Time-Dependent Dynamics in Networked Sensing and Control

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Outline

☐ Previous Work
☐ Network Properties and Difficulties
☐ Stability Regions and Traffic Locus
☐ Co-Simulation Methodology and Results
☐ Conclusions
Previous Work

- Nilsson’s Assumptions
- Walsh et al.: MATI

- Zhang: $h_{suff}$

- Branicky, Liberatore, Phillips: Co-Simulation for Co-Design (ACC ’03)
NSCS Difficulties

- Packet delays, dropped packets
- Delays related to:
  - Computation and Propagation—fixed delay per link
  - Transmission—related to link speed
  - Queuing—related to link buffer size
- Dropped packets related to:
  - Collisions (but not in a switched network)
  - Bandwidth and Queuing—related to link speed and link buffer size
NSCS Difficulties Illustrated
Network Delays

- Delays are bounded by $[\tau_{\text{min}}, \tau_{\text{max}}]$

$$
\tau_{\text{min}} = \sum_{L \in \mathcal{L}} \delta_L + \frac{8P}{\eta_L} \\
\tau_{\text{max}} = \sum_{L \in \mathcal{L}} \delta_L + \frac{8P(\beta_L + 1)}{\eta_L}
$$

- $\mathcal{L}$: Set of links in path
- $\delta_L$: Fixed computation and propagation
- $P$: Size of NSCS packet (bytes)
- $\eta_L$: Link speed (bits/second)
- $\beta_L$: Buffer size of link (number of packets)
Packet Loss

- Packet loss due to network congestion
- Packet loss changes sampling period in discrete set: \( \{h, 2h, 3h, \ldots\} \)
- Over a long time, calculate the effective sampling period:

\[
h_{\text{eff}} = \max \left\{ 8h \sum_{i \in N} \frac{S_i}{h_i}, h \right\}
\]
Effective Sampling Period
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Stability Region

- Previous work has developed a Sampling Period and Delay Stability Region (SPDSR)

- Analytical bound on system stability assuming fixed sampling period and fixed delays
SPDSR

Sampling Period and Delay Stability Region

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Traffic Locus

- Describes where (on average) in the SPDSR the system will perform given certain parameters

- Vary:
  - Number of plants
  - Queue size
  - Sampling period
  - Packet size
  - etc.
Traffic Locus (Cont.)
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Co-Simulation Methodology

- Simultaneously simulate both the dynamics of the control system and the network activity

- Achieved through ns-2 network simulator
  [http://vorlon.cwru.edu/~vxl11/NetBots/]

- Vary parameters to achieve interesting results
  - Number of plants
  - Cross-traffic
  - Sample scheduling
  - Etc.
Network Topology

- 10 Mbps link between plants (2-4) and router (1), with 0.1 ms fixed link delay
- 1.5 Mbps T1 line between router (1) and controller (0), with 1.0 ms fixed link delay
- First plant (2) under observation
- Delays are asymmetric
Control System

- Assumes full-state feedback
- Non-linear equations linearized about the unstable equilibrium
- Sampled at 50 ms
- Feedback designed via discrete LQR
- Control signal is cart acceleration

\[
\ddot{\phi} + \frac{3B_R}{4ML^2} \dot{\phi} - \frac{3g}{4L} \sin \phi = -\frac{3}{4L} \dddot{x}
\]
Baseline Simulation

- One plant on the network
- No cross-traffic
- No bandwidth contention
- Delays fixed at \( t_{\text{min}} \)
- No lost packets
- Slight performance degradation due to fixed delays
Threshold Behavior

- 147 Plants on the network (just more than the network bottleneck)
- No cross-traffic
- Performance slightly worse than baseline
Threshold Behavior (Cont.)

- Delays are asymmetric and variable
- Delay ranges from \( \_\text{min} \) to \( \_\text{max} \)
- 147 plants slightly exceeds network bandwidth
- Packet drops due to excessive queuing
Cross-Traffic

- 130 Plants on network
- Bursty FTP cross-traffic at random intervals
- Performance similar to threshold case
Cross-Traffic (Cont.)

- Delays are asymmetric and variable
- Delay ranges in $\ldots_{\text{min}}$ to $\ldots_{\text{max}}$, depending on traffic flow
- 130 plants below network bandwidth, but cross-traffic exceeds
- Packet drops due to queuing
Over-Commissioned

- 175 Plants on network – well above network bandwidth
- No cross-traffic
- Performance degrades substantially
Over-Commissioned (Cont.)

- Delays asymmetric
- $\tau_{sc}$ quickly fixed at $\tau_{max}$
- $\tau_{ca}$ still fixed at $\tau_{min}$
- 175 plants well above network bandwidth
- Many packet drops due to excessive queuing
SPDSR from Simulations

Stability Regions

- Analytical
- Experimental

Delay/Sampling Period vs. Sampling Period (s)
Conclusions

- Controlled physics depend on real-time communications properties.
- Analytical stability criteria are interesting and helpful, but they do not completely describe the stability of a dynamic NSCS.
- "Average-case" analysis cannot explain poor system performance -- analysis must account for exact network dynamics.
Website – NSCS Repository

http://home.case.edu/ncs/