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

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
Introduction

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.

Overview of NCS Research Issues

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:
- Hierarchical structure:

Fig. 1. NCS in the direct structure.

Fig. 2. NCS in the hierarchical structure.
Overview of NCS Research Issues

- NCS Configuration:
  - Direct structure:

![Diagram showing NCS configuration with direct structure]

- Hierarchical structure:

![Diagram showing NCS configuration with hierarchical structure]

- Delays in-the-loop:

![Diagram showing delays in-the-loop in NCS configuration]

Reference:
- Overstreet & Tzes 99
- Tipsuwan & Chow 02
- Tipsuwan & Chow 03
Overview of NCS Research Issues

• Delays in-the-loop:

\[ \tau_{SC} \]: sensor-to-controller delay

\[ \tau_{CA} \]: controller-to-actuator delay

Fig. 4. Timing diagram of network delay propagations.

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• 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

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Overview of NCS Research Issues

• 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

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• 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.

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Overview of NCS Research Issues

- Delay Models:

\[ f_T(\tau^{ca}_k) = \delta(\tau_k^{ca} - a) \cdot (1 - p_{ca}) + \delta(\tau_k^{ca} - b) \cdot p_{ca} \]

\[ f_T(\tau^{sc}_k) = \begin{cases} \delta(\tau_k^{sc} - a) \cdot (1 - p_{sc}), & \tau_k^{sc} = a, \\ p_{sc}/(b - a^+), & \tau_k^{sc} \in (a, b), a < b, \\ 0, & \tau_k^{sc} \notin (a, b). \end{cases} \]
Overview of NCS Research Issues

- **Experimental Data of Network Delays:**
  - Low load network traffic

- **Add two additional low-load nodes with different priorities**

- **Nine-node network**

  
  \[ U = \frac{0.0128}{0.05} + \frac{0.0128}{0.05} = 0.51 \]

  
  Figure 4.3 Measured delays for sensor to controller, \( T_{s1c} \), and from controller to actuator, \( T_{c1a} \). The experiment was the only load on the bus. The messages were 8 bytes long, the delay is almost constant.

  
  \[ U = \frac{0.0128}{0.05} + \frac{0.0128}{0.05} = 0.51 \]

  
  Figure 4.3 Measured delays for sensor to controller, \( T_{s1c} \), and from controller to actuator, \( T_{c1a} \). The experiment was the only load on the bus. The messages were 8 bytes long, the delay is almost constant.
Effects of Delays in-the-loop:

- Performance degradation:

\[ G_C(s) = \frac{\beta K_P (s + (K_I / K_P))}{s}, \quad G_P(s) = \frac{2029.826}{(s + 26.29)(s + 2.296)} \]

\[ K_P = 0.1701, \quad K_I = 0.378, \]

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- Destabilization: Root locus approach

\[ \beta = 1 \]
\[ \tau^{ca} = \tau^y = \tau / 2 \]

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- Destabilization: Bode plot approach

\[ \beta \]
\[ M(w) \]
\[ \phi(w) \]

Malek-Zavarei & Jamshidi 87
Overview of NCS Research Issue

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

Networked Control Methodology

- 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