KFUPM

EE 550 – Linear Control Systems

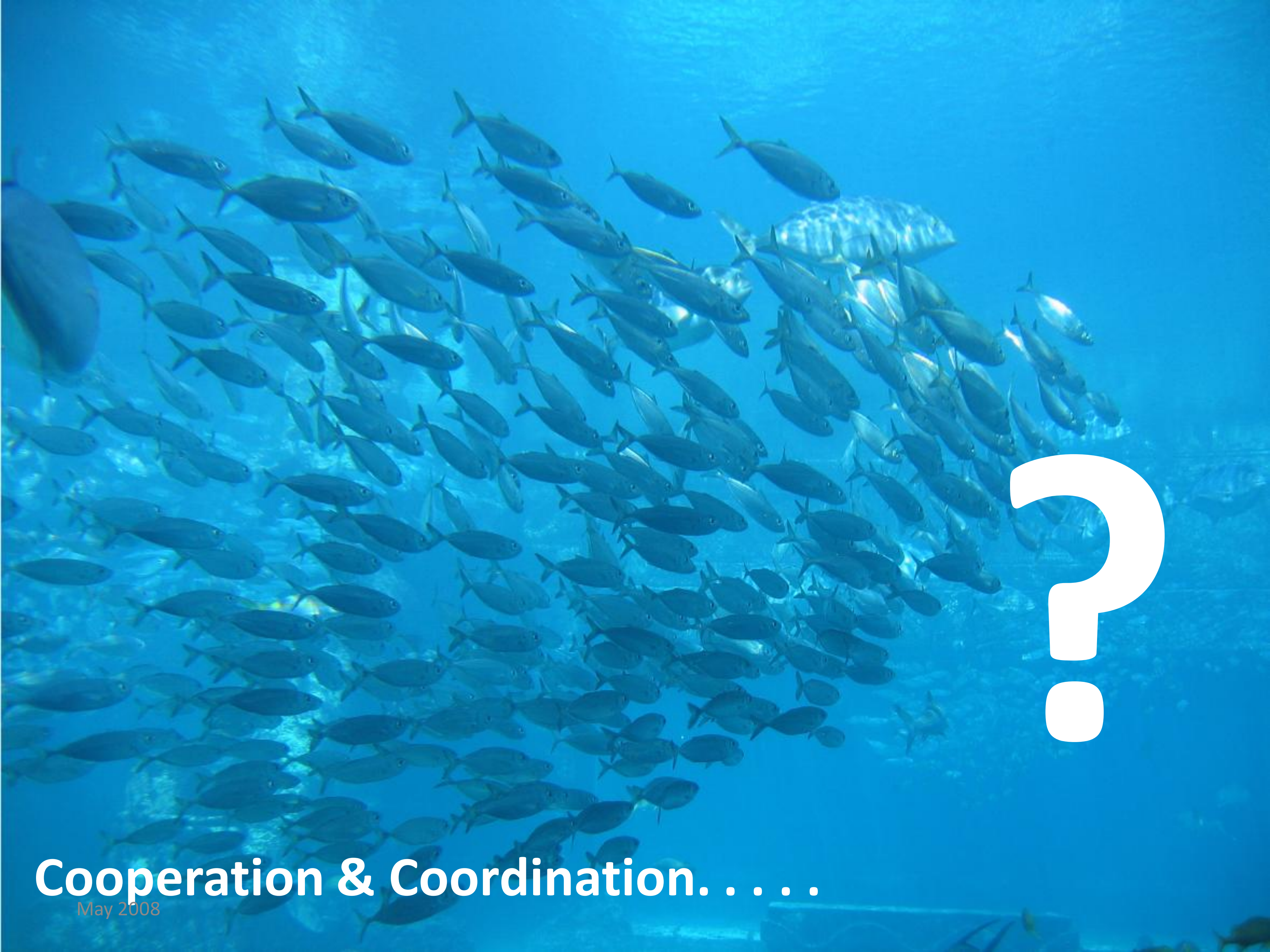
Course Paper

Cooperative Control of