Servo Motor Diagnostics using Anomaly Detection

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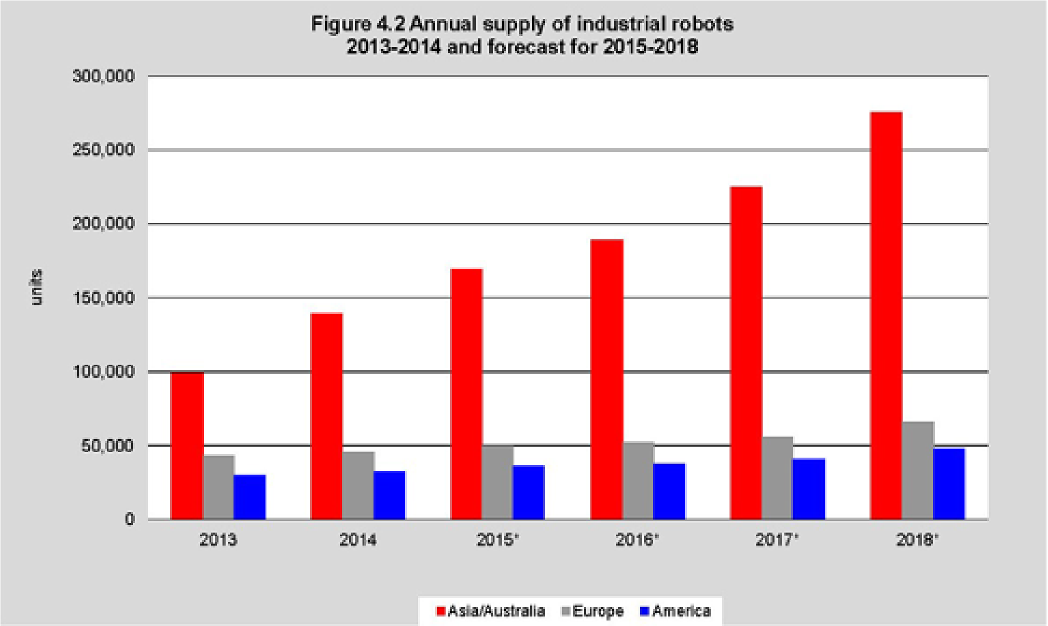
Contents

- Monitoring Systems for Robot Diagnosis
- Prognostics and Health Management (PHM) for robot
- Simulation Study
  – Model-based Fault Detection and Isolation (FDI)
- Servo Motor Demonstration and Comparison
  – Model-based FDI
  – Unsupervised Learning
- Conclusion

Industrial Robots

- Increased robot usage on factory



Source: IFR World Robotics 2015

- Breakdown of robot
  - 2015 GM Russia Operation Breakdown for 2 Months
    - Losses over $100 million
    - Approximately $1.6 million a day

Contents

Prognostics and Health Management (PHM)

- Key component
  - Servo motor
- Dynamic movement (6-axis)

- PHM
  - Data-driven
    - Unsupervised Learning
    - Supervised Learning
  - Model-based
    - Hardware Redundancy
    - Analytic Redundancy
      - Residual Generation
        - Output Estimation
          - Observer
        - Parity Space
        - Parameter Estimation

