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

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Learning Objective

- Understand the fundamentals of fault-tolerant control methods

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Topics To Be Covered

- **Hardware fault-tolerant control method**
- **Software fault-tolerant control method**

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Review

- **Condition monitoring**

Can we classify the fault diagnosis methods?

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Key Point:Threshold calculation

Mean+deviation+small tolerance number

Mean +α $\times$deviation ($\alpha > 1$)

Solve the equation to derive the threshold. For example, linear system can be expressed by

$$\dot{x}(t) = Ax(t) + Bu(t)$$

$$y(t) = Ce^{At}x(0) + \int_0^t Ce^{A(t-\tau)}Bu(\tau)d\tau + Du(t)$$

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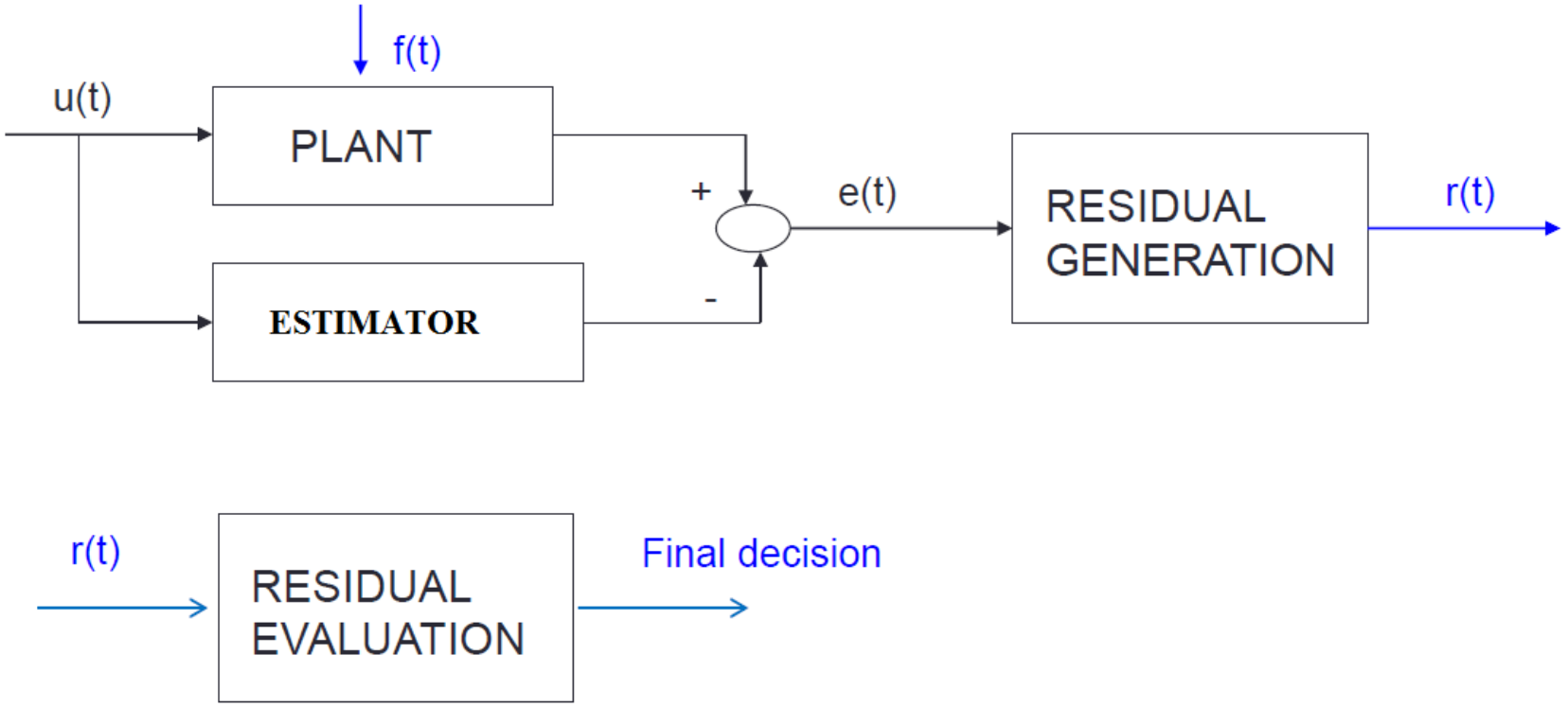
Review



Review:Model includes

- Estimator (linear or nonlinear model observer)
- Filter (linear or nonlinear *Kalman* filters)
- Nonlinear neural network model (nonlinear systems)

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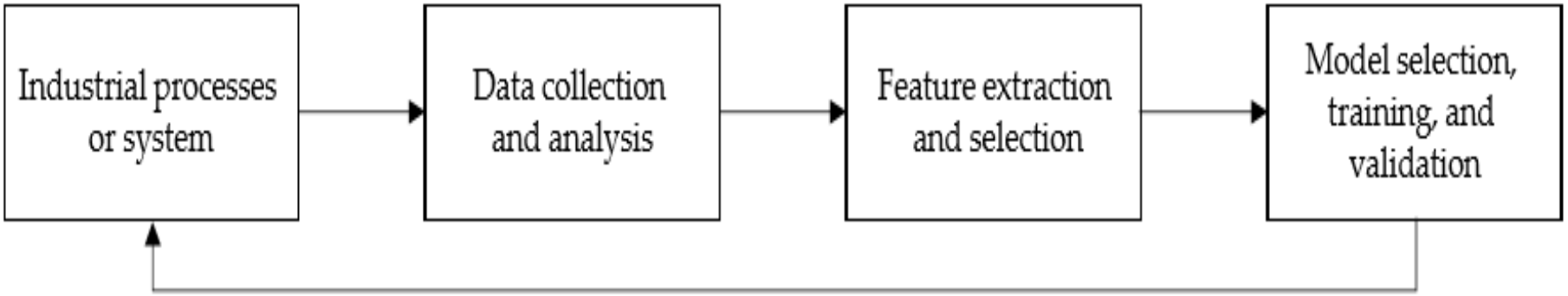
Review



Implementation procedure of a conventional FDD method (or system).

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1.Fault Tolerant control (FTC)

It is concerned that a control system can accommodate faults and continues to work properly when faults occur. Its aim is to prevent that simple faults develop into serious failure.

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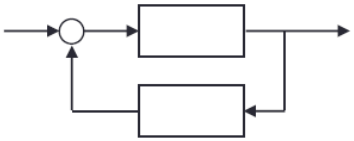
Industrial Processes Automation

Automatic control



FD scheme

Fault Tolerant Control

Predictive Maintenance

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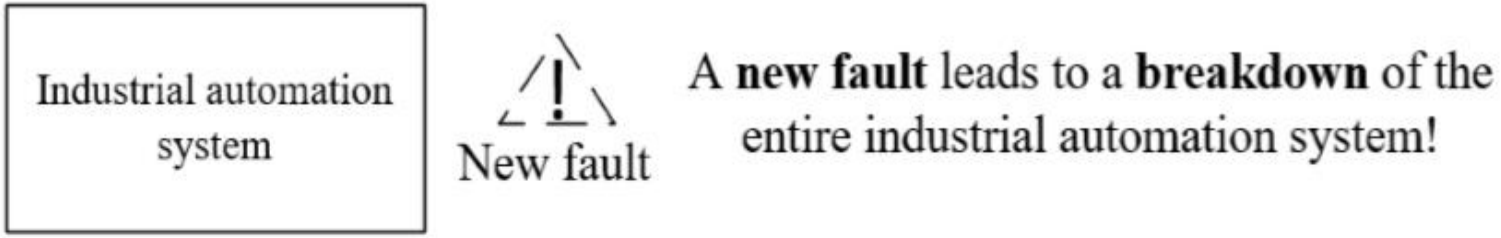
General case



New approach

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2 Fault Tolerant control (FTC)

- Traditional FTC methods
- Modern FTC methods

3.Traditional FTC method

If finding faults, manual service (call service).

For example

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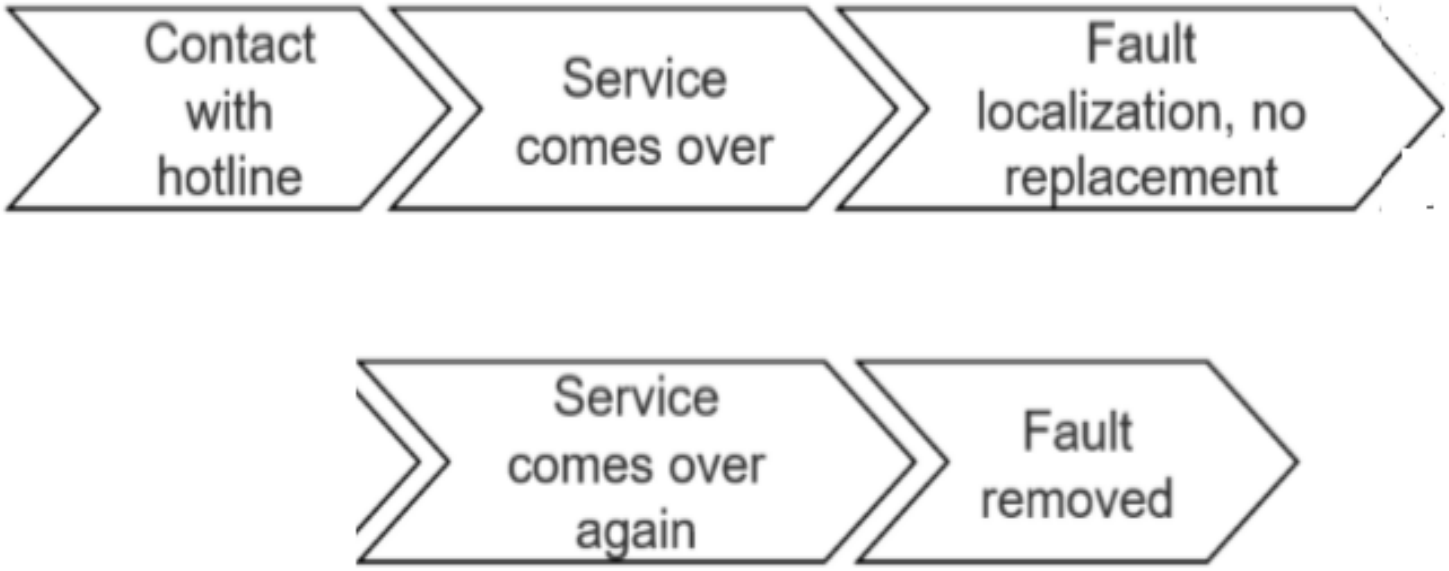
Traditional handling method



Corrective maintenance procedure by maintenance staff

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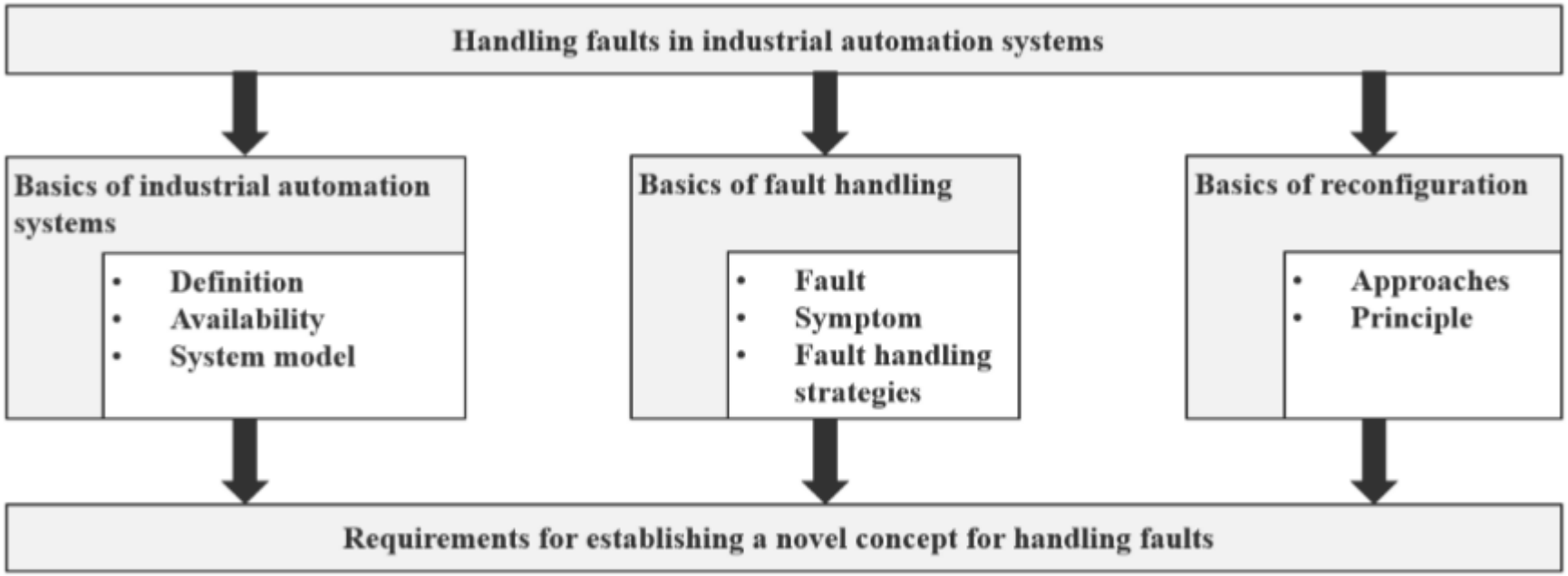
Advantages:

- **Robustness**

Disadvantages:

- Delays and interruptions of real-time programs caused by manual repair action;
- The inaccessibility of some systems to manual repair; and
- The excessively high costs of lost time and of maintenance in many installations.

