Cyber-physical systems are engineered systems whose operations are monitored and controlled by a computing and communication core embedded in objects and structures in the physical environment.
Towards Cyber-Physical Systems

- Internet
- WWW
- Ubiquitous computing

- Remote sensing
- Monitoring environments
- Wireless sensor networks

- Closing the loop
- Critical infrastructures
- Humans in the loop

Outline

- Introduction
- Case study I: Goods transportation
- Case study II: Building management
- Cross-cutting scientific challenges
- Conclusions
The transportation system is a cyber-physical system.
Mainly without global control and optimization.
New technology has dramatic potentials.

Demands from Goods Road Transportation

- Goods transportation accounts for
  30% of CO2 emissions
  15% of greenhouse gas emissions
  of the global fossil fuel combustion
- Expected to increase by 50% for 2000-2020


Life cycle cost for European heavy-duty vehicles

- 24% of long haulage trucks run empty
- 57% average load capacity

*Dr. H. Ludanek, CTO, Scania*

Total fuel cost 80 k€/year/vehicle

*Schittler, 2003*
Technology Push

Sensor and communication technology  

Real-time traffic information

Vehicle platooning and semi-autonomous driving

Air Drag Reduction in Truck Platooning

5-10% fuel reduction potential

\[ F_{\text{air}} = \frac{1}{2} c_d A_d \rho u v^2 \]

Fuel-Optimal Goods Transportation

- Goods transported between cities over European highway network
- 2 000 000 long haulage trucks in European Union (400 000 in Germany)
- Large distributed control systems with no real-time coordination today

**Goal:** Maximize total amount of platooning with limited intervention in vehicle speed and route

---

Architecture for Future Coordinated Goods Transportation

Transport Planner ➔ Route Optimization ➔ Road Planner ➔ Road Segment Optimization ➔ Discrete Platoon Coordination ➔ Real-time Inter-Vehicle Control ➔ Advanced Vehicle Cruise Control

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Larson et al., 2013

Alam et al., 2012
Receding Horizon Cruise Control for Single Vehicle

Adjust driving force to minimize fuel consumption based on road topology info:

The total fuel consumption over time $T$ is:

$$ f = \int_0^T \delta(t) \left( \frac{1}{m} \cos \alpha \phi(t) + m g c \sin \alpha \right) dt $$

Require knowledge of road grade $\alpha$, not available in today’s navigators

Implemented as velocity reference change in advance cruise controller

Alam et al., 2011

Distributed Road Grade Estimation

RMS Road Grade Error

Aggregated N=10, 100, 1000 profiles of lengths 50 to 500 km

Sahlholm, 2011
Receding Horizon Cruise Control for Platoon

- How to jointly minimize fuel consumption for a platoon of vehicles?
  - Uphill and downhill segments; heavy and light vehicles

Dynamics of vehicle $i$ depend on distance $d_{i-1,i}$ to vehicle $i-1$:

$$\frac{dd_{i-1,i}}{dt} = v_{i-1} - v_i$$

$$m_i \frac{dv_i}{dt} = F_{\text{engine}}(\delta_i, \omega_{\text{rpm}}) - F_{\text{brakes}} - F_{\text{drag}}(v_i, d_{i-1,i})$$

$$= F_{\text{uphill}}(\delta_i, \omega_{\text{rpm}}) - F_{\text{drag}} - k^n v_i^n f_i(d_{i-1,i})$$

$$- k^n \cos \alpha_i - k^n \sin \alpha_i$$

Alam et al., 2013

When is it Fuel Efficient for a Heavy-Duty Vehicle to Catch Up with a Platoon?

Liang et al., 2013
When and where to create platoons?

