Predictive Maintenance in MATLAB

Terasoft

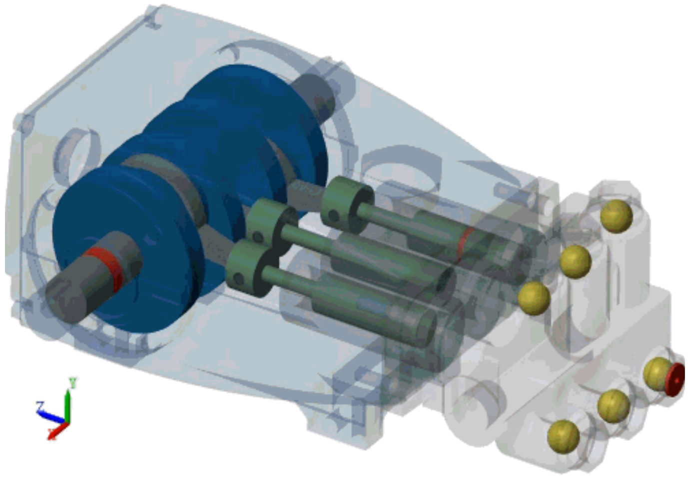
Application Engineer

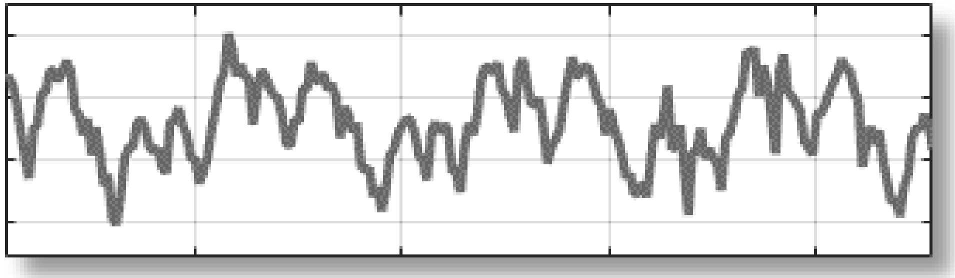
Jeffrey Liu

Outline

- Predictive Maintenance introduction
- Preprocessing the data (exercise 1)
- Feature extraction using diagnostic feature designer (exercise 2)
- Detecting fault using Classification Learner (exercise 3)
- Predicting remain useful life (exercise 4)
- Deployment

What is Predictive Maintenance?





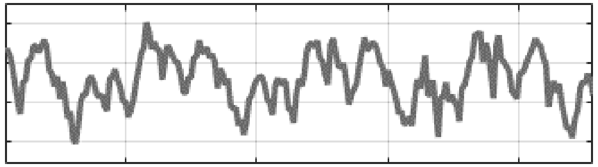
Translate

Turn off instant translation

English | Spanish | French | **Pump - detected**

English | Russian | Greek

Translate

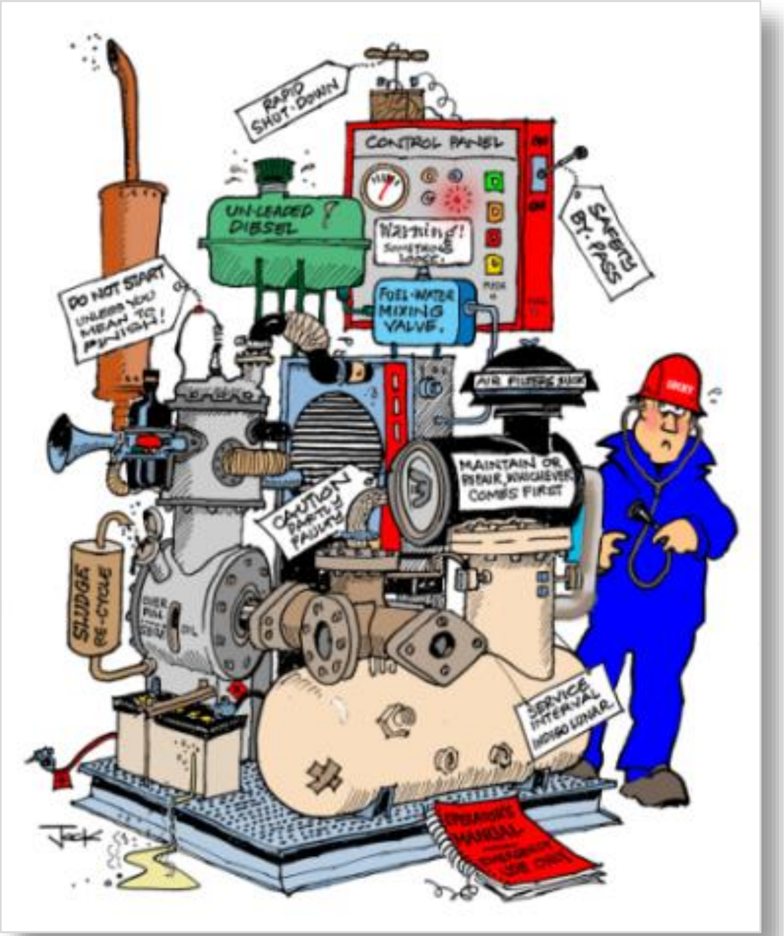


1/5000

I need help. One of my cylinders is blocked. I will shut down your line in 15 hours.

What do you expect from predictive maintenance?

- Maintenance cares about day-to-day operations
  - Reduced downtime
- Operations & IT look at the bigger picture
  - Improved operating efficiency
- Engineering groups get product feedback
  - Better customer experience
- Upper management wants to drive growth
  - New revenue streams



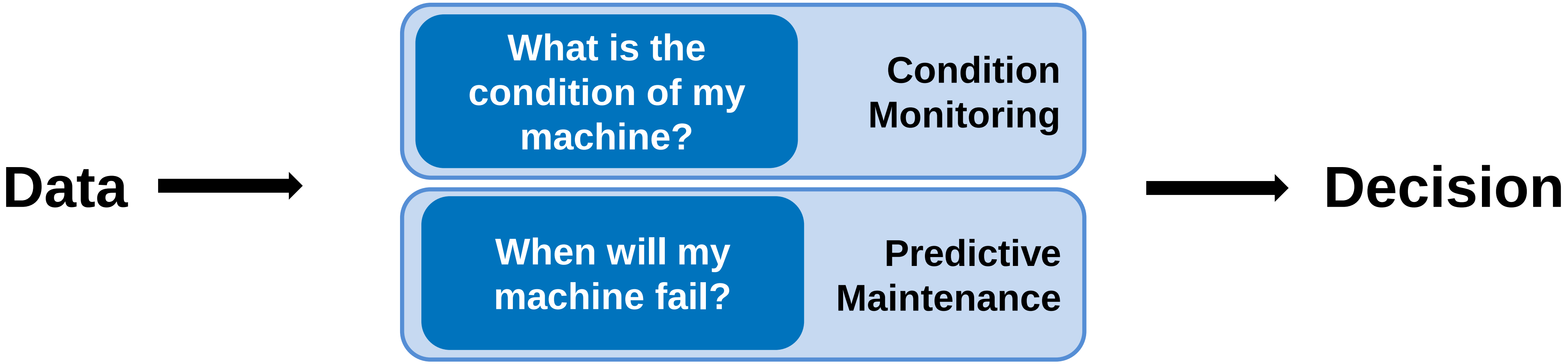
Source: Tensor Systems

Types of Maintenance

- Reactive – Do maintenance once there's a problem
  - Example: replace car battery when it fails
  - Problem: unexpected failures can be expensive and potentially dangerous
- Scheduled – Do maintenance at a regular rate
  - Example: change car's oil every 5,000 miles
  - Problem: unnecessary maintenance can be wasteful; may not eliminate all failures
- Predictive – Forecast when problems will arise
  - Example: certain GM car models forecast problems with the battery, fuel pump, and starter motor
  - Problem: difficult to make accurate forecasts for complex equipment

What does a Predictive Maintenance algorithm do?

Helps make maintenance decisions based on large volumes of complex data

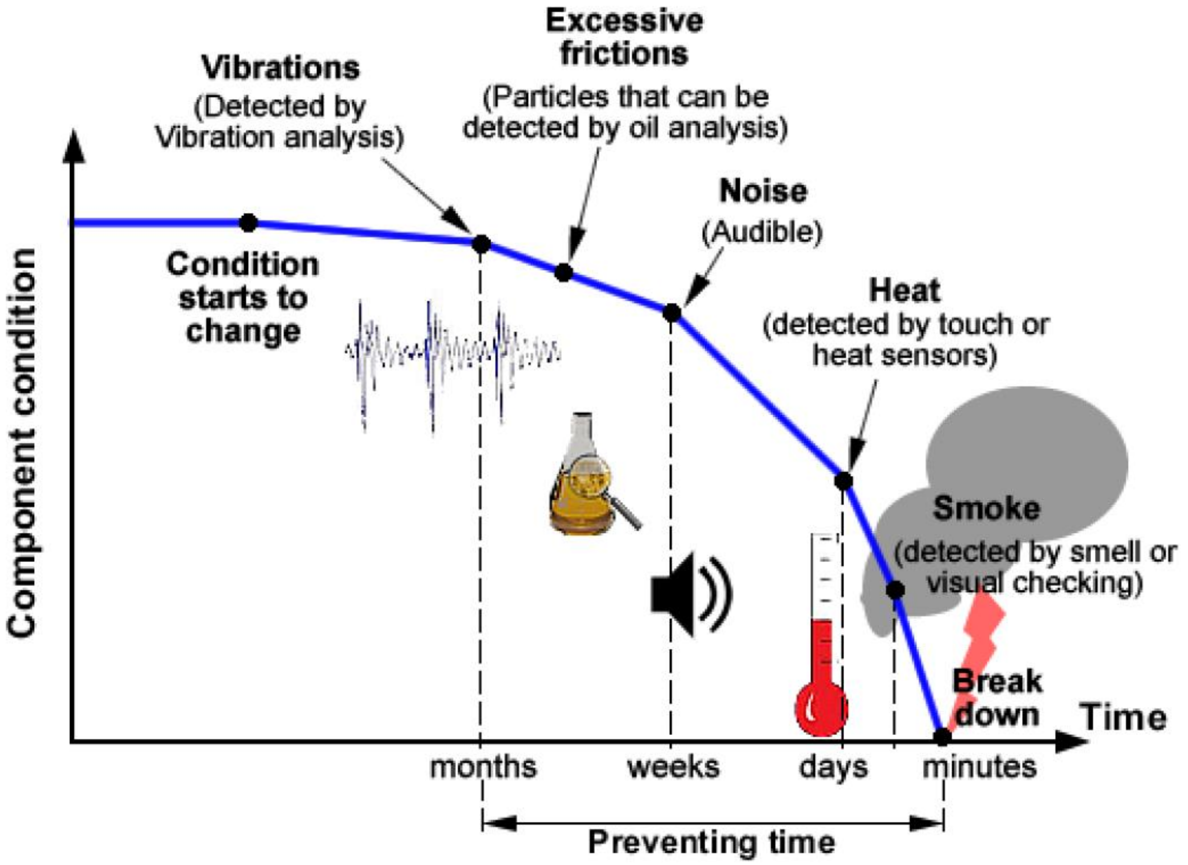


Condition Monitoring
Process of monitoring sensor data from machines (vibration, temperature etc.) in order to identify significant changes which can indicate developing faults

Predictive Maintenance
Technique that determines **time-to-failure/remaining useful life (RUL)** from sensor data & historical data in order to predict when maintenance should be performed

Before getting started on data...

