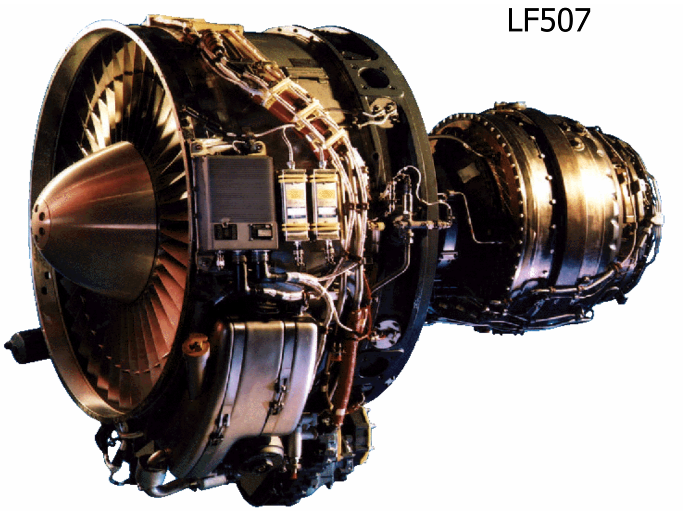
Lecture 16 - Health Management

- Diagnostics in control system design
  - BIT/BITE
- Fault tolerance - redundancy
- Systems health management applications
  - Added value – maintenance and support
- Statistical Process Control
- Parameter estimation

Diagnostics in Control Systems

- Control algorithms make less than 20% of the embedded control application code in safety-critical systems
- The remaining 80% deals with special conditions, fault accommodation
  - BIT (Built-in Test - software)
  - BITE (Built-in Test Equipment - hardware)
  - Binary results
  - Messages
  - Used in development and in operation