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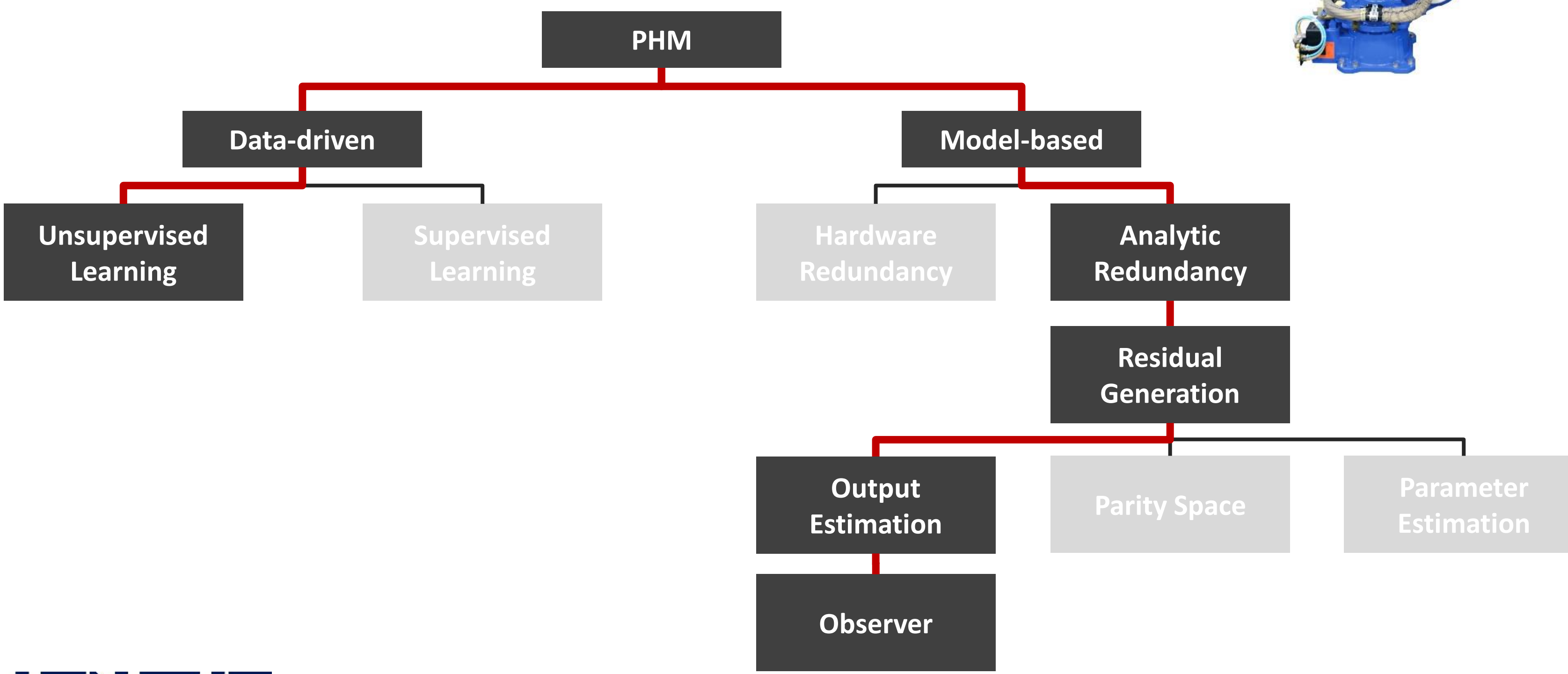
Prognostics and Health Management (PHM)

- Difficult to attach sensors due to dynamic movement of the arm
  - Mostly existing instrumentation are used (Encoder, Torque)
- In may cases, failure data is not available



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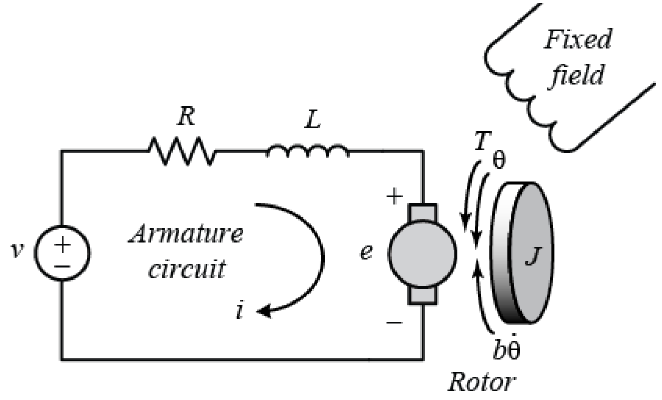
DC Motor Position: System Modeling

- System representation in state space



$$\frac{d}{dt}\begin{bmatrix}\theta \\ \dot{\theta} \\ i\end{bmatrix} = \begin{bmatrix}0 & 1 & 0 \\ 0 & -b/J & K/J \\ 0 & -K/L & -R/L\end{bmatrix}\begin{bmatrix}\theta \\ \dot{\theta} \\ i\end{bmatrix} + \begin{bmatrix}0 \\ 0 \\ 1/L\end{bmatrix}V + Ff$$

$$y = \begin{bmatrix}1 & 0 & 0\end{bmatrix}\begin{bmatrix}\theta \\ \dot{\theta} \\ i\end{bmatrix}$$

