

MathWorks
**AUTOMOTIVE
CONFERENCE 2024**
Europe

AI with Model-Based Design: Reduced-Order Modeling

Dr. Martin Büchel, MathWorks



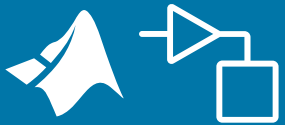
Key Takeaways



Challenge: High-fidelity models often prohibitively slow

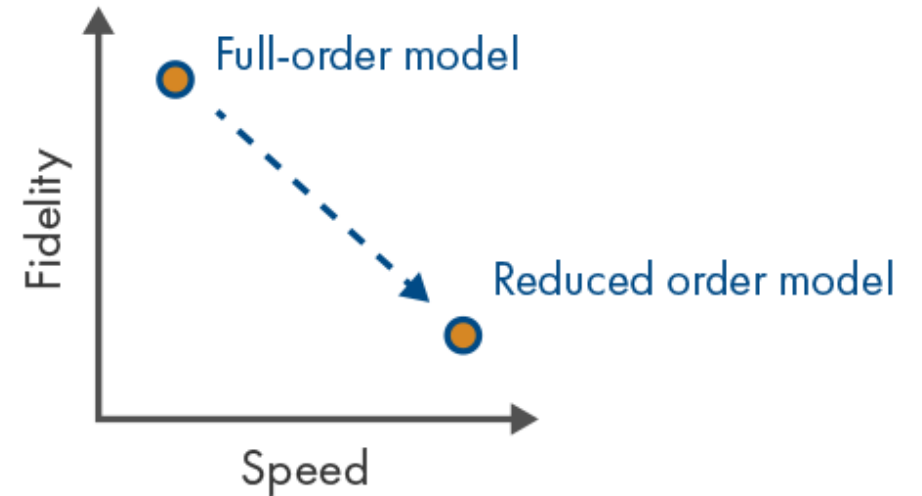
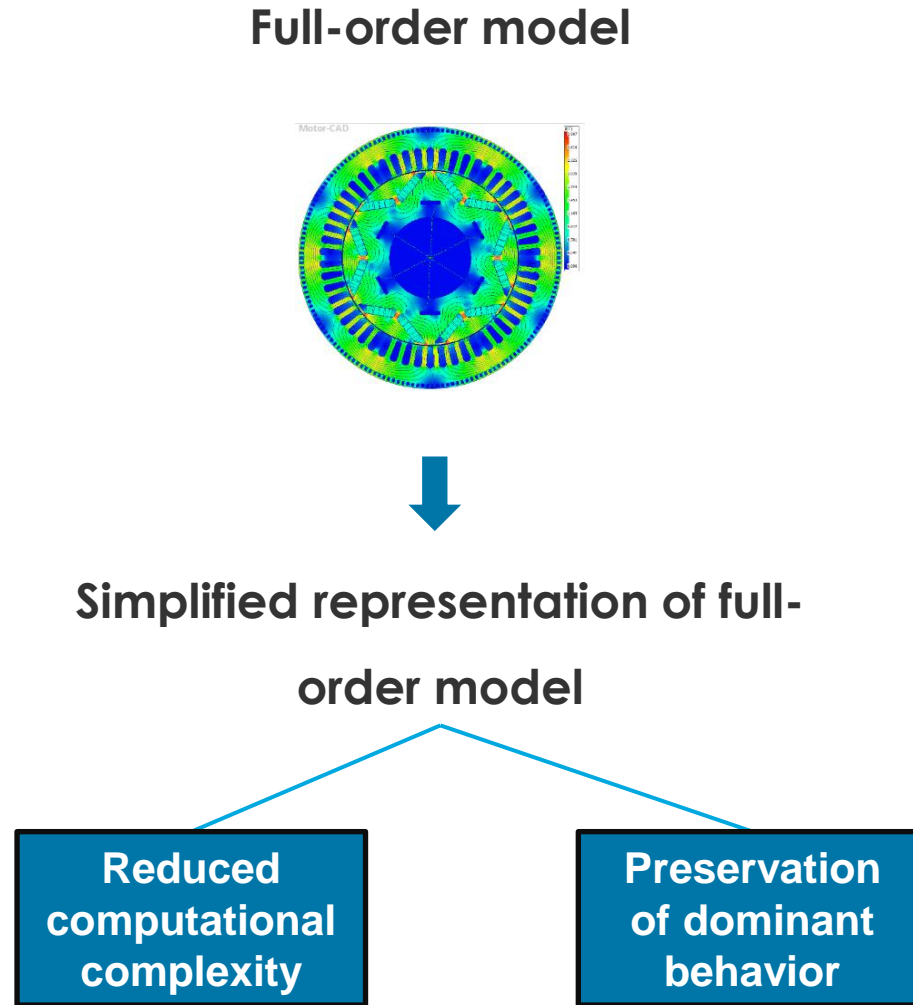


Artificial Intelligence techniques can be used to create faster **Reduced-Order Models (ROM)**

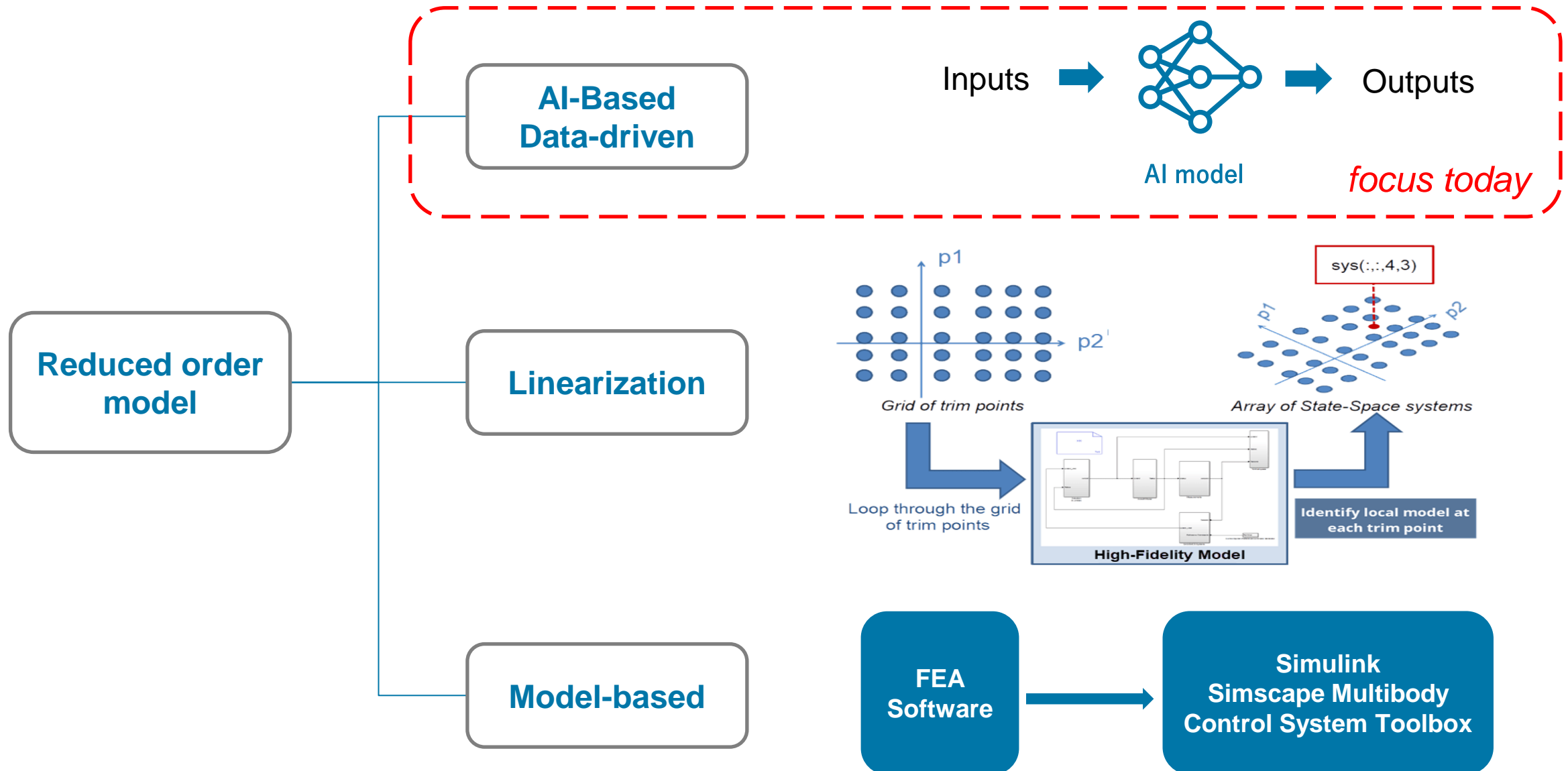


MATLAB & Simulink enables engineers to create ROMs **without prior AI knowledge**

What is Reduced Order Modeling (ROM)?

