EE5111: Industrial Control & Instrumentation Fault Diagnosis and Control (I)

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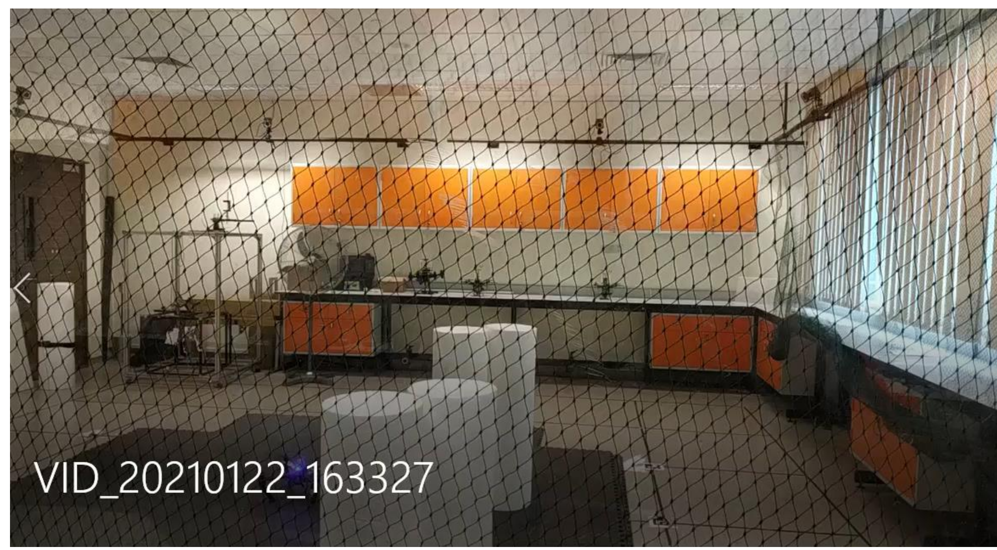
— Oct. 2021 —

Temasek Lab., NUS



Three parts:

- Fault, fault types and modelling.
- Fault detection scheme
- Fault-tolerant control

CA Grading (for all students)

- One report (homework) regarding fault and fault detection method (50%)
- One report (homework) regarding fault tolerant control (50%)

Learning Objectives

- Describe different types of faults.
- Understand the fundamentals of fault representations

Topics To Be Covered

- Faults
- Faulty types and modelling

Why do we need to have a fault management system or monitoring system?

Failure of two components in power-generating units caused Sept 2018 power outage
Read more at https://www.channelnewsasia.com/news/singapore/failure-of-two-components-in-power-generating-units-caused-last-10775696 Flats in Woodlands

On Saturday 1 June 1974 the Nypro (UK) site at Flixborough was severely damaged by a large explosion. It was discovered that a vertical crack in reactor No.5 was leaking cyclohexane

The Finnish Air Force DC-3 disaster occurred when a plane of this class crashed into a lake on 3 October 1978, killing all fifteen people on board. It was caused by a cracked exhaust valve

Our test in Holland Road

Did you know any fault monitoring system?

NUS has many red boxes which have fault monitoring systems.

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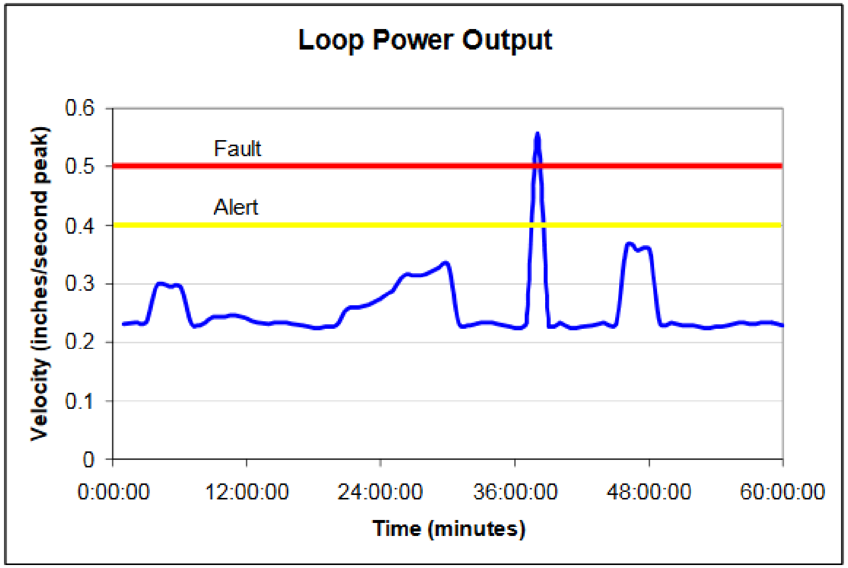
Four phases of fault monitoring

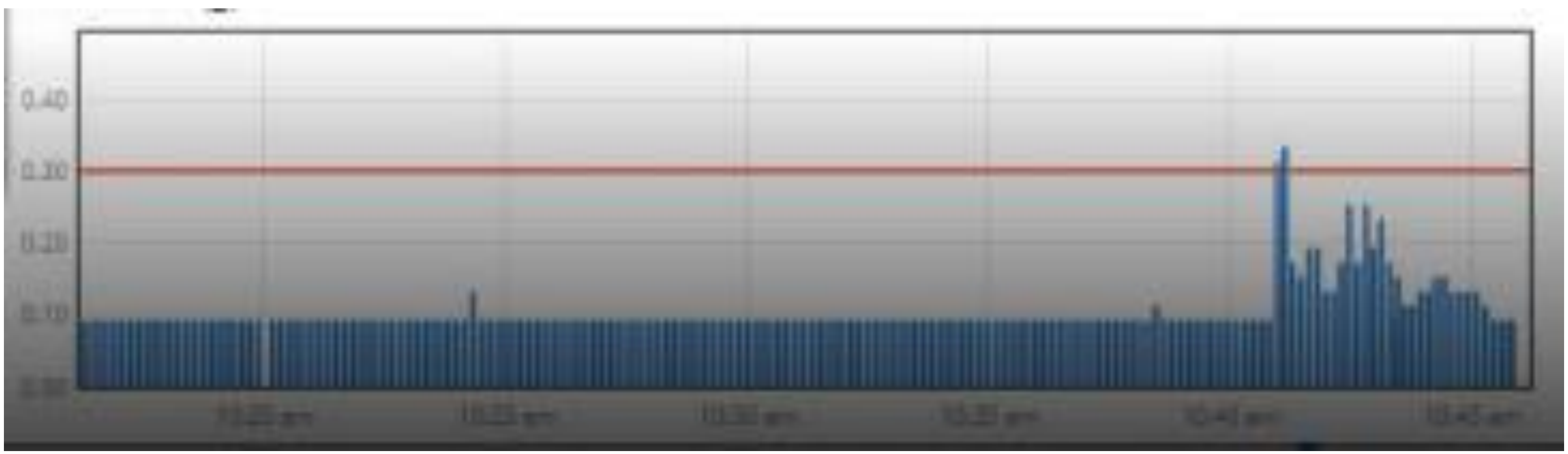
- **Information—collecting data**
- **Isolation-- fault diagnosis**
- **Alarms – generating warning signal**
- **Faults-- informing fault type**



Process Vibration Alarm Plot

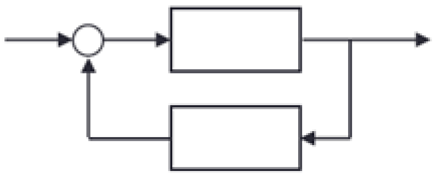
The key point in this monitoring system is

- fault diagnosis



Industrial Processes Automation

Automatic
control



Fault diagnosis

Fault tolerant control

Predictive
Maintenance

In this module, we will focus on

- **Automatic fault diagnosis (AFD).** The main function of AFD is to detect a fault and to find its location, providing information about fault in the system to enable fault-tolerant control to take place.
- **Automatic fault-tolerant control (AFTC). AFTC is a system** that possess the ability to accommodate system faults automatically.

1. Fault concept

Fault: an unpermitted deviation of at least one characteristic property or parameter of the system from the acceptable/usual/ standard condition. **A fault can be simply understood as an unexpected change in system *function* which hampers *normal control.***

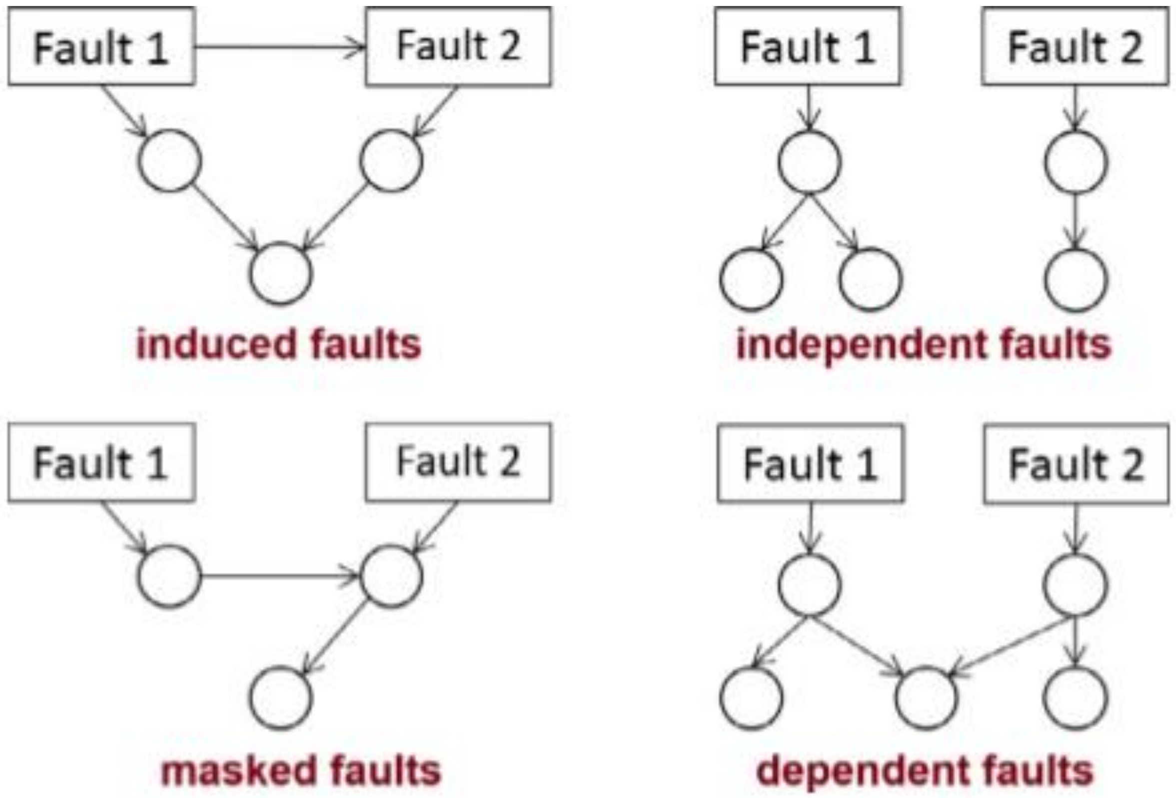
Failure: a permanent interruption of a system's ability to perform a required function under specified operating conditions.

