How to co-design wireless networked control systems

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Control for Societal-scale Challenges: Road map 2030

IEEE Control Systems Society

CONTROL FOR SOCIETAL-SCALE CHALLENGES: ROAD MAP 2030

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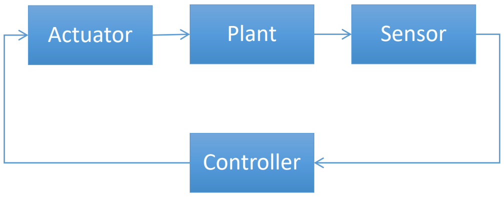
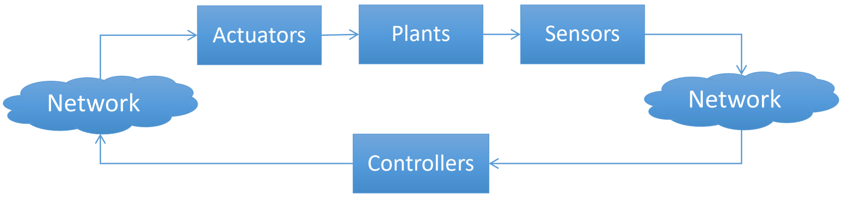
control systems


Actuator
Plant
Sensor
Controller

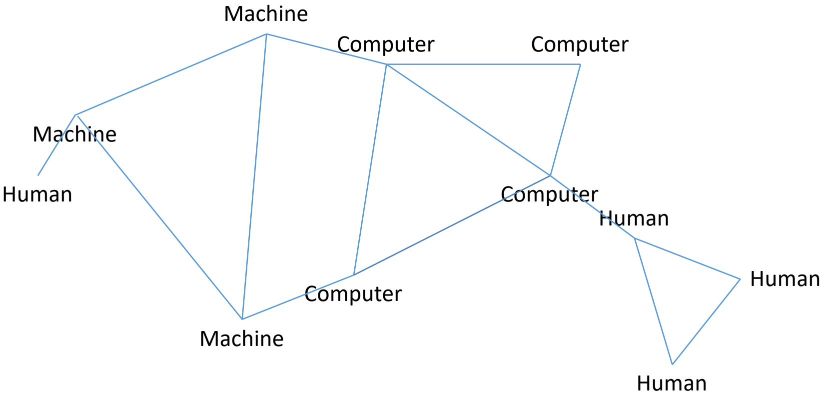
Networked control systems


Actuators
Plants
Sensors
Network
Network
Controllers

The networked control system design problems

1. How to design controllers to cope with network imperfections (delays, losses, outages, etc)?
2. How to design the communication network to support the need from control loops?
3. How to co-design control and communication to jointly optimize performance and resource use?

Cyber-Physical-Human Control Systems



Machine
Computer
Computer
Machine
Human
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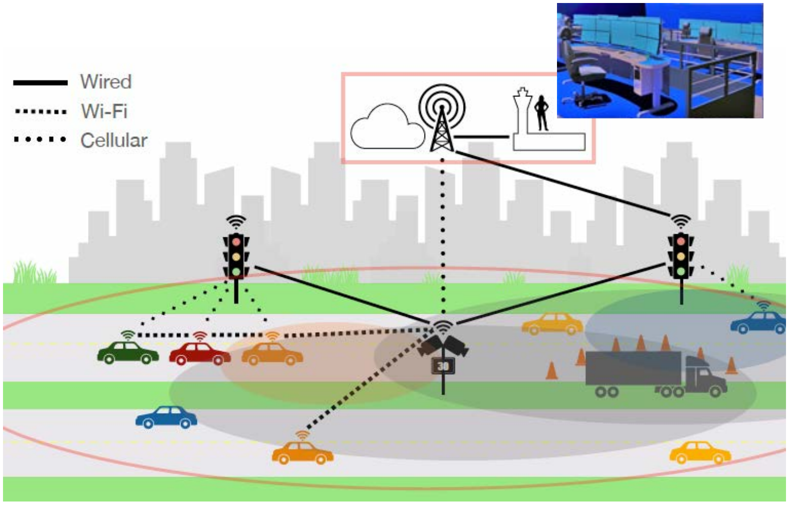
Human

Decisions need to be automatically made in tomorrow's complex networked autonomous systems

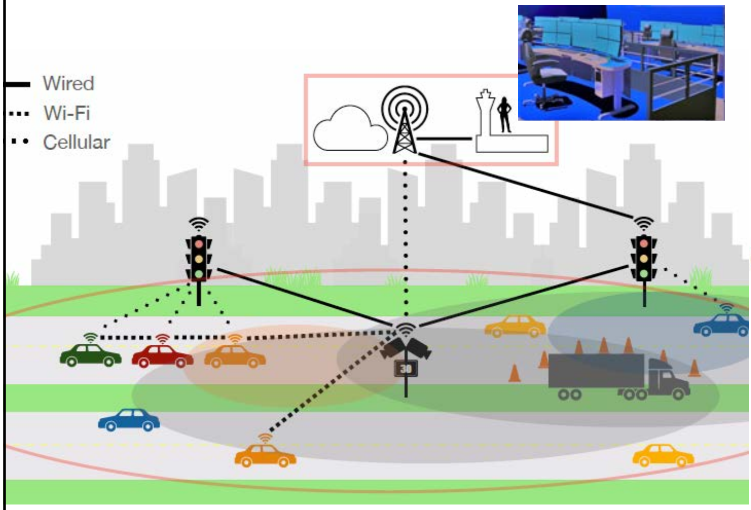
Remote control towers to support the operation of automated vehicle fleets

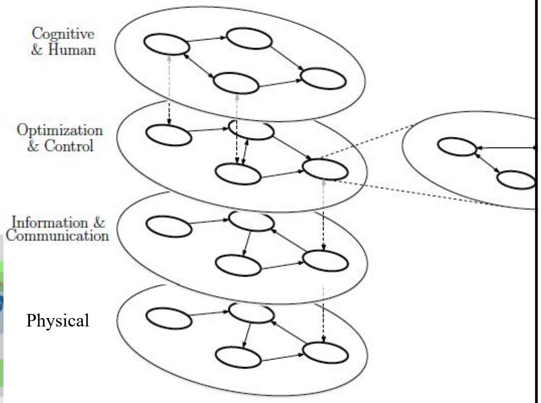


Jiang et al, *Human-centered design for safe teleoperation of connected vehicles, IFAC CPHS*, 2020

KTH, Scania, Ericsson

Designing multi-layer networked systems

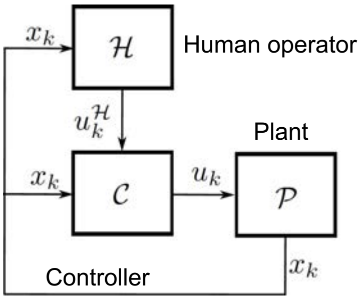




Keimer et al, *Integration of information patterns in the modeling and design of mobility management services,* Proceedings of IEEE, 2018.

Jiang et al, *Human-centered design for safe teleoperation of connected vehicles, IFAC CPHS*, 2020

