Elective in Robotics 2014/2015

Analysis and Control of Multi-Robot Systems

Introduction to the Course

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DIPARTIMENTO DI INGEGNERIA INFORMATICA
AUTOMATICA E GESTIONALE ANTONIO RUBERTI

SAPIENZA
UNIVERSITÀ DI ROMA

Organization

Lecturer:

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Course Web-site:

http://www.dis.uniroma1.it/~oriolo/mrs/

Schedule:

28/4/2015: **15:45-17:15**; **17:30-19:00** **(room A4)**

29/4/2015: **15:45-17:15**; **17:30-19:00** **(room A4)**

5/5/2015: **15:45-17:15**; **17:30-19:00** **(room A4)**

6/5/2015: **15:45-17:15**; **17:30-19:00** **(room A4)**

Organization

- Goals of the course:
  - Provide some theoretical tools for analyzing and synthetizing cooperative behaviors in multi-robot systems
  - Use these tools to illustrate some recent applications
    - In simulation
    - With real experiments (quadrotor UAVs)

- Topics of the course:
  - Algebraic Graph theory
  - Decentralized Control and Estimation
  - Consensus-like protocols
  - Graph Connectivity and Graph Rigidity
  - Passivity Theory
  - Port-Hamiltonian modeling
  - Formation Control

Multi-Robot Systems

Multi-Robot Systems are systems composed of multiple interacting dynamic units.

biologically inspired…

shimmering of giant honeybees
Kastberger G, Schmelzer E, Kranner I (2008) Social Waves in Giant Honeybees Repel Hornets. PLoS ONE 3(9): e3141.

synchronizing fireflies
Buck, J and Buck, E (1968) Mechanism of Rhythmic Synchronous Flashing of Fireflies. Science 22 159(3821):1319-1327.

Multi-Robot Systems

Multi-Robot Systems are systems composed of multiple interacting dynamic units.

Synchronization

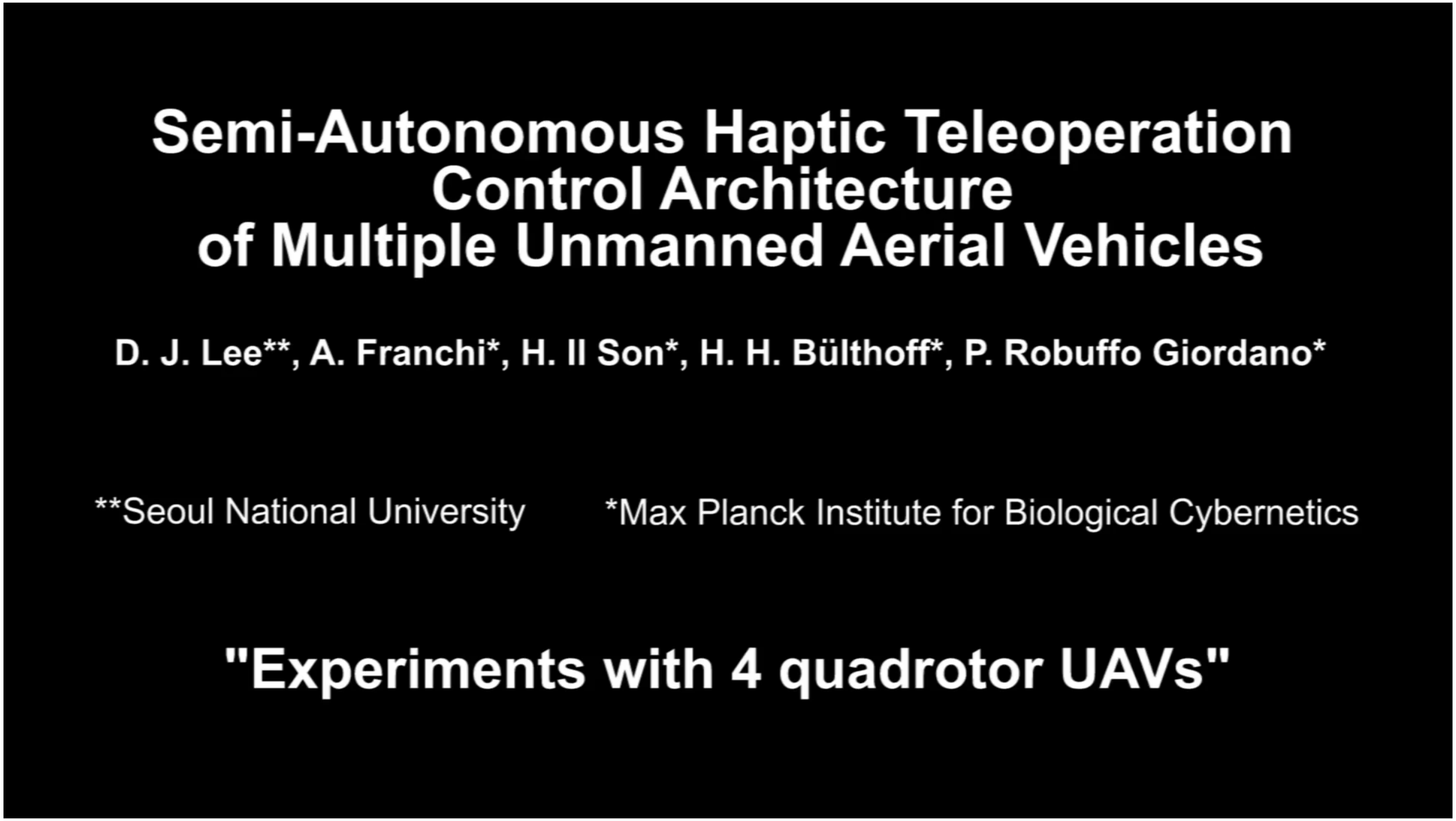
An agreement by multiple systems on a common state