Multi-Vehicle Systems

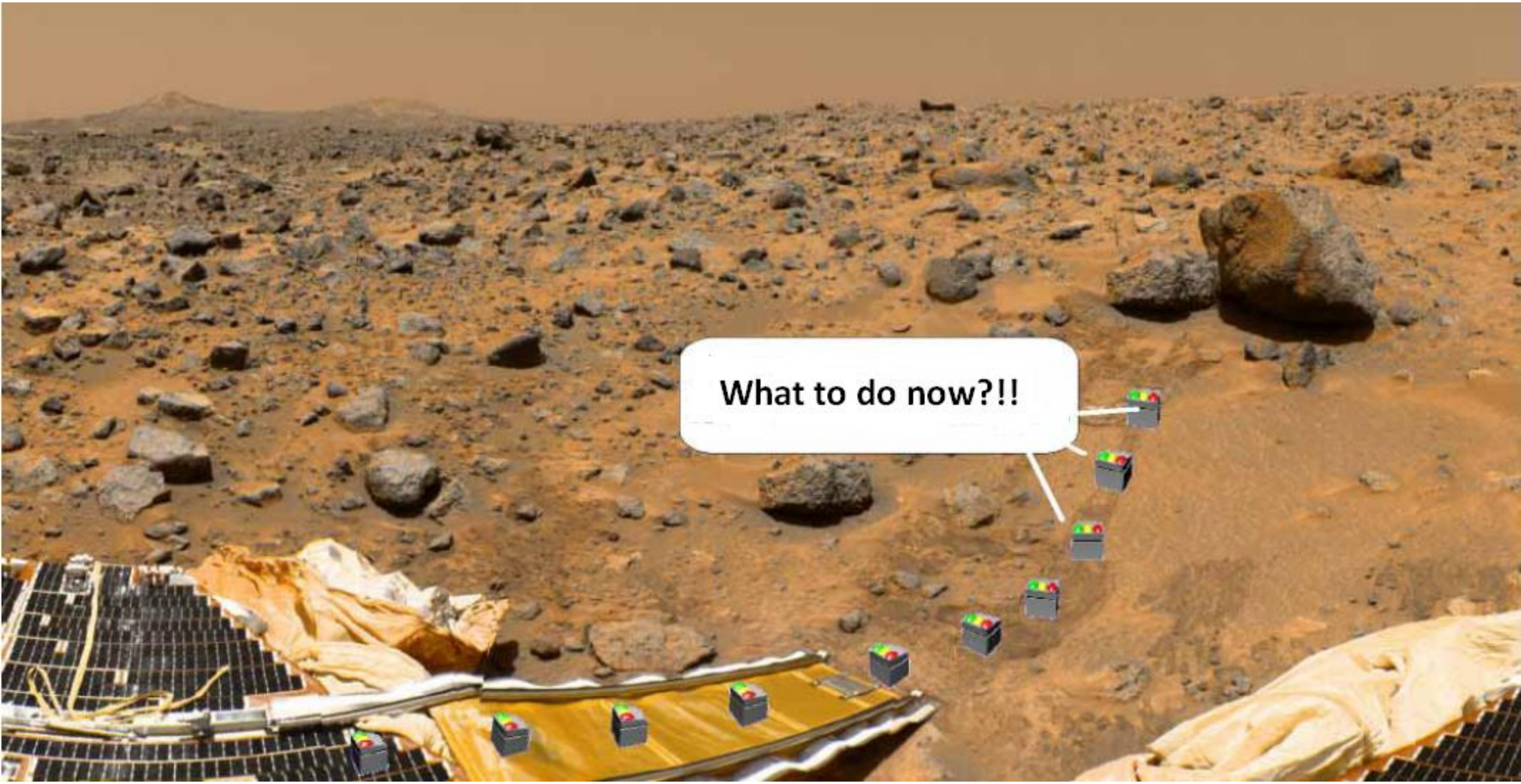
Mohammad Shahab (ID.227598),

Systems Engineering dept.

