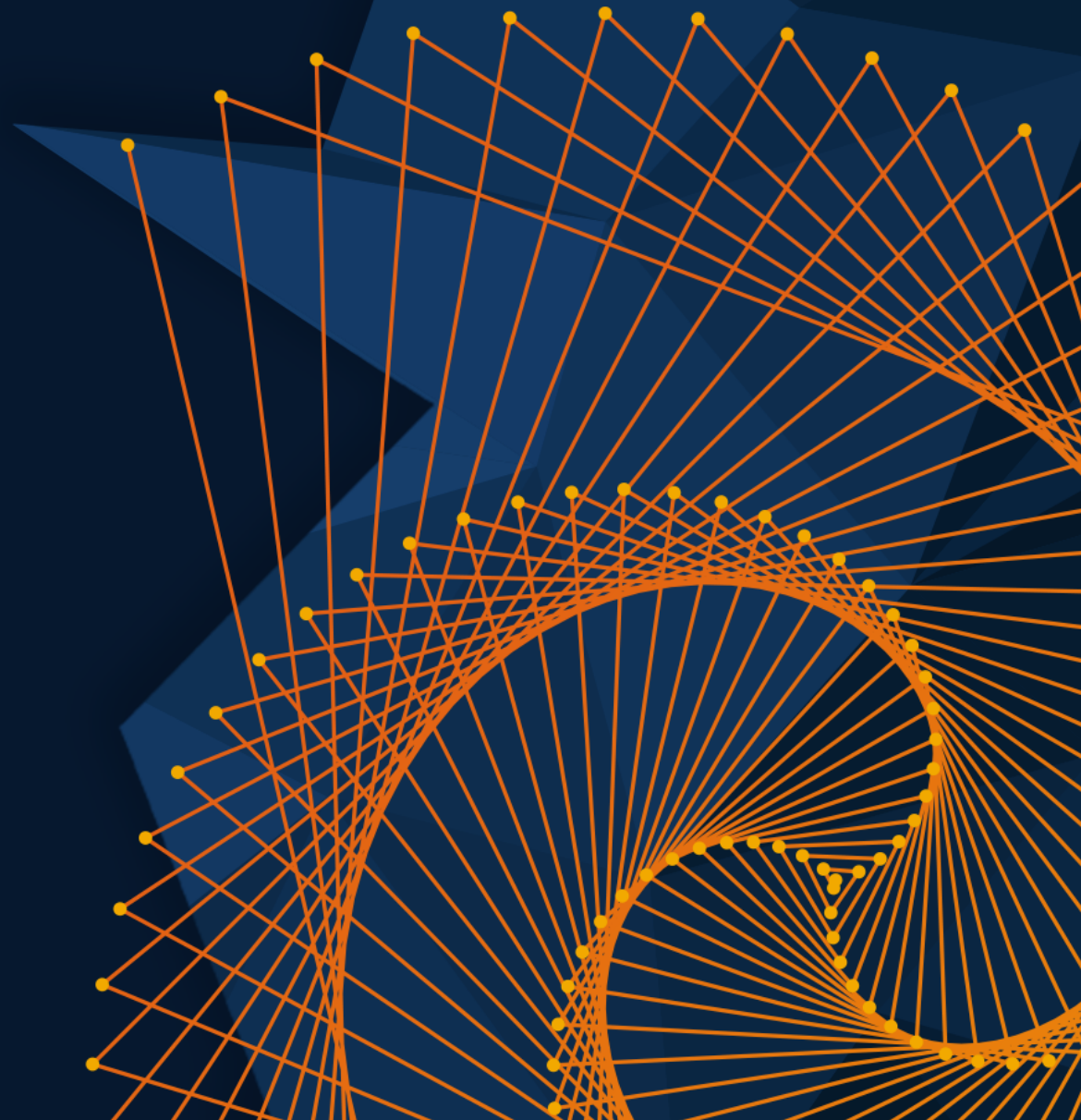
MATLAB EXPO

AI 기반 차수 축소 모델링

엄준상, 김종남 MathWorks

MathWorks



SIMULATION DEBUG MODELING FORMAT APPS VARIANT SUBSYSTEM

New Open Save Print FILE

Library Browser LIBRARY

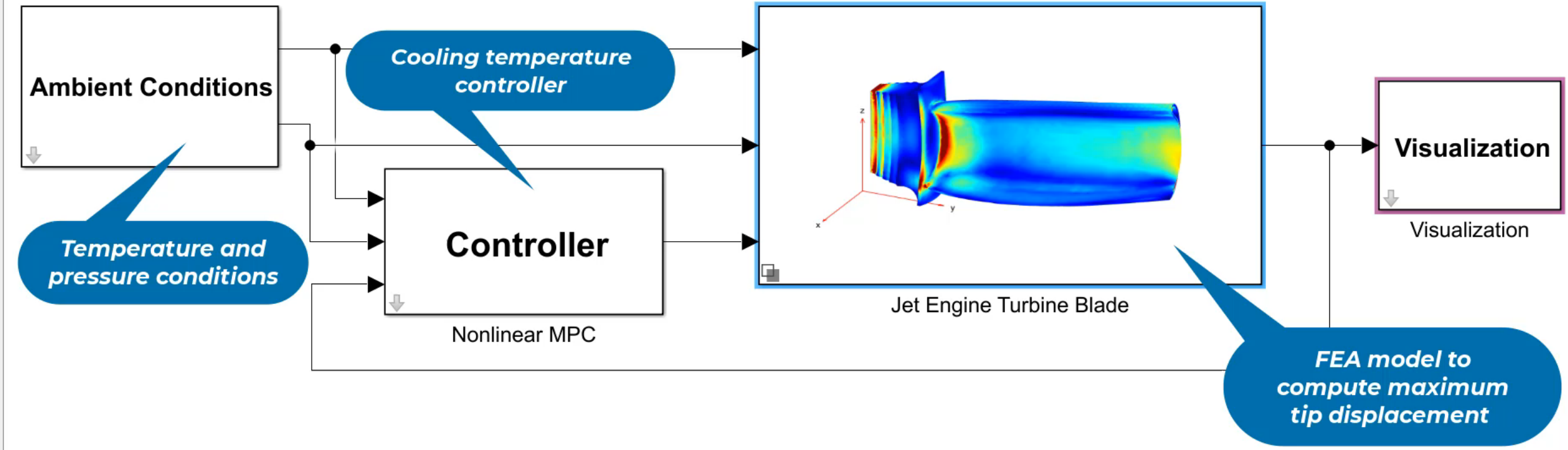
Log Signals Add Viewer Signal Table PREPARE

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



Ready 169% auto(FixedStepDiscrete)