Coordination

Managing of multiple interacting systems to achieve a team objective

Multi-Robot Systems

Multi-Robot Systems are systems composed of multiple interacting dynamic units.



Semi-Autonomous Haptic Teleoperation Control Architecture of Multiple Unmanned Aerial Vehicles

D. J. Lee, A. Franchi*, H. Il Son*, H. H. Bülthoff*, P. Robuffo Giordano***

**Seoul National University

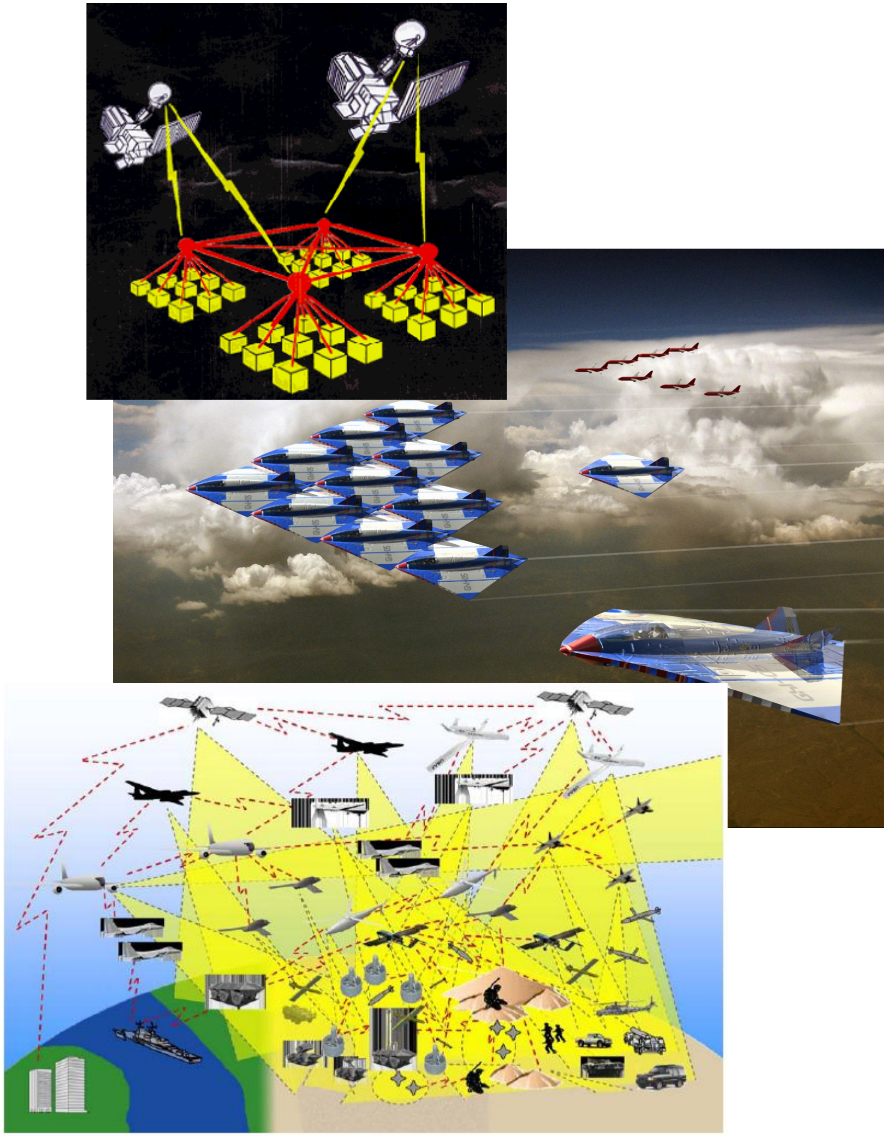
*Max Planck Institute for Biological Cybernetics

