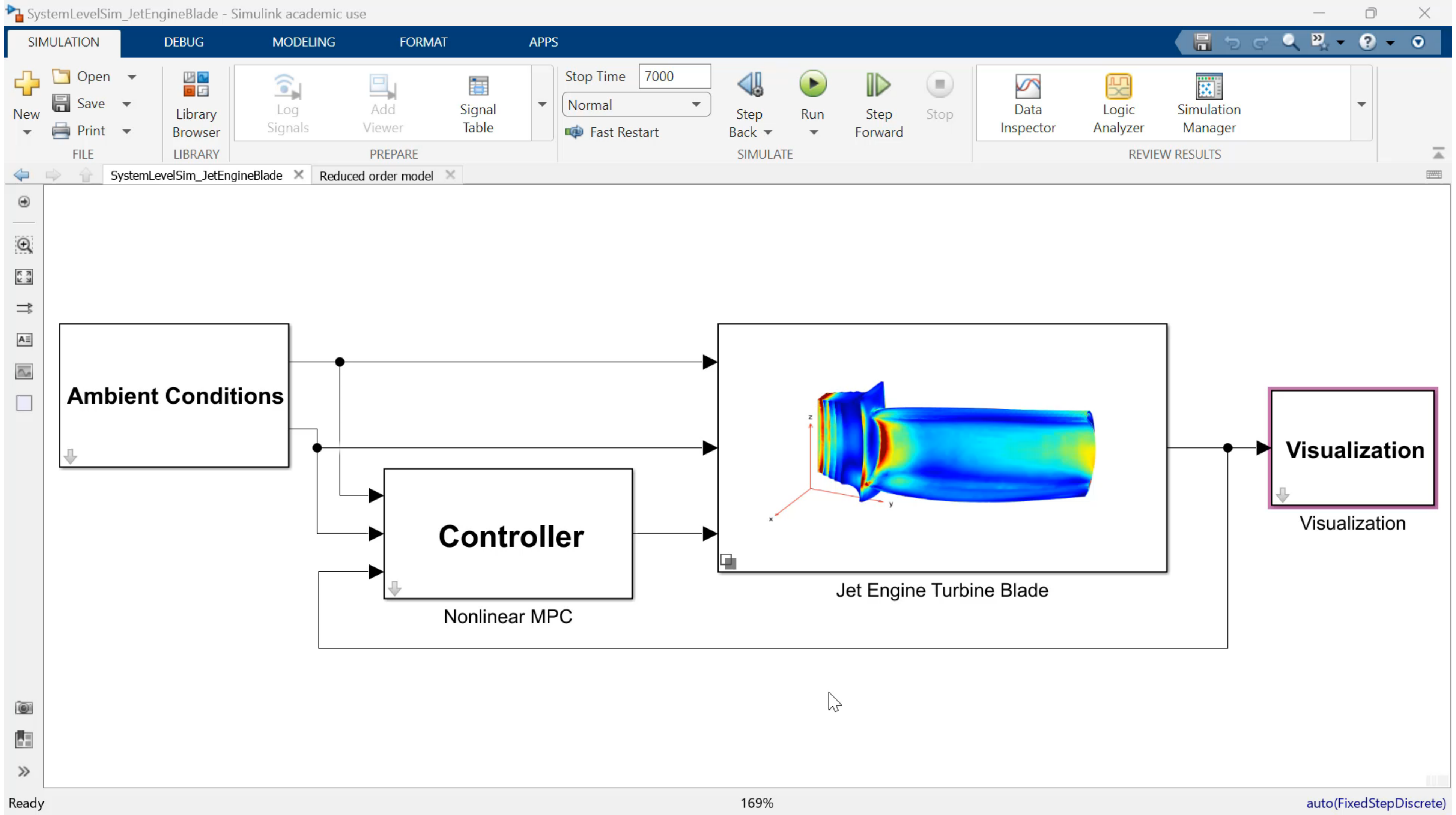
Integration of trained AI models into Simulink