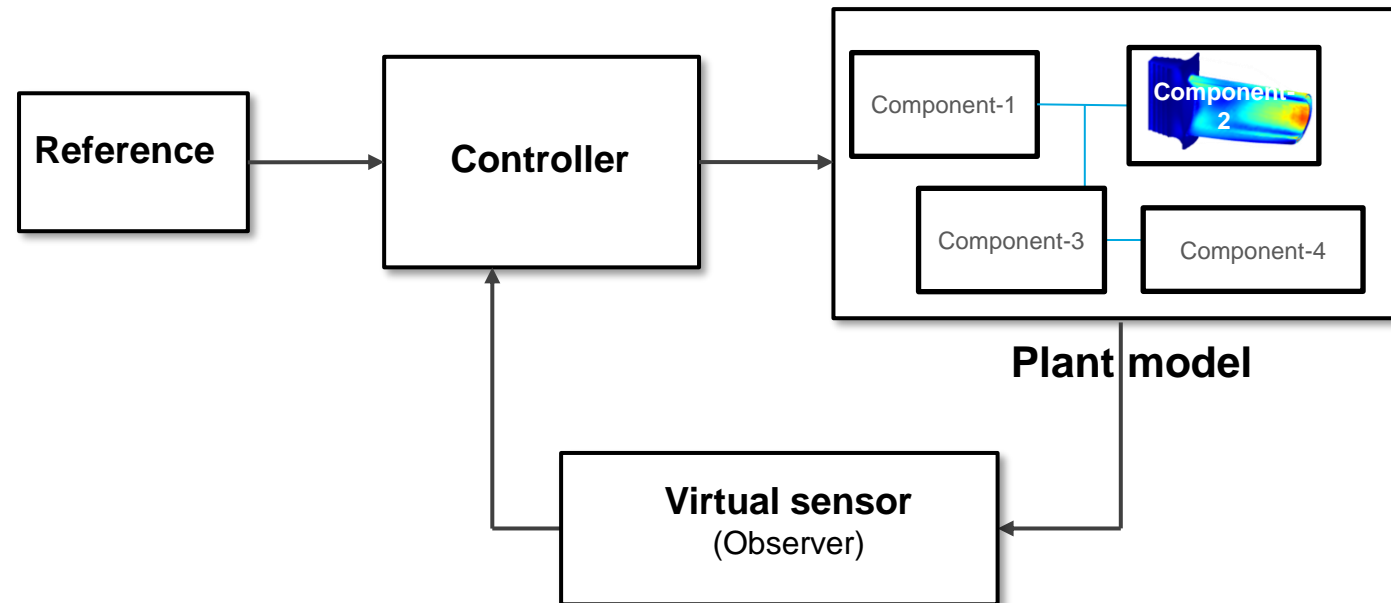


How to perform Reduced Order Modeling?