θ : angle

i : armature current

V : volatage

J : moment of intertia of the rotor

b : motor viscous friction constant

K : motor torque constant

R : electric resistance

L : electric inductance

F : fault matrix

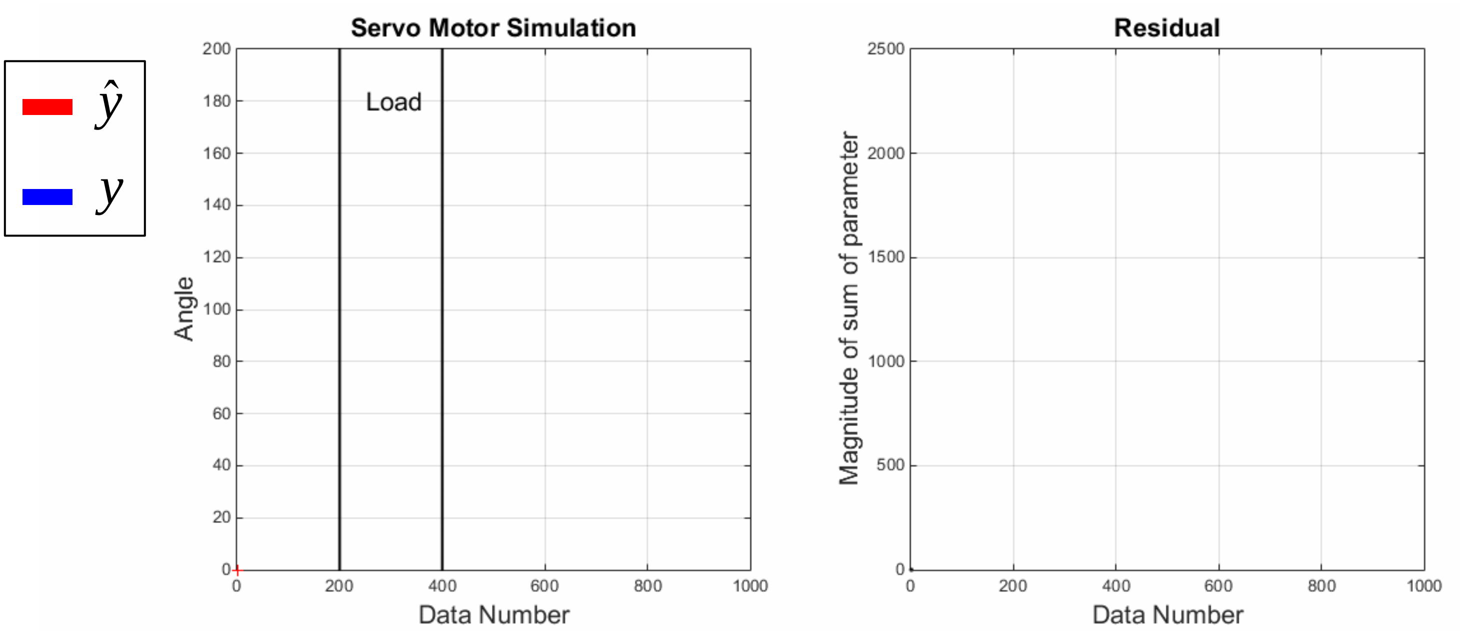
f : fault

http://ctms.engin.umich.edu/CTMS/index.php?example=MotorPosition&section=SystemModeling

Fault Modeling and Residual Design

- Fault modeling
  - Physically a load torque that acts on the inertia of the motor
- Residual Design
  - Parameter estimation from output error (Luenberger observer)

Fault	Observer	Residual
$F = \begin{bmatrix} 0 & 1 & 0 \end{bmatrix}^T$ $f(t)$: General Fault	$\dot{\hat{x}} = A\hat{x} + Bu + L(y - C\hat{x})$ $\hat{y} = C\hat{x}$	$y - \hat{y} = C\Phi\theta$ Φ: fault transition matrix