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

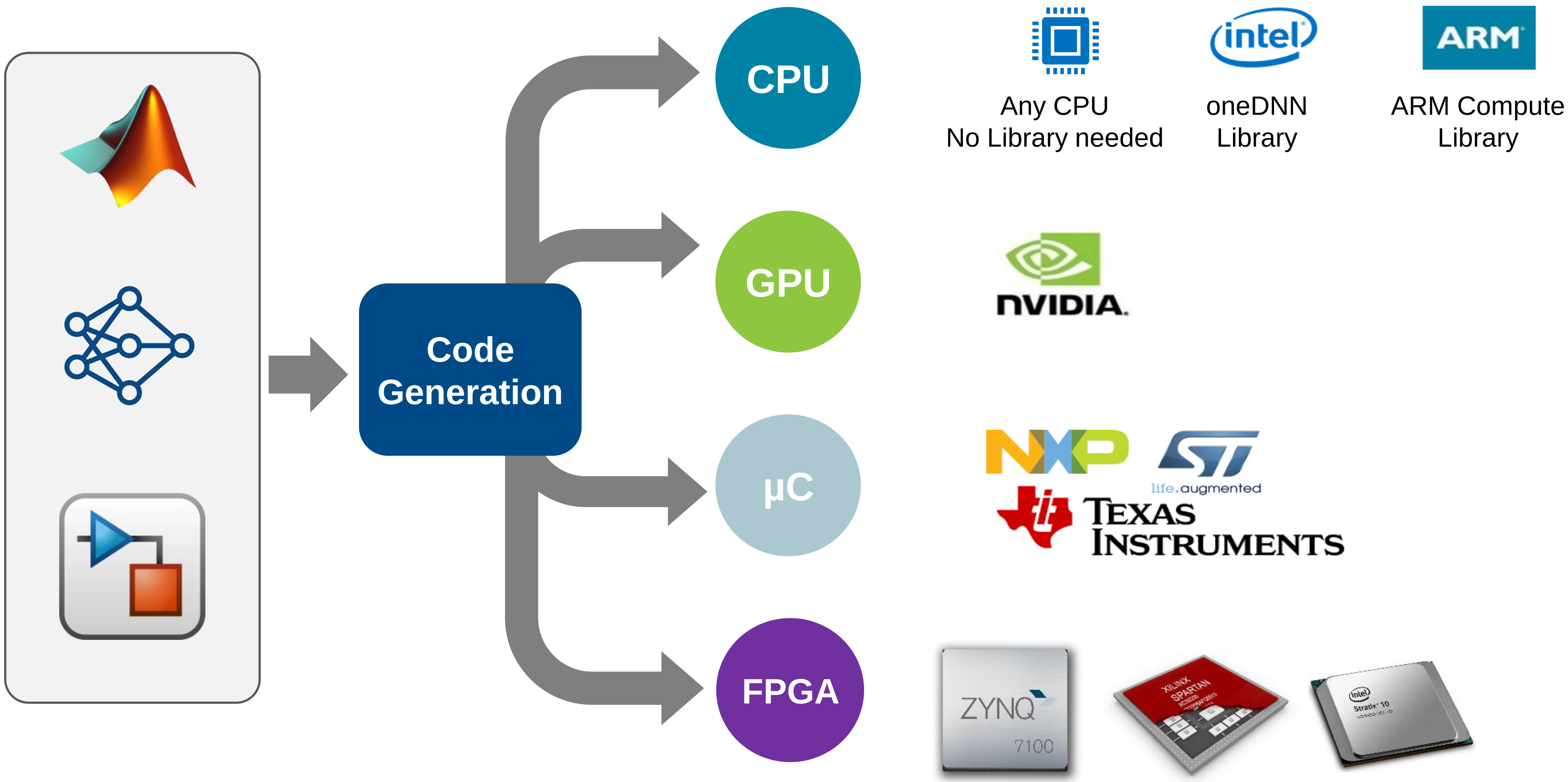
Neural state-space model is approximately 1e6x faster than the FEA model

