SPRING 2010

即時控制系統設計
Design of Real-Time Control Systems

Lecture 32
Introduction to Networked Control Systems

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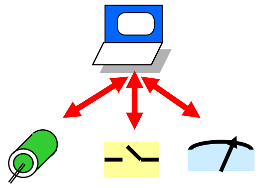
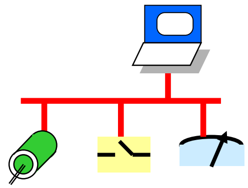
Real-Time Control Systems

- Controlled by one Computer Processor
  - Centralized control systems
  - Real-time operating systems
- Controlled by one Communication Medium
  - Distributed control systems
  - Real-time communications



Centralized Control System



Distributed Control System

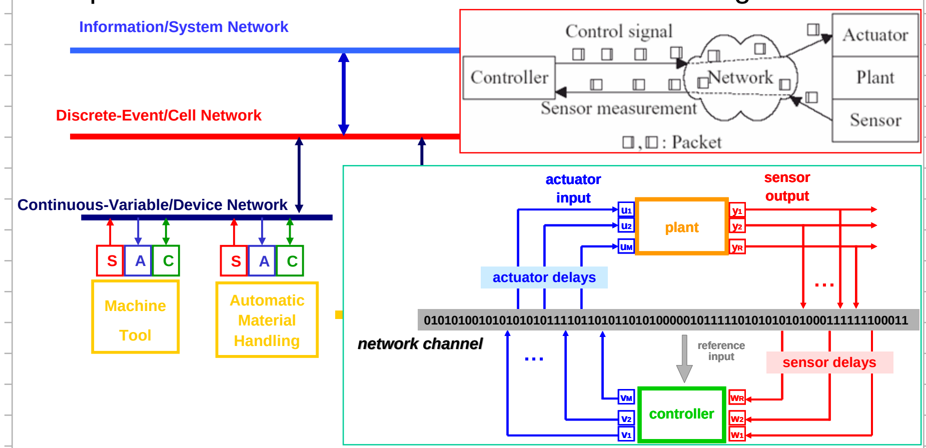
Networks:

- Enable remote data transfers & data exchange among users
- Reduce the complexity in wiring connections and the costs of media
- Provide ease in maintenance

- Data Networks:
  - > Slotted ALOHA & ARPANET around 1960-70
  - > Ethernet around 1980
- Control Networks:
  - > CAN (Controller Area Network) in 1983:
    - » By Robert Bosch, Germany, for car industries
  - > PROFIBUS (PROcess FIeld BUS) in 1987:
    - » By six German companies & five German institutes
  - > DeviceNet in 1994 (?):
    - » By Allen-Bradley/Rockwell Automation, for manufacturing-related industries

Networked Control Systems:

- Control systems with physically distributed processing power and network communication of control signals



- Motivations:
  - The overall NCS performance is always affected by network delays
  - Delays are widely known to degrade the performance of a control system
  - Existing constant time-delay control methodologies may not be directly suitable for controlling a system over the network since network delays are usually time-varying, especially in the Internet
  - Therefore, to handle network delays in a closed-loop control system over a network, an advanced methodology is required

- Research Overview:
  - NCS Configuration
    - » Direct structure
    - » Hierarchical structure
  - Delays in-the-loop
  - Delay Characteristics
    - » Cyclic service network
    - » Random access network
  - Effect of Delays in-the-loop
    - > Performance degradation
    - > Destabilization

- NCS Configuration:
  - Direct structure:

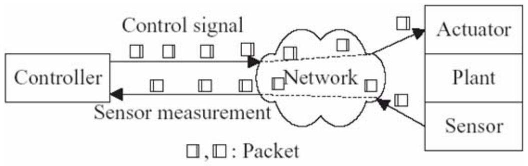


Fig. 1. NCS in the direct structure.