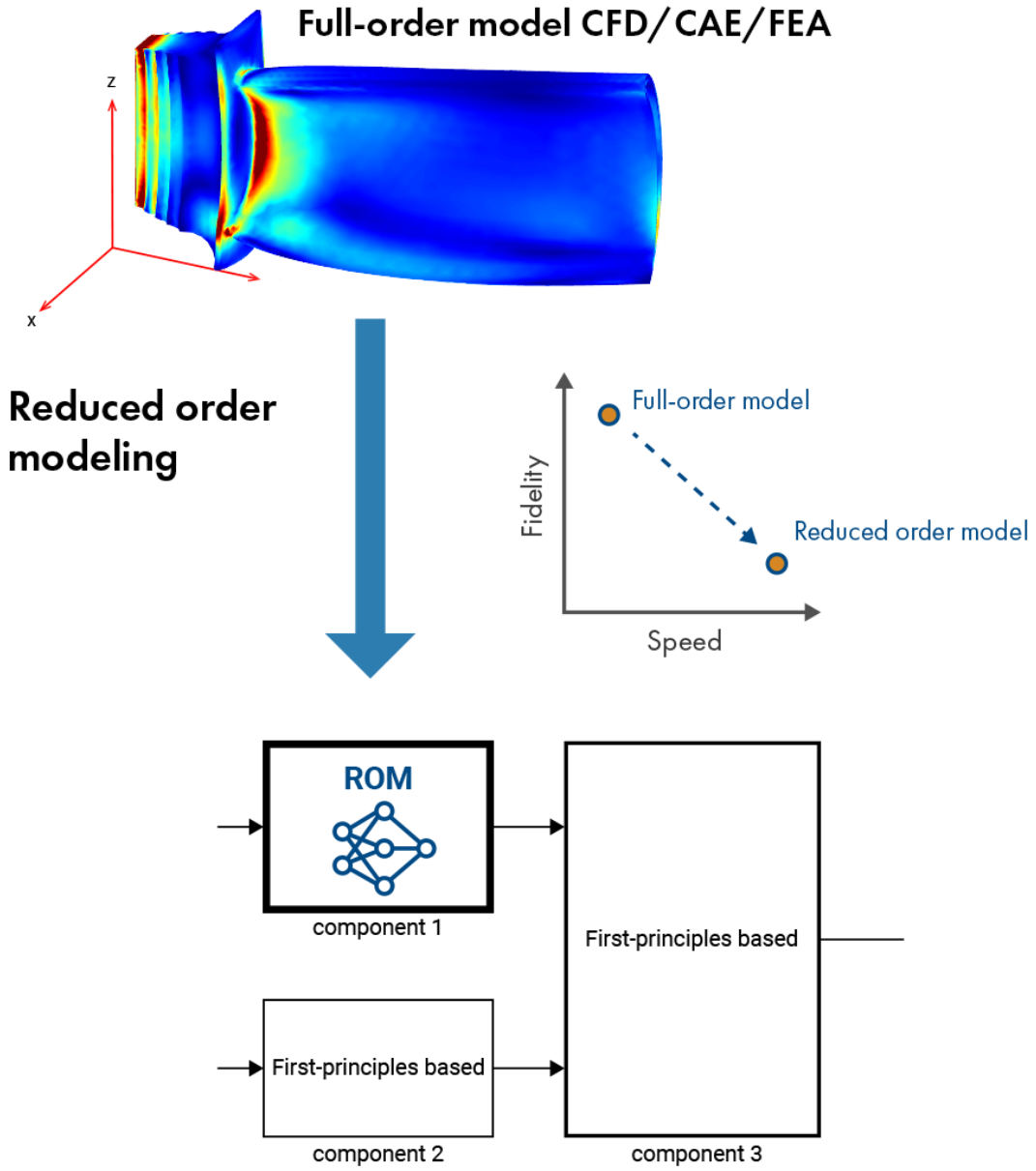
Reduced Order Modeling

What

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

Why

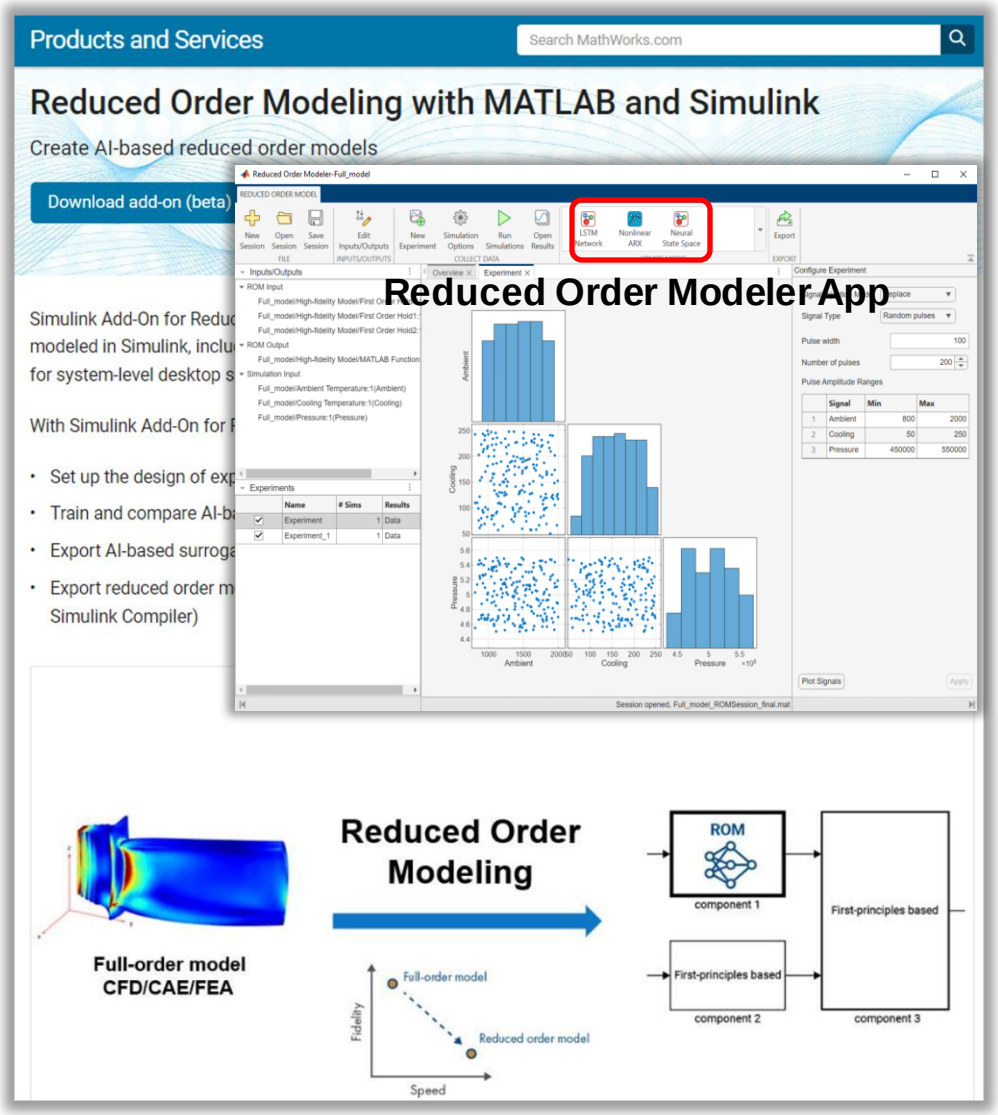
- Enable simulation of FEA models in Simulink
- Perform hardware-in-the-loop testing
- Perform control design
- Develop virtual sensors, Digital twins
- Enable desktop simulations for orders-of-magnitude longer timescales



Introducing Simulink Add-On for Reduced Order Modeling

Create AI-based reduced order models (ROM)

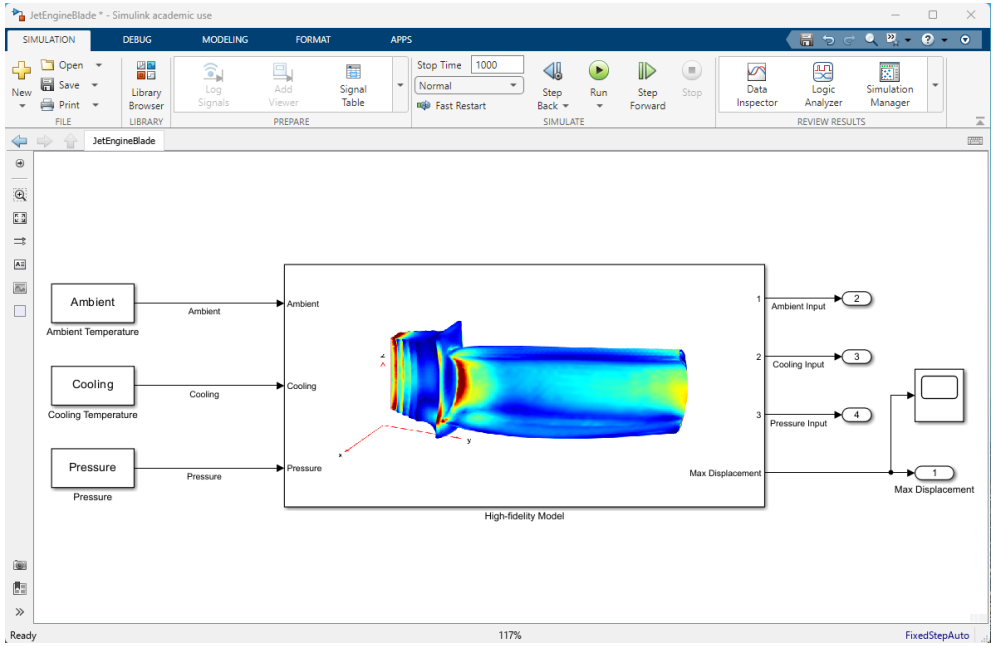
- **Set up Design of Experiments (DoE)**
- **Generate input-output data from full-order, high-fidelity subsystems**
- **Train and compare AI-based reduced order models using preconfigured templates**
- **Export trained reduced order models into Simulink or outside of Simulink through FMUs**



[Reduced Order Modeling with MATLAB and Simulink]