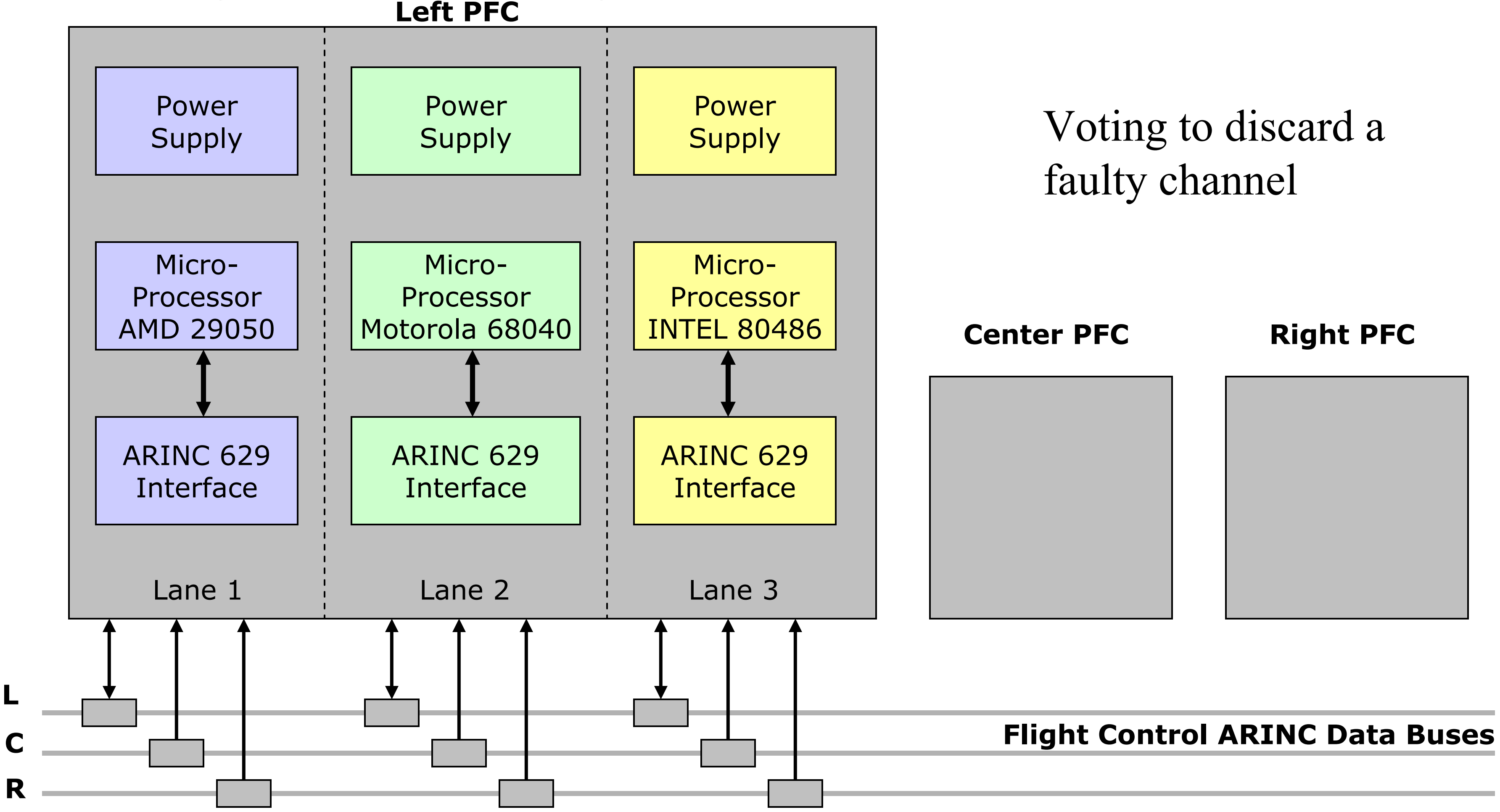
Example



Honeywell
LF507

Fault Tolerance: Hardware Redundancy

- Boeing 777 Primary Flight Computer (PFC) Architecture



Voting to discard a faulty channel

Analytical Redundancy

- Analytical Redundancy
  - correlate data from diverse measurements through an analytical model of the system
- Estimation techniques
  - KF observer
- Talked about in the literature
- Used only in much simplified form:
  - on loss of a sensor, use inferential estimate of the variable using other sensor measurements
  - on loss of an actuator, re-allocate control to other actuators

Systems Health Management

- Emerging technology - recent decade
  - Less established than most of what was discussed in the lectures
- Systems fault management functions
  - Abnormality detection and warning - something is wrong
  - Diagnostics - what is wrong
  - Prognostics - predictive maintenance
  - Accommodation – recover from fault
- On-line functions - control system
  - BIT (Built-in-test)
  - Accommodation; FDIR (Fault Detection, Identification, & Recovery)
- Off-line functions - enterprise system
  - Maintenance automation
  - Logistics automation