  - Hierarchical structure:

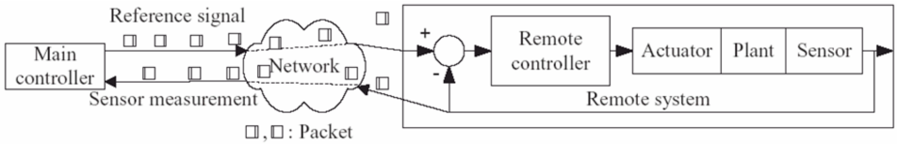


Fig. 2. NCS in the hierarchical structure.

- NCS Configuration:
  - Direct structure:

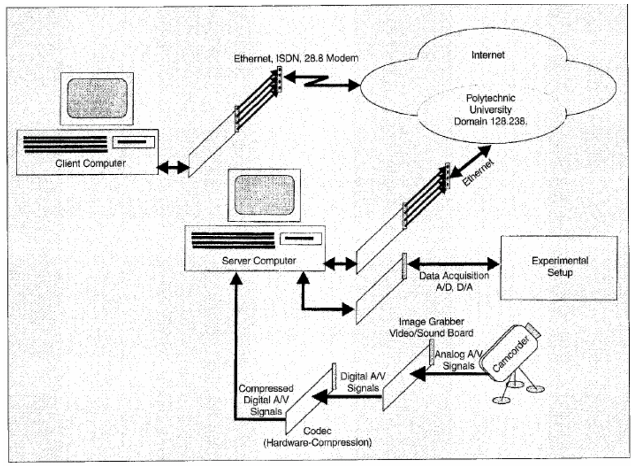


Fig. 9. I-abc network topology/experiment configuration.

- NCS Configuration:
  - Direct structure:

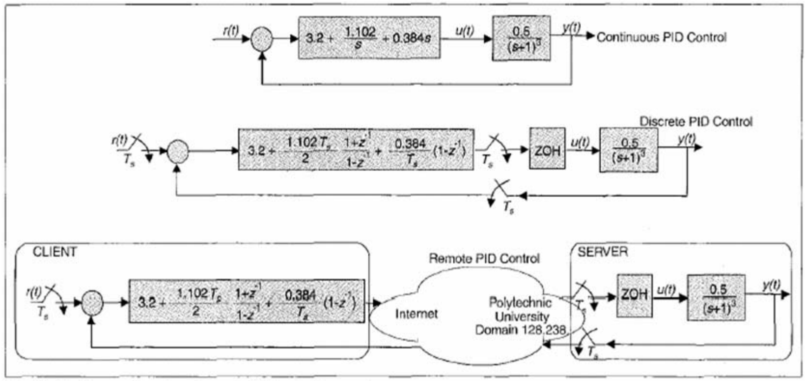


Fig. 10. Continuous, discrete and remote PID control concepts.

- NCS Configuration:
  - Direct structure:

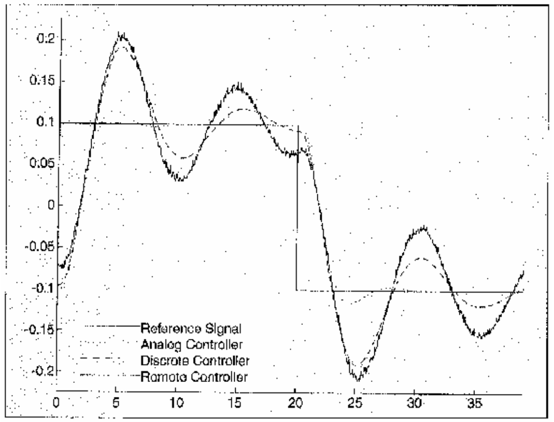


Fig. 13. System response with continuous, discrete and remote (T_s=2000 ms) control.

