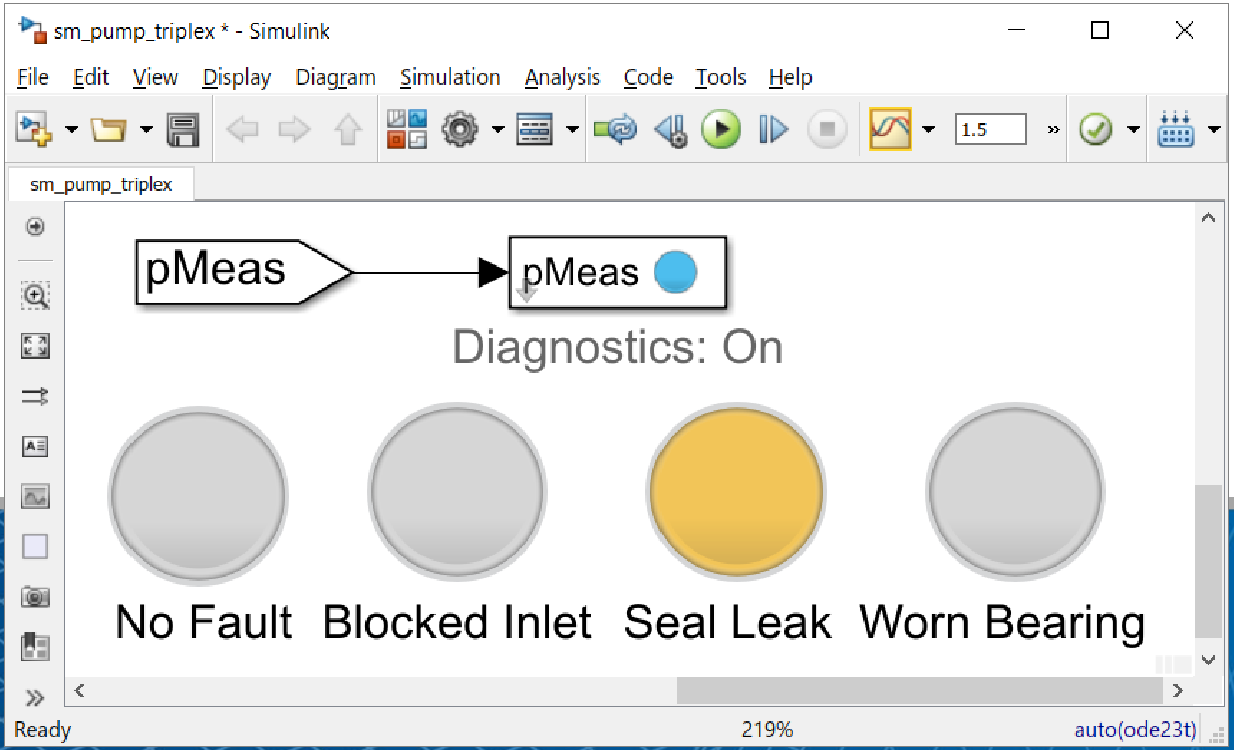
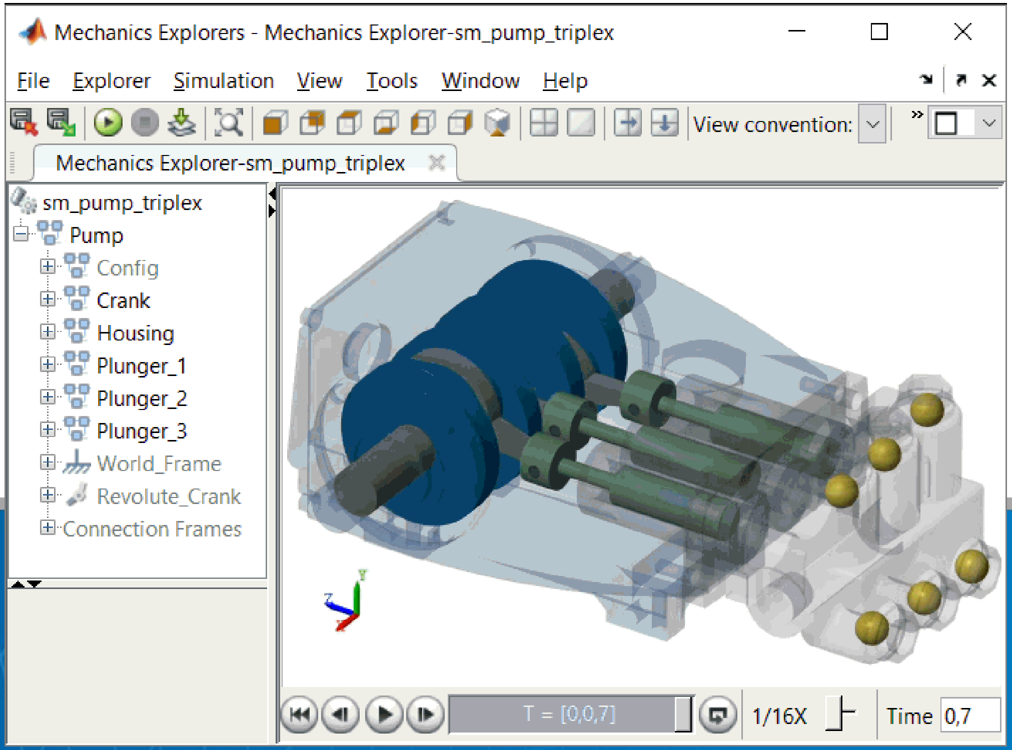
MATLAB EXPO 2018

Prädiktive Wartung eines digitalen Zwillings

Steve MIller

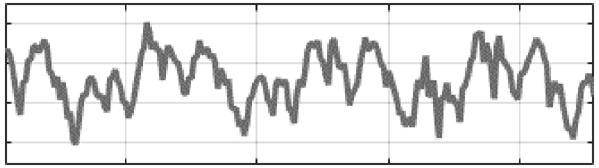
Predictive Maintenance Using Digital Twins



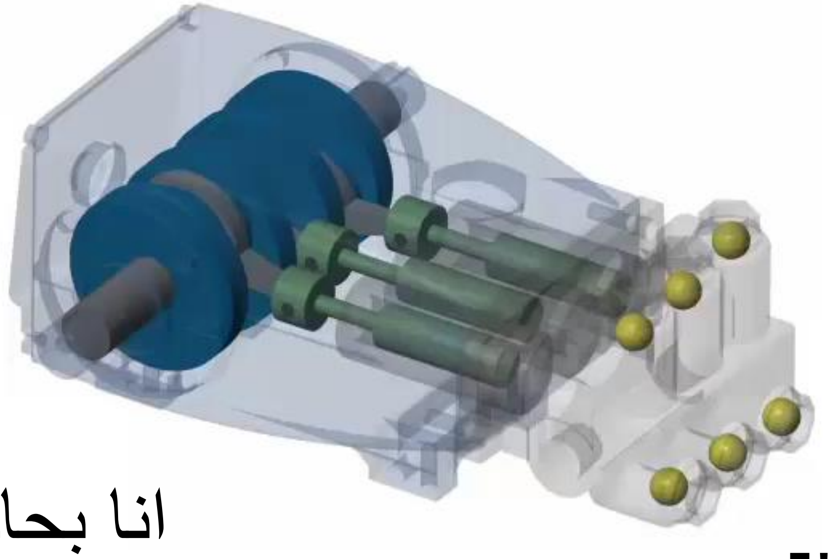


ฉันต้องการความช่วยเหลือ.

Ich brauche Hilfe.



Segítségre van szükségem.



Necesito ayuda.

Мне нужна помощь.

انا بحاجة الى مساعدة.

J'ai besoin d'aide.

I need help.

Χρειάζομαι βοήθεια.

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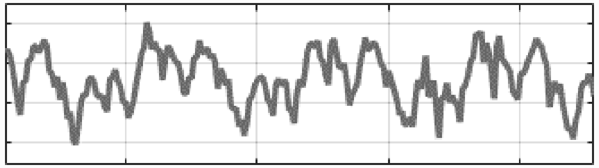

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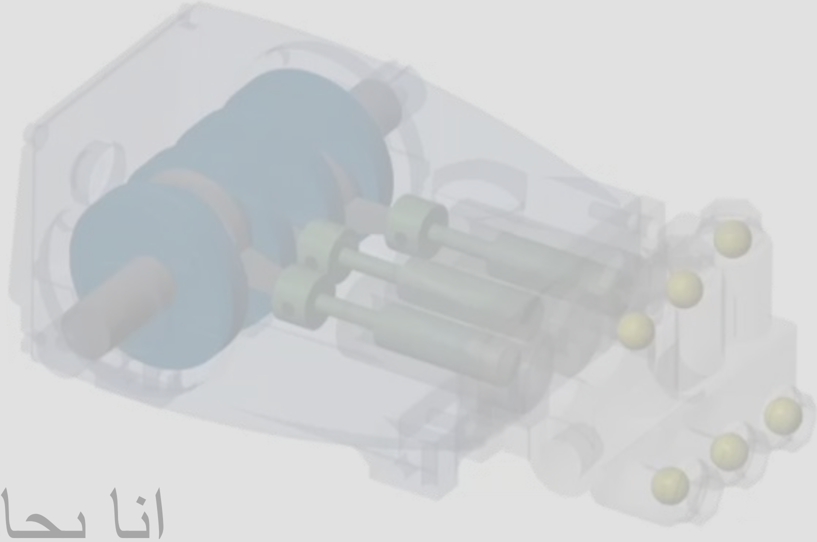

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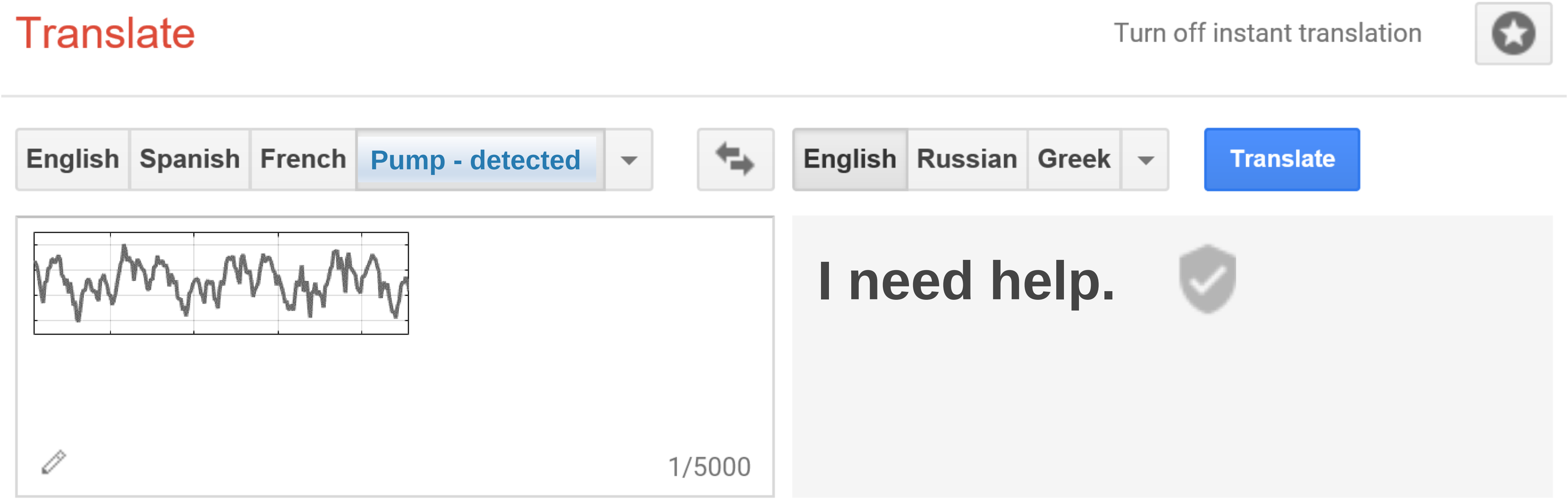
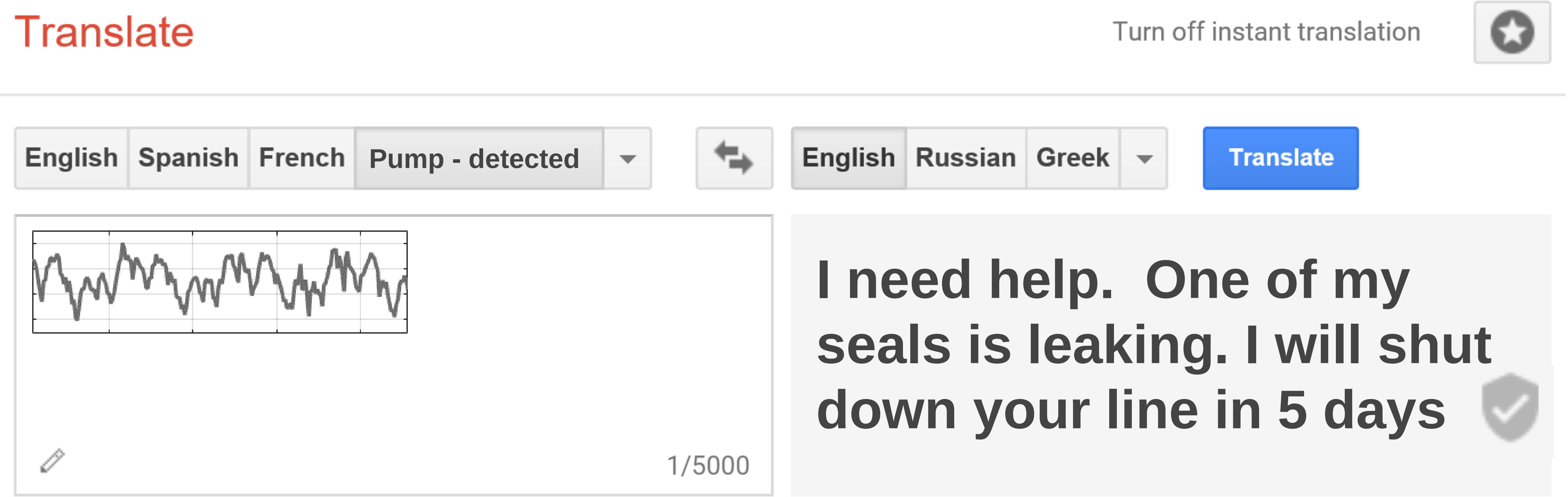
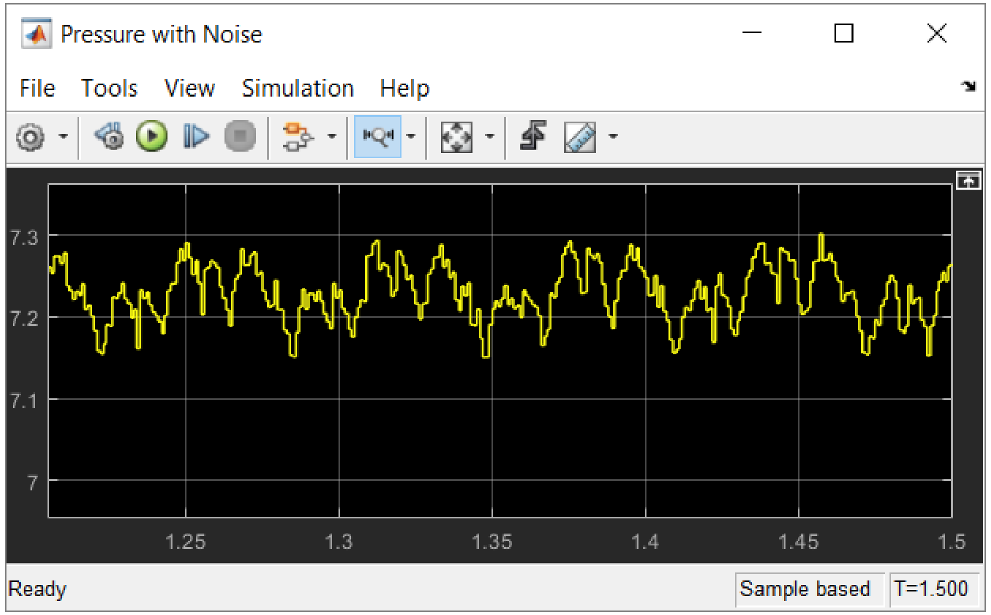

Translate
Turn off instant translation
English
Spanish
French
Pump - detected
English
Russian
Greek
Translate
1/5000

I need help.