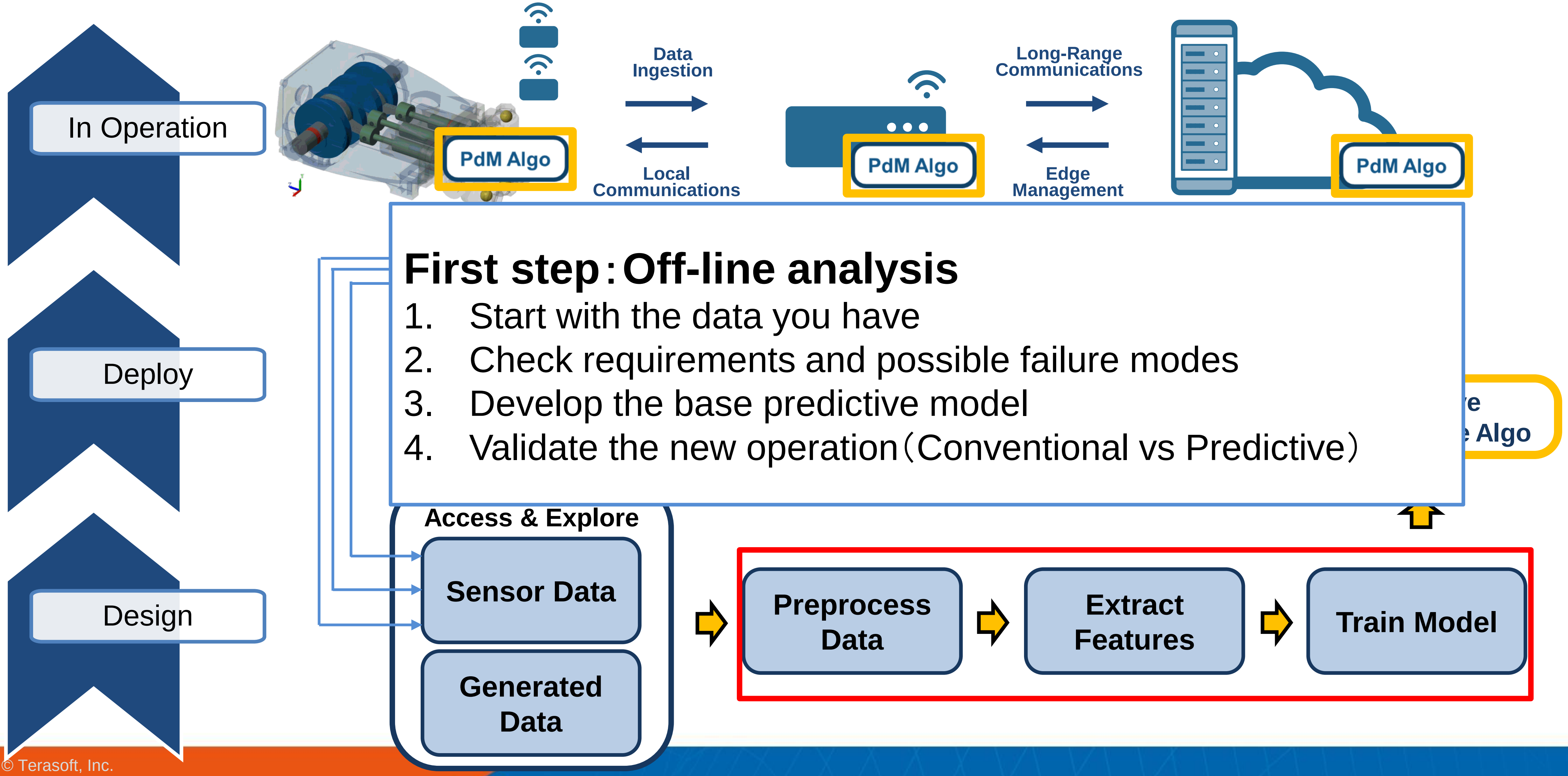
- What do you want to detect?
- How long before do you need to detect it?
- What are the accessible data?
- How much risk can you take?
- Apps on PC or deploy to the devices?



Typical development of a machine failure（Ex. Wind Turbine）

Tchakoua, Pierre, et al. "Wind turbine condition monitoring: State-of-the-art review, new trends, and future challenges." *Energies* 7.4 (2014): 2595-2630.

Predictive Maintenance Solution – Common Workflow



First step：Off-line analysis

1. Start with the data you have
2. Check requirements and possible failure modes
3. Develop the base predictive model
4. Validate the new operation（Conventional vs Predictive）

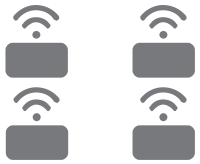
Predictive Maintenance Workflow : Four steps

Access and Explore Data → **Preprocess Data** → **Develop Predictive Models** → **Integrate Analytics with Systems**

Access and Explore Data

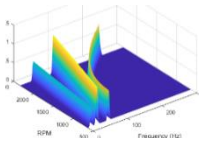
Business Data

Sensor Data

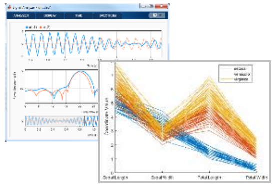


Preprocess Data

Data Reduction/ Transformation



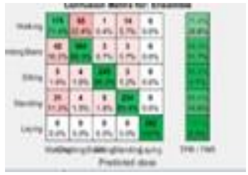
Feature Extraction



Develop Predictive Models

Model Creation

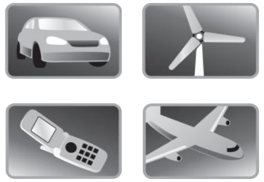
Model Validation



Integrate Analytics with Systems

Enterprise Systems

Embedded Devices



Predictive Maintenance Workflow : Four steps

Product examples

Access and Explore Data
- Simulink & Simscape
- OPC
- Database

Preprocess Data
- Wavelet
- Text Analytics
- Signal Processing
- Statistics & Machine Learning

Develop Predictive Models
- System Identification
- Neural Network

Integrate Analytics with Systems
- MATLAB Production Server
- Embedded Coder
- MATLAB Compiler SDK
- Simulink Coder
- MATLAB Compiler
- MATLAB Coder

MATLAB

Predictive Maintenance Workflow : Four steps

Product examples

Prerequisites

Access and Explore Data	Preprocess Data	Develop Predictive Models	Integrate Analytics with Systems

R2018a

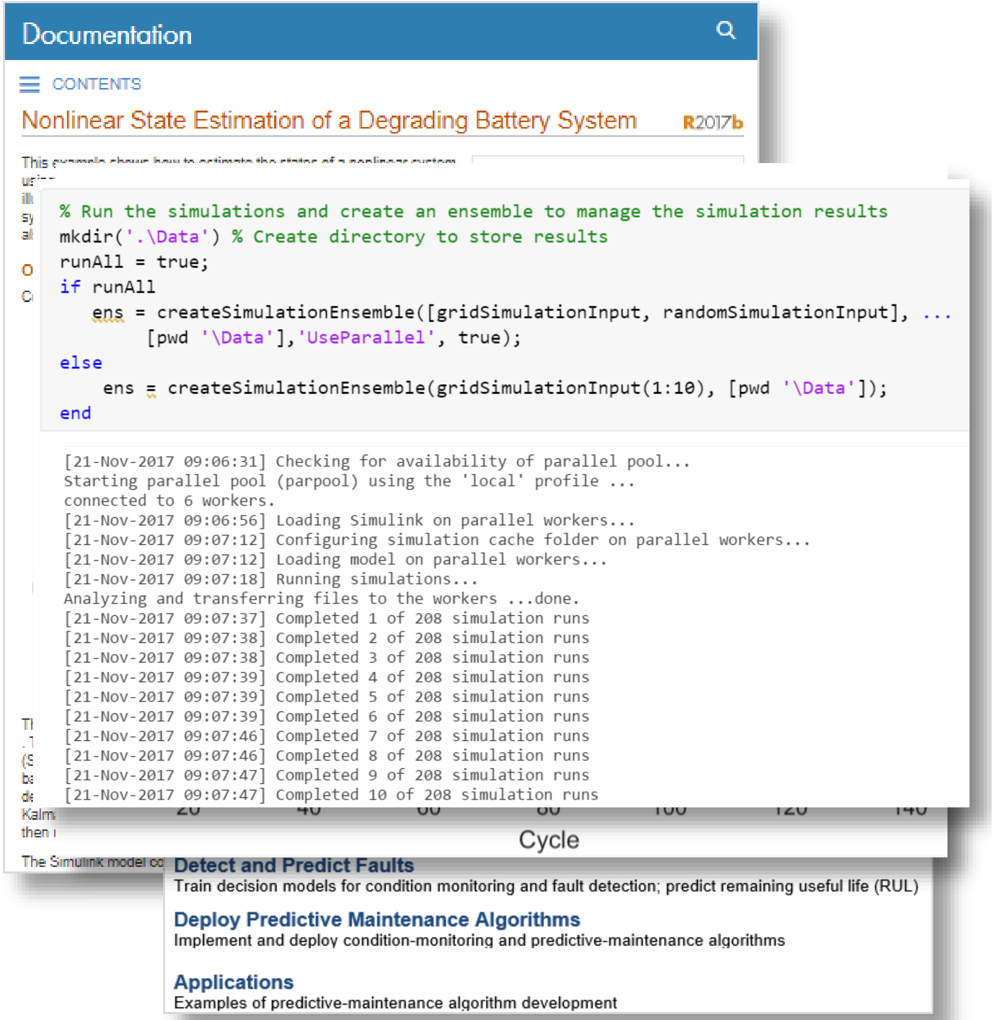
Predictive Maintenance

Access and Explore Data	Preprocess Data	Develop Predictive Models		Integrate Analytics with Systems	
Simulink & Simscape				MATLAB Production Server	Embedded Coder
OPC	Wavelet	Signal Processing	System Identification	MATLAB Compiler SDK	Simulink Coder
Database	Text Analytics	Statistics & Machine Learning	Neural Network	MATLAB Compiler	MATLAB Coder