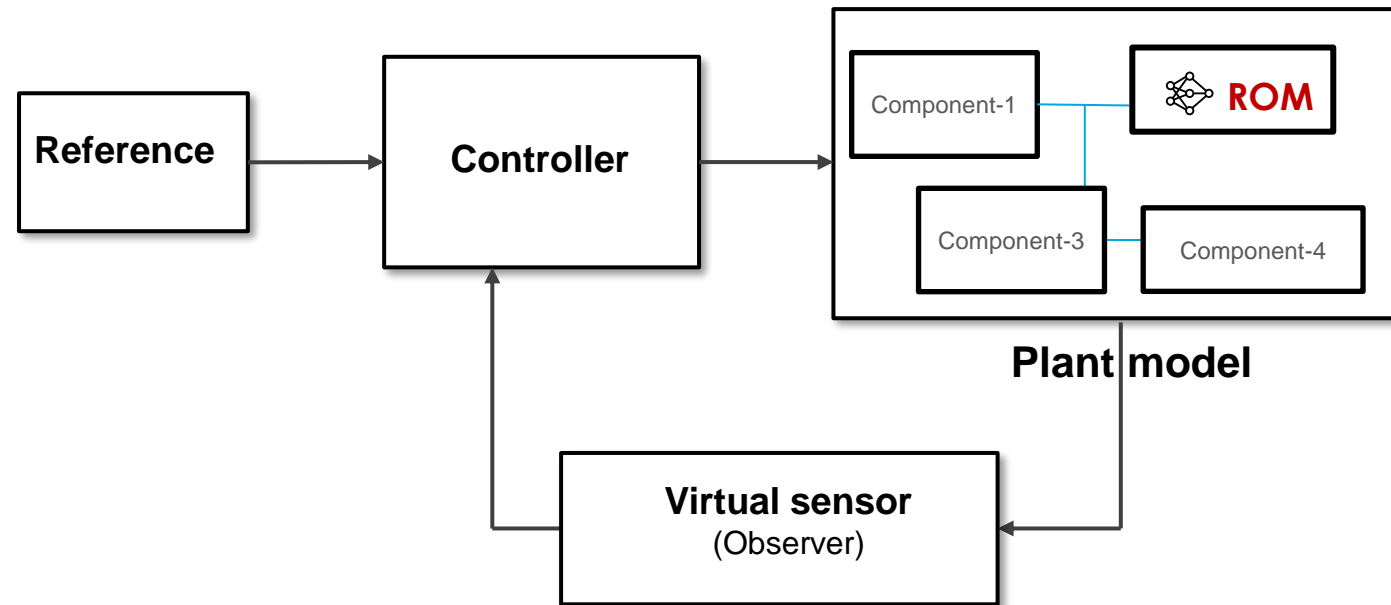
Applications of Reduced Order Modeling

- Perform simulations and SIL / HIL / PIL testing



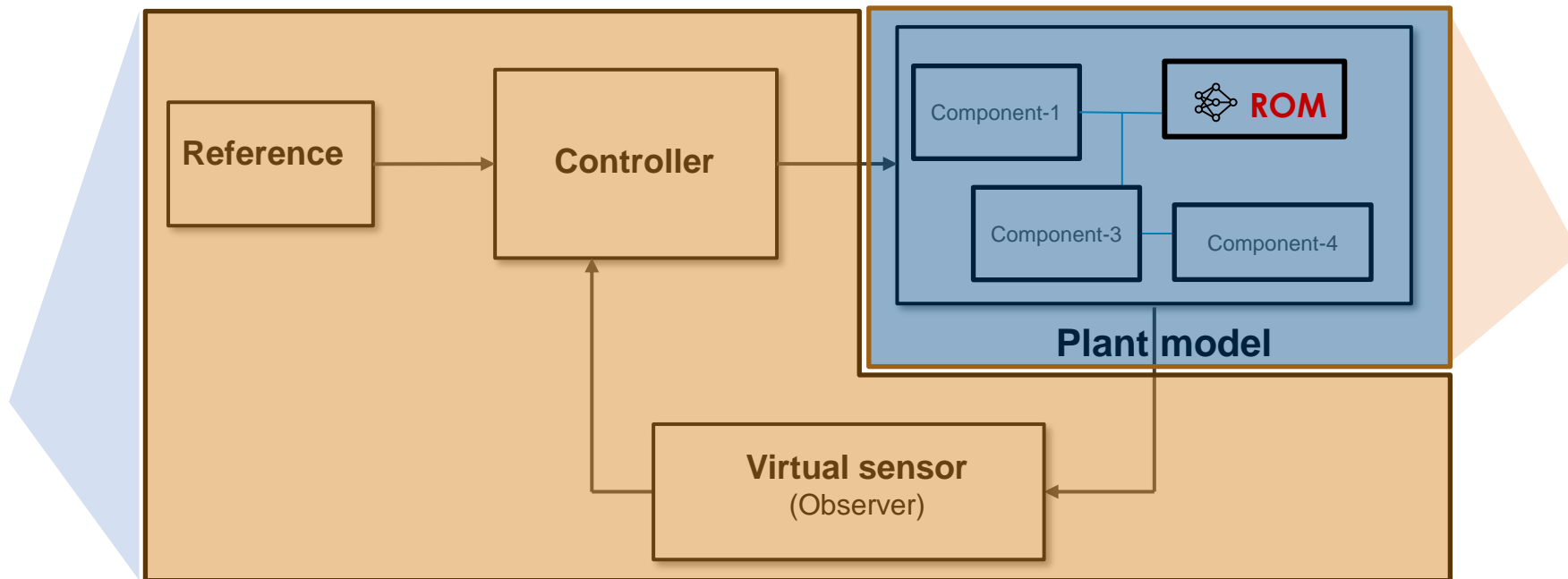
Applications of Reduced Order Modeling

- Perform simulations and SIL / HIL / PIL testing



Applications of Reduced Order Modeling

- Perform simulations and SIL / HIL / PIL testing



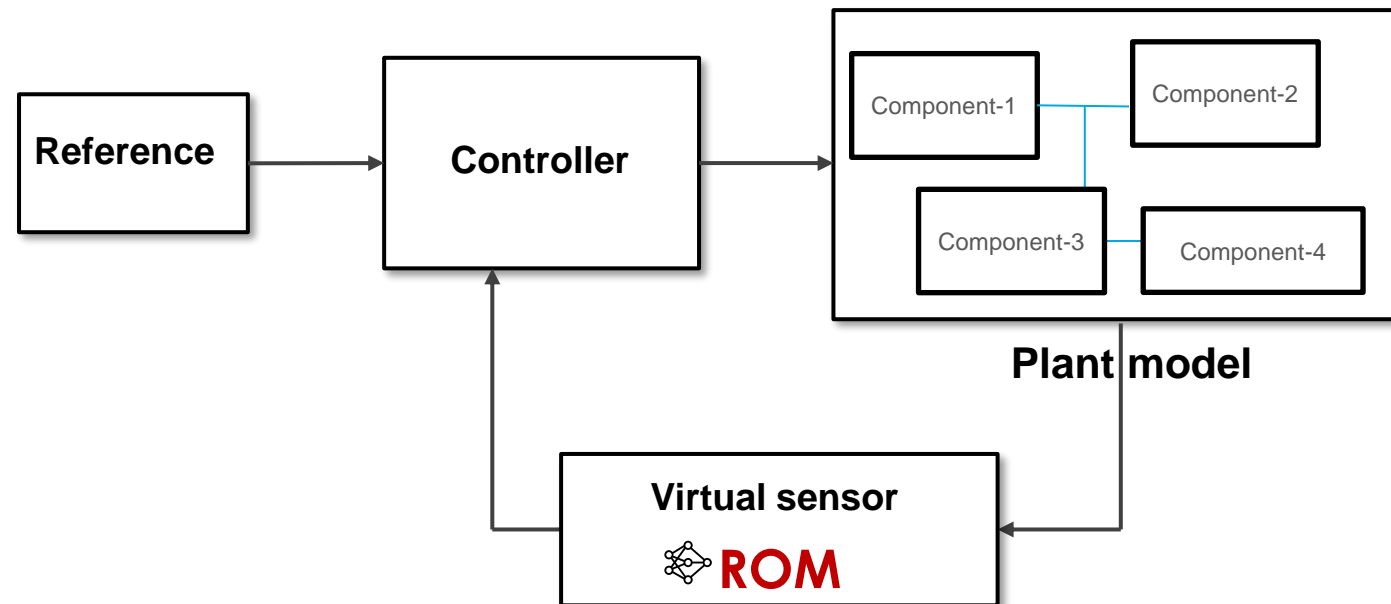
Control algorithm
deployed on the
embedded hardware