May 2008


?
Cooperation & Coordination. . . . .
May 2008

Mars Exploration



How to control each one?........ Command Center? Local Decision?

Automated Transportation Systems

How to arrange vehicles?... Straight line? Triangular?

Outline

1. **Motivation**
2. **Definitions: Cooperative Control**
    1. Consensus Problem
    2. Formation Control
    3. Other: Rendezvous, Flocking, Swarming
3. **Decentralized Control**
4. **Connectivity Graphs**
5. **Control Design**
6. **Research Directions**
7. **Simulation Examples**

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Motivation

- Distributed Operation
- Multi Agents: vehicles, manipulators, ants!
- Local Control: Local objectives, independent
- Limited Capability: Sensing range, Communication, Processing
- Global Objectives: Group goal, Higher-level command
- Complexity: too many agents
- Scalability, large and not fixed number of interconnected systems
- Dynamic: reactive and instantaneous actions

Cooperative Control, Definition

- is concerned with engineered systems that can be characterized as:

1. *collection* of
2. *interconnected* decision-making components (systems)
3. with *limited processing* capabilities,
4. *locally sensed information* and *limited inter-component communications,*
5. all seeking to achieve a *collective (global) objective*

- ‘multi-agent control’, ‘distributed control’, ‘networked control’, ‘swarms’ or ‘coordinated control’ = Cooperative Control

Consensus Problem

- *“the group to reach a position (or agreement) as whole”*

$$\lim_{t \to \infty} x_i(t) = \lim_{t \to \infty} x_j(t) \qquad (1)$$

x_i Position of vehicle *i*

- This behavior can be defined by

$$\dot{x}_i = \sum a_{ij} \cdot (x_i - x_j)$$

  – averaging

Formation Control

- *"to drive the agents to special configuration such that their relative position satisfy a desired spatial and physical constraints"*