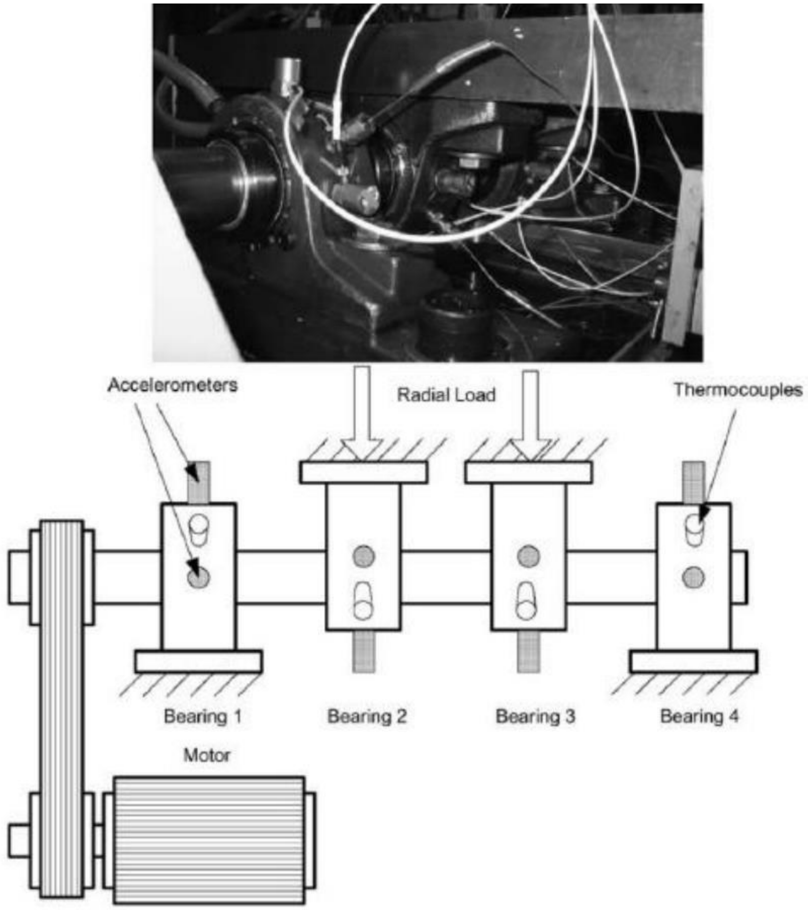
MATLAB

Common Challenges

- How do I get started with developing algorithms?
  - Reference examples
  - Workflow-based documentation
- How do I manage data and what if I don’t have any data?
  - Command line functions to organize data
  - Examples showing Simulink models generating failure data
- How do I choose condition indicators and estimate the RUL?
  - Functions for computing condition indicators
  - Functions provided for estimating RUL



Example: Features from Bearing Data



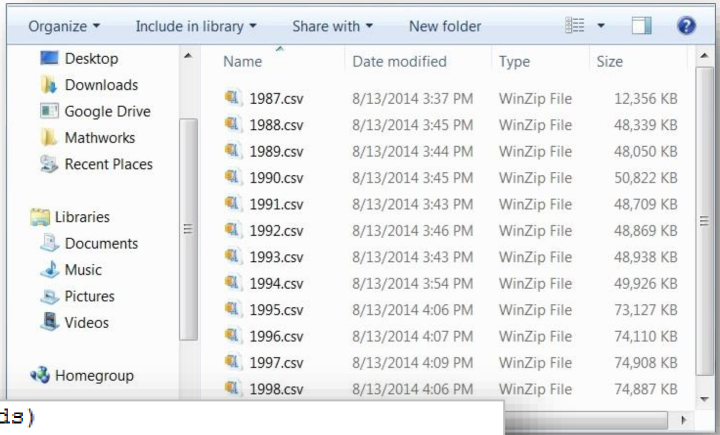
- 4 bearings installed on a shaft.
- Recorded over 7 days with 10 mins interval at 2000 RPM with load on shaft
- Each segment covers 1sec at 20kHz
- At the end of the experiment, failure occurred.

Data provided by NASA PCoE
J. Lee, et.al. "Bearing Data Set", NASA Ames Prognostics Data Repository (http://ti.arc.nasa.gov/project/prognostic-data-repository), NASA Ames Research Center, Moffett Field, CA

Access Big Data

`datastore`

- Easily specify data set
  - Single text file (or collection of text files)
  - Database (using Database Toolbox)
- Preview data structure and format
- Select data to import using column names
- Incrementally read subsets of the data




```
>> preview(ds)
ans =
    Year     Month     DayofMonth     DayOfWeek
    ____     _____     __________     _________
    1987     10        21             3
    1987     10        26             1
    1987     10        23             5
    1987     10        23             5
```

```
airdata = datastore('*.csv');
airdata.SelectedVariables = {'Distance', 'ArrDelay'};

data = read(airdata);
```

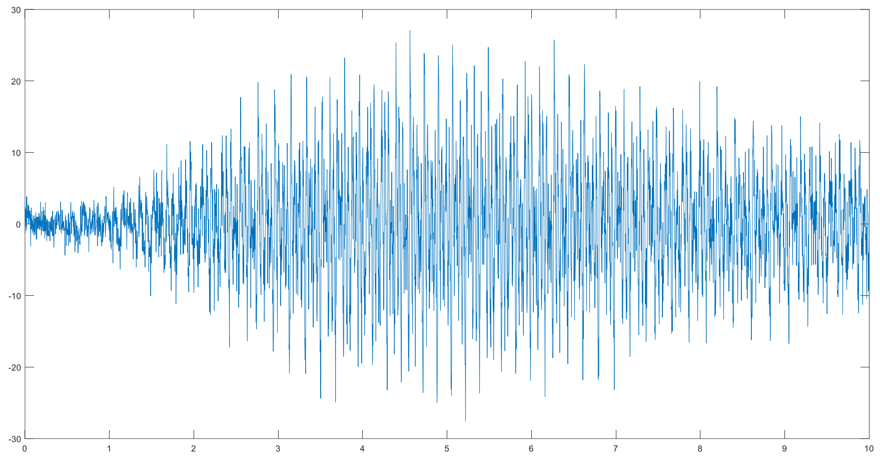
How to use “DATASTORE” function

Demo 1.1 : reading files with ‘datastore’

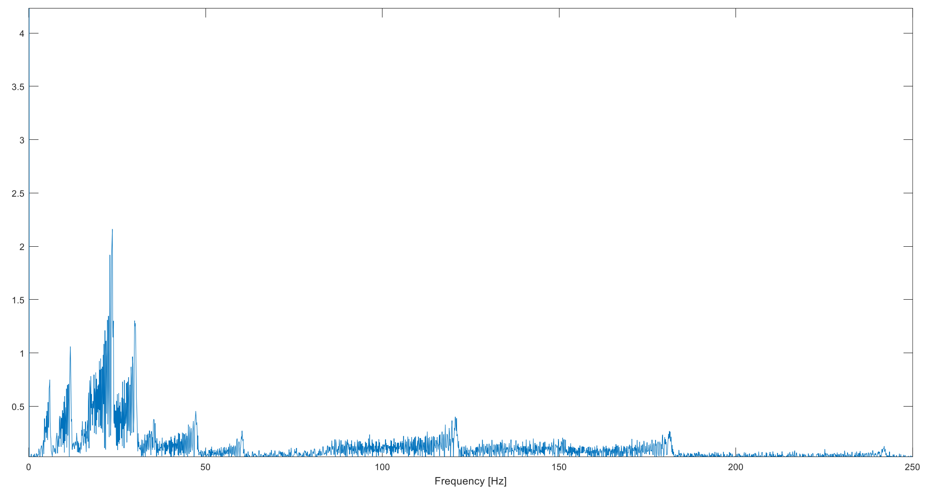
- `ds = datastore(location,Name,Value)`
  - Location:
    - file direction (‘C:\dir\data\file.csv’)
    - Read from HDFS (‘hdfs://myserver:7867/data/file1.txt’)
  - Name-Value Pair
    - TextscanFormats
    - SelectedVariableNames, SelectedFormat
    - Delimiter
    - ReadSize