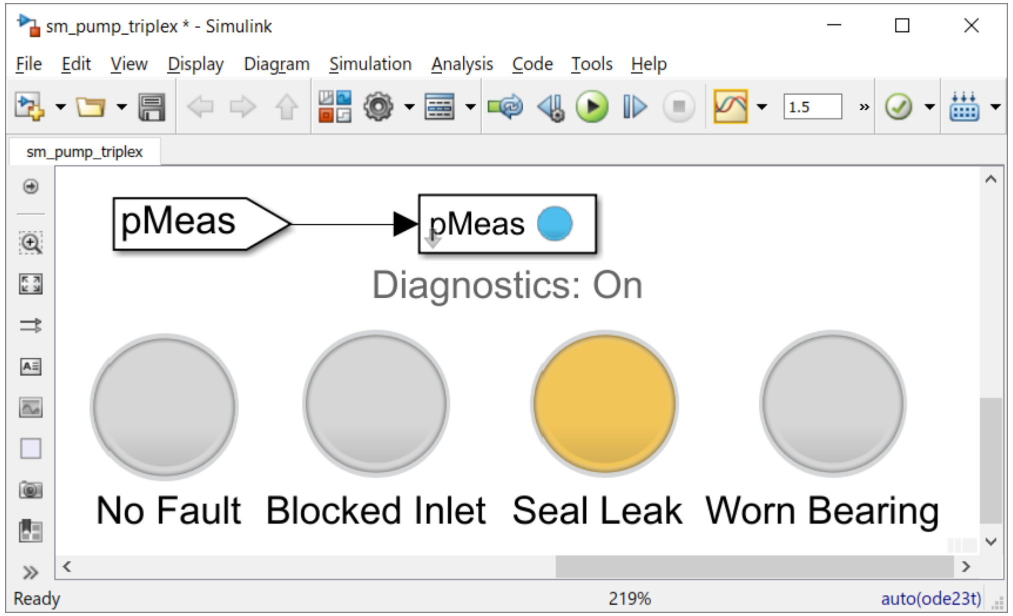
I need help. One of my seals is leaking. I will shut down your line in 5 days

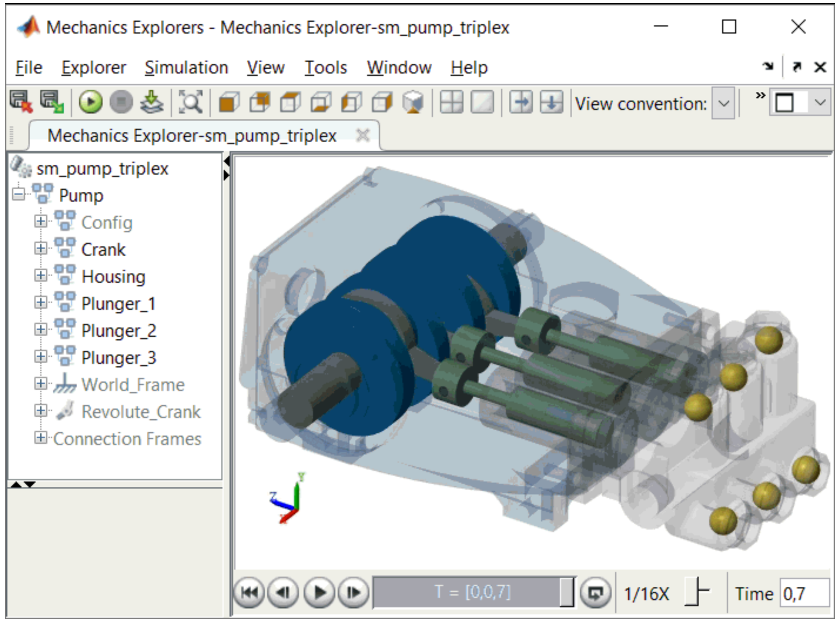
Prevent system downtime



by sending
sensor data

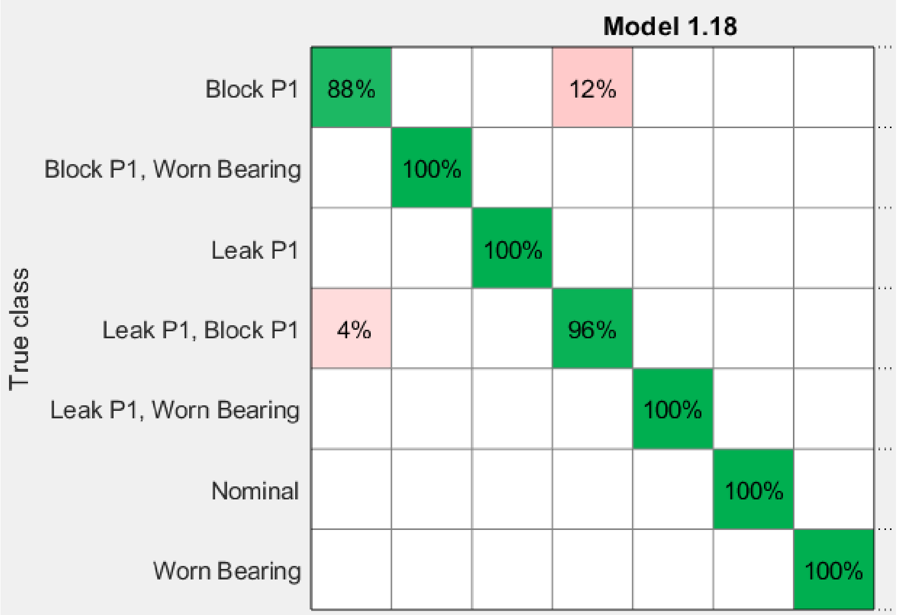
to a predictive
maintenance
algorithm





created using
a Digital Twin

and machine
learning
in MATLAB.

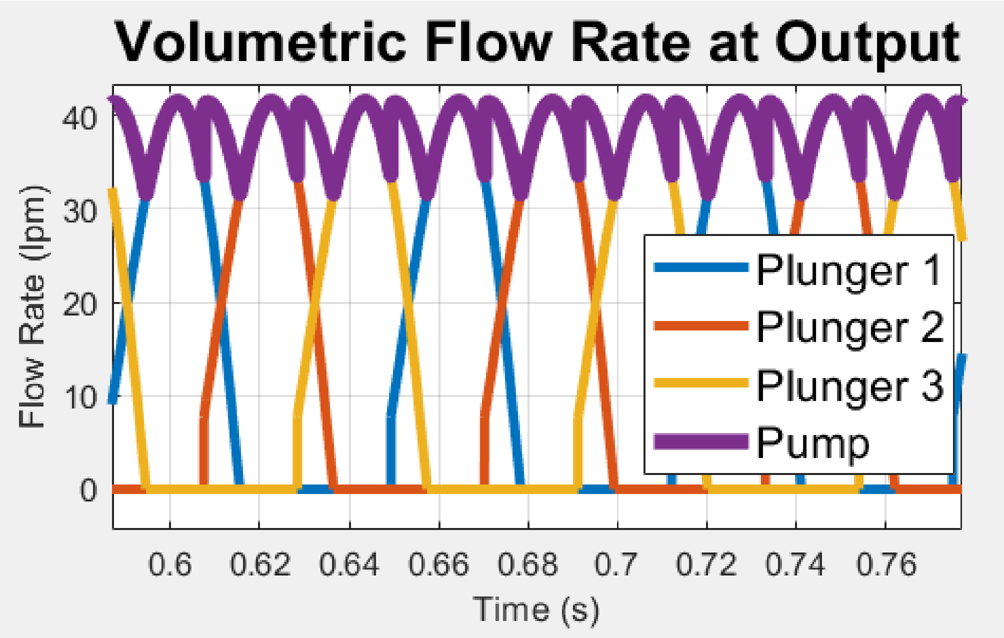


Model 1.18

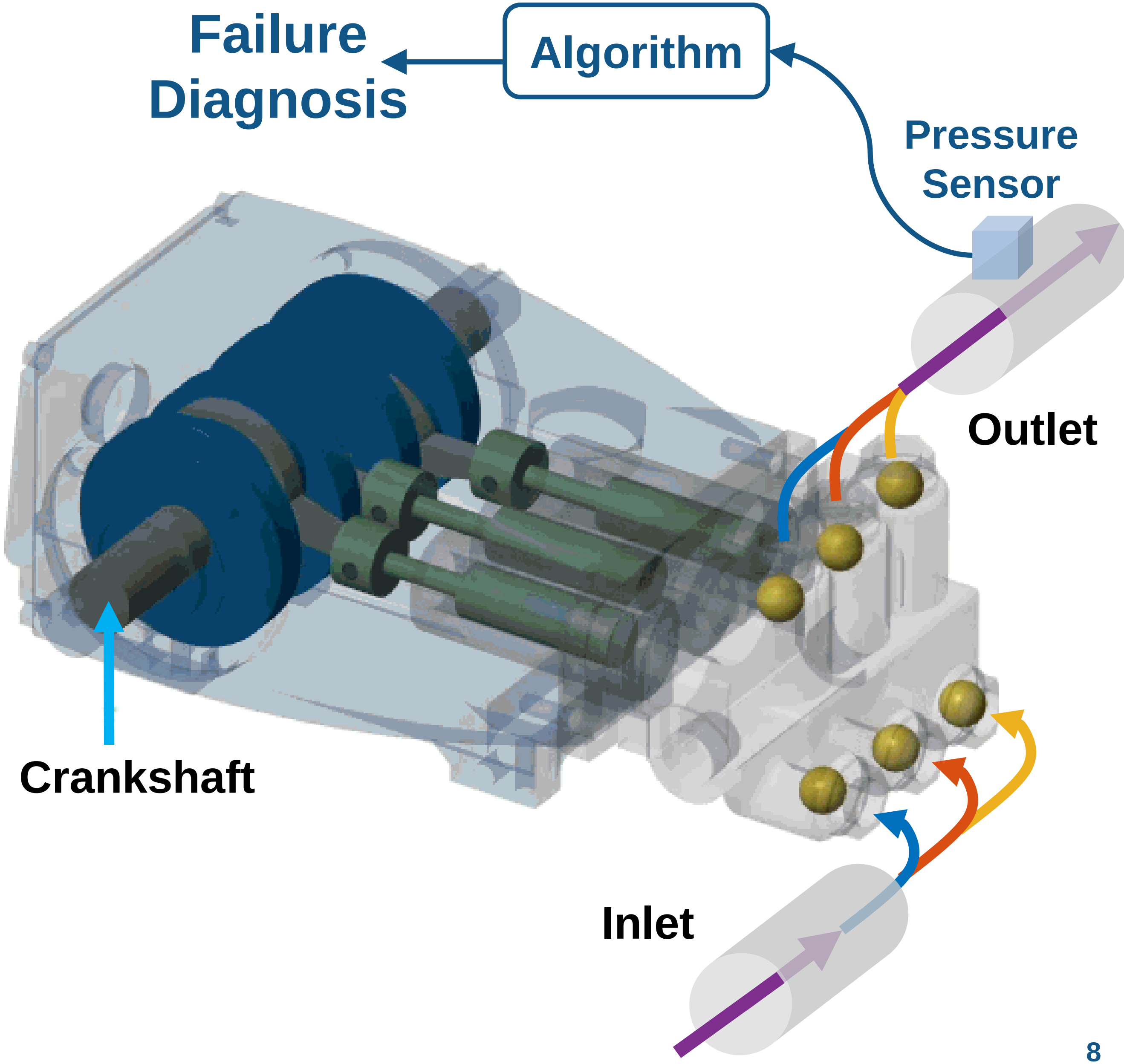
True class							
Block P1	88%			12%			
Block P1, Worn Bearing		100%					
Leak P1			100%				
Leak P1, Block P1	4%			96%			
Leak P1, Worn Bearing					100%		
Nominal						100%	
Worn Bearing							100%

Triplex Pump

- Crankshaft drives three plungers
  - Each 120 degrees out of phase
  - One chamber always discharging
  - Smoother flow than single or duplex piston pumps