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Demo Specifications

- System configuration
  - Arduino UNO
  - Servo motor

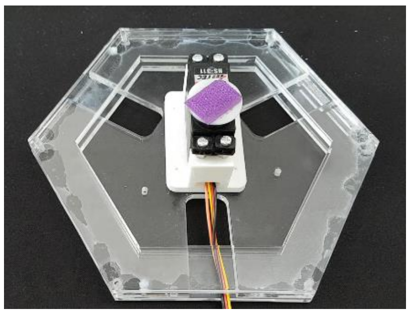
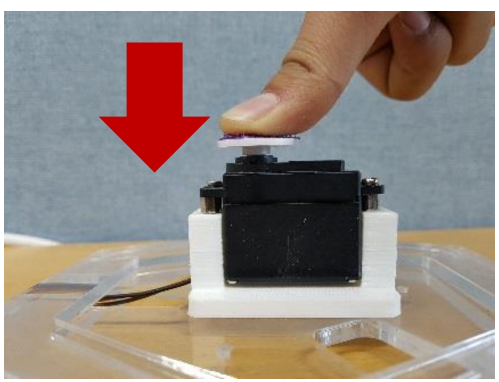


	Image	Specifications
Arduino UNO		ATmega328 Microcontroller, 32KB Flash Memory, 16MHz Clock Speed, 14 Digital 1/O Pins
HS-311 Servo Motor		Cored motor type, 4 slider potentiometer drive, 24 tooth spline style output shaft

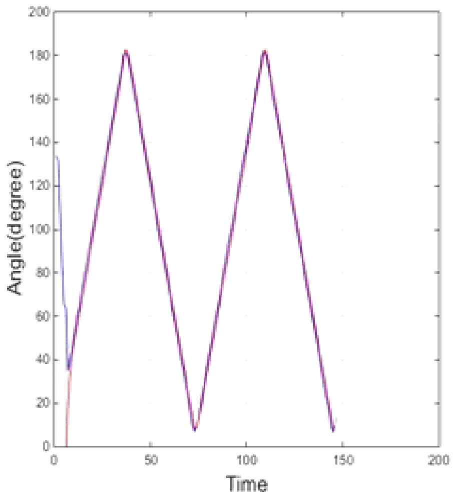
- Load generation
  - Anomaly is induced through manual press

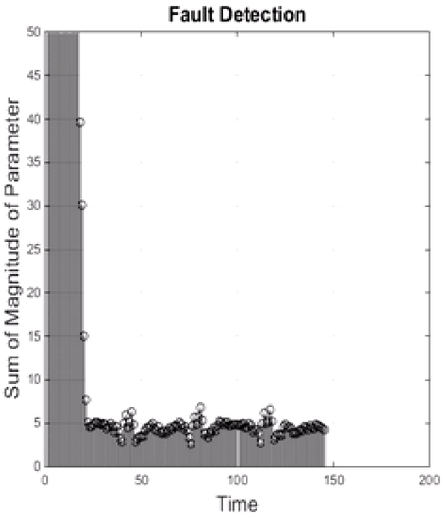


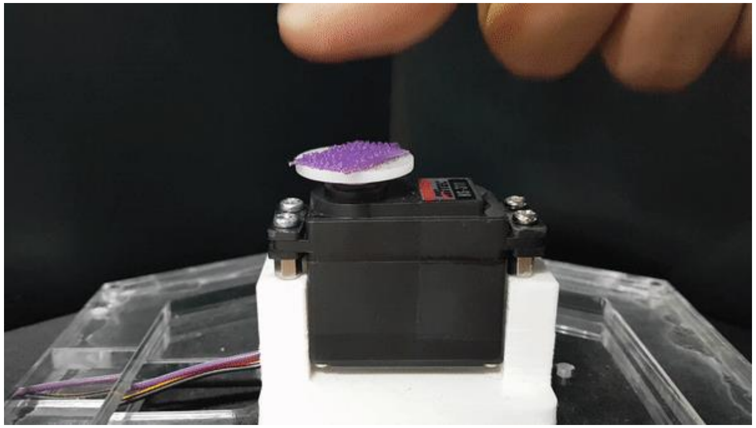
Servo Motor Testbed	
Operations	Repetitive movement (0 - 180 degree)
Sensor	Internal encoder
Sample Rate	50 Hz