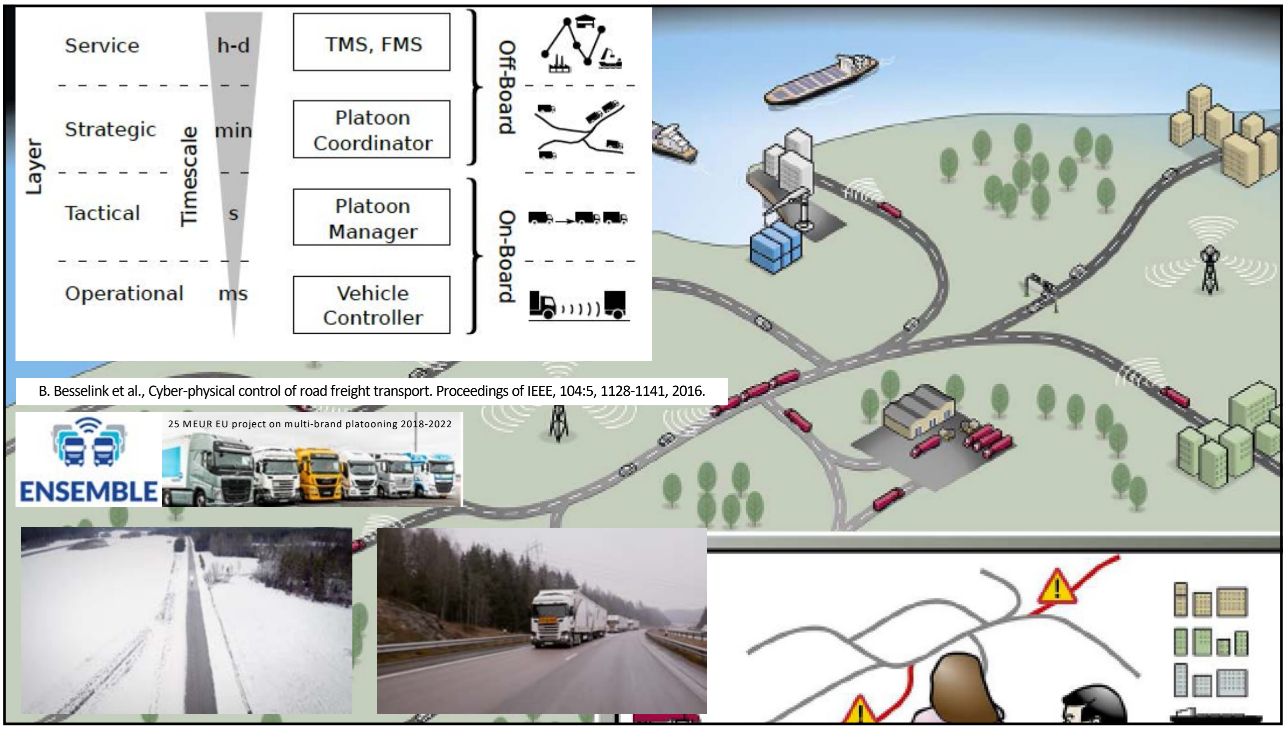
Shared-Autonomy Systems



Shared-autonomy systems mix human and automated decisions in a systematic way.

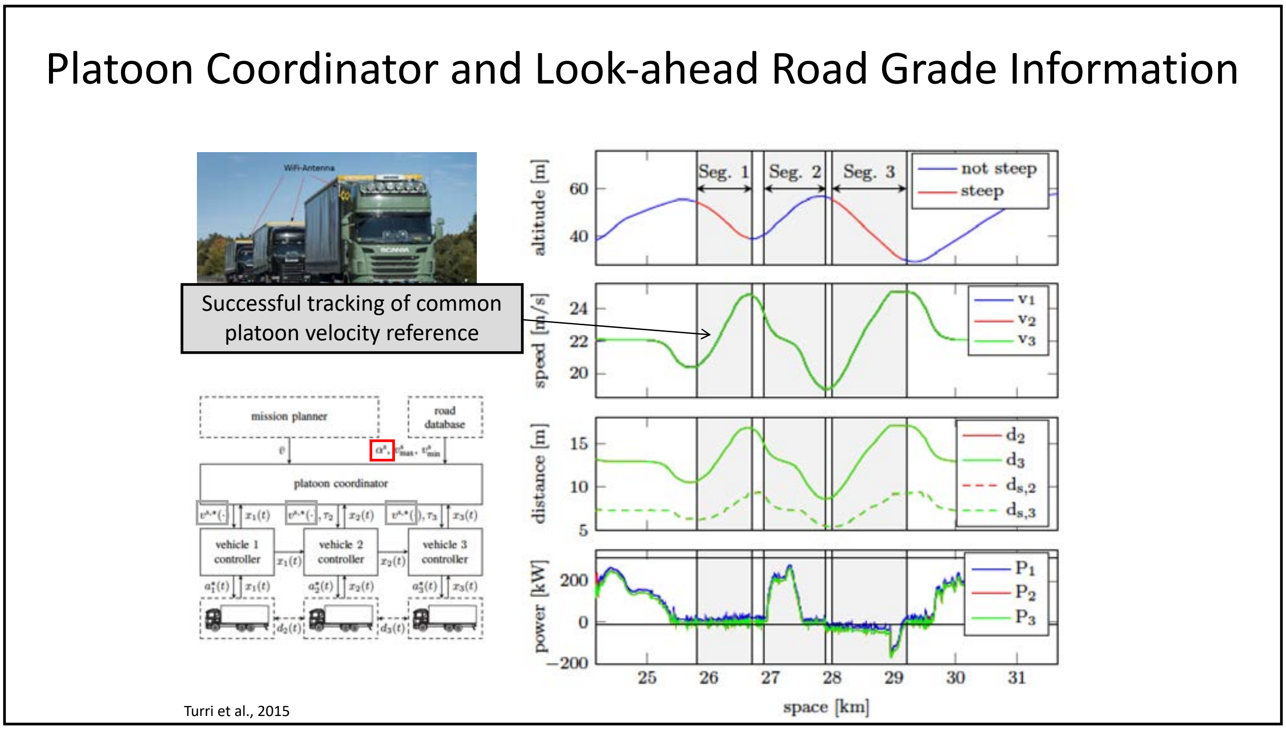
Teleoperation of trucks by Einride

Jiang et al., 2020



B. Besselink et al., Cyber-physical control of road freight transport. Proceedings of IEEE, 104:5, 1128-1141, 2016.

25 MEUR EU project on multi-brand platooning 2018-2022



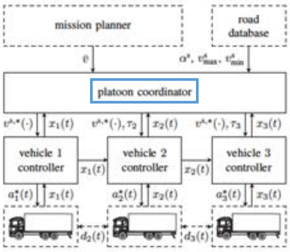
Platoon Coordinator and Look-ahead Road Grade Information

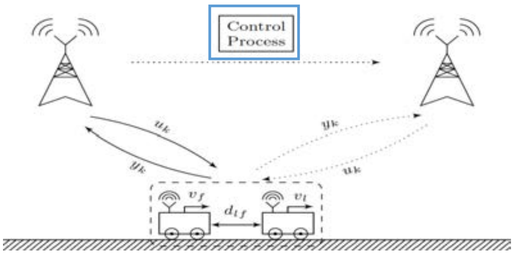
Successful tracking of common platoon velocity reference

Turri et al., 2015

Cellular Implementation of Platoon Coordinator

- Platoon coordinator generates common velocity reference: $v_i(t) \rightarrow v_{\text{ref}}(s_i(t))$.
- Can be computed in the cellular system
- New handover scheme for moving control computations

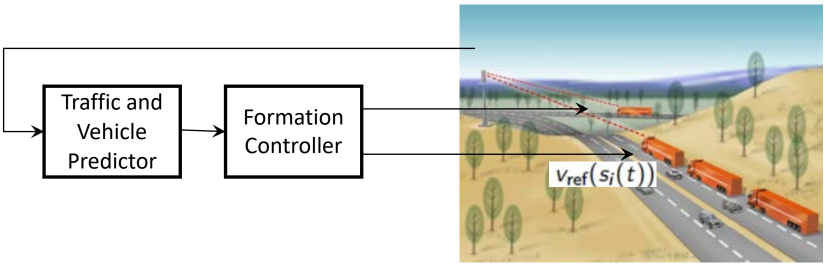




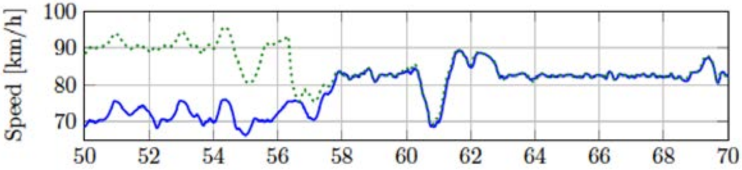
van Dooren et al., 2017

Platoon Formation

Feedback control of merging point based on real-time vehicle state and traffic information

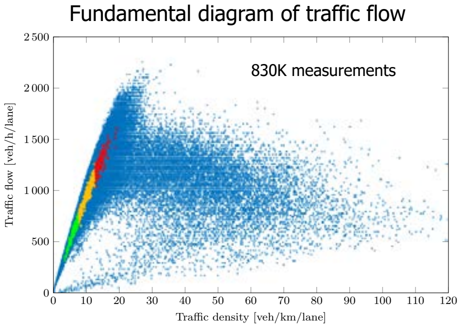


Optimal speed profiles for platoon formation



Liang et al., 2016; Cicic et al., 2017

Platoon Formation Experiments


Fundamental diagram of traffic flow

- 600 test runs on E4 in Nov 2015
- Traffic measurements from road units together with onboard sensors

Liang et al., 2016

Can controlled truck platoons be used to improve traffic conditions?

- Trucks act as bottlenecks moving in car traffic
- Regulate cars flowing into congested area

Lin et al., 2018; Cicic and J, 2018

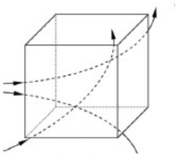
Cf., [Lebacque et al. 1998; Delle Monache & Goatin 2014]

Flows according to Euler and Lagrange

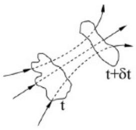
Leonhard Euler (1707-1783)

Joseph-Louis Lagrange (1736-1813)

Euler was looking at fluid motion focused on specific locations in the space through which the fluid flows as time passes.