System-level simulation

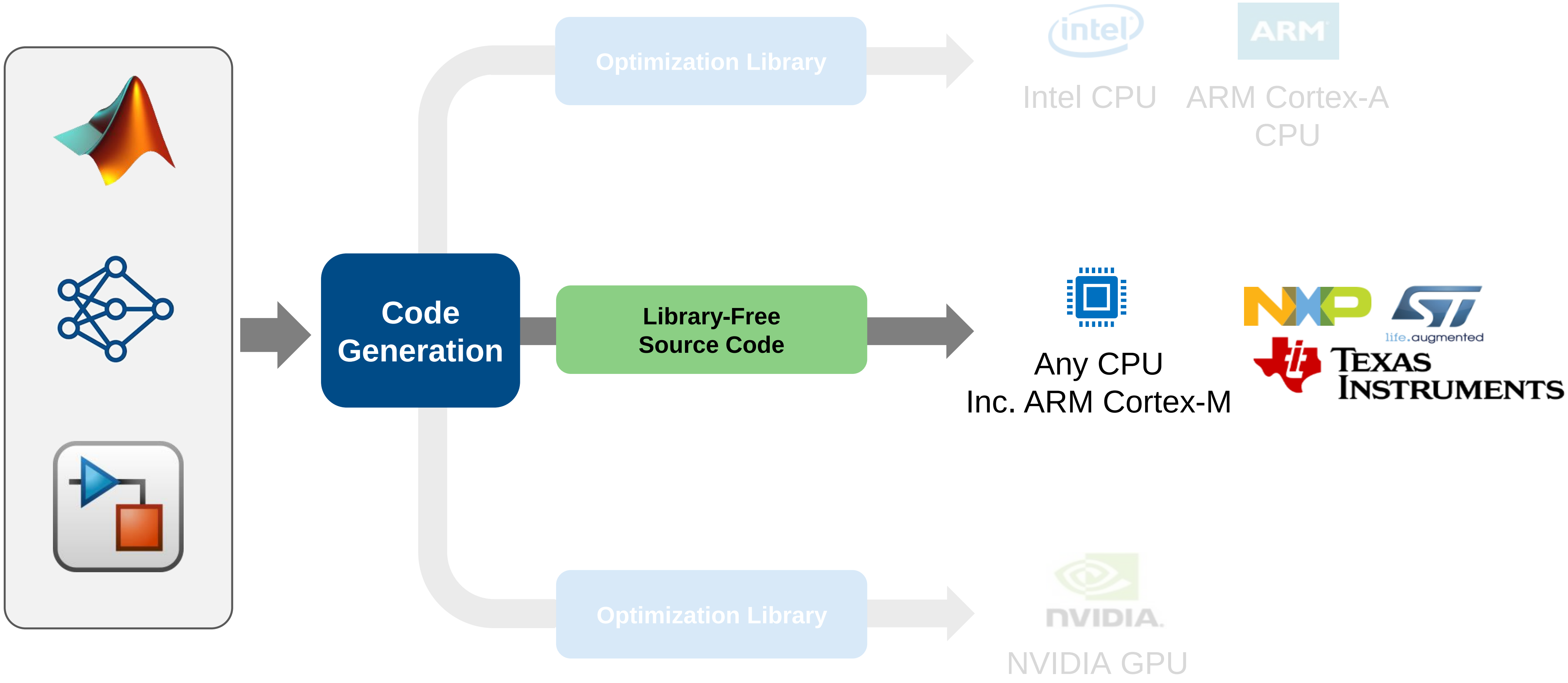


Data Preparation | AI Modeling | **Simulation & Test** | Deployment

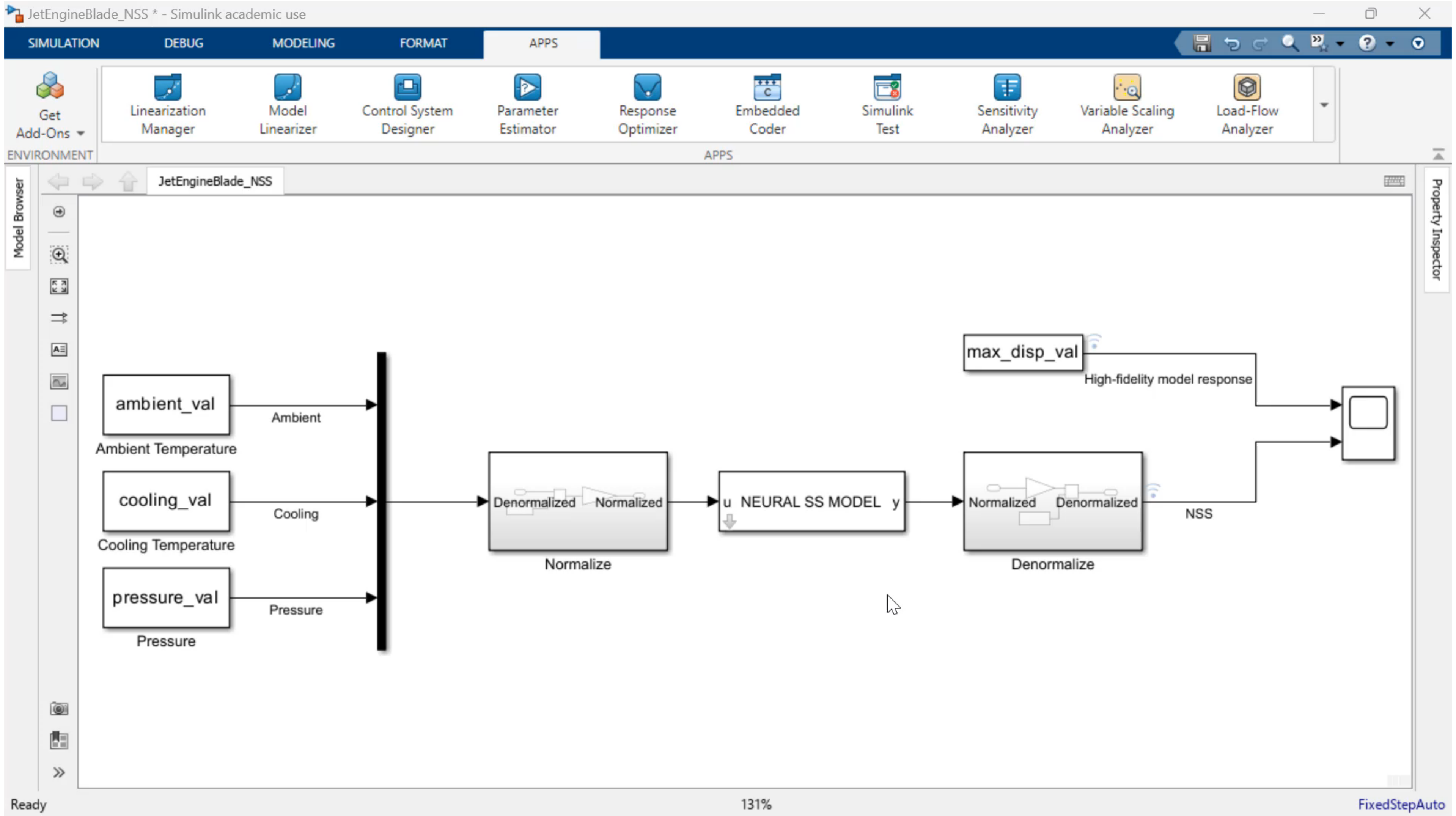
Deploy to target with zero coding errors