Clearly, a failure is a condition which is much more severe than a fault. When a fault occurs in an actuator for example, the actuator is still usable but may have a slower response or become less effective.

$$\text{Fault} \neq \boldsymbol{Failure}$$

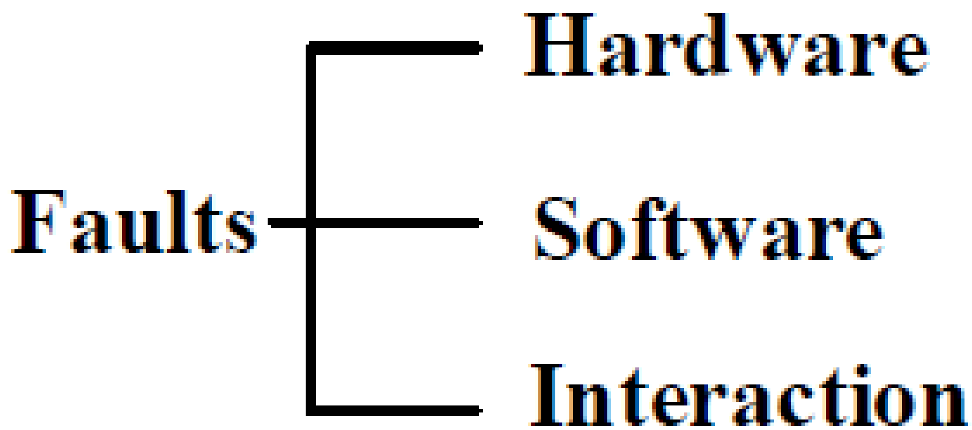
$$\text{Fault} \neq \text{collapse}$$

Faults may occur together



The four classes of multiple faults

2.Fault types:



- Hardware faults may arise in any physical

component of the system.

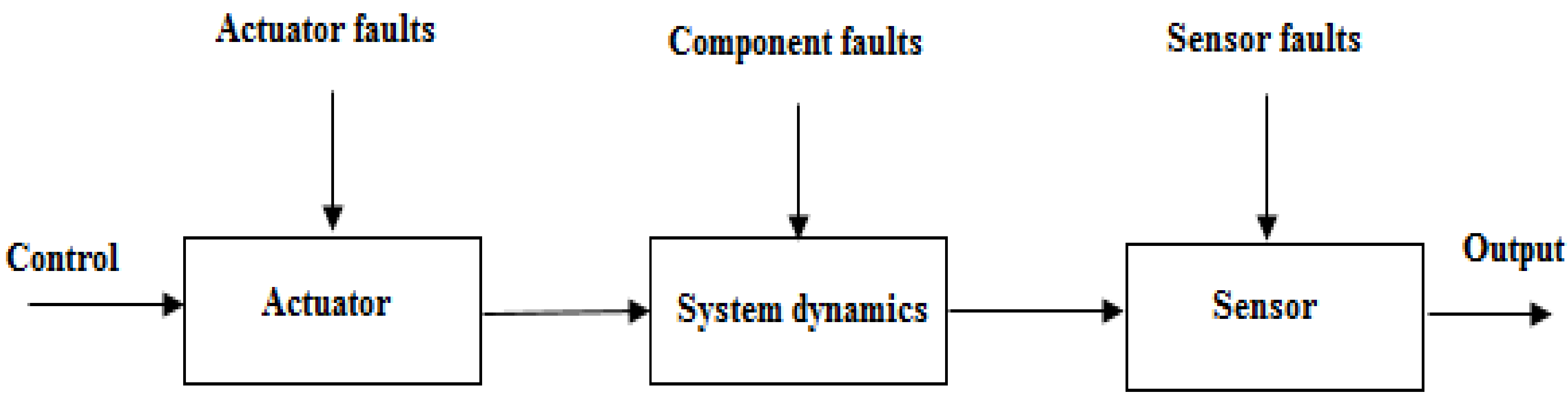
- Interaction faults are related faults which may be the result of external factors
- Software faults may regard faulty algorithms ,integration of different software units，and hack attack

Hack attack is critical issue in software fault

Spoofing drone

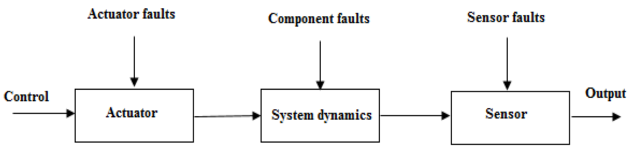
https://www.youtube.com/watch?v=6qQXVUze8oE

Hardware faults may occur in anywhere

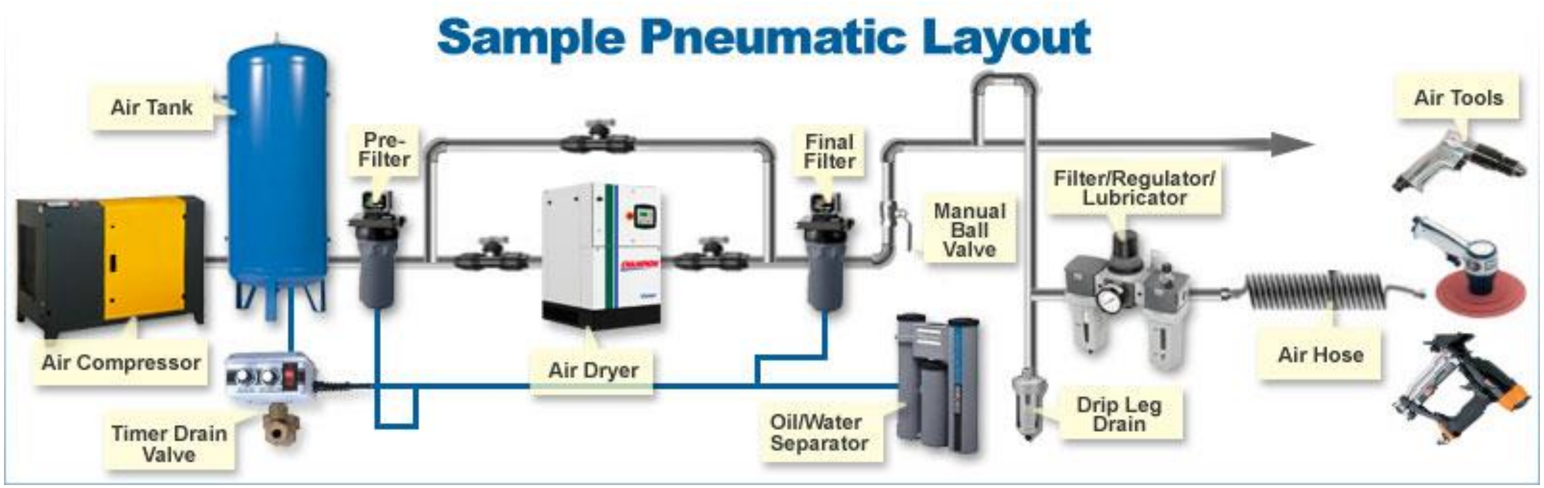


2.1Actuator faults:

An actuator is a device that converts energy into motion. It accepts a control command and produces a change in the system dynamics. An actuator is declared faulty if it affects the system inputs due to abnormal operation, material aging or the change of physical characteristics of components

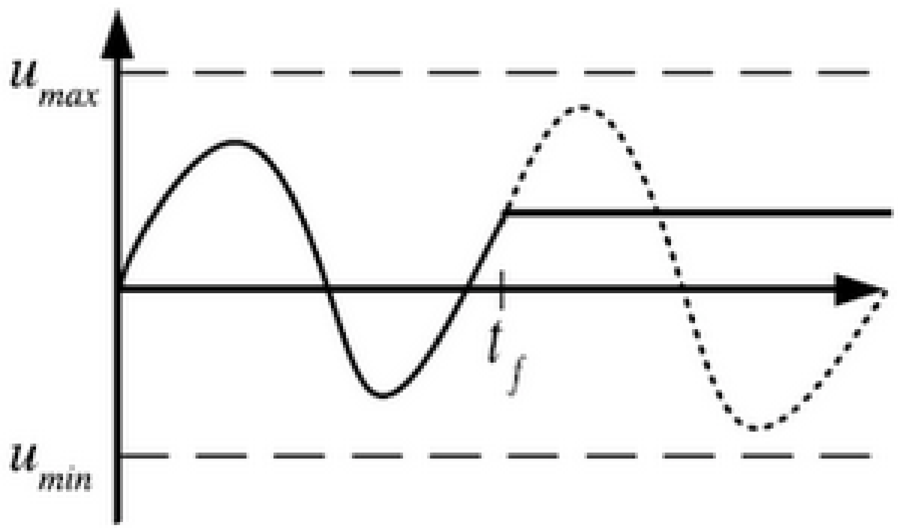


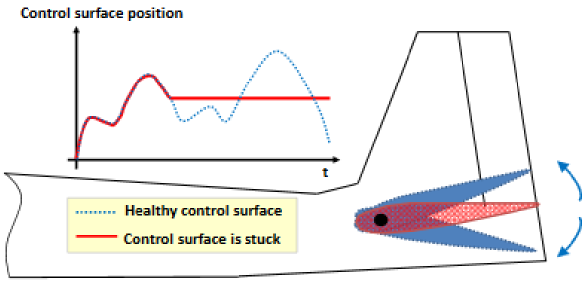
Actuators:


Sample Pneumatic Layout
Air Tank
Pre-Filter
Final Filter
Air Tools
Manual Ball Valve
Filter/Regulator/ Lubricator
Air Compressor
Air Dryer
Air Hose
Timer Drain Valve
Oil/Water Separator
Drip Leg Drain

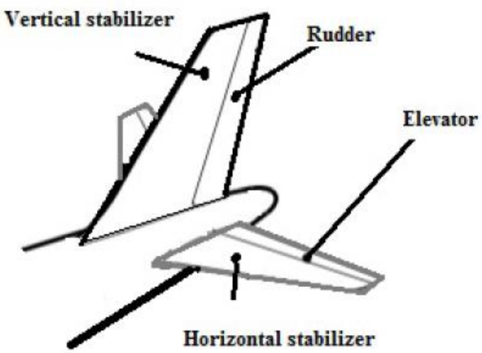
Four common actuator fault types:

- **Lock-in-place fault**

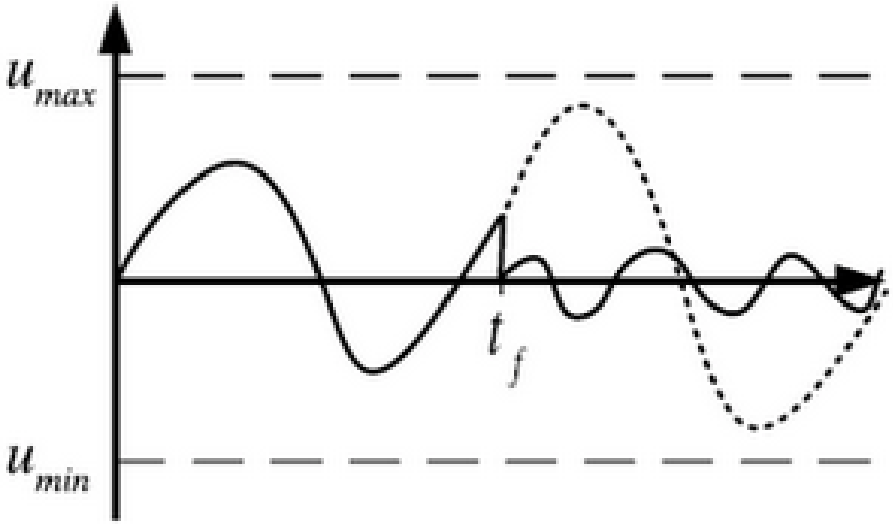


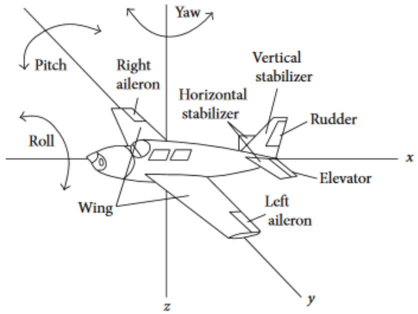


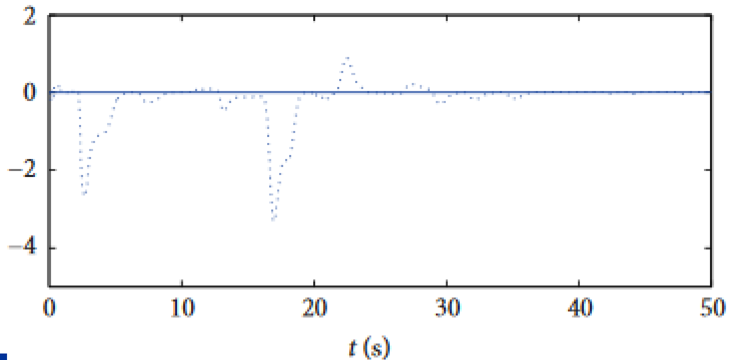
Elevator or ruder



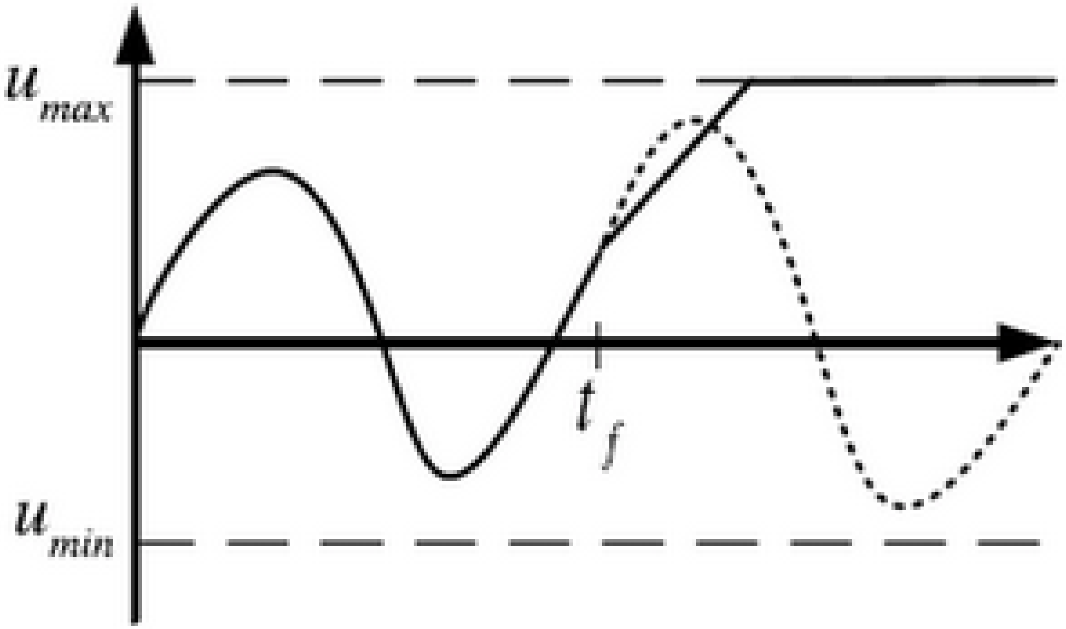
- **Floating around trim**

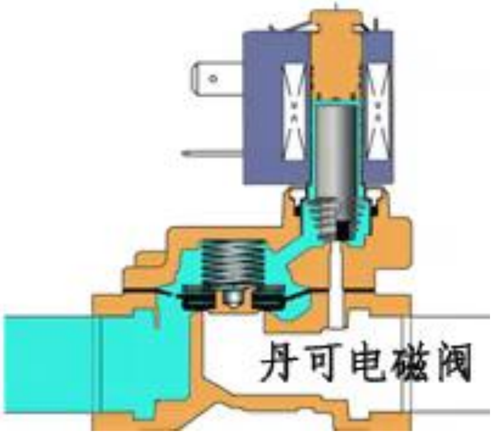




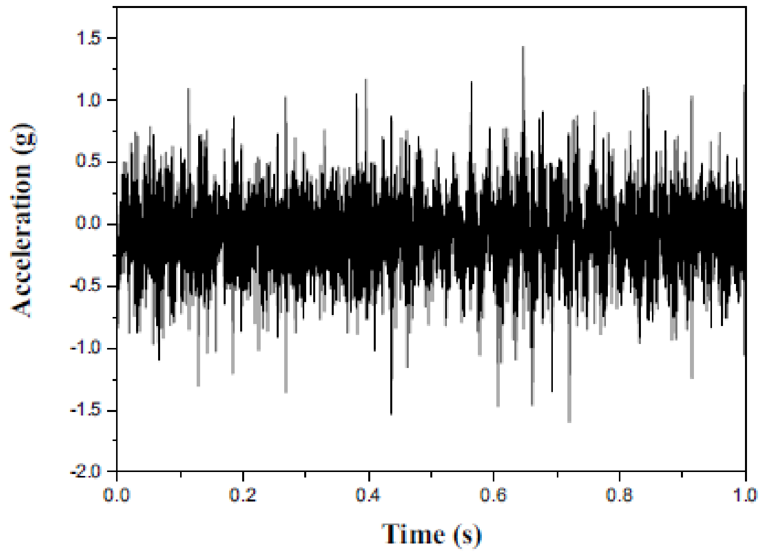


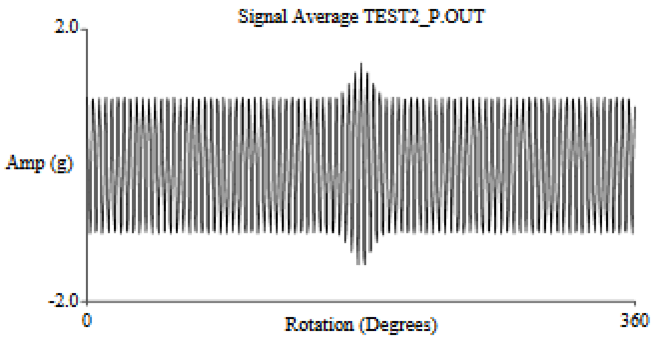
Hard-over fault

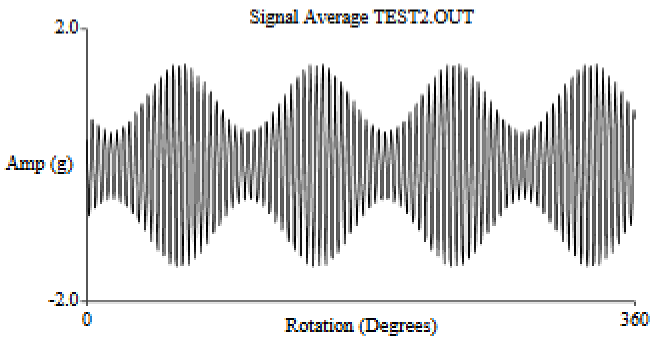




Vibration fault







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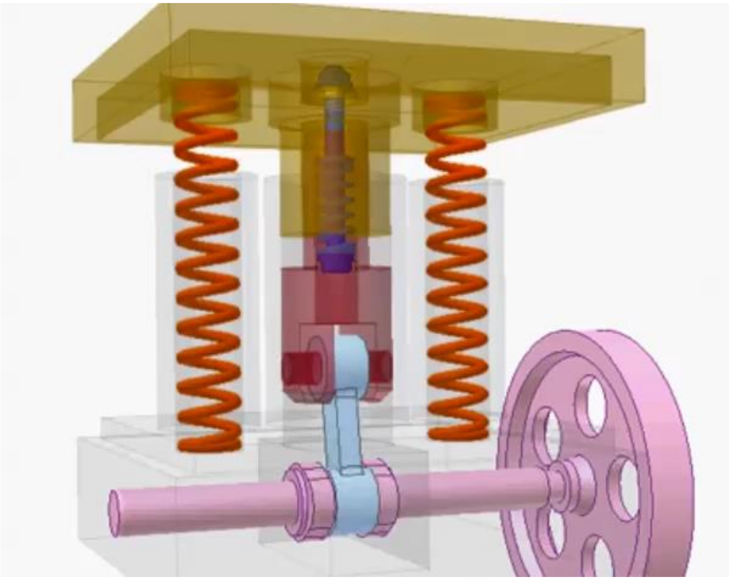
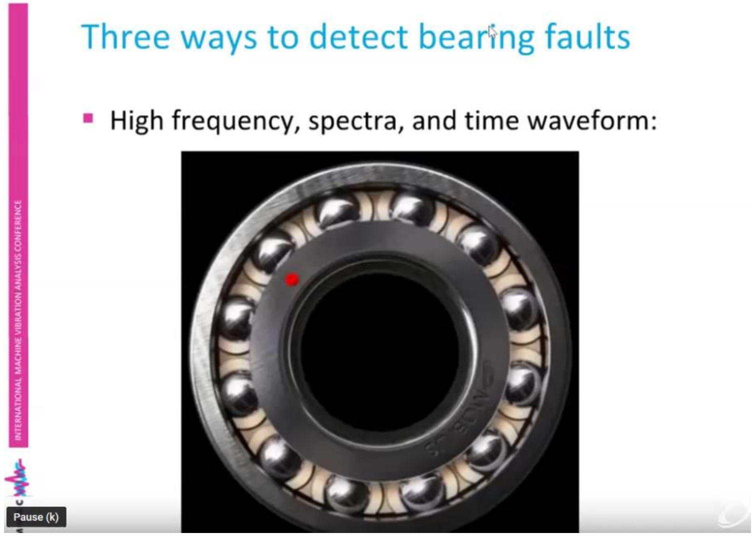
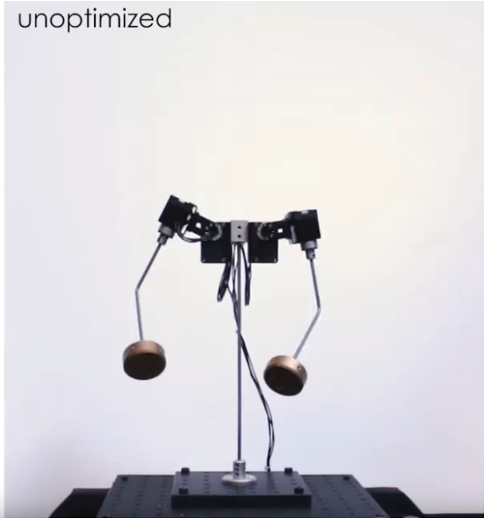
Good or bad vibration