Goal: Maximize total amount of platooning with limited intervention in vehicle speed and route
Platoon merge and split

Heavy-duty vehicle traffic without platooning

Merge and split platoons at highway intersections

Only vehicles that are relatively close in space and time platoon

Distributed optimization of platooning

Heavy-duty vehicle traffic without platooning

Predictive control decisions at network vertices on whether it is beneficial for a vehicle to catch up another vehicle at next intersection

With platooning
Numerical evaluations

- German road network with 300 trucks
- Random starting points and destinations
- 500 experiments

2-5% deployment enough for substantial benefit

Feasibility Study Based on Real Truck Data

- Position snapshot May 14 2013
- 2 200 Scania trucks
- 500 000 km² in Europe

- 875 long-haulage trucks over European region
- Trucks close in time and space (< r m) could adjust speed to platoon and then save 10% fuel during platooning
- Benefits:
  - r = 0.2 km: 78 trucks platooned, 0.16% savings
  - r = 1 km: 241 trucks platooned, 0.38% savings
  - r = 5 km: 778 trucks platooned, 1.2% savings

Larson et al., 2013
Stockholm-Zwolle 24/7 Testing

- Real-time fleet management
- Platooning in real traffic
- Fuel reductions and safety
- Driver acceptance
- Public acceptance

Scania Transport Lab
Internal haulage company
20 trucks, 360,000 km/year
75 trailers, 92% loaded
65 drivers, 40 h work/week

Demonstrations

Rapport on vehicle platooning developed by KTH and Scania (Oct, 2011)

PhD student Assad Alam on Discovery Channel (Jan, 2012)
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Stockholm Royal Seaport

2010
• Oil depot
• Container terminal
• Ports
• Gas plant

2030
• 10,000 new homes
• 30,000 new work spaces
• 600,000 m² commercial space
• Modern port and cruise terminal
• 236 hectares sustainable urban district
• Walking distance to city centre

From a brown field area to a sustainable city district
Stockholm Royal Seaport

2010
- Oil depot
- Container terminal
- Ports
- Gas plant

2030
- 10,000 new homes
- 30,000 new work spaces
- 600,000 m² commercial space
- Modern port and cruise terminal
- 236 hectares sustainable urban district
- Walking distance to city centre

Project Goals
- CO₂ emissions <1.5 tons per person by 2020 (today 4.5)
- Fossil fuel-free by 2030

Energy Consumption and Enabling Technologies

Energy consumption in Europe
- 40% of total energy use is in buildings
- 76% of building energy is for comfort

Enabling Information and Communication Technology
- Total energy savings of up to 15% by 2020
- Buildings can save 2.4 GtCO₂e
- Enormous CPS potentials

Emerging Technologies for Energy Efficient Buildings

- Smart appliances for load shifting
- Electrical and thermal storage
- Local power and heat generation
- Optimized HVAC
- Local renewable power generation

Heating, Ventilation, and Air Conditioning

- Heat Exchanger
- Exhaust air
- Other rooms
- Fresh air
- T = 20 °C
- Air dampers
- Exhaust air outlet
- Fresh air inlet
- Radiator valve
- Radiators
- Hot water

**Optimal control problem**
Reduce energy use while keeping indoor temperature and air quality within comfort range
KTH HVAC Testbed

KTH Campus

KTH HVAC Testbed

People counter

Temp/CO2 sensor

Mote

Radiator valve

Chilled water valve

Heat Exchanger

Exhaust air

Other rooms

Fresh air

Hot water

A.C.

Air dampers

Exhaust air outlet

Temp/CO2 sensor

Mote

People counter

Radiator

Fresh air inlet

Exhaust air outlet
KTH HVAC Testbed

Hardware
- PLC integrated with existing HVAC SCADA system
- Wireless sensors
- People counter
- Weather station
- Occupancy schedules

Software
- Matlab and LabView interfaces
- Data logging 24/7
- Web server at hvac.ee.kth.se
- Remote monitoring and control

HVAC Control Architecture

Goal: Minimize energy use while satisfying comfort constraints
Approach: Scenario-based Model Predictive Control
- CO₂ MPC generates constraints for temperature MPC
- Probabilistic models of occupancy and weather forecasts errors
- Learn statistics from building operation to generate scenarios
- Air flow and temperature control from scenario-based optimization

Parisio et al., 2013
**CO₂ model**

\[ x_{CO₂}(k+1) = ax_{CO₂}(k) + bu_{CO₂}(k) + ew_{CO₂}(k) \]
\[ y_{CO₂}(k) = x_{CO₂}(k) \]

\[ w_{CO₂}(k) = \text{occupancy at } k, \ u_{CO₂}(k) = \dot{m}_{vent}(k)x_{CO₂}(k) \]