4. Modern fault tolerant control methods



basics concerning handling faults in industrial automation systems

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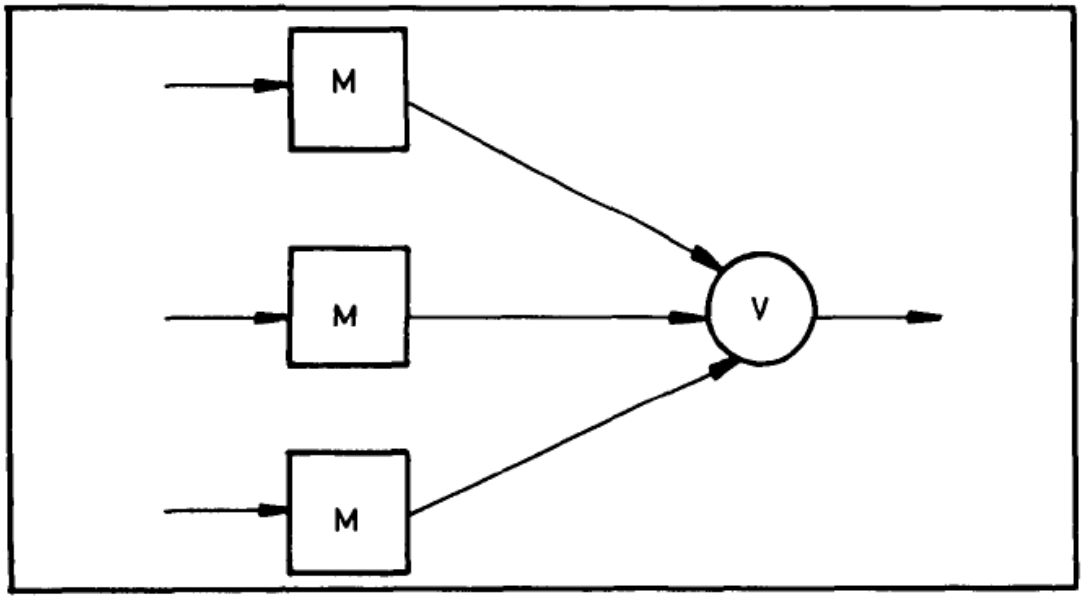
4. Modern fault tolerant control methods

- Hardware methods—use redundant hardware (spare) to accommodate faults
- Software methods--- use software to implement the designed algorithms to accommodate faults (less sensors)
- Mixed methods---use both automatic handling or intervention of skilled personals

4.1 Hardware methods

- **It is consisted of several redundant parts.**



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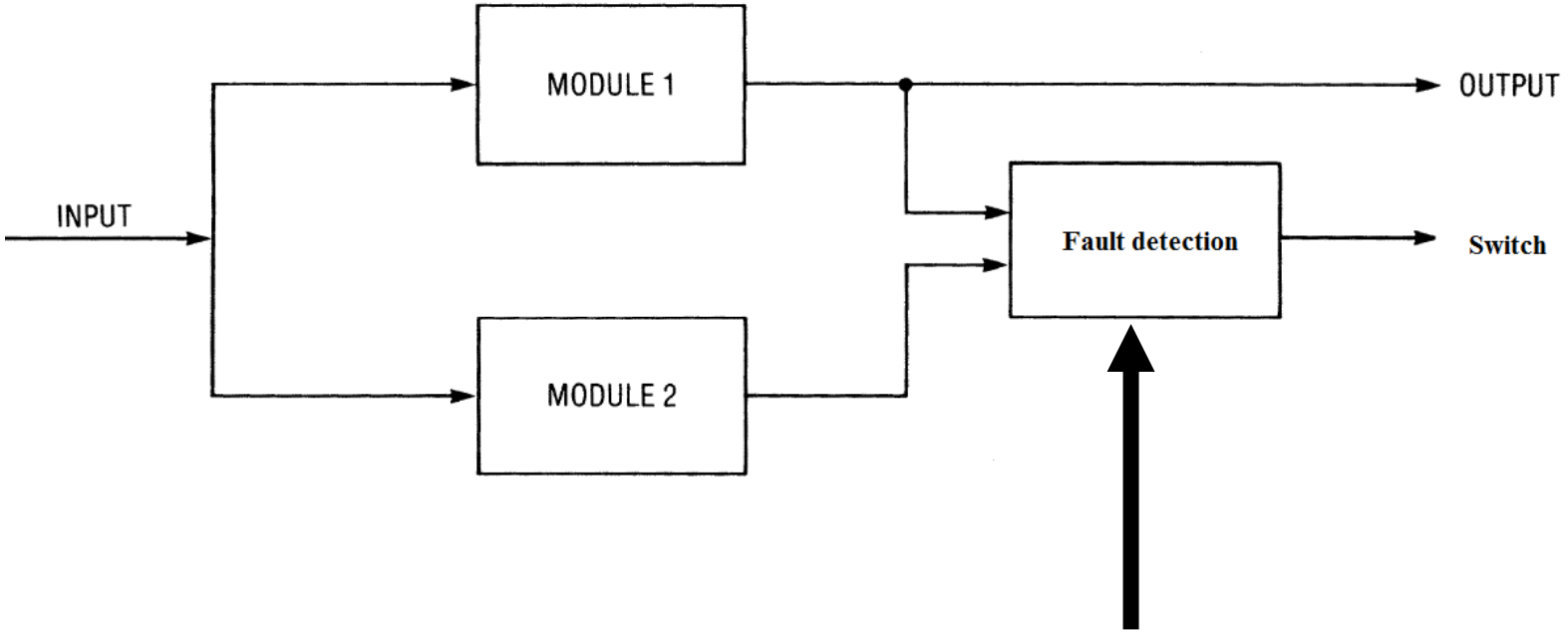
How does the hardware redundant parts work?
Method 1:



Time-domain fault detection method

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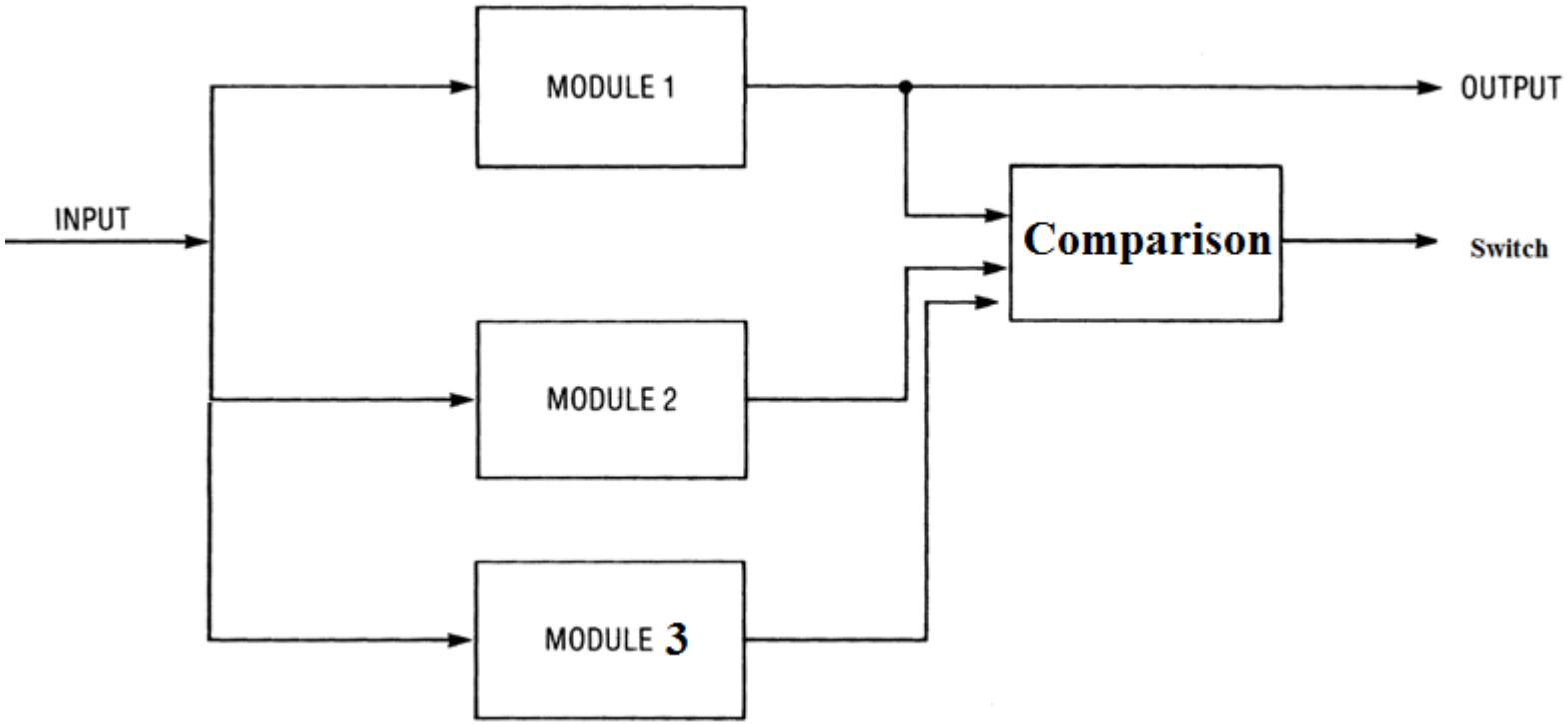
Method 2: there are at least 3 components



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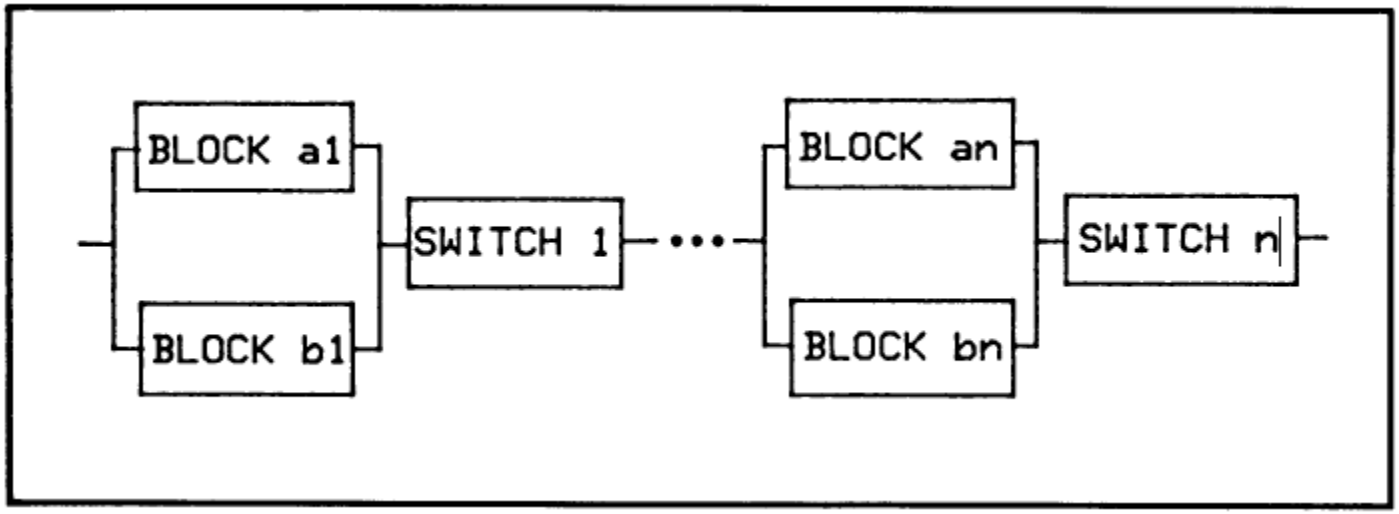
A complex fault-tolerant system

It is composed of a group of series-parallel duplex fault-tolerant units



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One example: Pixhawk PX4 2.4.8 Flight Controller Kit Set

Sensor:

•L3GD20 3 axis digital 16 bit gyroscope

•LSM303D 3 axis 14 bit accelerometer /magnetometer

•MPU6000 6 axis accelerometer / magnetometer (**redundant component)**

•MS5611 high precision barometer

•GPS

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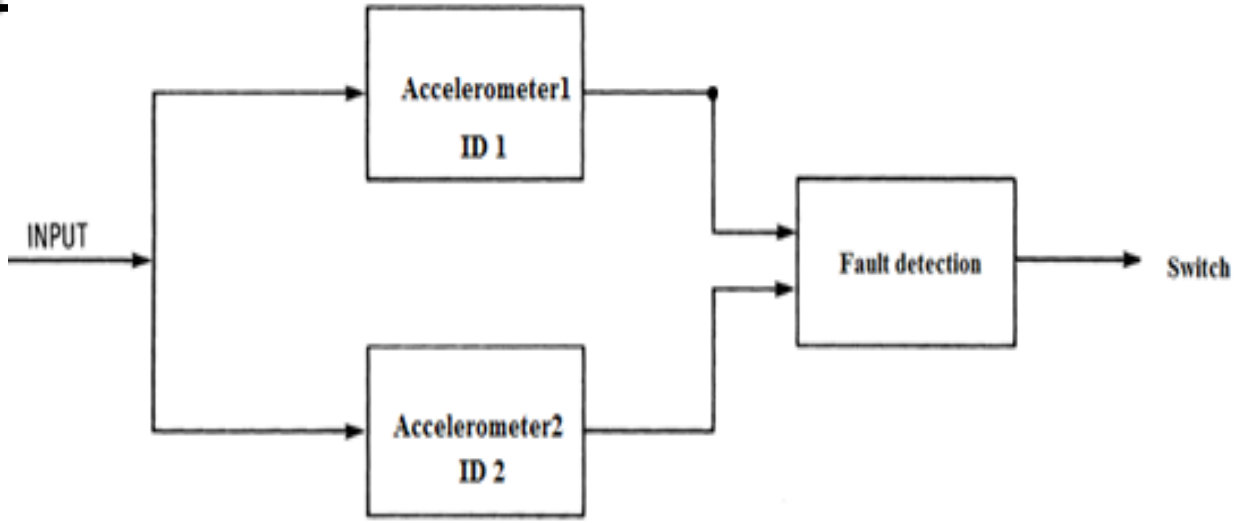
How does Pixhawk use two accelerometers for fault tolerant control?

ID1: accelerometer ; ID2: accelerometer

Default: use ID1



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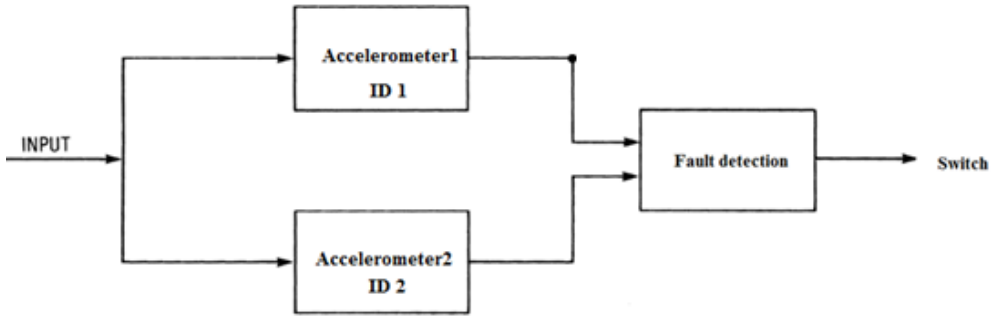


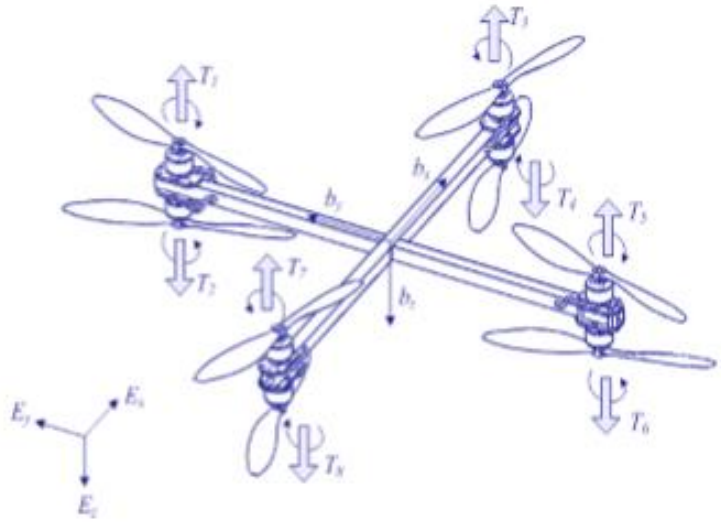
If velocity (GPS) changes, accelerometer should change; if it changes, it is ok; otherwise, switch to ID2.

Also, the fault detection checks the range of the accelerometer. If exceeding the range, switch to ID2.

