Dependable Internet of Things

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Industrial IoT for Industry 4.0

- 5.9+ billion hours operating experience
- 26,200+ wireless field networks
  [Emerson]

- $944.92 million by 2020
  [Market and Market]

Courtesy: Emerson Process Management
WirelessHART

- Reliability and predictability
  - Multi-channel TDMA MAC
  - One transmission per channel
  - Redundant routes
  - Over IEEE 802.15.4 PHY

- Centralized network manager
  - Collect topology information
  - Generate routes and schedule
  - Change when devices/links break

**Industrial wireless standard for process automation**
The Control Challenge

Most of today’s industrial wireless networks are for monitoring.

Dependable control requires

• **real-time**
• **control performance**
• **resilience to loss**

Source: [https://www.automation.com](https://www.automation.com)
Towards Dependable Wireless Control

1. Real-time wireless networks and analysis

2. Optimizing control performance over wireless

3. Resilient yet efficient wireless control under loss.

*Cannot be accomplished by wireless or control design alone ➔

**Cyber-Physical Co-design of Wireless and Control**
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Cyber-Physical Co-design of Wireless and Control
The Real-Time Problem

- A feedback control loop incurs a flow $F_i$
  - Route: sensor $\rightarrow$ ... $\rightarrow$ controller $\rightarrow$ ... $\rightarrow$ actuator
  - Generate packet every period $P_i$
  - Multiple control loops share a network

- Each flow must meet deadline $D_i (\leq P_i)$
  - Stability and predictable control performance

- Research problems
  - Real-time transmission scheduling $\rightarrow$ meet end-to-end deadlines
  - Fast schedulability analysis $\rightarrow$ adapt to wireless dynamics through admission control and rate adaptation
Delays in WirelessHART

A transmission is delayed by

- **channel contention**: all channels are assigned to other transmissions
- **transmission conflict** over a same node
  - contributes significantly to latency!

- 1 and 5 conflict
- 4 and 5 conflict
- 3 and 4 do not
Fast Delay Analysis

- Compute upper bound of the delay for each flow
  - Sufficient condition for real-time guarantees

- Channel contention $\rightarrow$ multiprocessor task scheduling
  - A channel $\rightarrow$ a processor
  - Flow $F_i$ $\rightarrow$ a task with period $P_i$, deadline $D_i$, execution time $C_i$
  - Leverage existing response time analysis for multiprocessors

- Account for delays due to transmission conflicts

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Delay due to Conflict

- Low-priority flow $F_l$ and high-priority flow $F_h$ conflict $\rightarrow$ delay $F_l$

- $Q(l,h)$: #transmissions of $F_h$ sharing nodes with $F_l$
  - In the worst case, $F_h$ can delay $F_l$ by $Q(l,h)$ slots

- Conflicts contributes significantly to delays
  - Delay analysis [TC 2015]
  - Scheduling [RTSS 2010]
Real-Time Wireless Networking

- **WirelessHART stack in TinyOS** [IoTJ 2017]
  - Implementation on a 69-node testbed
  - Network manager (scheduler + routing)

- **Energy-efficient routing** [IoTDI 2016]

- **Emergency communication** [ICCPS 2015]

- **Channel selection** [INFOCOM 2017]

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Optimize Control over Wireless

Observation
- Wireless resource is scarce and dynamic
- Cannot afford separating wireless and control designs

Cyber-Physical Co-Design
- Holistic co-design of wireless and control

Examples
- Rate selection for wireless control [TECS 2014]
- Scheduling-control co-design [ICCPS 2013]
Rate Selection for Wireless Control

- Optimize the sampling rates of control loops sharing a WirelessHART network.

- Rate selection must balance control and network delay.
  - Low sampling rate → poor control performance
  - High sampling rate → long delay → poor control performance
Control Performance Index

- Digital implementation of control loop $i$
  - Periodic sampling at rate $f_i$
  - Performance deviates from continuous counterpart

- Control cost of control loop $i$ under rate $f_i$ [Seto RTSS’96]
  - Approximated as $\alpha_i e^{-\beta_i f_i}$ with sensitivity coefficients $\alpha_i, \beta_i$

- Overall control cost of $n$ loops: $\sum_{i=1}^{n} \alpha_i e^{-\beta_i f_i}$

*Interface between cyber and physical designs!*
The Rate Selection Problem

- Constrained non-linear optimization

- Determine sampling rates \( f = \{ f_1, f_2, \cdots, f_n \} \)

minimize control cost \( \sum_{i=1}^{n} \alpha_i e^{-\beta_i f_i} \)

subject to \( delay_i \leq 1 / f_i \) \( \text{Delay bound} \)

\( f_i^{\text{min}} \leq f_i \leq f_i^{\text{max}} \)
Polynomial Time Delay Bounds

- In terms of decision variables (rates), the delay bounds are:
  - Non-linear
  - Non-convex
  - Non-differentiable
Cyber-Physical Co-Design

- Relax delay bound to simplify control optimization
- Derive a convex and smooth, but less precise delay bound.
- Rate selection becomes a convex optimization problem.