$$\dot{x}_i = \sum (x_i - x_j - r_{ij})$$

- Or <u>in general</u>

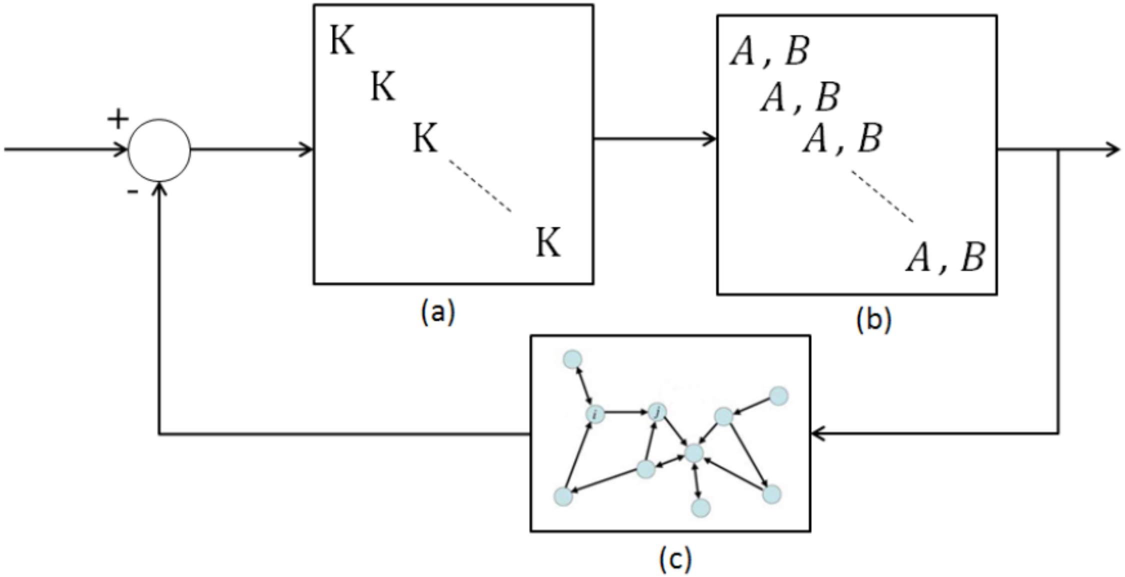
$$\dot{x}_i = \sum g(x_i - x_j)$$

Other concepts

- **Swarms**
  - *"to move or gather in group"*
  - a specific formation (shape) is not maintained
  - 'swarm' often used for *natural biological systems*
- **Rendezvous**
  - *"to meet at a pre-arranged position and time"*
  - when an agent is approaching its destination faster than other, it tries *dynamically* to slow down to meet the requirement of the group in position and time (**Military** application)
- **Flocking,** Rules of *Reynolds*:
  - to stay close to neighboring flock mates (Cohesion);
  - to avoid collision with neighboring flock mates (Separation);
  - to match velocity of neighboring flock mates (Alignment).

Decentralized Control

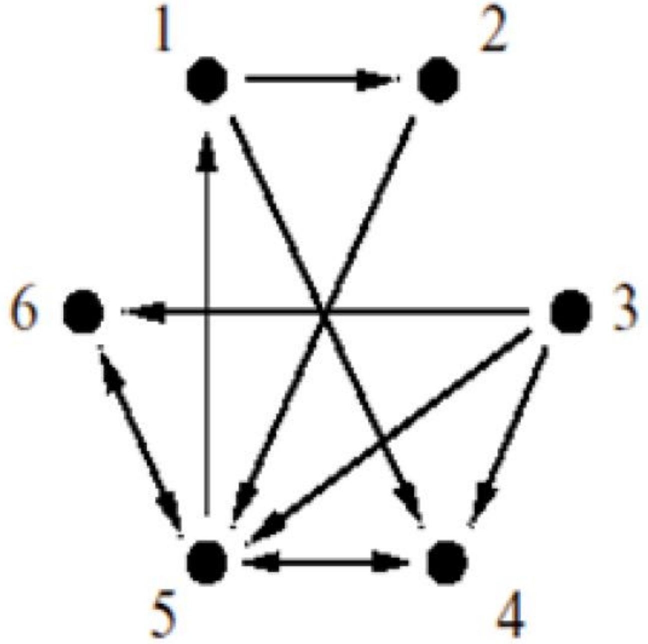
- Decisions (control) of each individual agent is computed *locally*
  - No Central center of control
  - No coupling
- Decentralized Controller:
  - properly designed to meet the objective of the whole group
  - cooperation needs sharing information, through *communication*



Connectivity Graphs

- Utilize ***Graph Theory***
  - Assuming access to neighbor's state (position), only neighbors!
  - Vehicle 1 can 'see' 2,4 (so, neighbors) & vehicle 3 'see' 4,5,6
  - This connectivity graph is characterized by **Laplacian Matrix**

$$L = \begin{bmatrix} 1 & -\frac{1}{2} & 0 & -\frac{1}{2} & 0 & 0 \\ 0 & 1 & 0 & -1 & 0 & 0 \\ 0 & 0 & 1 & -\frac{1}{3} & -\frac{1}{3} & -\frac{1}{3} \\ 0 & 0 & 0 & 1 & -1 & 0 \\ -\frac{1}{3} & 0 & 0 & -\frac{1}{3} & 1 & -\frac{1}{3} \\ 0 & -\frac{1}{2} & 0 & 0 & -\frac{1}{2} & 1 \end{bmatrix}$$