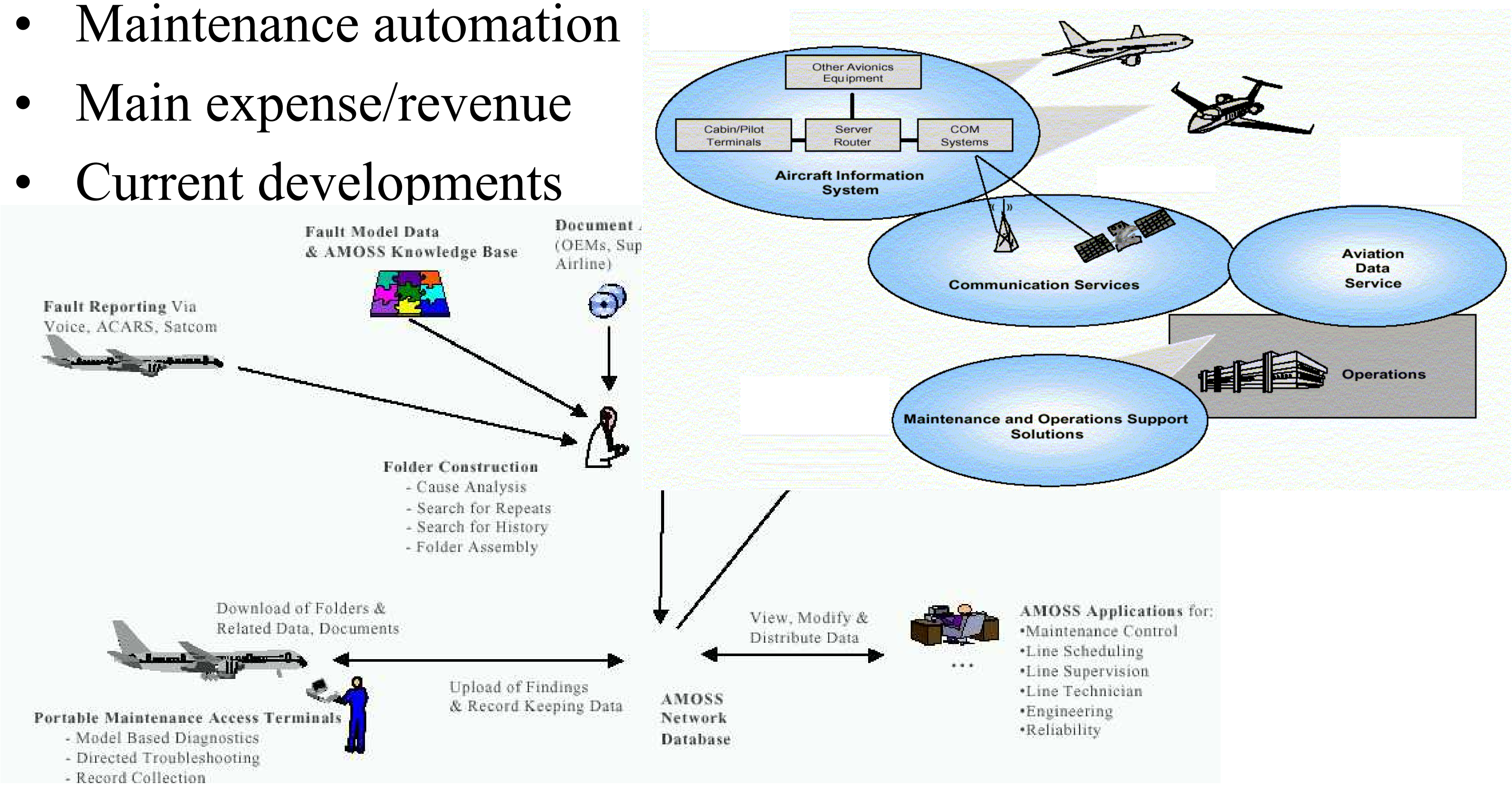
Vehicle Health Management

- IVHM - Integrated Vehicle Health Management - On-board
- PHM - Prognostics and Health Management - On-ground
- Vehicles: space, air, ground, rail, marine
  - Integrated systems, many complex subsystems
  - Safety critical, on-going maintenance, on-board fault diagnostics

Airline Enterprise - Maintenance

- Integrated on-board and on-ground system
- Maintenance automation
- Main expense/revenue
- Current developments