- NCS Configuration:
  - Hierarchical structure:

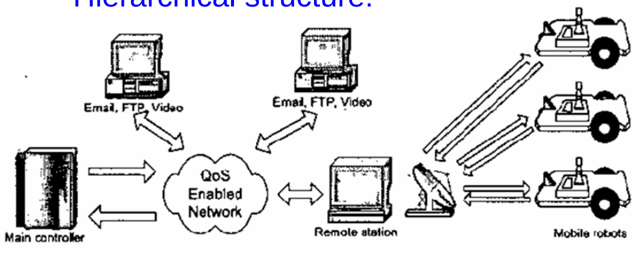


Fig. 1. Distributed mobile robot system configuration

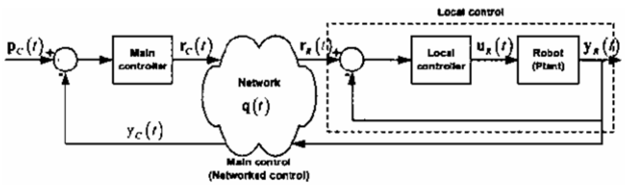
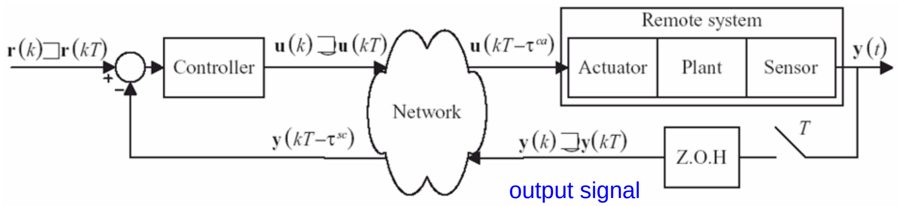


Fig. 2. Block diagram of main and local controllers

- Delays in-the-loop:

reference signal

control signal



output signal

Fig. 3. General NCS configuration and network delays for NCS formulations.

▪ Delays in-the-loop:

τ^{sc}: sensor-to-controller delay

τ^{ca}: controller-to-actuator delay

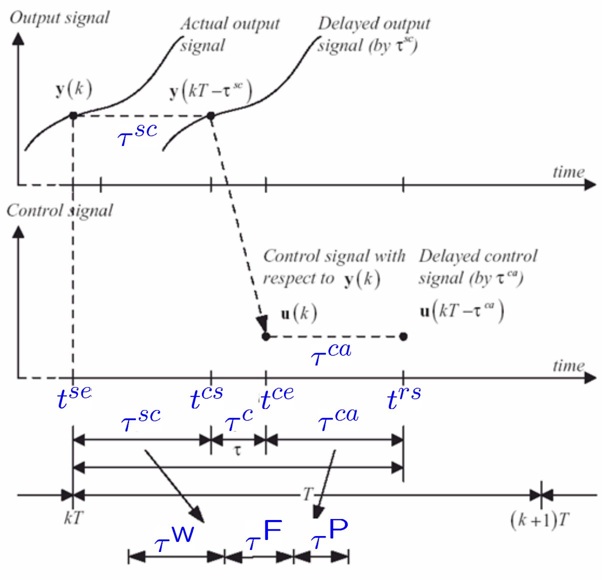
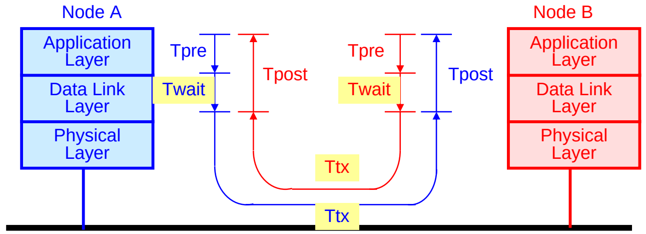


Fig. 4. Timing diagram of network delay propagations.