Plant model running
on the real-time
target machine

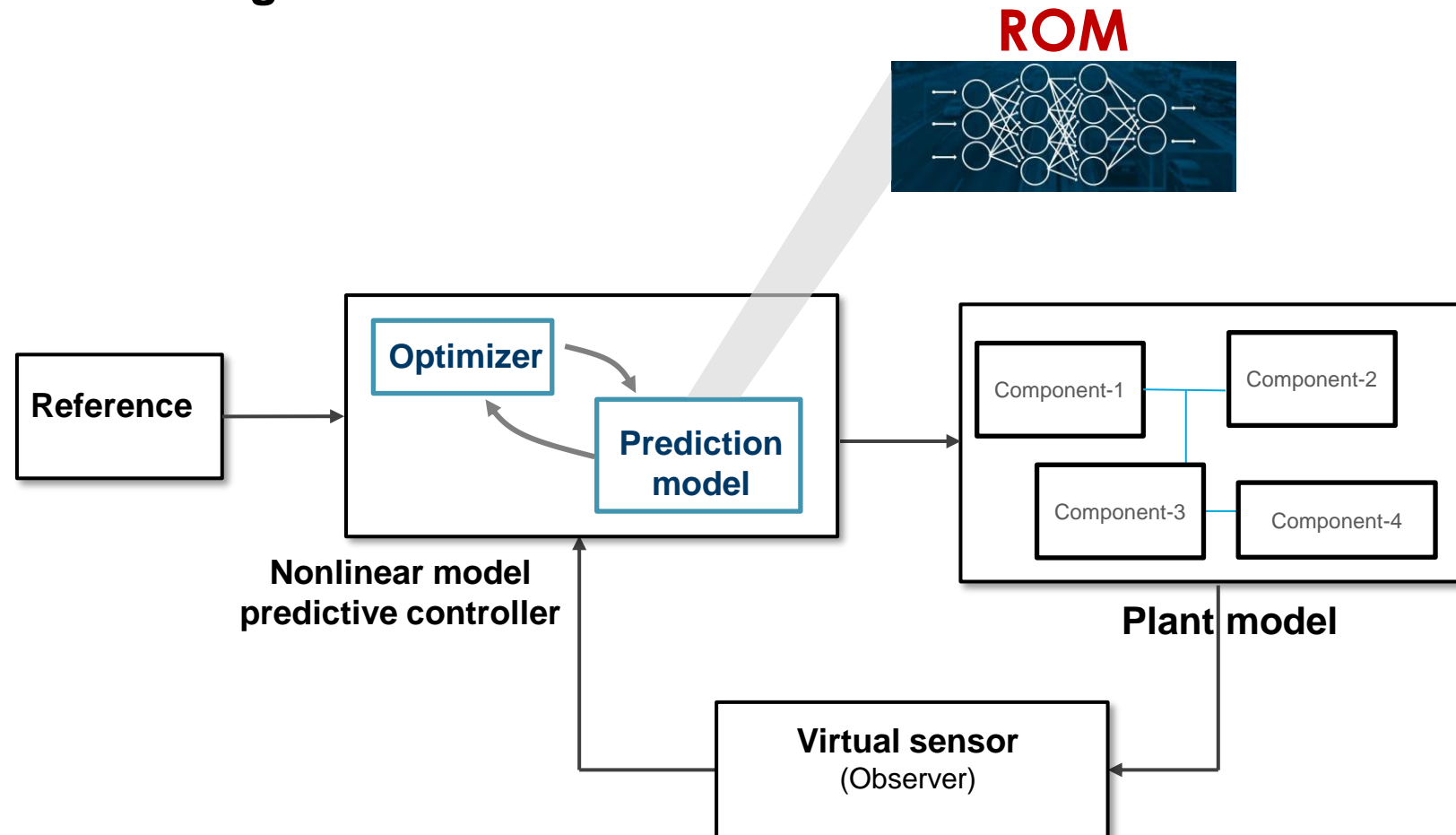
Applications of Reduced Order Modeling

- Perform simulations and SIL / HIL / PIL testing
- **Virtual sensor modeling**



Applications of Reduced Order Modeling

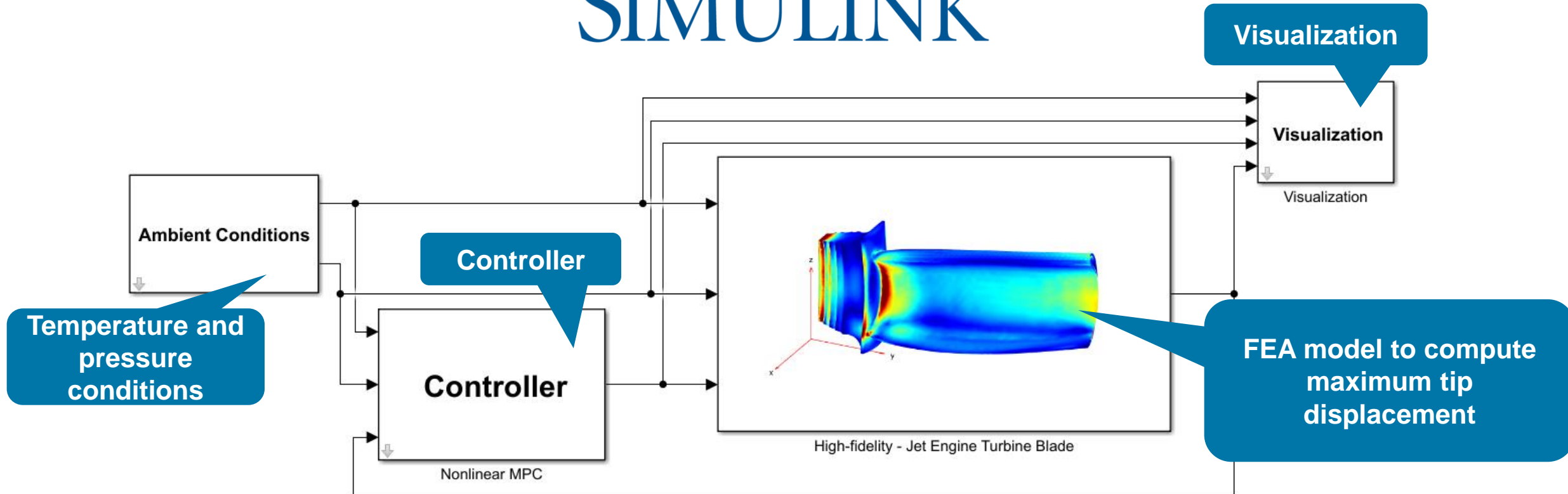
- Perform simulations and SIL / HIL / PIL testing
- Virtual sensor modeling
- **Control design**



Example overview

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

SIMULINK®

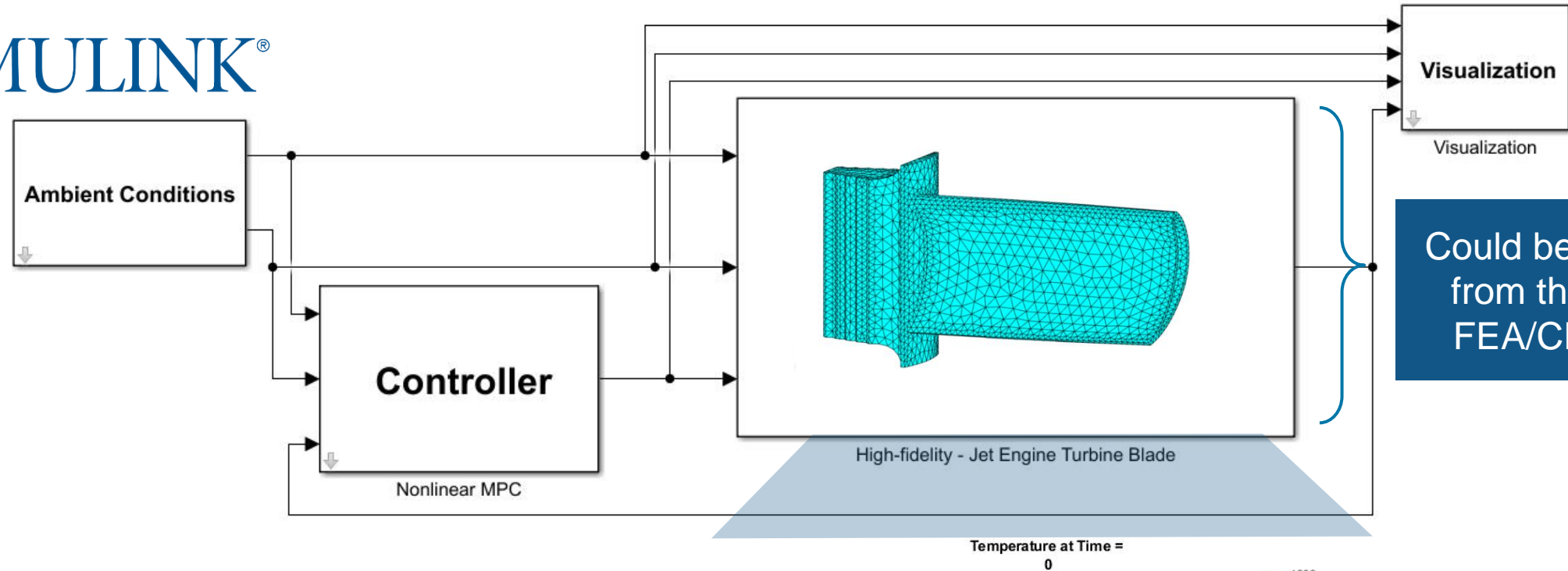


Closed-loop temperature control

Example overview

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

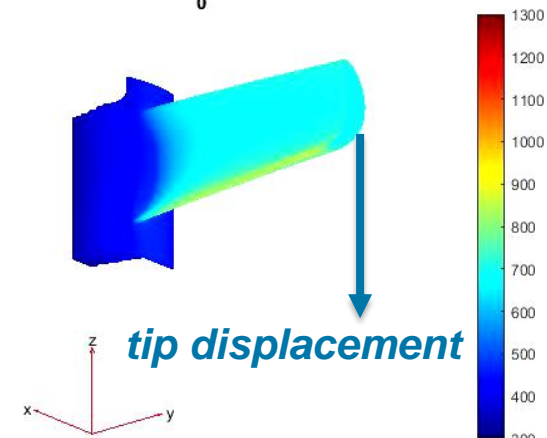
SIMULINK®



~30 seconds per time step for solving FEA models



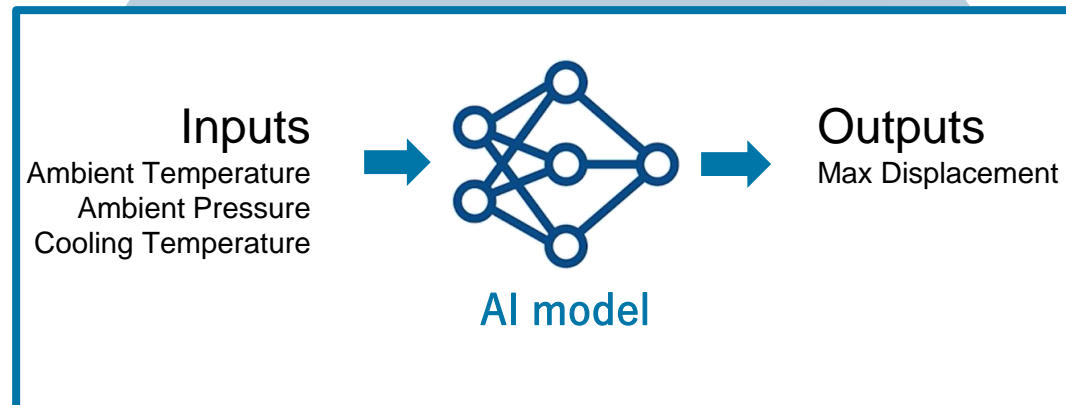
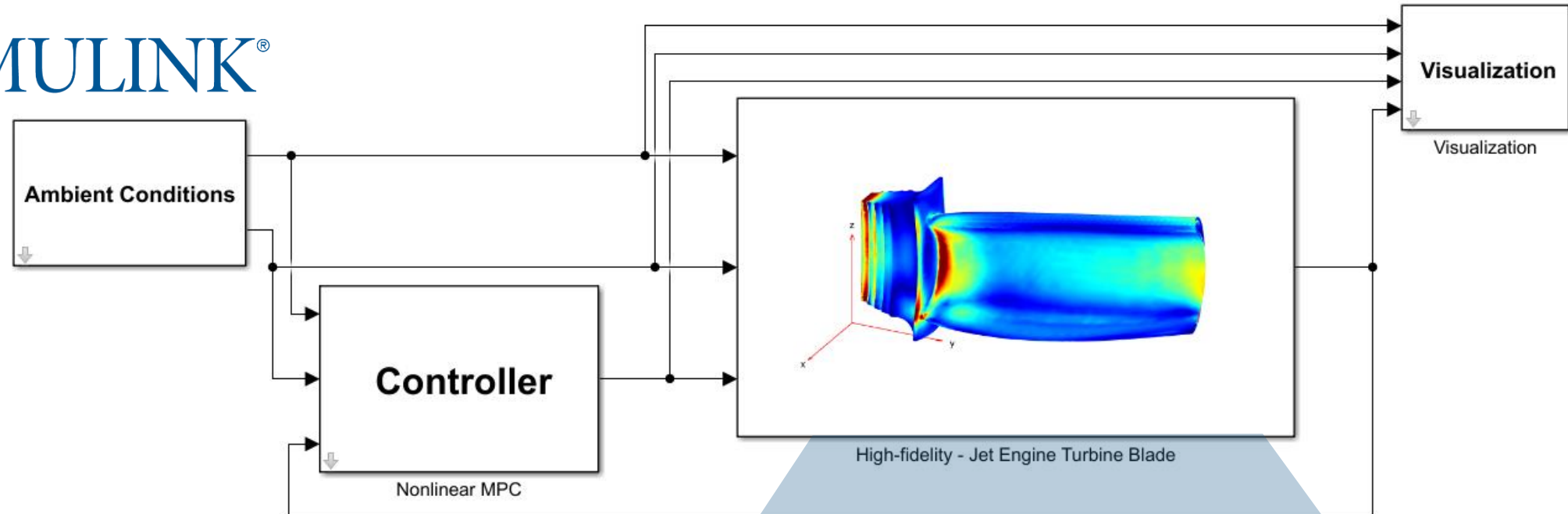
Not suitable for control design and HIL testing



