Distributed Control over Wireless Networks

Marco Zimmerling

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The Problem

Wireless Sensor and Actuator Networks

Control Performance

Reference input $r(\tau)$

Reference

Controller

Physical System
The Problem

Wireless Sensor and Actuator Networks

Control Performance

Diagram:

- Actuator
- Physical System
- Sensor
- Controller
- Reference

Control input: $u(\tau)$
Reference input: $r(\tau)$
System output: $y(\tau)$
Example: Lighting Control

- **Dimmer**
- **Gallery**
- **Photodiode**

**Controller**
- Target voltage: $u(\tau) [V]$
- Current light intensity: $y(\tau) [Lux]$
The Problem

Wireless Sensor and Actuator Networks

Control Performance

Distributed Control over Wireless Networks
The Problem

Wireless Sensor and Actuator Networks

Control Performance

Introduction and Motivation
Problems Affecting Control Performance
Compensation Strategy for Delay and Jitter
Summary

The Problem

Physical System

Controller

Reference

Sensor

spatially distributed

wireless links

Actuator
The Problem

Wireless Sensor and Actuator Networks

Control Performance

Distributed Control over Wireless Networks
Control versus Communication Theory

- Control theory: ideal channels
  - No (or at least deterministic) communication and computation delays
  - Synchronous, periodic sampling and actuation
  - No packet drop-outs

- Communication theory: imperfect channels
  - Non-deterministic communication delays (time-varying)
  - Asynchronous communication
  - Packet loss unavoidable in wireless communication
Wireless Sensor and Actuator Networks (WSANs)
Wireless Sensor and Actuator Networks (WSANs)

- Base Station
- Sensor
- Actuator
- Controller

16-bit RISC, 8 MHz, 48 kB flash
IEEE 802.15.4, 250 kbps, 2.4 GHz
$ 99 (USD)
WSAN Possibilities

- Battery-powered $\implies$ independence
- Flexible deployments $\implies$ flexible network architectures
- Application in inaccessible, hazardous areas
- Different sensors on a single module $\implies$ multi-purpose
- Local (pre-)processing $\implies$ distributed computation
- Data exchange using low-power radio $\implies$ collaboration
- Low price $\implies$ many sensors (>1000) $\implies$ heaps of data
WSAN Problems from Control Perspective

Problems: delay, jitter, packet loss
⇝ Control performance degrades
⇝ Even system instability
WSAN Problems from Control Perspective

Problems: delay, jitter, packet loss
\[ \Rightarrow \text{Control performance degrades} \]
\[ \Rightarrow \text{Even system instability} \]

Integral absolut error (IAE):

\[ J(t) = \int_0^t |r(\tau) - y(\tau)| \, d\tau \]
Good versus Bad Control Performance

- ideal
- without delay comp.
- with delay comp.
Causes and Types of Delay/Jitter

- Causes of **communication** delay/jitter:
  - Node mobility $\rightarrow$ varying transmission distances
  - Sleep scheduling $\rightarrow$ dynamic network topology
  - Adaptive MAC and routing protocols $\rightarrow$ variation in paths, number of hops, . . .
  - External disturbances

- Causes of **computation** delay/jitter:
  - Varying execution times of different control computations
  - Competing processes

- Types of delay/jitter:
  - **Sampling jitter**: sampling interval varies
  - **Sampling-actuation jitter**: delay between sampling and actuation varies
Delays in Control Loop

- Actuator
- Physical System
- Sensor
- Controller
- Reference
Delays in Control Loop

Actuator → Physical System → Sensor

Controller

communication delay/jitter

Reference

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Delays in Control Loop

- **Actuator** → **Physical System** → **Sensor**
- **Controller**
- **Reference**

1. Communication delay/jitter
2. Computation delay/jitter

- **Delay and Jitter**
- **Packet Loss**
- **Throughput**
- **Control versus Communication Performance**
Delays in Control Loop

Actuator → Physical System → Sensor

- (3) Communication delay/jitter
- (1) Communication delay/jitter
- (2) Computation delay/jitter

Controller

Reference
Packet Loss

- Causes of **packet loss**:
  - Transmission errors
  - Buffer overflows due to congestion
  - Long delays (outdated packets are discarded)

- Consequences:
  - Controller is **not up-to-date**
  - Control inputs must be **estimated**

- **Unavoidable** in presence of radio interference, multi-hop communication, variable transmit power, node mobility

- Packet loss is highly dependent on transmission distance
Packet Loss versus Transmission Distance

The graph shows the relationship between packet loss rate and transmission distance. As the distance increases, the packet loss rate also increases, indicating a decrease in transmission quality with greater distance.
High data rate $\rightarrow$ fine-grained control

How to increase the data rate?
- Deploy more sensors
- Increase sampling rate of sensors

However, this can cause
- Network congestion $\rightarrow$ many retransmissions $\rightarrow$ delay/jitter
- High energy consumption at nodes $\rightarrow$ nodes die quickly $\rightarrow$ reduced visibility or even network partition

Trade-off between control and communication performance
Control versus Communication Performance

- Out of Control
- Networked Control
- Continuous Control
- Digital Control

Performance scales:
- Out of Control
- Unacceptable Performance
- Acceptable Performance
- Best

Delay scales:
- Slower
- Faster

Points:
- $\omega_A$
- $\omega_B$
- $\omega_C$
Impact of Network Architecture

Integrated controller

Stand-alone controller
Example: Networked Control System (NCS)

- Process
  - Sensor
    - time-driven $h$
  - Actuator
    - event-driven

- Wireless Network
  - PD Controller
    - event-driven
  - Disturbance
    - $\sim$ long random delays
Simulation and Analysis using TrueTime

- Based on MATLAB/Simulink
- Simulation of task execution on nodes
- Simulation of simple communication models
- Facilitates to study impact of different
  - Communication models
  - Delay/jitter compensation strategies
  - Task scheduling policies
NCS Model in TrueTime
NCS Model in TrueTime
NCS Model in TrueTime

$h = 10 \text{ ms}$

IDEAL

no interf. task

$0 \text{ ms}$

no disturbance

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Distributed Control over Wireless Networks
NCS Model in TrueTime

- Process
- Sensor
  - DELAY
  - $h = 10$ ms
- Actuator
- Wireless Network
  - 1.5 ms
- PD Controller
  - 0.5 ms
- Disturbance
  - 50% high priority packets

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Distributed Control over Wireless Networks
Delay/Jitter Compensation through Gain Scheduling

- **Delay sensor → controller:**
  - Assumption: packets from sensor are timestamped
  - Controller can determine actual delay

- **Delay controller → actuator:**
  - Assumption: probability distribution of delay is known
  - Controller can estimate expected delay

- *(Rough) idea:*
  - **Precalculated controller parameters** for different delays
    - Proportional gain: $K_p$
    - Derivative gain: $K_d$
  - Select corresponding parameters based on current delay
  - Compute control signal via linear interpolation using
    - Selected controller parameters
    - Current error $(r(\tau) - y(\tau))$
Control Performance

ideal
without delay comp.
with delay comp.
Summary

- WSANs allow for highly embedded, ubiquitous sensing, actuation, and control
- Delay, jitter, and packet loss degrade control performance
- Adaptive control algorithms for compensation
- Joint design of communication and control infrastructure
- Early, iterative analysis throughout design process with powerful tools (Jitterbug, TrueTime)
Further Reading I