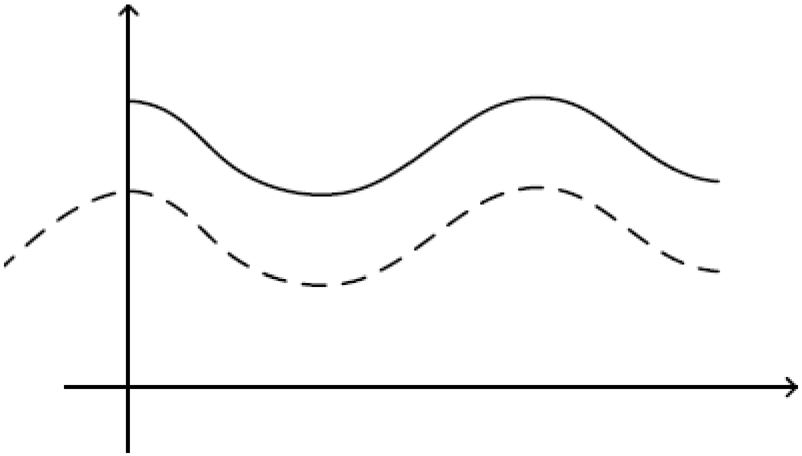
2.2 Sensor faults:

Sensor is used representing the whole sensor system which is consisted of sensing parts, transducer and interfacing components. Due to some factors such as design, long time running, environment etc, sensor may not work well and *become* destructive as a result of misreading. Intuitively, a sensor is declared faulty if its measurement gives an incorrect value from the actual measurand.

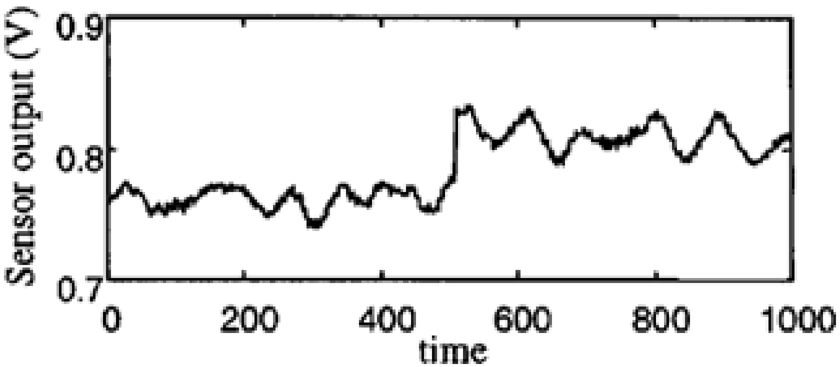
https://tech.alpsalpine.com/prod/e/html/sensor.html

Four common sensor fault types:

- **Bias fault** –the output of the sensor adds an amount of errors to the normal state

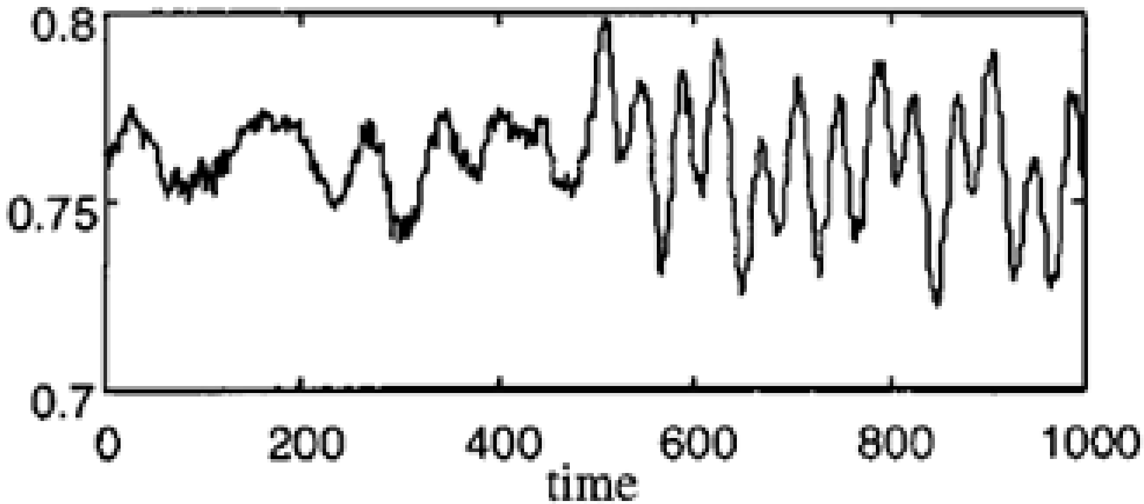


(a) bias fault



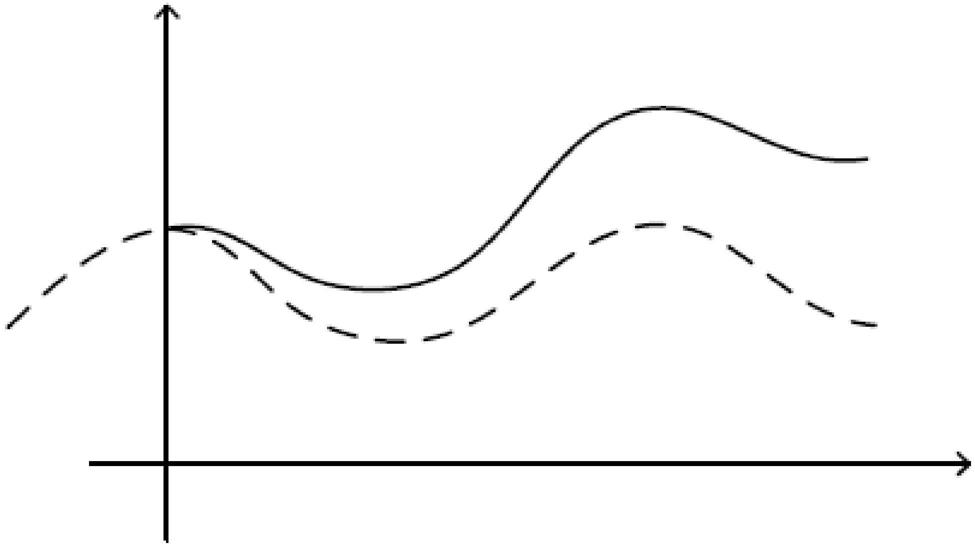
The signal including a bias fault

- **Cyclic fault** –the output of the sensor keeps periodic oscillations of constant amplitude from the normal state



