Final Demo

- Demo time: **12/7 (1pm - 3:25pm)**.

- New location: **Brauer 3015**

- Brauer 3015 will also be open on **12/2 (1pm – 2pm)**
  - No lecture
  - Opportunity to rehearse and test your demo in the new room
Final Demo

- In class on **12/7 (1pm - 3:25pm)**.

- 12 min per team.

- Set up and **test** your demo in advance.

- All expected to attend the entire session. It’ll be fun!

- Submit a video before class as backup.
Final Report

- **Submit by 12/14/2021, 11:59pm**

- **Report**
  - Style follows conference papers in the reading list
  - 6 pages, double column, 10 pts font
  - Use templates on the class web page

- **Materials**
  - Web page
  - Slides of your final presentation
  - Source code
  - Documents: README, INSTALL, HOW-TO-RUN
  - Video
Suggested Outline

- Abstract
- Introduction
- Goals and Requirements
- Design
- Implementation
- Experiments
- Related Works
- Lessons Learned
- Conclusion and Future Work
Peer Review

➢ For fairness in team projects.

➢ Email me on 12/14/2021

  □ Percentage of contributions of each team member.

  □ Brief justification.
Holistic Control for Cyber-Physical Systems

Chenyang Lu
Industrial Internet of Things (IIoT)

- IIoT powers industrial revolution
  - Industry 4.0
  - Industrial Internet

- Technologies underlying IIoT
  - Wireless sensor-actuator networks
  - Edge computing
  - Machine learning

[Links]
Wireless for IIoT

Benefits
- Ease of deployment
- Reduction of wiring costs
- Flexibilities for sensor placement

Offshore
- 18.65+ billion hours operating experience
- 53,501+ wireless field networks
  [Emerson]

Onshore
- $123 billion by 2021
  [Forbes]

Courtesy: Emerson Process Management
Challenges of IIoT

Wireless networks and edge computing are not ready for control today

IoT-driven control requires
- Control performance
- Resiliency
- Energy efficiency
Cyber-Physical Systems Approach

- Close integration of
  - computing
  - communication
  - physical processes

Performance, resiliency and efficiency of IoT-driven control
Contributions: Holistic Control

- **Holistic control** of networks, computing platforms, and physical plants.

- **Holistic wireless control**
  - Close the loop between network management and plant control
  - Adaptation based on the states of both physical plants and wireless networks

- **Holistic edge control**
  - Exploit multi-tier computing platforms for high-performance control
  - Learning-based switching multi-tier control

- **Hybrid cyber-physical simulators**: integrate simulated plants with
  - real wired/wireless networks (WCPS-RT)
  - real computing platforms (WCPS-EC)
Contributions: Holistic Control

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Separate Network Management and Plant Control

- Wireless network: reliable protocols to reduce loss at high resource cost
- Control: robust controllers to tolerate data loss and physical disturbance
- Operate in isolation!
CPS Approach: Holistic Control

- Close the loop of network management and plant control
- Holistic controller manages network configurations and plant control
  - based on states of the plant and the network

![Diagram]

- Improve control performance
- Enhance resiliency
- Reduce resource cost under
  - cyber and physical disturbances
Holistic Control Framework

- **Holistic controller**
  - plant controller $\rightarrow$ actuation $\rightarrow$ physical plant
  - network controller $\rightarrow$ network reconfiguration protocol (NRP) $\rightarrow$ wireless network

- Closing the loop: control based on both plant and network states
Adapting Transmission Schedule

- Holistic Controllers
  - Plant Controller
  - Predicted Plant States
  - Network Controller (Optimal Scheduler)
  - Predicted Link Quality
  - Optimal Schedule

- Multiple control loops share the same wireless network
  - under limited network capacity

- Optimize the overall control performance
  - under both cyber and physical disturbances

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Adapting Transmission Schedule

**Holistic Controllers**

- **Plant Controller**: predict and control plant states
- **Network Controller**: generates *schedule* based on predicted physical plant states + network link quality
- **NRP**: updating transmission schedule of a TDMA network with a star topology
Plant and Network Performance

- Predict plant states
  - packet of loop $i$ at $t = k$ arrives, $\hat{u}_i(k)$ is actuated (closed loop):
    $$\hat{x}^c_i(k + 1) = f_i(x_i(k), \hat{u}_i(k))$$
  - packet of loop $i$ at $t = k$ is lost, $\hat{u}_i(k - 1)$ is actuated (open loop):
    $$\hat{x}^o_i(k + 1) = f_i(x_i(k), \hat{u}_i(k - 1))$$

