Evaluating Low-Power Wireless Cyber-Phyiscal Systems

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Motivation

Autonomous Driving

Factory Automation

[U.S. Department of Transportation]

[KUKA Robter GmbH]
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- Wireless CPS facilitate monitoring and control at unprecedented flexibility and low cost
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[Image 98x136 to 209x197]
[Image 237x136 to 318x197]

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- Will have to meet same high dependability requirements as wired CPS
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Especially due to mission- or even safety-critical applications
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Need for a standard approach for end-to-end evaluation of the whole wireless CPS, including communication, control, and embedded computing
Model and Challenges of Wireless CPS

Physical systems with sensors (S) and actuators (A)

- Sensor measurements sent to controller
- Computed control input sent back to system
- e.g., for stabilization, set-point tracking, . . .

Challenges
- Classical control: communication assumed perfect
- Wireless CPS: Have to consider delays, packet losses, . . .
- More challenging for systems with fast dynamics and unstable systems
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Characteristics of Low-Power Wireless Network

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- Minimum end-to-end delay then is a few tens of ms.
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Requirements for an Evaluation Approach

- Suitable physical System
  - Well-known system
  - Dynamics should match timescale of control, computing, and network elements
  - Realistic and versatile
    - Variety of realistic control tasks and communication requirements
    - Push state of the art low-power wireless networking and embedded computing to its limits
  - Promote adoption and reproducibility
    - Affordable in terms of cost and efforts required to adopt it
    - Reproduce experiments
  - Agnostic to control and network
    - Should be applicable to different system solutions
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Physical System: Cart-pole System

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- Manageable regarding size, affordability, and portability
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Control Tasks: Stabilization

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Wireless Multi-Hop Network

Controller
Control Tasks: Stabilization

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- Can vary number of control loops or have one controller for multiple systems
- Test scalability of network and embedded computing
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Application example: Factory automation
Control Tasks: Multi-agent Synchronization

- Goal: Synchronize whole or part of the state

\[ e_{ij} = s_i - s_j \]

\[ \lim_{t \to \infty} e_{ij} = 0 \quad \forall \ i, j \]

Increasing number of systems increases difficulty on control and networking side.

Central or local controller

Application examples: Platooning, formation control for drones
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Control Tasks: Synchronization and Stabilization

- Goal: Synchronize whole or part of the state while stabilizing the system
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- Most challenging problem
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Adding Simulated Pendulums

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- Simplifies testing of scalability and repeatability

Wireless Network
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Proposed Metrics for Evaluating Control and Networking

- Wireless CPS can be evaluated using different metrics

Primary metrics:
- End-to-end performance
- Quality of control (e.g., quadratic error between desired and actual state)
- Energy consumption

Secondary metrics:
- Evaluate individual parts of the system
- Classical network metrics (e.g., packet drop rate, latency, . . .)
- Control side: Packet drop tolerance, robustness to disturbances, . . .
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Current Research: Reliable Feedback Control over Multiple Hops
Multi-Hop Stabilization of two Cart-poles

- Reliable stabilization of two pendulums
Multi-Hop Stabilization of two Cart-poles

- Reliable stabilization of two pendulums
- Angle and input inside safe regime
Multi-Hop Synchronization of three Cart-poles

- Different frequency for real pendulums without synchronization, simulated pendulum perfectly stable
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- Oscillate with similar frequency in synchronization experiment
Multi-Hop Synchronization of three Cart-poles

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- Oscillate with similar frequency in synchronization experiment
- If one pendulum is fixed, the others react and try to synchronize
Conclusions

- Proposed an end-to-end evaluation approach for wireless CPS based on low-power networking technology that meets stated requirements
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- Allows for different scenarios that evaluate different capabilities
- Facilitate adoption and integration through simulated pendulums
References


Questions

▶ Is the cart-pole a good system for benchmarking?
▶ Are experimental results from a laboratory environment interesting for industry?
▶ Are these the relevant metrics? Are there other?
▶ What is missing to a real benchmark?