Connectivity Graphs

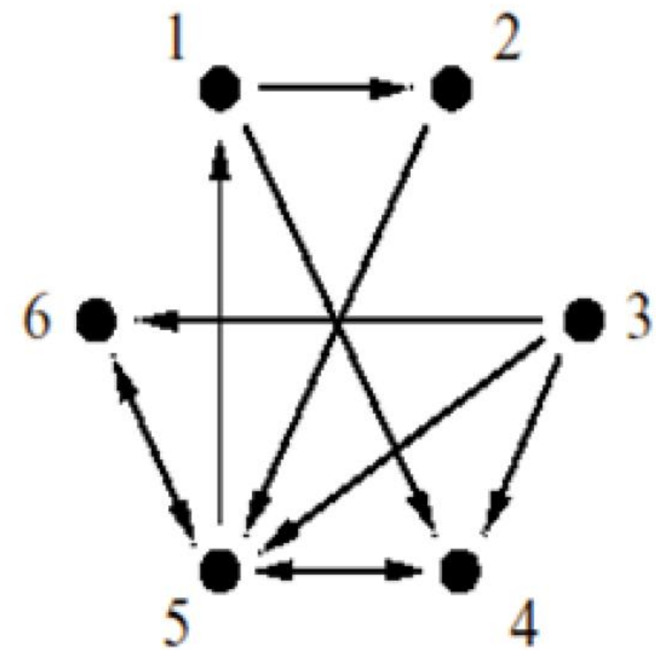
- **Recall**

$$\dot{x}_i = \sum_{\forall j \in \mathcal{N}_i} a_{ij} \cdot (x_i - x_j)$$

- So for a group of *N* vehicles,

$$\dot{\boldsymbol{X}} = -L\boldsymbol{X}$$

$$\boldsymbol{X} = [x_1 \quad x_2 \quad \cdots \quad x_N]^{\boldsymbol{T}},$$



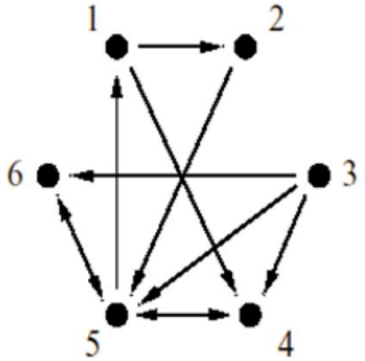
Convergence (Stability)

- You can check the eigenvalues of

$$-L.$$

- ***L*** could be *time-varying* (*because of communication losses*)
- A connected graph is when there is a path between any two agents
- For **undirected** graph (i.e. edges of a graph has no direction, both vehicles see the other)

  - *"Consensus is reached asymptotically if there exist infinitely many consecutive bounded time intervals such that the union of the graphs over such intervals is totally connected",* Jadbabaie *et al.*



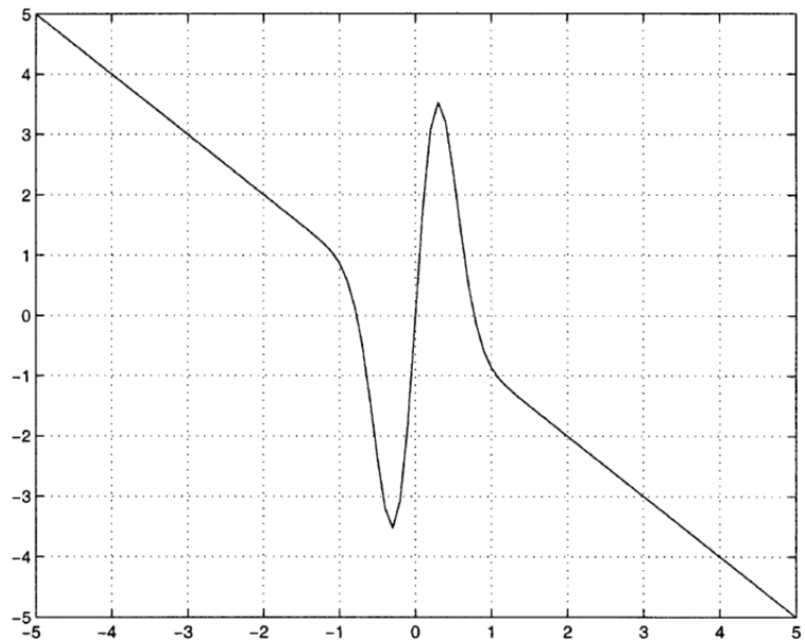
- Consensus point (steady state) = average of initial positions

Control Design (decentralized)