▪ Delays in-the-loop:



- Total end-to-end delay is the sum of
  - Pre-processing time: microprocessor
  - Waiting time: network protocol - MAC
  - Transmission time: data rate & length
  - Post-processing time: microprocessor

Depend on network protocol and loading

▪ Delay Characteristics:

- Cyclic Service Networks:
  - IEEE 802.4, SAE token bus, PROFIBUS,
    IEEE 802.5, SAE token ring, MIL-STD-1553B, FIP
  - Control and sensory signals are transmitted in a cyclic order with deterministic behaviors
  - Delays are periodic & can be simply modeled as a periodic function such as $\tau_k^{sc} = \tau_{k+N}^{sc}$ and $\tau_k^{ca} = \tau_{k+M}^{ca}$, N, M are constants
  - In practice, NCS may experience small variations on periodic delays due to several reasons such as discrepancies in clock generators

▪ Delay Characteristics:

- Random Access Networks:
  - Ethernet, CAN (?)
  - Significant parts of random network delays are waiting time delay due to queuing and frame collision on the networks
  - Sources of randomness:
    - > the queuing time delay at a switch or a router
    - > The propagation time delays from different network paths
  - Delay models:
    - > Constant delay
    - > Poisson process such as Markov chain
    - > Fluid flow model, ARMA model etc.

- Delay Models:

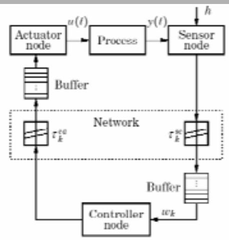


Figure 2.5 In Luck and Ray (1990) buffers are introduced after the varying communication delays to make the system time-invariant. The buffers must be longer than the worst case communication delay.

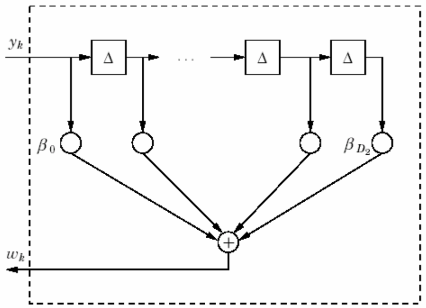
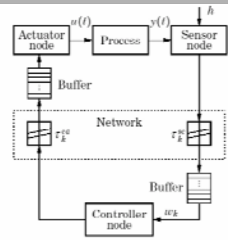


Figure 2.6 The network model used in Krtolica *et al.* (1994). The sampled signal, y_k, is delayed a number of samples due to communication delay. The controller reads the signal w_k. Only one of the β_i coefficients is one, the others are zero.

Luck & Ray 90, Krtolica et al. 94, Nilsson 98

- Delay Models:



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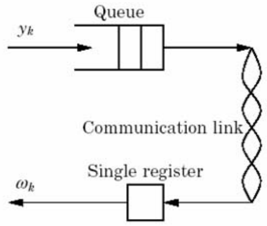


Figure 2.7 Block diagram of the transmission from the sensor node to the controller node in Chan and Özgüner (1995). The sampled signal y_k is delayed during the transmission to the controller node. The controller reads the sensor value ω_k from a register in the controller node. A simple form of timestamping is done by appending every message with the size of the queue when the message was sent.

Luck & Ray 90, Krtolica et al. 94, Chan & Ozguner 95, Nilsson 98

- Delay Models:

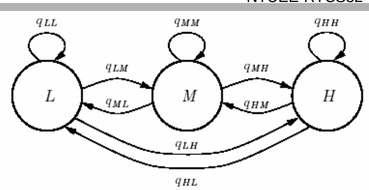


Figure 3.1 An example of a Markov chain modeling the state in a communication network. L is the state for low network load, M is the state for medium network load, and H is the state for high network load. The arrows show possible transitions in the system.

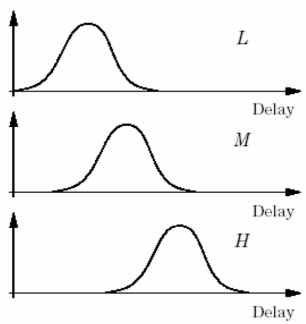


Figure 3.2 The delay distributions corresponding to the states of the Markov chain in Figure 3.1. L is the state for low network load, M is the state for medium network load, and H is the state for high network load.