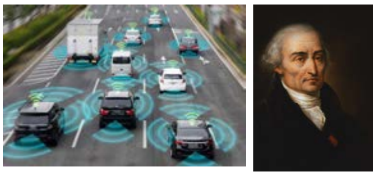


Lagrange was looking at fluid motion where the observer follows an individual fluid parcel as it moves through space and time

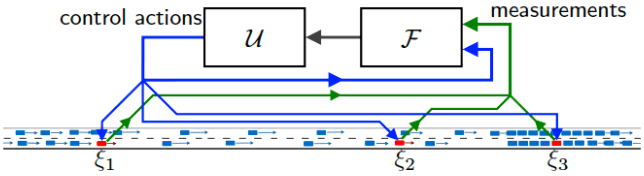


From Eulerian to Lagrangian traffic control

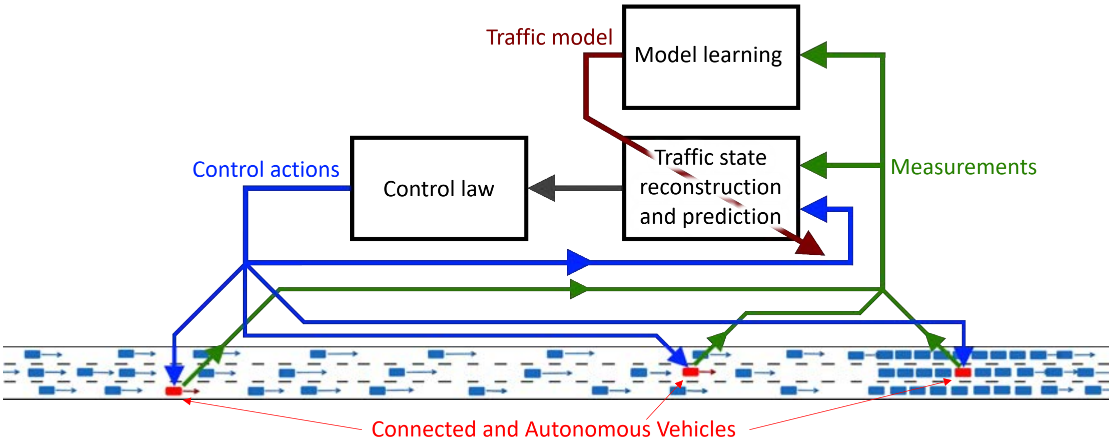
Leonhard Euler (1707-1783)
Stationary observer of the flow
Traffic control based on fixed infrastructure
High deployment costs and limited flexibility



Joseph-Louis Lagrange (1736-1813)
Observers moves with the flow
Traffic control based on mobile sensors and actuators
Need for a new system theoretic foundation



Lagrangian traffic control system

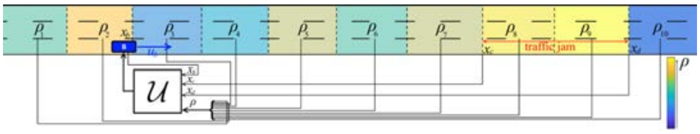


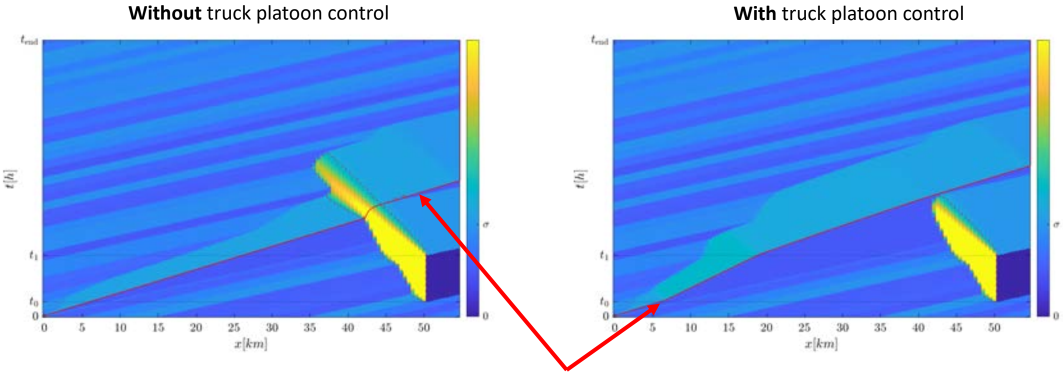
$$\frac{\partial \rho(x,t)}{\partial t} + \frac{\partial Q(\rho(x,t),x,t)}{\partial x} = 0$$

[Čičić, 2021]

Physics-informed machine learning [Raissi et al., 2019; Barreau et al., 2021]

Control truck platoon velocity to dissipate traffic congestion

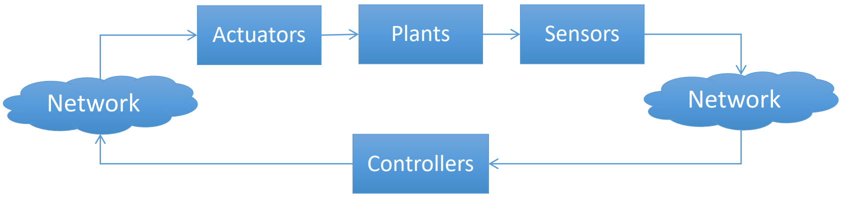




Truck platoon trajectory

Cicic and J, 2018

Networked control systems



The networked control system design problems

1. How to design controllers to cope with network imperfections (delays, losses, outages, etc)?
2. How to design the communication network to support the need from control loops?
3. **How to co-design control and communication to jointly optimize performance and resource use?**

Joint Design of Plant and Network Controls

Plant model:

$$\mathcal{P}: x_{k+1} = Ax_k + Bu_k + w_k$$
$$x_0 \sim \mathcal{N}(0, \Sigma_0)\ w_k \sim \mathcal{N}(0, W)$$

Network model:

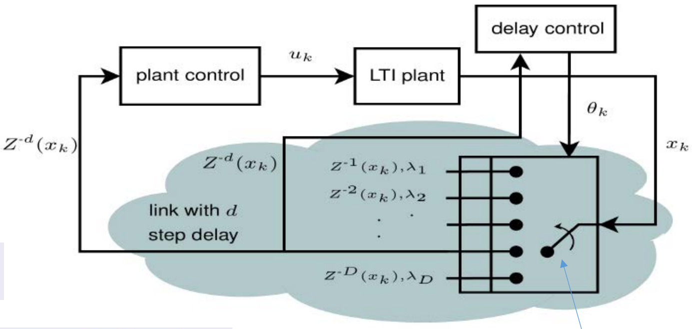
$$\text{delay variable: } d \in \{1, \ldots, D\}$$
$$Z^{-d}(x_k) \rightarrow x_k \text{ delivered at } k + d$$

$$\theta_k^i = \begin{cases} 1, & \text{link with } i \text{ step delay is selected at time } k \\ 0, & \text{link with } i \text{ step delay is not selected at time } k \end{cases}$$

Associated communication price $\rightarrow$ λ_d for d-step delay

$$\lambda_1 > \lambda_2 > \ldots > \lambda_D, \quad \lambda_d \in \mathbb{R}_{\geq 0}$$

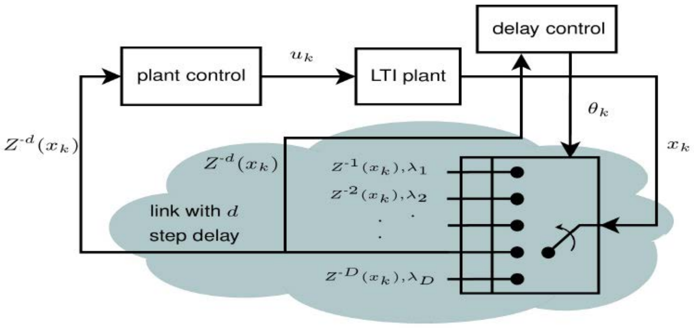
One link to be selected at each time $\rightarrow \sum_{i=1}^{D} \theta_k^i = 1, \ \forall\ k$



Network resource control algorithm decides on how urgently sensor data should be delivered to the controller

Maity et al., 2018

Information Structure and Optimal Control



Information available at delay control:

$$\mathcal{I}_k \triangleq \{\mathcal{Y}_0,\ldots,\mathcal{Y}_{k-1},u_0,\ldots,u_{k-1},\cup_{t=1}^{k-1}\{\theta_t\}\}$$

$$\mathcal{Y}_k=\{\theta_{k-1}^1 x_{k-1},\theta_{k-2}^2 x_{k-2},\ldots,\theta_{k-D}^D x_{k-D}\}$$

Information available at plant control:

$$\bar{\mathcal{I}}_k \triangleq \{\mathcal{I}_k,\mathcal{Y}_k,\theta_k\}$$

Joint optimal control cost function:

$$J(u,\theta)=\mathsf{E}\left[\underbrace{\sum_{t=0}^{T-1}\left[x_t^\top Q_1 x_t+u_t^\top R u_t\right]+x_T^\top Q_2 x_T}_{\text{control cost}}+\underbrace{\sum_{t=0}^{T-1}\theta_t^\top\Lambda}_{\text{delay cost}}\right]$$

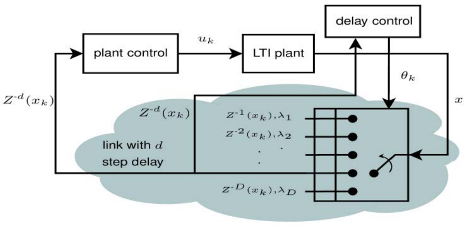
where $\Lambda \triangleq [\lambda_1,\ldots,\lambda_D]^\top$, $Q_1\succeq 0$, $Q_2\succeq 0$, and $R\succ 0$.