Second example: Redundant drone

Quadrotors

Octorotors stability



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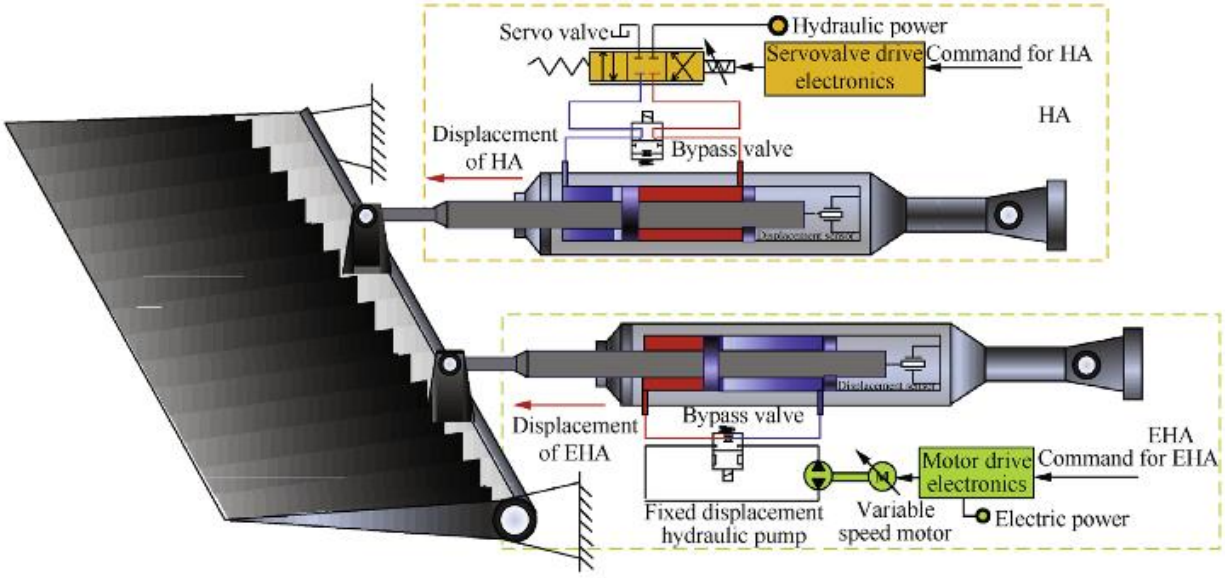
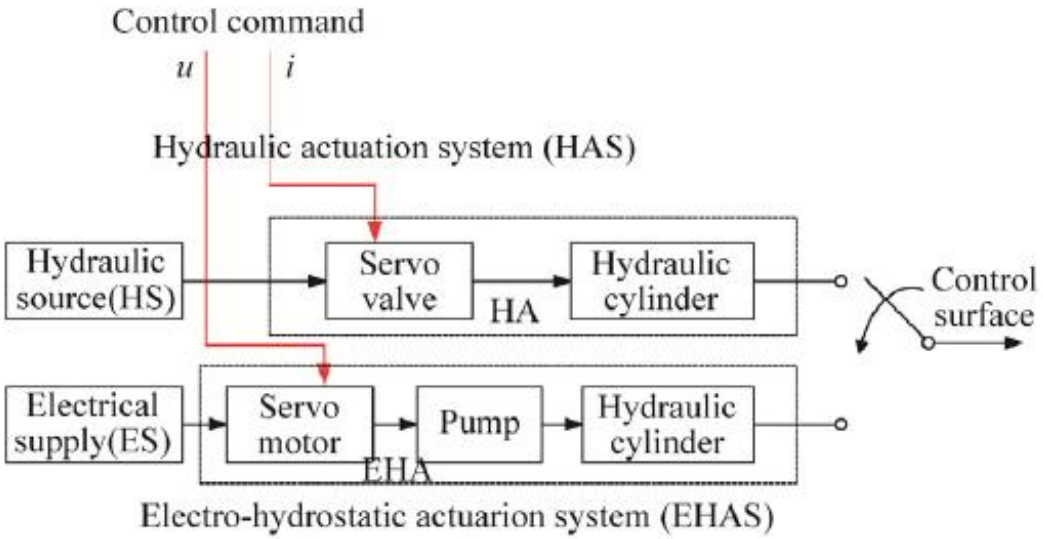
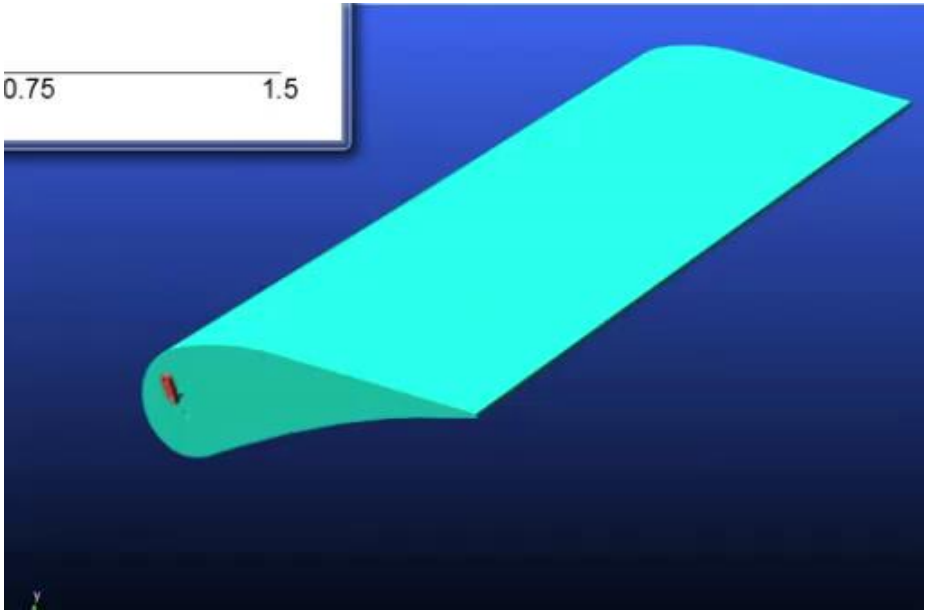
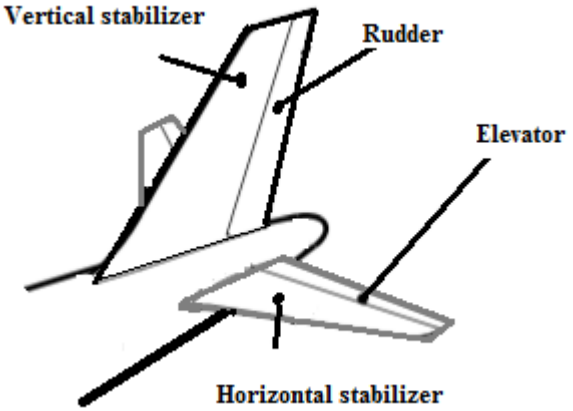
Third example: Control surface

- Dissimilar Redundant Actuation Systems, composed of Hydraulic Actuator (HA) and Electro-Hydrostatic Actuator (EHA), have been used in A380 and A350. In the normal operating condition, only HA drives the control surface while EHA is in the follower mode, i.e. backup mode. **If the HA breaks down and its failure is detected, the failed HA will be cut off, which will cause the EHA to carry on the mission of actuating control surface**




Control command
u
i
Hydraulic actuation system (HAS)
Hydraulic source(HS)
Servo valve
HA
Hydraulic cylinder
Control surface
Electrical supply(ES)
Servo motor
Pump
Hydraulic cylinder
EHA
Electro-hydrostatic actuarion system (EHAS)


0.75
1.5


Vertical stabilizer
Rudder
Elevator
Horizontal stabilizer

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Main advantage:

Since the backup hardware has the same functional behavior as the faulty unit, this can keep the consistency and maintain the same control performance

Disadvantages:

- It requires a large investment of effort in constructing the prototype
- Size

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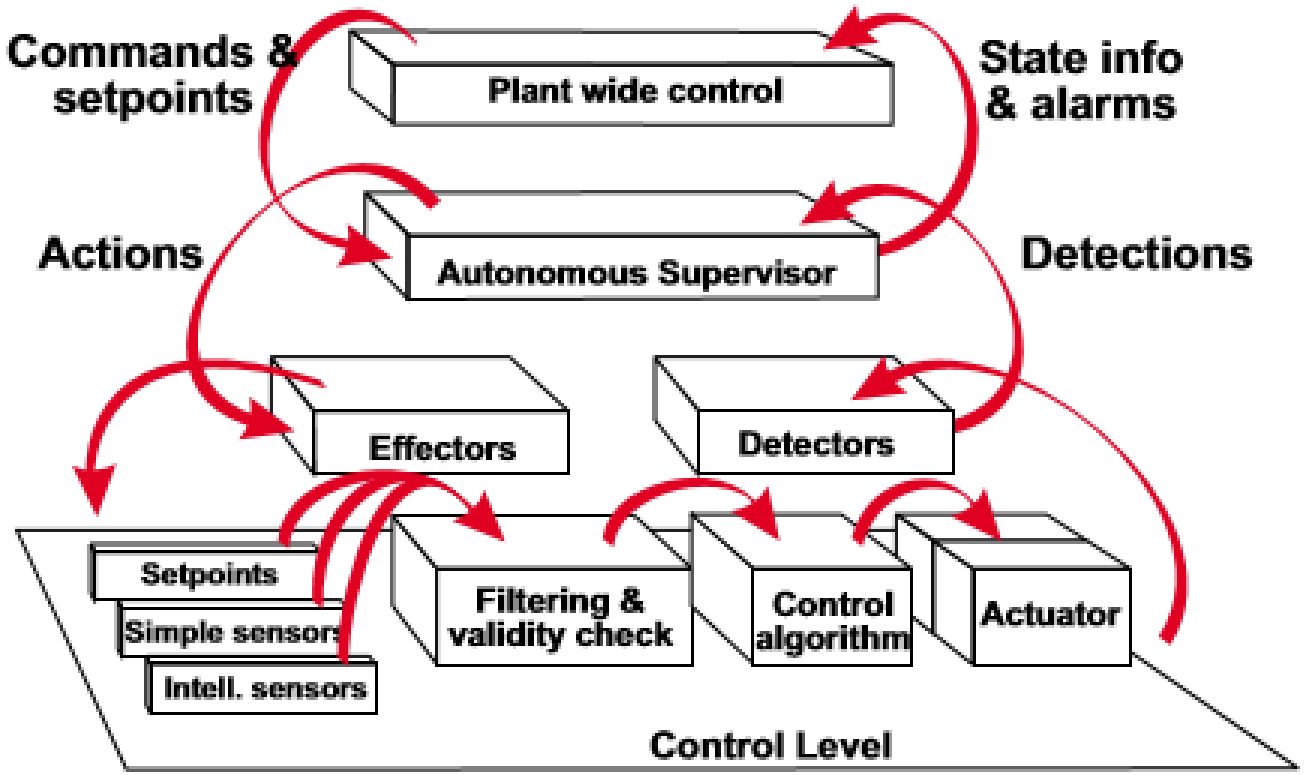
4.2 Software–based fault-tolerant control (also called the model-based FTC)

Software Control Architecture



Model-based fault-tolerant control

The main goal of the model-based FTC system is to design the controller, which enables stability and satisfactory performance, not only when all control components are healthy, but also in cases when there are faults.

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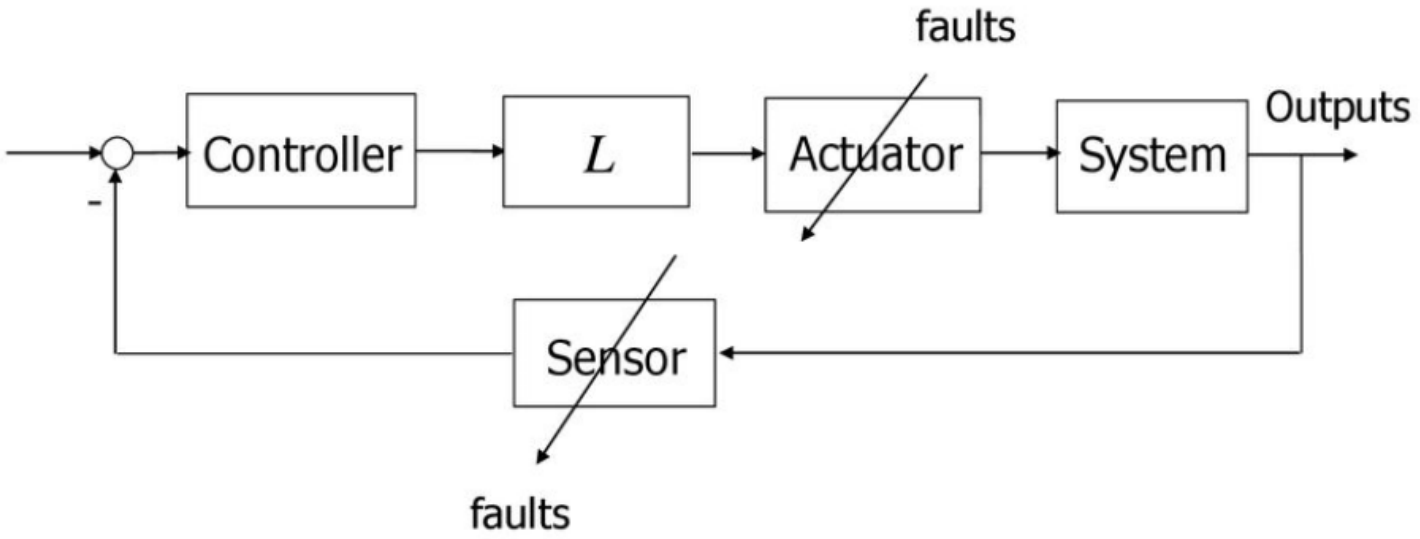
Model-based fault-tolerant control

- **Passive FTC---** It is designed to be robust against a set of predefined faults
- **Active FTC ---** It reacts to the faults actively by reconfiguring control actions.
- **Hybrid** FTC --- It uses a mixed techniques to do FTC or controls a mixed system.

4.2.1 Passive FTC

FTC is a robust control against a set of predefined faults, therefore there is no need for fault diagnosis.



It should be noted that the passive fault-tolerant controller is similar to the robust approach when uncertain systems are considered. Further, such a controller works sub-optimally for the nominal plant because its parameters are prearranged so as to get a trade-off between the performance and fault tolerance

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Main features of passive FTC:

- Robust fixed structure controller
- Faults have been considered at the controller design stage.

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Example 1 of (4.2.1):

The pre-defined fault is $f = B_f u$. Thus, a linear system plus actuator fault is given by

$$\dot{x} = Ax + B(u + f)$$

$$\dot{x} = Ax + (B + BB_f)u$$

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The pre-defined fault is $f = B_f u$. Thus, a linear system plus actuator fault is given by

$$\dot{x} = Ax + (B + BB_f)u$$

In this system, we use the feedback control

$$u = Kx$$

The closed-loop system is given by

$$\dot{x} = \left[A + \left(B + BB_f\right)K\right]x$$

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Control goal: We have to design the control gain K such that

$$\left[A + \left(B + BB_f\right)K\right] \text{ and } A + BK$$

are stable, i.e., the real parts of the eigenvalues of $A + \left(B + BB_f\right)K$ and A+BK are negative.