"Experiments with 4 quadrotor UAVs"

From Nature to Engineered Systems

Course Goals

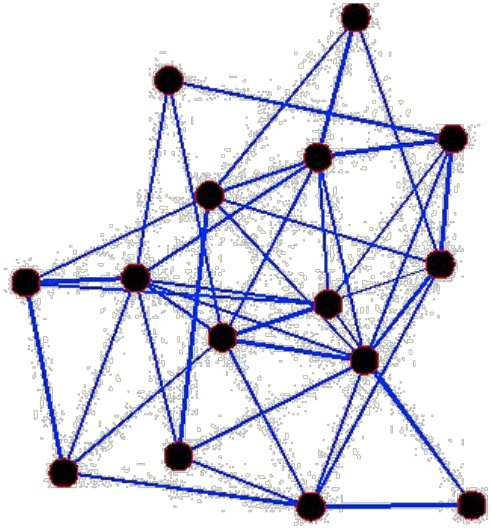
- Modeling of multi-robot systems
  - Dynamics
  - Interconnections
- Analysis of multi-robot systems
  - Stability and performance
  - Convergence
- Applications of multi-robot systems
  - Formation Control
  - Localization
  - Bilateral Shared Control

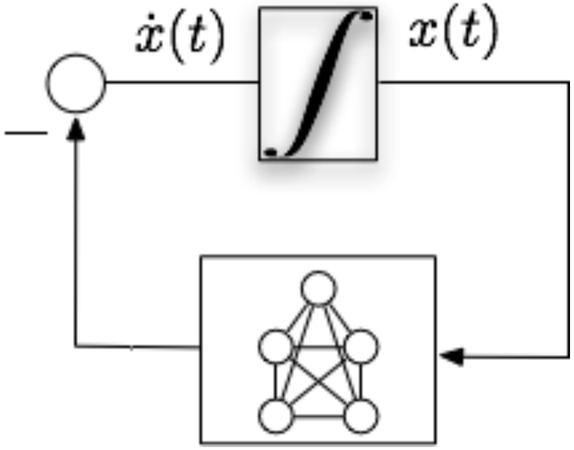


From Nature to Engineered Systems

Course Goals

- Graph Theory
  - Algebraic graph theory
- Consensus and Agreement Protocols
  - undirected/directed communication
- Networks as Systems
  - graph theory ⇔ systems theory