Non-classical control problem because of the information structure, cf. [Witsenhausen, 1971].

Maity et al., 2018

Information Structure and Optimal Control

Find optimal plant control and network delay control:



$$(u^*,\theta^*)=\arg\min_{u,\theta} J(u,\theta)$$

$$J(u,\theta)=\mathsf{E}\left[\underbrace{\sum_{t=0}^{T-1}\left[x_t^\top Q_1 x_t+u_t^\top R u_t\right]+x_T^\top Q_2 x_T}_{\text{control cost}}+\underbrace{\sum_{t=0}^{T-1}\theta_t^\top\Lambda}_{\text{delay cost}}\right]$$

- What is the structure of the optimal solution?
- Is the optimal plant controller estimator based?
- How find the optimal delay controller?

Maity et al., 2018

Optimal Plant Control and Separation Principle

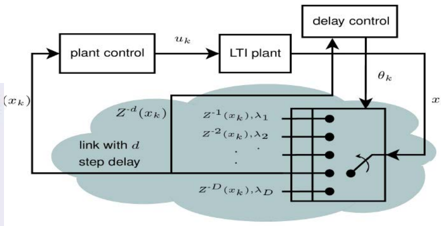
Theorem

Given $\bar{\mathcal{I}}_k$, the optimal control policy $u_k^* = g_k^*(\bar{\mathcal{I}}_k)$, $k \in \{0, \ldots, T-1\}$ is a linear feedback of the form

$$u_k^* = -(R + B^\mathsf{T} P_{k+1} B)^{-1} B^\mathsf{T} P_{k+1} A \mathsf{E}[x_k | \bar{\mathcal{I}}_k]$$

P_k satisfies the RE

$$P_k = Q_1 + A^\mathsf{T}\left(P_{k+1} - P_{k+1} B \left(R + B^\mathsf{T} P_{k+1} B\right)^{-1} B^\mathsf{T} P_{k+1}\right) A$$
$$P_T = Q_2$$



$$(u^*, \theta^*) = \arg\min_{u,\theta} J(u, \theta)$$

$$J(u,\theta) = \mathsf{E}\left[\underbrace{\sum_{t=0}^{T-1}\left[x_t^\mathsf{T} Q_1 x_t + u_t^\mathsf{T} R u_t\right] + x_T^\mathsf{T} Q_2 x_T}_{\text{control cost}} + \underbrace{\sum_{t=0}^{T-1} \theta_t^\mathsf{T} \Lambda}_{\text{delay cost}}\right]$$

- Optimal plant controller is based on estimator
- Optimal plant controller does not depend on the delay control

Maity et al., 2018

Optimal Plant Control and Separation Principle

Theorem

Given $\bar{\mathcal{I}}_k$, the optimal control policy $u_k^* = g_k^*(\bar{\mathcal{I}}_k)$, $k \in \{0, \ldots, T-1\}$ is a linear feedback of the form

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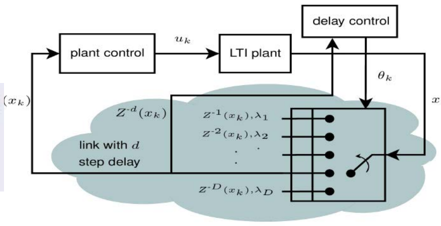
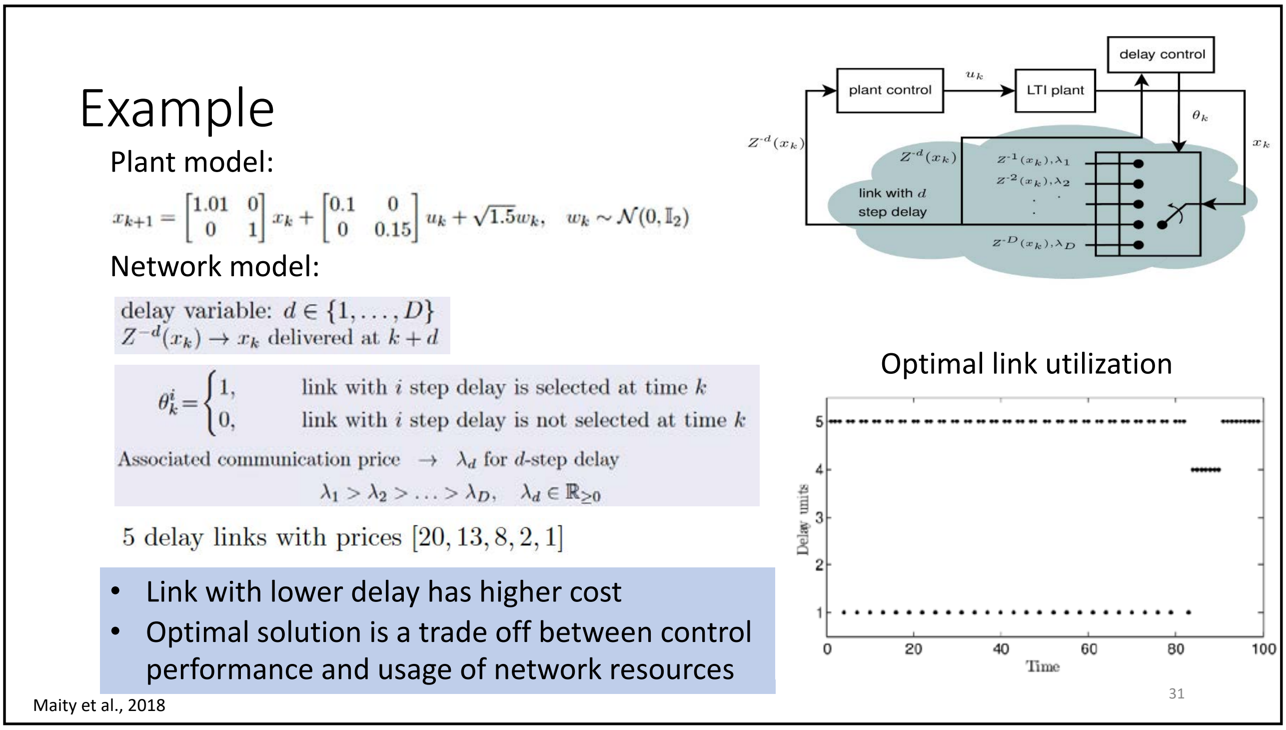


$$\hat{x}_k = \mathsf{E}[x_k | \bar{\mathcal{I}}_k] = \sum_{i=1}^{\min\{D,\ k+1\}} b_{i,k} \mathsf{E}[x_k | x_{k-i}, U^{k-1}]$$

$$b_{i,k} = \prod_{d=1}^{i-1} \prod_{j=1}^{d} \left(1 - \theta_{k-d}^j\right) \left(\vee_{l=1}^{D} \theta_{k-i}^l\right)$$
$$\forall i \in \{1, \cdots, D\},\ b_{i,k} \in \{0,1\},\ \sum_{i=1}^{\min\{D,k+1\}} b_{i,k} = 1$$

- Optimal plant controller is based on estimator (separation principle holds)
- Optimal plant controller does not depend on the delay controller
- But the estimator is a nonlinear function of the delay control

Maity et al., 2018



Example

Plant model:

$$x_{k+1} = \begin{bmatrix}1.01 & 0\\ 0 & 1\end{bmatrix} x_k + \begin{bmatrix}0.1 & 0\\ 0 & 0.15\end{bmatrix} u_k + \sqrt{1.5} w_k, \quad w_k \sim \mathcal{N}(0, \mathbb{I}_2)$$

Network model:

delay variable: $d \in \{1, \ldots, D\}$
$Z^{-d}(x_k) \to x_k$ delivered at $k + d$

$$\theta_k^i = \begin{cases} 1, & \text{link with } i \text{ step delay is selected at time } k \\ 0, & \text{link with } i \text{ step delay is not selected at time } k \end{cases}$$