Volumetric Flow Rate at Output



Failure Diagnosis

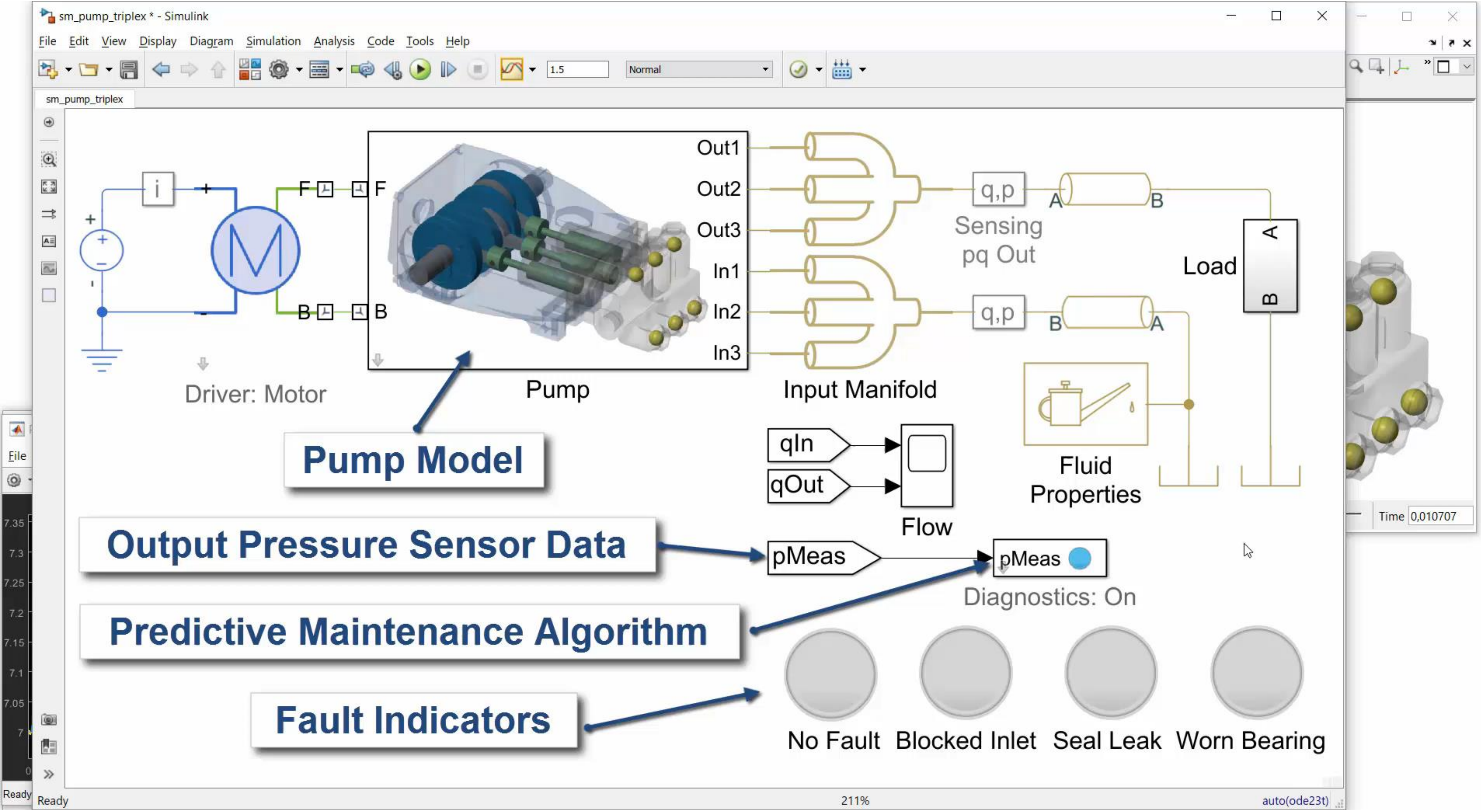
Algorithm

Pressure Sensor

Outlet

Crankshaft

Inlet



Pump Model

Output Pressure Sensor Data

Predictive Maintenance Algorithm

Fault Indicators

Agenda

- Predictive Maintenance Workflow

- Build a Digital Twin
  - Model physical system
  - Tune using measured data

- Create Predictive Model
  - Model component failure
  - Generate training data
  - Select and train classification model

- Deploy Fault Diagnostics Algorithm

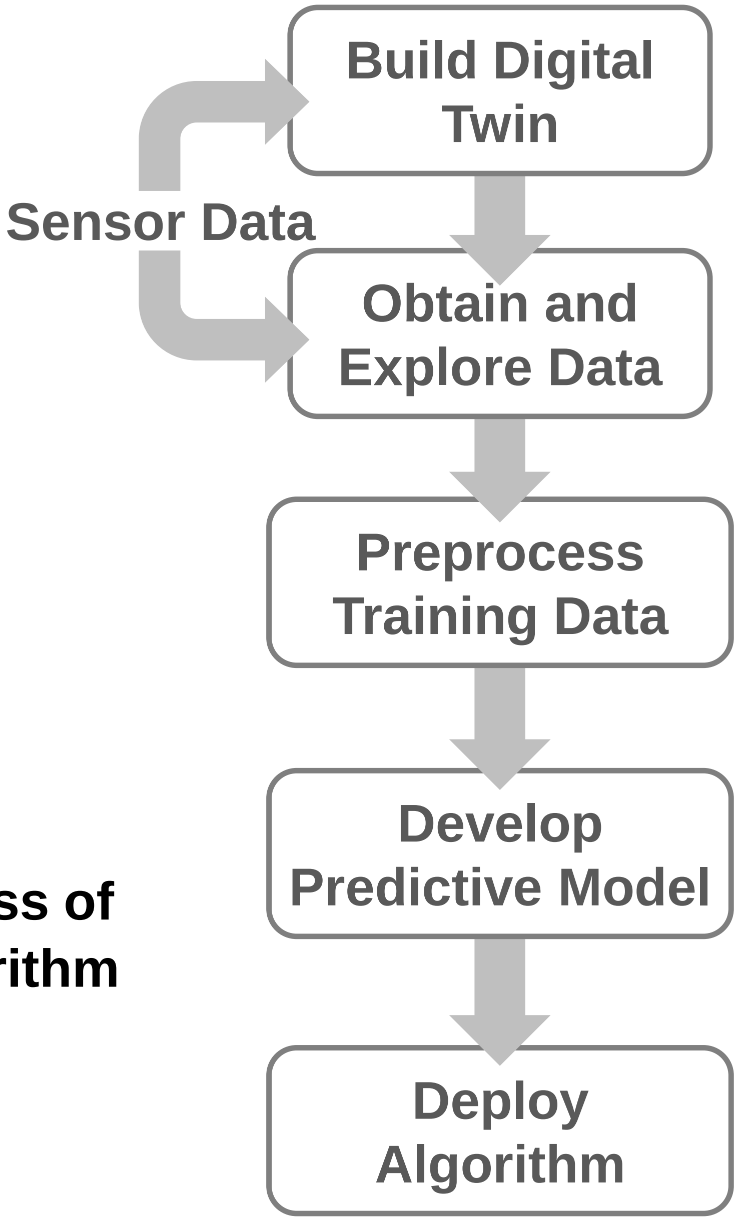
Predictive Maintenance Workflow

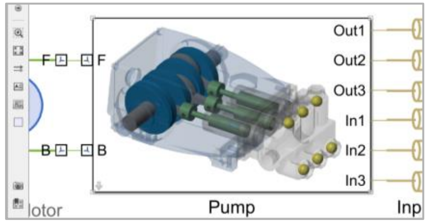
- Sensor data isn‘t always available
  - Failure conditions difficult to reproduce
  - Time consuming or costly to generate

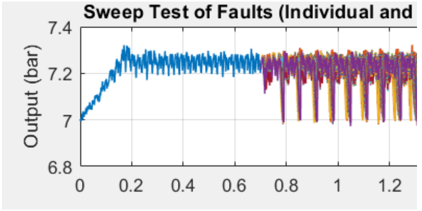
  Solution: Build digital twin and generate sensor data using simulation

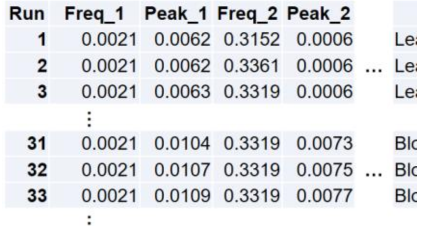
- Developing algorithm is complex
  - Requires complex concepts and analysis

  Solution: Use MATLAB to simplify process of developing and deploying algorithm

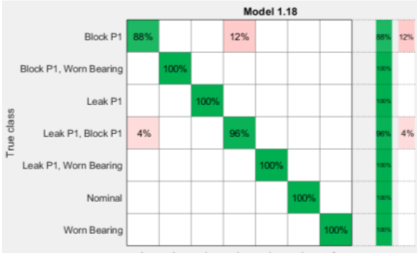

Sensor Data
Build Digital Twin
Obtain and Explore Data
Preprocess Training Data
Develop Predictive Model
Deploy Algorithm

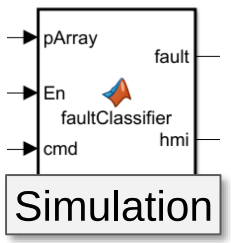




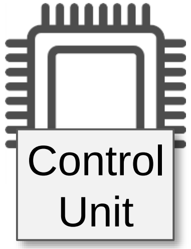


Run	Freq_1	Peak_1	Freq_2	Peak_2		
1	0.0021	0.0062	0.3152	0.0006		Lea
2	0.0021	0.0062	0.3361	0.0006	…	Lea
3	0.0021	0.0063	0.3319	0.0006		Lea
⋮						
31	0.0021	0.0104	0.3319	0.0073		Blo
32	0.0021	0.0107	0.3319	0.0075	…	Blo
33	0.0021	0.0109	0.3319	0.0077		Blo
⋮						





Simulation


Control Unit

5"
12,000 PSI
5"
12,000 PSI
BAKER HUGHES

Baker Hughes Develops Predictive Maintenance Software for Gas and Oil Extraction Equipment Using Data Analytics and Machine Learning

Challenge

Develop a predictive maintenance system to reduce pump equipment costs and downtime

Solution

Use MATLAB to analyze nearly one terabyte of data and create a neural network that can predict machine failures before they occur

Results

- Savings of more than $10 million projected
- Development time reduced tenfold
- Multiple types of data easily accessed

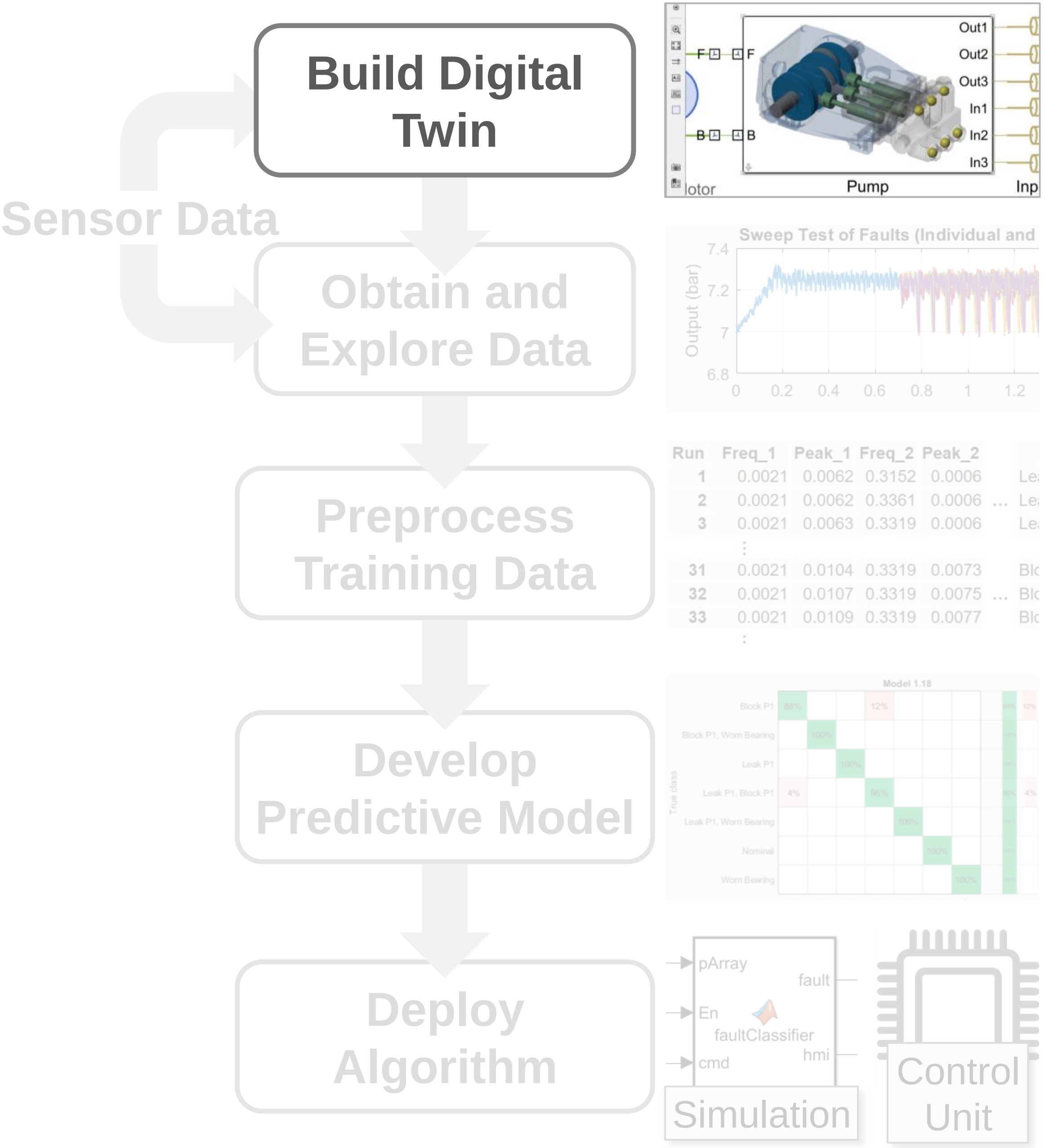
Truck with positive displacement pump.

> *"MATLAB gave us the ability to convert previously unreadable data into a usable format; automate filtering, spectral analysis, and transform steps for multiple trucks and regions; and ultimately, apply machine learning techniques in real time to predict the ideal time to perform maintenance."*
>
> *- Gulshan Singh, Baker Hughes*

Link to user story

Agenda

- Predictive Maintenance Workflow
- Build a Digital Twin
  - Model physical system
  - Tune using measured data
- Create Predictive Model
  - Model component failure
  - Generate training data
  - Select and train classification model
- Deploy Fault Diagnostics Algorithm