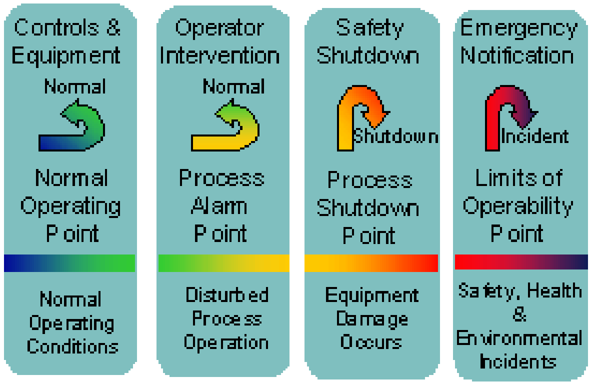
Military

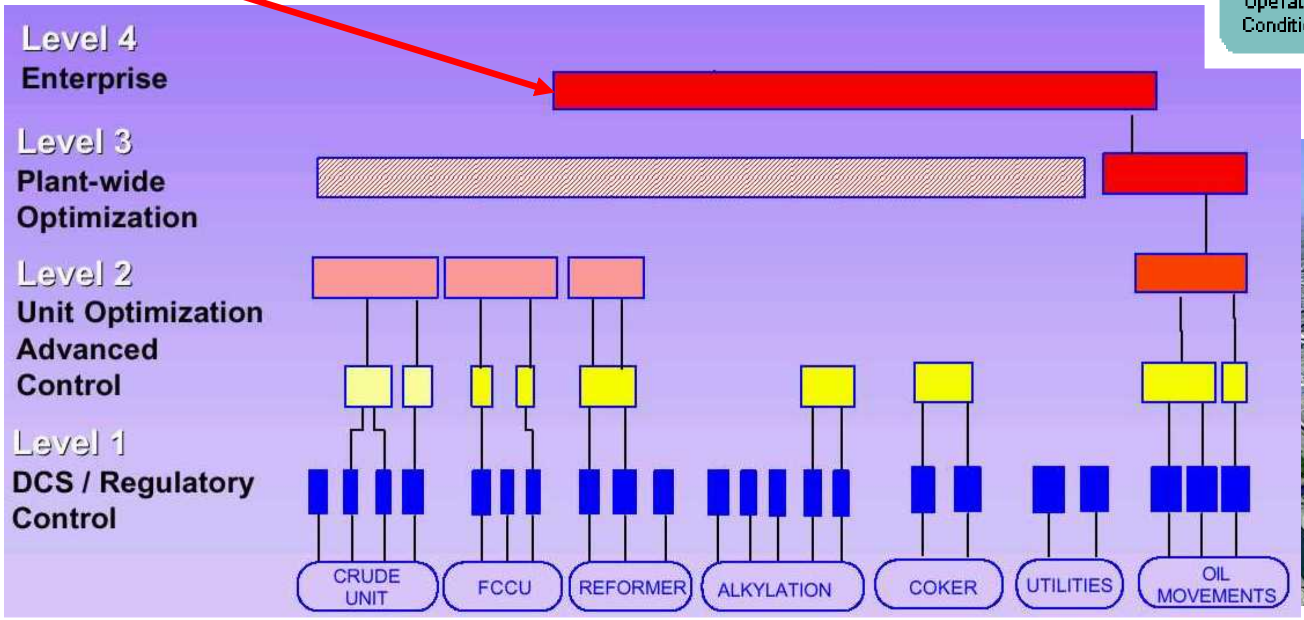


Industrial Plants

- Abnormal Situation Management
  - large cost associated with failures and production disruption
  - solutions are presently being deployed