- Methods of DATASTORE object
  - preview, read, readall

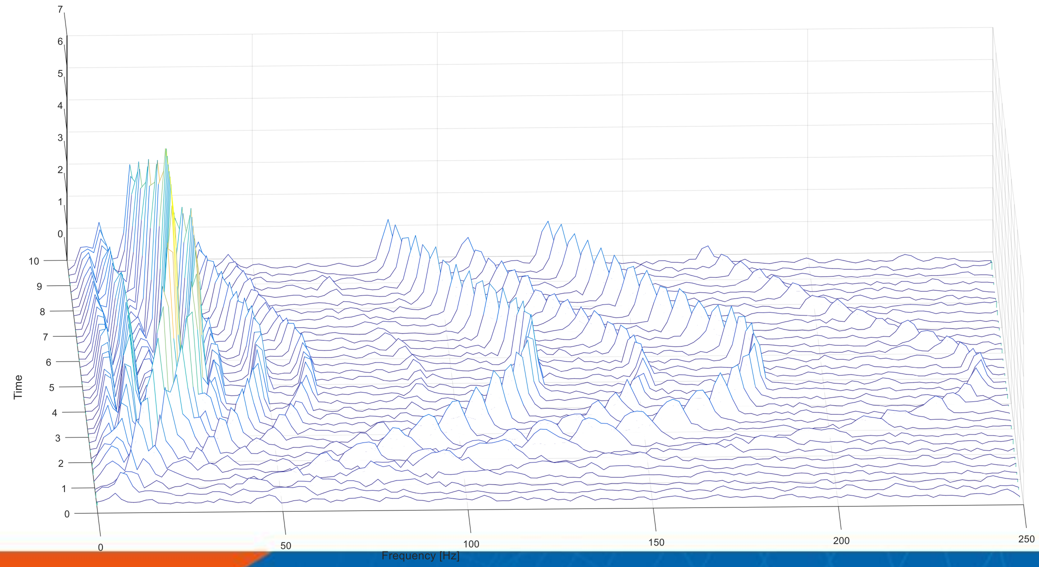
Feature Extraction : Signal Processing Techniques



Time domain

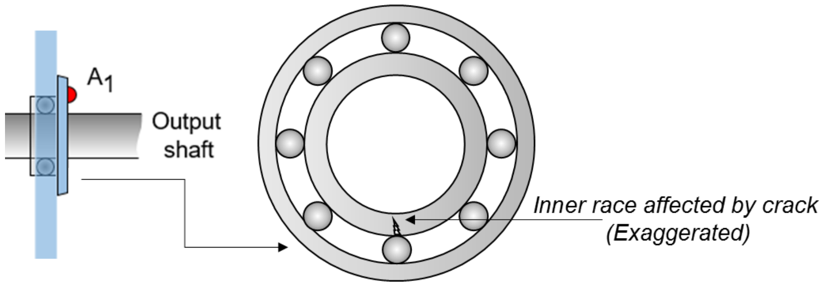


Frequency domain

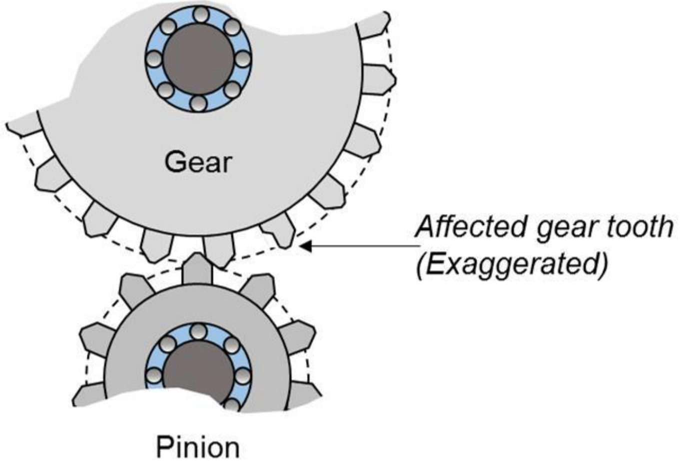


Frequency-RPM map waterfall

Common Feature for Vibration Analysis

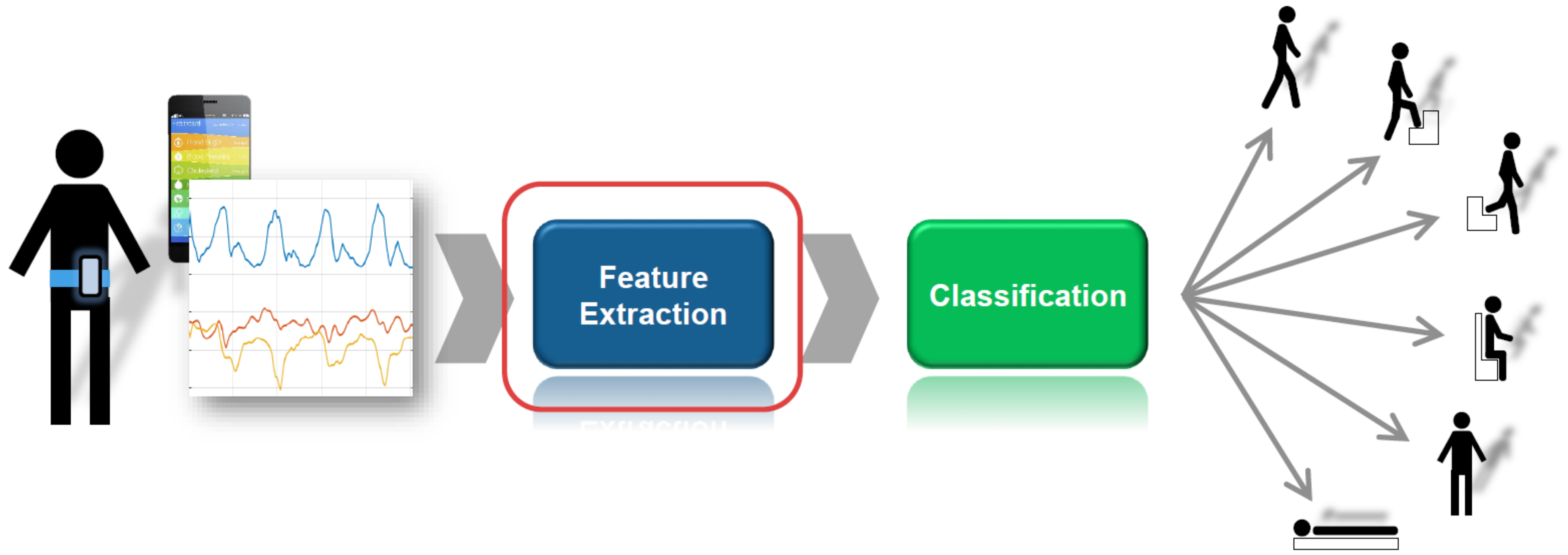


Ball bearing cross−section (Magnified)



- 常見旋轉機械故障類型
  - 軸不平衡
  - 軸彎曲
  - 不對中 (平行、角度)
  - 鬆動
  - 油膜旋振
  - 油膜晃蕩
  - 內環損傷
  - 外環損傷
  - 氣隙不均
  - 轉子條斷裂
  - 齒輪偏心
  - 齒輪磨耗
  - 齒輪不對中
- 常見的振動訊號特徵
  - Root mean square
  - Peak frequency
  - Harmonics components
  - Crest factor
  - Entropy, Energy, Kurtosis
  - Largest Lyapunov exponent
  - Envelope spectrum
  - Mean frequency
  - Variance of frequency
  - Standard Deviation
  - Kurtosis
  - Skewness
  - etc...

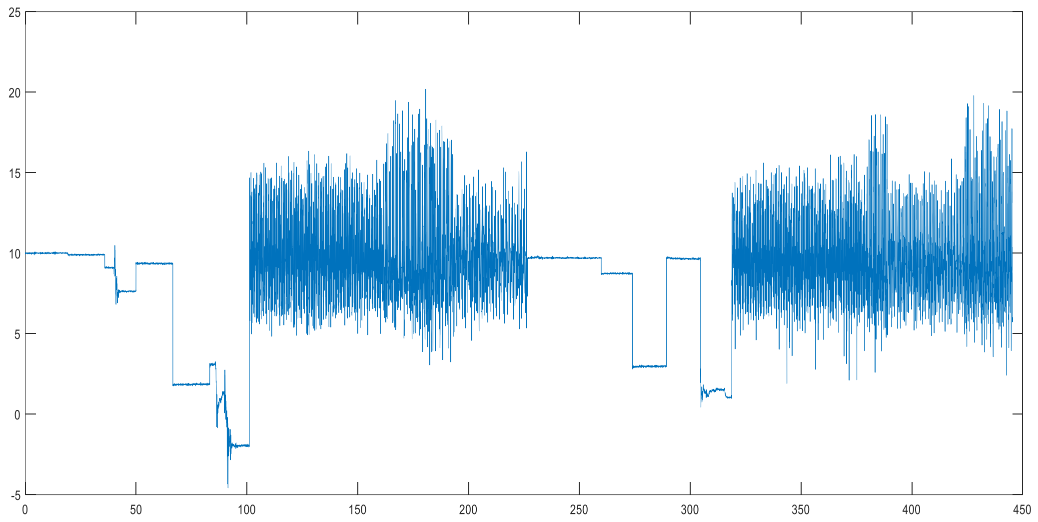
Signal Processing on Human Activity Data