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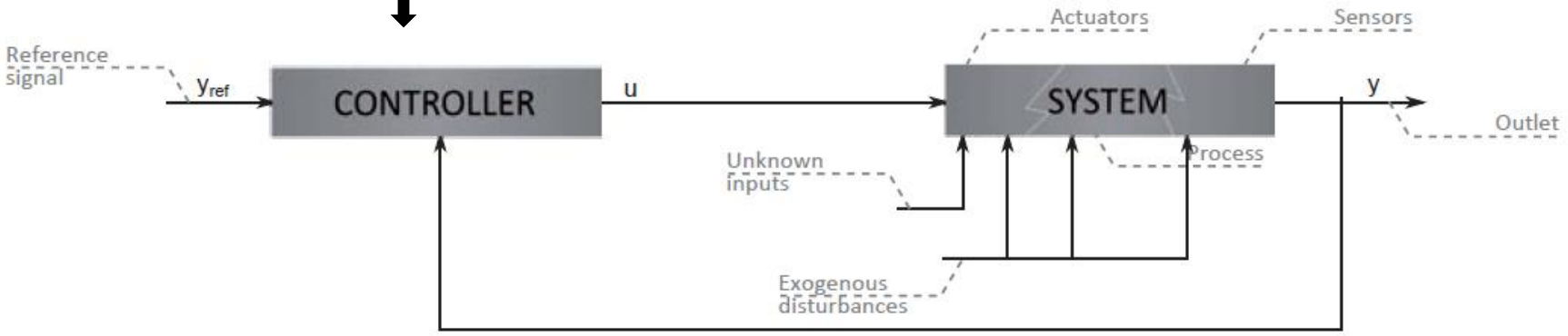
Passive control

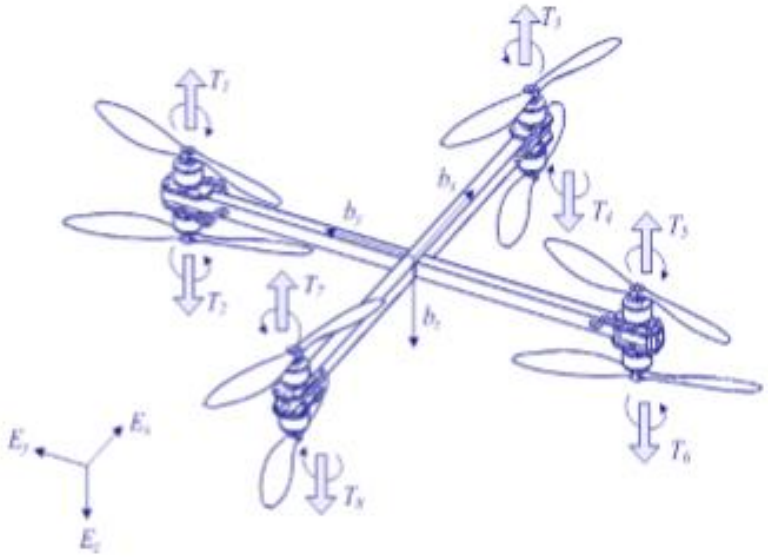
$$\left[A + \left(B + BB_f\right)K\right] \text{ and } A + BK$$

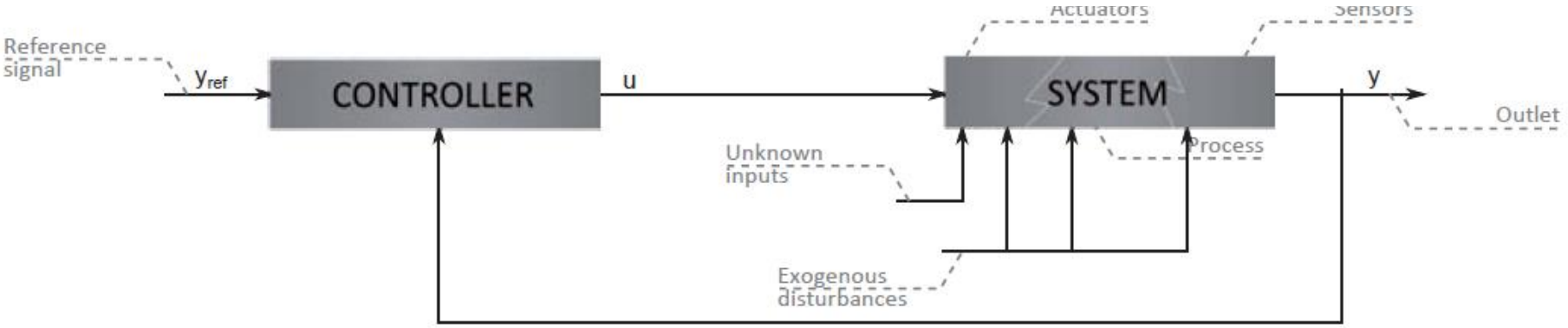
$$u = Kx$$



An example of passive FTC

Consider failures of one or two motors failures





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Passive Fault-Tolerant Control of an Octorotor using Super-Twisting Algorithm: Theory and Experiments

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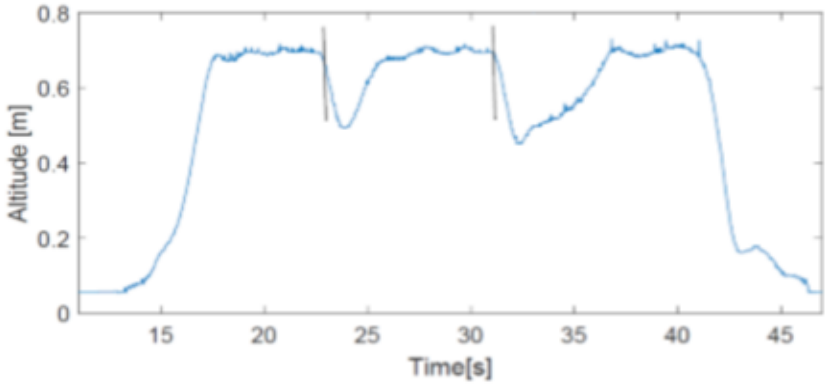
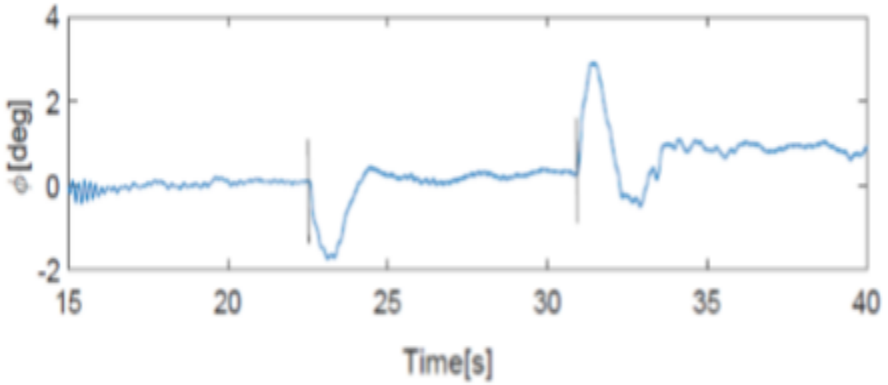
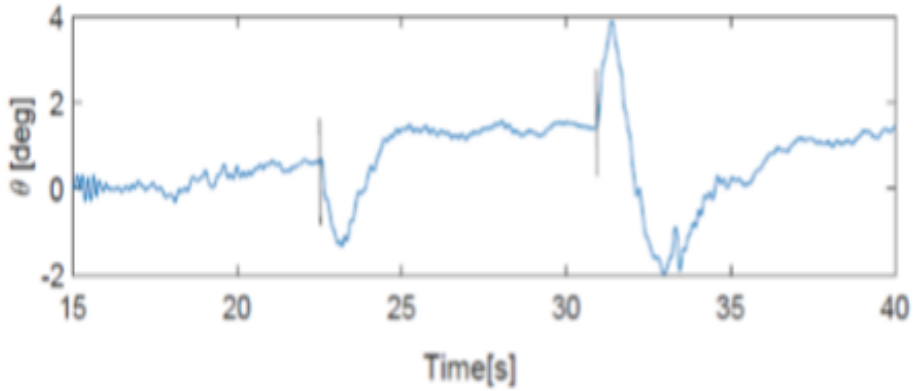
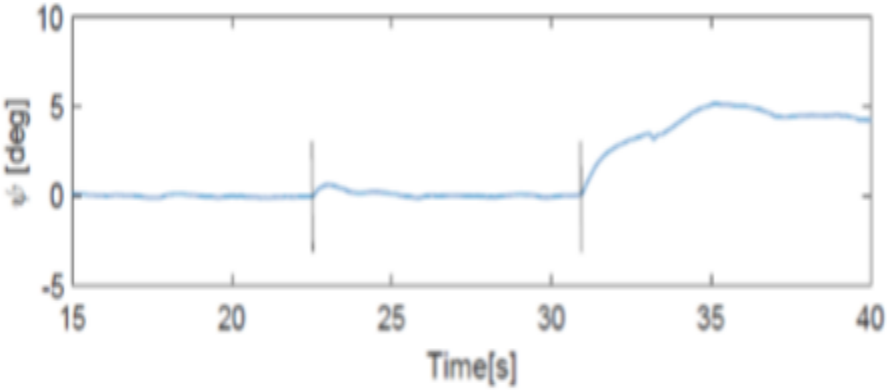
Altitude after two motor failures.
The faults are injected respectively at times t6 = 22.5s and t2 = 31s.



Euler angles after motor failures







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Advantages:

- **We can design the robust control to achieve an acceptable performance**
- Avoiding the time delay

Main disadvantage:

- A limited number of faults can be tolerated, i.e., *expected faults* can be handled.
- Solution is often conservative, which cannot meet some performance requirements

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4.2.2. Active FTC

- An active FTC is sometimes referred to as self-repairing, reconfigurable, restructurable, or self-healing control systems.
- To achieve fault tolerance, the control system relies heavily on fault diagnosis

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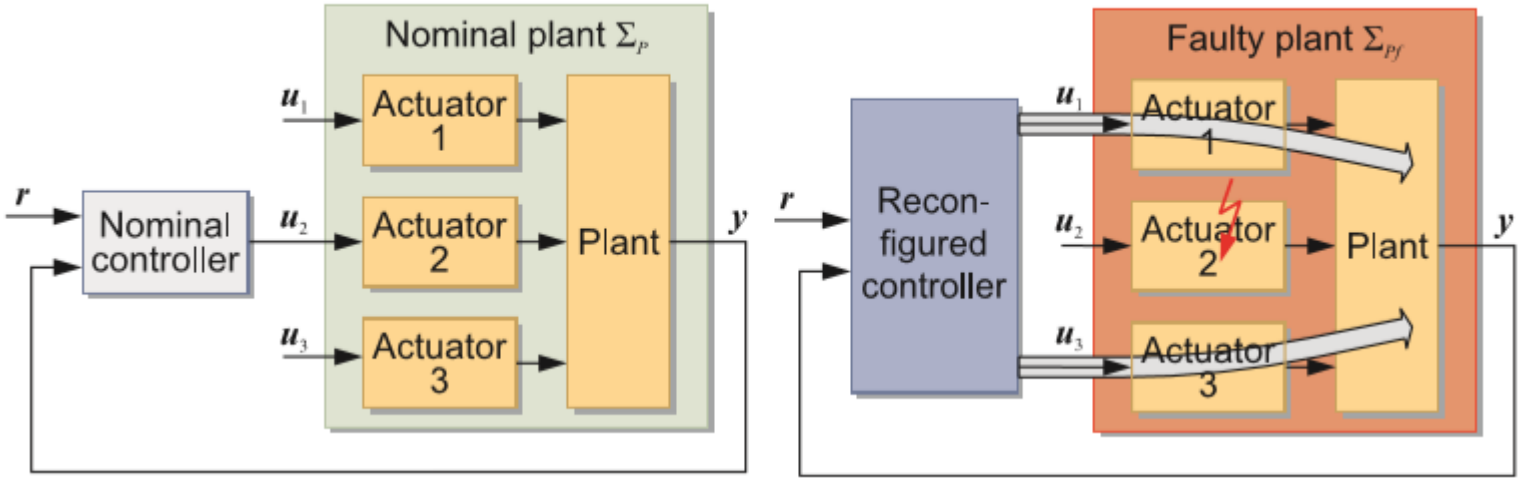
Control reconfiguration idea



For the nominal plant, the controller uses the input u2 (left). If the corresponding actuator fails, the control loop is broken and an adjustment of the controller to the faulty plant is impossible unless other control inputs are used (right). In the reconfigured closed-loop system the effect of the controller on the plant is re-routed around the faulty actuator (two arrows).

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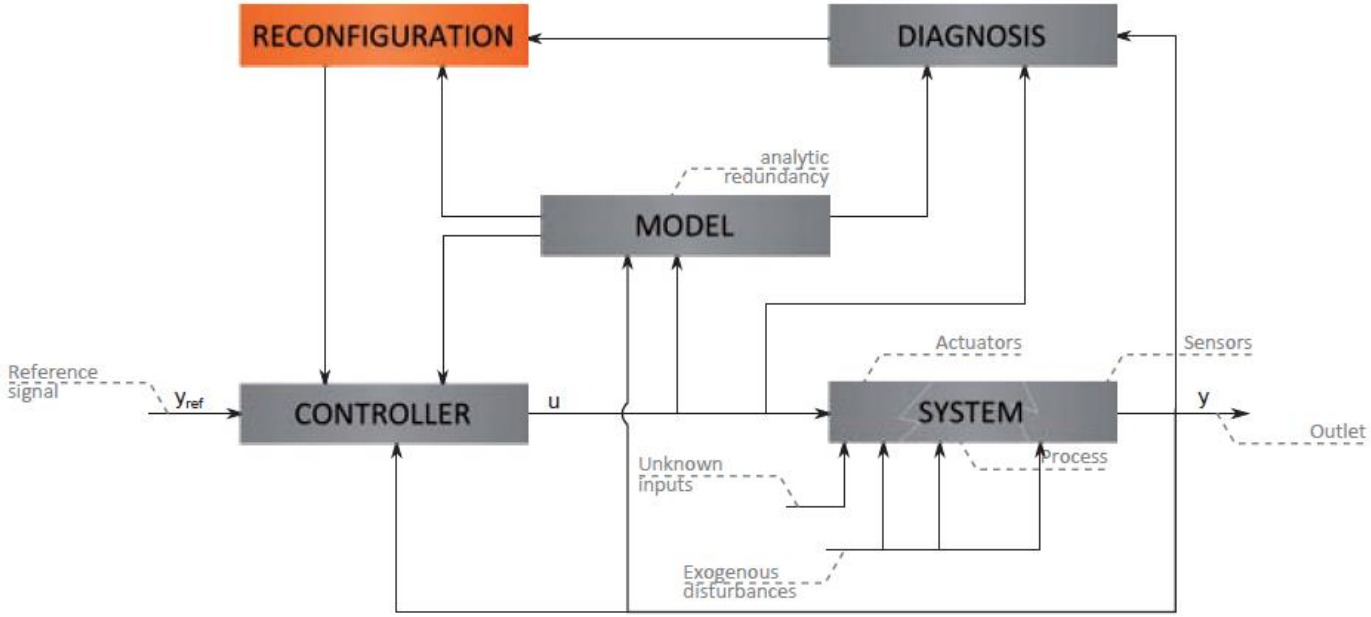
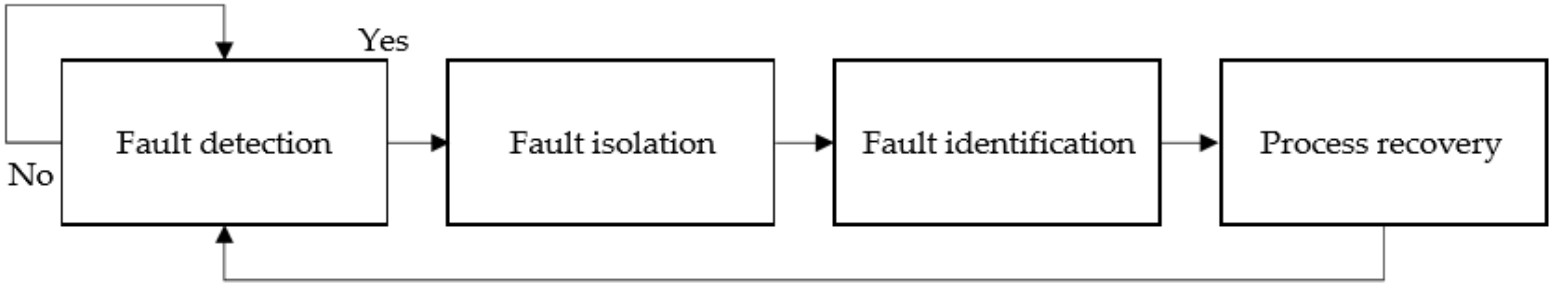
FTC blocks: Type 1