Example overview

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

SIMULINK®



Introducing Simulink Add-On for Reduced Order Modeling

The screenshot shows a webpage with a blue header containing 'Products and Services' and a search bar. The main heading is 'Reduced Order Modeling with MATLAB and Simulink'. Below it, there is a sub-heading 'Create AI-based reduced order models' and a blue button labeled 'Download add-on (beta)'. The main text describes the Simulink Add-On for Reduced Order Modeling, stating it provides an app for creating ROMs of subsystems modeled in Simulink. It lists several capabilities: setting up design of experiments, training AI-based ROMs, exporting surrogate models to Simulink, and exporting ROMs as FMUs. At the bottom, a diagram illustrates the ROM process: a 'Full-order model CFD/CAE/FEA' (represented by a 3D model of a turbine) undergoes 'Reduced Order Modeling' to produce a 'ROM' (represented by a neural network icon) and a 'First-principles based' model (represented by a block diagram). A graph shows 'Fidelity' vs 'Speed' with a dashed arrow pointing from the 'Full-order model' to the 'Reduced order model'. The ROM and First-principles based models are shown as components in a system architecture.

Products and Services

Reduced Order Modeling with MATLAB and Simulink

Create AI-based reduced order models

[Download add-on \(beta\)](#)

Simulink Add-On for Reduced Order Modeling provides an app for creating reduced order models (ROMs) of subsystems modeled in Simulink, including full-order, high-fidelity third-party simulation models. You can use reduced order models for system-level desktop simulation, hardware-in-the-loop (HIL) testing, control design, and virtual sensor modeling.

With Simulink Add-On for Reduced Order Modeling, you can:

- Set up the design of experiments and generate input-output training data from a full-order, high-fidelity subsystem
- Train and compare AI-based reduced order models using pre-configured templates
- Export AI-based surrogate models to Simulink for system-level simulation, control design, and HIL testing
- Export reduced order models as Functional Mockup Units (FMUs) for use outside of MATLAB and Simulink (with Simulink Compiler)

Full-order model CFD/CAE/FEA

Reduced Order Modeling

ROM
component 1

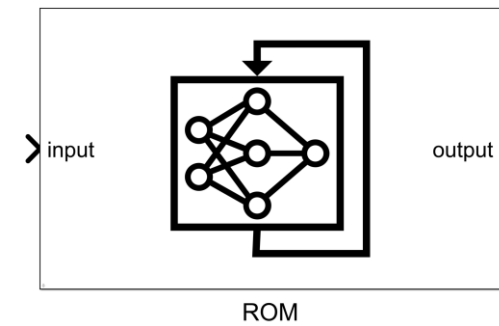
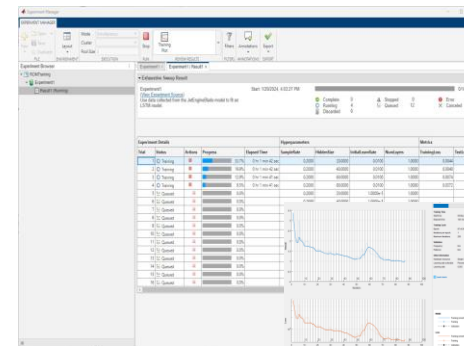
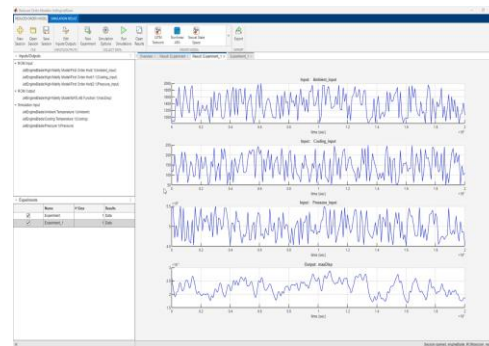
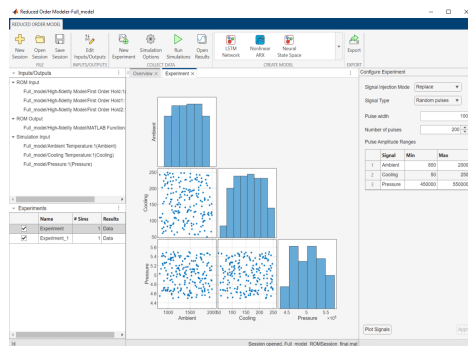
First-principles based
component 2

First-principles based
component 3

Fidelity vs Speed graph showing the trade-off between fidelity and speed for full-order and reduced order models.

[Reduced Order Modeling with MATLAB and Simulink](#)

Workflow for Reduced Order Modeling App





Reduced Order Modeler-Full_model

REDUCED ORDER MODEL

Inputs/Outputs: ROM Input, ROM Output, Simulation Input
 Experiments: Experiment, Experiment_1

Configure Experiment

Signal Injection Mode: Replace
 Signal Type: Random pulses
 Pulse width: 100
 Number of pulses: 200

Pulse Amplitude Ranges

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

Plot Signals [Apply]

Session opened, Full_model_ROMSession_final.mat



Software interface showing a configuration window for an experiment. The main workspace displays several plots: a bar chart for Ambient Temperature, a scatter plot for Cooling Temperature, and other smaller plots. The right-hand panel, titled "Configure Experiment", contains the following settings:

- Signal Injection Mode: Replace (selected)
- Signal Type: Replace
- Pulse width: 100
- Number of pulses: 200
- Pulse Amplitude Ranges table:

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

At the bottom of the interface, a smaller version of the process flow diagram is visible, with the "Design experiments" step highlighted in blue.

Design experiments

Run experiments

Train ROM

Export

The screenshot displays the 'Reduced Order Modeler-JetEngineBlade' software interface. The 'Run Options' dialog box is open, showing logging settings. The 'Logging' section includes the following options:

- Include data logging setup from Simulink model
- Only log reduced order model inputs and outputs
- Log Simulink Model States
- Log to file
- File location:
- Use Parallel

The background shows a multi-panel plot with the following axes and data series:

- Ambient Temperature: 1**: A bar chart showing a single high-value pulse.
- Cooling Temperature: 1**: A scatter plot showing a distribution of values between 50 and 250.
- Pressure: 1**: A scatter plot showing a distribution of values between 4.4 and 5.6, with a corresponding bar chart to its right.

At the bottom of the interface, a progress bar indicates the current step: **Run experiments**.