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



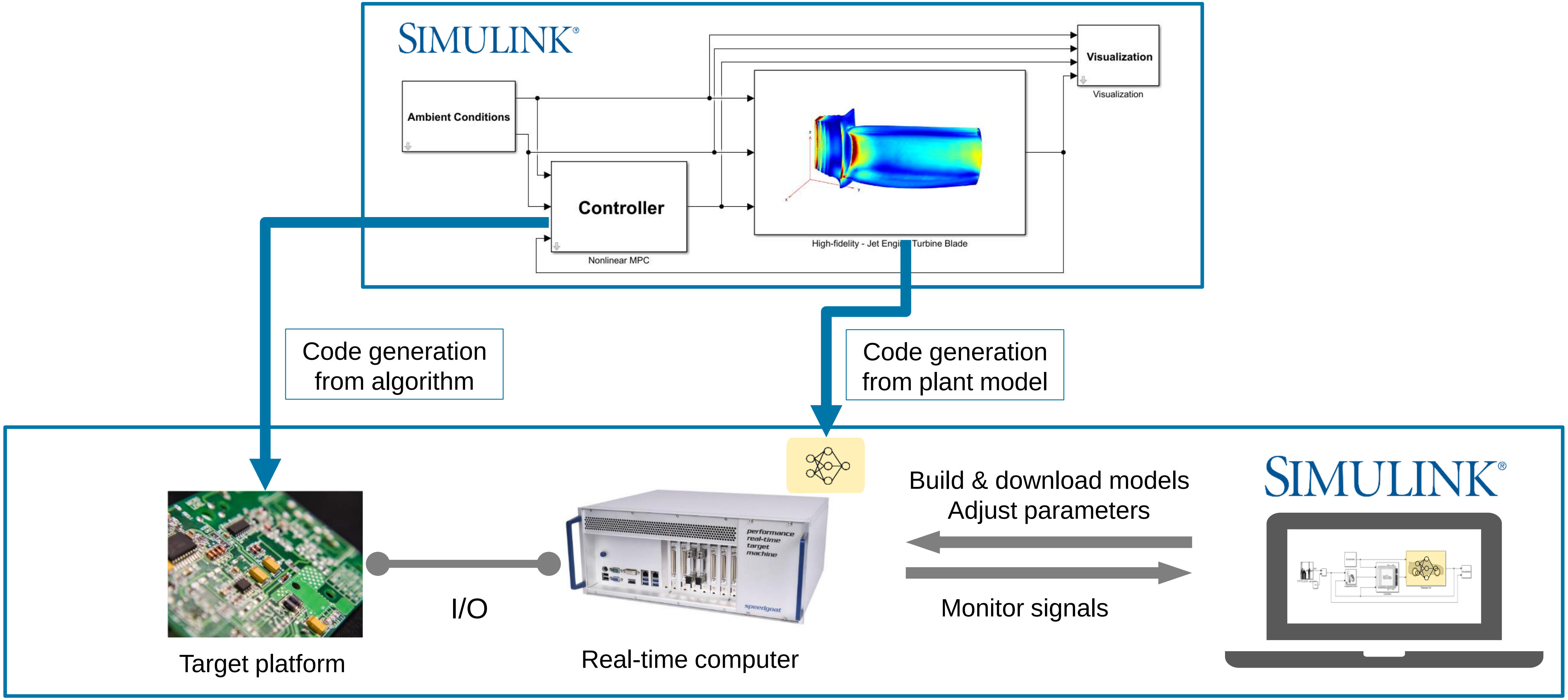
Generate Library-Free C Code for Deep Learning Networks