**Temperature model**

\[ x_T(k+1) = A_T x_T(k) + B_T u_T(k) + E_T w_T(k) \]
\[ y_T(k) = C_T x_T(k) \]

\[ w_T(k) = (\text{outside temperature, solar radiation, internal heat gain}) \]
\[ u_T(k) \rightarrow |Q_{venting}|, Q_{heating} \rightarrow (\dot{m}_{vent}(k), T_{sa}(k), T_{rad}(k)) \]

Parisio et al., 2013
Scenario-based CO$_2$ MPC

**Chance Constraints**

\[ P \left[ \dot{m}_{\text{vent}}^\text{CO}_2(k) \leq \dot{u}_{\text{CO}_2}(k) \leq \dot{m}_{\text{vent}}^\text{max}_\text{CO}_2(k) \right] \geq 1 - \alpha \quad (\text{flow rate}) \]

\[ P \left[ y_{\text{min}} \leq y_{\text{CO}_2}(k) \leq y_{\text{max}} \right] \geq 1 - \alpha \quad (\text{air quality}) \]

**Inputs Constraints**

\[ u_{\text{min}} \leq u_{\text{CO}_2}(k) \leq u_{\text{max}} \]

**Cost Function**

\[ \sum_{k=0}^{N-1} c'(u(k)\Delta k) \quad (\text{minimize energy use}) \]

**Compute Control Inputs**

\[ \dot{m}_{\text{vent}}^\text{CO}_2(k) = \frac{u_{\text{CO}_2}(k)}{x_{\text{CO}_2}(k)} \]

---

Scenario-based Temp MPC

**Chance Constraints**

\[ P \left[ y_{\text{min}} \leq y_T(k) \leq y_{\text{max}} \right] \geq 1 - \alpha_T \quad (\text{thermal comfort}) \]

**Inputs Constraints**

\[ u_{\text{min}} \leq u_T(k) \leq u_{\text{max}} \]

**Cost Function**

\[ \sum_{k=0}^{N-1} c'_T(u_T(k)\Delta k) \quad (\text{minimize energy use}) \]

**Compute Setpoints for the Low-level Controllers**

\[ \left( \dot{m}_{\text{vent}}(k), T_{sa}(k), T_{rad}(k) \right) = f \left( \dot{m}_{\text{vent}}^\text{CO}_2(k), u_T(k) \right) \]

Parisio et al., 2013
How to Handle Chance Constraints

$\omega := \text{random variable (weather, occupancy, \ldots)}$

### Uncertainty Modeling

$\omega(k) = \tilde{\omega}(k) + \bar{\omega}(k)$

- $\tilde{\omega}(k)$ := forecast
- $\bar{\omega}(k)$ := forecast error

---

Approximating Chance Constraints [Calafiore, 2010]

- extract a limited number $S = \frac{2}{\alpha} \left( \ln \left( \frac{1}{\beta} \right) + N \cdot n_u \right)$ of i.i.d. outcomes (called **scenarios**)
- approximate $\mathbb{P}[y_{\min} \leq y(k) \leq y_{\max}] \geq 1 - \alpha$ with $y_{\min} \leq y(\tilde{\omega}^j(k)) \leq y_{\max}, \ \forall j = 1, \ldots, S$
- remove redundant constraints: $\max_j \{ y(\tilde{\omega}^j(k)) \} \leq y_{\max}$
Evaluations on HVAC Testbed

**AHC actuation commands** (Existing controller)

Parisio et al., 2013

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Evaluations on HVAC Testbed

**AHC actuation commands**

$E_{SMPC} = 1.27 \text{ kWh}$, $E_{AHC} = 1.39 \text{ kWh}$ (savings: 8.4%)
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Cyber-Physical Systems Challenges

Societal Scale
• Global and dense instrumentation of physical phenomena
• Interacting with a computational environment: closing the loop
• Security, privacy, usability