- **Performance Output**

$$z_i = G(x_i) = \sum_{\forall j \in \mathcal{N}_i} g(x_i - x_j)$$

Interaction Function



- One proposed design

$$u_i = -K \sum_{\forall j \in \mathcal{N}_i} a_{ij} \cdot (x_i - x_j)$$

- Other design

$$u_i = - \sum g(x_i - x_j - d_{ij}) \cdot (x_i - x_j - d_{ij})$$

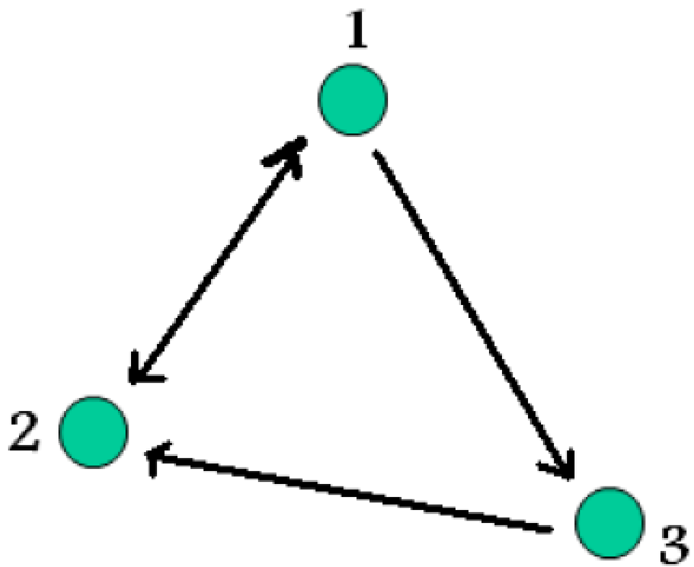
  - g(.) could be designed from the concept of Artificial Potential Force,
  - Provide collision avoidance also

Research Directions

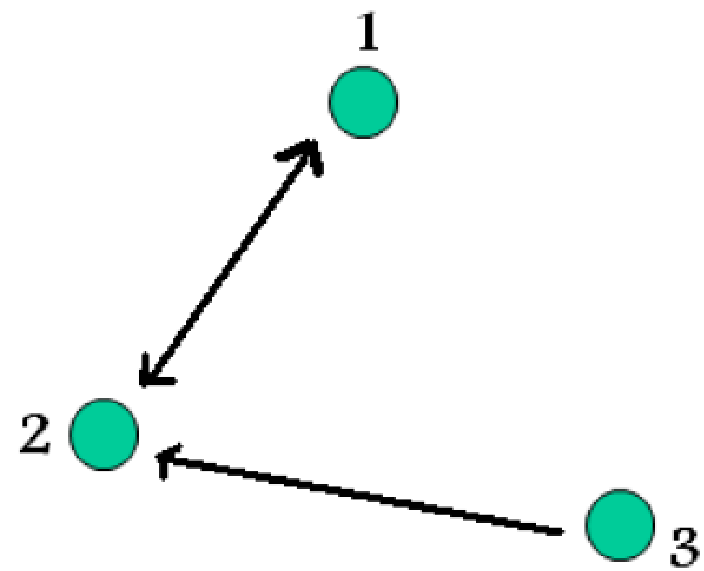
- **Cooperative State Estimation**
  - accessibility to other vehicles state, not necessarily!
  - existence of noise
  - Estimating $(x_i - x_j)$ (x_i *not required*)
- **Hybrid Control:** *Control Theory & Computing*
  - non-smooth dynamics (discontinuous)
  - for example: all of a sudden new vehicle join the group, *N* changed
- **Stochastic Approaches**
  - To *model* change of connectivity graphs
- **Time-delay Systems**
  - delays in information exchange between vehicles

Simulation

- Consider **2** connectivity graphs



$$L = \begin{bmatrix} 1 & -{}^{1}\!/_{2} & -{}^{1}\!/_{2} \\ 0 & 1 & -1 \\ -1 & 0 & 1 \end{bmatrix}$$