Nilsson 98

- Delay Models:

$$f_\tau(\tau_k^{ca}) = \delta(\tau_k^{ca} - a)\cdot(1 - p_{ca}) + \delta(\tau_k^{ca} - b)\cdot p_{ca}$$

$$f_\tau(\tau_k^{sc}) = \begin{cases} \delta(\tau_k^{sc} - a)\cdot(1 - p_{sc}), & \tau_k^{sc} = a, \\ p_{sc}/(b - a^+), & \tau_k^{sc} \in (a, b],\ a < b, \\ 0, & \tau_k^{sc} \notin (a, b], \end{cases}$$

Tipsuwan & Chow 03, Krtolica et al. 94, Nilsson 98

Experimental Data of Network Delays:

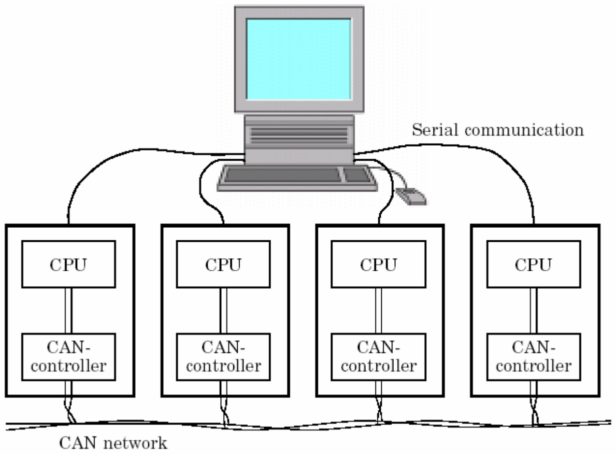


Figure 4.1 The CAN experimental system with the four one-card computers. The nodes are connected with a twisted pair CAN. Serial communications to the nodes are used for data collection.

Experimental Data of Network Delays:

- Low load network traffic

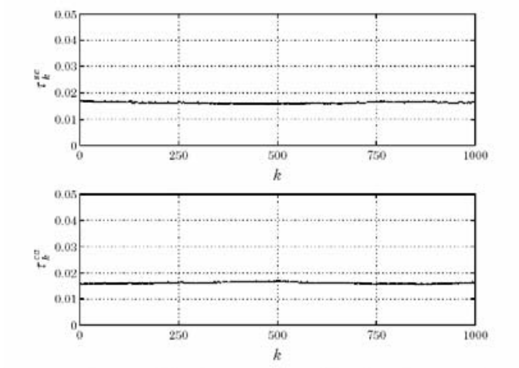


Figure 4.3 Measured delays for sensor to controller, τ_k^{sc}, and from controller to actuator, τ_k^{ca}. The experiment was the only load on the bus. The messages were 8 bytes long. The delay is almost constant.

- Period: 50 ms
- Data rate: 10 kbps
- Data size: 8 bytes/128 bits
- Tx time: 12.8 ms
- CPU time: 3.4 ms

$$U = \frac{0.0128}{0.05} + \frac{0.0128}{0.05} = 0.51.$$

Experimental Data of Network Delays:

- Add two additional low-load nodes with different priorities

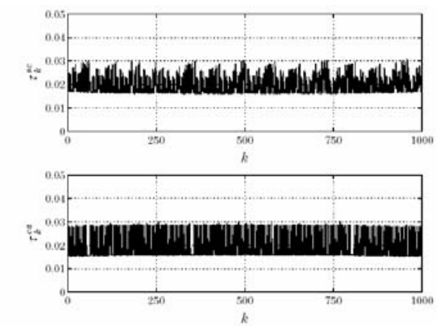


Figure 4.7 Load: Two senders with periods 80 ms and 100 ms and lower pri Message length: 8 bytes.