Distributed Services
• Self-configuring, self-optimization
• Reliable performance despite uncertain components, resilient aggregation

Programming the Ensemble
• Local rules with guaranteed global behavior
• Distributing control with limited information

Network Architectures
• Heterogeneous systems: local sensor/actuator networks and wide-area networks
• Self-organizing multi-hop, resilient, energy-efficient routing
• Limited storage, noisy channels

Real-Time Operating Systems
• Extensive resource-constrained concurrency
• Modularity and data-driven physics-based modeling

1000 Radios per Person
• Low-power processors, radio communication, encryption
• Coordinated resource management, spectrum efficiency

Sastry & J, 2010
How to analyze, design, and implement networked control with
- Guaranteed **global objective** from local interactions
- **Physical dynamics** coupled with information interactions
- Tradeoff **computation-communication-control** complexities
- **Robustness to** external disturbances other **uncertainties**

- Decentralized control extensively studied:
  - Witsenhausen; Ho & Chu; Sandell & Athans; Anderson & Moore; Siljak; Davison & Chang; Rotkowitz & Lall; etc
- Typically assumes full model information (knowledge of all \(P_j\))
- What if at the design of \(C_1\) only surrounding \(P_j\)’s are known?
The role of plant model information

Inter-vehicle distances \( d_{12} \) and \( d_{23} \) are locally controlled through vehicle torques \( u_i \).

\[
\begin{bmatrix}
    v_1(t) \\
    d_{12}(t) \\
    v_2(t) \\
    d_{23}(t) \\
    v_3(t)
\end{bmatrix} =
\begin{bmatrix}
    -g_1/m_1 & 0 & 0 & 0 & 0 \\
    1 & 0 & -1 & 0 & 0 \\
    0 & 0 & -g_2/m_2 & 0 & 0 \\
    0 & 0 & 1 & 0 & -1 \\
    0 & 0 & 0 & 0 & -g_3/m_3
\end{bmatrix}
\begin{bmatrix}
    v_1(t) \\
    d_{12}(t) \\
    v_2(t) \\
    d_{23}(t) \\
    v_3(t)
\end{bmatrix}
= \begin{bmatrix}
    v_1(t) \\
    w_1(t) \\
    v_2(t) \\
    w_2(t) \\
    v_3(t) \\
    w_3(t) \\
    v_4(t) \\
    w_4(t)
\end{bmatrix}
\]

How does knowledge of the vehicle mass \( m_i \) influence performance?

Example

\[
x_1(k+1) = a_{11}x_1(k) + a_{12}x_2(k) + u_1(k)
\]
\[
x_2(k+1) = a_{21}x_1(k) + a_{22}x_2(k) + u_2(k)
\]

\[
J = \sum_{k=1}^{\infty} \|x(k)\|^2 + \|u(k)\|^2
\]

Keep \( J \) small, when

Controller 1 knows only \( a_{11} \) and \( a_{12} \)
Controller 2 knows only \( a_{21} \) and \( a_{22} \)

\[
u_1(k) = -a_{11}x_1(k) - a_{12}x_2(k)
\]
\[
u_2(k) = -a_{21}x_1(k) - a_{22}x_2(k)
\]

achieves \( J \leq 2J^* \)

No limited plant model information strategy can do better.

Langbort & Delvenne, 2011
Why Limited Plant Model Information?

**Complexity**
Controllers are easier to implement and maintain if they mainly depend on local model information.

**Availability**
The model of other subsystems is not available at the time of design.

**Privacy**
Competitive advantages not to share private model information.

Networked Control System
Networked Control System

Plant Graph

Control Graph
Networked Control System

Plant Graph

\[ x_i(k+1) = A_i x_i(k) + \sum_{j \in \mathcal{N}_i} A_{ij} x_j(k) + B_i u_i(k) \]

Plant: \( P = (A, B, x_0) \in \mathcal{M} \times \mathbb{R} \times \mathbb{R}^n \)

\( x_i \in \mathbb{R}^{n_i} \) and \( u_i \in \mathbb{R}^{m_i} \)
Plant Graph

\[ x_t(k+1) = A_t x_t(k) + \sum_{j \neq t} A_{ij} x_j(k) + B_t u_t(k) \]