Demo for Model-based FDI

- Residual = sum of magnitude of parameter

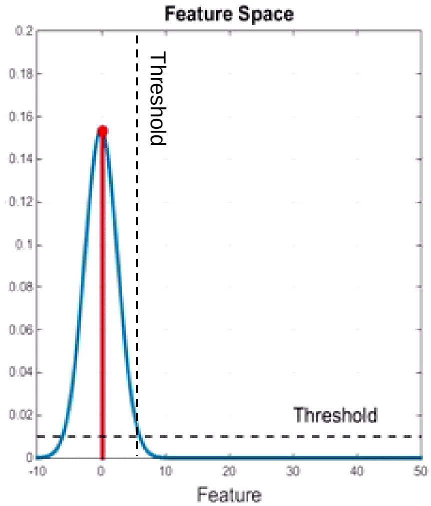


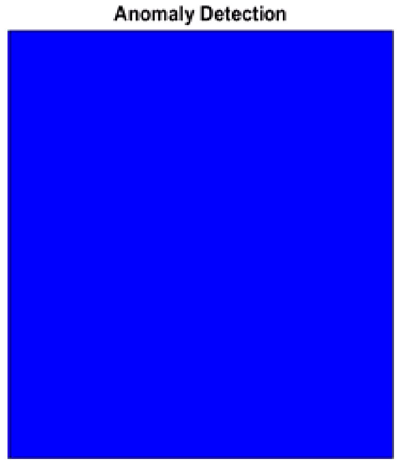


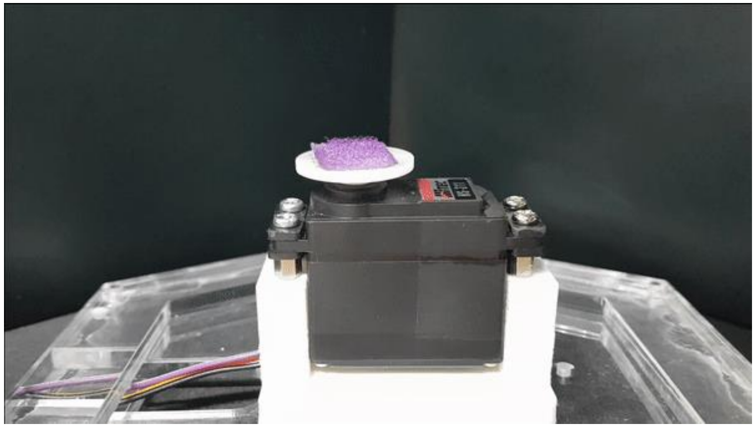


Demo for Unsupervised Data-driven Method

- Unsupervised Learning
  - Selected Feature: $u[k]-y[k]$
  - Normal state training: Gaussian distribution
  - Decision Making: Mahalanobis distance



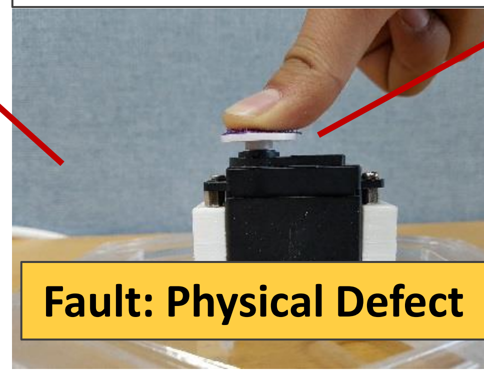




Data-driven vs. Model-based

Data-driven
Feature
Anomaly Detection
Classification
Training Process

System



Model-based
Residual
Fault Detection
Fault Isolation
Modeling Process

Data-Driven

Unsupervised Learning → Training Process → Decision Making → Anomaly Detection

Model-based

Observer based → System & Fault Modeling → Decision Making → Fault Detection

Data-driven vs. Model-based

Data-driven
Feature
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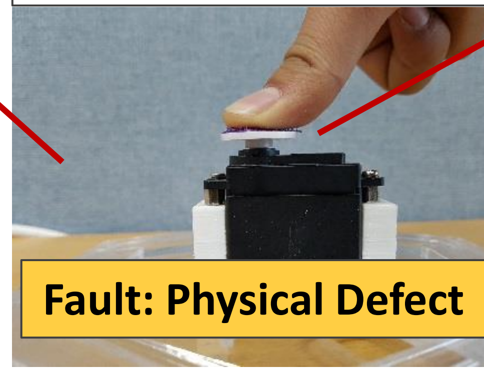