Generate data for training

Physical system

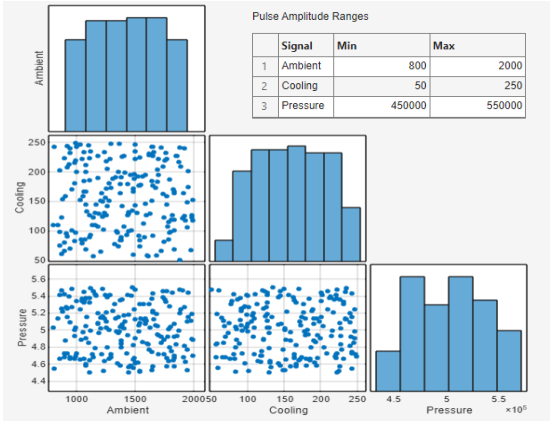


Simulink/Simscape

Data Preparation | AI Modeling | Simulation & Test | Deployment

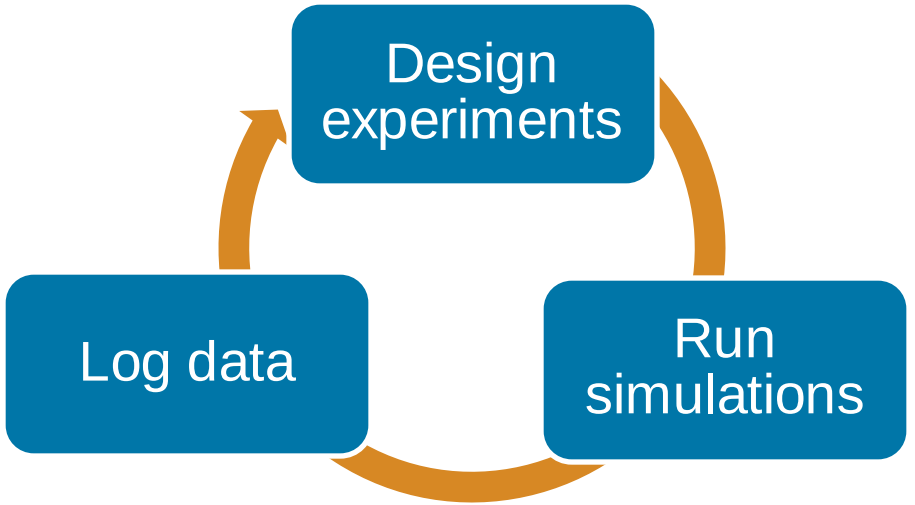
Synthetic Data Generation

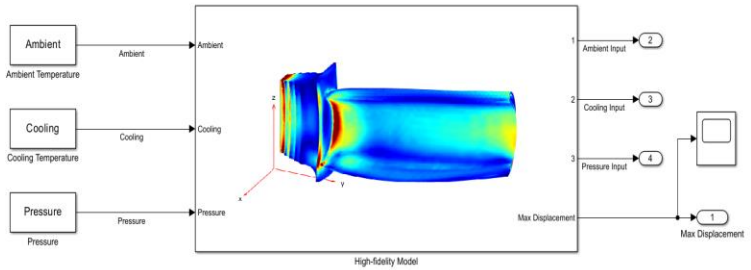
Design of Experiments



Input features
Ambient Temperature
Ambient Pressure
Cooling Temperature

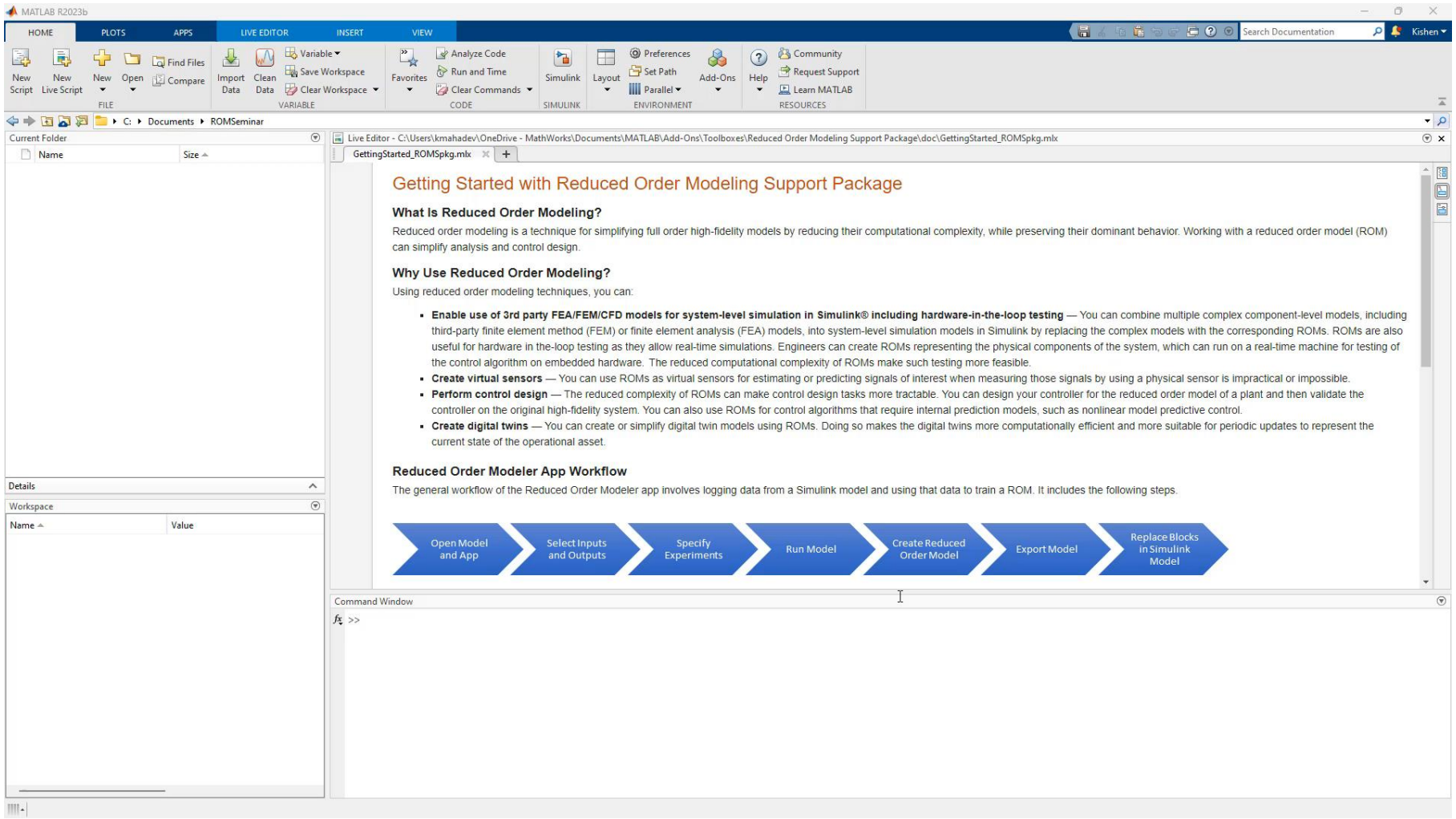
Response
Max Displacement





Synthetic Data Generation

Design of Experiments



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)

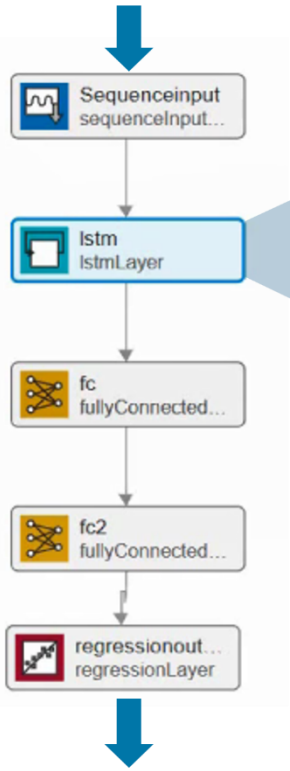
Experiments

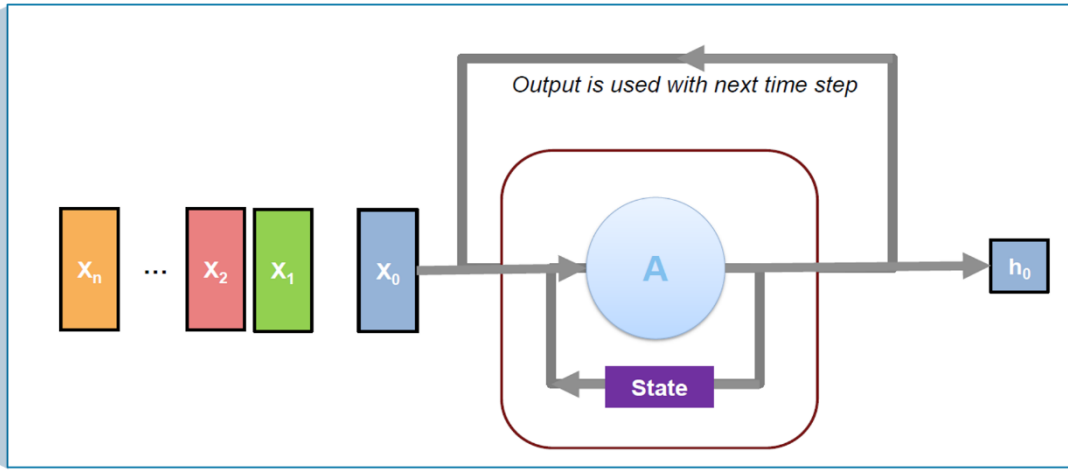
	Name	# Sims	Results
☑	Experiment	1	Data
☑	Experiment_1	1	Data