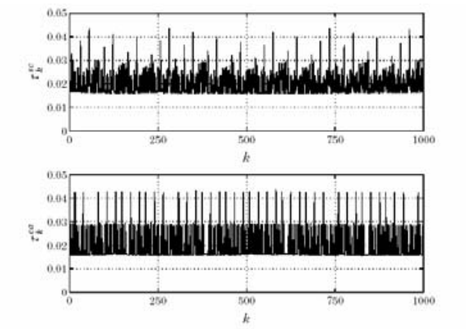
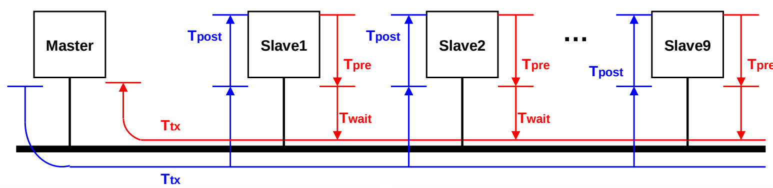


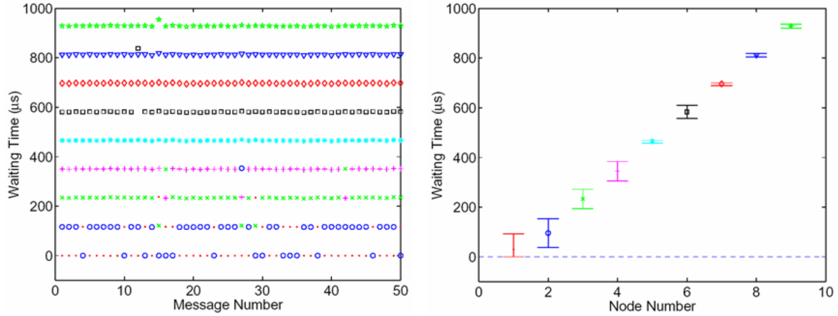
Figure 4.8 Load: Two load processes, one with period 80 ms and higher priority, and one with period 100 ms and lower priority. Message length: 8 bytes.

$$U = \frac{0.0128}{0.05} + \frac{0.0128}{0.05} + \frac{0.0128}{0.08} + \frac{0.0128}{0.1} = 0.80.$$

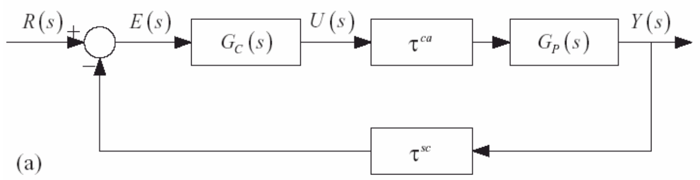
Experimental Data of Network Delays:

- Nine-node network





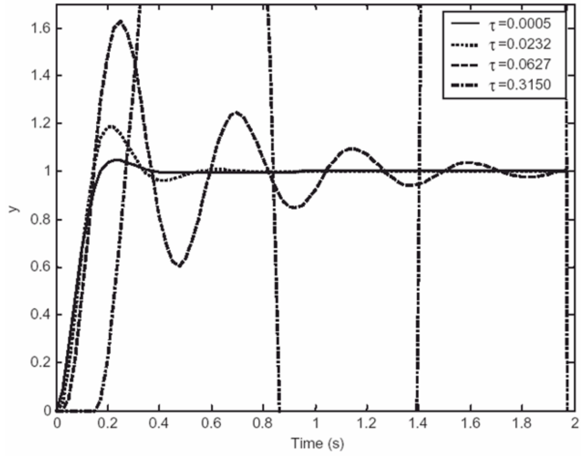
- Effects of Delays in-the-loop:
  - Performance degradation:



$$G_C(s) = \frac{\beta K_P(s + (K_I/K_P))}{s}, \qquad G_P(s) = \frac{2029.826}{(s+26.29)(s+2.296)},$$

$$K_P = 0.1701, \quad K_I = 0.378,$$

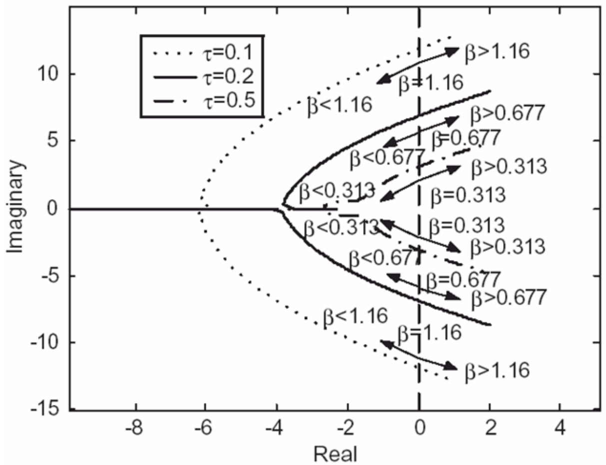
- Effects of Delays in-the-loop:
  - Performance degradation:



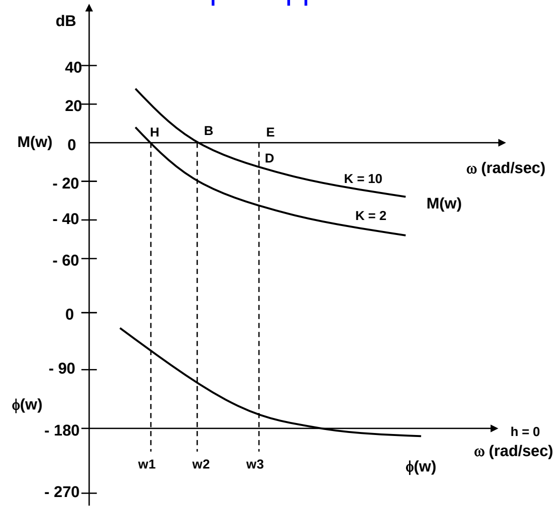
$$\beta = 1$$

$$\tau^{ca} = \tau^{sc} = \tau/2$$

- Effects of Delays in-the-loop:
  - Destabilization: Root locus approach



- Effects of Delays in-the-loop:
  - Destabilization: Bode plot approach



- Effects of Delays in-the-loop:
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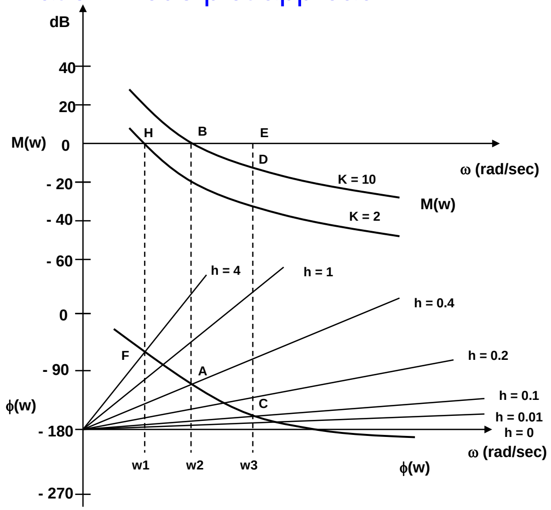

- Networked Control Methodology:
  - Assumptions

1. Augmented Deterministic Discrete-Time Model Methodology
2. Queuing Methodology
3. Optimal Stochastic Control Methodology
4. Perturbation Methodology
5. Sampling Time Scheduling Methodology
6. Robust Control Methodology
7. Fuzzy Logic Modulation Methodology
8. Event-Based Methodology
9. End-User Control Adaptation Methodology