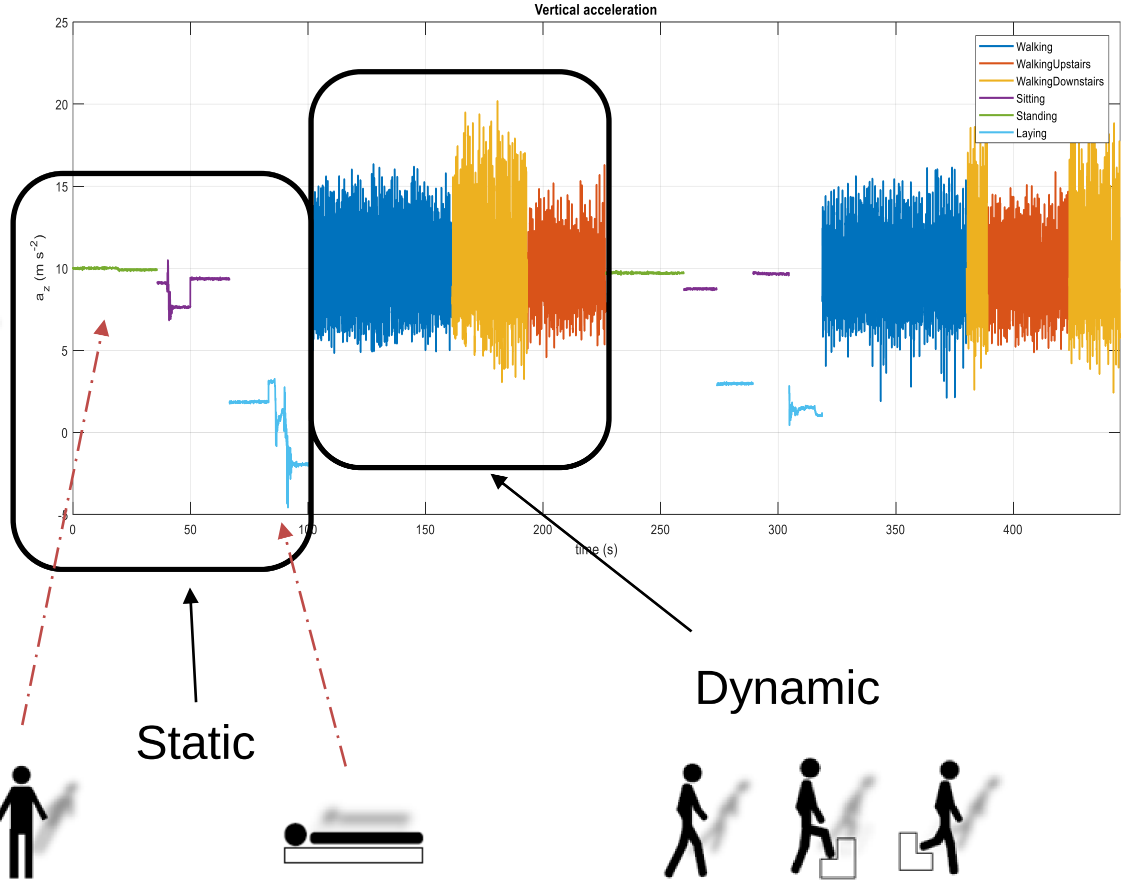


Dataset courtesy of:
DavideAnguita, Alessandro Ghio, Luca Oneto, Xavier Parra and Jorge L. Reyes-Ortiz. *Human Activity Recognition on Smartphones using a Multiclass Hardware-Friendly Support Vector Machine.* International Workshop of Ambient Assisted Living (IWAAL 2012). Vitoria-Gasteiz, Spain. Dec 2012
http://archive.ics.uci.edu/ml/datasets/Human+Activity+Recognition+Using+Smartphones

Insight from Visualization by Activity

Human Activity Analysis and Classification

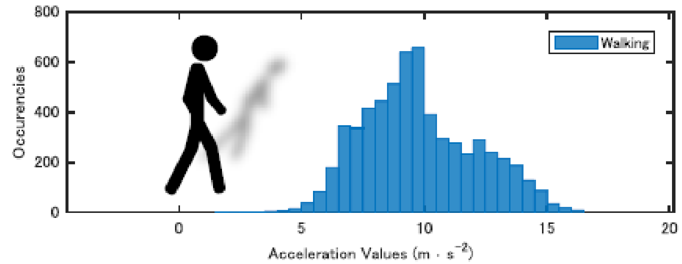


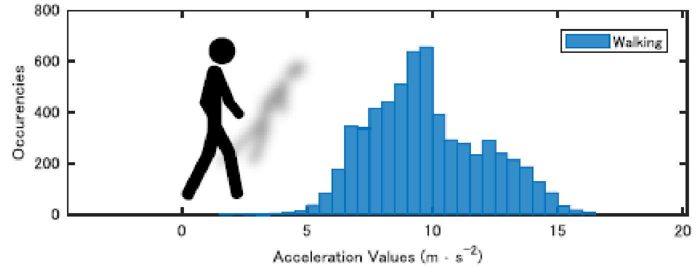


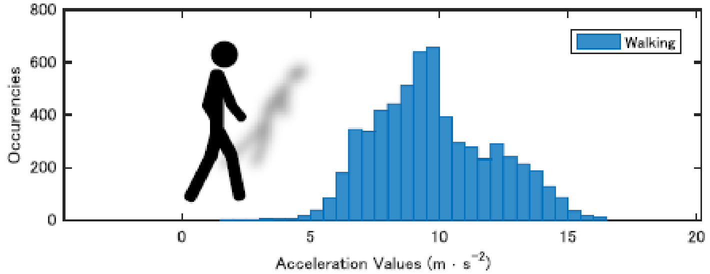
Features from Histogram Visualization

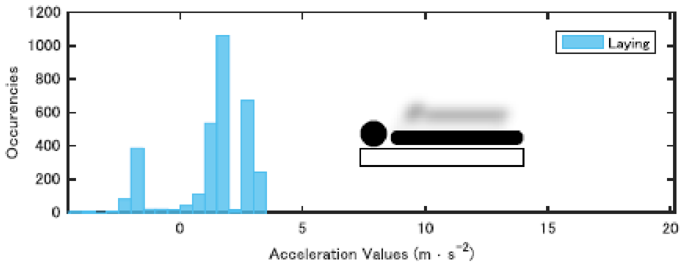
Demo 1.2 : Extracting standard deviations from sensor signal

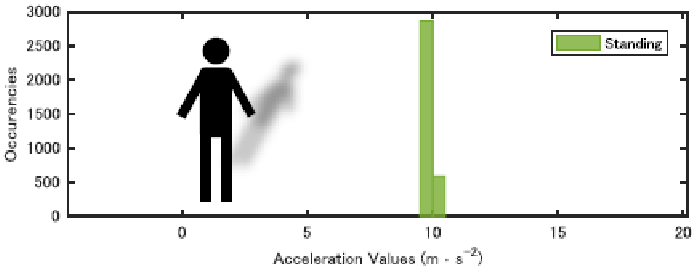
What are the differentiators?

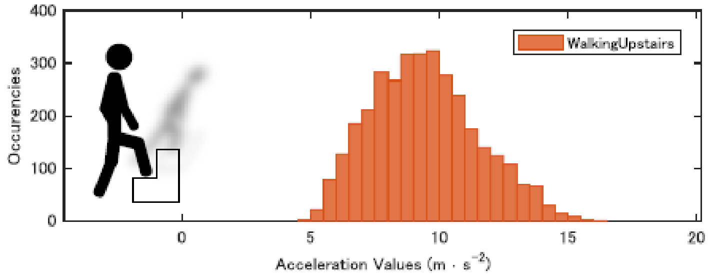












Mean value!

RMS!

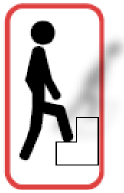
Ummm..

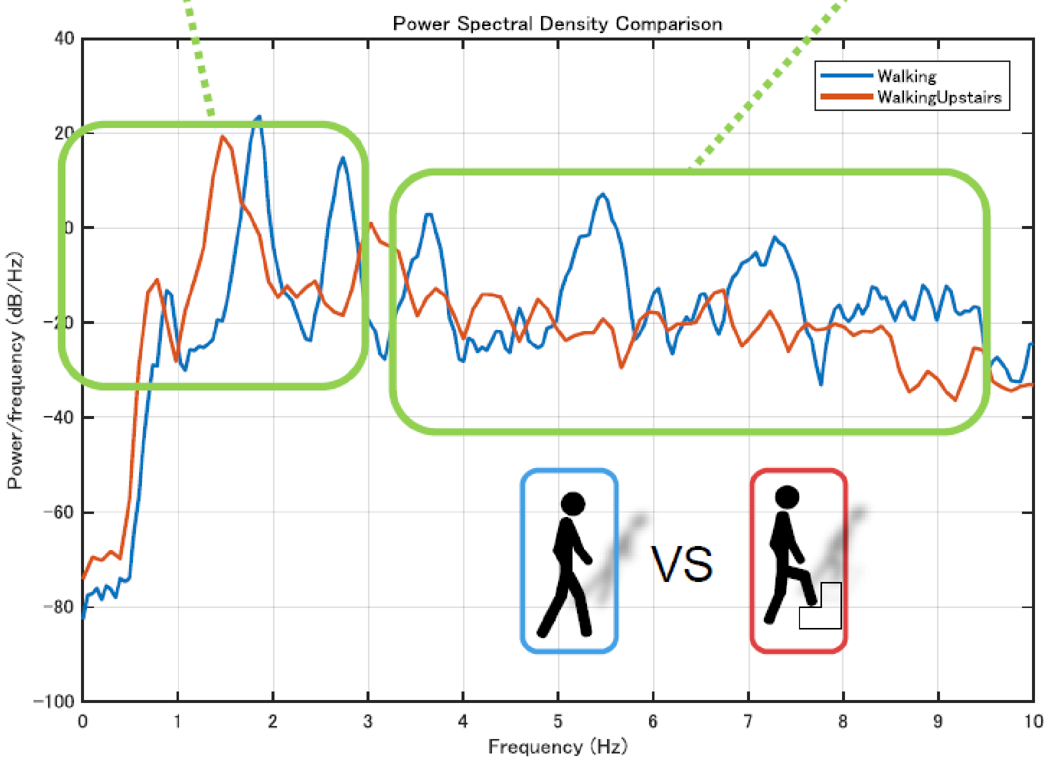
Features from Spectral Visualization

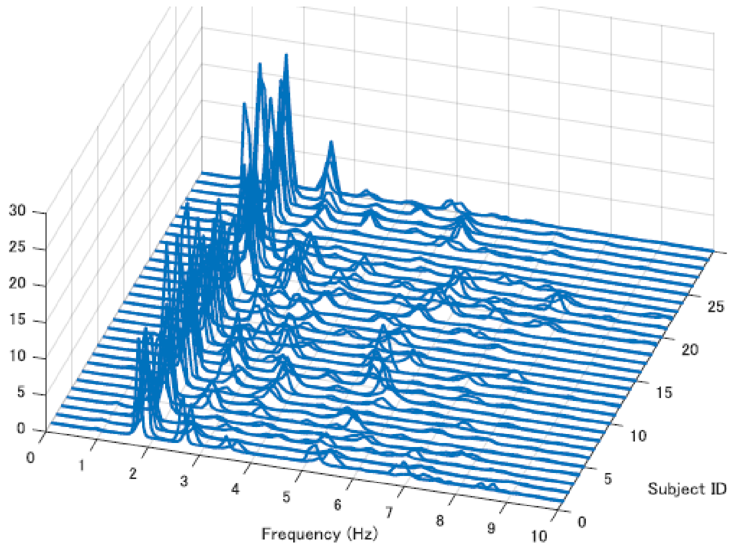
Human Activity Analysis and Classification