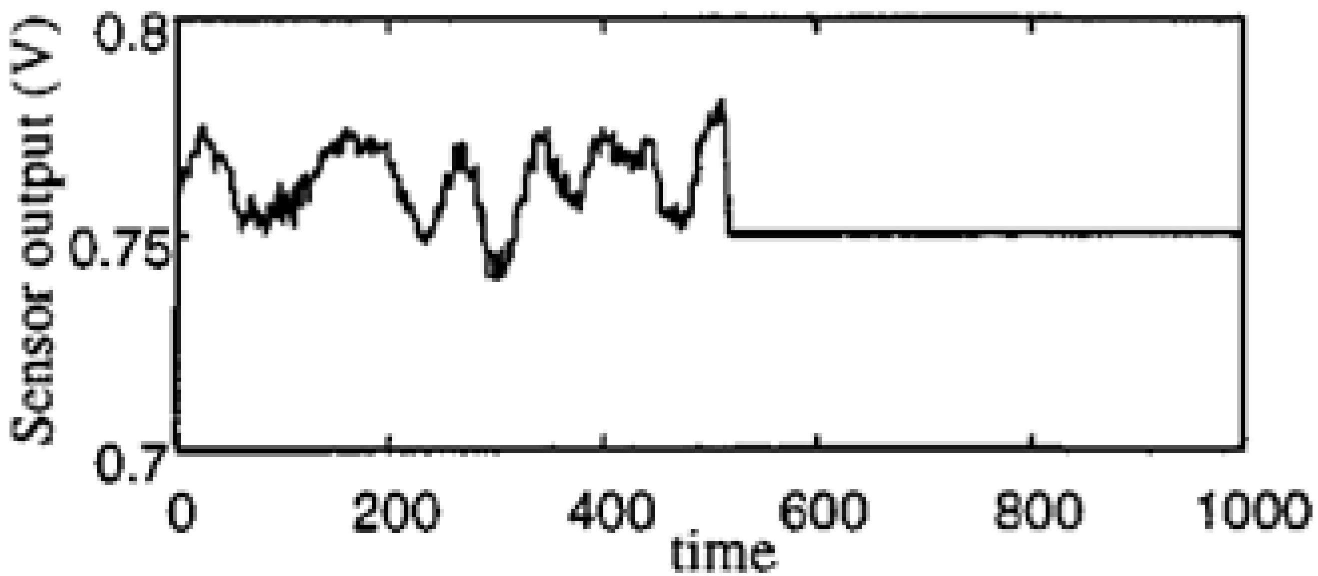
The signal including a cyclic fault

- **Drift fault**– the output of the sensor keeps increasing or decreasing almost linearly from the normal state



drifting fault

- **Stuck fault**– the sensor's output gets stuck at a certain point



The signal including a stuck fault

2.3 Component faults:

In the system component fault, it depends on the plant seriously and is very difficult to find common fault types. Different plants have different component fault types.

In general, components such as mechanical parts and electronic units may have possibility of fault occurrence.

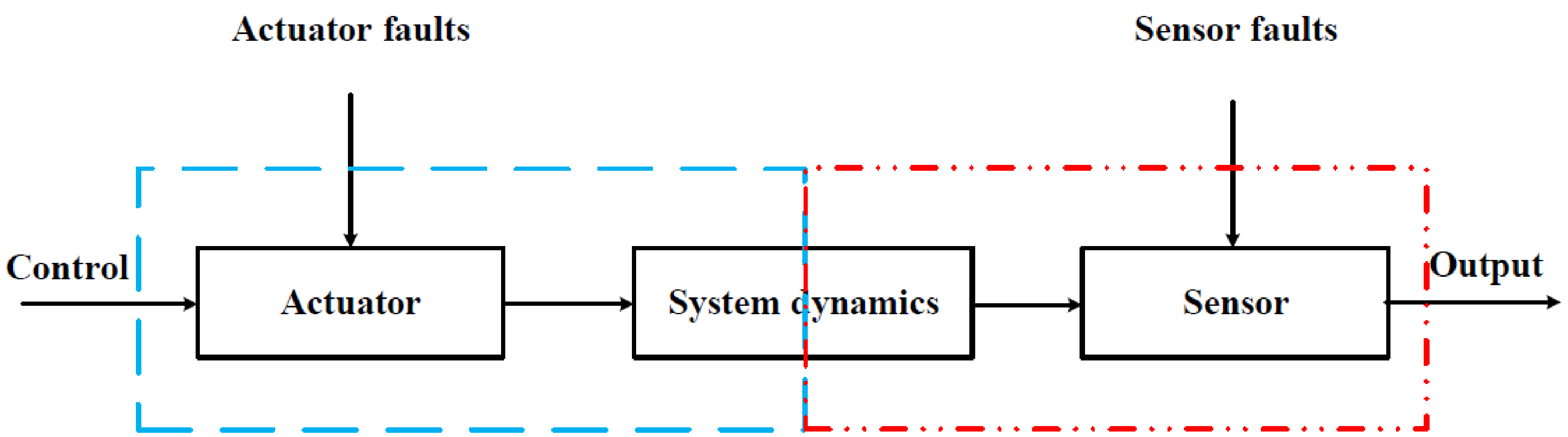
Example 1:

- Nuclear power has three different classes of plant component faults: 1)heaters stuck with a fixed power output; 2)sprayers stuck with a fixed mass flow rate; 3)the communication is disconnected between the controller and actuators

Example 2:

Electrical powers system has four types of plant component faults: transformers, rotating machines, human errors, and environmental conditions.

In fact, the system component faults can be merged into both the actuator and sensor faults.



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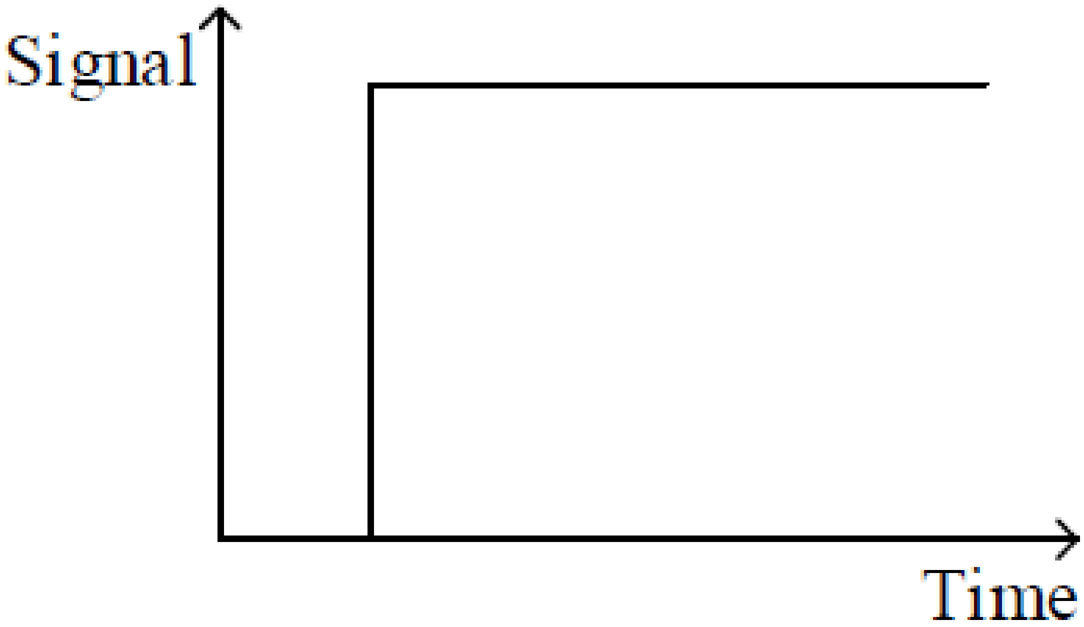
Mathematical form of faults:

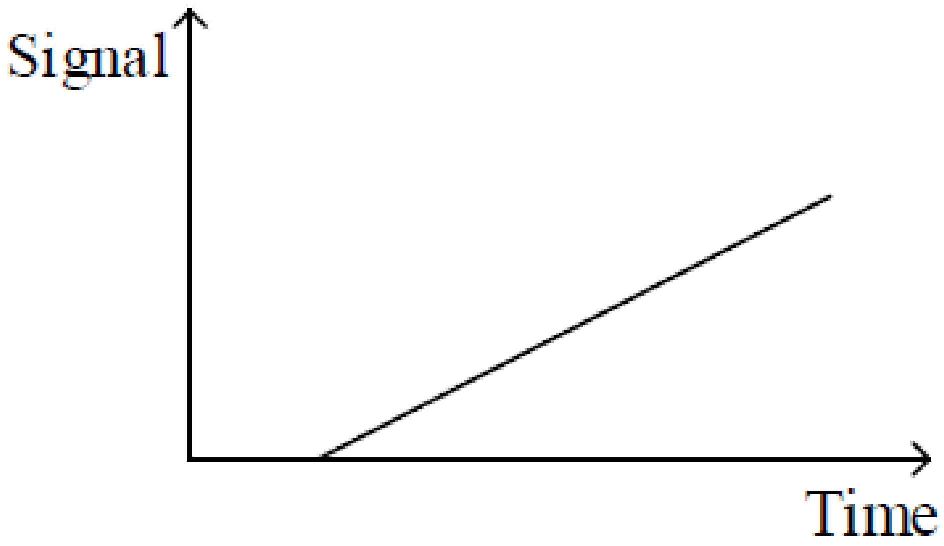
A fault is represented by its time profile, which includes <u>the time duration and the evolution mode of occurrence or disappearance,</u> and <u>its function (signature)</u>. It includes two parts: time profile and fault function.