Model-based
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Data-Driven

Unsupervised Learning → Training Process → Decision Making → Anomaly Detection

Model-based

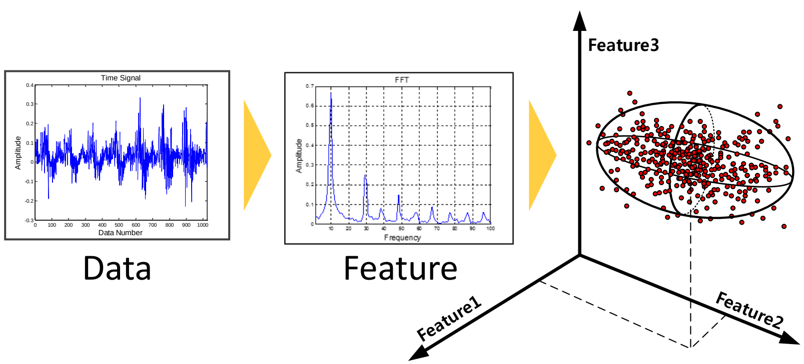
Observer based → System & Fault Modeling → Decision Making → Fault Detection

Data-driven vs. Model-based

- Data-driven methods
  - Normal states based on feature
- Model-based methods
  - Normal states based on residual

Training Process

- Acquire normal data
- Feature extraction
  - Represents normal state
- Normal state cluster in feature space



System & Fault Modeling

- System representation

$$x[k+1] = Ax[k] + Bu[k]$$
$$y[k] = Cx[k]$$

- Fault Modeling

$$f[k] = \sum_n R_{n+} e^{j\alpha_{n+}} e^{j(n\omega)k} + R_{n-} e^{j\alpha_{n-}} e^{-j(n\omega)k}$$

- Residual Design

$$\text{residual} = \begin{cases} = 0 & \text{if no fault} \\ \neq 0 & \text{if fault exists} \end{cases}$$

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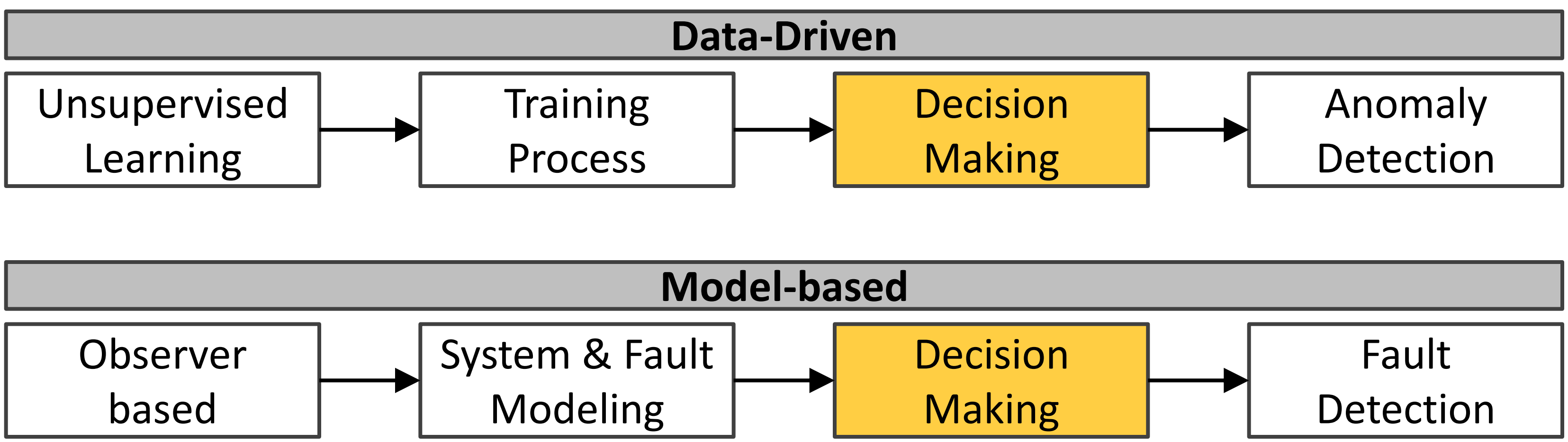
Data-driven vs. Model-based