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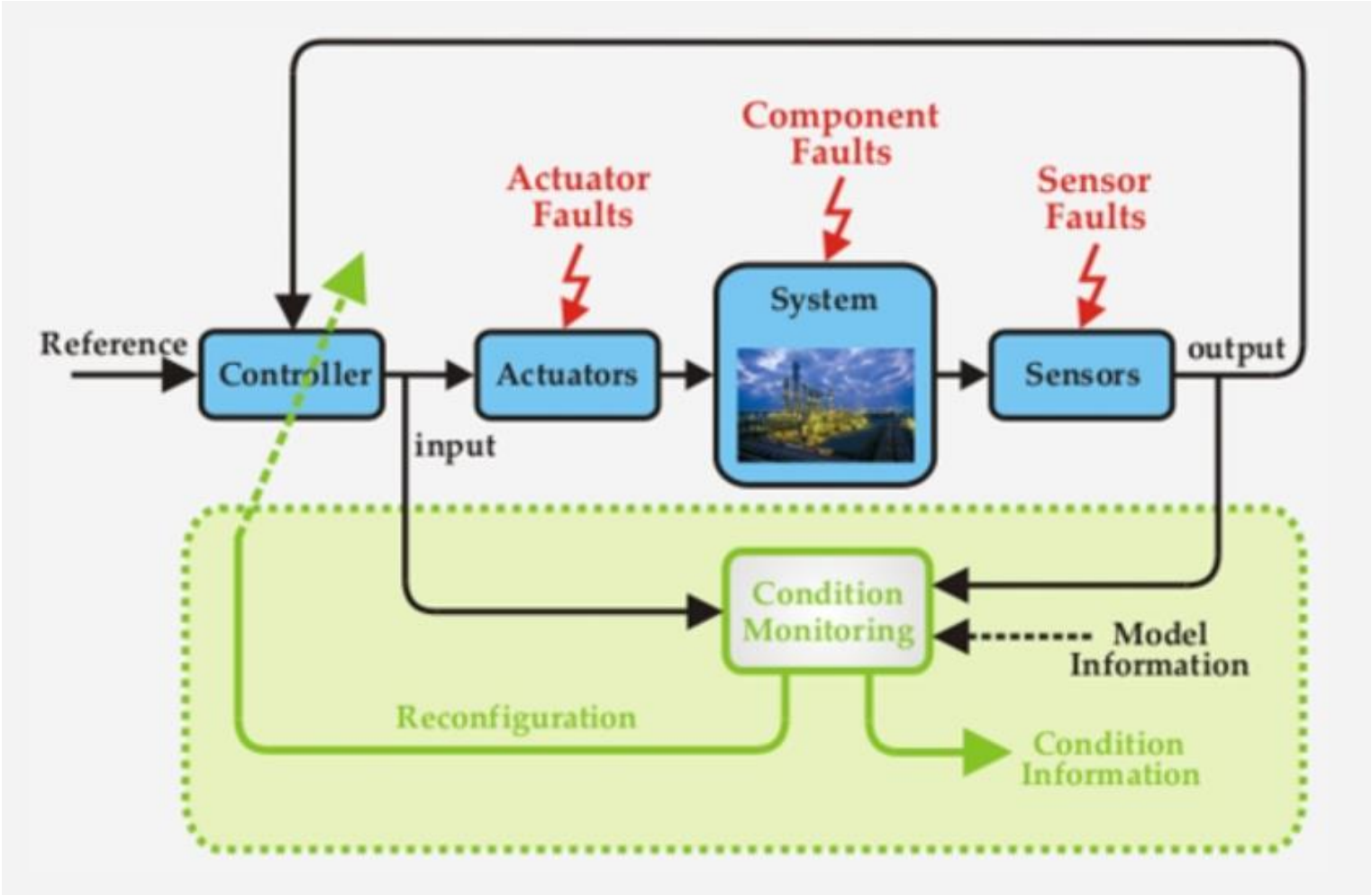
FTC blocks: Type 2



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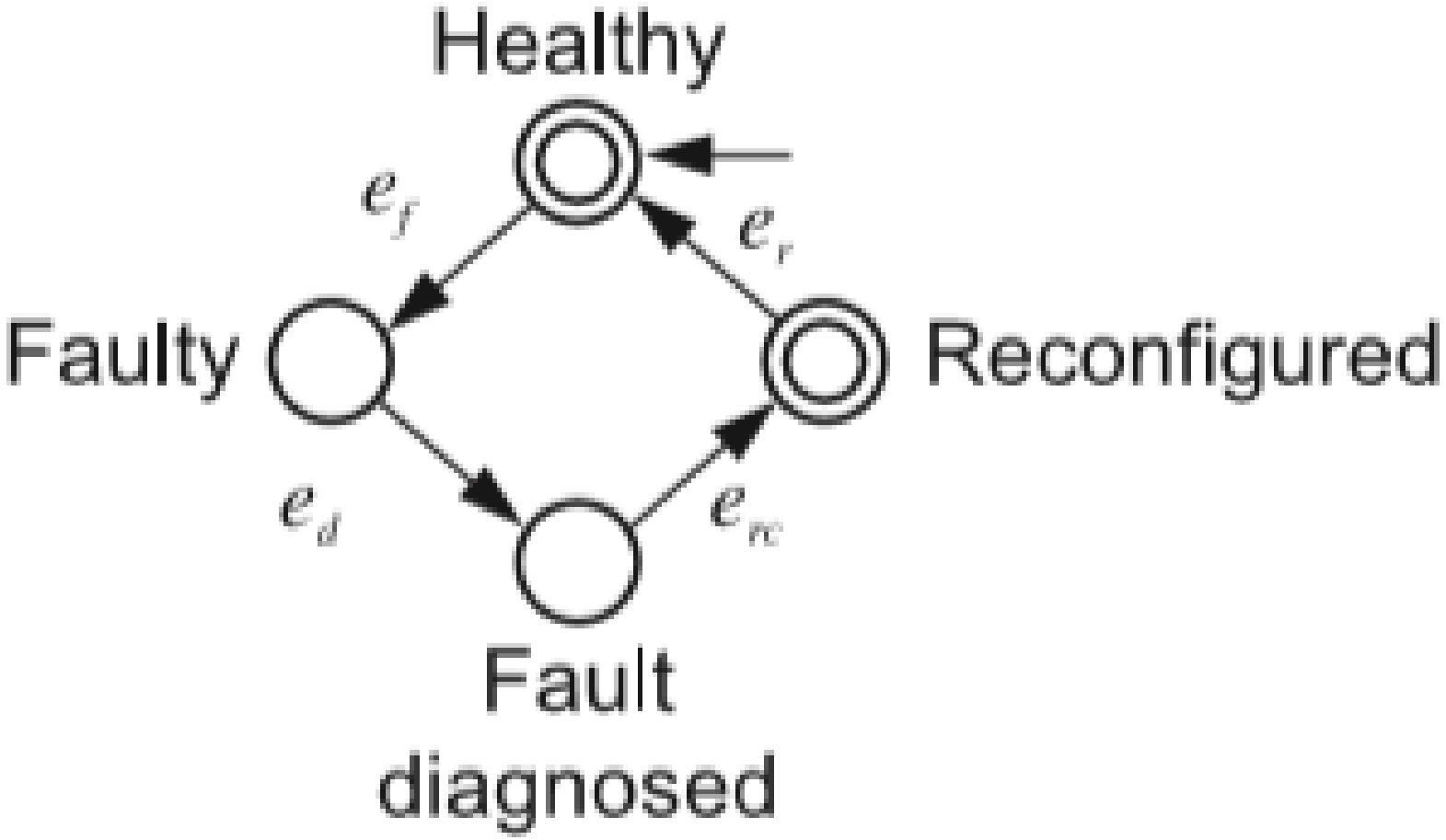
Logic relationships among system, fault diagnosis and FTC



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Method 1: fault function is known

i.e., f is known (we can obtain it off-line)

$$\dot{x} = Ax + B(u + f)$$

The configured controller should be capable of canceling the fault function f.

Assume that the normal control is

u_n. Then, when the fault is detected, the configured control is $u_n + \hat{f}$

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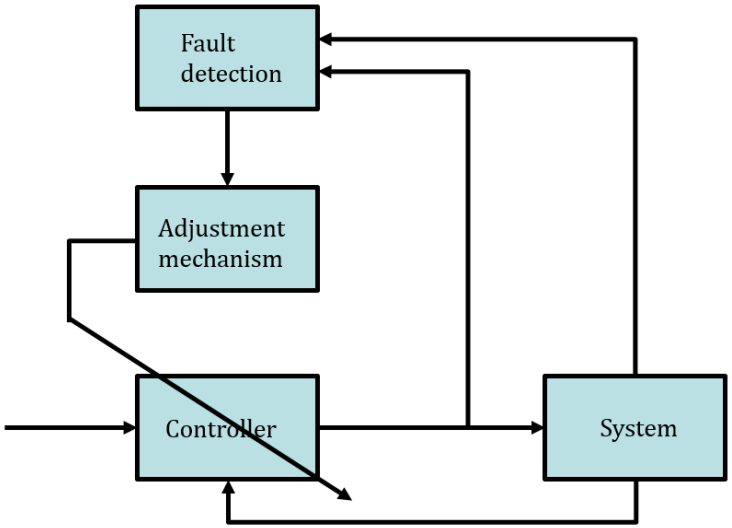
The fault tolerant control is given by

$$u = \begin{cases} u_n, & if\ no\ fault \\ u_n + \hat{f}, & if\ fault\ is\ detected \end{cases}$$

Approach 2: The structure of fault function is known, but the coefficients are unknown.

$$f = c_1\varphi_1(t) + c_2\varphi_2(t) + \cdots + c_n\varphi_n(t)$$

- **Adaptive control is used,**



The FTC is given by

$$u = \begin{cases} u_n, & \text{if no fault} \\ u_n - \hat{f}, & \text{if fault is detected} \end{cases}$$

$\hat{f} = \sum_{i=1}^{n} \hat{c}_i \varphi_i(t)$ where $\hat{c}_i$ is obtained by an adaptive law.

$$\dot{\hat{c}}_i = -\gamma_i \varphi_i(t) ResidualSignal$$

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Method 3: The fault function is unknown.

Artificial Intelligence (AI) should be used to learn the unknown fault and achieve FTC. Neural network, fuzzy logic system and adaptive learning algorithms can be used to develop an on-line estimator of the fault function.

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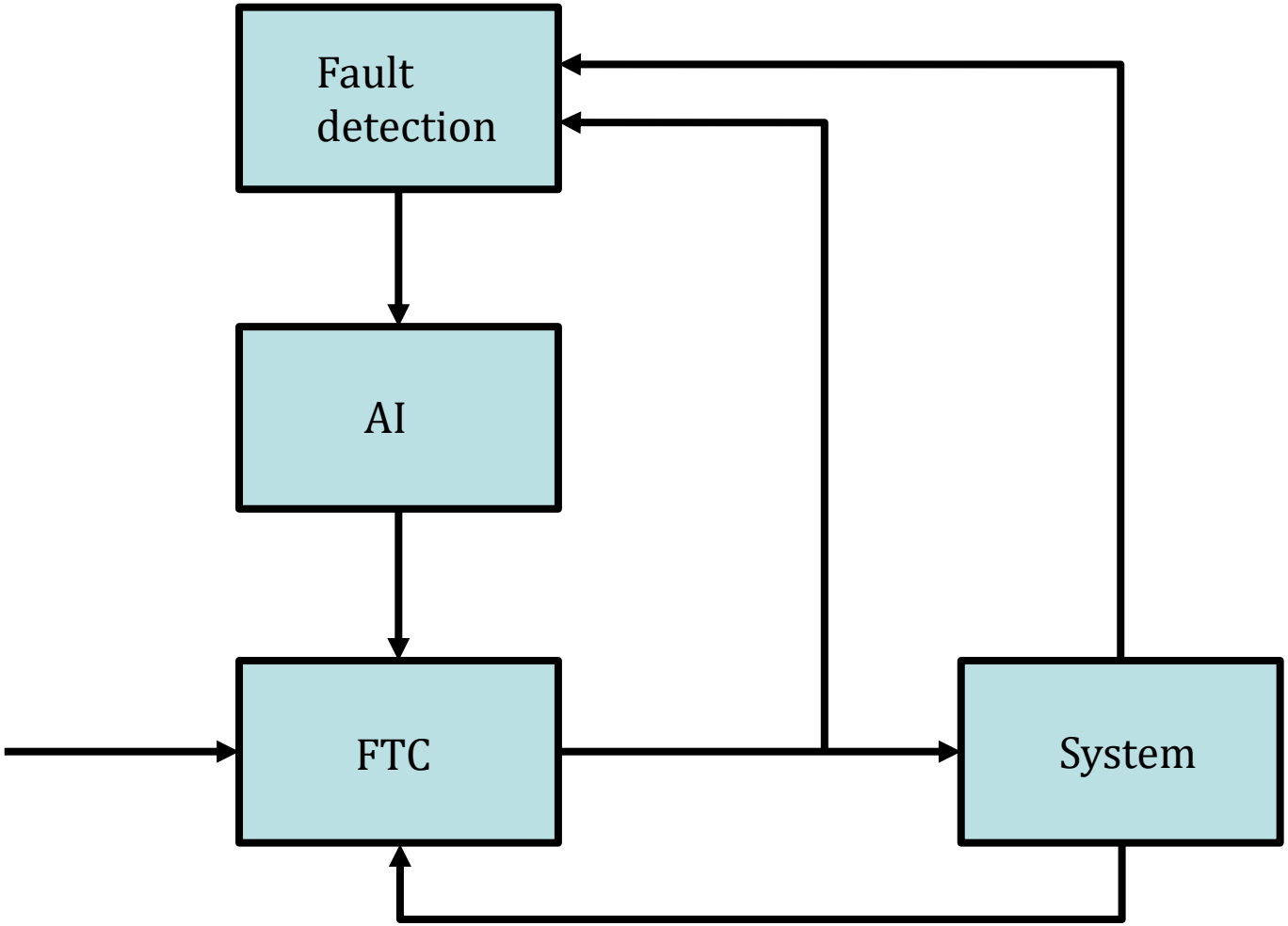
AI-based fault-tolerant control



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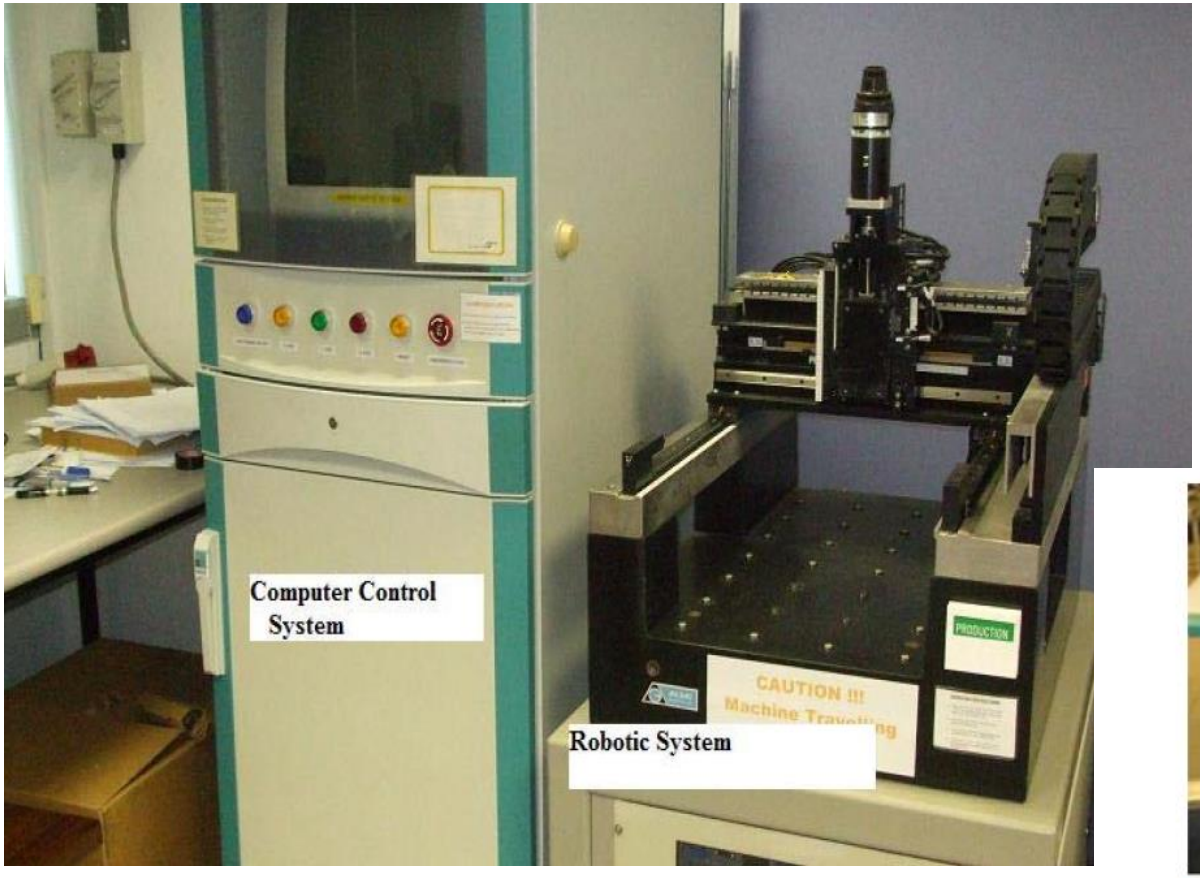
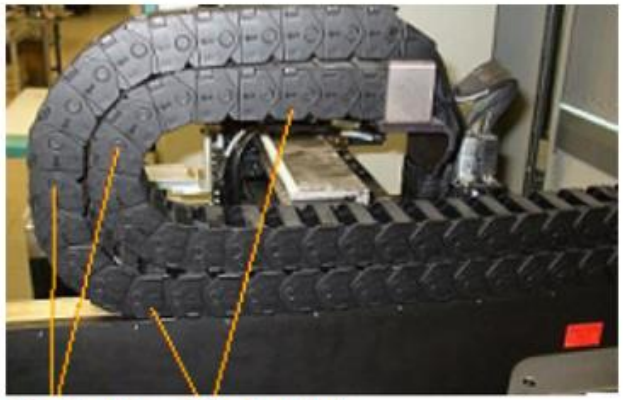
Example 1: FTC using approach 3