Optimize control performance efficiently at run time!

Towards Dependable Wireless Control

1. Real-time wireless networks and analysis

2. Optimizing control performance over wireless

3. Resilient yet efficient control under data loss.

This cannot be accomplished by wireless or control design alone → Cyber-Physical Co-design of Wireless and Control
Resilient Control under Data Loss

- Data loss causes instability and degrades control performance.

- Addressed in separation
  - Control: control design to tolerate data loss.
  - Wireless: redundancy reduces loss at high resource cost.
  - But how much redundancy is sufficient?

- Cyber-physical co-design
  - Incorporate resilient control design
  - Tailor wireless protocols for control design
  - Resilient wireless control at low resource cost
State Observer estimates system states based on a system model even if there is no new data from sensors.

Handle Data Loss from Controller

- **Model Predictive Control**
  - Controller computes control inputs in the next $w+1$ sampling periods: $u(k), u(k+2), \ldots, u(k+w)$.
  - Actuator applies $u(k)$.

- **Buffered actuation**
  - Actuator buffers previous control inputs $u(k+1), \ldots, u(k+h)$ ($h \leq w$).
  - Applies buffered control input if updated input is lost.
  - Buffer size of $h \rightarrow$ tolerate $h$ consecutive packet loss.
Exothermic Reaction Plant

Plant: nonlinear chemical reaction
Control input: $u_1$ and $u_2$
Objective: Maintain temperature in Tank 2

Wireless Cyber-Physical Simulator (WCPS)
- Integrate TOSSIM and Simulink
- Capture dynamics of both wireless networks and physical plants
- Holistic simulations of wireless control
- Open source: wcps.cse.wustl.edu
Impact of Data Loss from Sensor

System is highly resilient to packet loss from sensors

Extended Kalman filter under 60% loss from sensor
Actuation is **more sensitive** to data loss than sensing.

→ *Data losses are not equal!*

Actuation buffer (size 8) under 60% loss to actuator
Routing in WirelessHART

- Source routing: single path routing $\rightarrow$ efficient but unreliable.
- Graph routing: every node on the primary path has a backup path $\rightarrow$ reliable at cost of capacity and energy.
- Entire network uses a **uniform** routing strategy.
  
  - But sensing and actuation need **different** levels of reliability?!
Asymmetric Routing

- Differentiated routing for sensing and actuation

- State observer handles data loss from sensors

- Source routing from sensors
  - State observer compensates for lower reliability
  - Save network resource

- Actuation is more sensitive to data loss

- Graph routing to actuators
  - High reliability
  - High resource cost, but needed for control

Tailor routing to control
Spend wireless resource where control needs it
Maximum Absolute Error

(a) 5Hz Control

(b) 3Hz Control

-73dBm Noise

- Source/Graph performs close to Graph/Graph at 3Hz sampling rate.
- Efficiency allows higher sampling rate with Source/Graph → further improve control performance!

Towards Dependable Wireless Control

- Real-time, predictable wireless networking
  - Protocols and delay analysis for latency guarantees

- Optimize control performance over wireless
  - Incorporate scheduling analysis in rate selection

- Resilient wireless control under data loss
  - Tailor routing strategies for control needs

- Cyber-physical co-design helps overcome the dependability challenges!
Engineering Building Blocks

- Industrial IoT have arrived
  - WirelessHART, ISA100…
  - World-wide field deployments

- WirelessHART implementation and enhancements

- WCPS: Wireless Cyber-Physical Simulator
  - Enable holistic simulations of wireless control systems
Real-Time Cloud for Industrial IoT

- Support real-time applications in the cloud.
  - Latency guarantees.
  - Real-time performance isolation.
  - Resource sharing between real-time and non-real-time workloads.

- Real-time cloud stack.
  - RT-Xen → real-time virtual machine scheduling (*included in Xen*)
  - VATC → real-time network I/O on a virtualized host.
  - RT-OpenStack → real-time cloud resource management.
For More Information


- Wireless Cyber-Physical Simulator: http://wcps.cse.wustl.edu