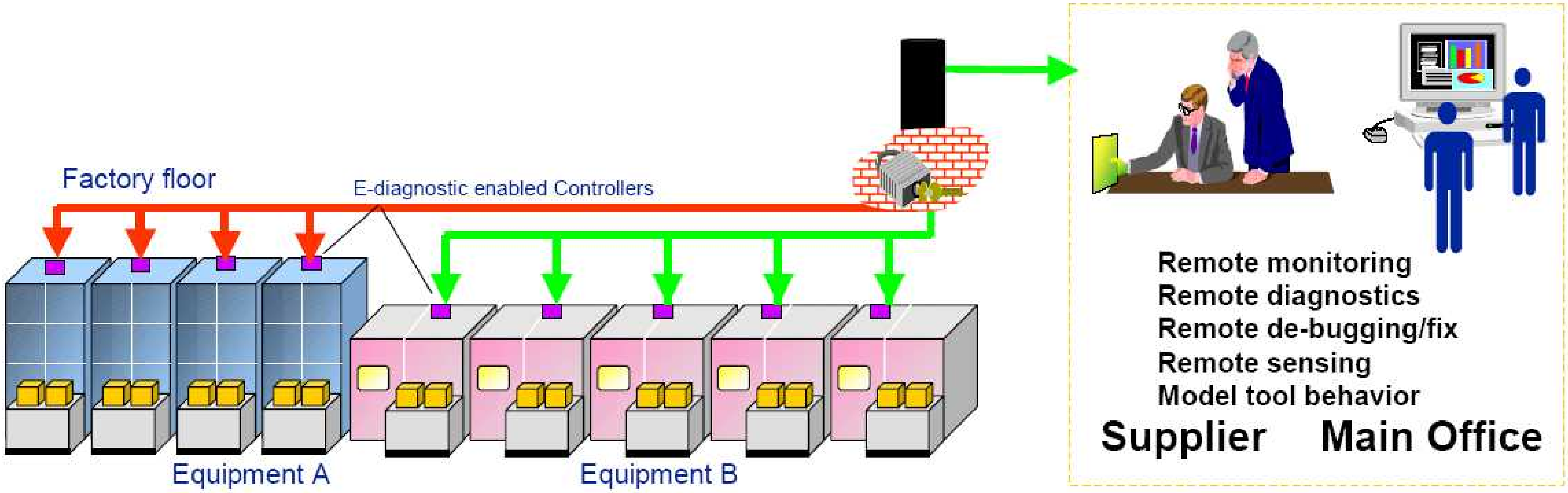
Layers of Protection





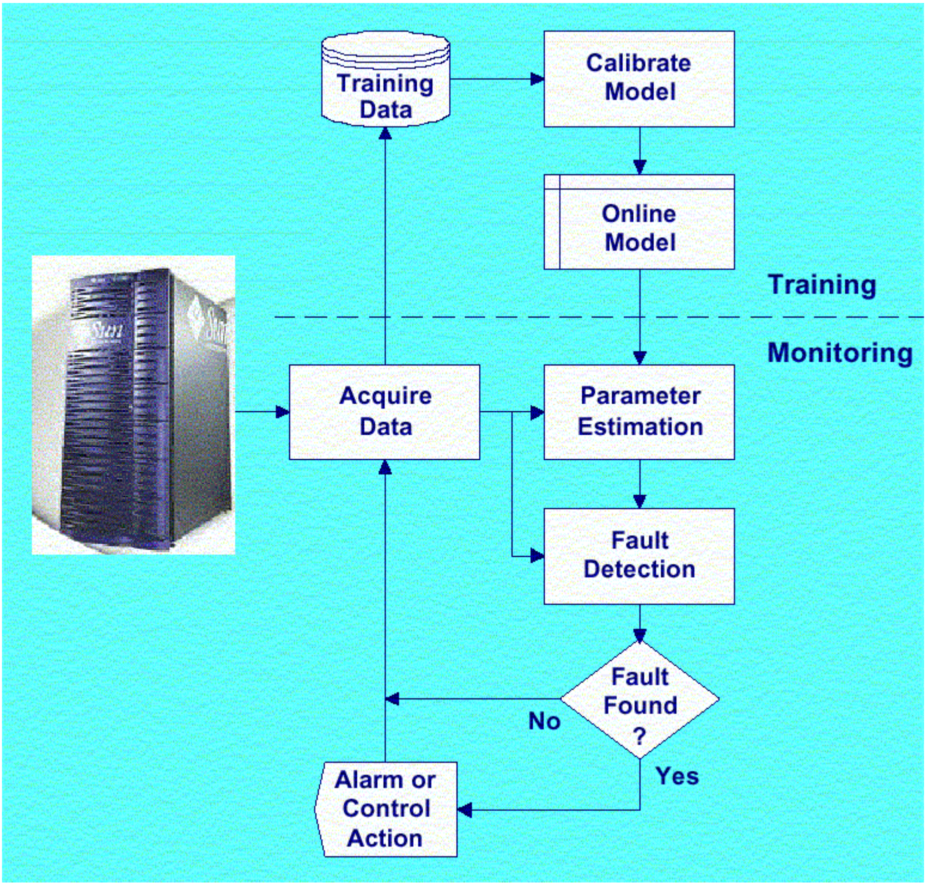
Semiconductor Manufacturing

- E-diagnostics initiative by SEMATECH, since 2001
- Consortium of all major semiconductor companies
- Now a part of SEMATECH e-Manufacturing
- Prototype demonstration in 2005



Computing

- Autonomic computing
  - Fault tolerance
  - Automated management, support, security
  - IBM, Sun, HP - Scientific American, May 2002
- Sun Storage Automated Diagnostic Environment
  - Health Management and Diagnostic Services



K.Gross, Sun Microsystems

Abnormality Detection - SPC

- SPC - Statistical Process Control (univariate)
  - discrete-time monitoring of manufacturing processes
  - early warning for an off-target quality parameter
- SPC vs. EPC
  - EPC (Engineering Process Control) - ‘normal’ feedback control
  - SPC - operator warning of abnormal operation
- SPC has been around for 80 years
- Three main methods of SPC:
  - Shewhart chart (20s)
  - EWMA (40s)
  - CuSum (50s)

SPC: Shewhart Chart

- Process model - SISO
  - quality variable randomly changes around a steady state value
  - the goal is to detect change of the steady state value

$$X(t) \approx \begin{cases} N(\mu_0, \sigma^2), & t \le T \\ N(\mu_1 \ne \mu_0, \sigma^2), & t > T \end{cases}$$

- Shewhart Chart

$$Y(t) = \frac{X(t) - \mu_0}{\sigma} \qquad \text{detection:} \quad Y(t) > Z = c_1$$

  - Simple thresholding for deviation from the nominal value μ_0
  - Typical threshold of 3σ <=> 0.27% probablity of false alarm