Associated communication price $\rightarrow$ λ_d for d-step delay

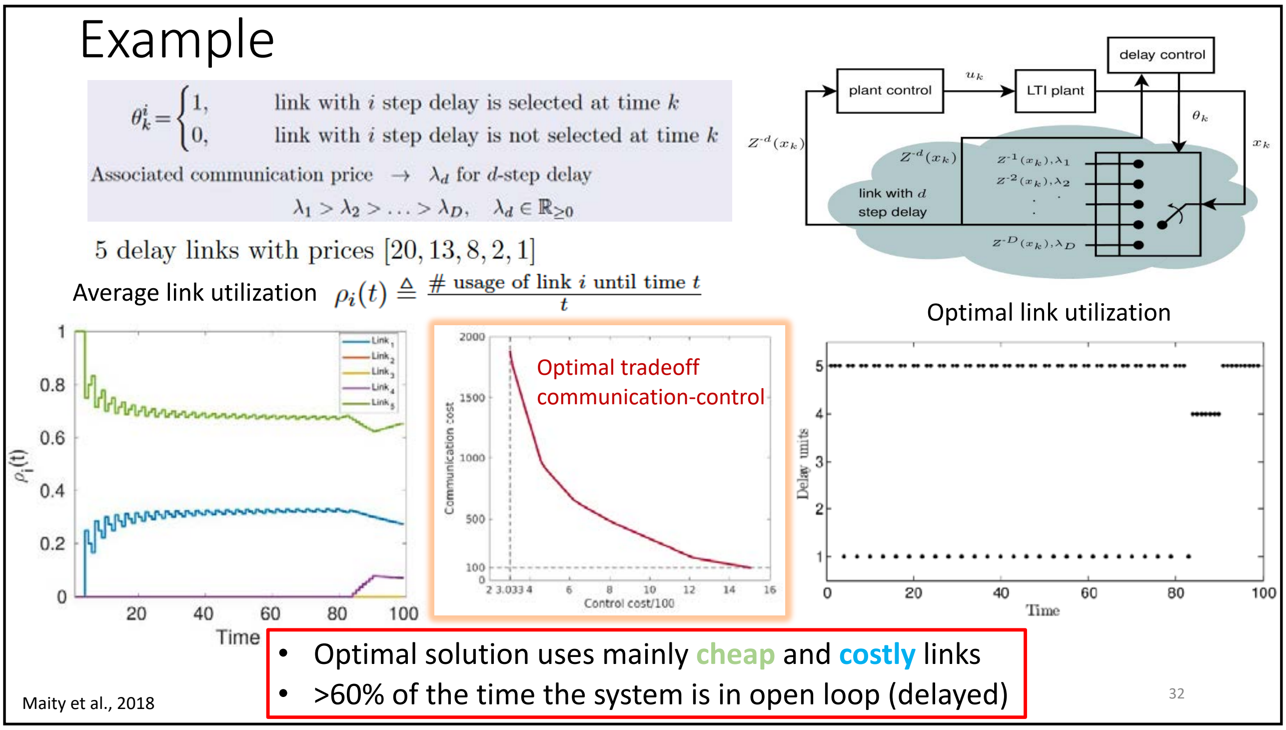
$$\lambda_1 > \lambda_2 > \ldots > \lambda_D, \quad \lambda_d \in \mathbb{R}_{\geq 0}$$

5 delay links with prices $[20, 13, 8, 2, 1]$

- Link with lower delay has higher cost
- Optimal solution is a trade off between control performance and usage of network resources

Optimal link utilization

Maity et al., 2018



Example

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5 delay links with prices $[20, 13, 8, 2, 1]$

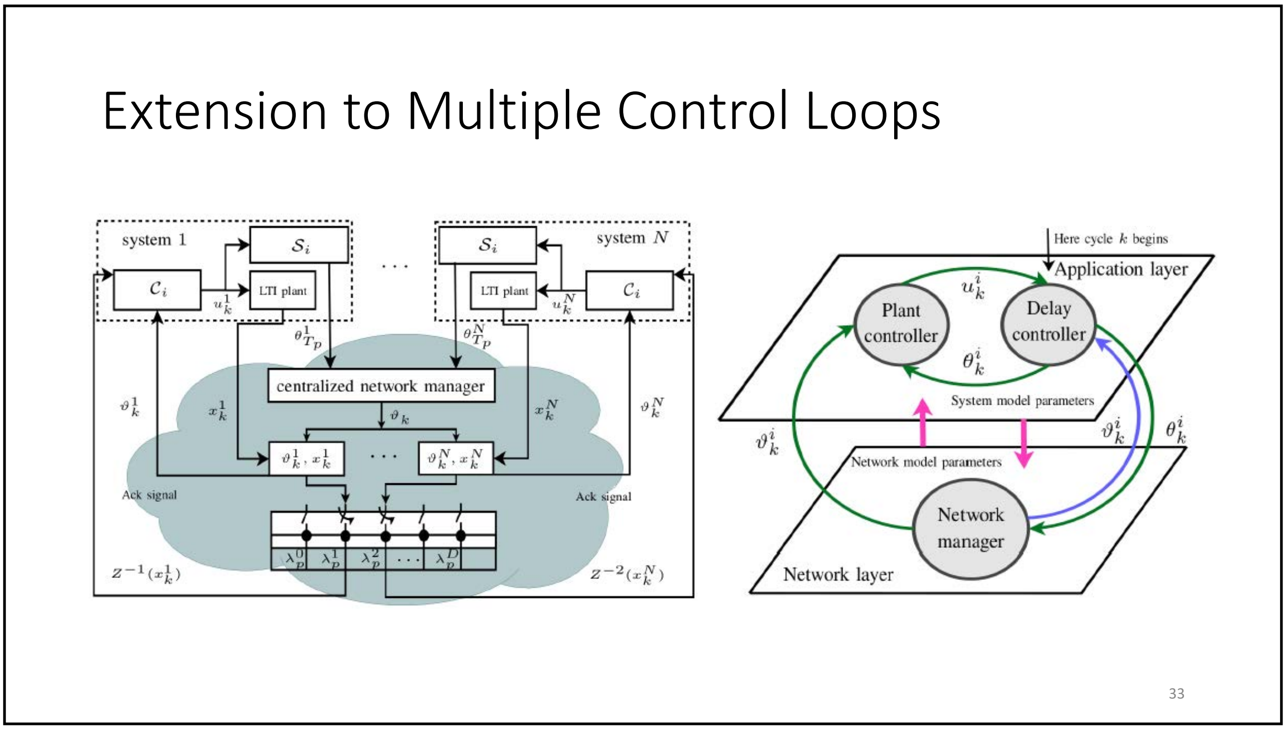
Average link utilization $\rho_i(t) \triangleq \dfrac{\#\text{ usage of link } i \text{ until time } t}{t}$

Optimal tradeoff communication-control

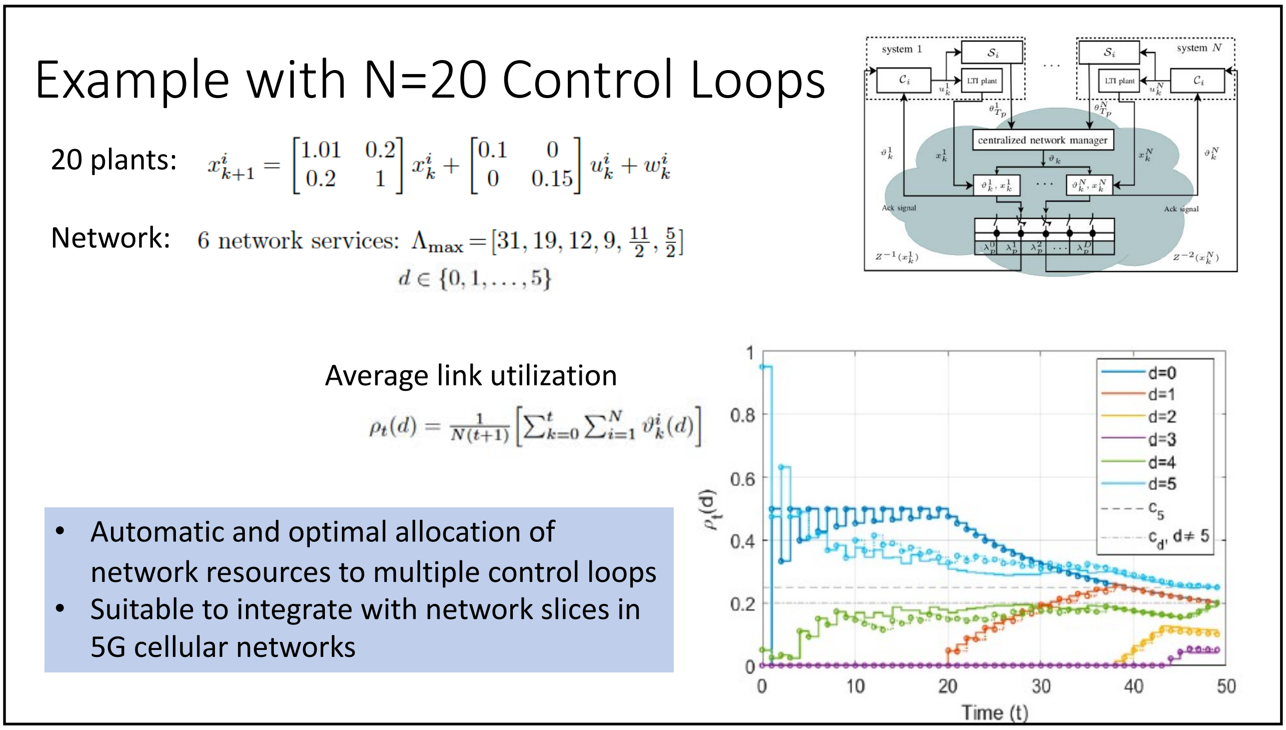
Optimal link utilization

- Optimal solution uses mainly cheap and costly links
- >60% of the time the system is in open loop (delayed)