Peaks at (relatively) the lower frequency
→ Slower movement

Less activity at higher frequency
→ Smoother movement







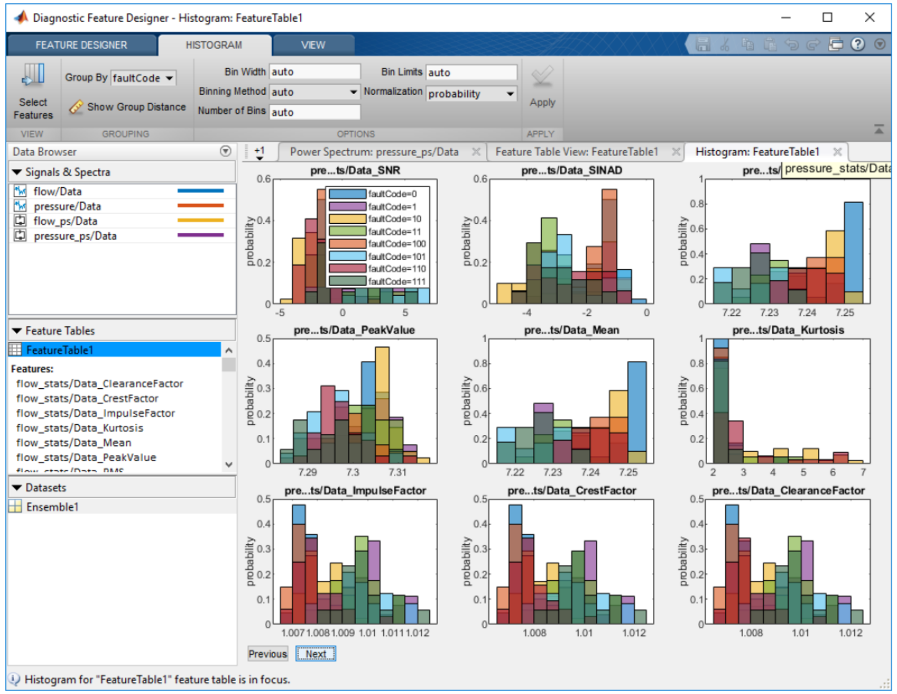
Same trend observed from 3D plot

The Diagnostic Feature Designer App

>> diagnosticFeatureDesigner

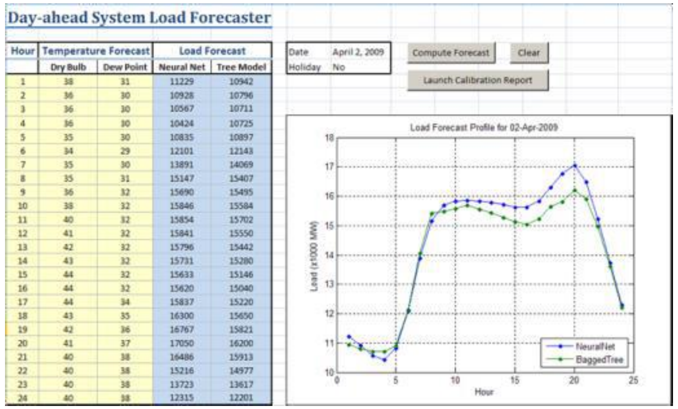
Using this app, you can:

- ✓ Import measured or simulated data from individual files, an ensemble file, or an ensemble datastore that references files external to the app.
- ✓ Interactively visualize data to plot the ensemble variables you import or that you compute within the app.
- ✓ Generate features from your variables, and visualize their effectiveness using histograms. Features include signal statistics, nonlinear metrics, rotating machinery metrics, and spectral metrics.
- ✓ Use conditional ranking with labeled features
- ✓ Use prognostic ranking with features extracted from run-to-failure data

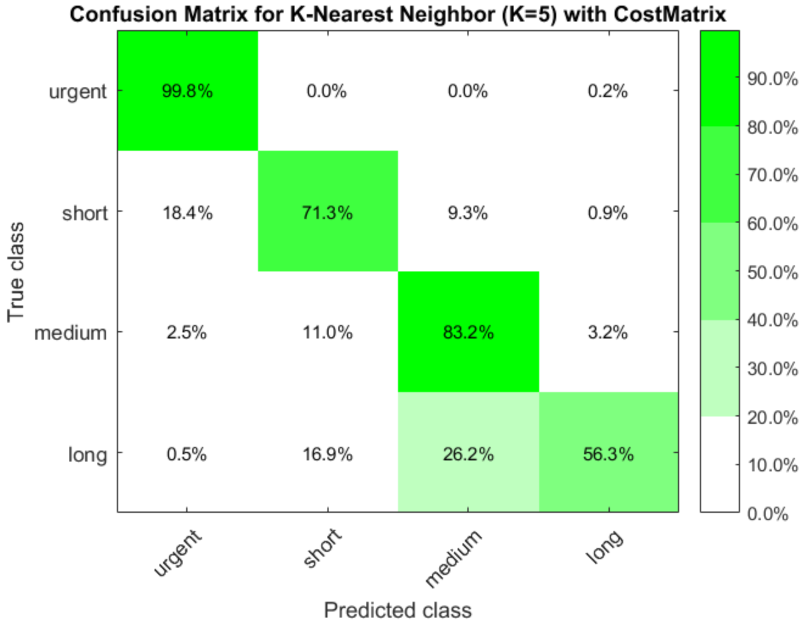


Overview -Machine Learning

Characteristics and Examples



- Characteristics
  - Too many variables
  - System too complex to know the governing equation*(e.g., black-box modeling)*



- Examples
  - Pattern recognition *(speech, images)*
  - Financial algorithms *(credit scoring, algo trading)*
  - Energy forecasting *(load, price)*
  - Biology *(tumor detection, drug discovery)*
  - Engineering *(fleet analytics, predictive maintenance)*

Overview – Machine Learning

Algorithm types

Type of Learning | **Categories of Algorithms**

Machine Learning

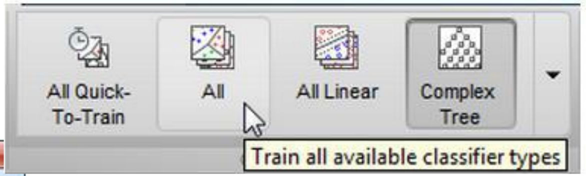
- **Unsupervised Learning** → **Clustering**
  - **Group** and **interpret** data based only on input data
- **Supervised Learning** → **Classification**, **Regression**
  - Develop **predictive model** based on both **input and output** data