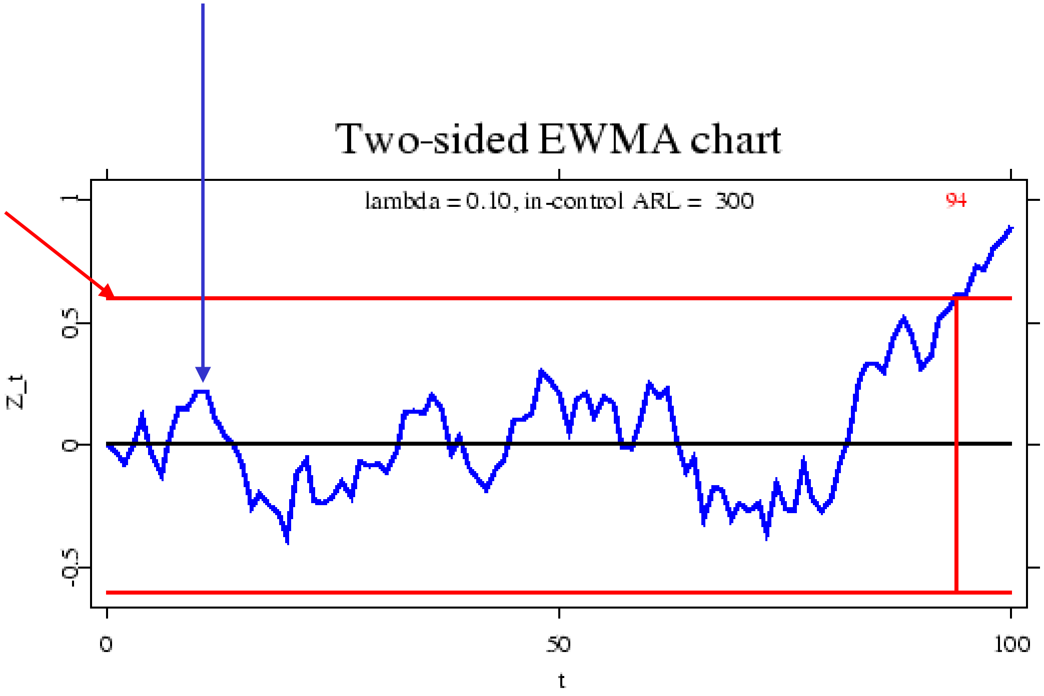
SPC: EWMA

- EWMA = Exponentially Weighted Moving Average
- First order low pass filter

$$Y(t+1) = (1-\lambda)Y(t-1) + \lambda X(t)$$

  - Detection threshold

$$Z = c_2\sqrt{\lambda(2-\lambda)}$$



SPC: CuSum

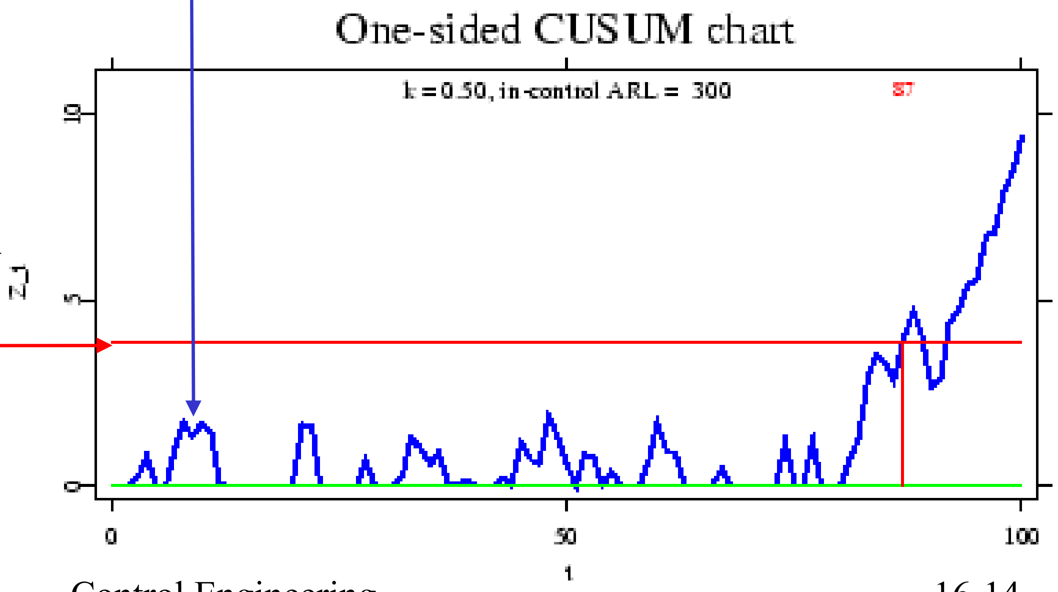
- CuSum = Cumulative Sum
  - a few modifications
  - one-sided CuSum most common

$$Y(t+1) = \max\left\{0, Y(t) + \frac{X(t)-\mu_0}{\sigma} - k\right\}$$

$$k = \frac{\mu_1 + \mu_0}{2\sigma}$$

  - Detection threshold

$$Z = c_3$$



Multivariate SPC - Hotelling's T^2

- The data follow multivariate normal distribution

$$X(t) \approx N(\mu, \Sigma)$$

$$X(t) = \Sigma^{1/2} Y(t) + \mu$$

Uncorrelated white noise

- Empirical parameter estimates

$$\mu = E(X) \approx \frac{1}{n} \sum_{t=1}^{n} X(t)$$

$$\Sigma = E\left((X-\mu)(X-\mu)^T\right) \approx \frac{1}{n} \sum_{t=1}^{n} (X(t)-\mu)(X^T(t)-\mu^T)$$