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

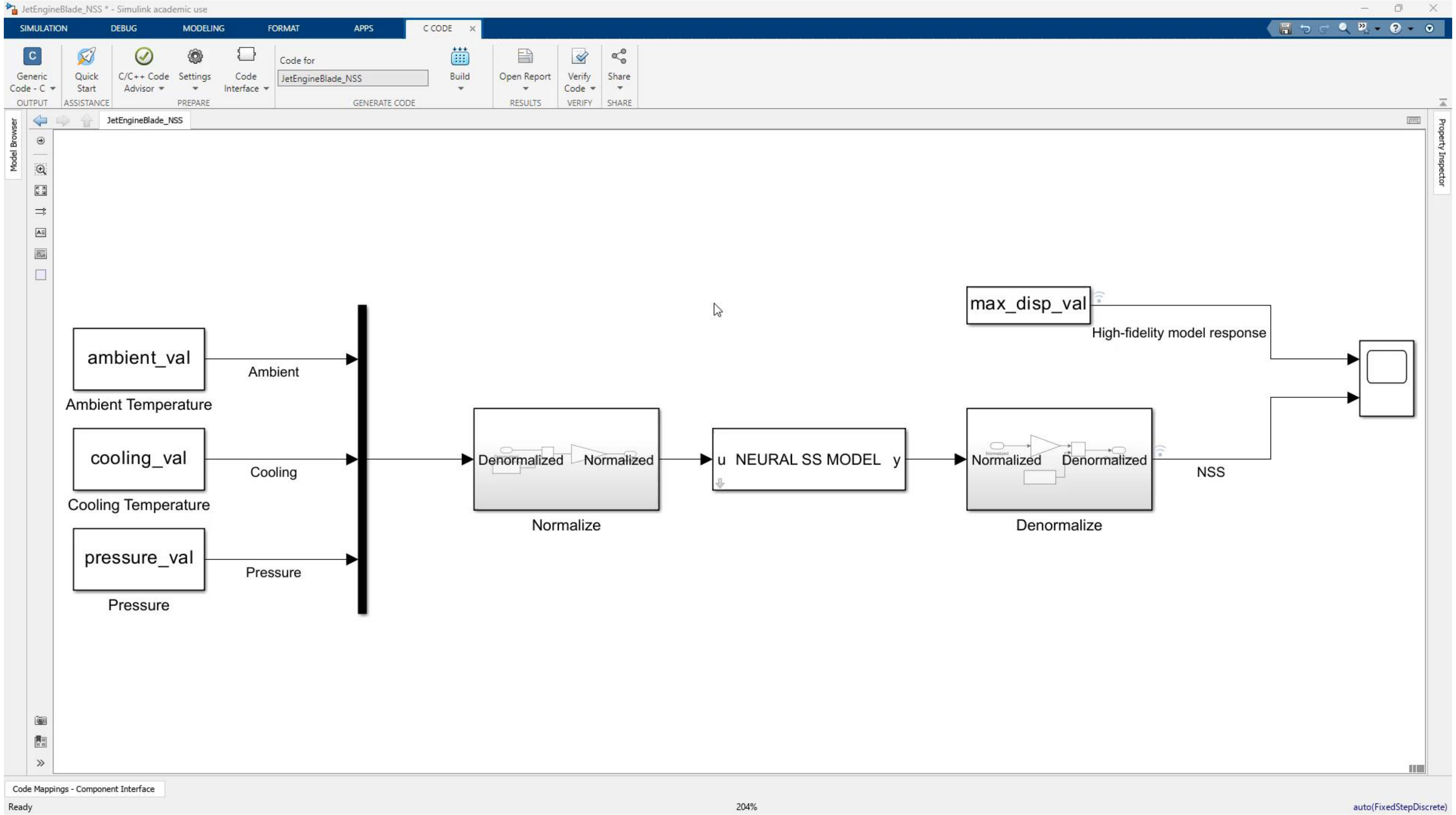
Hardware-in-the-loop simulation

System-level integration and test



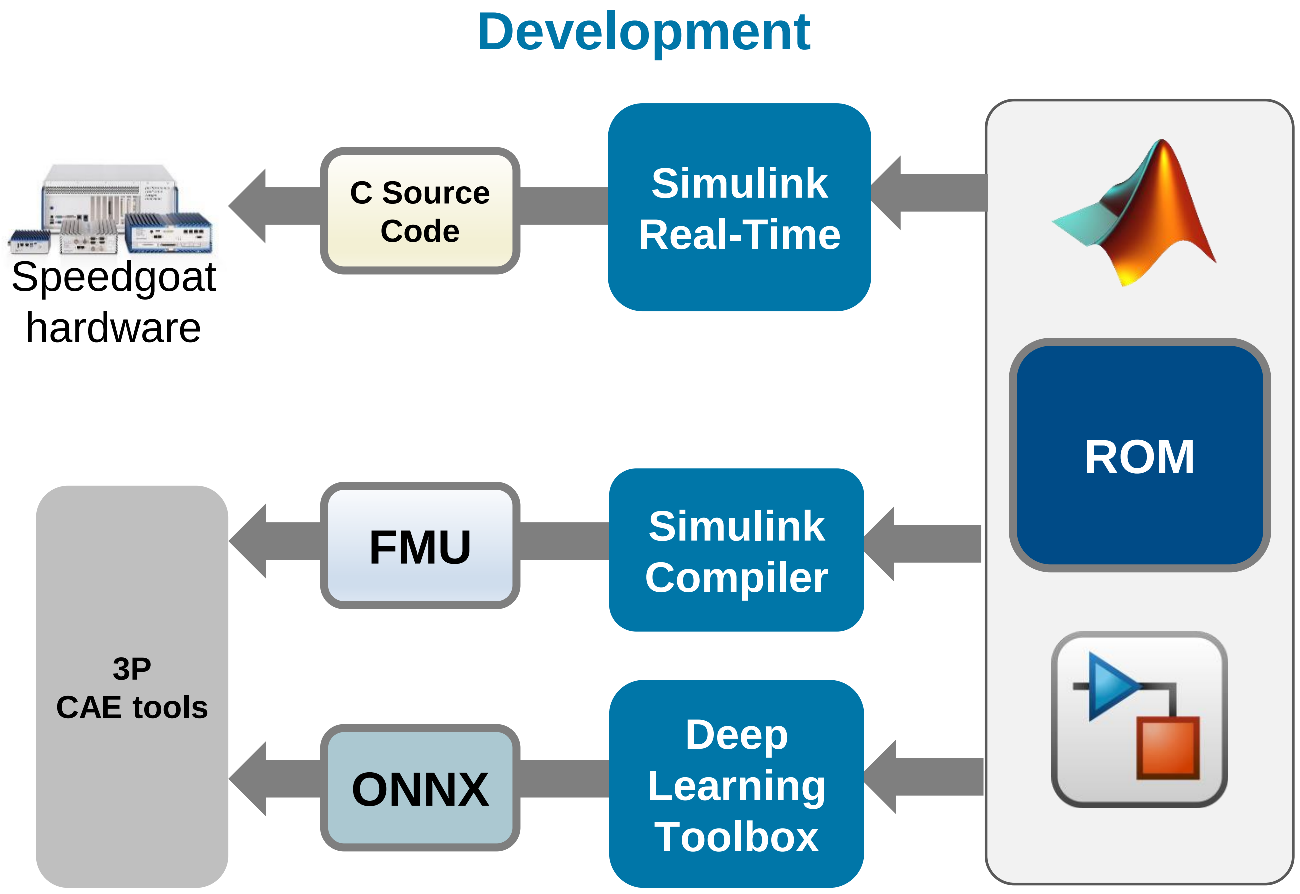
Data Preparation | AI Modeling | Simulation & Test | **Deployment**

Hardware-in-the-loop simulation



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

Use ROMs outside of Simulink for development



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

Manage AI tradeoffs for your system

	LSTM Long Short-Term Memory Network	**Neural State Space** (Neural ODE)
Training Speed	Better	Okay
Interpretability	Worse	Okay
Inference Speed	Okay	Better
Model Size	Okay	Better
Accuracy (RSME)	Better	Better