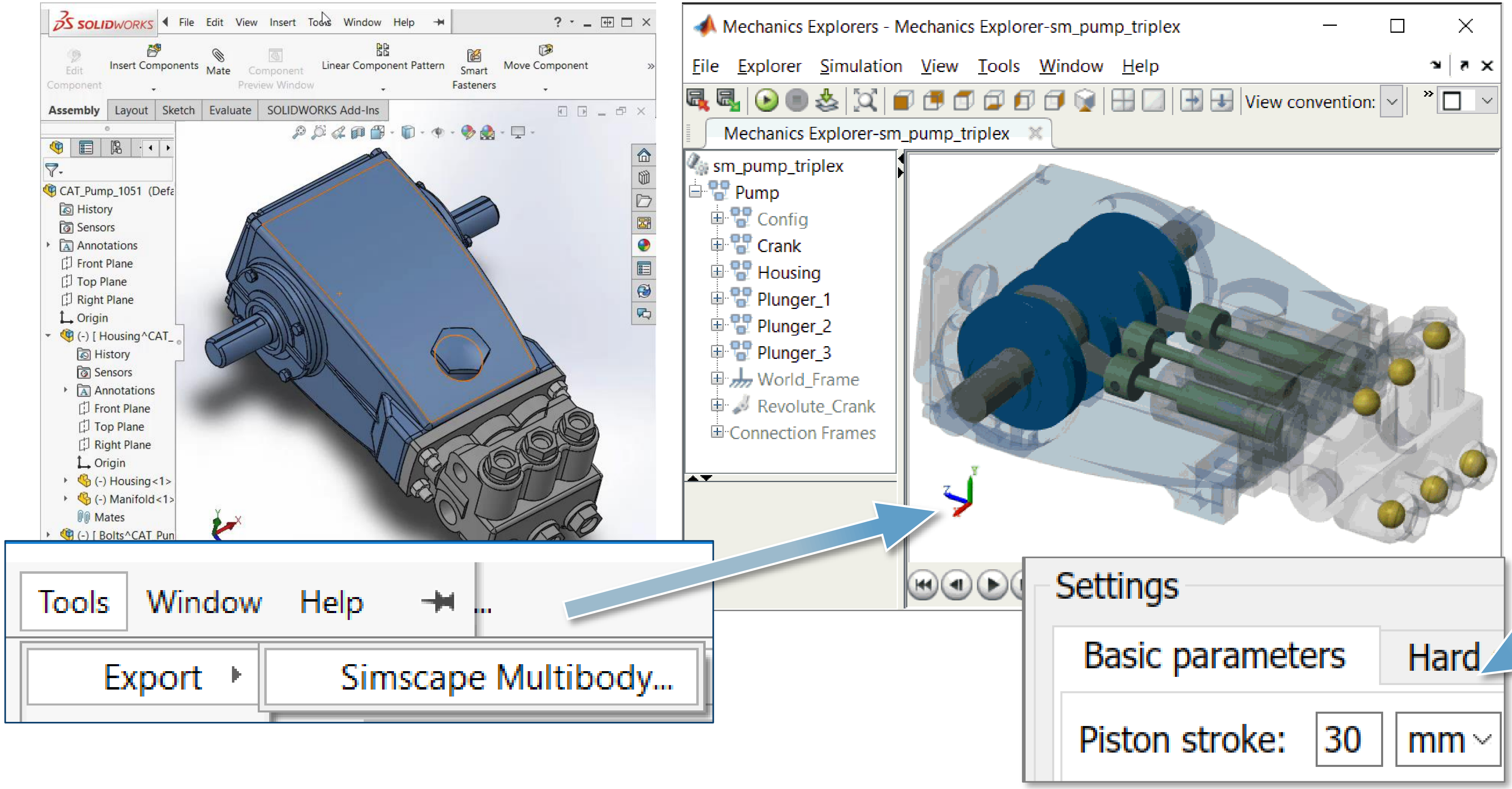
Run	Freq_1	Peak_1	Freq_2	Peak_2		
1	0.0021	0.0062	0.3152	0.0006		Le
2	0.0021	0.0062	0.3361	0.0006	...	Le
3	0.0021	0.0063	0.3319	0.0006		Le
⋮						
31	0.0021	0.0104	0.3319	0.0073		Bl
32	0.0021	0.0107	0.3319	0.0075	...	Bl
33	0.0021	0.0109	0.3319	0.0077		Bl
⋮						

Build Digital Twin of Hydraulic Pump

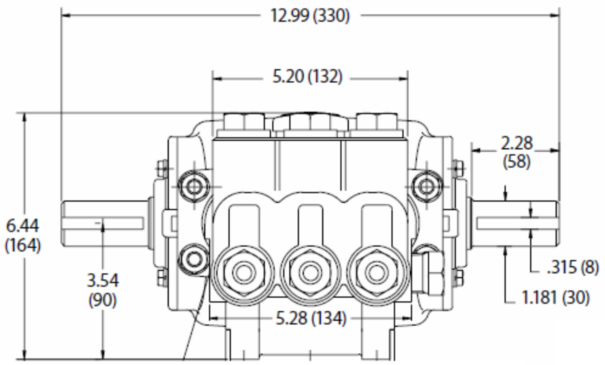
Import CAD Data

Digital Twin (Dynamic Model)

Tune to Datasheet



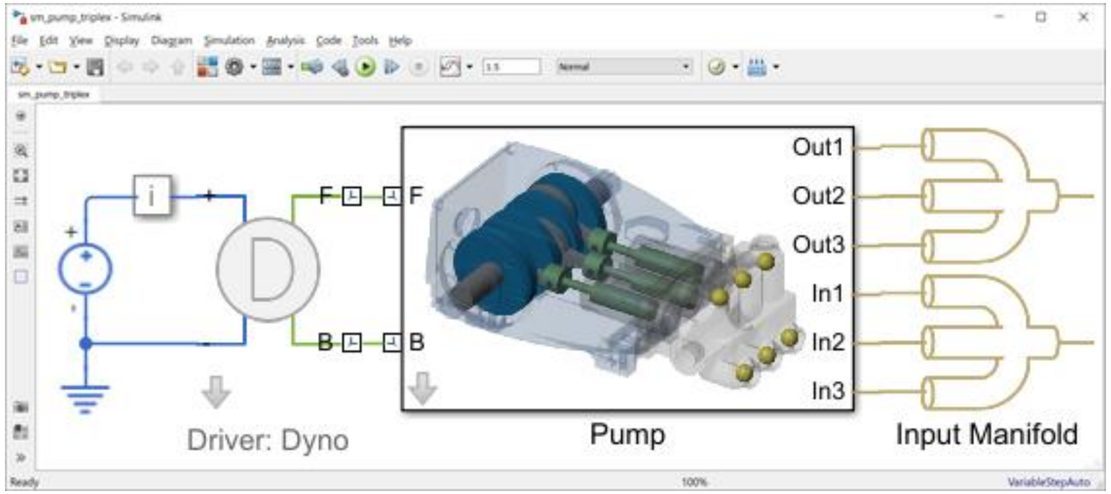
Piston stroke: 30 mm



COMMON SPECIFICATIONS	U.S.	Metric
Bore	0.945"	24 mm
Stroke	1.18"	30 mm
Crankcase Capacity	42 oz.	1.26 l
Shaft Diameter	1.181"	30 mm

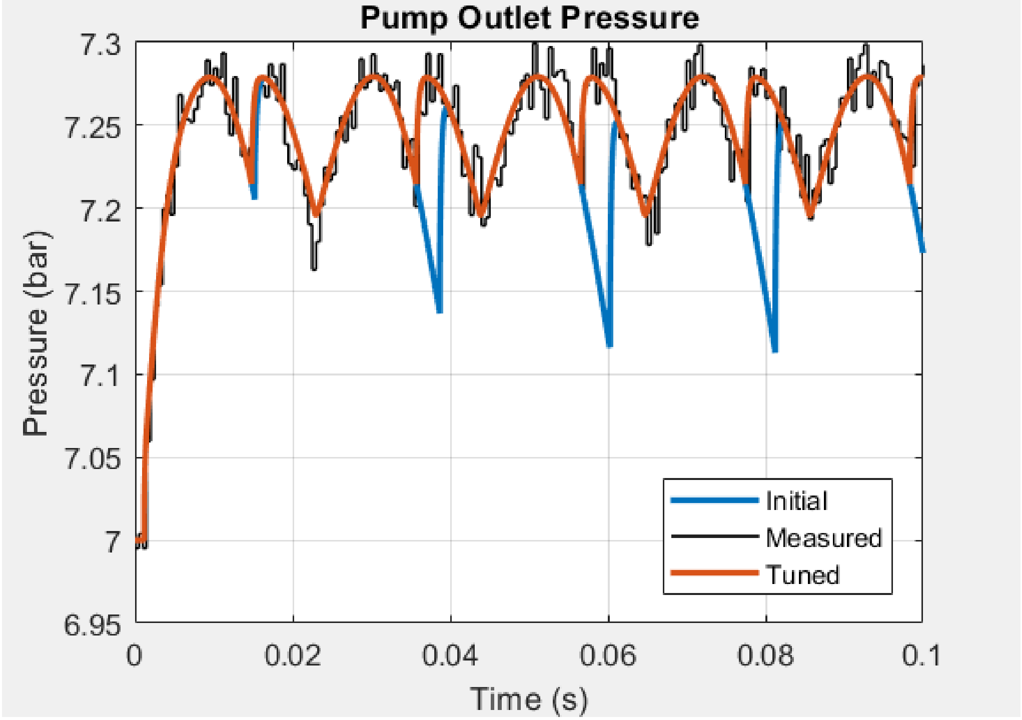
Estimate Parameters Using Measured Data

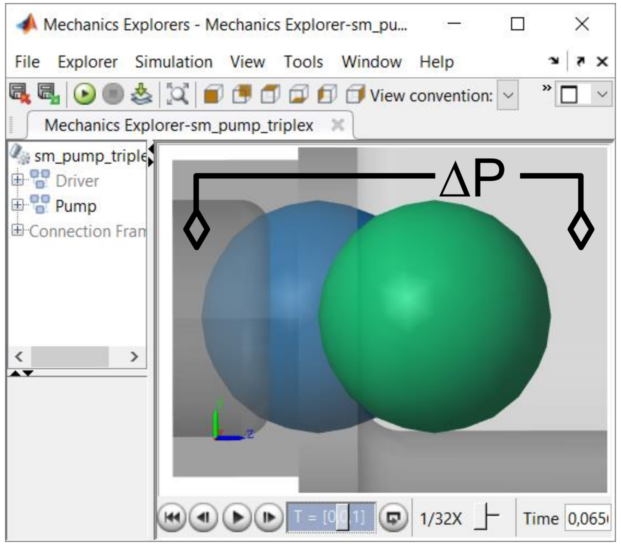
Model:


sm_pump_triplex - Simulink
File Edit View Display Diagram Simulation Analysis Code Tools Help
F
B
Out1
Out2
Out3
In1
In2
In3
Driver: Dyno
Pump
Input Manifold
Ready
100%
VariableStepAuto

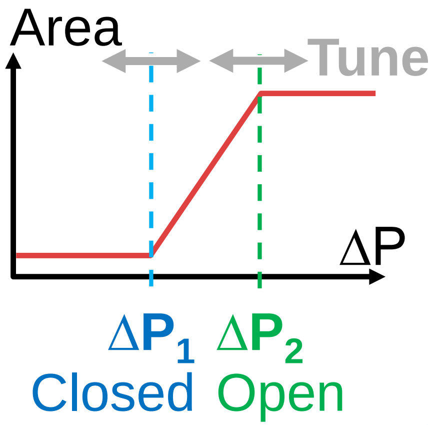
Challenge: Simulation results do not match behavior of real system

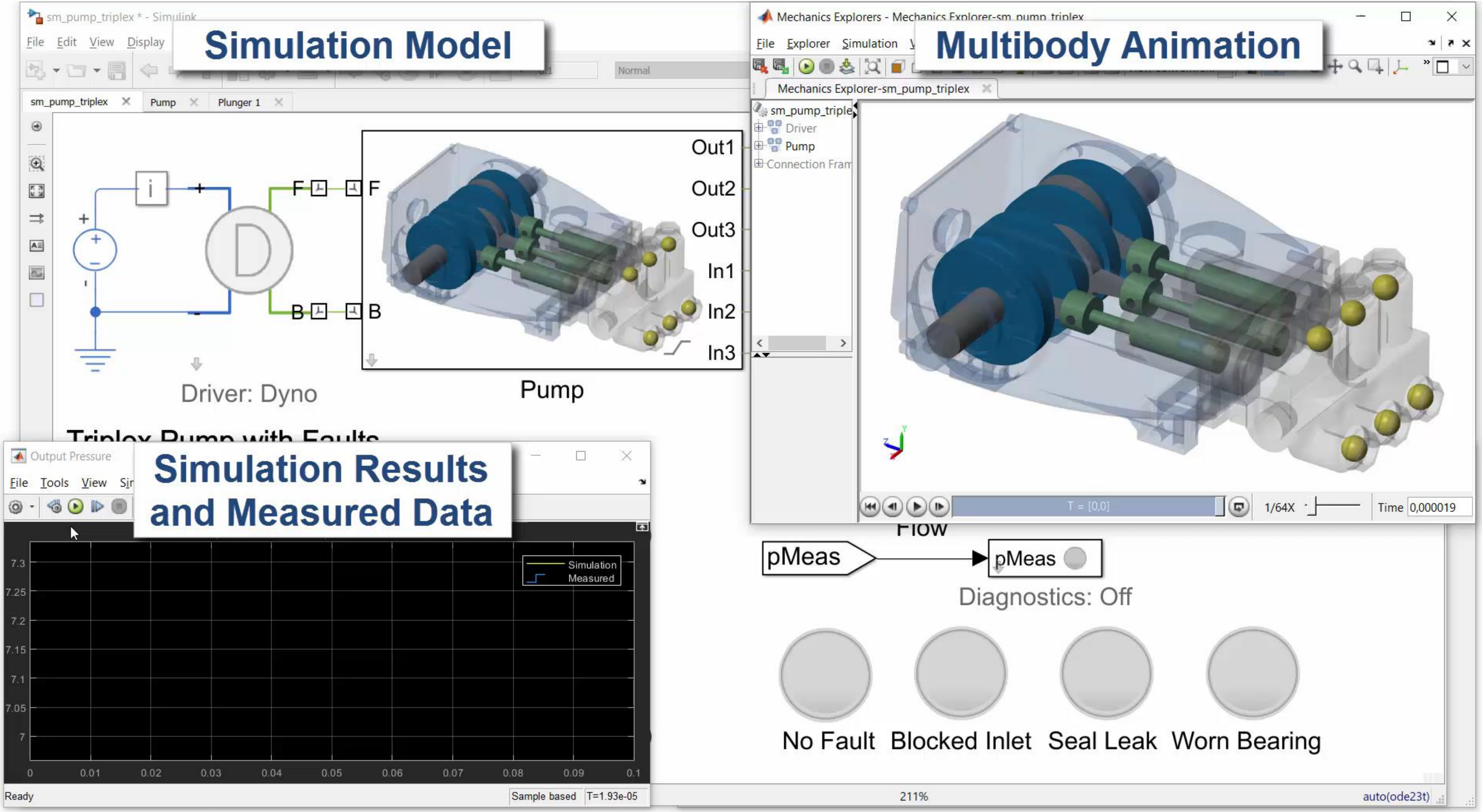
Solution: Use Simulink Design Optimization to automatically tune model parameters




Mechanics Explorers - Mechanics Explorer-sm_pu...
File Explorer Simulation View Tools Window Help
View convention:
Mechanics Explorer-sm_pump_triplex
sm_pump_triple
Driver
Pump
Connection Fran
ΔP
1/32X
Time 0,065

