Decentralized and distributed control

Introduction

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EECI-HYCON2 Graduate School on Control 2012
Supélec, France
Outline

1. Course information and scheduling
Outline

1 Course information and scheduling

2 Control of large-scale systems
Outline

1. Course information and scheduling
2. Control of large-scale systems
3. Decentralized and distributed control: motivating examples
Outline

1. Course information and scheduling
2. Control of large-scale systems
3. Decentralized and distributed control: motivating examples
4. Course description
European Embedded Control Institute

- Lightweight association based on volunteer work created in 2006 in the framework of the HYCON network of excellence. Currently supported by the network of excellence HYCON2 "Highly-complex and networked control systems"
- Mission: "to become a long-term world-wide renowned focal point by stimulating new collaborative research on networked and embedded control"
- Members: about 20 european universities and research centers
- Education: since 2007 EECI organizes each year the Graduate School on Control
  - Several modules (18 this year) on many different topics in control theory
Course information

Course on decentralized and distributed control

- Module M4 of the European Embedded Control Institute (EECI-HYCON2) Graduate School on Control 2012
- Eligible for 2nd Year Master Degree credits and Scientific Thesis modules

Exam for getting 3 ECTS

The exam will take place on Friday at 13:00 How it works:

- A set of papers has been distributed to students that will take the exam
- Each student chooses 1 paper and presents it in 20 min. No constraints on the presentation style and no need of professional presentations!
## Schedule of the course

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<th>Time</th>
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Course information

Entry requirements
State-space approach to system and control theory for linear systems.

Course material

- Recommended books:

- Detailed references to specific papers will be provided during the course.

- An updated version of the slides will be available at the webpage http://sisdin.unipv.it/lab/personale/pers_hp/ferrari/EECI_DEDICO.php
Control of large-scale systems
Centralized control

Feedback control of Multi Input Multi Output (MIMO) systems

- $u$: control variables
- $y$: outputs
- possible external setpoints
Centralized control

Feedback control of Multi Input Multi Output (MIMO) systems

- \( u \): control variables
- \( y \): outputs
- possible external setpoints

Pros

- Simple conceptual framework: one system one controller
- Studied for decades. Many controller design procedures available for linear systems
Centralized control

Feedback control of Multi Input Multi Output (MIMO) systems

\[
\begin{array}{c}
C \\
\text{System}
\end{array}
\]

- \( u \): control variables
- \( y \): outputs
- possible external setpoints

Cons

Pitfalls for large-scale systems (many inputs, states and outputs)
- Offline design: model-based controller synthesis can be prohibitive if the system model is huge and system structure is not exploited
- Real-Time (RT) operations: in a sampling interval
  - Transmission of system measurements to an unique controller might be challenging for systems deployed over a wide area
  - computation of the control variables might become unfeasible

Centralized control might be also unappealing for economical, political or societal reasons
Decentralized control

Decentralized regulators for MIMO systems

- Controllers attached to input/output channels

\[
\begin{align*}
C_1 & \quad C_2 & \quad C_3 \\
\text{System} & \quad & \\
u_1 & & u_2 \\
\quad & & y_2 \\
u_3 & & y_3 \\
\end{align*}
\]
Decentralized control

Decentralized regulators for MIMO systems

- Controllers attached to input/output channels

Pros

Advantages in RT operations:

- Parallel computation of control variables
- Easier communication if controllers, sensors and actuators are collocated
Decentralized control

Decentralized regulators for MIMO systems

Controllers attached to input/output channels

Cons

Absence of communication between controllers limits the achievable performance
Distributed control

Distributed regulators for MIMO systems

Controllers attached to input/output channels (as in decentralized schemes)
Controllers can communicate
Distributed control

Distributed regulators for MIMO systems

Controllers attached to input/output channels (as in decentralized schemes)
Controllers can communicate

Pros
Advantages in RT operations:
- Parallel computation of control variables
- One can tune the trade-off between communication burden and performance
Distributed control

Distributed regulators for MIMO systems

- Controllers attached to input/output channels (as in decentralized schemes)
- Controllers can communicate

Remarks on distributed control

- Middle ground between centralized and decentralized schemes
- Communication network can be part of the design problem
- Challenges due to network non idealties (delays, packet drops etc ...)