Result: Experiment_1

Inputs

- Ambient Temperature
- Cooling Temperature
- Pressure





AI-based ROM using LSTMs

Capture time dependencies in time-series data

Outputs

- Max Displacement

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)
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Experiments

	Name	# Sims	Results
☑	Experiment	1	Data
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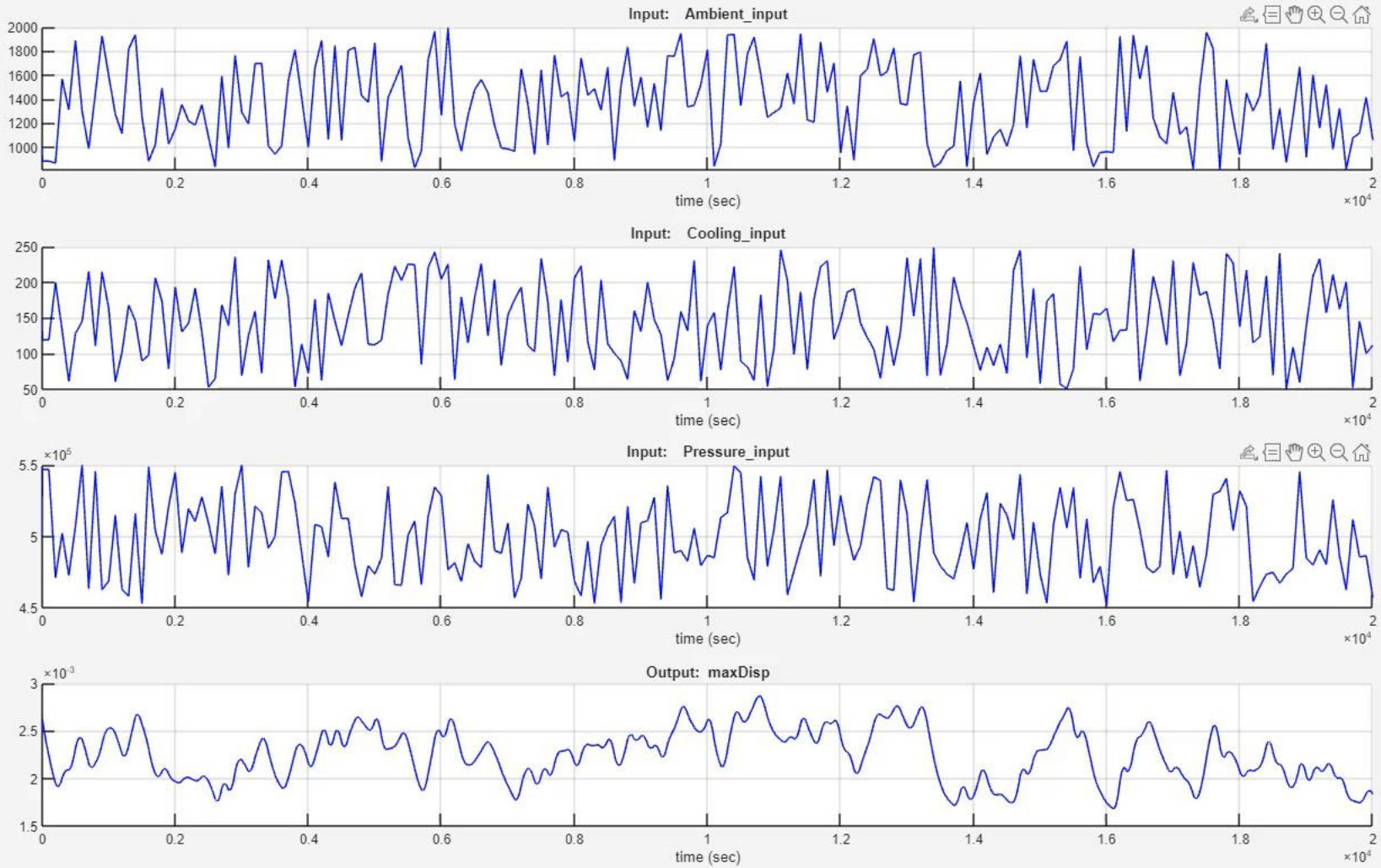
Overview | Result: Experiment | Result: Experiment_1 | Experiment_1



Session opened, engineBlade_ROMsession_results.mat

Reduced Order Modeler-JetEngineBlade

REDUCED ORDER MODEL | SIMULATION RESULT

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

FILE | INPUTS/OUTPUTS | COLLECT DATA | EXPORT

Inputs/Outputs

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Experiments

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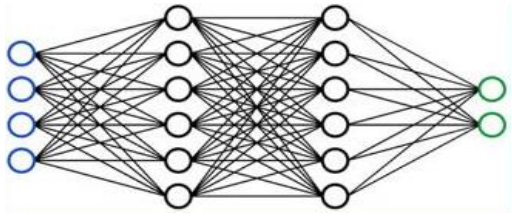
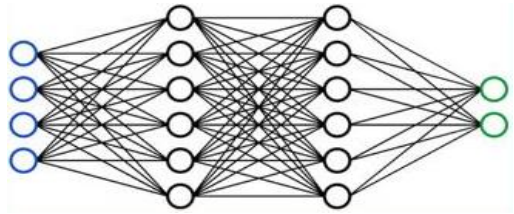
☑	Experiment_1	1	Data

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

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  - JetEngineBlade/Cooling Temperature:1(Cooling)
  - JetEngineBlade/Pressure:1(Pressure)

Experiments

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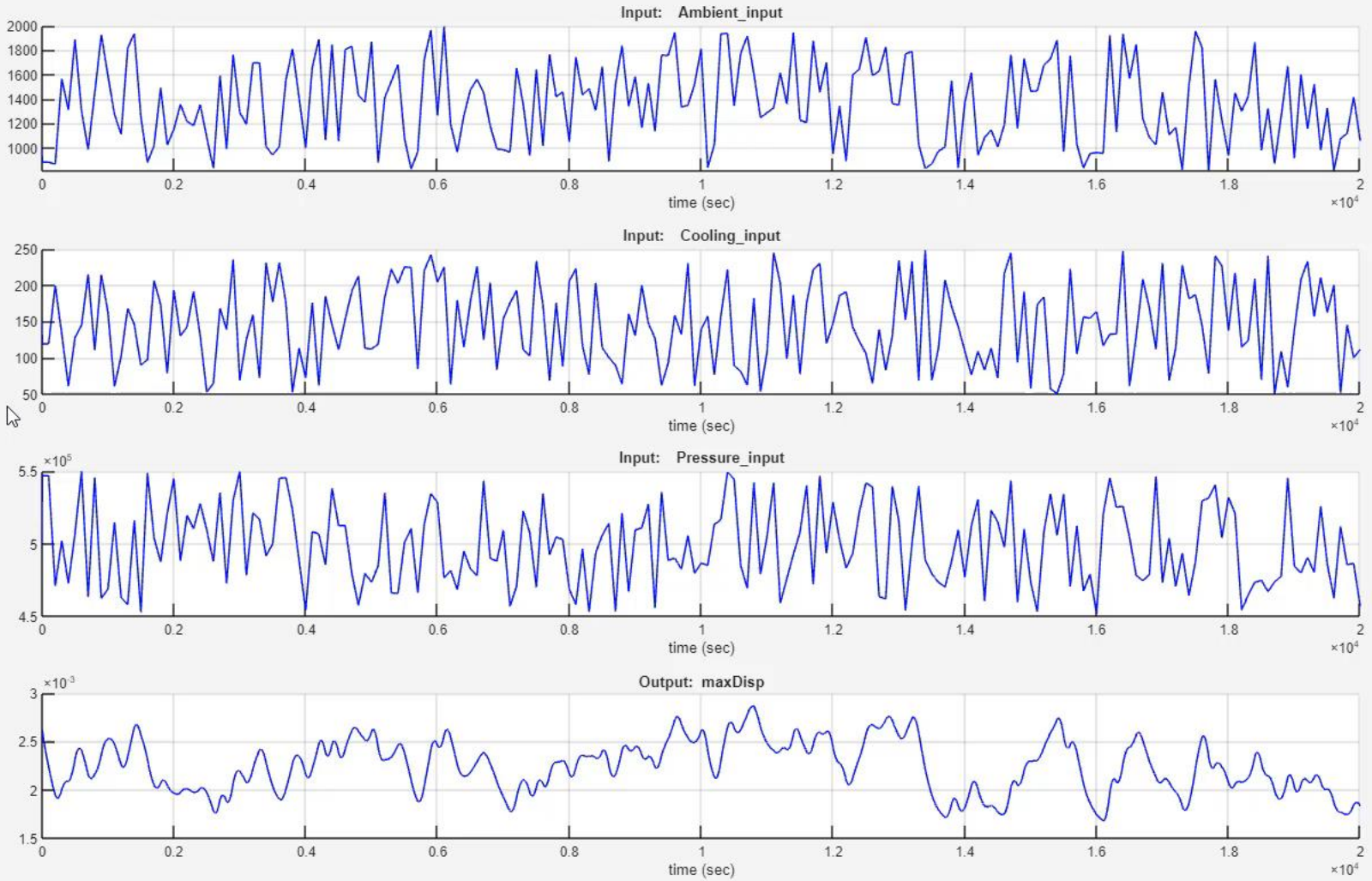
Overview | Result: Experiment | Result: Experiment_1 | Experiment_1