Check Valve Characteristic





Simulation Model

Multibody Animation

Simulation Results and Measured Data

Agenda

- Predictive Maintenance Workflow
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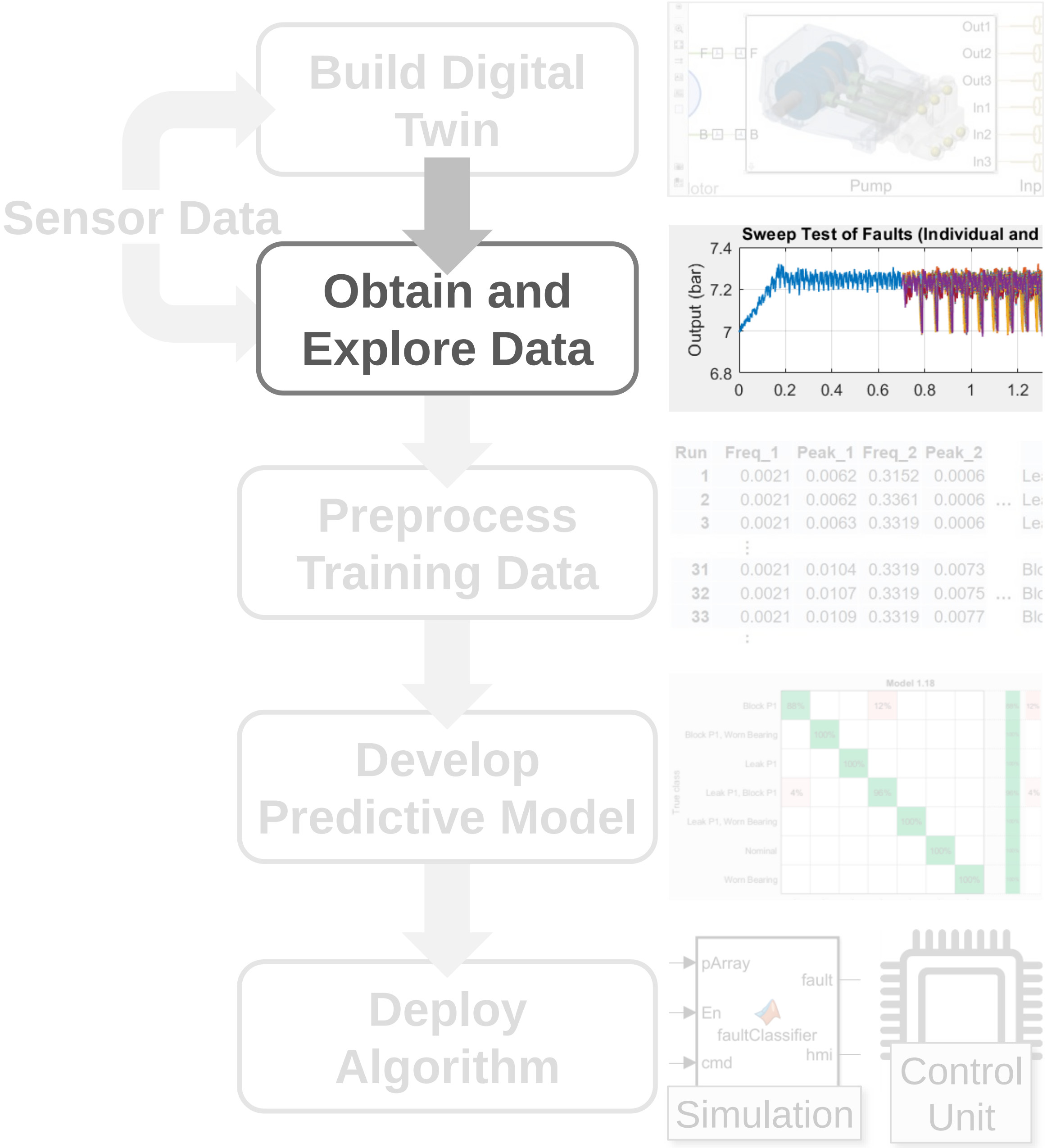
  - Select and train classification model
- Deploy Fault Diagnostics Algorithm



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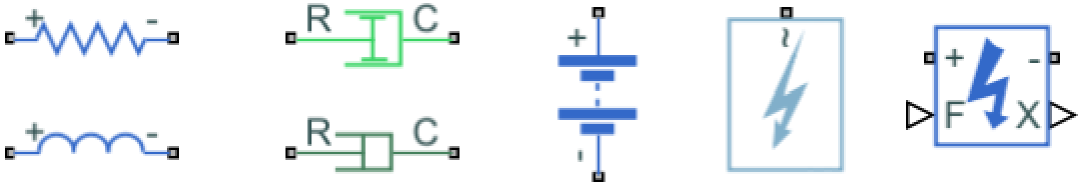
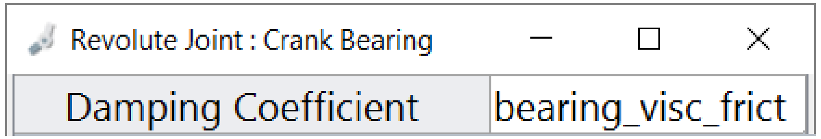
1	0.0021	0.0062	0.3152	0.0006		Le
2	0.0021	0.0062	0.3361	0.0006	...	Le
3	0.0021	0.0063	0.3319	0.0006		Le
⋮						
31	0.0021	0.0104	0.3319	0.0073		Blc
32	0.0021	0.0107	0.3319	0.0075	...	Blc
33	0.0021	0.0109	0.3319	0.0077		Blc
⋮						

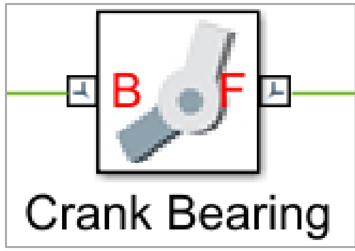
Model Component Failure

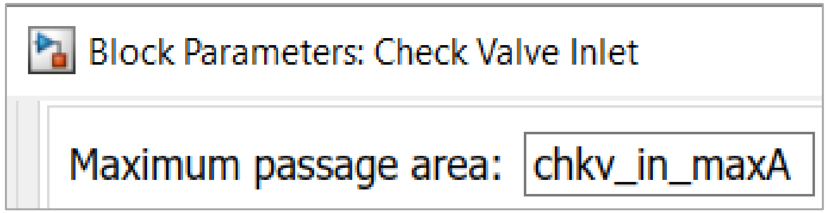
- Generic faults in many components
  - Short circuit, open circuit, friction, fade, etc.
  - Trigger based on time or conditions
- Adjust parameter values
  - Worn bearing adds friction
  - Blocked inlet has reduced passage area
- Adjust network
  - Seal leakage adds flow path
- Custom effects in Simulink
  - Broken winding applies no torque for 1/3 of every revolution




Revolute Joint : Crank Bearing

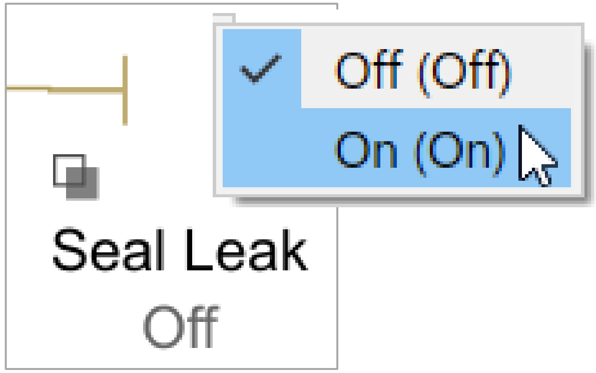
Damping Coefficient: bearing_visc_frict



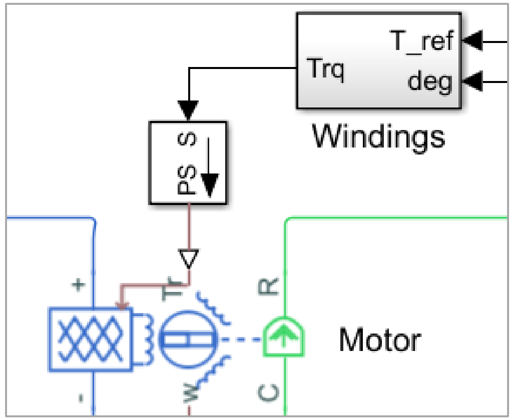

Block Parameters: Check Valve Inlet

Maximum passage area: chkv_in_maxA

A
B
Check Valve

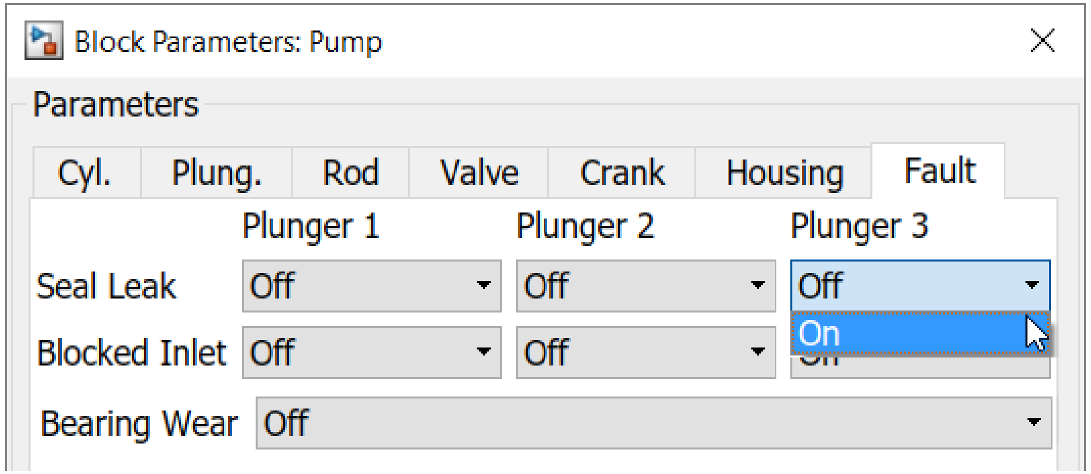

✓ Off (Off)

On (On)



Model Component Failure in Pump

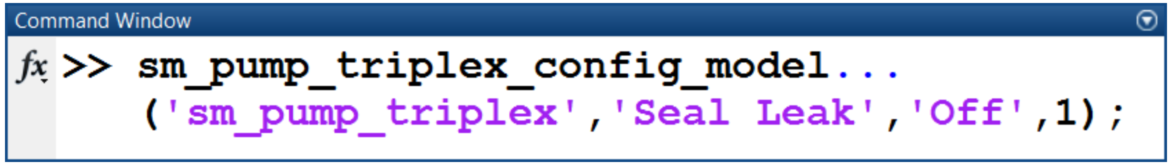
- Enable from UI or MATLAB
- Visual indication of fault



Block Parameters: Pump

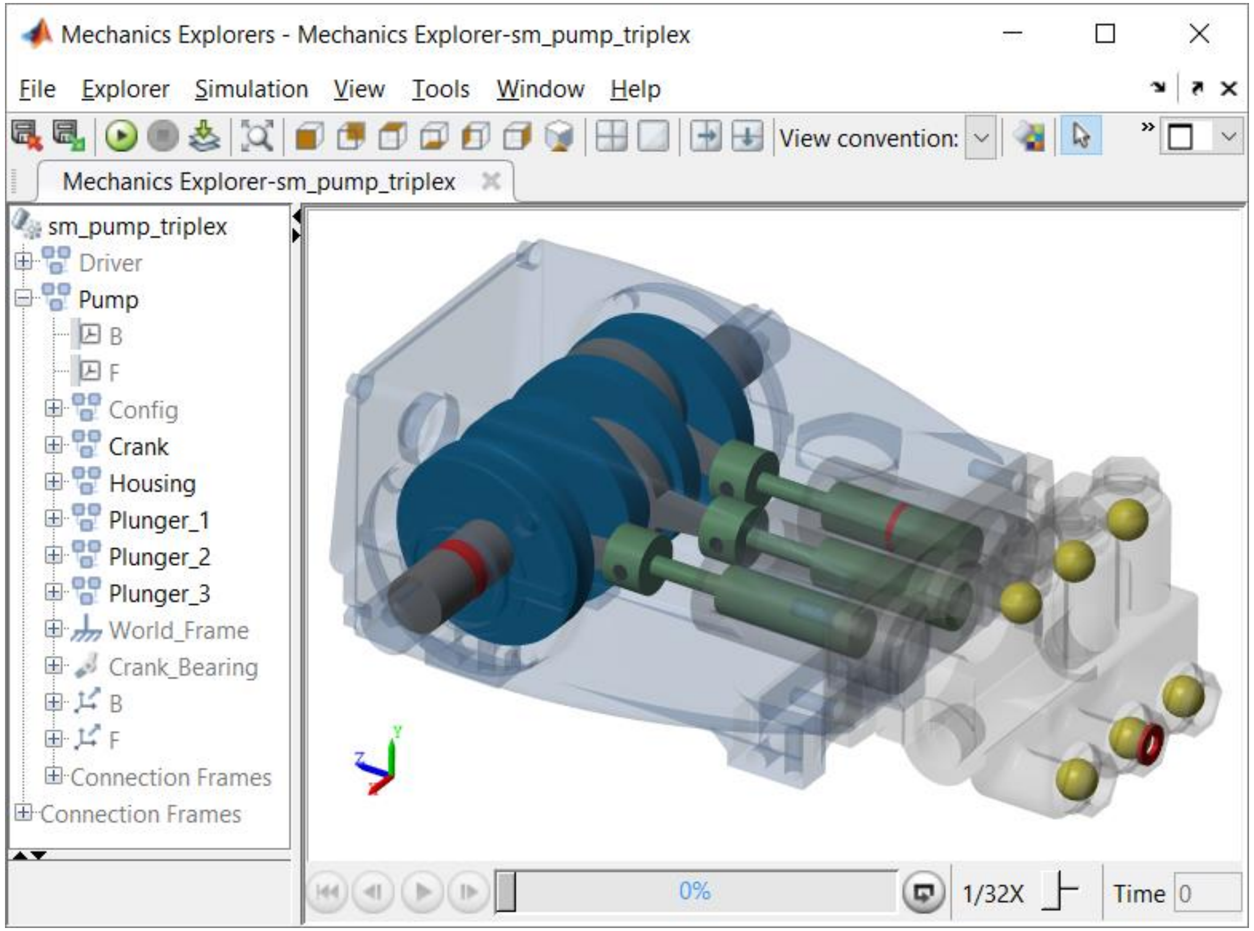
Parameters

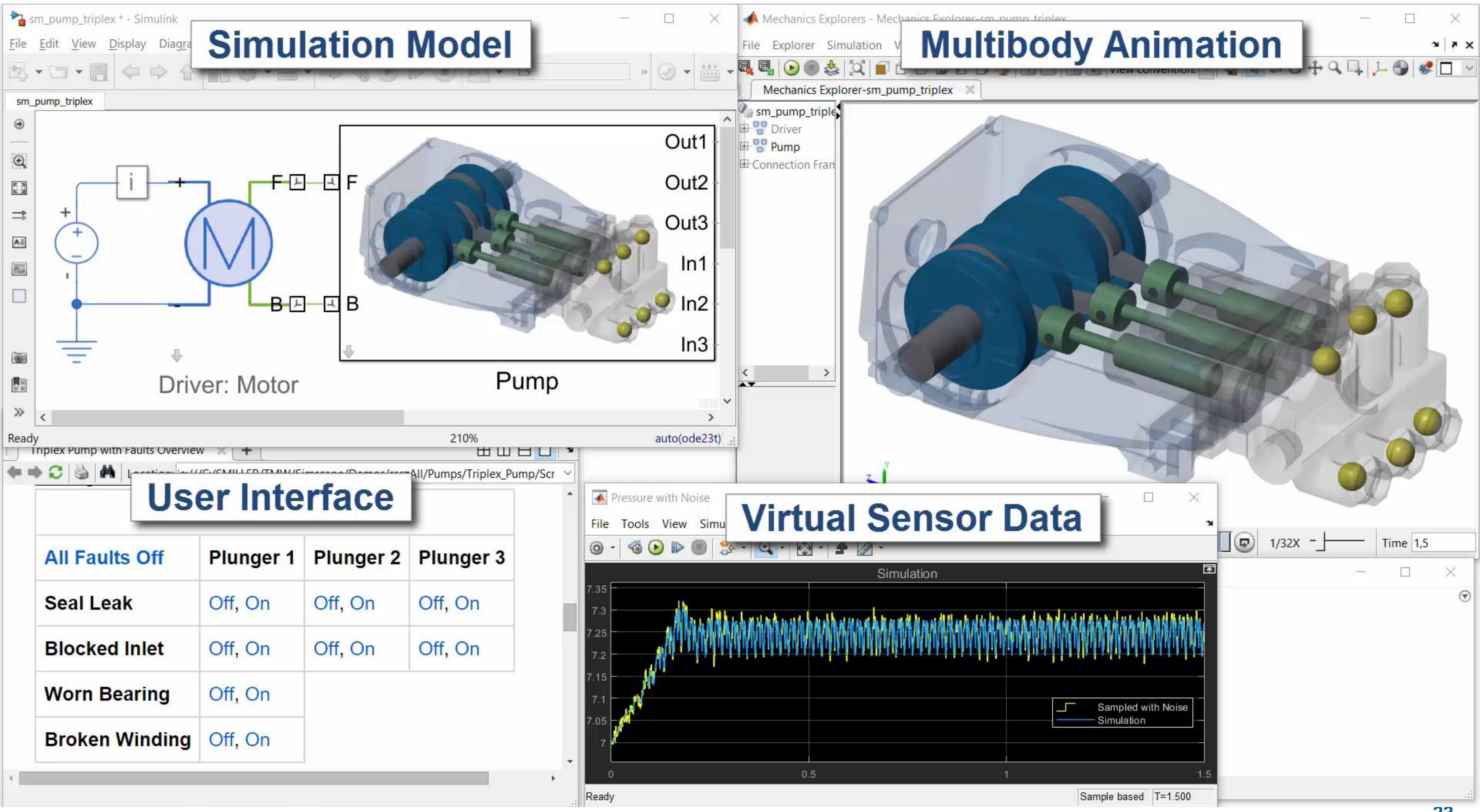
	Plunger 1	Plunger 2	Plunger 3
Seal Leak	Off	Off	Off On
Blocked Inlet	Off	Off	Off
Bearing Wear	Off		