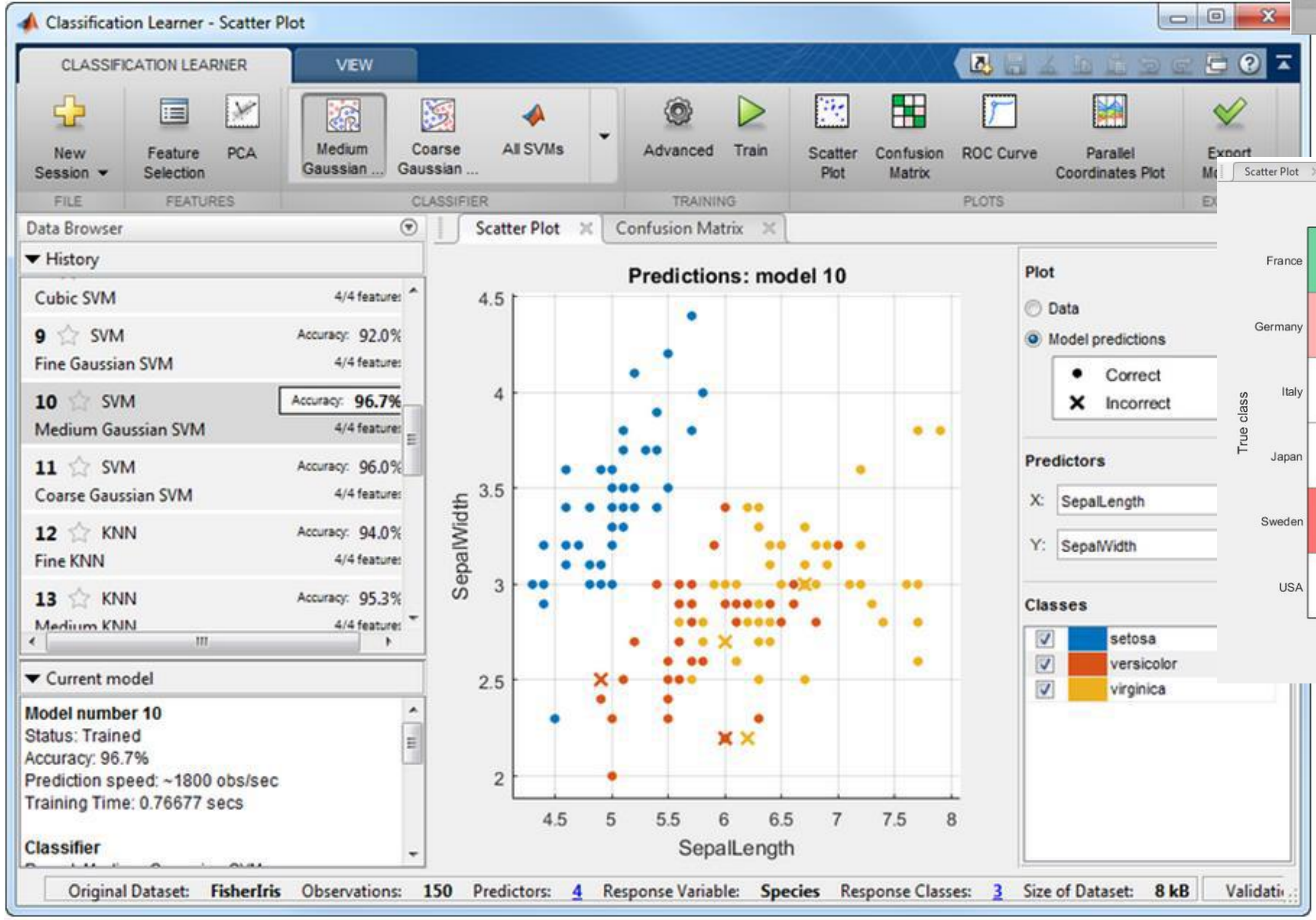
>> classificationLearner

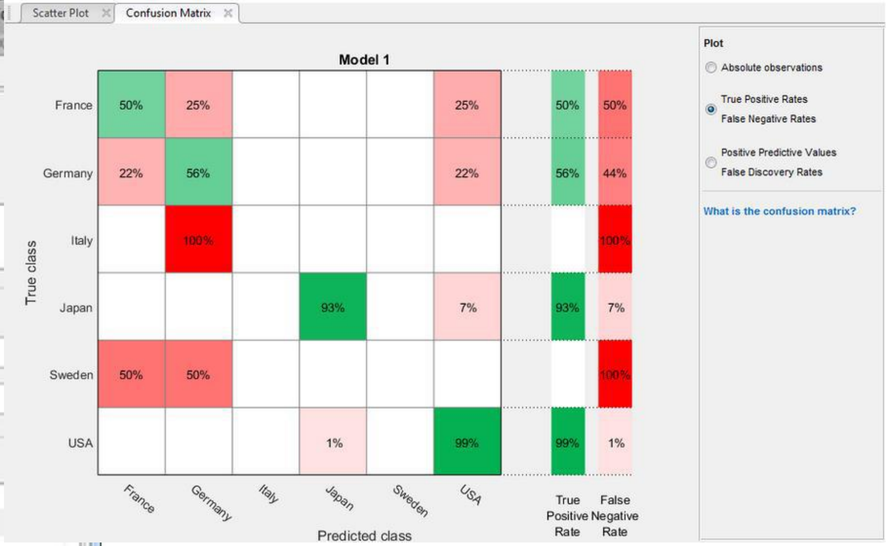
>> regressionLearner

The Classification Learner APP

>> classificationLearner

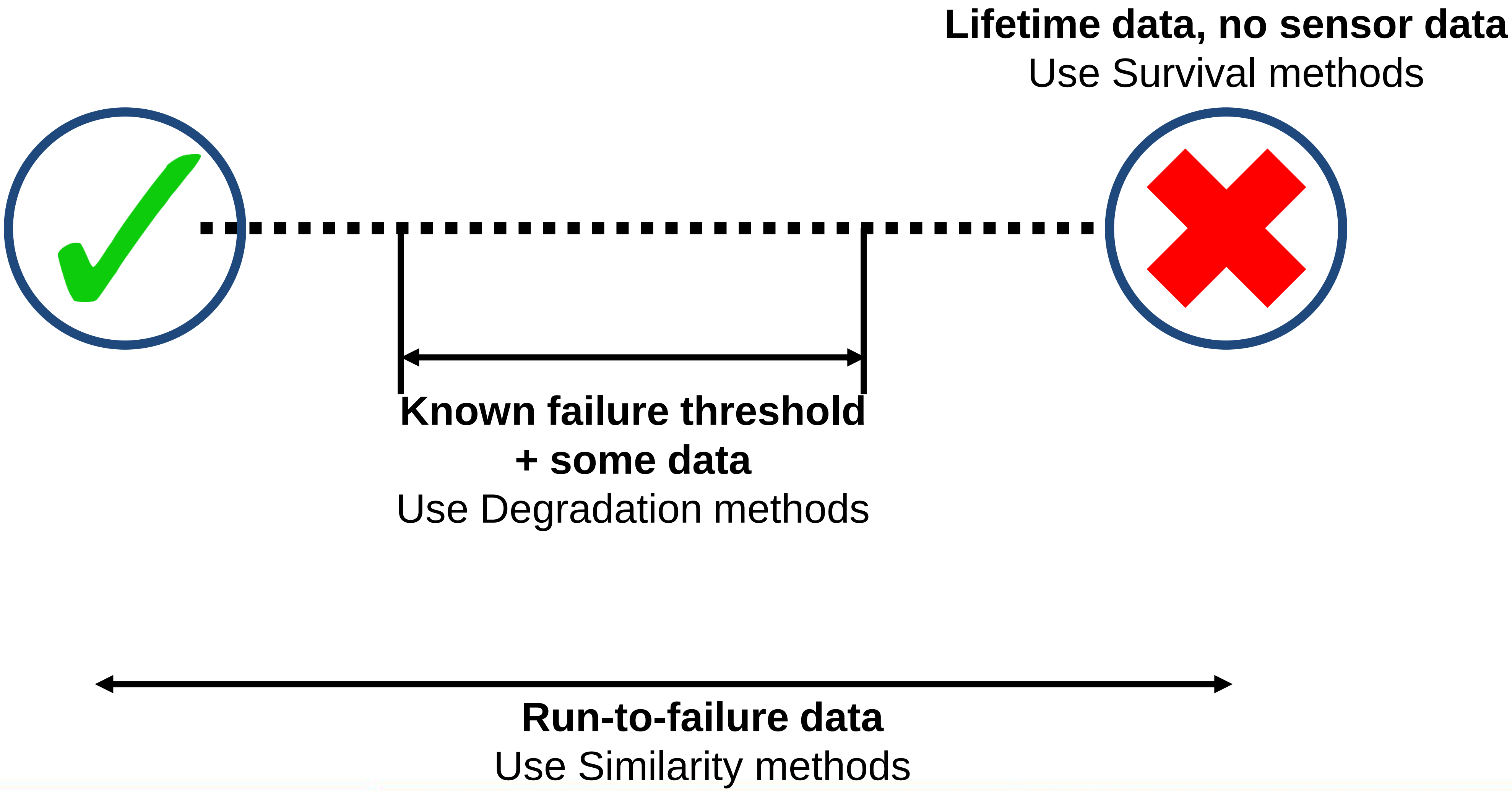






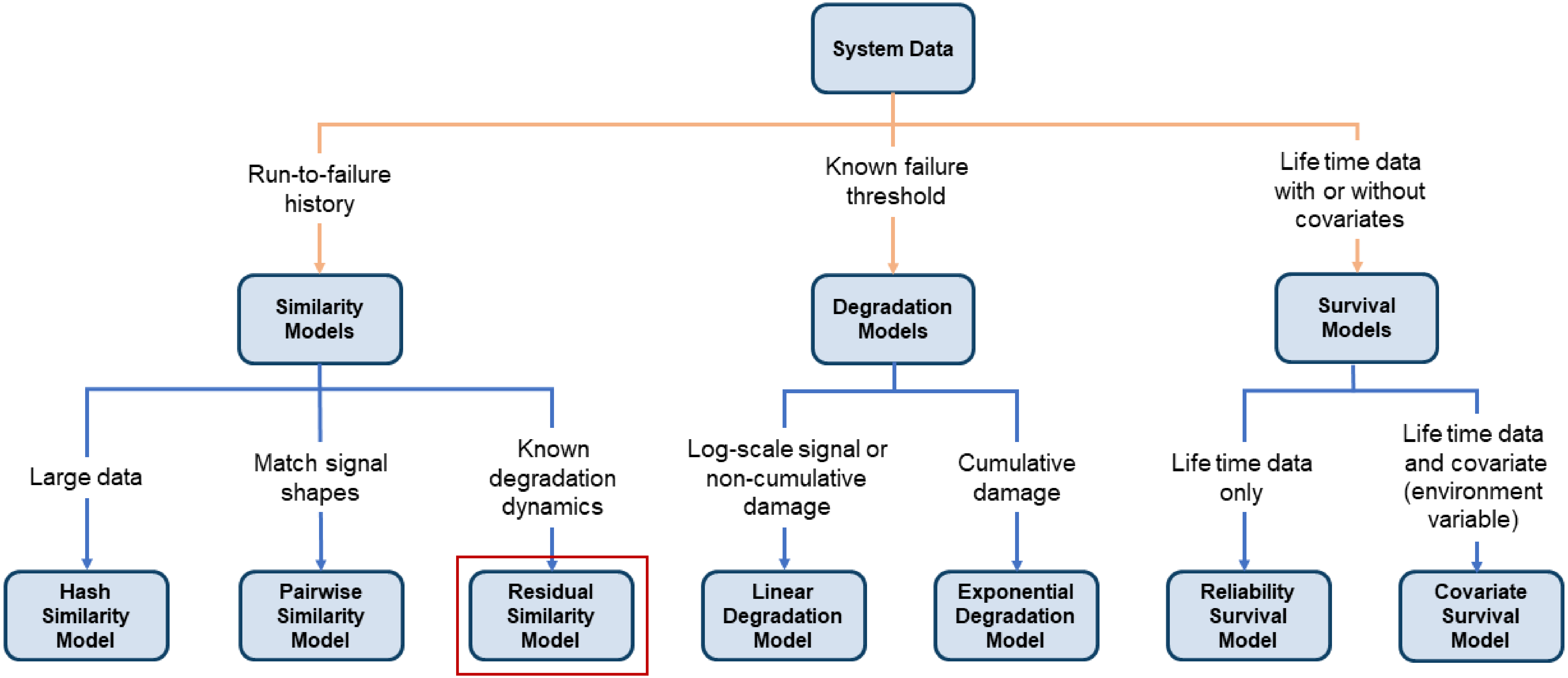
Remaining Useful Life (RUL) Estimation Methods

Requirement: Need to know what constitutes failure data



RUL Methods and when to use them

Requirement: Need to know what constitutes failure data



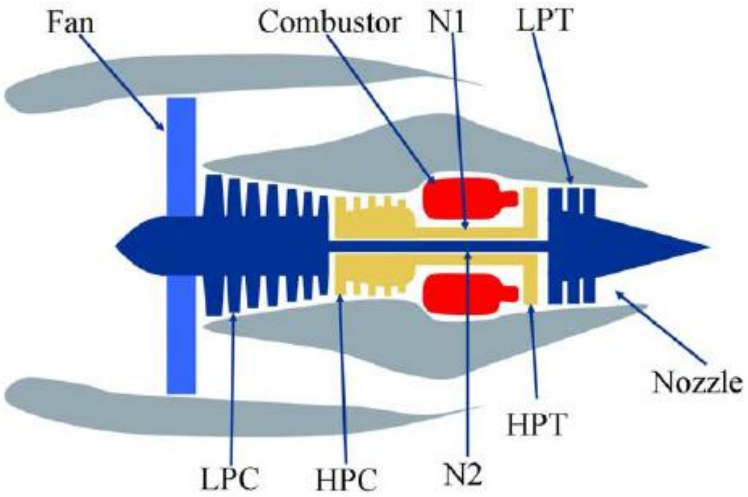
[Details on model selection in the documentation]()

Predictive Maintenance of Turbofan Engine

Sensor data from 200 engines of the same model

Forecast Remaining Useful Life

- Have some combination of:
  - Sensor data from the equipment
  - Known failure thresholds
  - Runtime to failure of similar equipment
- Use condition monitoring to determine when system starts degrading
- Can we predict how much longer we can use our equipment once degradation begins?