A linear model is identified

$$\ddot{x} = -2.110\dot{x} + 0.058u - 0.166sgn(\dot{x}) - 0.121e^{-\frac{\dot{x}^2}{0.001^2}} sgn(\dot{x}) + \eta(x,t)$$

An estimator is given by

$$\dot{\hat{x}} = \begin{bmatrix} 0 & 1 \\ 0 & 0 \end{bmatrix}\hat{x} + \begin{bmatrix} 0 \\ 1 \end{bmatrix}\begin{bmatrix} 0 \\ -2.110\dot{x} + 0.058u - (0.166 + 0.121e^{-\frac{\dot{x}^2}{0.001^2}})sgn(\dot{x}) \end{bmatrix}$$

$$+ \begin{bmatrix} 50 & 0 \\ 100 & 2.11 \end{bmatrix}\begin{bmatrix} \tilde{x} \\ \dot{\tilde{x}} \end{bmatrix}$$

Fault detection

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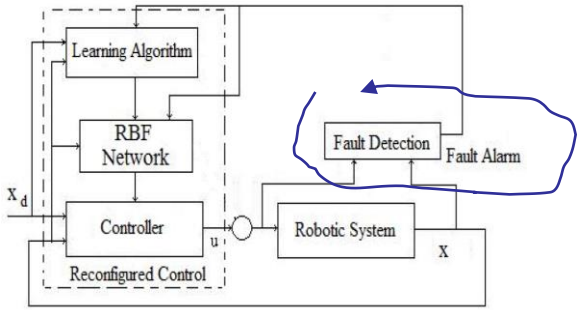
Threshold is given by

$$\varpi = \frac{1}{43.5137}\int_0^t 1.2\left[e^{-4.2982(t-\tau)} - e^{-47.8119(t-\tau)}\right]d\tau$$
$$\leq 0.0046 \times 1.2 = 0.0055$$

If the residual signal <threshold, no fault ; otherwise, fault occurs.



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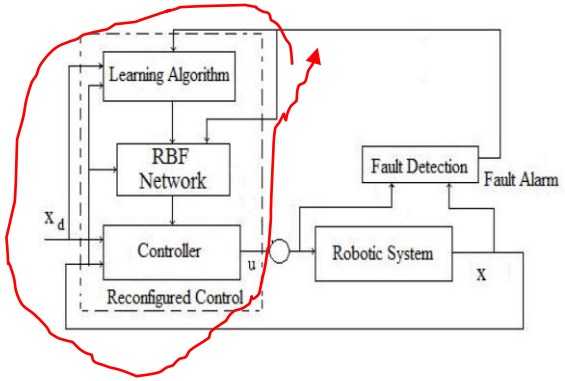
Fault tolerant control is given by

$$u = G^{-1}(q)\{-F(x) - \sigma - \Lambda R - D[\| \tilde{y} \|]\hat{W}^T \Phi(x)\},$$

$$D[\| \tilde{y} \|] = \begin{cases} 0 & if \ \| \tilde{y} \| \leq \varpi \\ 1 & otherwise \end{cases}$$



Neural network is given by

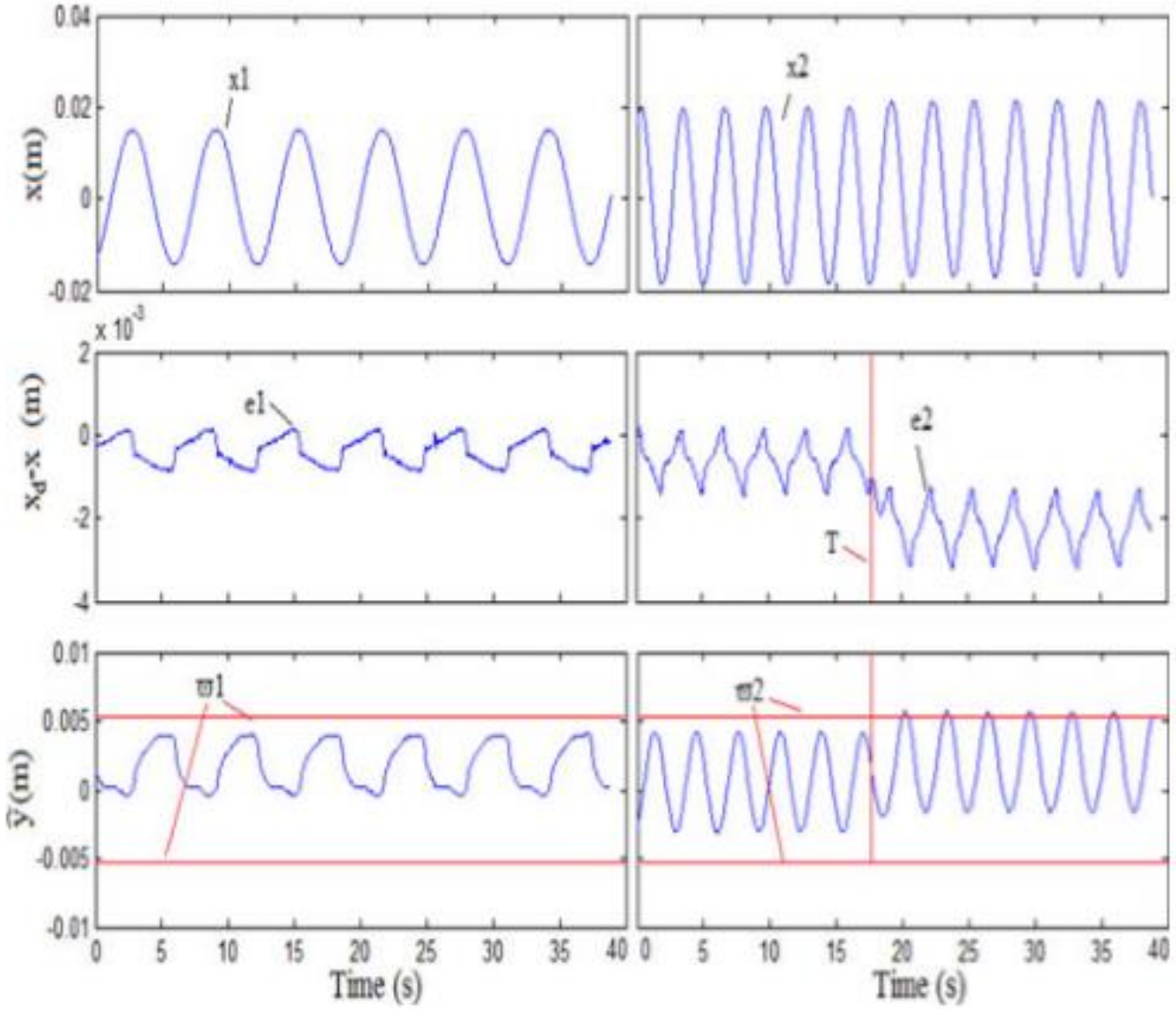
$$\hat{W}^T \Phi(x) = \sum_{i=1}^{10} \hat{w}_i \phi_i(x), \text{ i.e., 10 units,}$$

$$\dot{\hat{W}} = \Upsilon[\Phi(x) R^T - \rho(\hat{W} - W_a)] D[\| \tilde{y} \|]$$

[1] Automated fault diagnosis and accommodation control for mechanical systems, S Huang, KK Tan, M Xiao, IEEE/ASME Transactions on Mechatronics 20 (1), 155-165,2015

[2] Intelligent fault-tolerant control of liner drivees using soft computing, S.Huang,M.Xiao,K.K.Tan, International Journal of Robotics and Automation 30 (5), 1-11, 2015

Real-time control



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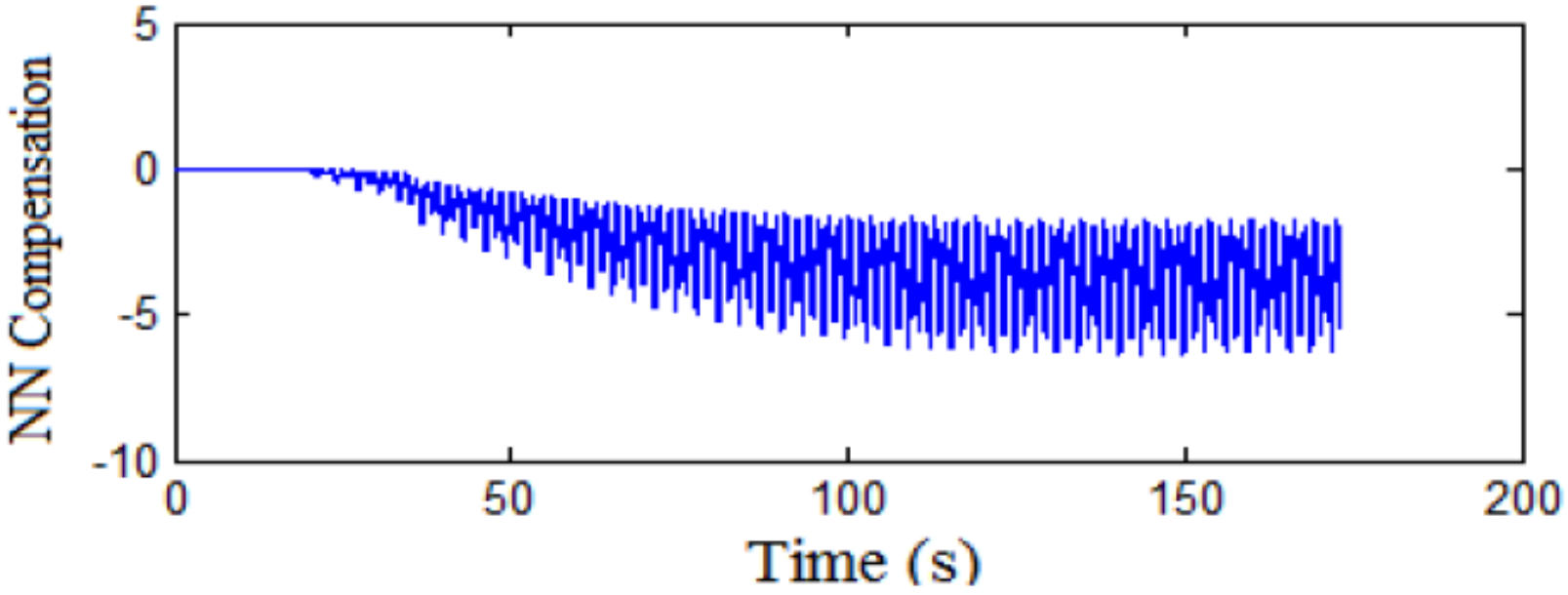
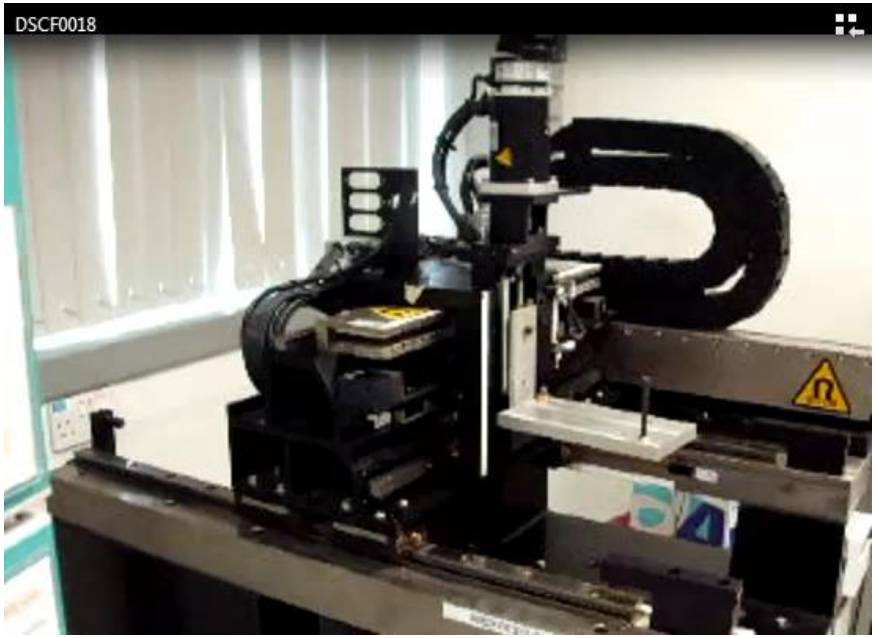
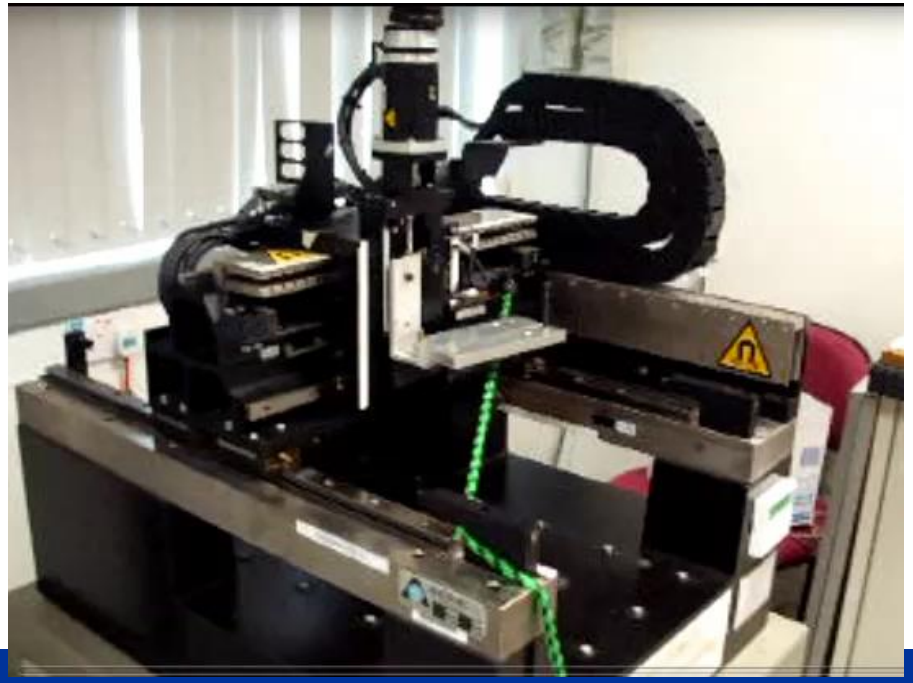
Neural network output