Command Window

```
fx >> sm_pump_triplex_config_model...
      ('sm_pump_triplex','Seal Leak','Off',1);
```





Simulation Model

Multibody Animation

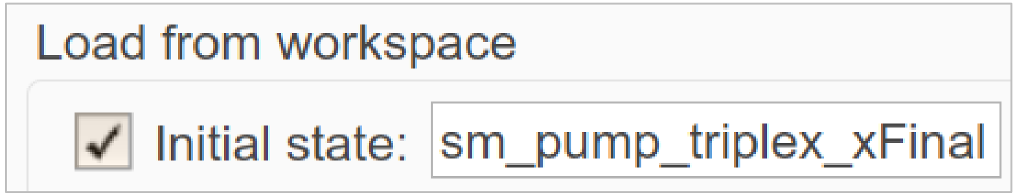
User Interface

Virtual Sensor Data

All Faults Off	Plunger 1	Plunger 2	Plunger 3
Seal Leak	Off, On	Off, On	Off, On
Blocked Inlet	Off, On	Off, On	Off, On
Worn Bearing	Off, On		
Broken Winding	Off, On		

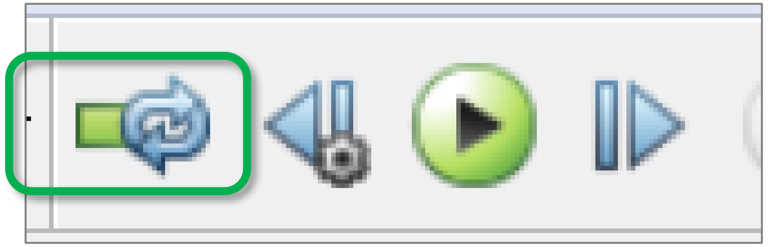
Quickly Create Sensor Data Using Parallel Computing and Initial State

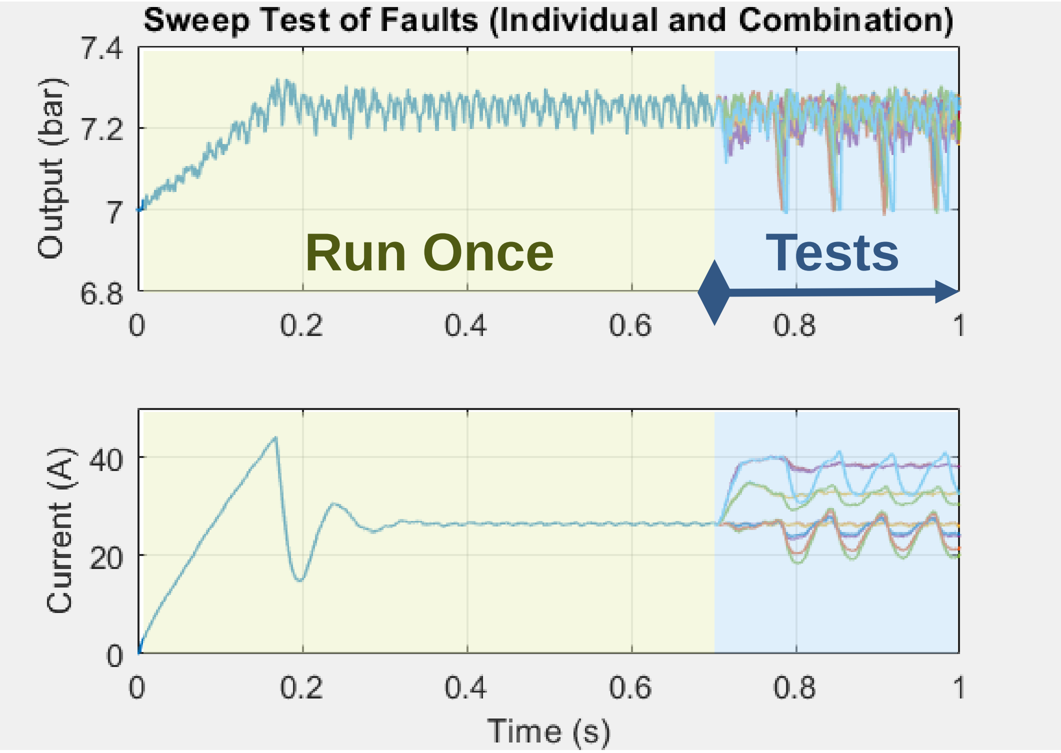
- Classification model requires data at various levels of failure for all fault combinations of interest
  - Many tests required
- Speed up tests
  - Start from steady state



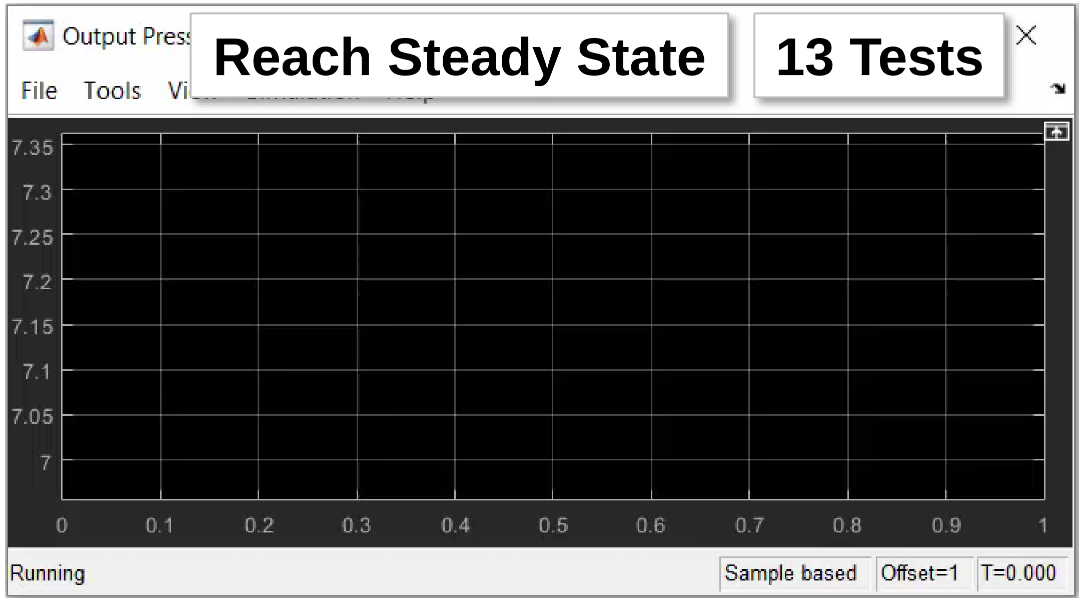
Load from workspace

☑ Initial state: sm_pump_triplex_xFinal





Sweep Test of Faults (Individual and Combination)



Reach Steady State

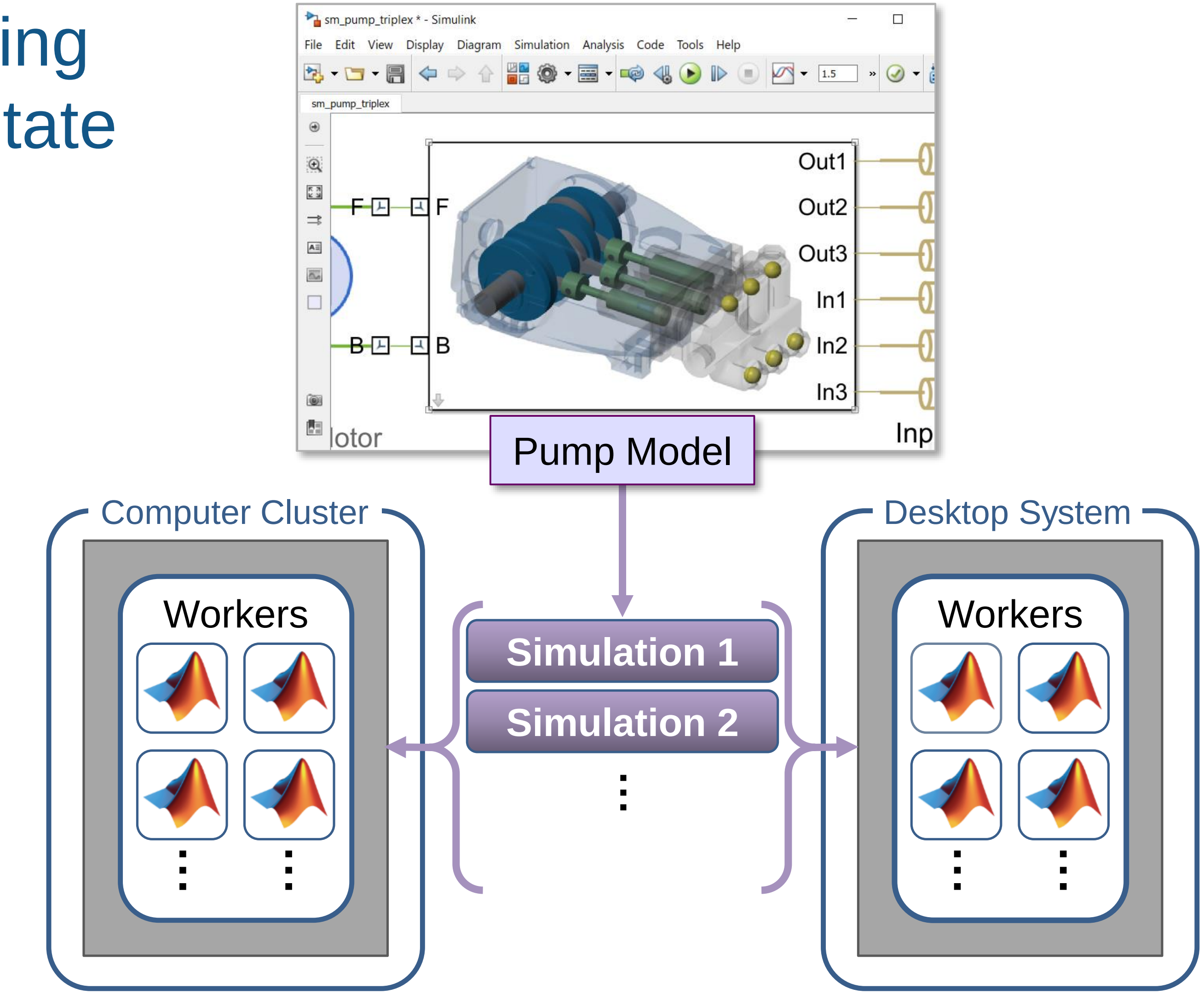
13 Tests

Running | Sample based | Offset=1 | T=0.000

Quickly Create Sensor Data Using Parallel Computing and Initial State

- Classification model requires data at various levels of failure for all fault combinations of interest
  - Many tests required
- Speed up tests
  - Start from steady state
  - Run tests in parallel

  Distribute to multiple desktop workers or across a computing cluster



Running simulations in parallel speeds up your testing process.