Session opened, engineBlade_ROMsession_results.mat

Reduced Order Modeler-JetEngineBlade

REDUCED ORDER MODEL | SIMULATION RESULT

New Session | Open Session | Save Session | 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

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  - JetEngineBlade/Ambient Temperature:1(Ambient)
  - JetEngineBlade/Cooling Temperature:1(Cooling)
  - JetEngineBlade/Pressure:1(Pressure)

Experiments

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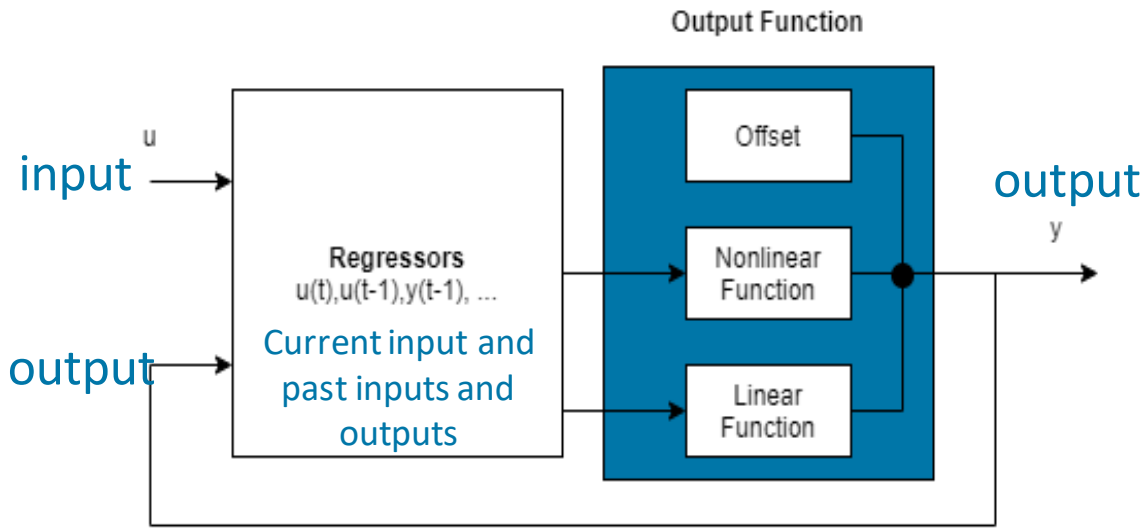


AI-based ROM using Nonlinear ARX

Extend linear models and model nonlinear behavior using flexible nonlinear functions

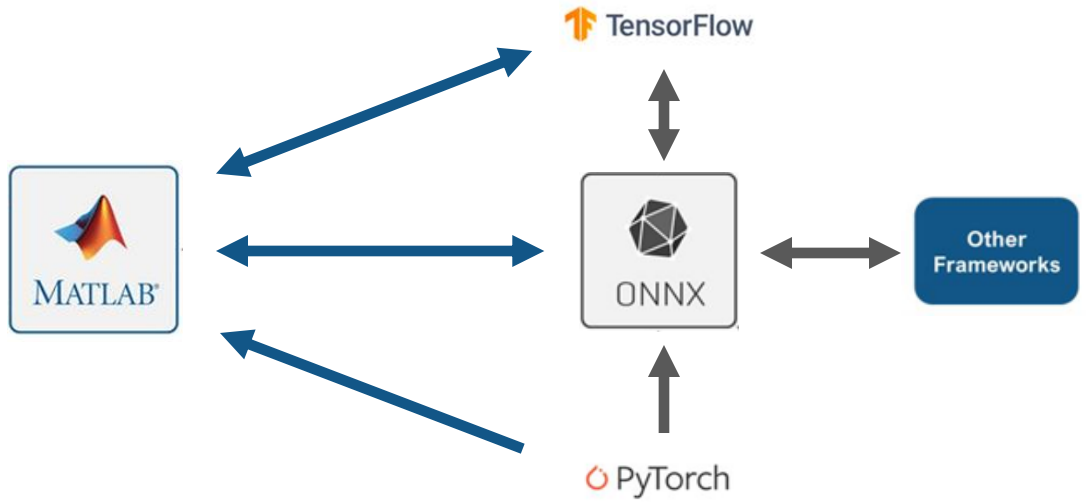
Data Preparation | **AI Modeling** | Simulation & Test | Deployment

Session opened, engineBlade_ROMsession_results.mat

MATLAB interoperates with other frameworks

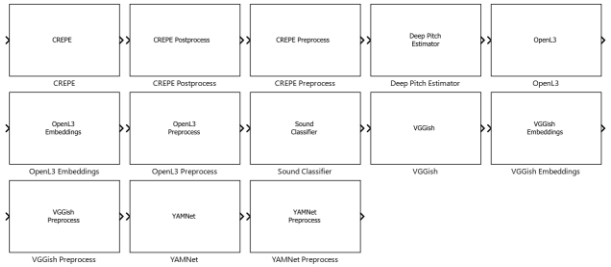
Framework interoperability bridges the gap between data science, engineering and production

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

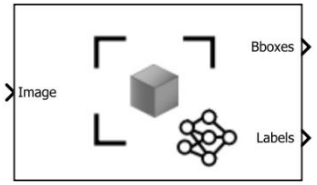


AI libraries in Simulink are expanding to include more AI blocks for more applications