Video





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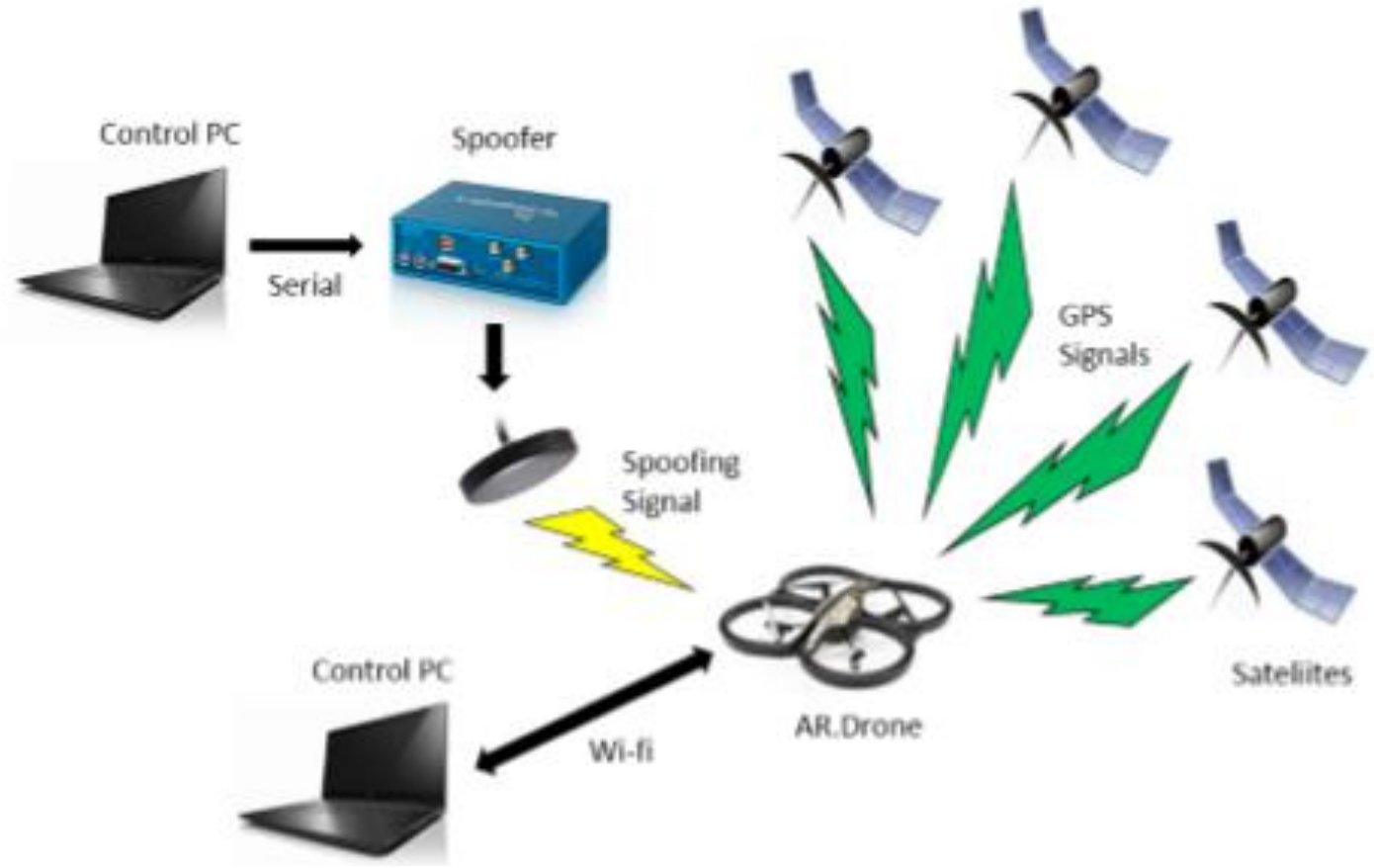
Active FTC against cyber-physical attacks



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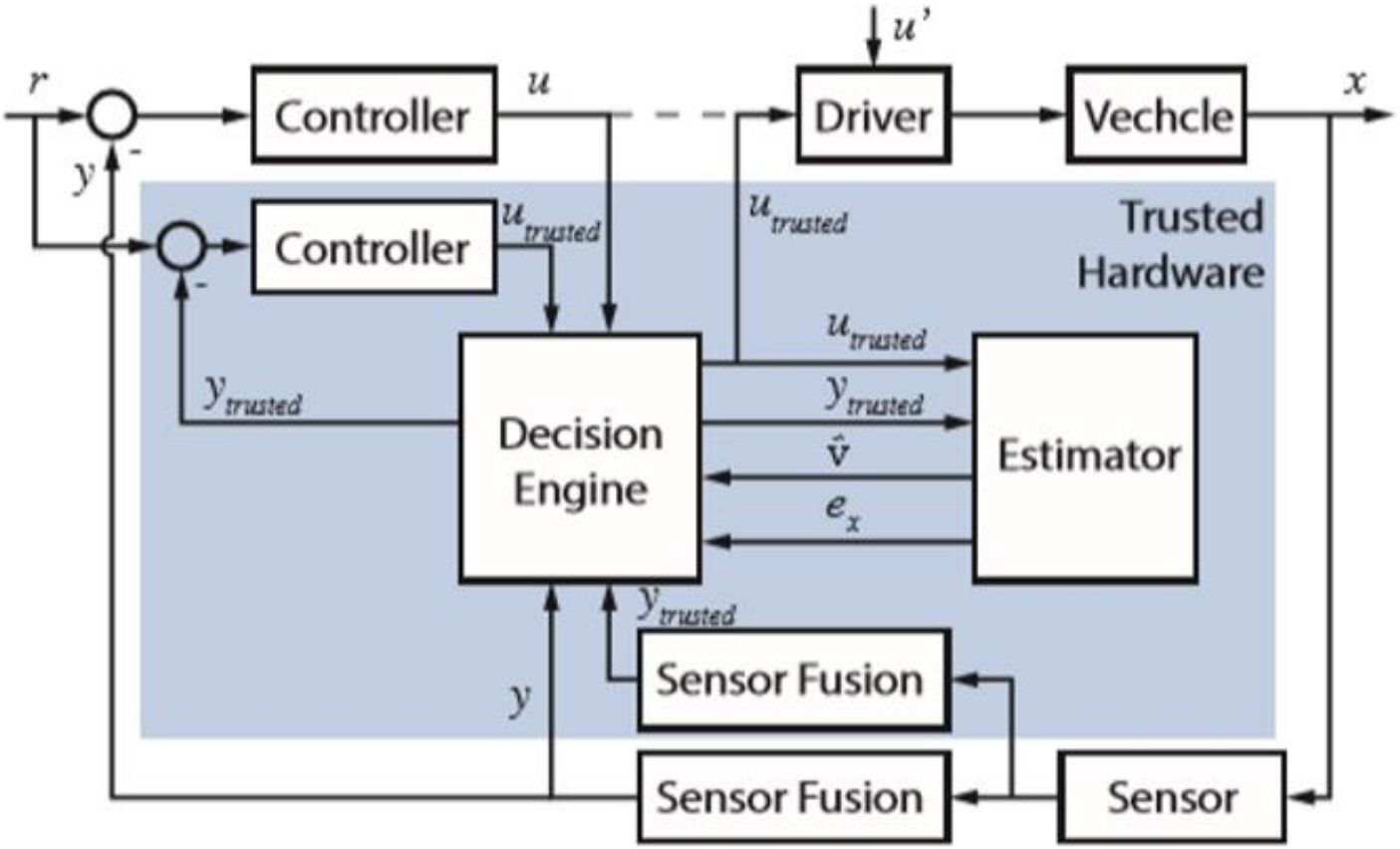

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Comparison between passive and active FTCs

- They have the same function which can accommodate faults
- What is the difference between both

A passive FTC is a fixed controller for all situations

An active FTC reacts to the diagnosed faults by exercising the controls accordingly so that the stability can be maintained and the performance still be acceptable.

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4.2.2. Hybrid FTC

- **Hybrid FTC is mixed passive/active FTC (combining both) strategy**
- Other hybrid FTC---Hybrid systems are dynamical systems that involve the interaction of continuous and discrete dynamics

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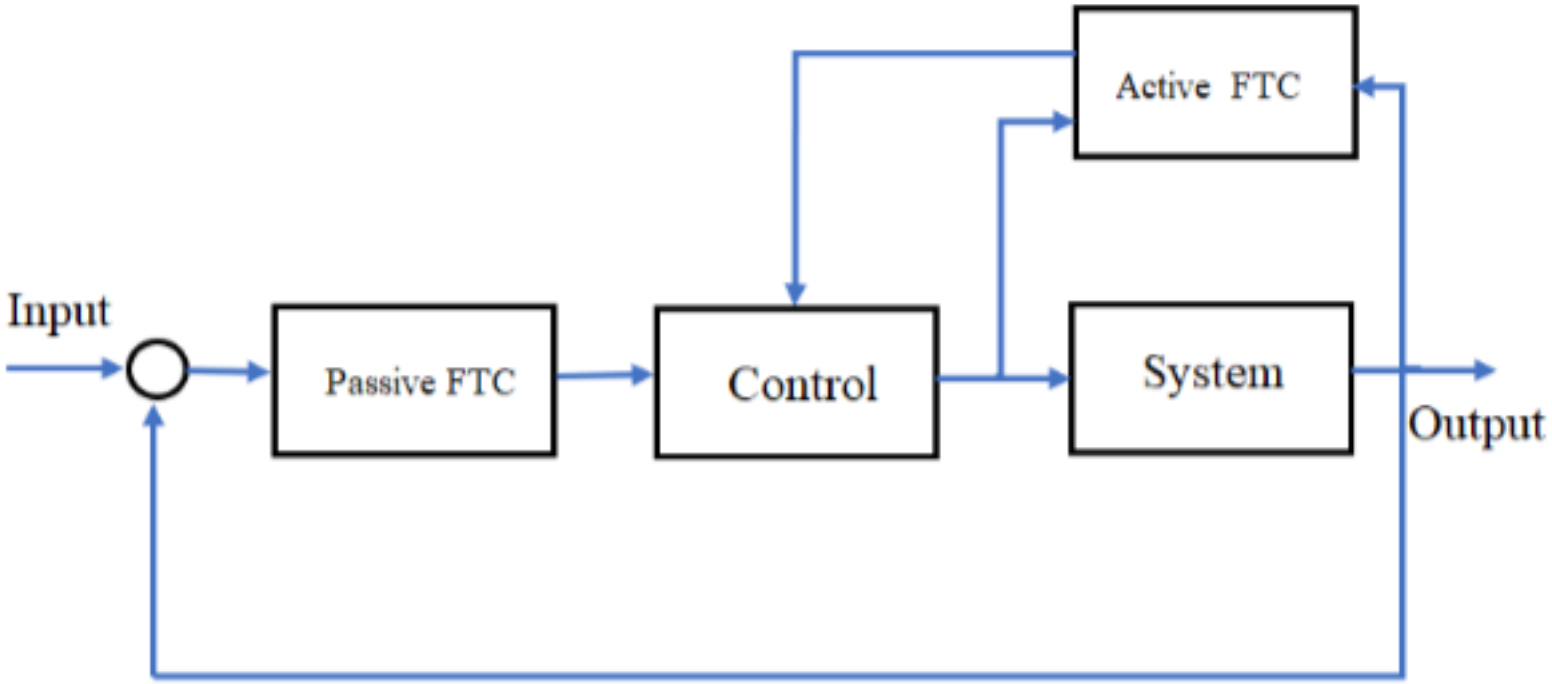
One type of hybrid FTC blocks



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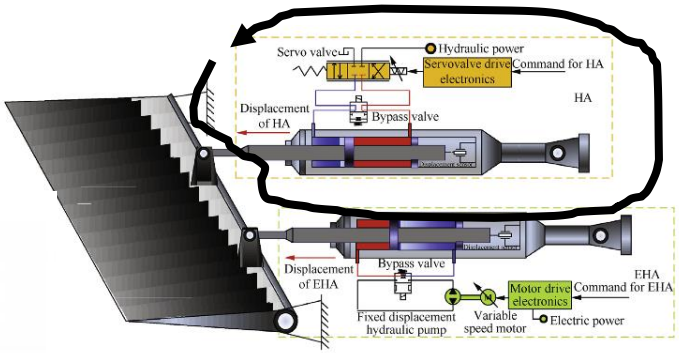
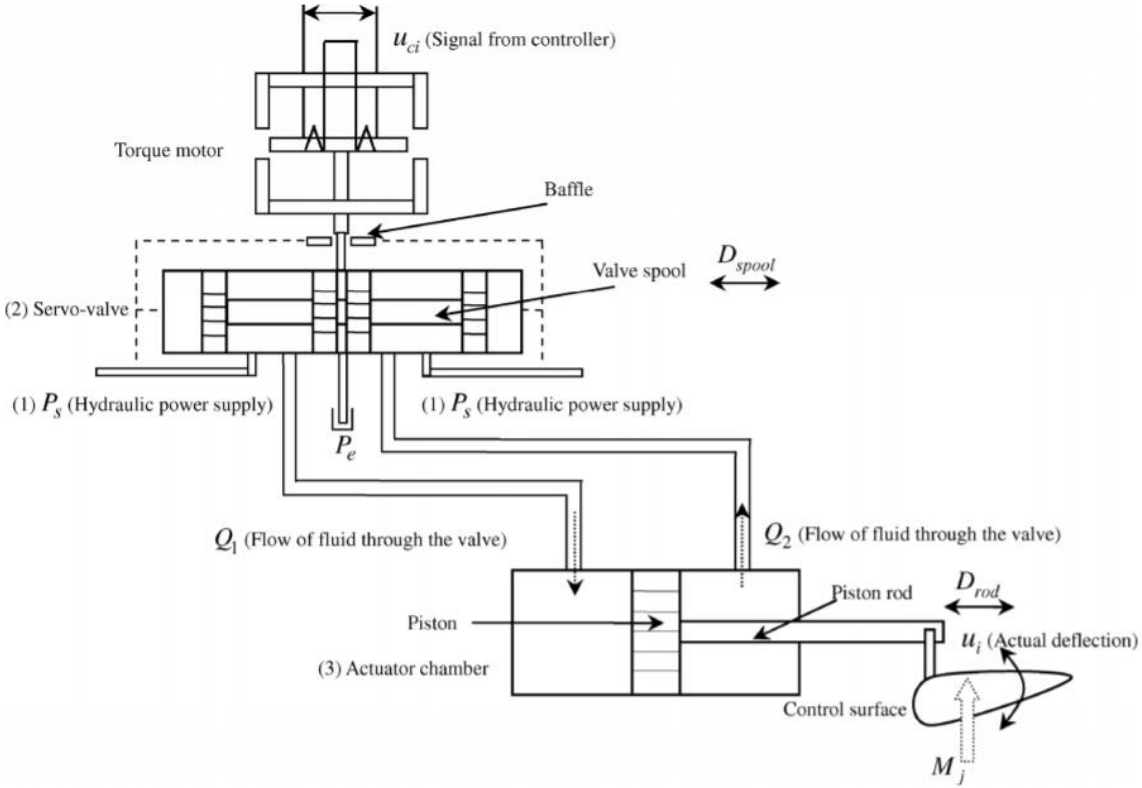
An example of hybrid FTC