Maity et al., 2018



Extension to Multiple Control Loops



Example with N=20 Control Loops

20 plants: $x_{k+1}^i = \begin{bmatrix} 1.01 & 0.2 \\ 0.2 & 1 \end{bmatrix} x_k^i + \begin{bmatrix} 0.1 & 0 \\ 0 & 0.15 \end{bmatrix} u_k^i + w_k^i$

Network: 6 network services: $\Lambda_{\max} = [31, 19, 12, 9, \frac{11}{2}, \frac{5}{2}]$
$d \in \{0, 1, \ldots, 5\}$

Average link utilization

$$\rho_t(d) = \frac{1}{N(t+1)} \left[\sum_{k=0}^{t} \sum_{i=1}^{N} \vartheta_k^i(d) \right]$$

- Automatic and optimal allocation of network resources to multiple control loops
- Suitable to integrate with network slices in 5G cellular networks

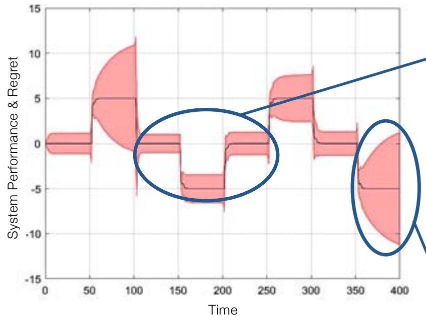
Performance Error vs. QoS for a Networked Control Problem

Autonomous robot supposed to follow a given path

Control systems: $x_{t+1} = Ax_t + Bu_t + w_t$

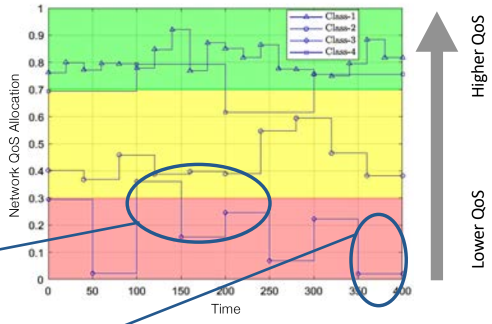
Control plus communication cost: $p(t) = \| x_t \|^2 + \| u_t \|^2 + \lambda$

Regret defined as how much does robot deviate from the planned path



Low performance regret, due to satisfactory QoS in time interval [100-250]

High performance regret, due to receiving low QoS in time interval [350-400]

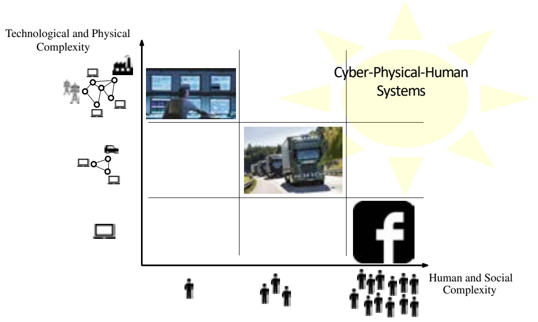


- Communication resources in slice-format (5G):
  - ➡ ULL/HB (>10ms/<1Gbps)
  - ➡ ULL/MB (>10ms/50 Mbps-1 Gbps)
  - ➡ LL/LB (10-50ms/>50 Mbps)

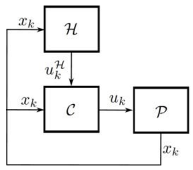
Mamduhi et al., 2023

Conclusions

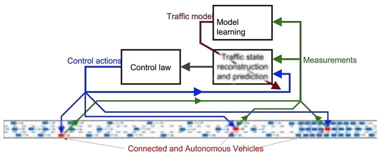
Scalability & predictability



Human & AI networks



Decision-making & physics-informed machine learning

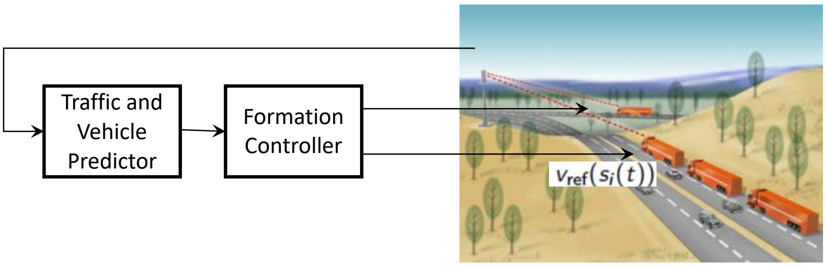


Safety & efficiency

people.kth.se/~kallej

Platoon Formation

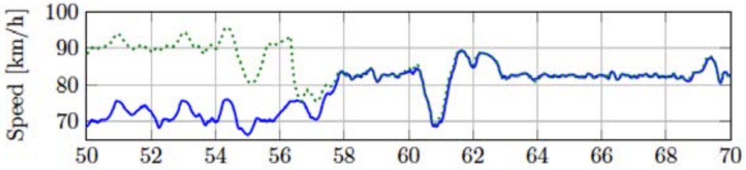
Feedback control of merging point based on real-time vehicle state and traffic information



Traffic and Vehicle Predictor

Formation Controller

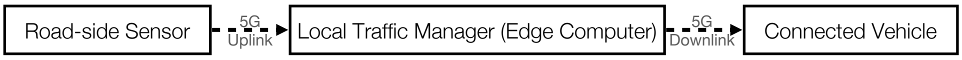
Optimal speed profiles for platoon formation



