Formal Methods for the Control of Large-scale Networked Nonlinear Systems with Logic Specifications

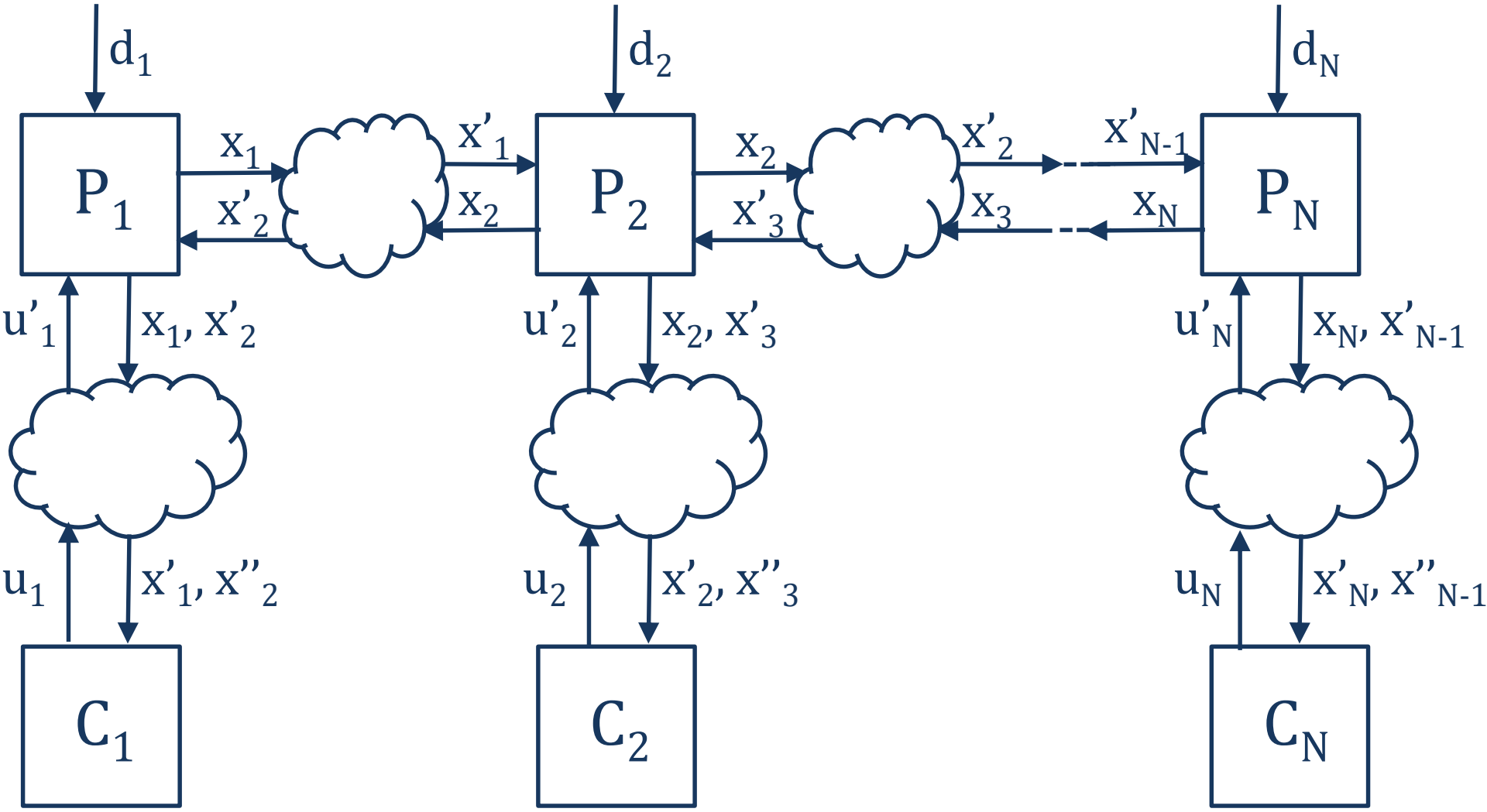
Basilica di Santa Maria di Collemaggio, L'Aquila (Italy), 1287

Lecture L15:

Conclusions

Speaker: Giordano Pola

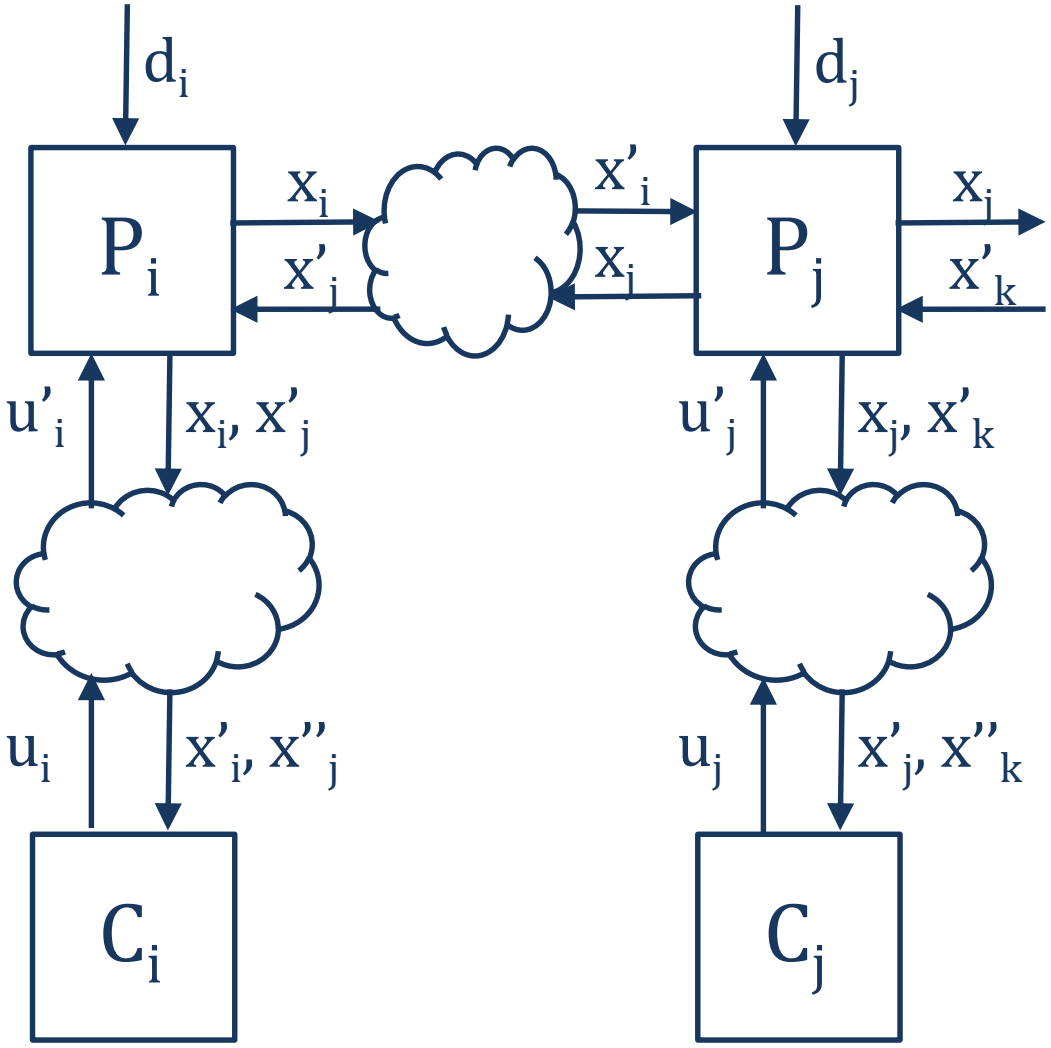
We considered a fairly general model of CPSoS



Critical aspects of CPSoS …

- Heterogeneity: plants, controllers and specifications described in different mathematical frameworks
- Non-ideal communication infrastructure: control action delivered with delay on the basis of delayed and corrupted measure of the states of the plants, lack of information (packet drops), etc.
- Complexity: large number of systems composed of several, possibly distributed sub-systems
- Logic specifications

The approach we took …



… a complementary approach :

- Single plants with no disturbances and delays
- Control design with logic specifications
- Efficient algorithms for control design
- Single plants with disturbances
- Single plants with delays
- Single, possibly unstable, plants
- Single plant, controller and communication infrastructure
- Decentralized control of networks of control systems with logic specifications

