Part II: Control of Cyber-physical systems

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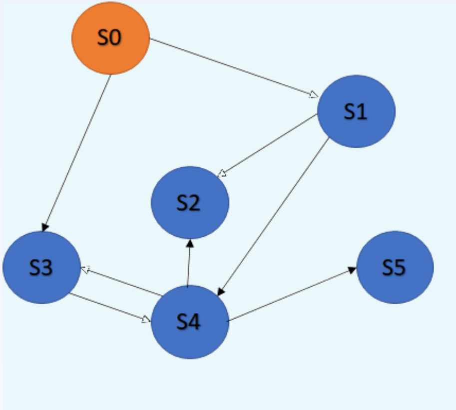
General formulation

- In this second part we will consider CPS described as multi-agents systems modeled by means of directed graphs (digraphs)



- Each node S_i of the graph is a dynamical LTI system
- Edges are used to model communication between agents

General formulation

We will consider multi-agents control problems (generically called here *synchronization problems*) where the CPS is made up of

- 1 *leader node* S_0
- N *follower nodes* S_i $(i = 1, 2, \ldots, N)$
- The agents cooperate in order to perform a task possibly dictated (to some extent) by the leader node
- In order to perform the assigned task the follower nodes exploit information shared on the communication network represented by the digraph $\mathcal{G} = \{\mathcal{V}, \mathcal{E}\}$
- Examples: autonomous vehicles platooning, unmanned air vehicles (UAVs) formation control, control of autonomous mobile robots team, ...

General formulation: cooperative tracking problems

- In this part we will mainly focus on *cooperative tracking problem* where the task to be performed is dictated by the leader node S_0 which generates the desired target trajectory (acting as a command generator exosystem)
- We will use the term *cooperative regulator problem* when the consensus is sought among agents in the absence of a leader node

- Assumption: the N follower agent are identical

- Possible peculiar problems of CPSs:
  - Each agents may be subjected to actuator/sensor faults/attacks
  - Information flow through the network may be affected by time-delay

Course material: Part II

- **Lecture Slides/Notes**
- **Scientific papers** (suggested during lessons)

Further readings: one more book....

B5 *Cooperative Control of Multi-Agent Systems*, F. Lewis et al., Springer London , 2013

Agents mathematical models

- The dynamics of the **leader node** S_0 is described by

$$\dot{x}_0 = Ax_0, \; y_0 = Cx_0 \tag{1}$$

where $x_0 \in \mathbb{R}^n$, $y_0 \in \mathbb{R}^p$

- The dynamics of the N identical **follower nodes** S_i is described by

$$\dot{x}_i = Ax_i + Bu_i, \; y_i = Cx_i \tag{2}$$

where $x_i \in \mathbb{R}^n$, $u_i \in \mathbb{R}^m$, $y_0 \in \mathbb{R}^p$ and $i \in \mathcal{N} = \{1, 2, \ldots, N\}$

- The triple (A, B, C) is *stabilizable* and *detectable*

Communication network modeling

- The **follower nodes** S_i share information through a communication network represented as a digraph $\mathcal{G} = \{\mathcal{V}, \mathcal{E}\}$ with N nodes $\mathcal{V} = \{v_1, v_2, \dots, v_N\}$ and a set of edges (arcs) $\mathcal{E} \subset \mathcal{V} \times \mathcal{V}$
- The **leader node** S_0 send information to some of the follower nodes
- The **leader node** S_0 is not affected by any of the follower node
- To describe connection between the leader node and the graph $\mathcal{G}$ of follower nodes we define the **augmented graph** $\overline{\mathcal{G}} = \{\overline{\mathcal{V}}, \overline{\mathcal{E}}\}$ where $\overline{\mathcal{V}} = \{v_0, v_1, \dots, v_N\}$, $\overline{\mathcal{E}} \subset \overline{\mathcal{V}} \times \overline{\mathcal{V}}$

Part II outline

- Experimental modeling of the agents
  - Set-membership identification
- Modeling of the communication network
  - review of basic graph-theory
  - basic consensus problem with continuous-time agents
- Cooperative control of multi-agents systems
  - Structural properties of LTI systems (review and extension)
  - Optimal linear quadratic (LQ) control of continuous-time systems
  - Distributed optimal control of multi-agent systems
- Additional topics possibly considered (depending on available time)
  - Formation control
  - Platooning
  - Cooperative control in presence of actuator/sensors attacks
  - Cooperative control in presence of communication network delay