Results are specific to Jet Engine Blade Example

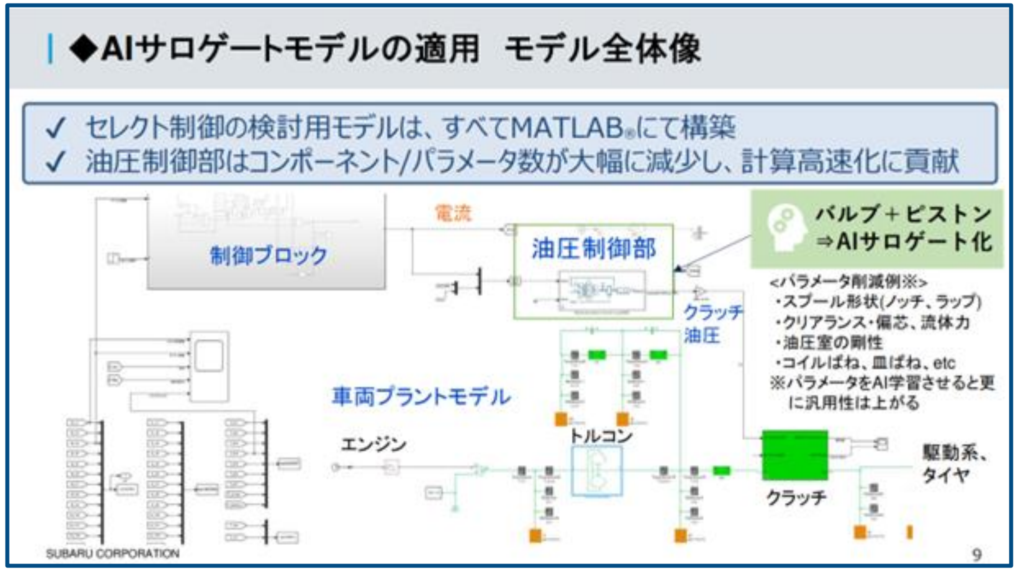
Better ●   Okay ●   Worse ●

SUBARU Uses AI Surrogate Model to Reduce Transmission Control System Analysis Time

Using MATLAB, engineers at Subaru developed a surrogate AI model to optimize transmission hydraulic systems, achieving a 99% reduction in calculation times compared to the original third-party 1D model.

Key Outcomes/Advantages:

- Achieved a 99% reduction in calculation time compared to the original 1D model
- Constructed AI surrogate model in MATLAB that can reproduce waveforms with arbitrary current, oil temperature, and source pressure readings
- Accurately reproduced waveforms, even in oil temperature ranges where the model has not been trained



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

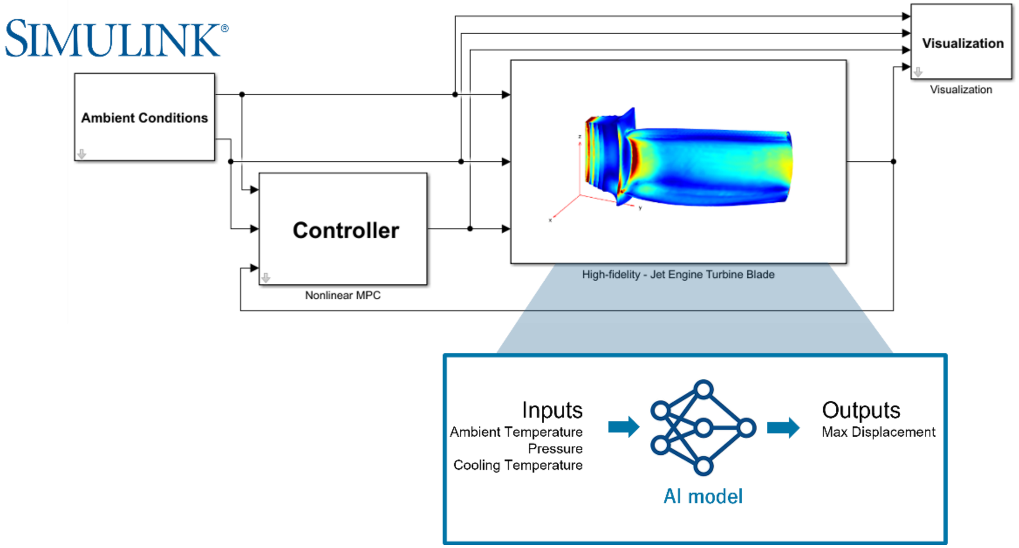
The AI model can now reproduce waveforms at any source pressure, oil temperature, and current. The calculation time can be significantly reduced while ensuring the accuracy of hydraulic waveforms.

[Link to user story]

Key Takeaways

Enable	Reuse of full-order high-fidelity models for system-level simulations, Hardware-in-the-Loop (HIL) testing, nonlinear control design, and virtual sensor modeling
Explore	Various ROM techniques in MATLAB to find the best method.

- **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**



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