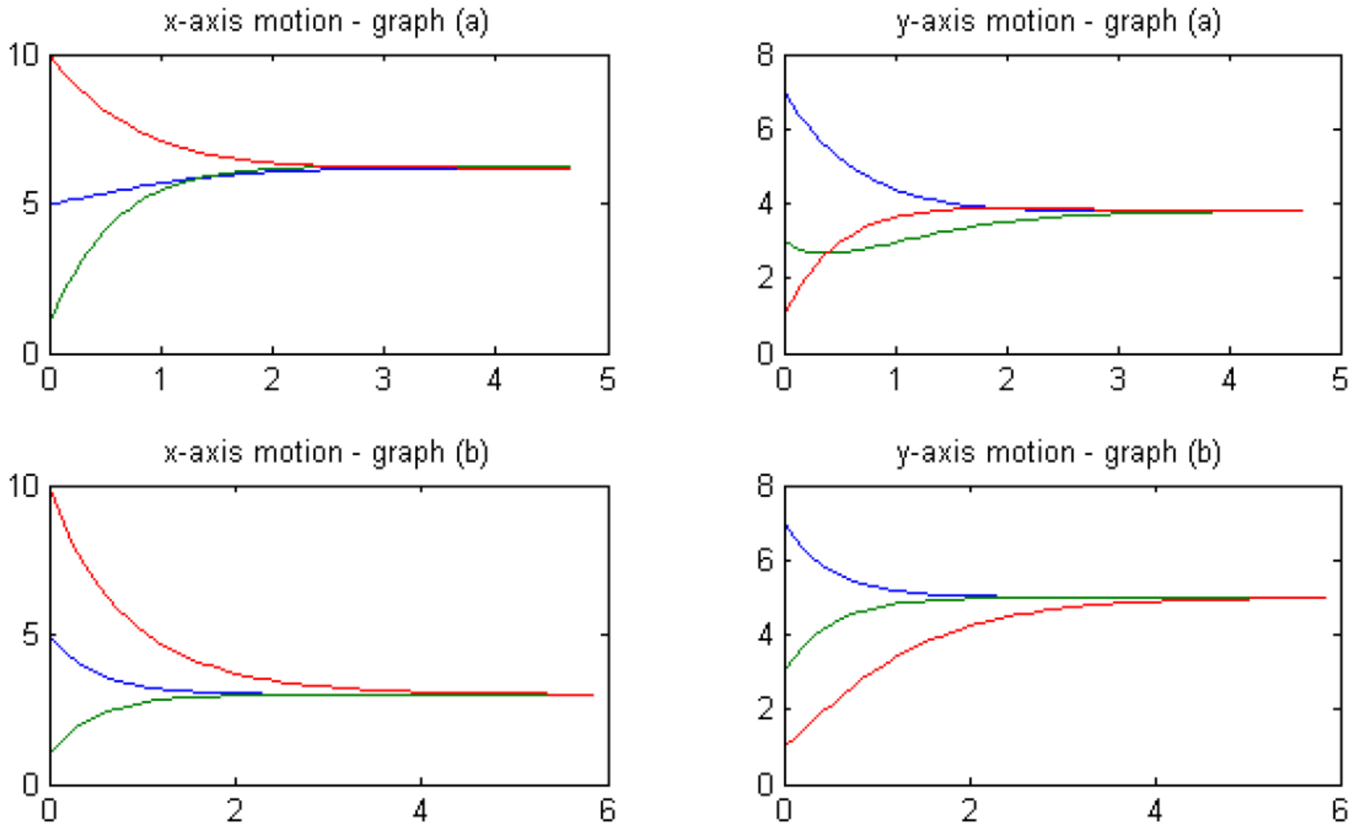


(b)

Simulation Result

- 3 vehicles, 2D motion with single-integrator (i.e. 1st order) system.

$$\dot{X} = -LX$$



Cooperative Control, Ending Remarks

- Relatively new field of research
- Bio-inspired
- Wide and *interesting* applications
- Decentralized Solution
- Graph theory & Control Theory

THANKS

- ***Q & A***