For the term time, faults can be grouped into abrupt, incipient and intermittent faults.

Abrupt fault exhibits a sudden change as step-like deviation. An example of an abrupt failure is a control valve jam. It may be caused by hardware damage.



Incipient fault shows a slowly developing nature as drift-type. For example, a slow drift in a sensor, is more invisible and its effect is not obvious. It may be caused by aging of mechanical components



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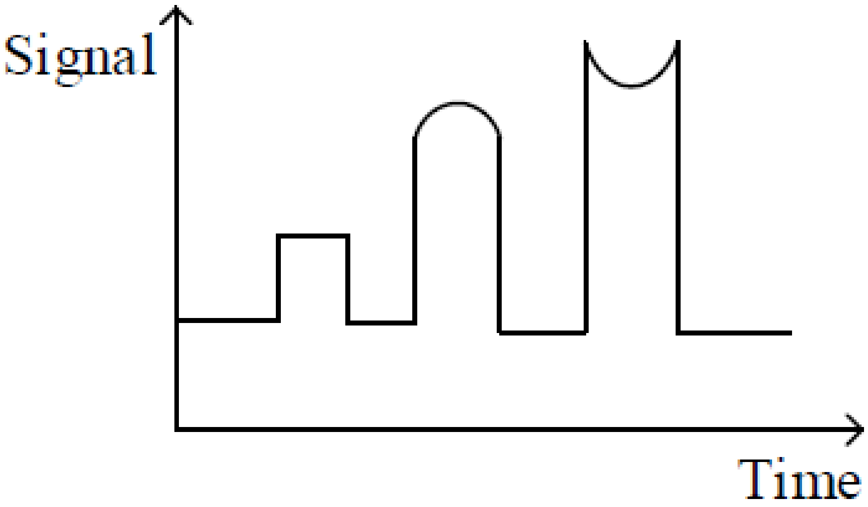
Intermittent fault manifests itself intermittently in an unpredictable behavoir. For example, a worn out roller in a printer cannot grip the paper and causes intermittent paper jams. Intermittent fault can be considered as a temporary fault and it will recover to its normal state. It may be caused by incorrect installation during initial manufacture and assembly. Also, male and female connectors



3. Fault Modeling

For the time-dependent fault, the following model is given by

$$f(t) = \boxed{\alpha(t - T_0)} F(t)$$

where $\alpha(t - T_0)$ is the time-profile of the fault, T_0 is the fault occurrence time, and $F(t)$ characterizes the change in the fault.

We have to modelling two terms.

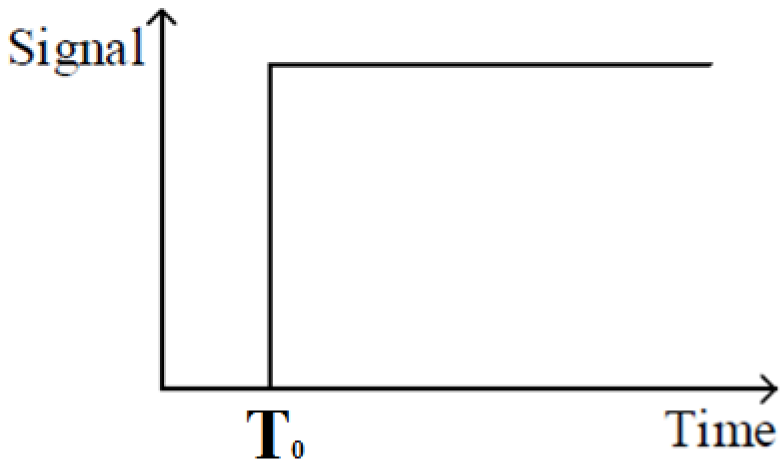
Why?

3.1. Time profile

$$f(t) = \alpha(t - T_0)F(t)$$

Abrupt fault–it is represented by a time-function described by

$$\alpha(t - T_0) = \begin{cases} 0, & t < T_0 \\ 1, & t \geq T_0 \end{cases}$$

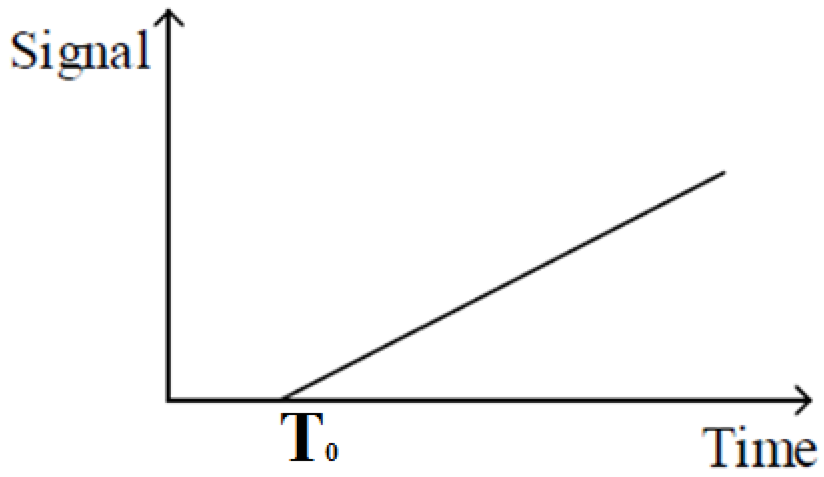


Incipient fault–

it is represented by a time-function described by

$$\alpha(t - T_0) = \begin{cases} 0, & t < T_0 \\ 1 - e^{-\rho(t-T_0)}, & t \geq T_0 \end{cases}$$

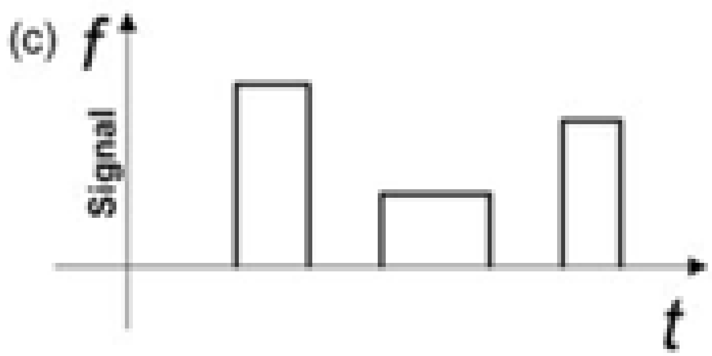
$\rho > 0$ *is the constant*



Intermittent fault–

it is represented by a time-function described by

$$\alpha(t-T)=\begin{cases} 0 \quad , & t \le T_0 \\ \delta(T_0 < t \le T_1), & T_0 < t \le T_1 \\ \vdots & \\ \delta(T_{n-1} < t \le T_n), & T_{n-1} < t \le T_n \end{cases}$$



3.2. Modeling of fault function

$$f(t) = \alpha(t - T_0)\boxed{F(t)}$$

There are two ways for modeling fault function

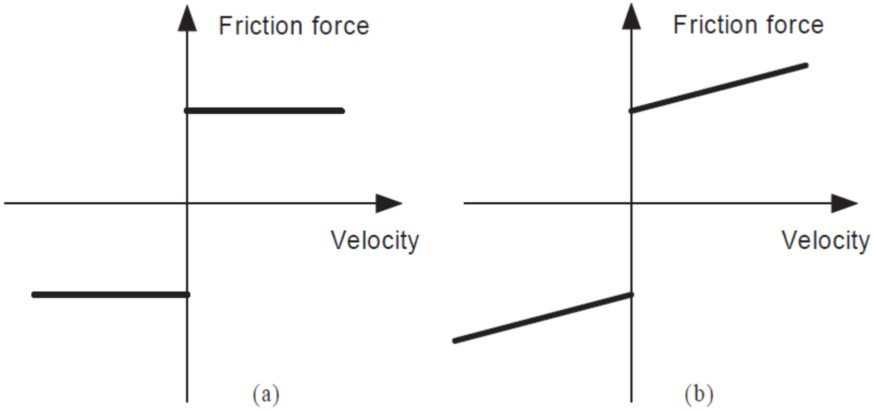
1.Mechanism model

2. Black-box model

3.1.1 Mechanism model

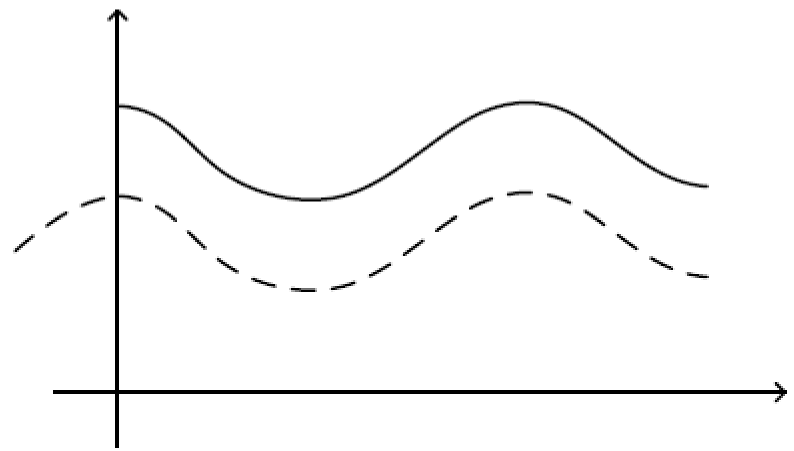
We know the working principle and derive a mathematical model.