Specialized

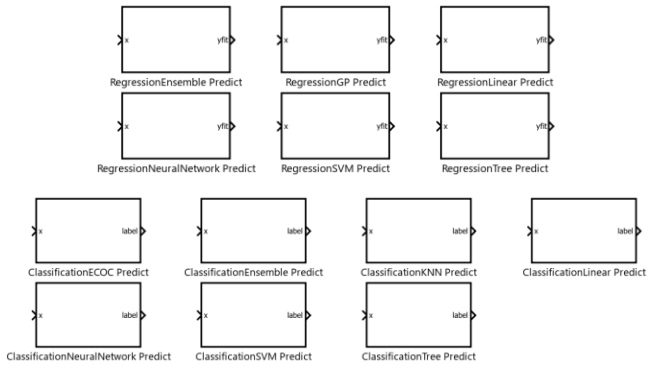


Audio Toolbox

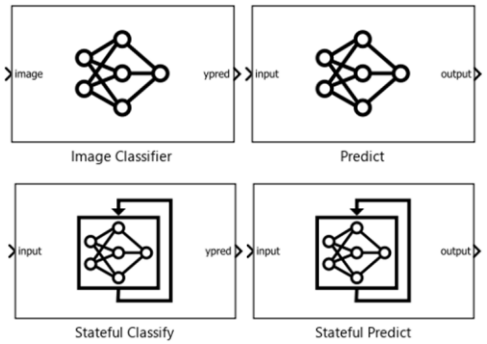


Computer Vision Toolbox

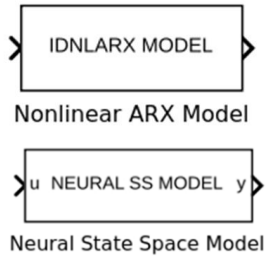
AI Core



Statistics and Machine Learning Toolbox



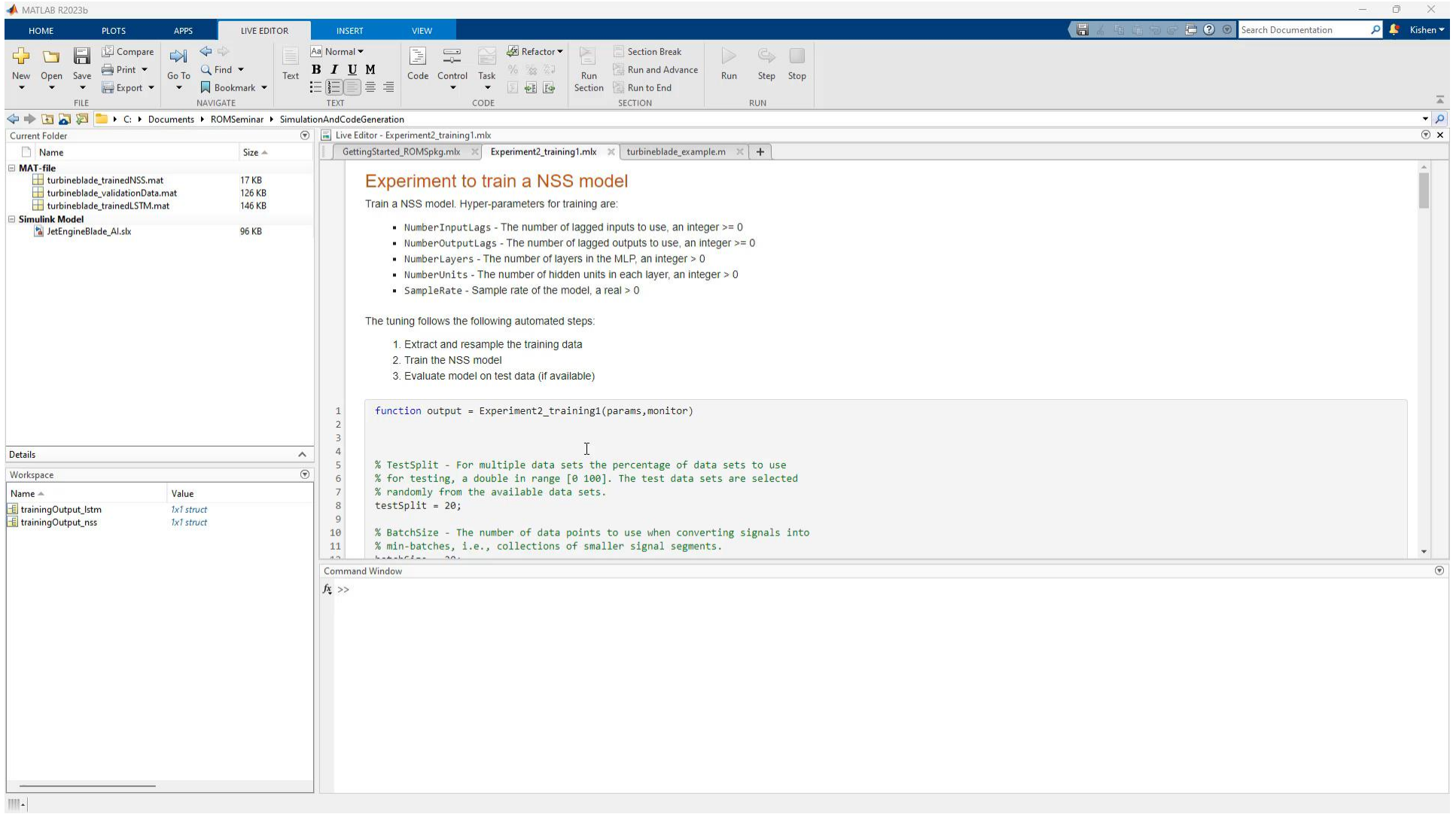
Deep Learning Toolbox



System Identification Toolbox

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

Integration of trained AI models into Simulink



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

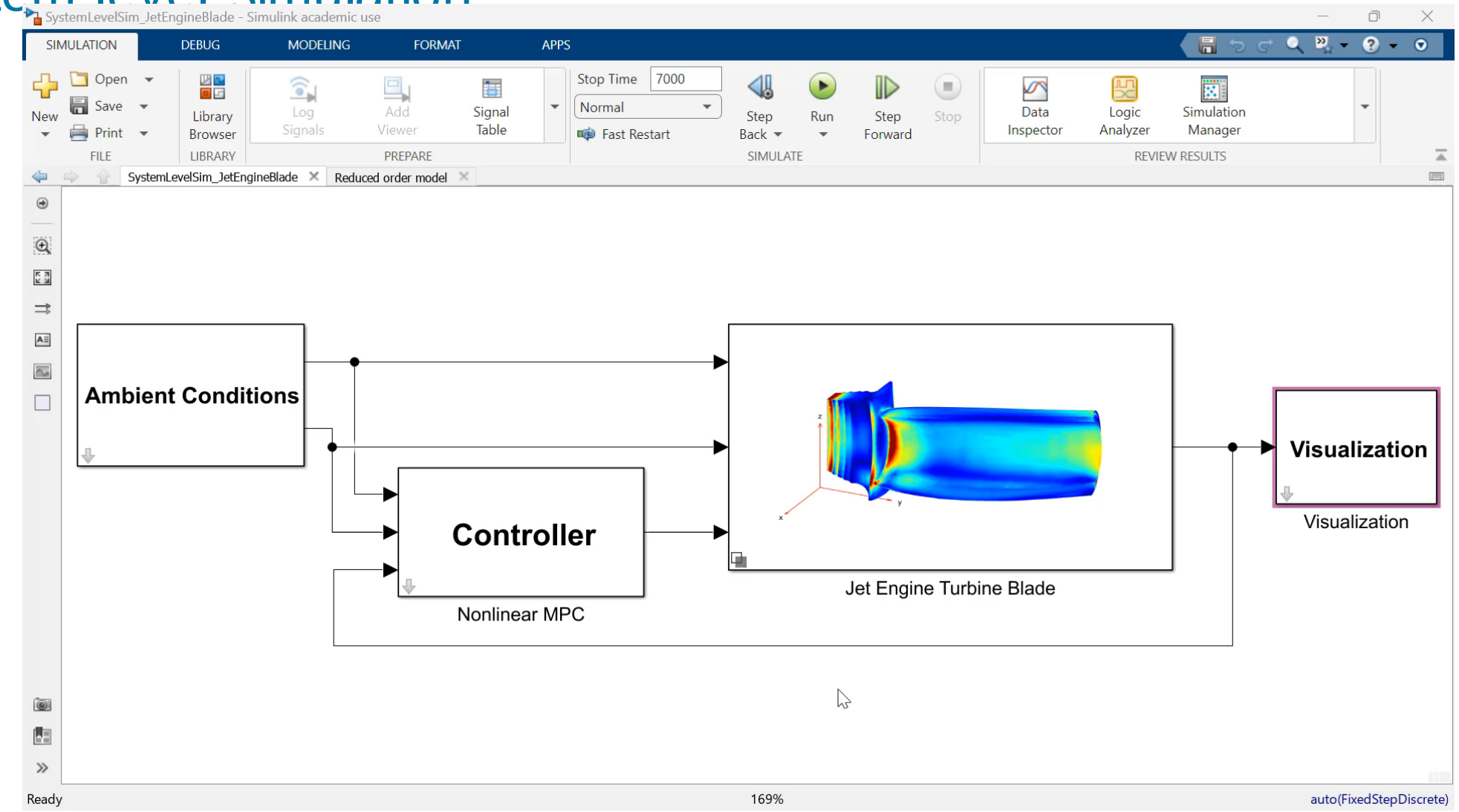
Integration of trained AI models into Simulink

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

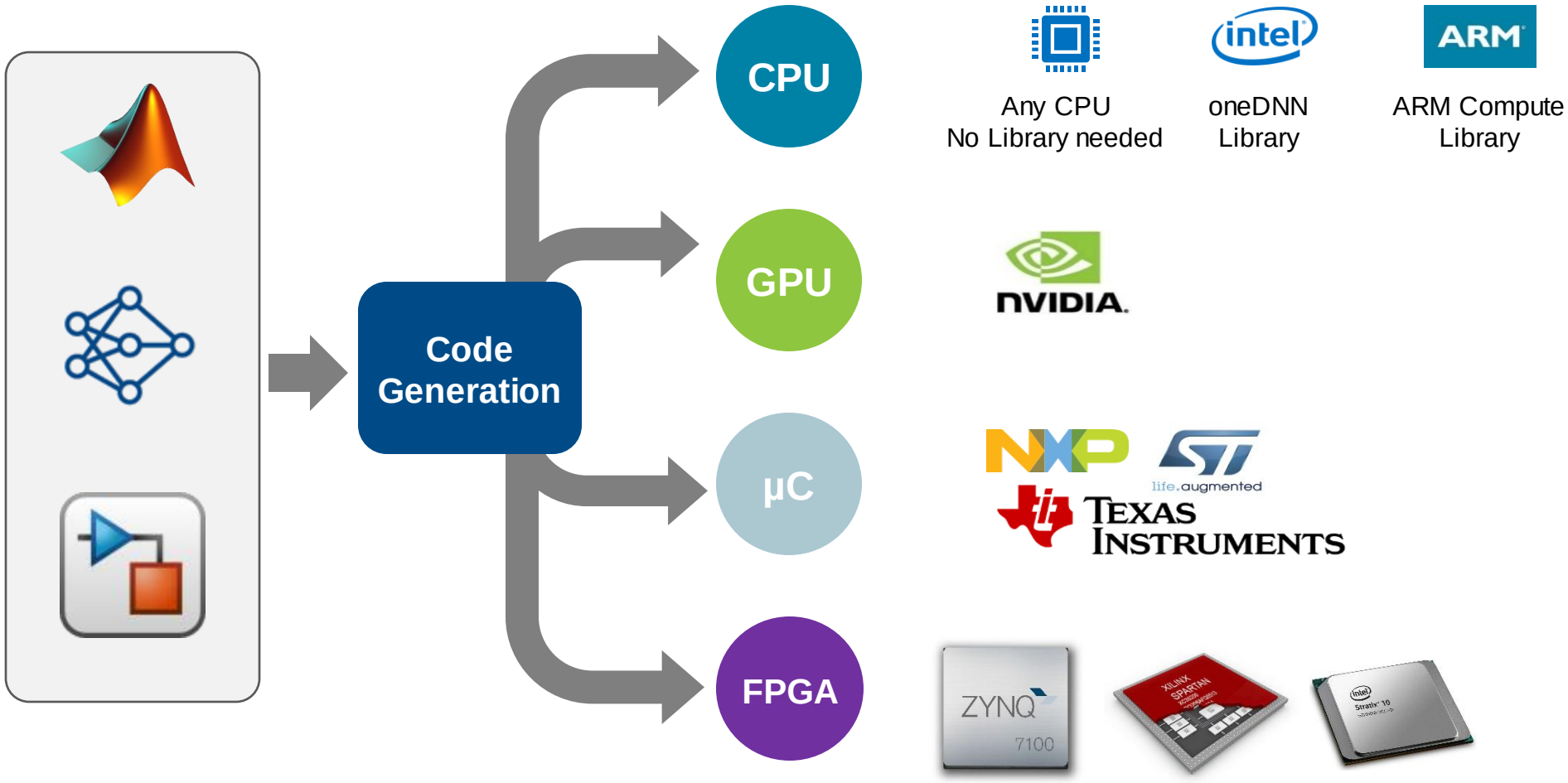
Neural state-space model is approximately 1e6x faster than the FEA model