Agenda

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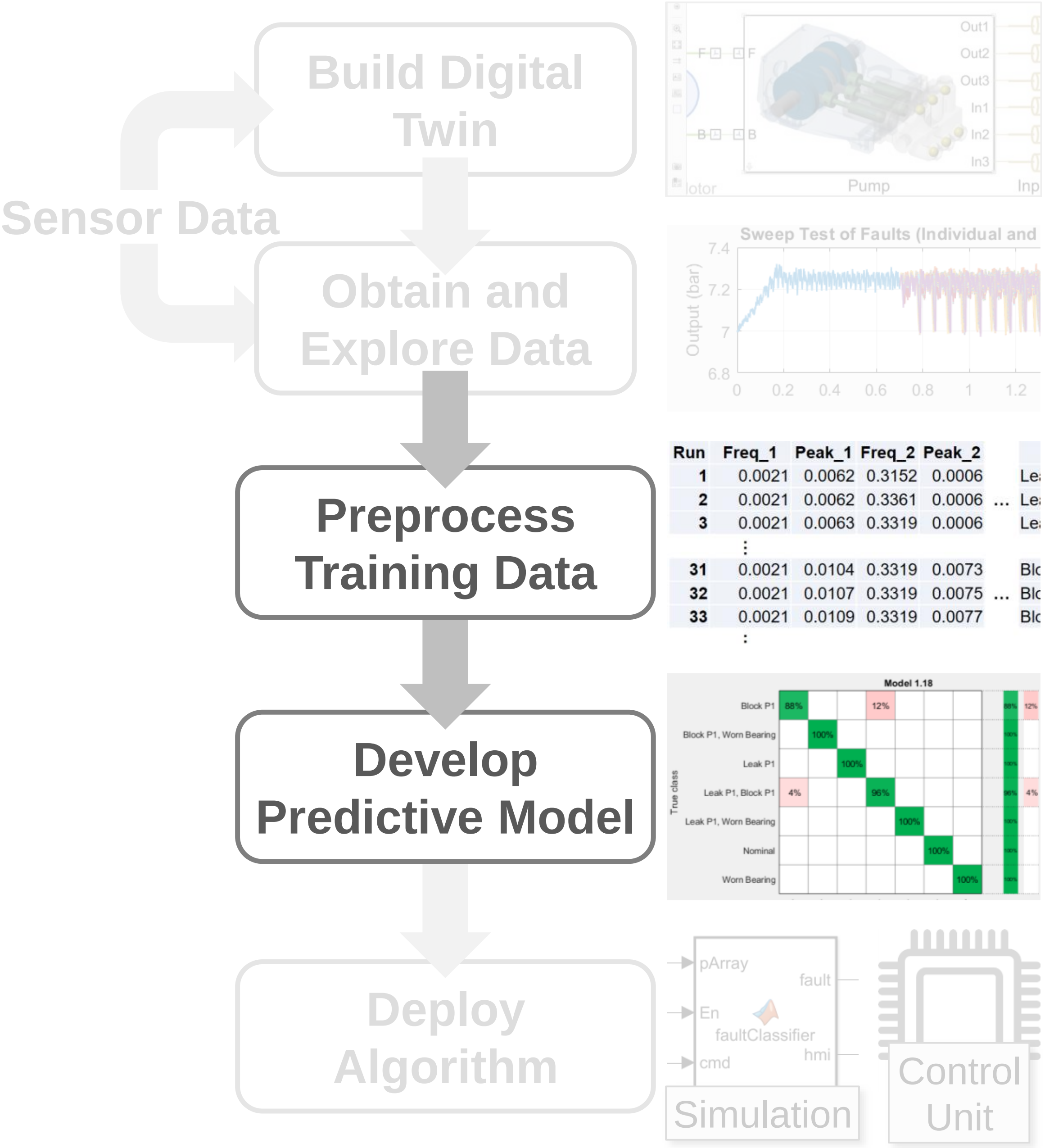

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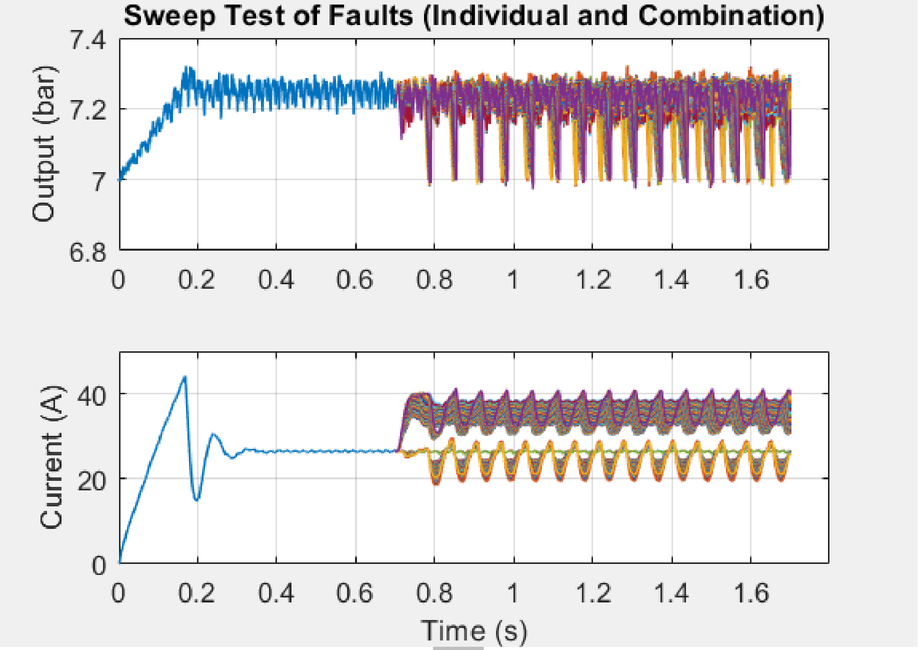
1	0.0021	0.0062	0.3152	0.0006		Le
2	0.0021	0.0062	0.3361	0.0006	...	Le
3	0.0021	0.0063	0.3319	0.0006		Le
	⋮					
31	0.0021	0.0104	0.3319	0.0073		Blc
32	0.0021	0.0107	0.3319	0.0075	...	Blc
33	0.0021	0.0109	0.3319	0.0077		Blc
	⋮					

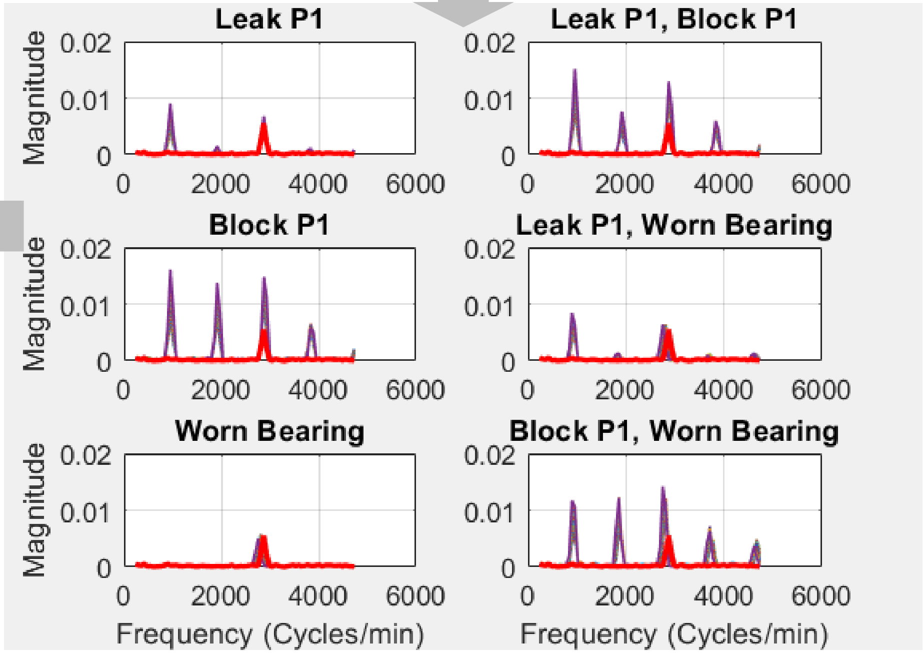
Extract Training Data from Sensor Measurements

- Perform FFT on results
  - Save frequencies, magnitudes, fault type

Classification Model Training Data

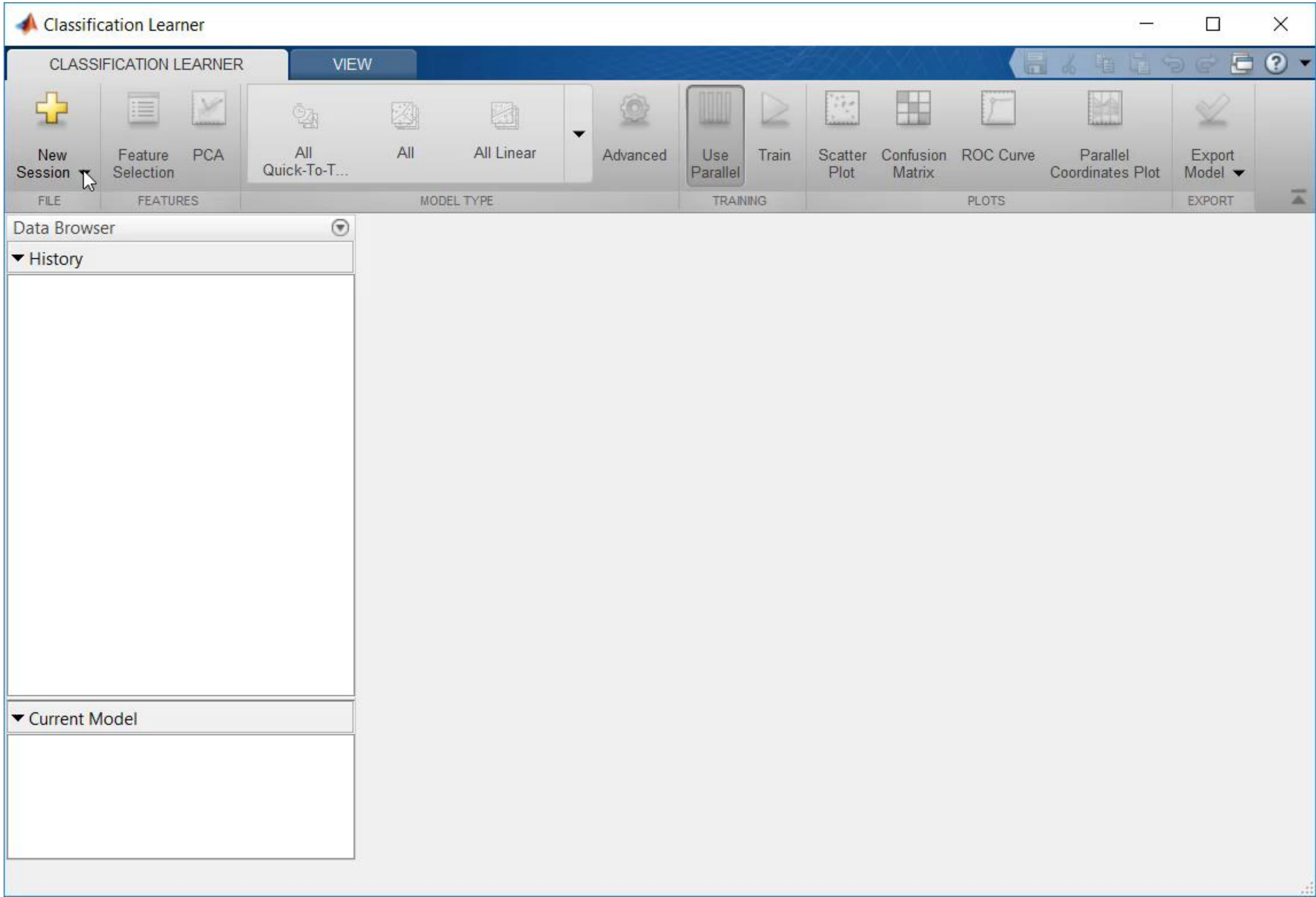
Run	Freq_1	Peak_1	Freq_2	Peak_2		Fault
1	0.0021	0.0062	0.3152	0.0006		Leak_P1
2	0.0021	0.0062	0.3361	0.0006	…	Leak_P1
3	0.0021	0.0063	0.3319	0.0006		Leak_P1
	⋮					⋮
31	0.0021	0.0104	0.3319	0.0073		Block_P1
32	0.0021	0.0107	0.3319	0.0075	…	Block_P1
33	0.0021	0.0109	0.3319	0.0077		Block_P1
	⋮					⋮
91	0.0021	0.0092	0.3319	0.0042		Leak P1, Block P1
92	0.0021	0.0095	0.3319	0.0044	…	Leak P1, Block P1
93	0.0021	0.0097	0.3319	0.0045		Leak P1, Block P1
	⋮					⋮
181	0.0021	0.0055				Nominal





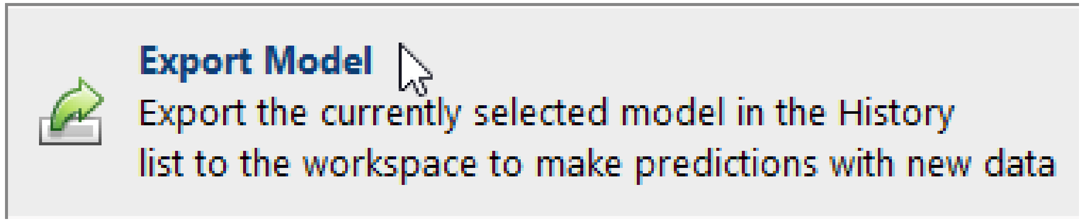
Evaluate all Classification Models

- Select data for training
- Train classifers
- Evaluate results
- Export trained classifer for testing in Digital Twin



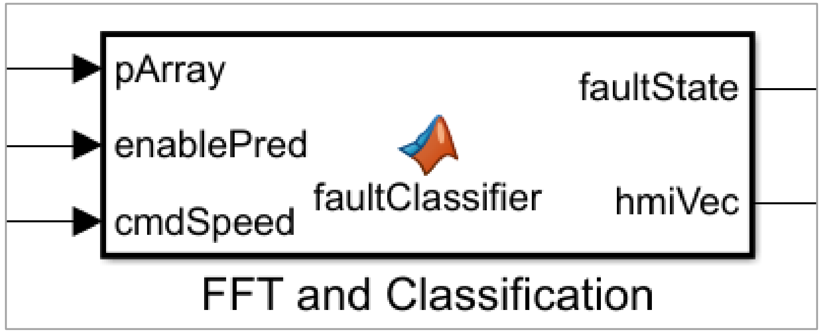
Test Algorithm in Simulation

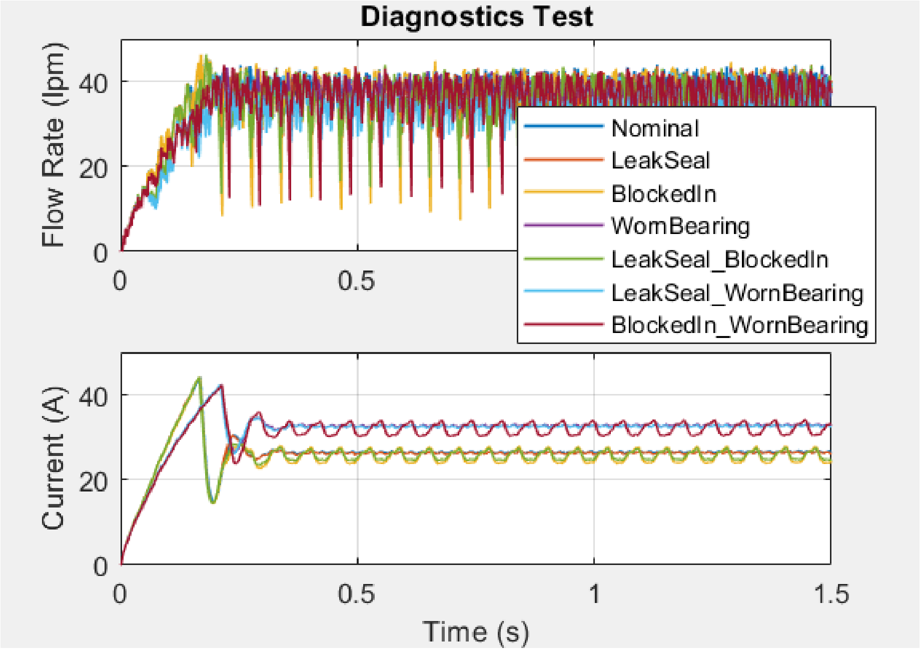
- Connect trained algorithm to digital twin
  - Verify behavior on new scenarios before deploying in embedded code