- Classify the state
  - based on the similarity of the predefined normal state
- Similarity can be represented differently



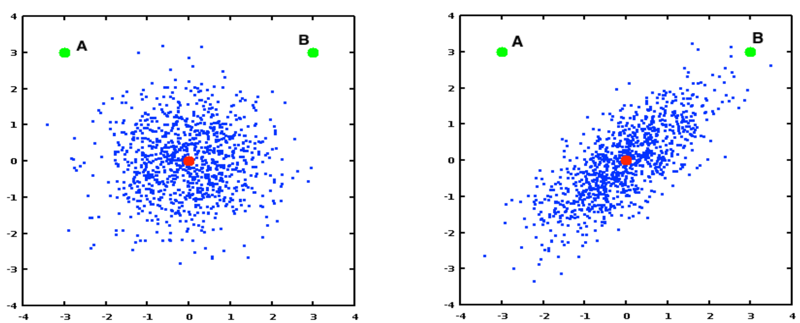
Data-driven vs. Model-based

- Classify the state
  - based on the similarity of the predefined normal state
- Similarity can be represented differently

Decision Making (Classification)

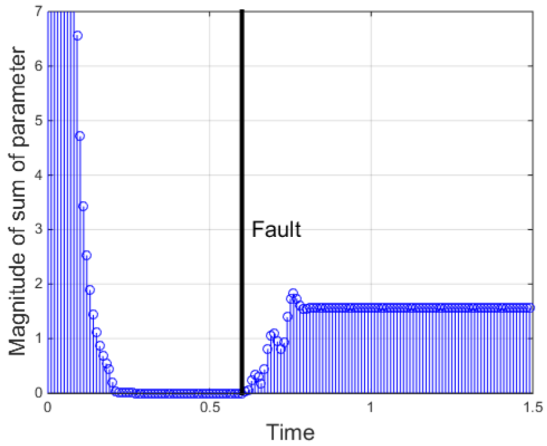
- Mahalanobis Distance
  - Statistical distance of two points

$$D = \sqrt{(x-\mu)^T \Sigma^{-1} (x-\mu)} > \varepsilon \quad \Rightarrow \quad \text{Anomaly}$$



- Residual-based threshold

$$\text{residual} = \begin{cases} = 0 & \text{if no fault} \\ \neq 0 & \text{if fault exists} \end{cases}$$

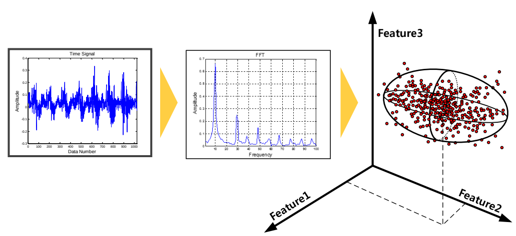


Conclusion

- Importance of robot diagnosis has increased
  - More robots are being adopted
  - Servo motors are the key component of robots
- Anomaly detection and fault detection
  - Unsupervised learning (Mahalanobis distance)
  - Model-based fault detection (Observer-based residual)

<table>
<tr><th></th><th>Data-driven</th><th>Model-based</th></tr>
<tr><td>Training/ Modeling</td><td>

- Define normal state



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$$x[k+1] = Ax[k] + Bu[k] + Ff[k]$$
$$y[k] = Cx[k]$$

</td></tr>
<tr><td>Feature/ Residual</td><td>

$$u[k] - y[k]$$

</td><td>

$$y[k+1] - \hat{y}[k+1]$$

</td></tr>
<tr><td>Decision Making</td><td>

$$D = \sqrt{(x-\mu)^T \Sigma^{-1} (x-\mu)} > \varepsilon$$

</td><td>

$$\text{residual} = \begin{cases} = 0 & \text{if no fault} \\ \neq 0 & \text{if fault exists} \end{cases}$$

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