Plant: \( P = (A,B,x_0) \in \mathcal{P} \times \mathcal{S} \times \mathbb{R}^n \)
\( x_t \in \mathbb{R}^{n_t} \) and \( u_t \in \mathbb{R}^{n_u} \)

\[ \mathcal{A} = \{ A \in \mathbb{R}^{n \times n} | A_{ij} = 0 \in \mathbb{R}^{n \times n_j} \text{ for all } 1 \leq i, j \leq q \text{ such that } (S_p)_{ij} = 0 \} \]

\[ S_p = \begin{bmatrix} 1 & 1 & 0 \\ 0 & 1 & 1 \\ 0 & 1 & 1 \end{bmatrix} \quad A = \begin{bmatrix} A_{11} & A_{12} & 0_{n_1 \times n_3} \\ 0_{n_2 \times n_1} & A_{22} & A_{23} \\ 0_{n_3 \times n_1} & A_{32} & A_{33} \end{bmatrix} \]

Plant Graph

\[ x_t(k+1) = A_t x_t(k) + \sum_{j \neq t} A_{ij} x_j(k) + B_t u_t(k) \]

Plant: \( P = (A,B,x_0) \in \mathcal{P} \times \mathcal{S} \times \mathbb{R}^n \)
\( x_t \in \mathbb{R}^{n_t} \) and \( u_t \in \mathbb{R}^{n_u} \)

\[ \mathcal{A} = \{ A \in \mathbb{R}^{n \times n} | A_{ij} = 0 \in \mathbb{R}^{n \times n_j} \text{ for all } 1 \leq i, j \leq q \text{ such that } (S_p)_{ij} = 0 \} \]

\[ S_p = \begin{bmatrix} 1 & 1 & 0 \\ 0 & 1 & 1 \\ 0 & 1 & 1 \end{bmatrix} \quad A = \begin{bmatrix} A_{11} & A_{12} & 0_{n_1 \times n_3} \\ 0_{n_2 \times n_1} & A_{22} & A_{23} \\ 0_{n_3 \times n_1} & A_{32} & A_{33} \end{bmatrix} \]

\[ B = \begin{bmatrix} B_{11} & 0_{n_1 \times n_3} & 0_{n_1 \times n_3} \\ 0_{n_2 \times n_1} & B_{22} & 0_{n_2 \times n_3} \\ 0_{n_3 \times n_1} & 0_{n_3 \times n_2} & B_{33} \end{bmatrix} \]
Control Graph

\[ u(k) = Kx(k) \]

\( \kappa = \{ K \in \mathbb{R}^{n \times n} | K_{ij} = 0 \in \mathbb{R}^{n_i \times n_j} \text{ for all } 1 \leq i, j \leq q \text{ such that } (s_K)_{ij} = 0 \} \)

\[ S_K = \begin{bmatrix} 1 & 0 & 0 \\ 1 & 1 & 0 \\ 0 & 1 & 1 \end{bmatrix} \quad K = \begin{bmatrix} K_{11} & 0_{n_1 \times n_2} & 0_{n_1 \times n_3} \\ K_{21} & K_{22} & 0_{n_2 \times n_3} \\ 0_{n_3 \times n_1} & K_{32} & K_{33} \end{bmatrix} \]

Design Graph

\[ K = \Gamma(P) = \Gamma(A, B) \]

The map \([\Gamma_{i1} \quad \cdots \quad \Gamma_{iq}]\) is only a function of \(\{[A_{j1} \quad \cdots \quad A_{jq}], B_{ij} | (s_C)_{ij} \neq 0\}\).

\[ S_C = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 1 \\ 0 & 1 & 1 \end{bmatrix} \]
Design Graph

\[ K = \Gamma(P) = \Gamma(A, B) \]

The map \([\Gamma_{i1}, \ldots, \Gamma_{iq}]\) is only a function of \([\{A_{j1}, \ldots, A_{jq}\}, B_{jj}, (s_c)_{ij} \neq 0\}].

\[ S_c = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 1 \\ 0 & 1 & 1 \end{bmatrix} \]

\([\Gamma_{i1}, \Gamma_{i2}, \Gamma_{i3}]\) is a function of \([\{A_{21}, A_{22}, A_{23}\}, B_{22}, {A_{31}, A_{32}, A_{33}}\}].