Reduced Order Modeler-JetEngineBlade

REDUCED ORDER MODEL SIMULATION RESULT

Inputs/Outputs
 - ROM Input
 JetEngineBlade/High-fidelity Model/First Order Hold:1(Ambient_input)
 JetEngineBlade/High-fidelity Model/First Order Hold:1(Cooling_input)
 JetEngineBlade/High-fidelity Model/First Order Hold:2:1(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
<input checked="" type="checkbox"/>	DoE_experiment	1	Data
<input checked="" type="checkbox"/>	DoE_experiment2	1	Data

Input: Ambient_input
 2000
1800
1600
1400
1200
1000
0 0.2 0.4 0.6 0.8 1 1.2 1.4 1.6 1.8 2
time (sec) $\times 10^4$

Input: Cooling_input
 250
200
150
100
50
0 0.2 0.4 0.6 0.8 1 1.2 1.4 1.6 1.8 2
time (sec) $\times 10^4$

Input: Pressure_input
 5.5×10^5
5
4.5
0 0.2 0.4 0.6 0.8 1 1.2 1.4 1.6 1.8 2
time (sec) $\times 10^4$

Output: maxDisp
 3×10^{-3}
2.5
2
1.5
0 0.2 0.4 0.6 0.8 1 1.2 1.4 1.6 1.8 2
time (sec) $\times 10^4$

Design experiments Run experiments **Train ROM** Export

_results.mat



Reduced Order Modeler-JetEngineBlade

REDUCED ORDER MODEL SIMULATION RESULT

Inputs/Outputs

- ROM Input
 - JetEngineBlade/High-fidelity Model/First Order Hold 1(Ambient_input)
 - JetEngineBlade/High-fidelity Model/First Order Hold 1:1(Cooling_input)
 - JetEngineBlade/High-fidelity Model/First Order Hold 2:1(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
<input checked="" type="checkbox"/>	DoE_experiment	1	Data
<input checked="" type="checkbox"/>	DoE_experiment2	1	Data

Input: Ambient_input

Hyperparameters

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

State Network (f)

Output Network (g)

Neural State Space model
(also known as **Neural ODE**)

Design experiments

Run experiments

Train ROM

Export

The screenshot displays the Experiment Manager application window. The interface includes a top toolbar with options like 'New', 'Open', 'Save', 'Duplicate', 'Layout', 'Mode', 'Cluster', 'Pool Size', 'Restart', 'Training Plot', 'Test Data Plot', 'Filters', 'Annotations', and 'Export'. Below the toolbar is the 'Experiment Browser' showing a tree view of 'ExperimentProject3' with sub-items 'Experiment1', 'Result2', and 'Result1'. The main area shows 'Exhaustive Sweep Result' for 'Experiment1', starting on 1/15/2024 at 9:48:54 AM, with 36/36 trials completed. A summary table indicates 36 Complete, 0 Running, 0 Discarded, 0 Stopped, 0 Queued, 0 Error, and 0 Canceled. Below this is a detailed table of experiment results.

Experiment Details				Hyperparameters						Information		Metrics	
Status	Actions	Progress	Elapsed Time	NumberInput...	NumberOutput...	NumberLayers	NumberUnits	SampleRate	TrainingMSE	Loss	TestMSE		
1	Complete	100.0%	0 hr 5 min 16 sec	0.0000	0.0000	2.0000	16.0000	0.2000	0.0214	0.9276	0.0519		
2	Complete	100.0%	0 hr 7 min 34 sec	1.0000	0.0000	2.0000	16.0000	0.2000	0.0272	3.2502	0.0368		
3	Complete	100.0%	0 hr 6 min 29 sec	0.0000	1.0000	2.0000	16.0000	0.2000	0.0573	1.9528	0.1116		
4	Complete	100.0%	0 hr 14 min 15 sec	1.0000	1.0000	2.0000	16.0000	0.2000	0.0361	3.6828	0.0553		
5	Complete	100.0%	0 hr 13 min 51 sec	0.0000	2.0000	2.0000	16.0000	0.2000	0.1076	3.3881	0.1943		
6	Complete	100.0%	0 hr 14 min 40 sec	1.0000	2.0000	2.0000	16.0000	0.2000	0.0475	9.6849	0.0871		
7	Complete	100.0%	0 hr 14 min 59 sec	0.0000	0.0000	3.0000	16.0000	0.2000	0.0208	0.9332	0.0444		
8	Complete	100.0%	0 hr 15 min 16 sec	1.0000	0.0000	3.0000	16.0000	0.2000	0.0145	2.8449	0.0358		
9	Complete	100.0%	0 hr 16 min 4 sec	0.0000	1.0000	3.0000	16.0000	0.2000	0.0352	1.8716	0.0932		
10	Complete	100.0%	0 hr 15 min 35 sec	1.0000	1.0000	3.0000	16.0000	0.2000	0.0154	2.9724	0.0535		
11	Complete	100.0%	0 hr 16 min 15 sec	0.0000	2.0000	3.0000	16.0000	0.2000	0.2199	3.6474	0.3241		
12	Complete	100.0%	0 hr 15 min 54 sec	1.0000	2.0000	3.0000	16.0000	0.2000	0.0374	7.3887	0.0910		
13	Complete	100.0%	0 hr 13 min 7 sec	0.0000	0.0000	2.0000	32.0000	0.2000	0.0195	0.9328	0.0396		
14	Complete	100.0%	0 hr 12 min 11 sec	1.0000	0.0000	2.0000	32.0000	0.2000	0.0188	3.3358	0.0562		
15	Complete	100.0%	0 hr 11 min 56 sec	0.0000	1.0000	2.0000	32.0000	0.2000	0.0537	2.2448	0.1004		
16	Complete	100.0%	0 hr 12 min 38 sec	1.0000	1.0000	2.0000	32.0000	0.2000	0.0342	3.8684	0.0290		
17	Complete	100.0%	0 hr 12 min 20 sec	0.0000	2.0000	2.0000	32.0000	0.2000	0.1214	3.4628	0.2559		
18	Complete	100.0%	0 hr 12 min 47 sec	1.0000	2.0000	2.0000	32.0000	0.2000	0.0452	8.2722	0.0937		
19	Complete	100.0%	0 hr 12 min 18 sec	0.0000	0.0000	3.0000	32.0000	0.2000	0.0328	1.1057	0.0552		
20	Complete	100.0%	0 hr 12 min 30 sec	1.0000	0.0000	3.0000	32.0000	0.2000	0.0146	2.7313	0.0426		
21	Complete	100.0%	0 hr 12 min 37 sec	0.0000	1.0000	3.0000	32.0000	0.2000	0.0376	1.9406	0.0975		
22	Complete	100.0%	0 hr 12 min 50 sec	1.0000	1.0000	3.0000	32.0000	0.2000	0.0197	2.9531	0.0543		
23	Complete	100.0%	0 hr 12 min 55 sec	0.0000	2.0000	3.0000	32.0000	0.2000	0.0800	3.0261	0.1701		
24	Complete	100.0%	0 hr 13 min 12 sec	1.0000	2.0000	3.0000	32.0000	0.2000	0.0352	7.3551	0.0890		
25	Complete	100.0%	0 hr 11 min 31 sec	0.0000	0.0000	2.0000	64.0000	0.2000	0.0182	1.1432	0.0354		
26	Complete	100.0%	0 hr 10 min 52 sec	1.0000	0.0000	2.0000	64.0000	0.2000	0.0554	3.8685	0.0537		
27	Complete	100.0%	0 hr 10 min 38 sec	0.0000	1.0000	2.0000	64.0000	0.2000	0.0115	3.1377	0.0743		
28	Complete	100.0%	0 hr 11 min 17 sec	1.0000	1.0000	2.0000	64.0000	0.2000	0.0115	3.1377	0.0743		



Plot Filters Annotations **Export**

Training Output
 Export training function output for selected trial to MATLAB workspace

Results Table
 Export results of all trials to MATLAB workspace as a MATLAB table