System

\[
\begin{align*}
C_1 & \quad \quad C_2 & \quad \quad C_3 \\
\quad u_1 \quad y_1 & \quad \quad u_2 \quad y_2 & \quad \quad u_3 \quad y_3 \\
\end{align*}
\]
Decentralized and distributed control

De/Di regulators

\[ C_1 \quad C_2 \quad C_3 \]

\[ u_1 \quad y_1 \quad u_2 \quad y_2 \quad u_3 \quad y_3 \]

System

\[ C_1 \quad C_2 \quad C_3 \]

\[ u_1 \quad y_1 \quad u_2 \quad y_2 \quad u_3 \quad y_3 \]

System
Decentralized and distributed control

De/Di regulators

System

Remarks

- Decentralized control has been studied since the 70’s, mainly for linear and unconstrained systems
- Recent renowned interest triggered by advances in technology and telecommunications
  - sensor networks that enable the monitoring and control of processes spread over large geographical areas
  - smart actuators with onboard communication and computation capabilities
Exploiting system structure

Graph of $N$ dynamically coupled systems

- Subsystems with their own inputs $u_i$, states $x_i$ and outputs
- Bold arrows represent physical coupling and define the coupling graph
  - edge $(j, i)$ iff $x_j$ influences $\Sigma_i$

Set of neighbors to subsystem $\Sigma_i$

$\mathcal{N}_i = \{ j : (i, j) \text{ is an arc of the coupling graph} \}$

In the example: $\mathcal{N}_3 = \{1, 2\}$
Exploiting system structure

Graph of $N$ dynamically coupled systems

Sometimes subsystems are naturally defined

Temperature control in buildings

- subsystems: rooms or thermal zones
- coupling: heat transfer
- actuators: radiators/chillers
Exploiting system structure

Graph of $N$ dynamically coupled systems

- More often there are degrees of freedom in decomposing a large-scale MIMO system into a set of physically coupled subsystems

Remarks on decomposition

Guideline: define subsystems that are loosely coupled

- Ideal case for controller design: totally decoupled subsystems
Exploiting system structure

De/Di regulators

\[ \Sigma_1 x_1 \xrightarrow{u_1} C_1 \]

\[ \Sigma_2 x_2 \xrightarrow{u_2} C_2 \]

\[ C_3 x_3 \xrightarrow{u_3} \Sigma_3 \]

Farina, Ferrari Trecate ()
Exploiting system structure

Decentralized synthesis of De/Di regulators

How difficult is the offline design of a single controller?

- Centralized synthesis: some design step requires the model of the whole plant
- Decentralized synthesis: controllers can be designed independently using a partial model of the system

Pure decentralized synthesis guaranteeing stability is available only for special system structures (e.g. cascade of subsystems)
Decentralized and distributed control: motivating examples
Frequency control in power network

Power network model

\[ \Delta P_{L,1} \quad \Delta P_{ref,1} \quad \Sigma_1 \quad \Delta \omega_1 \]

\[ \Delta P_{ref,3} \quad \Sigma_3 \quad \Delta \omega_3 \]

\[ \Delta P_{L,2} \quad \Delta P_{ref,2} \quad \Sigma_2 \quad \Delta \omega_2 \]
Frequency control in power network

Power network model

- \( \Sigma_i \): power generation area equipped with primary load frequency control. Linearized model with
  - input \( \Delta P_{\text{ref},i} \): deviation of reference power from the nominal value
  - output \( \Delta \omega_i \): deviation of frequency from the nominal value
  - disturbance \( \Delta P_{L,i} \): deviations from nominal load

- Arrows: tie lines
Frequency control in power network

Power network model

Goal

Design the Automatic Generation Control (AGC) layer for computing $\Delta P_{\text{ref},i}$, $i = 1 : 3$ using states of the whole network in order to guarantee that $\Delta \omega_i \to 0$ as $t \to +\infty$ for step loads $\Delta P_{L,i}$.
Frequency control in power network