Liang et al., 2016; Cicic et al., 2017

Future 5G Ride: Kista Innovation Park Network Experiments

Evaluation of 5G network performance in intelligent transport scenarios

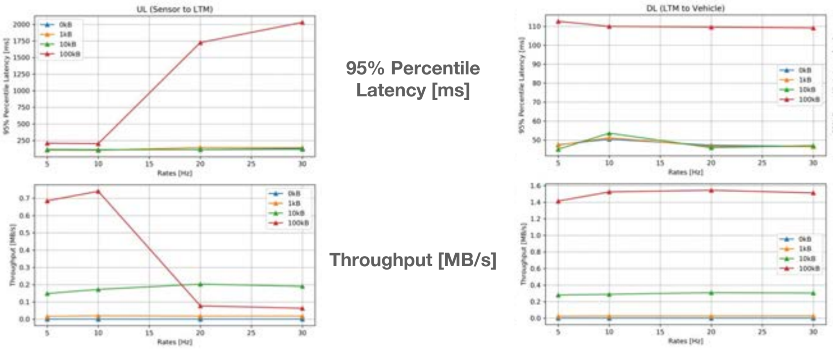


Road-side Sensor

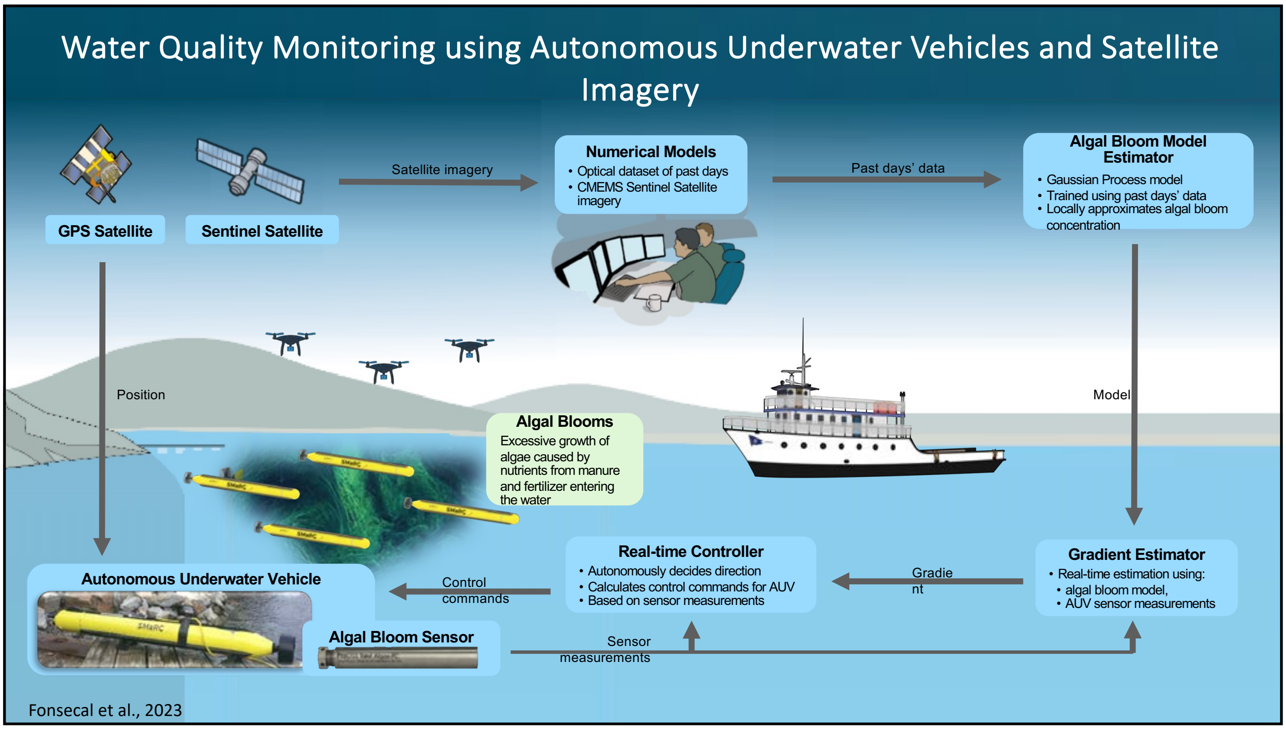
Local Traffic Manager (Edge Computer)

Connected Vehicle

Evaluate loaded 5G network's ability to communicate safety-critical data with SVEA platform



Jiang et al., 2023



Water Quality Monitoring using Autonomous Underwater Vehicles and Satellite Imagery

GPS Satellite

Sentinel Satellite

Satellite imagery

Numerical Models
- Optical dataset of past days
- CMEMS Sentinel Satellite imagery

Past days' data

Algal Bloom Model Estimator
- Gaussian Process model
- Trained using past days' data
- Locally approximates algal bloom concentration

Position

Model

Algal Blooms
Excessive growth of algae caused by nutrients from manure and fertilizer entering the water

Autonomous Underwater Vehicle

Control commands

Real-time Controller
- Autonomously decides direction
- Calculates control commands for AUV
- Based on sensor measurements

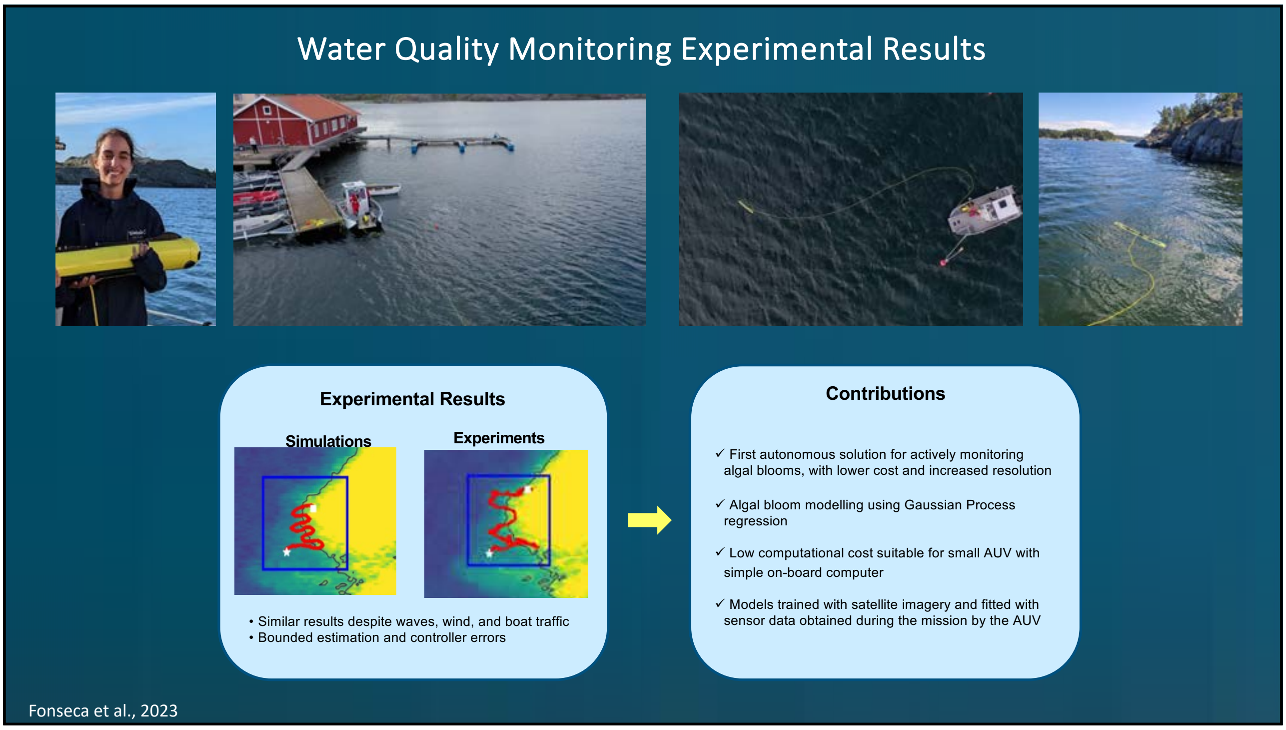
Gradient

Gradient Estimator
- Real-time estimation using:
  - algal bloom model,
  - AUV sensor measurements

Algal Bloom Sensor

Sensor measurements

Fonsecal et al., 2023



Water Quality Monitoring Experimental Results

Experimental Results

Simulations

Experiments

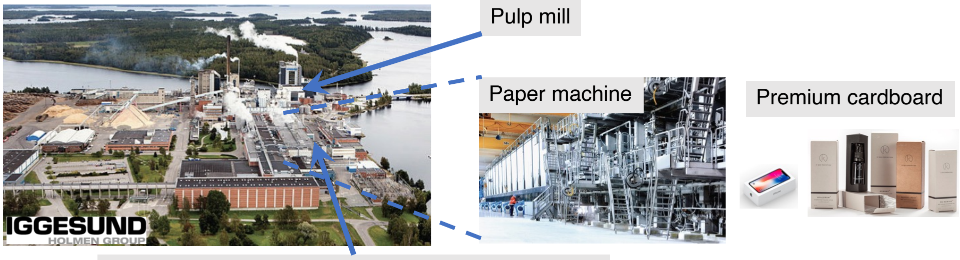
- Similar results despite waves, wind, and boat traffic
- Bounded estimation and controller errors

Contributions

- ✓ First autonomous solution for actively monitoring algal blooms, with lower cost and increased resolution
- ✓ Algal bloom modelling using Gaussian Process regression
- ✓ Low computational cost suitable for small AUV with simple on-board computer
- ✓ Models trained with satellite imagery and fitted with sensor data obtained during the mission by the AUV

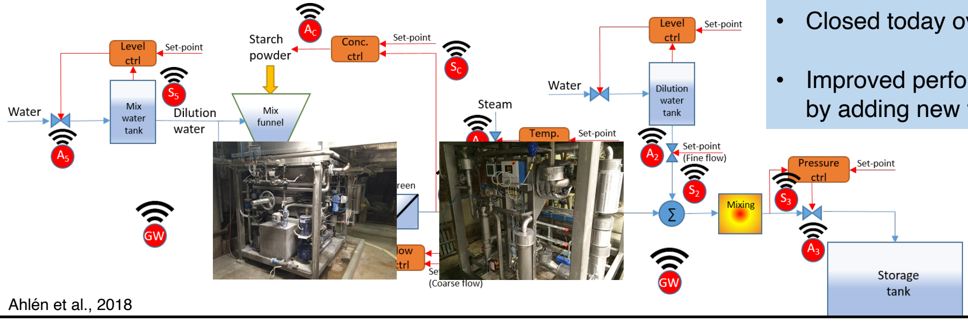
Fonseca et al., 2023

Wireless Control of Pulp and Paper Mill



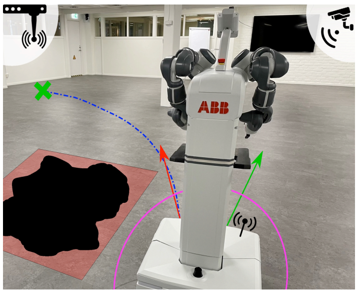
Starch cooker process producing cardboard coating