Experiment 1 | Result 2 x

Sweep Result

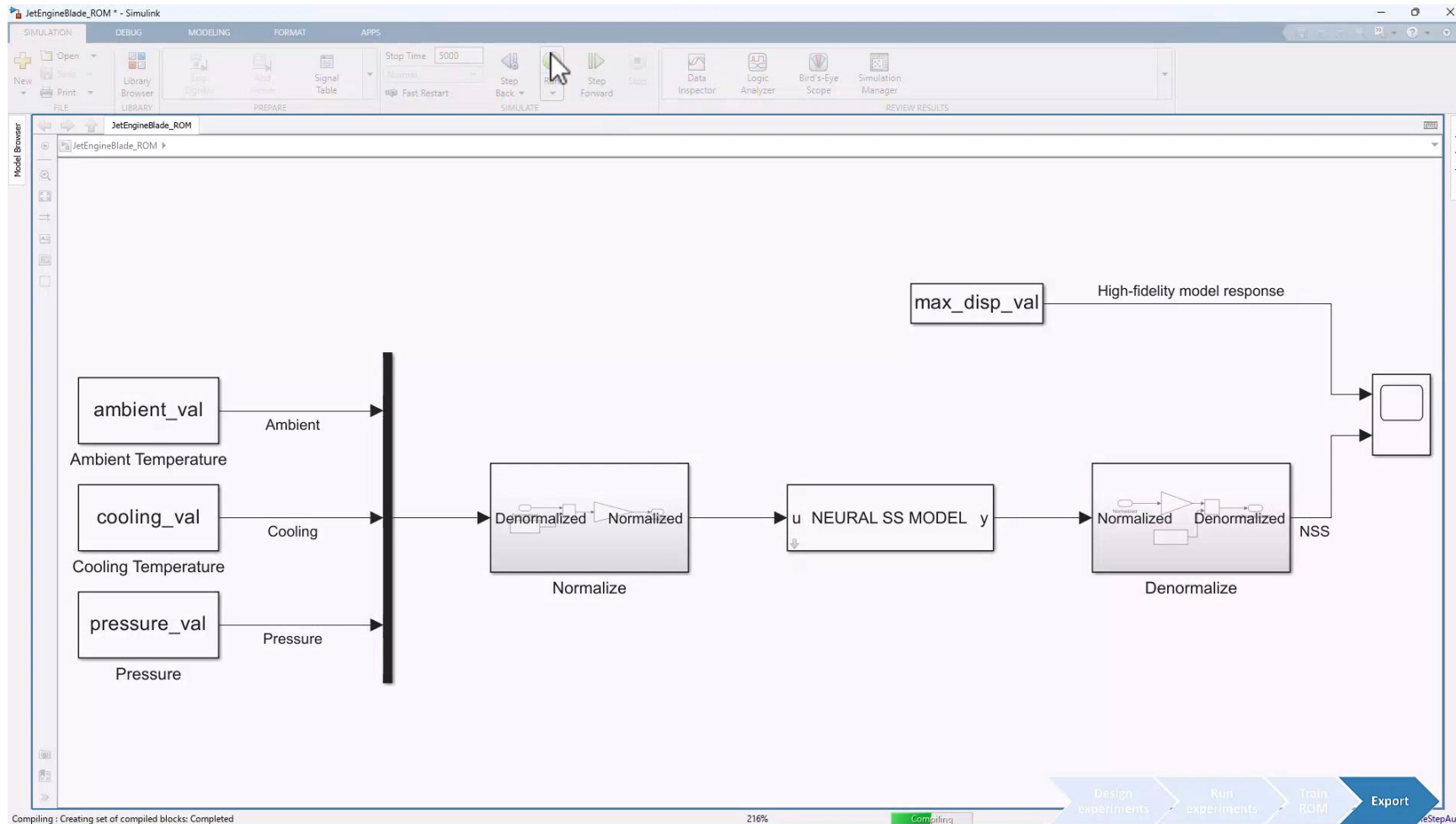
36/36 Trials

Complete 36 Stopped 0 Error 0
 Running 0 Queued 0 Canceled 0
 Discarded 0

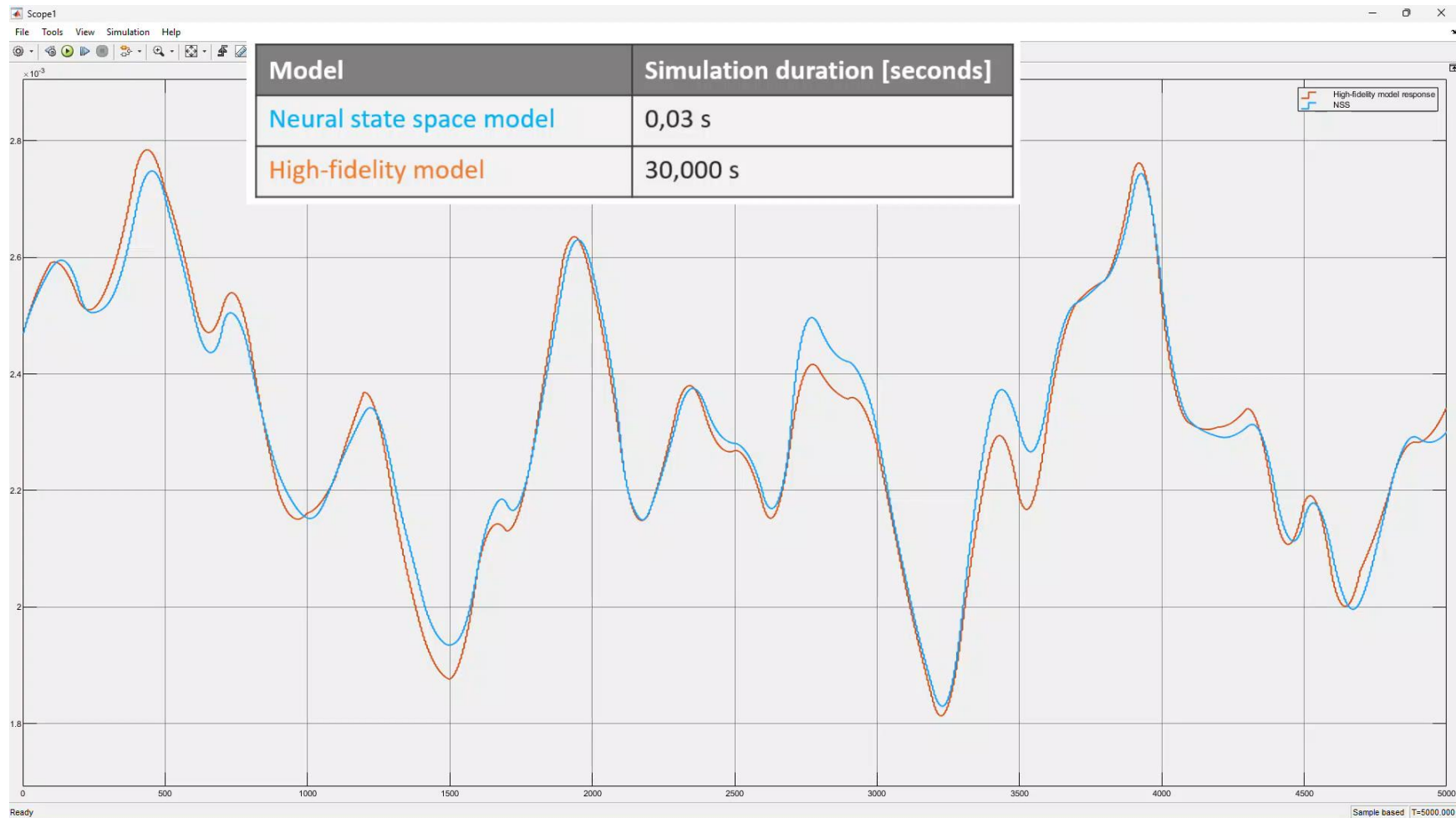
(Document Source)
 Selected from the JetEngineBlade model to fit a neural state-
 I. By default, 20% of the data sets are used as test data, and
 for training is set to 1000. Edit the training function to change
 age of test data used and the maximum number of training