Power network model

Pitfalls of a centralized controller
- Not scalable with the number of areas
- Not compatible with different regulation authorities
- A fault in the controller might compromise the whole network stability
Frequency control in power network

Case study: 4-area network

- Realistic parameter values from (Saadat, 2002)
- $\Sigma_i$ is a 4-th order LTI model
Frequency control in power network

Case study - Decentralized control

\[
\begin{align*}
\Delta P_{\text{ref},1} & \rightarrow \Delta \omega_1 \\
\Delta P_{\text{ref},2} & \rightarrow \Delta \omega_2 \\
\Delta P_{\text{ref},3} & \rightarrow \Delta \omega_3 \\
\Delta P_{\text{ref},4} & \rightarrow \Delta \omega_4
\end{align*}
\]
Frequency control in power network

Case study - Decentralized control

\[ P_{ref,1} \rightarrow P_{L,1} \rightarrow P_{ref,2} \rightarrow P_{L,2} \rightarrow P_{ref,3} \rightarrow P_{L,3} \rightarrow P_{ref,4} \rightarrow P_{L,4} \]

Simulation results

\[ \Delta P_{ref,i} \text{ for centralized and decentralized control} \]

\[ \Delta \omega_i \text{ for centralized and decentralized control} \]
Ramp metering in motorways

Intelligent transportation systems

Goal: advanced traffic management for

- improving driver satisfaction and safety
- minimize time spent in queues, congestion and pollution
## Ramp metering in motorways

### Intelligent transportation systems

<table>
<thead>
<tr>
<th>Various types of sensors, e.g. wireless magnetometers, for measuring vehicle density</th>
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<tbody>
<tr>
<td>Actuators: traffic lights (urban roads) variable speed limits, ramp metering</td>
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</table>

**Goal:** advanced traffic management for
- improving driver satisfaction and safety
- minimize time spent in queues, congestion and pollution
Ramp metering in motorways

Motorway scheme

Motorway model

- $\Sigma_i$: blocks of cells with at least an access point
- inputs: $u_i \in [0, 1]$ metering rates
- state: density of vehicles

Goal:
- minimize total time spent by all vehicles in the motorway or in queues at access points
Ramp metering in motorways

Motorway scheme

Pitfalls of centralized control

For large number of blocks

- High computational burden for small sampling times (≈10 s.)
- Difficult to transmit all measurements to a single location
- Lack of robustness to controller failure
Ramp metering in motorways

Motorway scheme

Current research
Development of distributed controllers in the EU-FP7 project HYCON 2
Course description
Course description

The course will cover basics on

1. Modelling of large-scale systems
2. Stability analysis for large-scale systems
3. Design of decentralized and distributed controllers for
   3.1 unconstrained systems
   3.2 constrained systems

Goal

Provide the necessary background for starting research in the field of De/Di control

Remarks

- To keep it simple, most results will be developed for Linear Time-Invariant (LTI) systems
- Before starting there will be a short review of multivariable centralized control
Course description

1. Modelling of large-scale systems

Focus on:
- Different equivalent representations of large-scale systems
- Decomposition of a model into subsystems
  - input/output pairs
  - subsystems with local states
2. Stability analysis for large-scale systems

Classic tools for checking stability of LTI systems become computationally prohibitive when applied to large-scale models. As an alternative, approaches based on the analysis of subsystems and the way they are interconnected will be presented.
3.1 De/Di controllers for large-scale *unconstrained* systems

- A summary of classic results developed in the 70’s and 80’s on system stabilizability and pole placement using decentralized controllers
- Some methods for the synthesis of De/Di controllers
  - Techniques based on LMIs (Linear Matrix Inequalities)
  - Pole placement through a specific channel
  - Recent approaches to the design of De/Di output feedback controllers
Course description

3.2 De/Di controllers for large-scale constrained systems

Methods based on Model Predictive Control (MPC).
- Introduction to MPC and dynamic noncooperative games
- Some De/Di MPC schemes with stability analysis (2 systems setting)