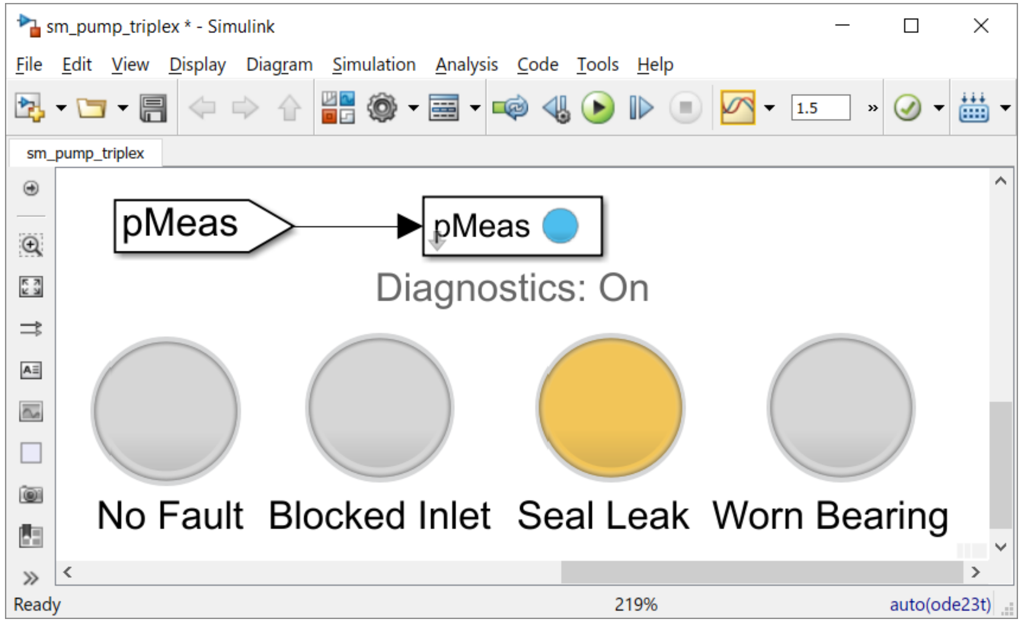


Export Model

Export the currently selected model in the History list to the workspace to make predictions with new data



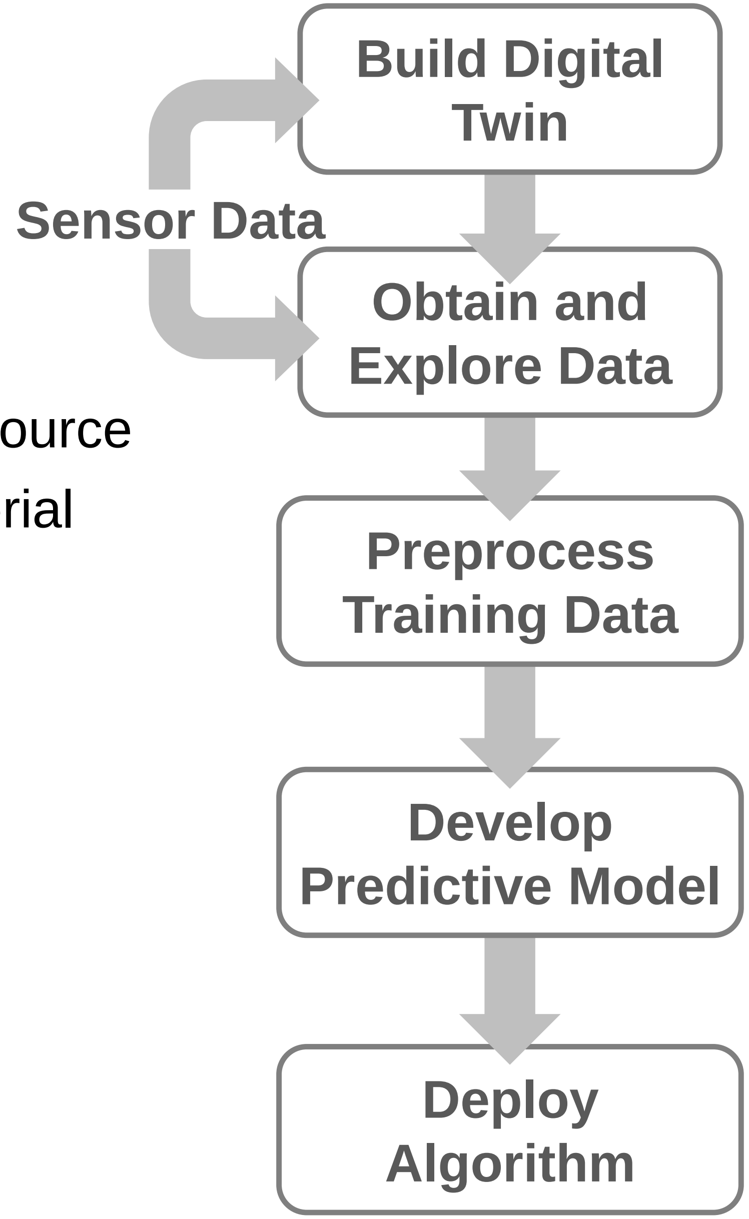


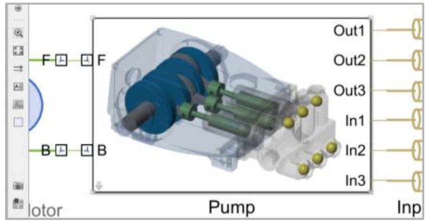


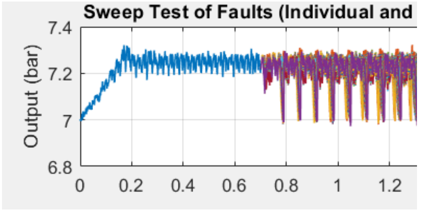
Automate Entire Algorithm Development Process

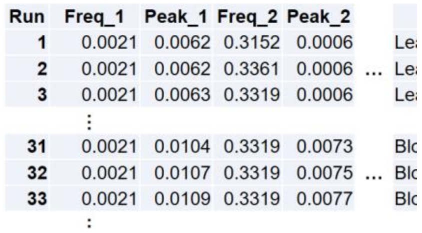
- Test and update algorithm when any aspect of system changes
  - Environment: temperature, fluid, power source
  - Supplier: Seals, valves, tolerances, material
  - Design: Larger, smaller, new markets

- Improve algorithm with new data
  - Tune digital twin with field data, automatically update algorithm

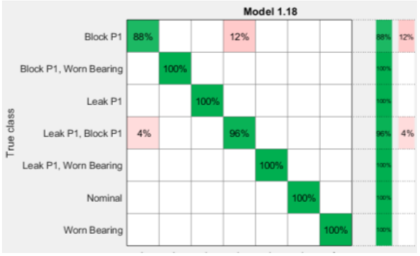


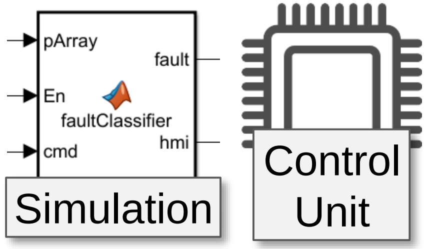




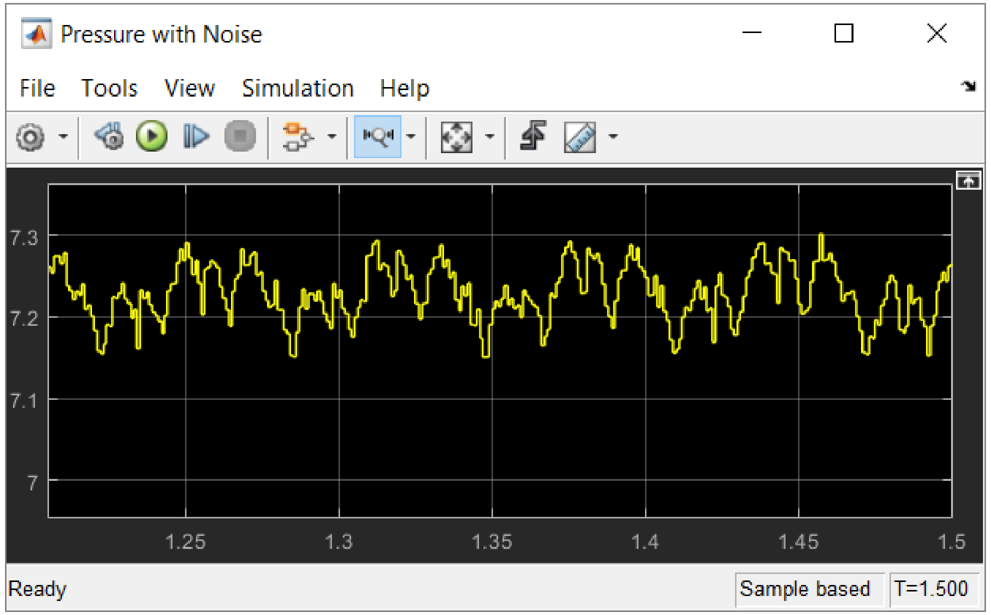


Run	Freq_1	Peak_1	Freq_2	Peak_2		
1	0.0021	0.0062	0.3152	0.0006		Le
2	0.0021	0.0062	0.3361	0.0006	...	Le
3	0.0021	0.0063	0.3319	0.0006		Le
	⋮					
31	0.0021	0.0104	0.3319	0.0073		Blc
32	0.0021	0.0107	0.3319	0.0075	...	Blc
33	0.0021	0.0109	0.3319	0.0077		Blc
	⋮					



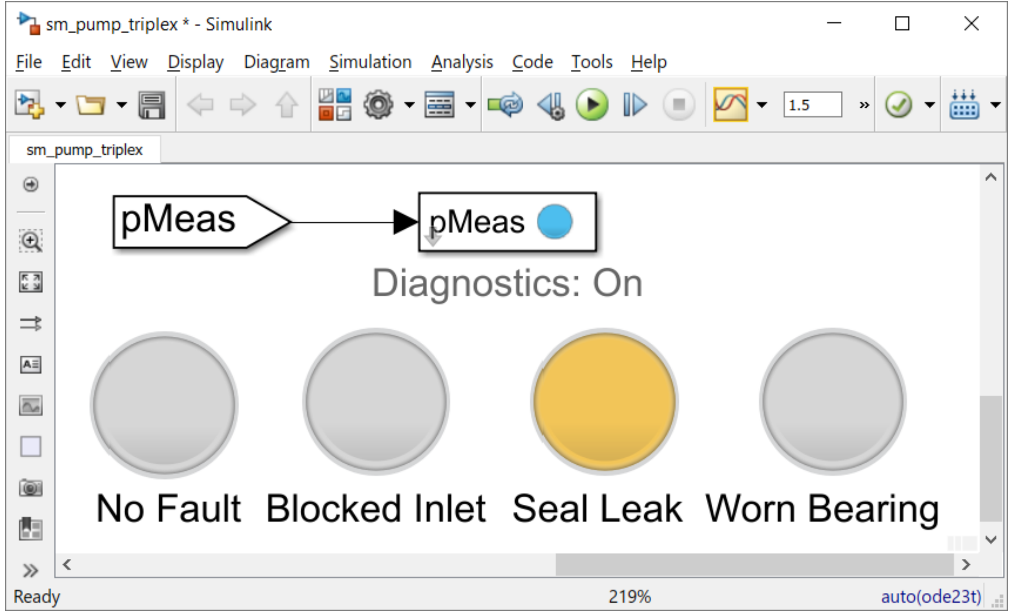


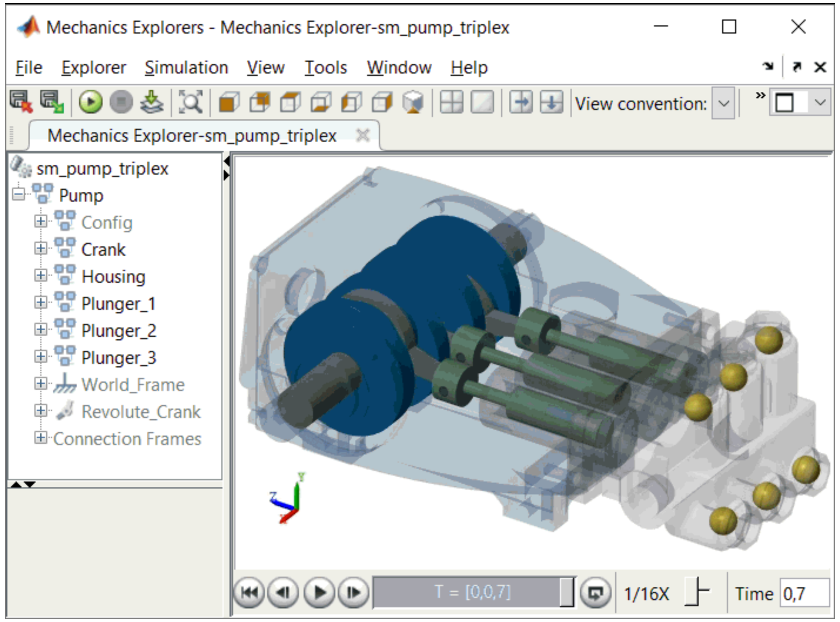
Prevent system downtime



by sending sensor data

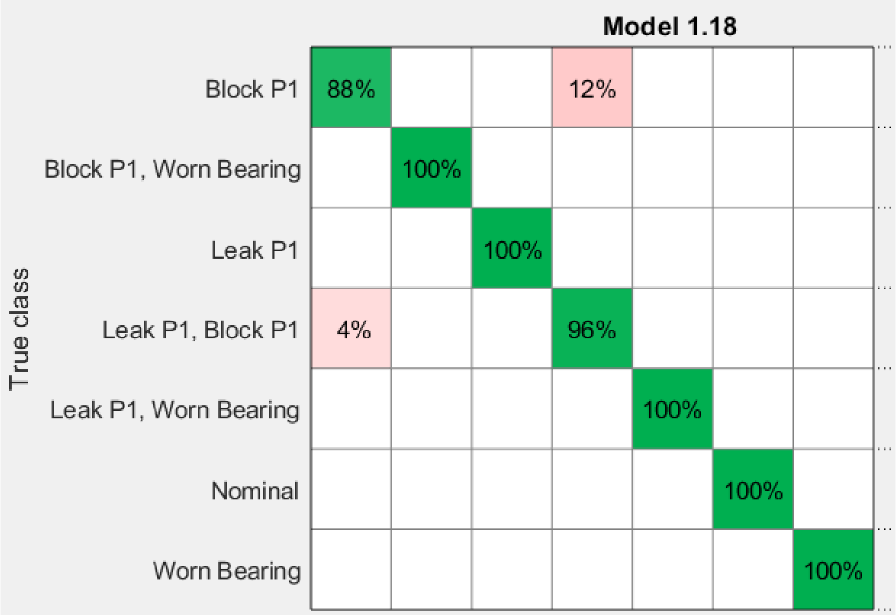
to a predictive maintenance algorithm





created using a Digital Twin

and machine learning in MATLAB.



Model 1.18

True class

Block P1	88%			12%			
Block P1, Worn Bearing		100%					
Leak P1			100%				
Leak P1, Block P1	4%			96%			
Leak P1, Worn Bearing					100%		
Nominal						100%	
Worn Bearing							100%