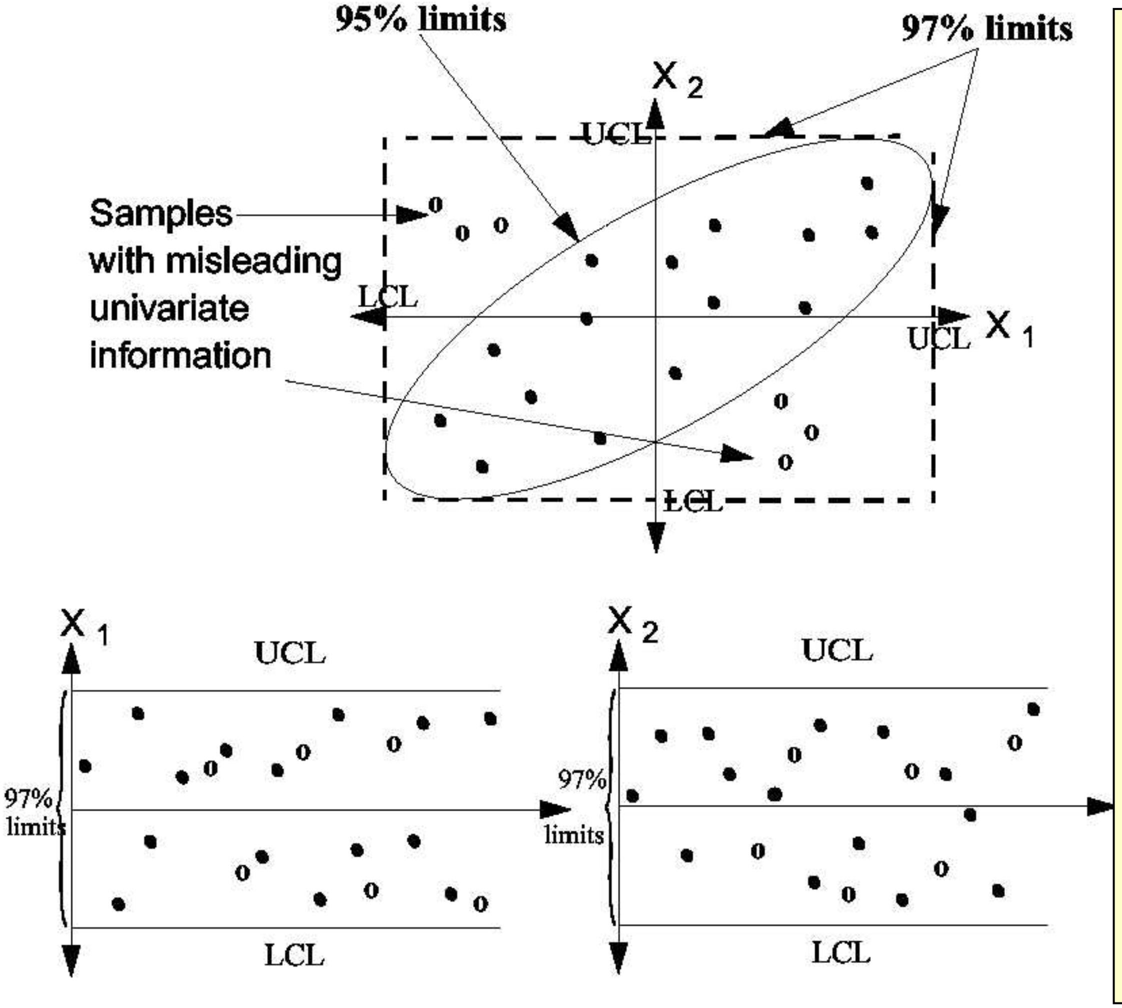
- The Hotelling's T^2 statistics is

$$T^2 = \left(X(t)-\mu\right)^T \Sigma^{-1} \left(X(t)-\mu\right)$$

$$T^2 = Y^T(t) Y(t)$$

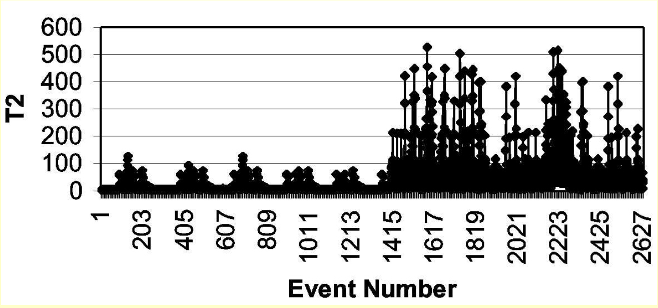
- T can be trended as a univariate SPC variable (almost)