- Predict network link quality
  - Metric: transmission failure ratio $\rho$
  - Holt’s additive trend prediction
Network Controller

On-line optimal dynamic scheduling problem

\[ \text{minimize} \quad m_k \]

Overall control cost of \( N \) loops sharing the same network

\[ E\left( J_i(x_i(k+1)) \right) = J_i(\hat{x}_i^c(k+1))(1 - \rho_i^{\eta_i}) + J_i(\hat{x}_i^o(k+1))\rho_i^{\eta_i} \]

subject to

Limited network capacity

Integer number of transmissions

Plant Controller

Predicted Plant States

Network Controller (Optimal Scheduler)

Predicted link failure ratio

Packet delivered?

Predicted plant performance

Optimal Schedule

NRP

Wireless Network

Packet delivered?
Network Reconfiguration Protocol

- Star-topology networks
- Multi-hop mesh network

- Asymmetric scheduling
  - Fix schedule for sensing flows
  - Adapt schedule for actuation flows

- Coordinator broadcasts the updated schedule in beacon
- Design and implement dynamic scheduling protocol

WCPS-RT for Hybrid Simulation

Wireless Cyber-Physical Simulator – Real-Time

**Simulink Desktop Real-Time**

- **Socket**
- **State Observer**
- **Serial**
- **Interfacing Block**
- **Serial**
- **Interfacing Block**
- **Socket**
- **Sensors**
- **Plant**
- **Actuators**
- **Socket**

**Controller Side**

- **Socket**
- **Holistic Controller**
- **Serial**
- **Interfacing Block**
- **Serial**
- **Interfacing Block**
- **Socket**
- **u_t, R or T_n**

**WCPS-RT: hybrid simulations**

- Real wireless networks + simulated physical plants
- Capture wireless dynamics that are hard to simulate accurately
- Leverage simulation support for controllers and plants

- Four double-water-tank control
- Dynamic scheduling based on plant and link states
Experimental Results

- Quality of links 1-4: 78%, 63%, 50%, 63%
- Plant response of feedback control loops 1-4:

  Dynamic scheduling adapts to both
  - physical disturbance
  - network interference
  in a holistic manner
Experimental Results

- Different background noise levels

Control performance metric:

\[ MAE = \frac{1}{n+1} \sum_{k=0}^{n} |x(k) - x_{ref}(k)|, \]

Dynamic scheduling enhances

- control performance
- resiliency
Adapting sampling rates of plant control
- Improve control performance and save energy
- Industrial multi-hop wireless mesh networks
  - Increasingly used in industrial automation
  - Challenging to reconfigure

Network Controller

On-line optimal rate selection problem

sampling rate for loop $i$ in next period

\[ \min J(x_t, R_i) = \sum_{j=0}^{T_f-1} J(x_{t+j}, R_{i+j}) \]

subject to

- Candidate rates
- System dynamics by rate lifting
- State feedback controllers

Control cost

LQR control performance

Energy cost

Control

Plant Controller

Plant States

Sampling Rate

Network Controller
(Rate Adapter)

Sampling Rate

NRP

on-line optimal rate selection problem

On-line optimal rate selection problem

sampling rate for loop $i$ in next period

\[ J(x_t, R_i) = \sum_{j=0}^{T_f-1} J(x_{t+j}, R_{i+j}) \]

subject to

- Candidate rates
- System dynamics by rate lifting
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Control cost

LQR control performance

Energy cost

Control

Plant Controller

Plant States

Sampling Rate

Network Controller
(Rate Adapter)

Sampling Rate

NRP
Reconfiguration in a Wireless Mesh Network

- **Glossy flooding**
  - One to many
  - Fast (propagation delay < 10 ms in 100-node mesh network)

- **Low-power Wireless Bus (LWB) protocol**
  - Maps all communication on fast Glossy floods → global TDMA schedules
  - Topology independent → suitable for network-wide adaptation

- **Reconfiguration approach:** piggyback and implicit scheduling

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Ferrari, F., et. al Low-power wireless bus. *In SenSys, 2012.*
Network Reconfiguration Protocols