HVAC Control Example

Plant Graph:

Design Graph:
Performance Metric

The **competitive ratio** of a control design method $\Gamma$ is defined as

$$r_p(\Gamma) = \sup_{P \in \mathcal{P}} \frac{J_p(\Gamma(A,B))}{J_p(\Gamma^*(P))}$$

A control design method $\Gamma'$ is said to **dominate** another control design method $\Gamma$ if

$$J_p(\Gamma'(A,B)) \leq J_p(\Gamma(A,B)),$$

for all $P = (A,B,x_0) \in \mathcal{P}$

with strict inequality holding for at least one plant.

When no such $\Gamma'$ exists, we say that $\Gamma$ is **undominated**.
Performance Metric

The competitive ratio of a control design method $\Gamma$ is defined as

$$r_p(\Gamma) = \sup_{P \in \mathcal{P}} \frac{J_p(\Gamma(A,B))}{J_p(K^*(P))}$$

A control design method $\Gamma'$ is said to dominate another control design method $\Gamma$ if

$$J_p(\Gamma'(A,B)) \leq J_p(\Gamma(A,B)) \quad \text{for all} \; P = (A,B,x_0) \in \mathcal{P}$$

with strict inequality holding for at least one plant.

When no such $\Gamma'$ exists, we say that $\Gamma$ is undominated.

$$J_p(K) = \sum_{k=1}^{\infty} x(k)^TQx(k) + \sum_{k=0}^{\infty} u(k)^TRu(k)$$

$Q$ and $R$ are block-diagonal positive definite matrices.

Remark: When $G_k$ is a complete graph

$$K^*(P) = -(R + B^T XB)^{-1}B^TXA$$

$$A^TXA - A^TXB(R + B^T XB)^{-1}B^TXA - X + Q = 0$$
Problem Formulation

Find the best control design strategy with limited model information:

\[ \min_{\Gamma \in \mathcal{R}} r_p (\Gamma) \]

Characterize the influence from
- Plant structure \((G_p)\)
- Controller communication \((G_K)\)
- Model limitation \((G_C)\)

Assumptions

- All subsystems are fully actuated:
  \[ B \in \mathbb{R}^{n \times n} \text{ and } \sigma(B) \geq \epsilon > 0. \]
- \(G_P\) contains no isolated node.
- \(G_C\) contains all self-loops.
- To simplify the presentation, fix \(\epsilon = 1\) and \(Q = R = I\).
Deadbeat Control Design

\[ \Gamma^A (A, B) = -B^{-1}A \]

Subcontroller \( i \) depends only on subsystem \( i \)'s model:

\[
\begin{bmatrix}
\Gamma^A_{i1}(A, B) & \ldots & \Gamma^A_{iq}(A, B)
\end{bmatrix} = -B_i^{-1}\begin{bmatrix} A_{i1} & \ldots & A_{iq} \end{bmatrix}
\]

\[
x(k + 1) = Ax(k) + Bu(k) ; x(0) = x_0,
\]

Lemma: \( G_K \supseteq G_P \) \( \implies \) \( r_p(\Gamma^A) = 2 \)

Farokhi et al., 2013
Deadbeat Control Design

Lemma: \( G_K \supseteq G_P \implies r_p(\Gamma^A) = 2 \)

* \( G_K \supseteq G_P \) means \( E_K \supseteq E_P \), so more controller communications than plant interactions

Farokhi et al., 2013
Deadbeat Control Design

Lemma: \( G_K \supseteq G_P \Rightarrow r_P(\Gamma^A) = 2 \)

- \( G_K \supseteq G_P \) means \( E_K \supseteq E_P \)
- \( J_P(\Gamma^A(A,B)) \leq 2J_P(K^*(P)) \)

If enough controller communication, then a simple (deadbeat) controller is quiet good