Multivariate SPC - Example

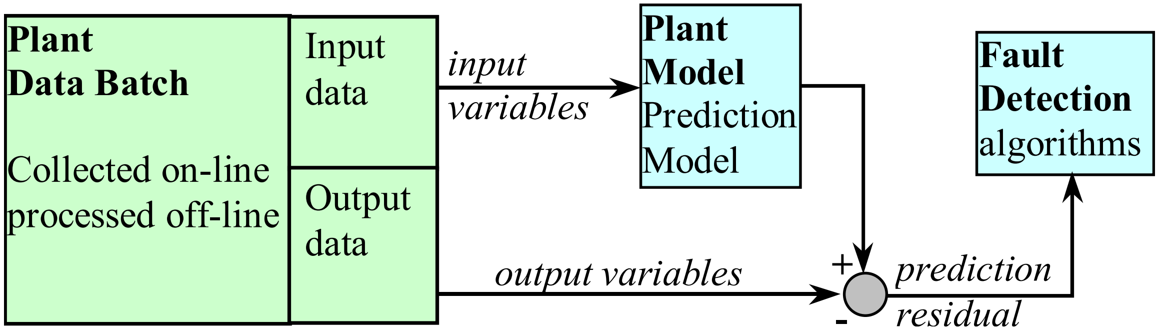


Example:

- MSPC for Cyber attack detection
- *X*(*t*) consists of 284 audit events in Sun’s Solaris Basic Security Module
- Ye & Chen, Arizona State



Model-based Fault Detection



Plant Data Batch

Collected on-line processed off-line

Input data

Output data

input variables

Plant Model Prediction Model

output variables

+

-

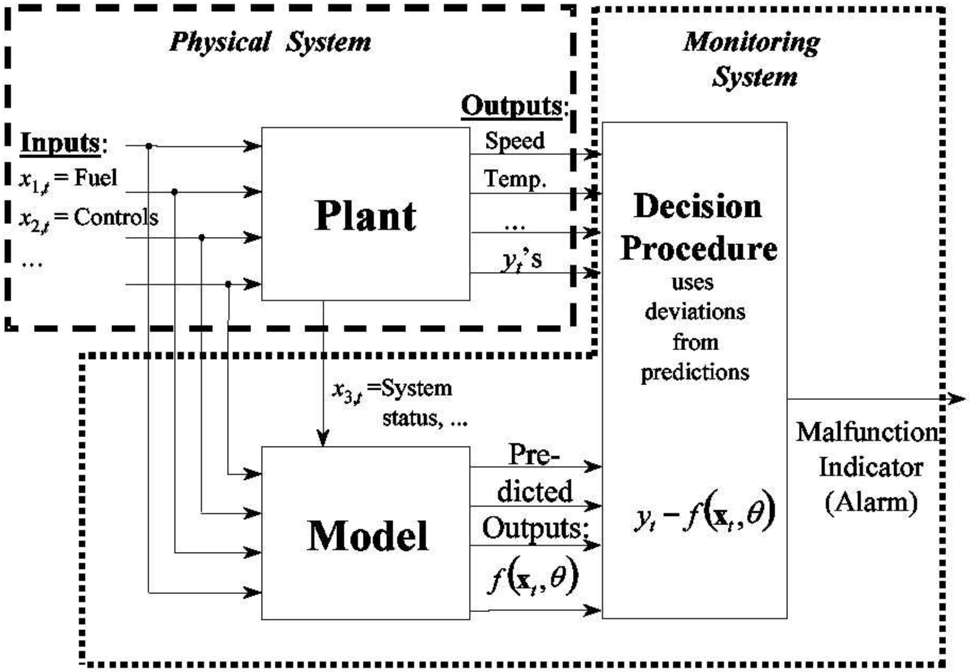
prediction residual

Fault Detection algorithms

- Compute model-based prediction residual
  - result of a simulation run

$$X = Y - f(U,\theta)$$

- If $\theta = 0$ (nominal case) we should have $X = 0$.
- X reflects faults



Model-based Fault Detection

- Compute model-based prediction residual $X(t)$ at cycle t
  - flight/trip/maneuver for a vehicle
  - update time interval or a batch for a plant
  - semiconductor process run
- $X(t)$ reflects modeling error, process randomness, and fault
- Use MSPC for detecting abnormality through $X(t)$
  - Hotelling's T^2
  - CuSum
- Does not tell us what the fault might be (diagnostics)

Parameter Estimation

- Residual model: $X = Y - f(U,\theta)$

$$X = \Phi\theta + \xi \qquad \Phi = -\frac{\partial f(U,\theta)}{\partial\theta}$$

- Fault models - meaning of θ
  - Sensor fault model - additive output change
  - Actuator fault model - additive input change
- Estimation technique
  - Fault parameter estimation - regression

$$\hat{\theta} = \left(\Phi^T\Phi + rI\right)^{-1}\Phi^T X$$