- All nodes store global static schedule (max rate)

\[ S \ f_{11} \ f_{21} \ f_{31} \ \cdots \ S \ f_{11} \ f_{21} \ f_{31} \ \cdots \ S \ f_{11} \ f_{21} \ f_{31} \ \cdots \]

- Holistic controllers piggyback and flood [rate + actuation command]

\[
f_{11} : \frac{1}{T} \text{ Hz} \quad f_{12} : \frac{1}{2T} \text{ Hz} \quad f_{13} : \frac{1}{4T} \text{ Hz}
\]

- Every node receives updated rates and calculates its schedule locally using implicit scheduling

- All nodes sleep at unassigned slots
Experimental Settings

- Physical plant and controller
  - Up to five 4-state load positioning plants

- Wireless testbed spanning three floors
  - 70 TelosB motes

- WCPS-RT
  - On-line rate adaptation (RA)
Experimental Results

- 1, 0.5, 0.25: Fixed rates of 1, 0.5, 0.25 Hz
- RA: Rate Adaptation

- RA has **comparable control performance** to fixed 1Hz sampling
- while consuming **40+% less energy** in the network!
Generalize Holistic Wireless Control

- Adapting transmission redundancy
  - Holistic controller: assign transmission redundancy based on physical and network states
  - NRP for WirelessHART mesh network

- Self-triggered control
  - Holistic controller: predict when actuation commands should be updated
  - NRP based on LWB protocol

Holistic wireless control

- Improve control performance
- Enhance resiliency
- Reduce resource cost


Holistic Control

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Industrial control systems are embracing new technologies

- **Edge** computing: on-premise computing resources
- **Wireless** networks: flexibility and easy deployment

Challenges

- Exploit edge computing to enhance **control performance**
- Maintain **stability** despite unreliable wireless networks
- **Resiliency** under wireless and physical disturbances

Source: https://www.automation.com
Local Control vs. Edge Control

Wired connection → Stability guarantee

Wireless network → Varying data loss

Computation capacity → Sophisticated control

Stability guarantee
Switching Multi-tier Control (SMC)

- **Objectives**
  - Optimize control **performance**
  - Guarantee **stability**

- **SMC**: Switch between local and edge controllers
  - **Optimal Platform Classifier**: select local or edge controller for **performance**
  - **Stability Switch**: switch to local controller to guarantee **stability**

- **Based on** cyber-physical states
  - network reliability
  - physical states
Switching Logic

Stability Switch guarantees stability

Sha, L., Using simplicity to control complexity. IEEE Software, 2001]

Optimal Platform Classifier selects the optimal control platform

$x \not\in PR$: switch to local controller to guarantee stability

$x \in PR$: OPC selects the optimal controller based on network conditions and physical states
Theoretical analyses of wireless control performance is challenging

**Learning-based** Optimal Platform Classifier

- Overcome restrictions of analytical modeling
- Applicable to a wide range of control and network technologies
Training the Optimal Platform Classifier

- Physical plant: PUMA 560
- Local: state feedback controller
- Edge: model predictive controller
- Wireless network: two-state Markov chain model

The Gilbert-Elliott link loss model
Optimal Platform Classifier for PUMA 560

- SVM model learns the non-linear boundary between the controllers
- When $x_e$ and $\beta$ are low, and $\alpha$ is high, OPC chooses edge control
- Testing accuracy: 90.98%
- Cost of misclassification is low
Case Study: Robotic Joint Position Control

- SMC dynamically optimizes control performance with stability guarantees.
- SMC outperforms local and edge control under changing network reliability.
- **Holistic control** based on physical and network states \(\rightarrow\) **resiliency!**
Conclusions

- Edge computing → **two-tier control architecture**
  - Tradeoff between computation capacity and communication reliability

- **Edge control** allows control systems to exploit edge computing safely
  - Machine Learning → optimize control performance
  - Stability Switch → guarantee system stability

- **Holistic control** based on cyber and physical states
  - Close the loop between network managers and physical control

Conclusions

- IIoT is powered by wireless communication, edge computing, and machine learning

- Holistic control of networks, computing platforms, and physical plants → performance, resiliency, efficiency of industrial automation

- Exploring the design space of holistic control
  - Holistic wireless control: adapting based on network and physical states
  - Holistic edge control: switching multi-tier control

- Real-time cyber-physical simulators
  - integrating simulated plants with real networks and multi-tier computing platforms
References