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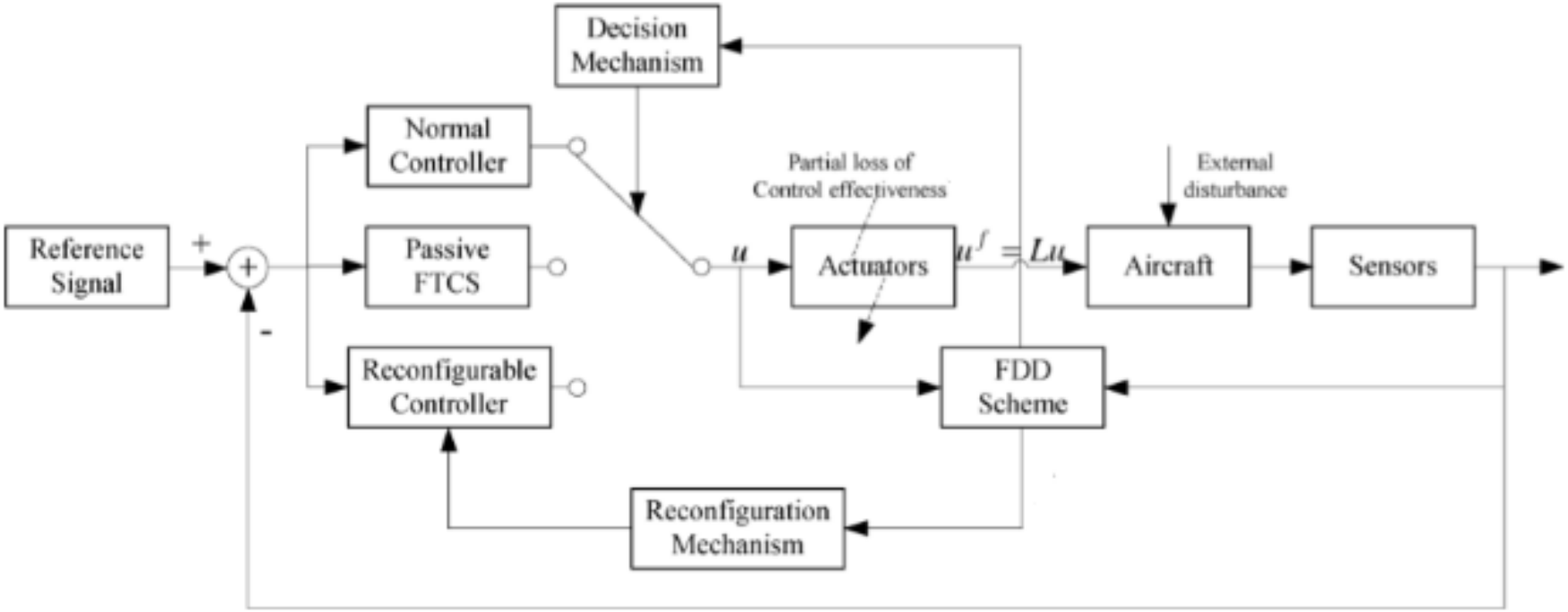
Hybrid FTC



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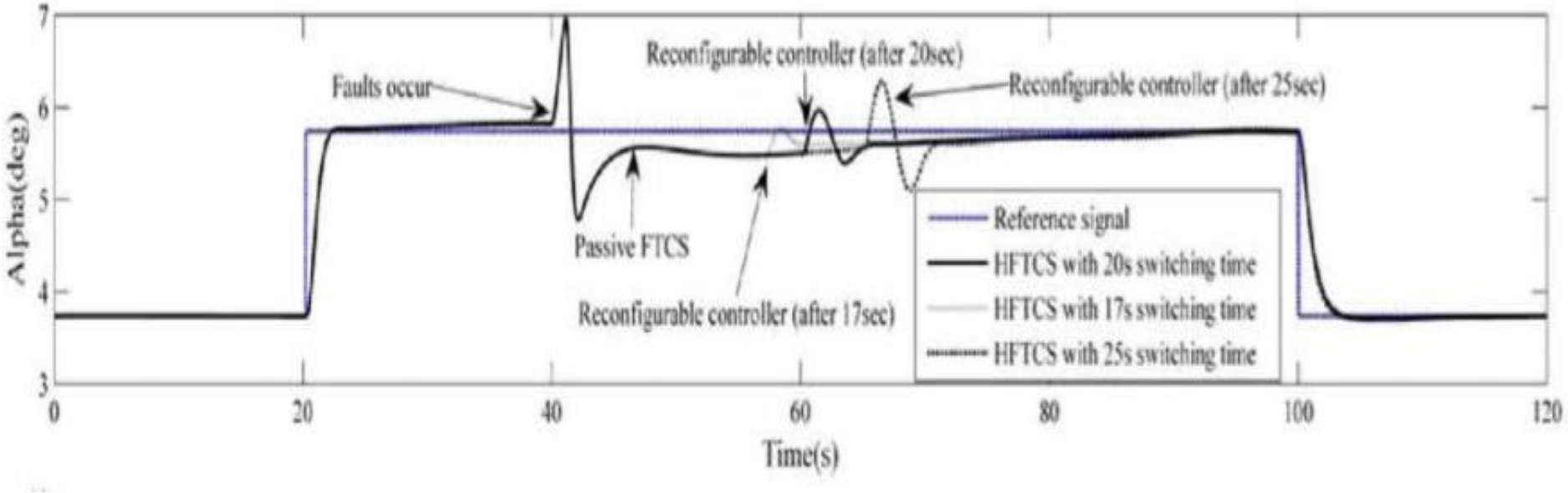
Results:



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4.3 Mixed Methods of FTC

- **This method uses various algorithms and techniques, even intervention of skilled personals, to handle faults to adapt new requirements, extend functionality, eliminate faults (effect) , and improve quality features.**
- **Usually, this method is used in industry**

Actions after decision

A1: Maintenance	Full functions: Instantaneously tune process parameter or exchange worn parts
A2: Repair	Full functions: Remove a fault such as exchange with replacement
A3: Reconfiguration	Partial functions: Using other or redundant components to keep a process in operation
A4: Change operation	Partial functions: Hindering a further fault expansion through changes of operation
A5: Stop operation	No functions: Shut down the entire system

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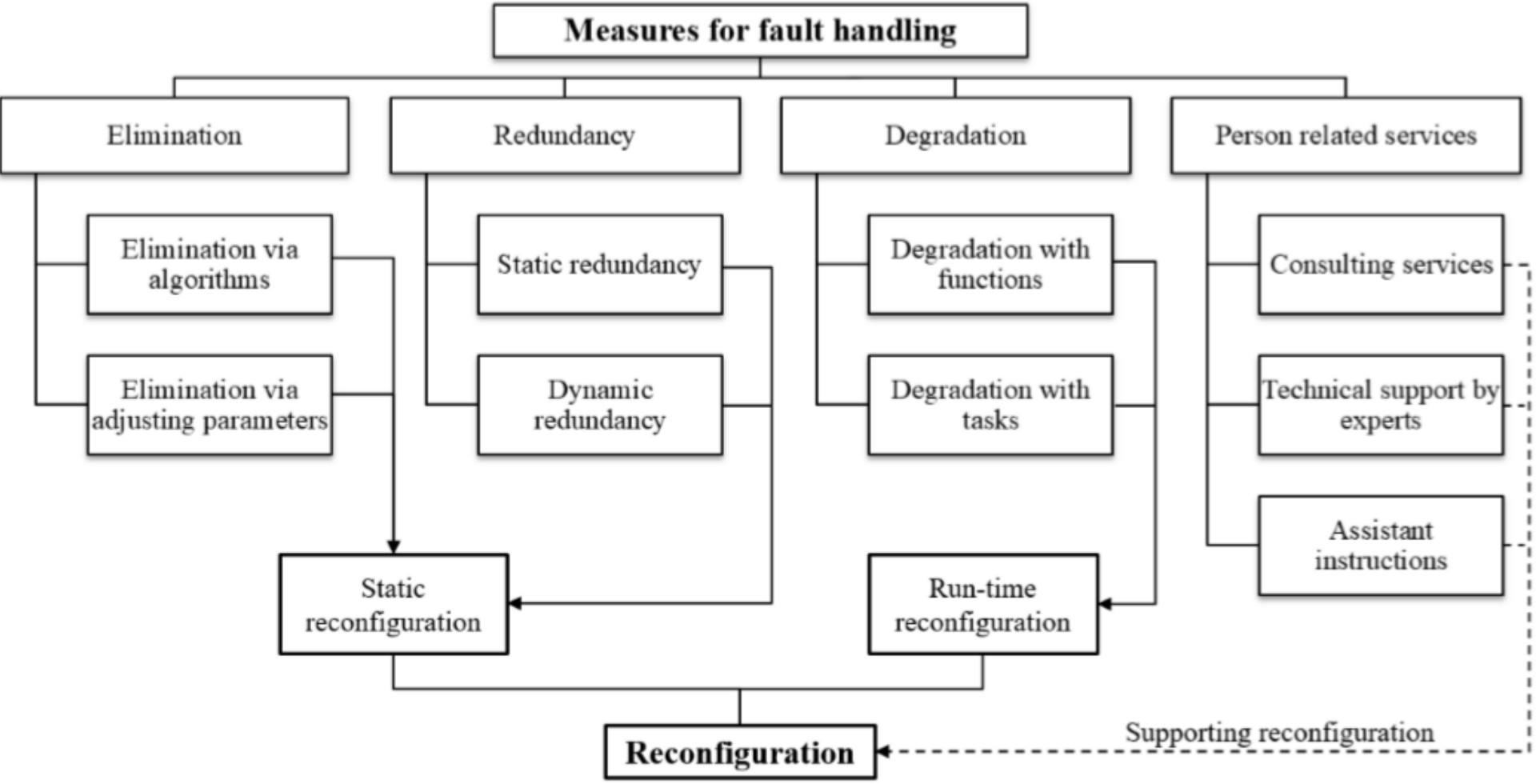

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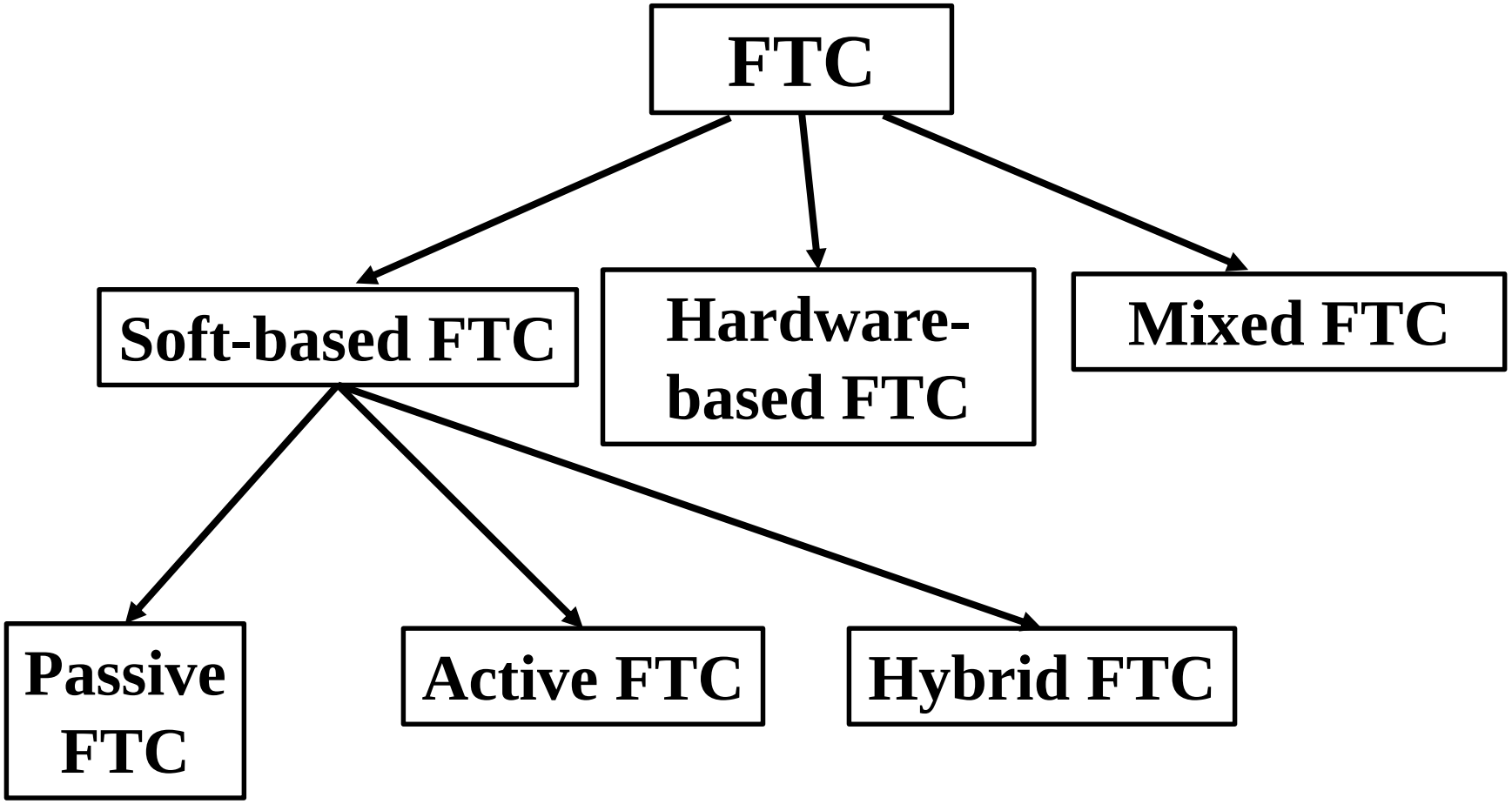
Summary

- There are two ways for designing fault-tolerant control: hardware method and model-based method.
- Our focus is on model-based fault-tolerant control. This includes passive and active FTCs.
- Neural network learning is still challenging.


FTC
Soft-based FTC
Hardware-based FTC
Mixed FTC
Passive FTC
Active FTC
Hybrid FTC

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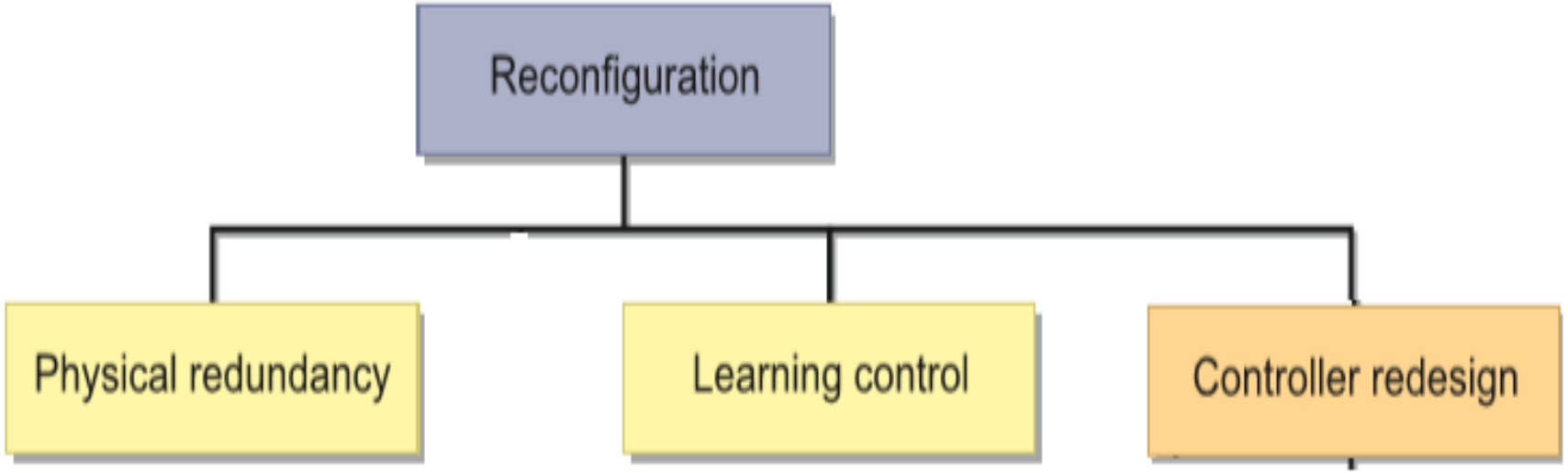
Reconfiguration



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Reference books:

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Thank you!

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Recess time 15 mins