- 1 000’s of control loops and sensors
- Closed today over fixed wired network
- Improved performance and flexibility by adding new wireless sensors

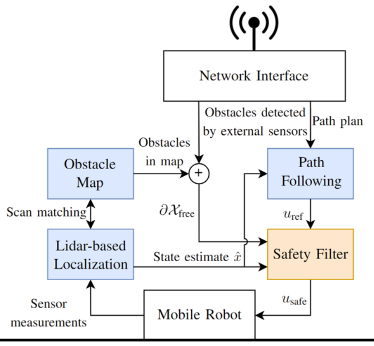


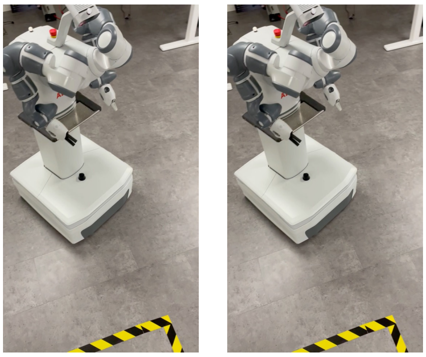
Ahlén et al., 2018

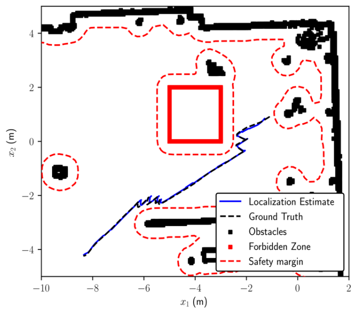
Safe Navigation of Mobile Robots using External Sensors



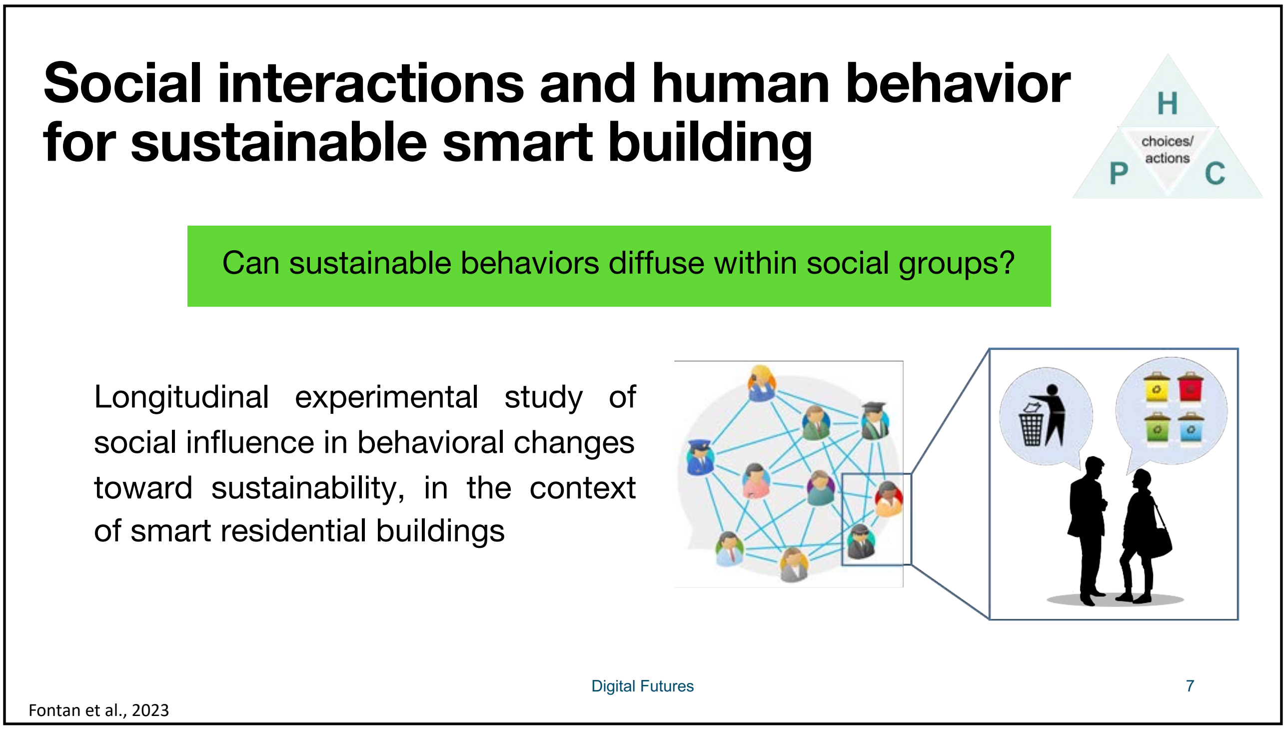
- Future low-cost mobile robots can navigate using fixed indoor sensors connected over 5G network
- Sensor and network resources need to automatically adapt to varying application needs
- Guarantee safety through novel uncertainty-aware safety filter that adjust planned trajectory to available resources







Miksits et al., 2023



Social interactions and human behavior for sustainable smart building

Can sustainable behaviors diffuse within social groups?

Longitudinal experimental study of social influence in behavioral changes toward sustainability, in the context of smart residential buildings

Digital Futures 7

Fontan et al., 2023

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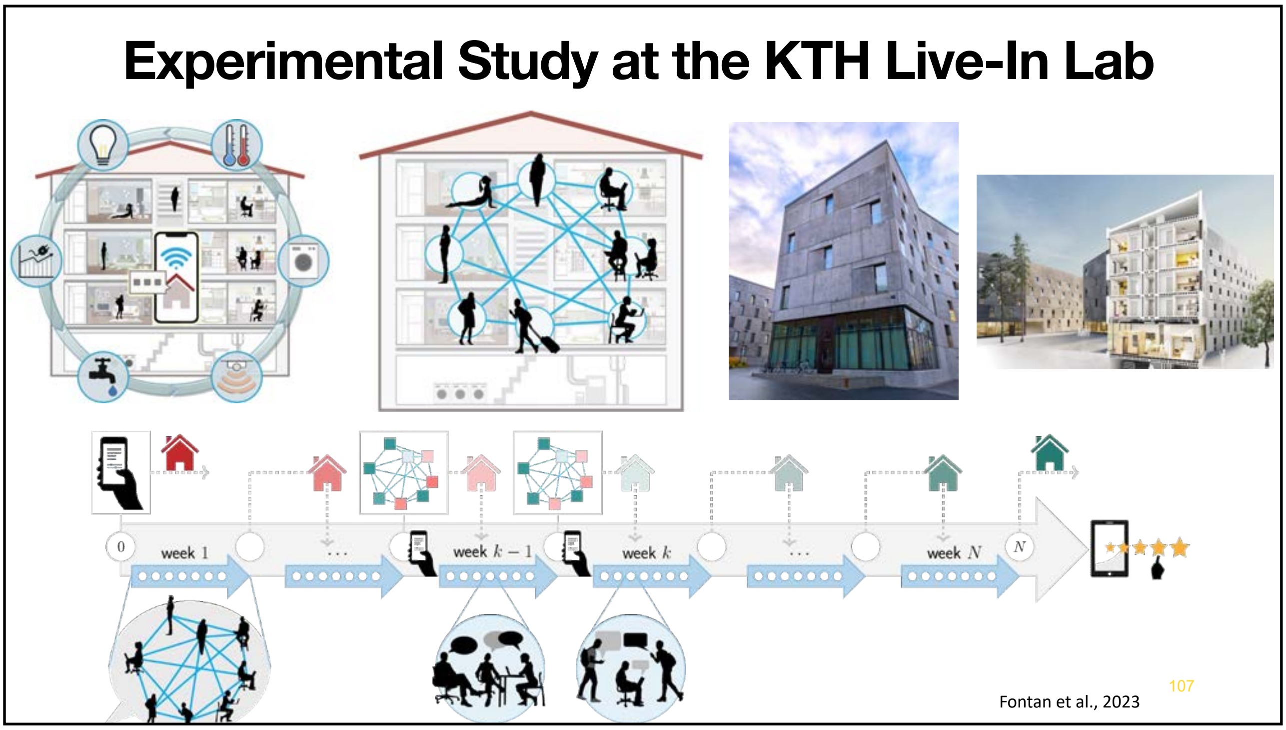

Experimental Study at the KTH Live-In Lab

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Fontan et al., 2023

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