System-level simulation



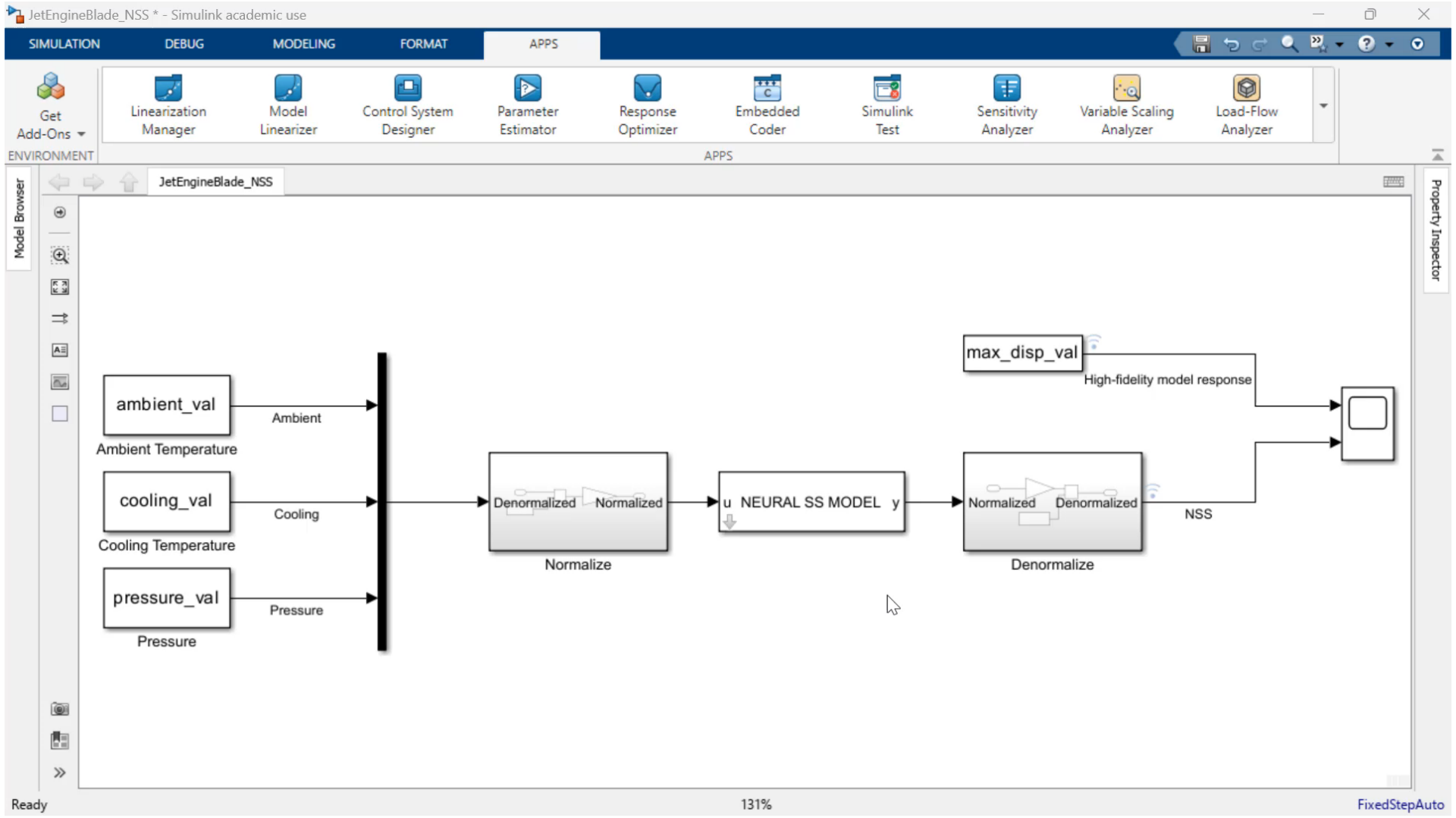
Data Preparation | AI Modeling | Simulation & Test | Deployment

Deploy to target with zero coding errors



Data Preparation | AI Modeling | Simulation & Test | Deployment

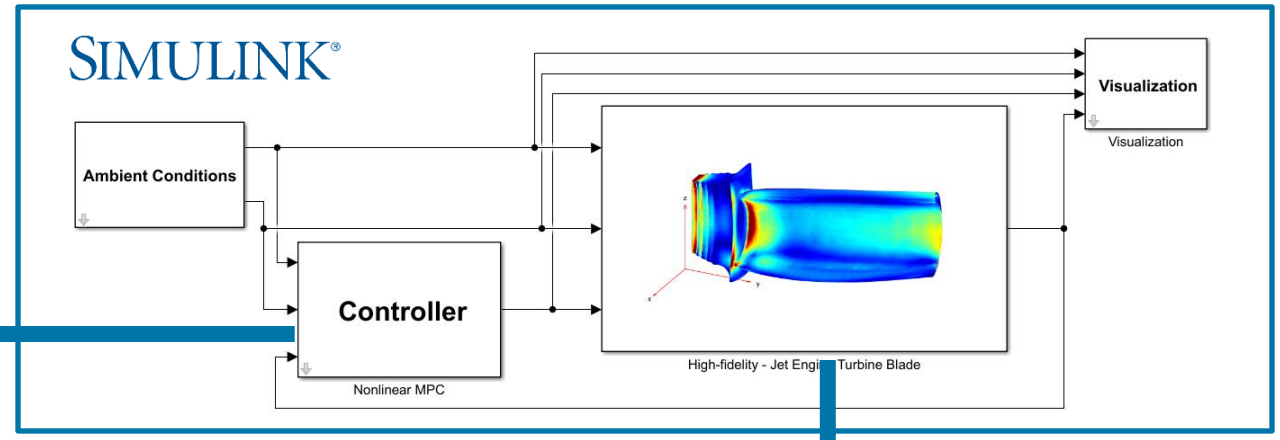
Generate Library-Free C Code for Deep Learning Networks