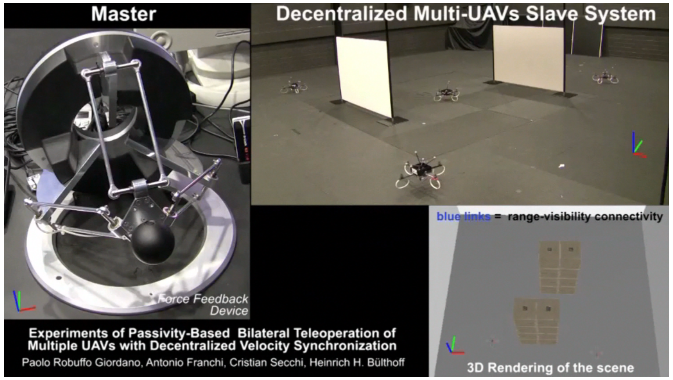




From Nature to Engineered Systems

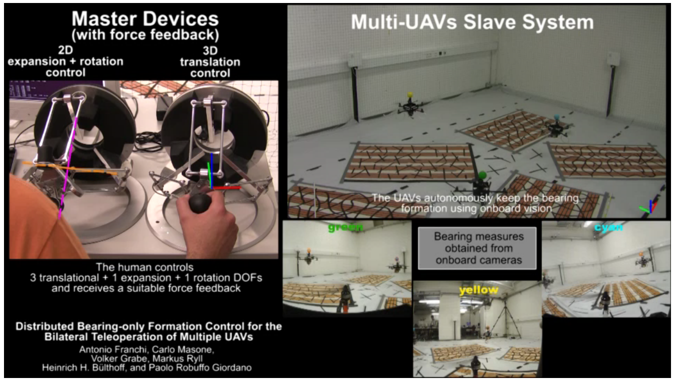
Course Goals

- Exploit energy-based techniques:
  - passivity
  - port-Hamiltonian modeling
- Passivity:
  - general and powerful framework
  - linear/nonlinear setting
  - related to I/O stability
- Port-Hamiltonian modeling
  - approach to model interconnected systems
  - based on the "energy flows"
  - strong link with passivity
- Applications
  - formation control of UAVs
  - connectivity maintenance
  - navigation and exploration



Experiments of Passivity-Based Bilateral Teleoperation of Multiple UAVs with Decentralized Velocity Synchronization

Paolo Robuffo Giordano, Antonio Franchi, Cristian Secchi, Heinrich H. Bülthoff



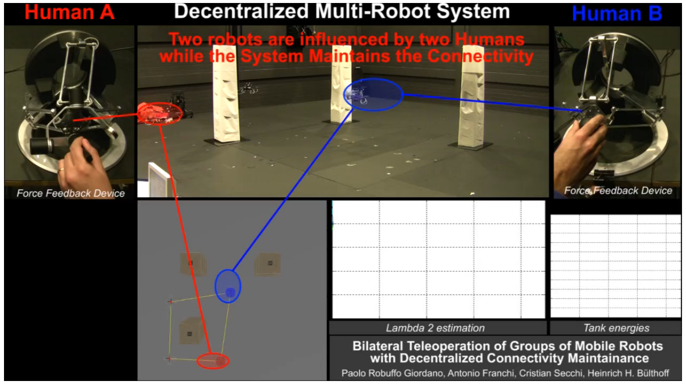
The UAVs autonomously keep the bearing formation using onboard vision

Bearing measures obtained from onboard cameras

The human controls 3 translational + 1 expansion + 1 rotation DOFs and receives a suitable force feedback

Distributed Bearing-only Formation Control for the Bilateral Teleoperation of Multiple UAVs

Antonio Franchi, Carlo Masone, Volker Grabe, Markus Ryll, Heinrich H. Bülthoff, and Paolo Robuffo Giordano



Two robots are influenced by two Humans while the System Maintains the Connectivity

Bilateral Teleoperation of Groups of Mobile Robots with Decentralized Connectivity Maintainance

Paolo Robuffo Giordano, Antonio Franchi, Cristian Secchi, Heinrich H. Bülthoff

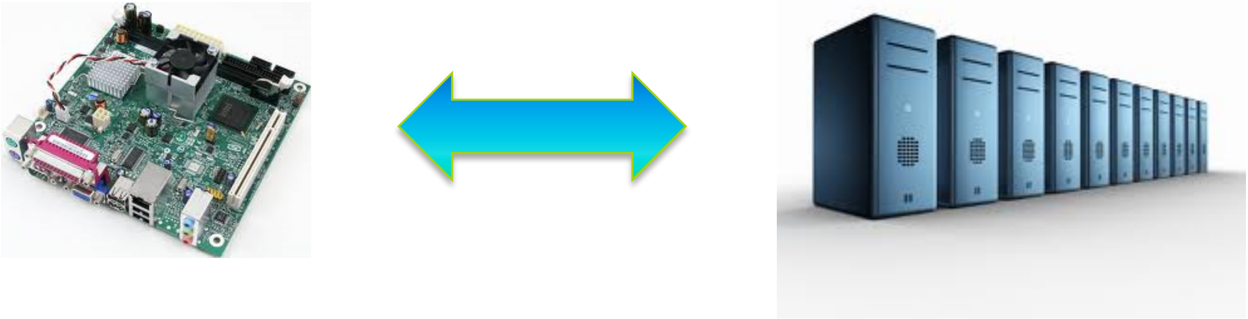
Networked Dynamic Systems

- **Decentralization**: limited sensing/communication and/or computing power

- Every agent must elaborate the gathered information to run its local controller