Design Strategies with Local Model Info

Theorem: \( G_P \) has no sink \( G_K \supseteq G_P \) \( G_P \) is fully disconnected \( \Rightarrow r_P(\Gamma) \geq r_P(\Gamma^A) = 2 \ \forall \Gamma \in \mathcal{E} \)

When \( G_P \) has no sink, there is no control design strategy \( \Gamma \) with a better competitive ratio \( r_P(\Gamma) = \sup_{\Gamma(A,B)} J_P(\Gamma(A,B))/J_P(K^*(P)) \) than deadbeat \( \Gamma^A \)

Farokhi et al., 2013
Example

\[ \begin{bmatrix} x_1(k+1) \\ x_2(k+1) \end{bmatrix} = \begin{bmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{bmatrix} \begin{bmatrix} x_1(k) \\ x_2(k) \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \end{bmatrix} u_1(k) + \begin{bmatrix} 1 \\ 0 \end{bmatrix} u_2(k) \]

- \( K^*(P) = -(I + X)^{-1}XA \)
- \( A^TXA - A^TX(I + X)^{-1}XA + I = X \)
- \( \Gamma^A(A, B) = -\begin{bmatrix} a_{11} & a_{12} \\ 0 & a_{22} \end{bmatrix} \)
- \( J_F(\Gamma^A(A, B)) \leq 2J_F(K^*(P)) \)
- \( \Gamma^A(A, B) = -\begin{bmatrix} w_{01} & w_{02} \\ 0 & w_{22} \end{bmatrix} \)
- \( J_F(\Gamma^A(A, B)) \leq J_F(\Gamma^A(A, B)) \leq 2J_F(K^*(P)) \)

and undominated

Motivating Example Revisited

- Regulating inter-vehicle distances \( d_{12} \) and \( d_{23} \)

\[ \begin{bmatrix} v_1(t) \\ v_2(t) \\ v_3(t) \end{bmatrix} = \begin{bmatrix} -\alpha_1/m_1 & 0 & 0 \\ 1 & -1 & 0 \\ 0 & 0 & -\alpha_3/m_3 \end{bmatrix} \begin{bmatrix} v_1(t) \\ v_2(t) \\ v_3(t) \end{bmatrix} + \begin{bmatrix} \alpha_1/m_1 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & \alpha_3/m_3 \end{bmatrix} \begin{bmatrix} u_1(t) \\ u_2(t) \\ u_3(t) \end{bmatrix} \]

\[ z(t) = \begin{bmatrix} d_{12}(t) \\ d_{23}(t) \\ u_1(t) \\ u_2(t) \\ u_3(t) \end{bmatrix} \]

- Find a saddle point of \( J(\Gamma, \alpha) = \|T_{sw}(s; \Gamma, \alpha)\|_\infty \) when \( \alpha = [m_1 m_2 m_3]^T \in [0.5, 1.0]^3 \) and \( \Gamma \) belongs to the set of polynomials of \( \alpha_i, i = 1, 2, 3 \), up to the second order.

\[ \inf_{\Gamma \in \mathcal{A}} \sup_{\alpha \in \mathcal{A}} J(\Gamma, \alpha) = \inf_{\Gamma \in \mathcal{A}} \sup_{\alpha \in \mathcal{A}} \|T_{sw}(s; \Gamma, \alpha)\|_\infty \]
Motivating Example Revisited

Control Design with Local Model Information
\[ \max_{\alpha \in \mathcal{A}} \| T_z w (s; \Gamma^{local}, \alpha) \|_\infty = 4.7905 \]

Farokhi & J., 2013

---

Motivating Example Revisited

Control Design with Limited Model Information
\[ \max_{\alpha \in \mathcal{A}} \| T_z w (s; \Gamma^{limited}, \alpha) \|_\infty = 3.5533 \]

25.8%

Farokhi & J., 2013
Motivating Example Revisited

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• Case study I: Goods transportation
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• Conclusions
Conclusions

- CPS architectures for large-scale control and optimization
- Applications to transportation and building management
- Influence of local plant models on global performance
- Testbed developments

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