	Actions	Progress	Elapsed Time	Hyperparameters					Information	Metrics	
				NumberInputL...	NumberOutpu...	NumberLayers	NumberUnits	SampleRate	TrainingMSE	Loss	TestMSE
te		100.0%	0 hr 12 min 38 sec	1.0000	1.0000	2.0000	32.0000	0.2000	0.0342	3.8684	0.0290
te		100.0%	0 hr 11 min 31 sec	0.0000	0.0000	2.0000	64.0000	0.2000	0.0182	1.1432	0.0354
te		100.0%	0 hr 15 min 16 sec	1.0000	0.0000	3.0000	16.0000	0.2000	0.0145	2.8449	0.0358
te		100.0%	0 hr 7 min 34 sec	1.0000	0.0000	2.0000	16.0000	0.2000	0.0272	3.2502	0.0368
te		100.0%	0 hr 13 min 7 sec	0.0000	0.0000	2.0000	32.0000	0.2000	0.0195	0.9328	0.0396
te		100.0%	0 hr 12 min 30 sec	1.0000	0.0000	3.0000	32.0000	0.2000	0.0146	2.7313	0.0426
te		100.0%	0 hr 10 min 58 sec	0.0000	0.0000	3.0000	64.0000	0.2000	0.0234	1.0063	0.0438
te		100.0%	0 hr 14 min 59 sec	0.0000	0.0000	3.0000	16.0000	0.2000	0.0208	0.9332	0.0444
te		100.0%	0 hr 5 min 16 sec	0.0000	0.0000	2.0000	16.0000	0.2000	0.0214	0.9276	0.0519
te		100.0%	0 hr 11 min 37 sec	1.0000	2.0000	2.0000	64.0000	0.2000	0.0606	7.2411	0.0528
te		100.0%	0 hr 15 min 35 sec	1.0000	1.0000	3.0000	16.0000	0.2000	0.0154	2.9724	0.0535
te		100.0%	0 hr 10 min 52 sec	1.0000	0.0000	2.0000	64.0000	0.2000	0.0554	3.8685	0.0537
te		100.0%	0 hr 10 min 52 sec	1.0000	1.0000	3.0000	32.0000	0.2000	0.0197	2.9531	0.0543
te		100.0%	0 hr 10 min 52 sec	1.0000	0.0000	3.0000	32.0000	0.2000	0.0328	1.1057	0.0552
te		100.0%	0 hr 10 min 52 sec	1.0000	1.0000	2.0000	16.0000	0.2000	0.0361	3.6828	0.0553

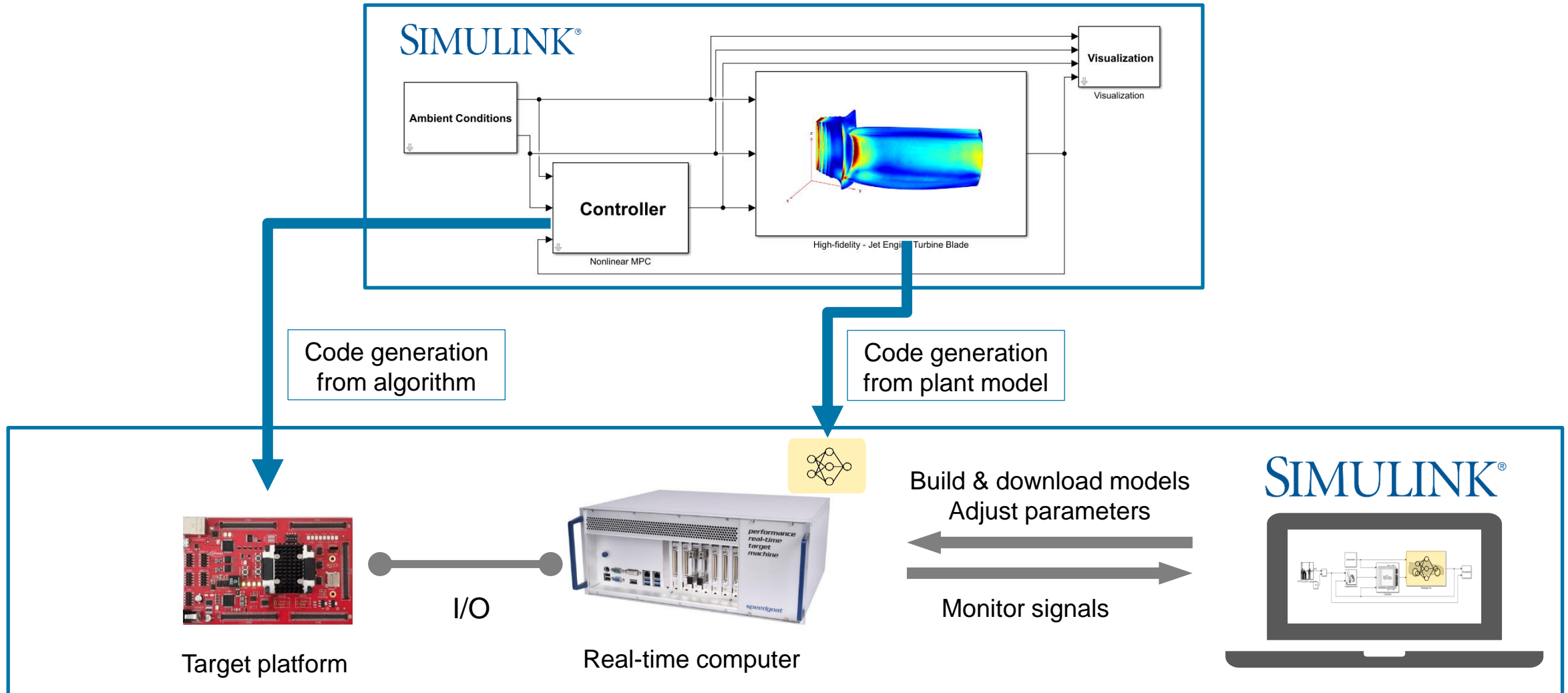
Design experiments → Run experiments → Train ROM → **Export**



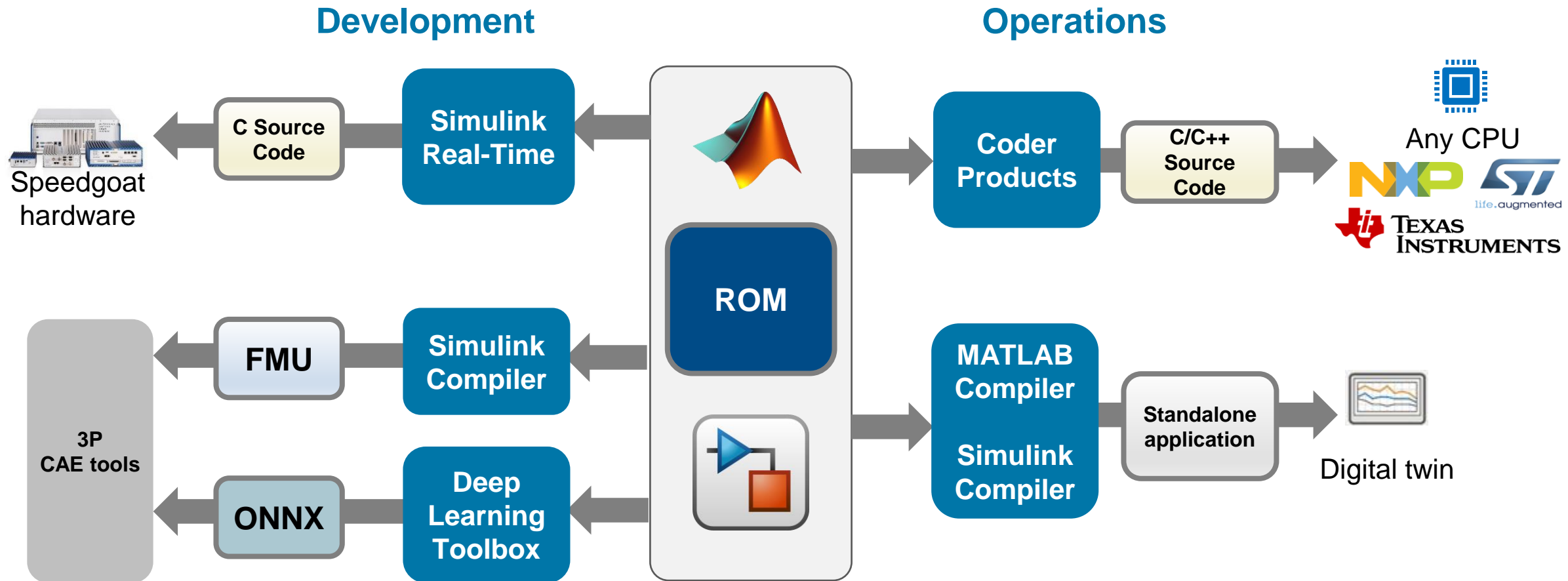
Simulation and test



Hardware-in-the-loop simulation



Deployment of Reduced Order Models



Key Takeaways



Challenge: High-fidelity models often prohibitively slow



Artificial Intelligence techniques can be used to create faster **Reduced Order Models (ROM)**



MATLAB & Simulink enables engineers to create ROMs **without prior AI knowledge**

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Thank you