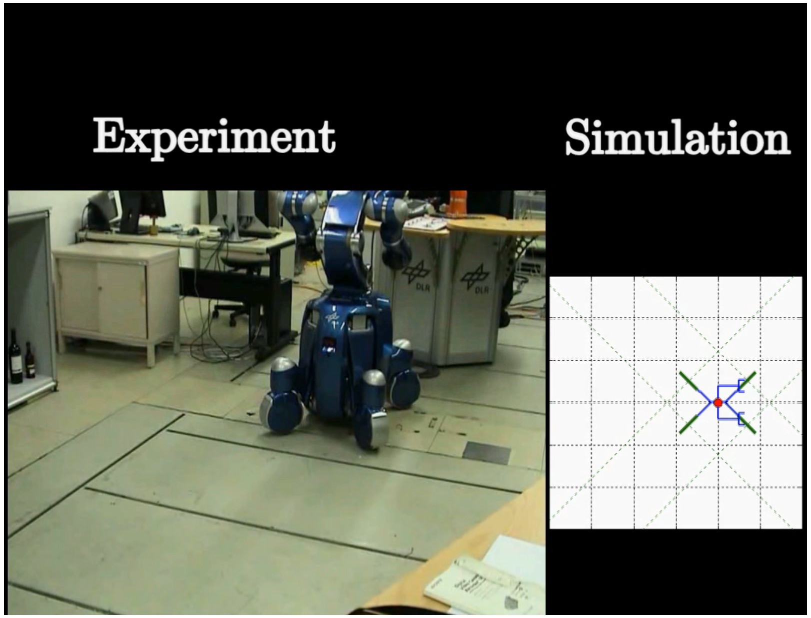
- The controller complexity is related to the amount of needed information

- If the whole state is needed, the complexity (~ computing power) increases with the number of agents
  - May easily become infeasible
  - And would need to know the whole state...



From Nature to Engineered Systems

Course Goals



- Another example of coordination

- The wheels must "coordinate" their orientations and spinning motion

- The result is a coordinate displacement of the "shared" platform chassis

- However, this is not exactly what we're aiming at!

- **Centralization**: this system is completely centralized
  - The wheels have no "independent brain"
  - A single central unit knows the whole state and commands the wheel actions
  - No constraints on sensing and commucation
  - What if instead of 4 wheels, there were 100 wheels? The controller (and communication) complexity grows with the number of components

From Nature to Engineered Systems

Course Goals

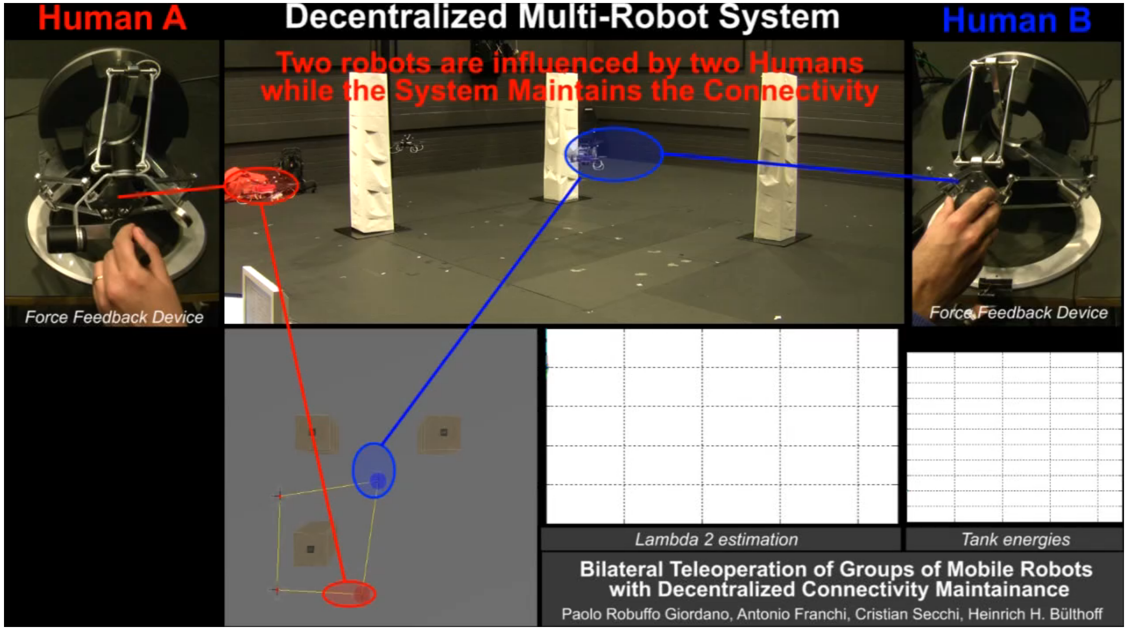
- In this example, no central unit is present