Data provided by NASA PCoE
https://ti.arc.nasa.gov/tech/dash/groups/pcoe/prognostic-data-repository

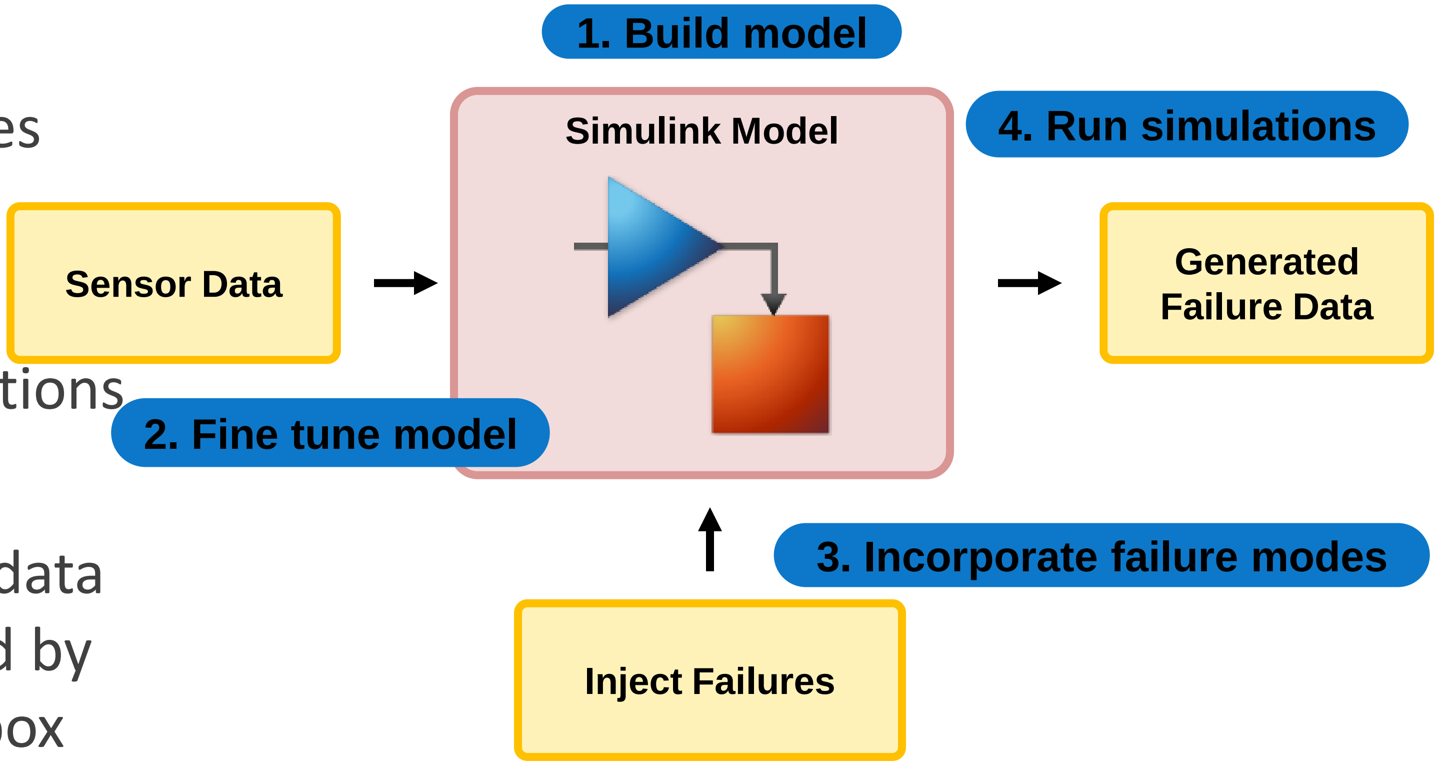
Failure Data Generation from Simulink

Use simulation data that is representative of actual machine failures to train your algorithm

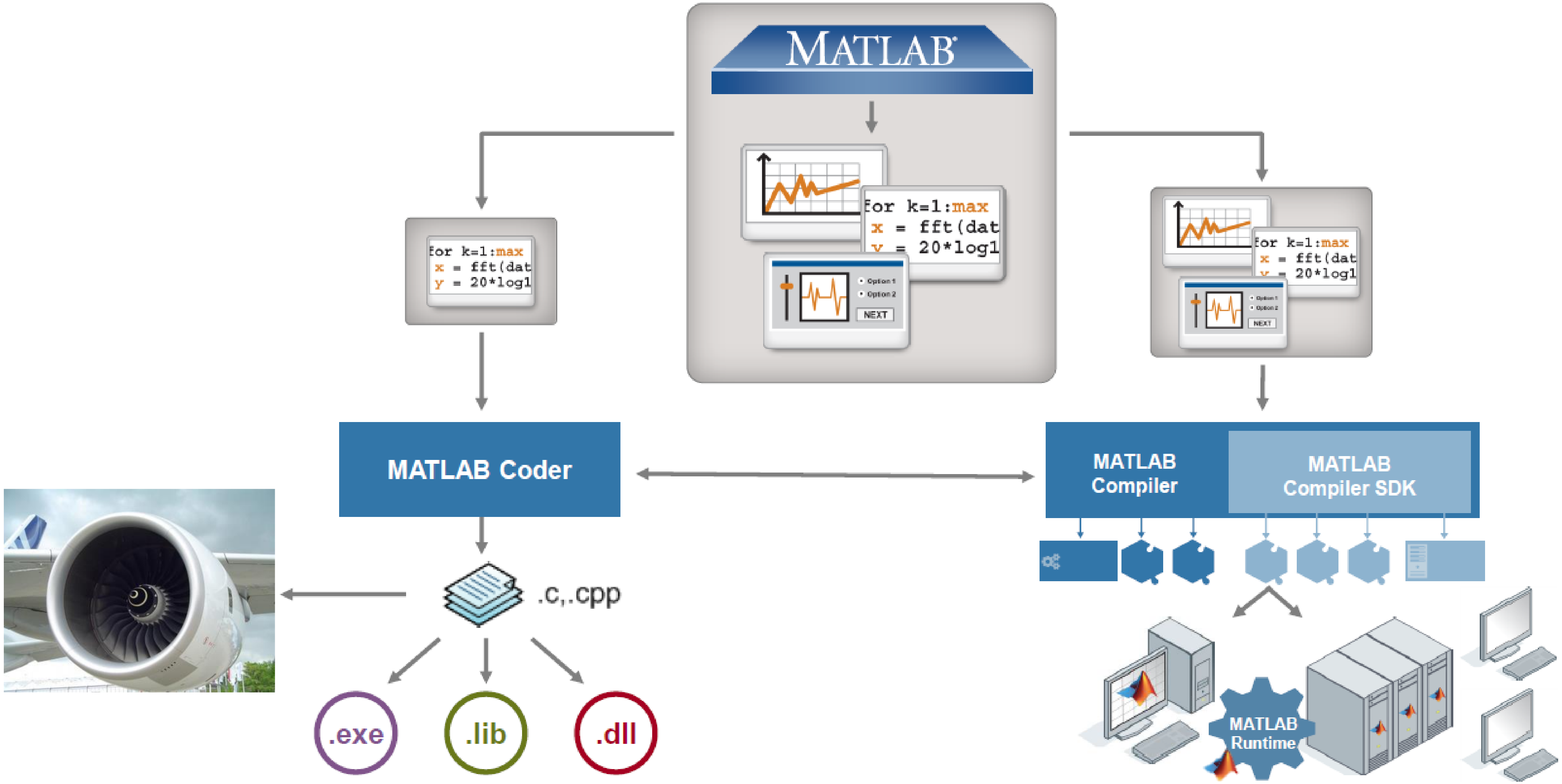
- Construct a model of your machine using Simulink and Simscape that captures its different failure modes

- Run multiple simulations of your model under different fault conditions

- Manage and label this simulated data using `ensemble` objects provided by the Predictive Maintenance Toolbox



Integrate analytics with your enterprise systems *MATLAB Compiler and MATLAB Coder*



Predictive Maintenance
Customer Examples

Pump Health Monitoring System

- Spectral analysis and filtering on binary sensor data and neural network model prediction
- More than $10 million projected savings

Online engine health monitoring

- Real-time analytics integrated with enterprise service systems
- Predict sub-system performance (oil, fuel, liftoff, mechanical health, controls

Production machinery failure warning

- Reduce waste and machine downtime
- MATLAB based HMI warns operators of potential failures
- > 200,000 € savings per year

Key Takeaways

- Frequent maintenance and unexpected failures are a large cost in many industries
- MATLAB enables engineers and data scientists to quickly create, test and implement predictive maintenance programs
- Predictive maintenance
  – Saves money for equipment operators
  – Increases reliability and safety of equipment
  – Creates opportunities for new services that equipment manufacturers can provide