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

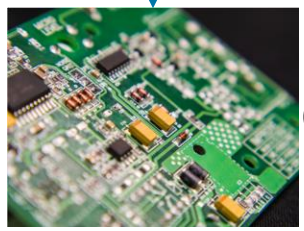
Hardware-in-the-loop simulation

System-level integration and test



Code generation from algorithm

Code generation from plant model



Target platform

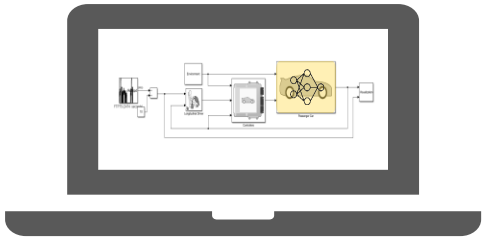
I/O

Real-time computer

Build & download models
Adjust parameters

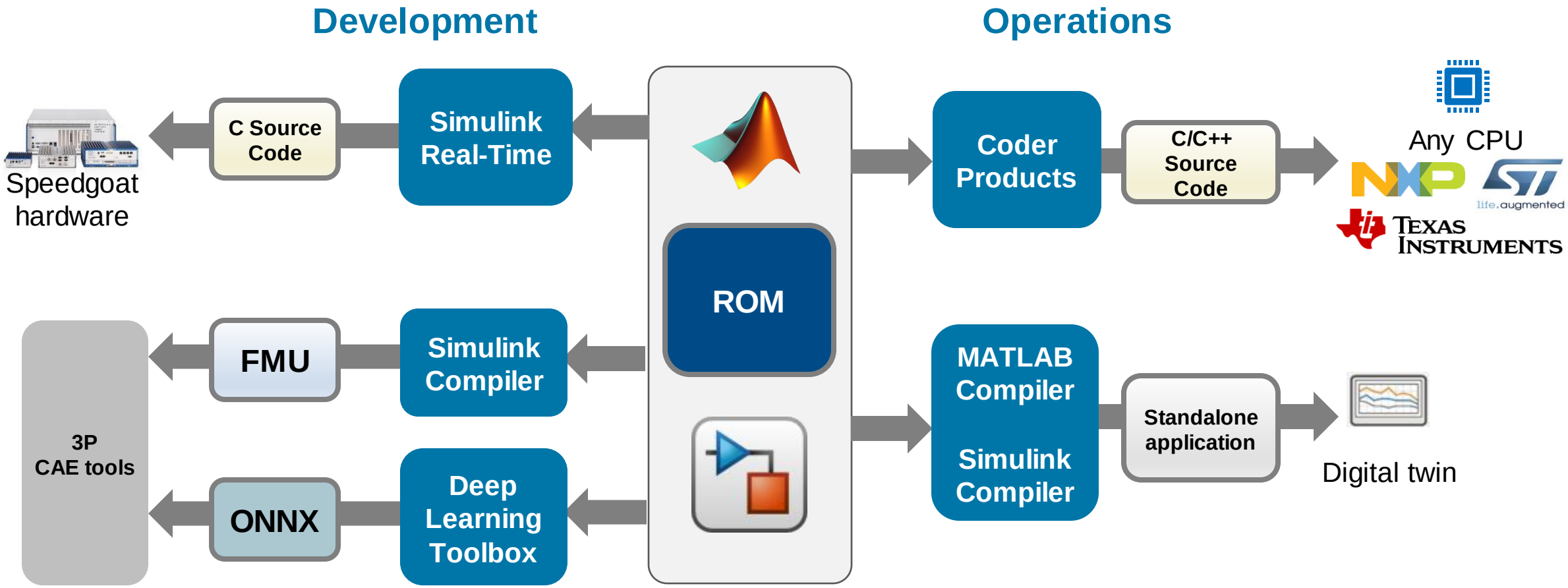
Monitor signals

SIMULINK



Data Preparation | AI Modeling | Simulation & Test | Deployment

Use ROMs outside of Simulink, for development and operation stages



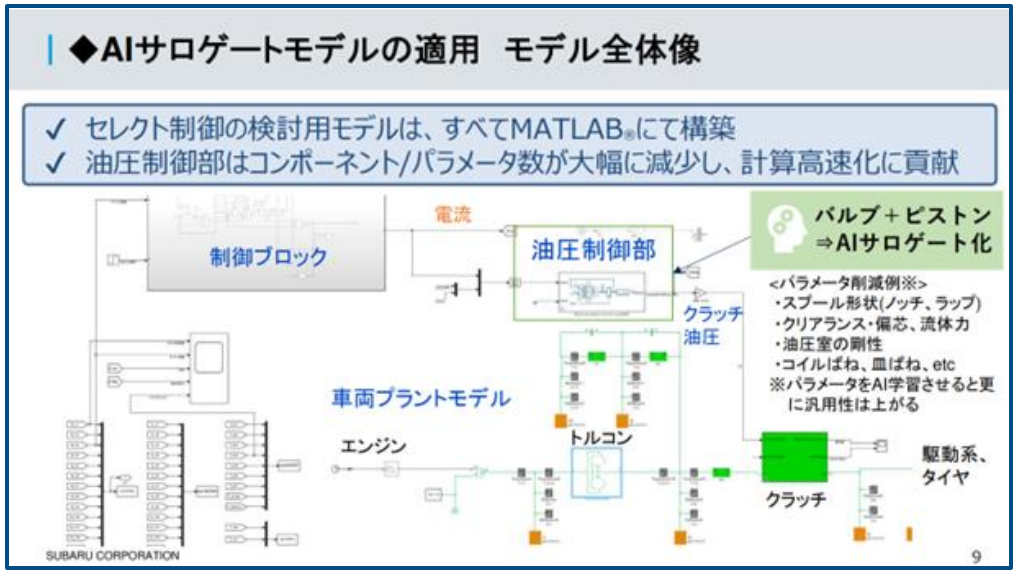
Data Preparation | AI Modeling | Simulation & Test | Deployment

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

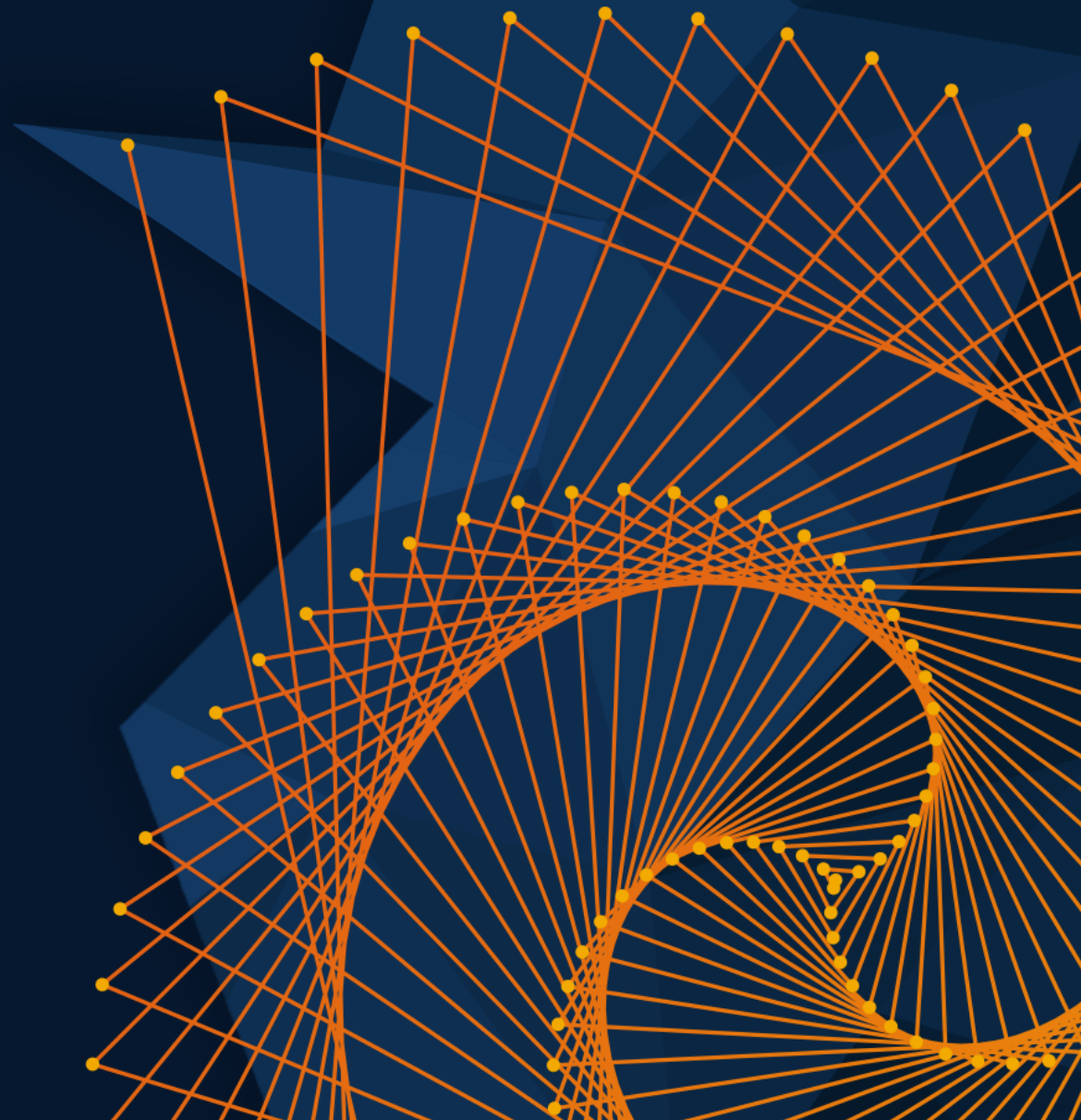


The AI surrogate model for studying selective control was built completely in MATLAB.

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

MATLAB EXPO



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