- Every agent has “its own brain”

- Relative communication and sensing depends on the current state
  - within some range
  - in visibility (no occlusions)

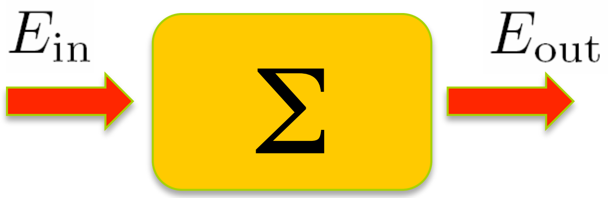
- **The complexity of each agent controller doesn’t depend on the number of agents**

- Of course:
  - harder to design
  - harder to analyze
  - but closer to how nature works!



Passivity

- **Passivity**: intuitively, something that does not produce internal energy



$E_{\text{out}} \leq E_{\text{in}}$

- A generic nonlinear system $\begin{cases} \dot{x} & = & f(x) + g(x)u \\ y & = & h(x) \end{cases}$

is said to be passive if there exists a storage function

$$V(x) \in \mathcal{C}^1 : \mathbb{R}^n \to \mathbb{R}^+$$

such that $\dot{V} \leq y^T u$ or equivalently

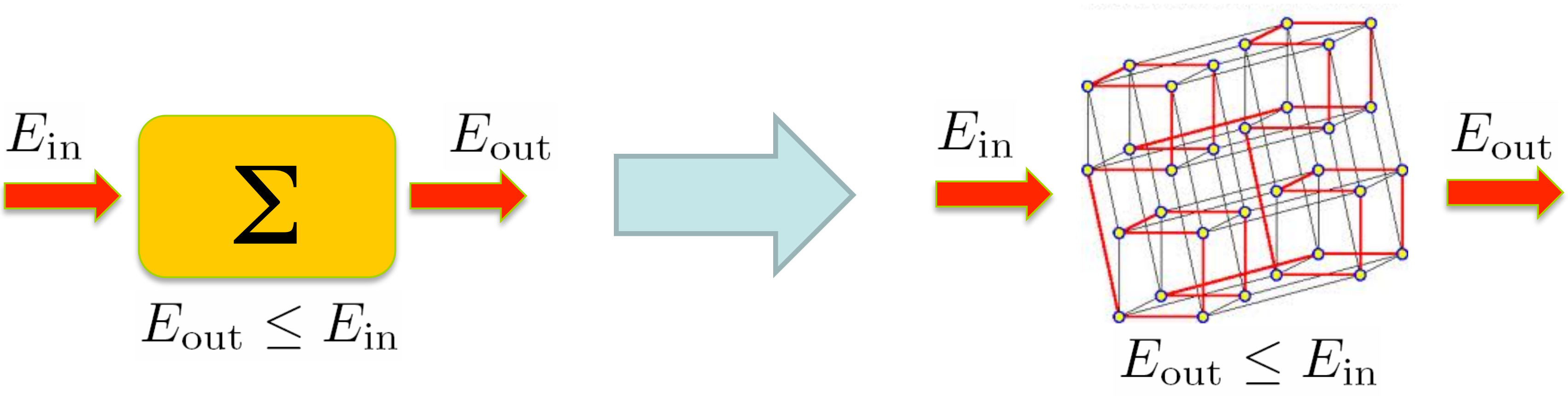
$$V(x(t)) \leq V(x(t_0)) + \int_{t_0}^{t} y^T(s)u(s)\mathrm{d}s$$

Current energy is at most equal to the initial energy + supplied energy from outside

- This condition can be interpreted as "no internal generation of energy"

Passivity: Internal Structure

- An intuition: proper interconnections of passive systems are passive



- Is this a general fact?
- Can we reduce a passive system into the “proper interconnection” of atomic passive sub-systems?

- Is there a network structure behind passivity?
  - … network structure -> multi-robot
  - … network structure + passivity -> port-Hamiltonian Modeling