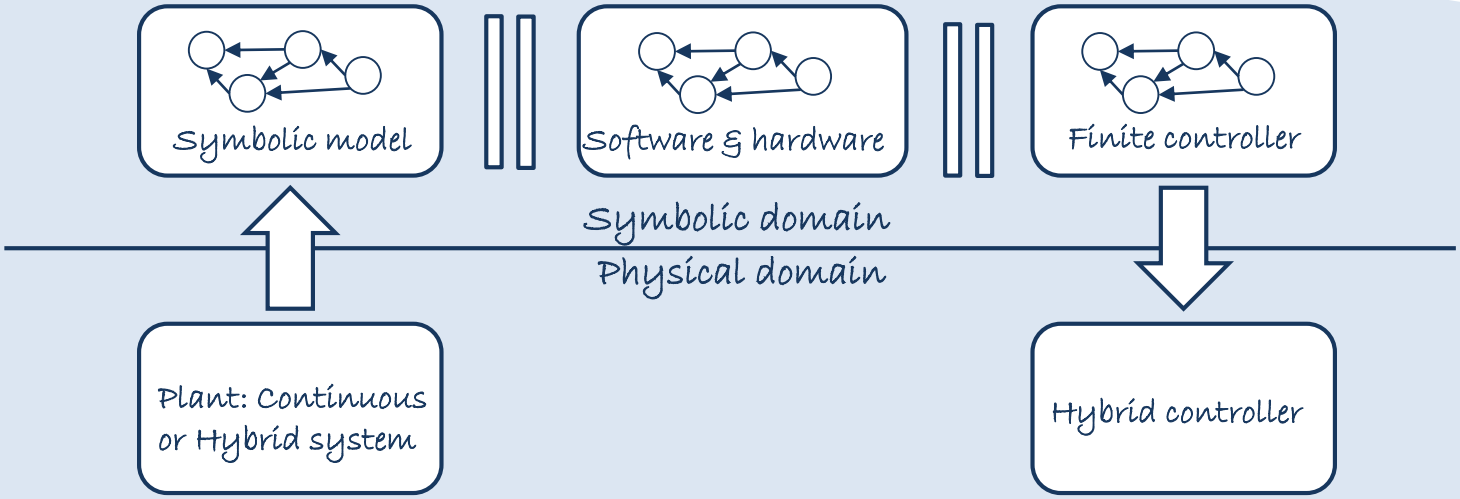
Solution based on Formal Methods

A three phases process :

#1. Construct the finite/symbolic model T approximating the plant system P

#2. Design a finite/symbolic controller C that solves the specification S for T

#3. Refine the controller C to the controller C' to be applied to P



Advantages :

- Integration of software and hardware constraints in the control design of purely continuous processes
- Logic specifications can be addressed

Advantages of the approach

- Correct-by-design approach handling nonidealities of CPSoS
- Systematic approach to enforce logic specifications
- The «completeness property»
  - A control strategy enforcing a (logic) specification on one system exists if and only if it exists on a bisimilar one
  - If the system is incrementally stable then an approximated bisimilar symbolic model can be effectively constructed
  - Example 1 in Lecture L6a shows that unstable linear systems do not admit approximated bisimilar symbolic models
- Incremental forward completeness
  - Mild assumption: at present there is no example of a FC nonlinear system that is not δ-FC !
  - Since symbolic models obtained are in simulation (and not bisimulation) with the original model, here the completeness property is lost in general

Disadvantages of the approach: Computational complexity!

Approaches to tame complexity:

s.c.c. = space computational complexity
t.c.c. = time computational complexity

Methodological approaches:

- On-the-fly algorithms

  Example in L7b with s.c.c. gain 57491 and t.c.c. gain 419 !
- Decentralized control architectures

  Example in L13 with t.c.c. gain 1046 !
- Multi-resolution approaches (see e.g. [Girard et al.,TAC16])
- …

Software tools:

- PESSOA (use of BDD)

  Example in L11 where construction of symbolic model of 34020088 transitions + control (without on-the-fly techniques) in 536s !
- SCOTS (performs even better than PESSOA !)
- …

Dedicated computing architectures:

- Parallel computing (not explored yet !)
- …

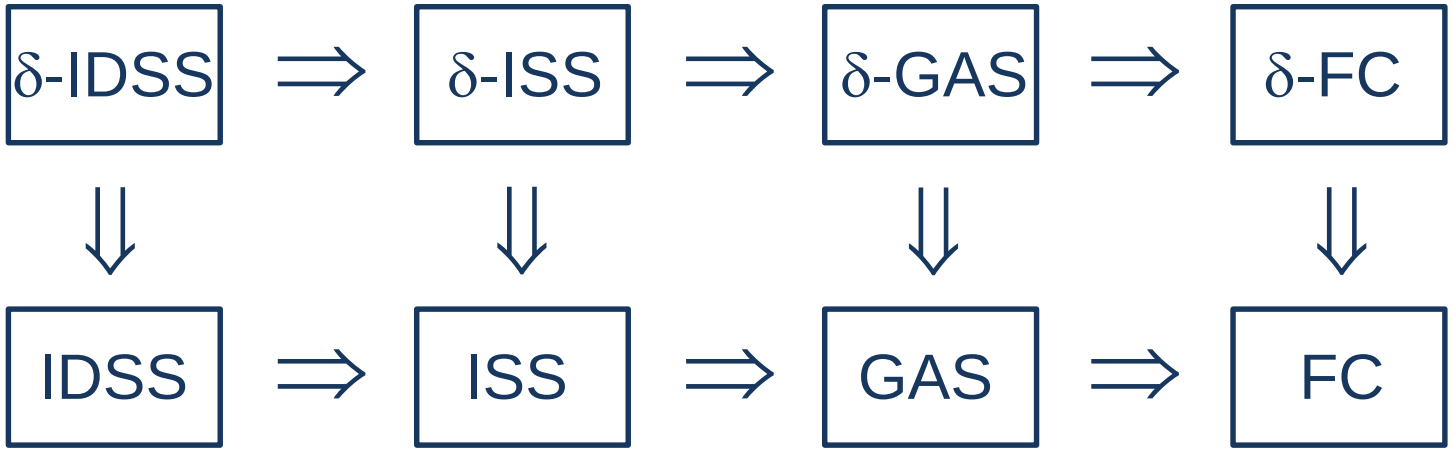
Control of CPSoS with an inter-disciplinary approach …

Methods from:

- **Control theory**
  nonlinear and time delay-systems, incremental stability, …
- **Discrete-event systems**
  regular languages, operators on automata, …
- **Theoretical computer science**
  bisimulation theory and its variants, …
- **Mathematics**
  approximation of functional spaces, …
- **Telecommunication**
  modeling of nonideal communication infrastructures, …

Some advanced methods used from control theory

Hierarchy of stability notions for nonlinear (and time-delay) systems



Some additional topics on Formal Methods @ UNIVAQ

- **Control of PWA systems with logic specifications**
  by G Pola and M D Di Benedetto
  - Pola, Di Benedetto, Symbolic Models and Control of Discrete-Time Piecewise Affine Systems: An Approximate Simulation Approach, TAC-2014
  - Pola, Di Benedetto, Sequences of Discrete Abstractions for Piecewise Affine Systems, ADHS-2012
- **Approximate diagnosability for metric and nonlinear control systems**
  by G Pola, M D Di Benedetto and Elena De Santis (UNIVAQ)
  - Pola, De Santis, Di Benedetto, Approximate diagnosability of metric transition systems, SEFM-2017, accepted
  - De Santis, Pola, Di Benedetto, On Approximate Diagnosability of Nonlinear Control Systems, CDC-2017, submitted
- **Stochastic equivalences and control for linear and descriptor systems**
  by G Pola, M D Di Benedetto, Costanzo Manes (UNIVAQ) and Arjan J. van der Schaft (Univ. of Groningen, NL)
  - Pola, Manes, van der Schaft, Di Benedetto, Equivalence notions for discrete-time stochastic linear control systems, TAC-2017, provisionally accepted as Paper
  - Pola, On Achievable Behavior of Stochastic Descriptor Systems, CDC-2017, submitted
  - Pola, Manes, Di Benedetto, On external behavior equivalence of continuous–time stochastic linear control systems, CDC-2016
  - Pola, Manes, van der Schaft, Di Benedetto, Model reduction of continuous–time stochastic linear control systems via bisimulation equivalence, CDC-2016
  - Pola, Manes, van der Schaft, Di Benedetto, Equivalence Notions for Discrete-Time Stochastic Control Systems, CDC-2015
- …

Future directions

Methodological issues

- Stochastic CPSoS
- Co-design of control algorithms with communication infrastructures
- Software tools
- …

Application domains

- Autonomous vehicle control with nonideal communication infrastructures
- Other applications: Micro-grid, Systems biology, …
- …

International collaborations on formal methods

- Paulo Tabuada, UCLA (USA)
- Antoine Girard, CNRS (France)
- Karl Henrik Johansson, KTH (Sweden)
- Majid Zamani, University of Munchen (Germany)
- Manuel Mazo, TUDelft (The Netherlands)
- Dimos Dimarogonas, KTH (Sweden)

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