An example: Friction model (a)Coulomb. (b) Coulomb + viscous



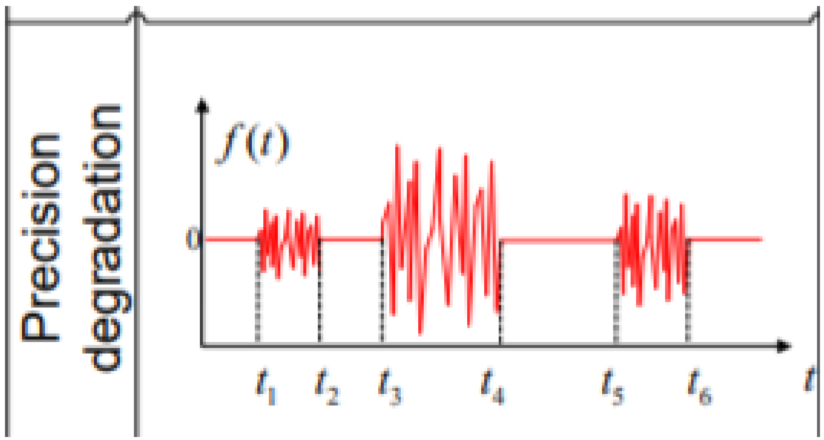
$$F = F_c sgn(\dot{x}) + F_v \dot{x}$$

Offset fault:



For example:accelerometer

Precision degradation:

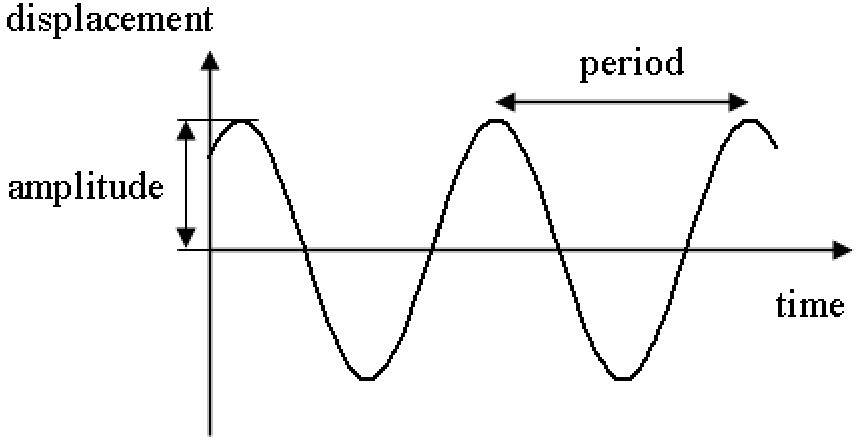


Another example: Vibration model

Line vibration which is vibrating at one frequency (f_V), at a magnitude of A_{rms}.

$$a(t) = A_{PK} \times sin(\omega_v \times t)$$

$$f_v = \frac{\omega v}{2\pi}$$



Advantages of mechanism model

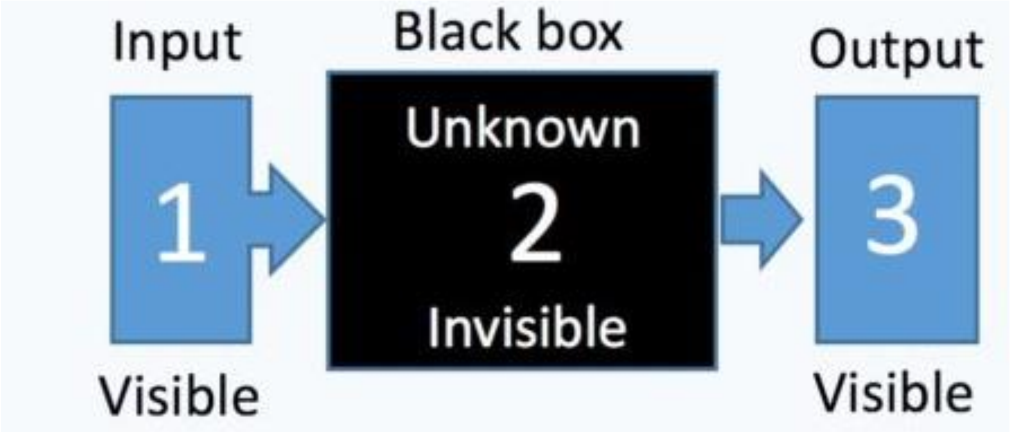
- It is based on a close interaction between experiment and modeling
- It allows integration of knowledge from study to study
- It provides a detailed understanding of the plant mechanisms

Disadvantages of mechanism model

- It requires a strong background knowledge
- No uniform formula for every plant

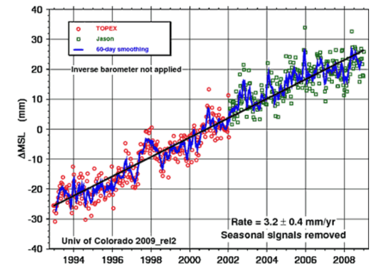
3.1.2 Black-box model (data-based method)

We don't know any working principle and obtain a mathematical model. But we need to have data: Input data and output data



Linear model: least square estimation method

$$y = b_0 + b_1 x_1 + \cdots + b_p x_p$$



By collecting data, packed vector X and Y are given by

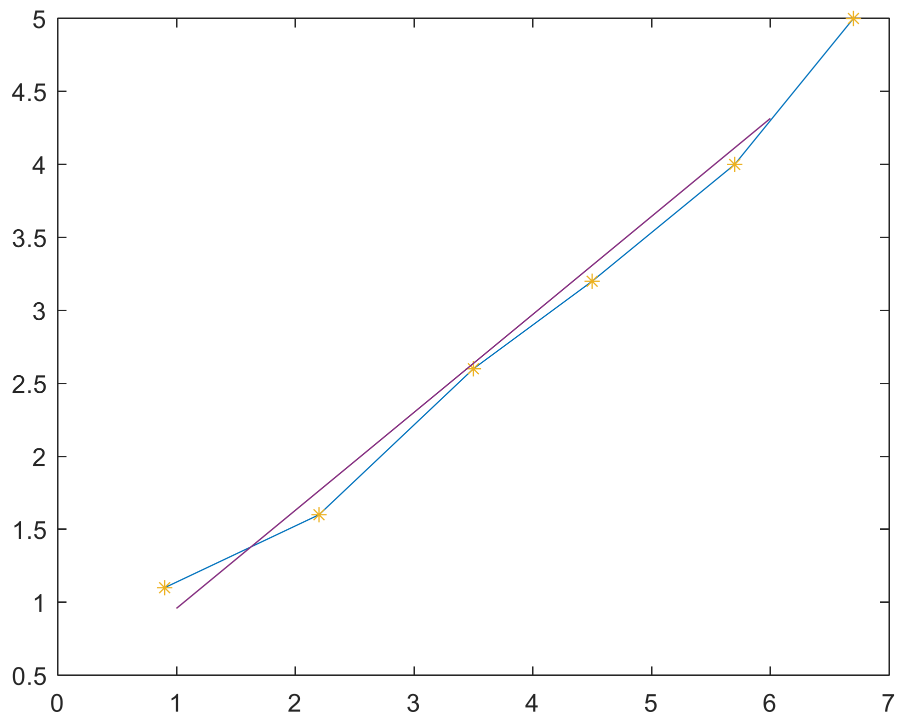
$$X = \begin{bmatrix} 1 & x_{11} & \cdots & x_{1p} \\ 1 & x_{21} & \cdots & x_{2p} \\ \vdots & \vdots & & \vdots \\ 1 & x_{n1} & \cdots & x_{np} \end{bmatrix} \qquad Y = \begin{bmatrix} y_1 \\ y_2 \\ \vdots \\ y_n \end{bmatrix}$$

Let $\hat{b}$ be the estimated vector of $b = [b_0, b_1, \ldots, b_p]^T$

$$\hat{b} = (X^T X)^{-1} X^T Y$$

The input/output data of a sensor fault is shown in the table below. Please find the linear relationship between the input and output

input	0.9	2.2	3.5	4.5	5.7	6.7
output	1.1	1.6	2.6	3.2	4.0	5.0



Nonlinear model:

$$\boldsymbol{y = f(x_1, x_2, \ldots, x_n)}$$

For example:

$$A = \pi r^2$$

$$\boldsymbol{y = e^{-x}}$$

or polynomial z=$\boldsymbol{x^2 + x^3y^5 + x^4y^{-1}}$

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Non-linear relationship between input and output

$$y = b_0 + b_1 x + b_2 x^2 + b_3 x^3 + \cdots + b_p x^p$$

$$X = \begin{bmatrix} 1 & x_{11} & x_{12}^{2} & \dots & x_{1p}^{p} \\ 1 & x_{21} & x_{22}^{2} & \dots & x_{2p}^{p} \\ & \vdots & & & \\ 1 & x_{n1} & x_{n2}^{2} & \dots & x_{np}^{p} \end{bmatrix} \qquad Y = \begin{bmatrix} y_1 \\ y_2 \\ \vdots \\ y_n \end{bmatrix}$$

Estimated coefficients $\hat{b} = (X^T X)^{-1} X^T Y$

Model output $\hat{Y} = X\hat{b}$

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Nonlinear model differs from linear one. It is necessary to choose the order number *p*.

$$y=b_0+b_1x+b_2x^2+b_3x^3+\cdots+b_px^p$$

How do we choose the number *p*?

$$e=Y-\hat{Y}, \qquad \hat{Y}=X\hat{b}$$

If |e|< tolerance number (user defined), *p* is ok; otherwise, *p*=*p*+1.

Continue to do $\hat{b}=(X^TX)^{-1}X^TY$

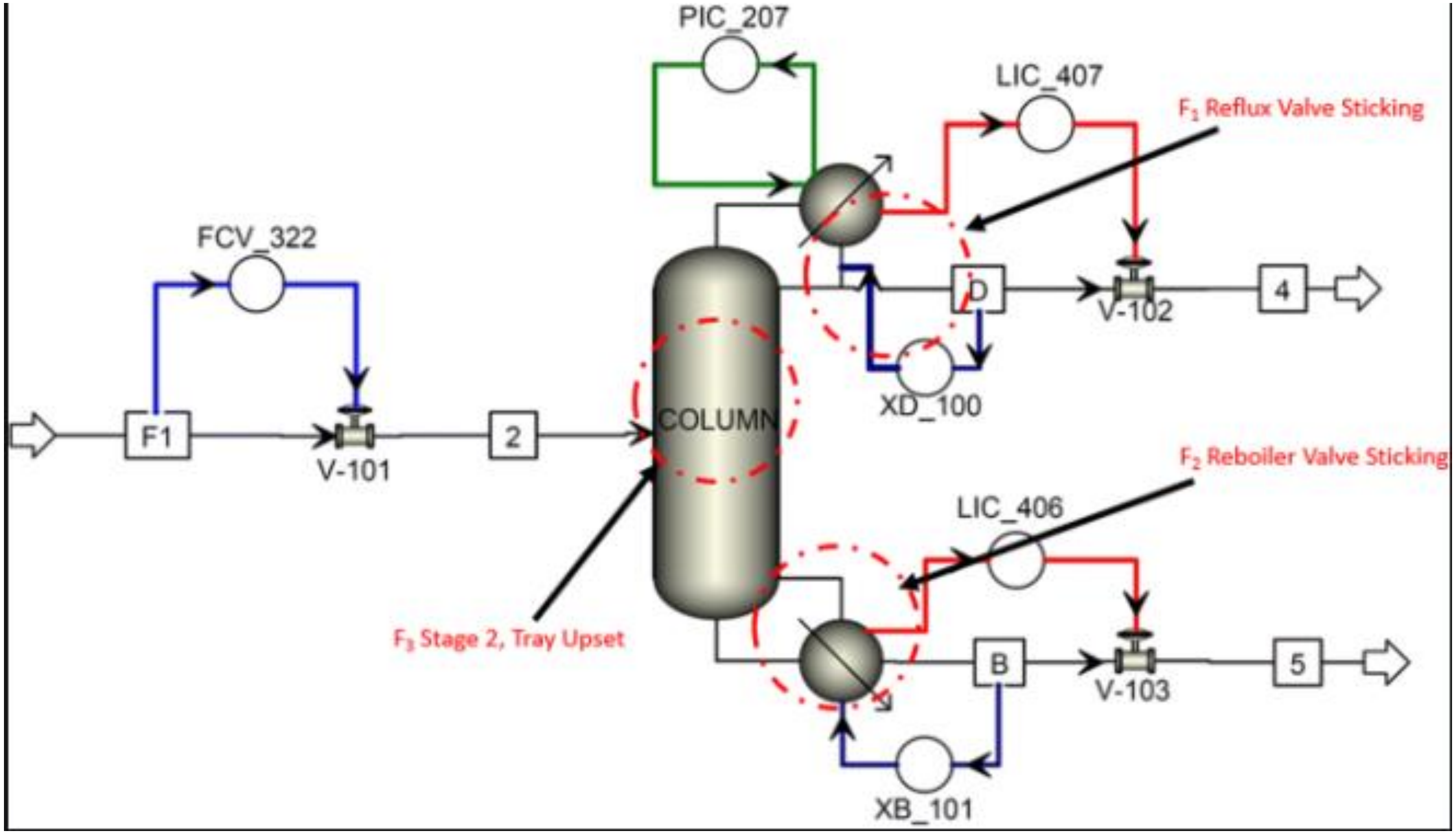
Nonlinear model built by

Neural networks (NNs)

$$\boldsymbol{y = f(x_1, x_2, \dots, x_n)}$$

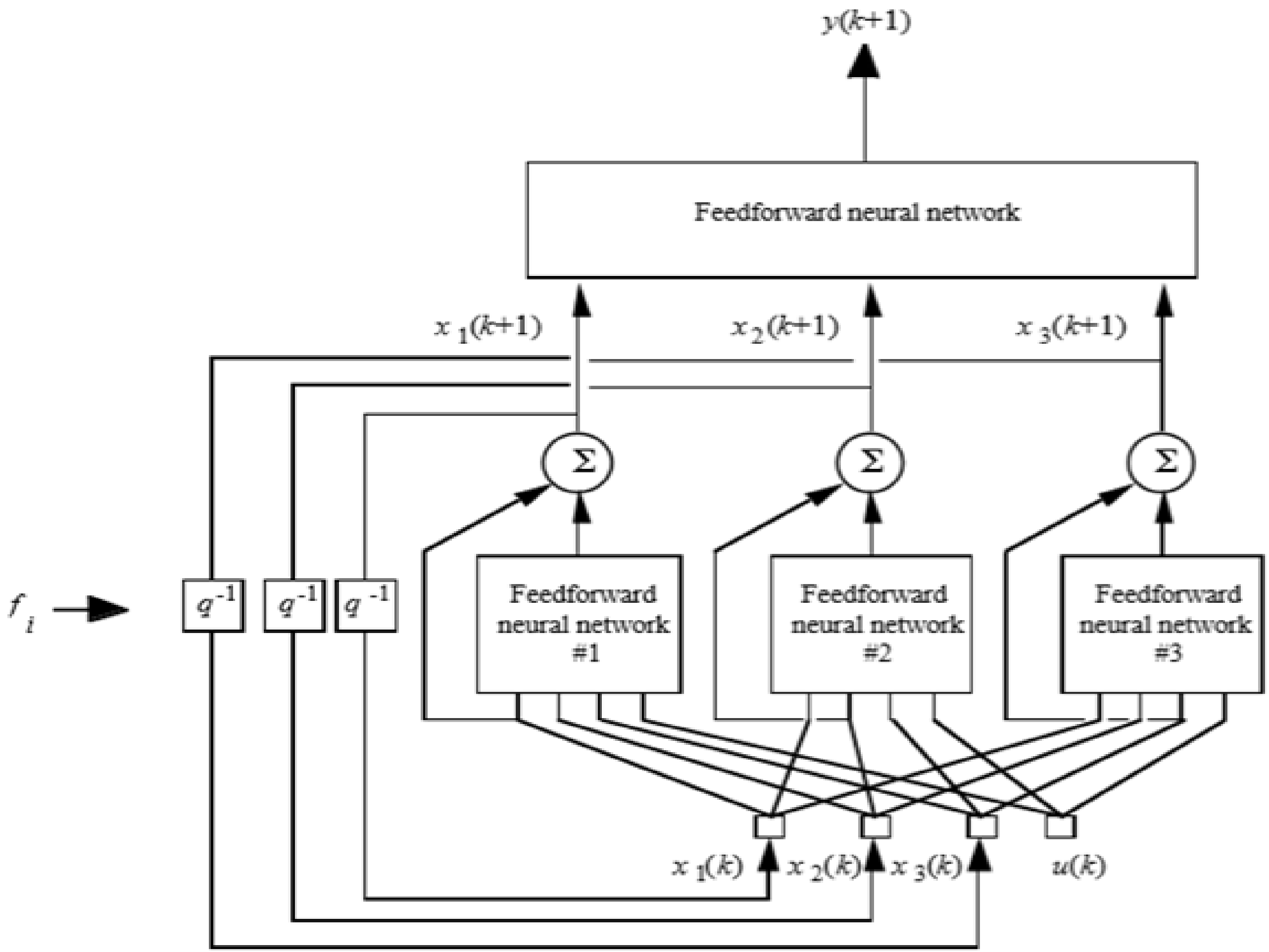
- NNs are usually used as a tool for modelling nonlinear functions because of their good capabilities in function approximation.
- It has been proven that NN can approximate any continuous function over a compact set

An example of black-box fault modeling in Distillation Column



Syed A. Taqvi, Lemma Dendana Tufa, Haslinda Zabiri, Abdulhalim Shah Maulud & Fahim Uddin *Neural Computing and Applications* **volume 32**, pages3503–3519(2020)

Neural network training for fault learning (record fault data and train neural network)



One example of neural network learning on MATLAB

Modeling a nonlinear curve by sampling points.

Main advantage of black-box model

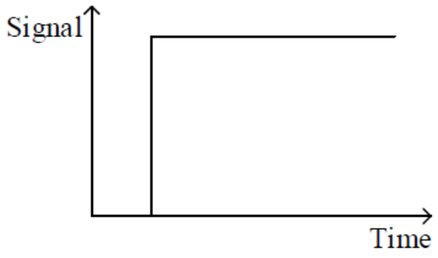
- You don't need to know any background knowledge.

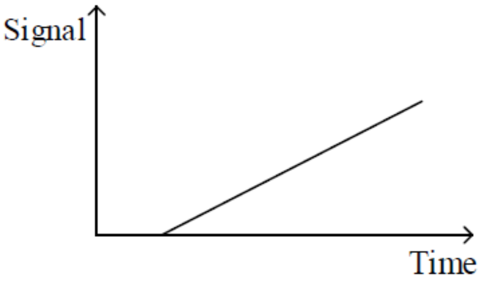
Disadvantages of black-box model

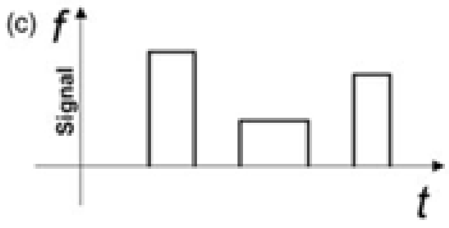
- You don't know what happens and why.

Summary

- Actuator has four types of faults
- Sensor has four types of faults
- Time profile of a fault , regardless of actuator or sensor faults. There are three types







- **Mathematical model of time profile of faults**

$$\alpha(t - T_0) = \begin{cases} 0, & t < T_0 \\ 1, & t \geq T_0 \end{cases}$$

$$\alpha(t - T_0) = \begin{cases} 0, & t < T_0 \\ 1 - e^{-\rho(t - T_0)}, & t \geq T_0 \end{cases}$$

$$\alpha(t - T) = \begin{cases} \delta(t \leq T_0), & t \leq T_0 \\ \delta(T_0 < t \leq T_1), & T_0 < t \leq T_1 \\ \vdots & \\ \delta(T_{n-1} < t \leq T_n), & T_{n-1} < t \leq T_n \end{cases}$$

- **Fault can be represented by a time profile of fault occurrence and fault function**

- **Fault modeling:**

  mechanism model and black-box model

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Any question?

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Reference

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