Application of Complex Networks:

Control of Networked

Multi-Agent Systems

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Complex Networks, Dec 25th, 2017

What Are ``Multi-Agent Systems''?

Cooperative Behaviors of Animals

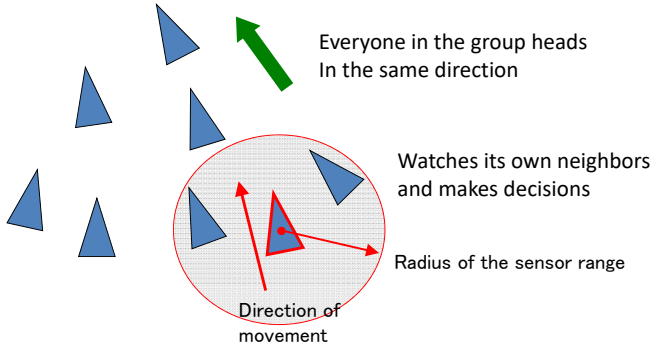
Wikipedia: Nikunj vasoya

Flickr User Critidoc

Wikipedia: Geoff Gallice

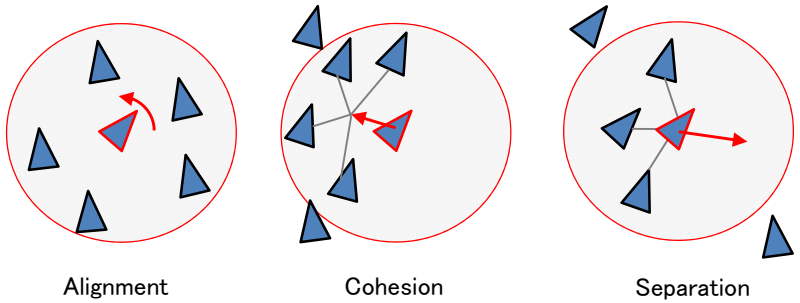
Model of Birds' Flocking: Boids

- Formation flying without any leader
- What are the simple control laws for each bird?



Model of Birds' Flocking: Boids

- Three rules: Use the information within its own sensor range only.



- Simulation-based study

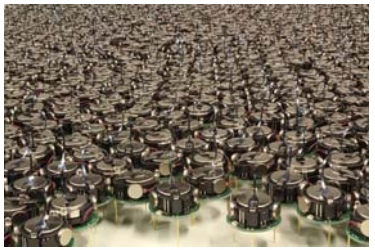
Raynolds (1987)

Boids Simulation

Autonomous Group Robots

Wikipedia: Halftermeyer

Wikipedia: Ralf Roletschek



Wikipedia: asuscreative

Dancing of Drones (ETH)

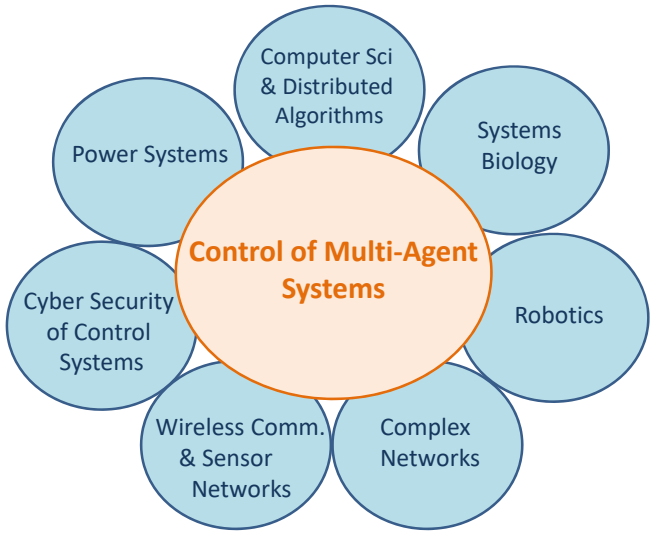
What Are Multi-Agent Systems?

- **Constituting elements**
  - Numerous agents which can make decisions autonomously
- **Cooperation**
  - Through mutual interactions, desired behaviors of the entire system can be realized
- **Tasks**
  - The agents possess a common goals/tasks

"Control" of multi-agent systems

- System theory not constrained by particular applications
- More complex and larger scale systems via networking

Relations to Other Areas



Outline

- What are Multi-Agent Systems?
- Application Examples
  - Groups of autonomous vehicles
  - Wireless sensor networks
- System Characterization
  - Information exchange among agents
  - Network structure and its description
- Related Areas

NecSys 2016

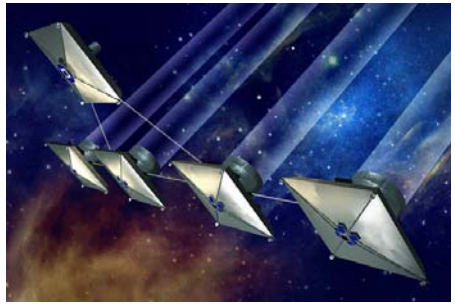
Dates: September 8th-9th, 2016

Place: Tokyo International Exchange Center, Odaiba

Cooperative Control of Vehicle Groups

Astronomical Observation by Groups of Satellites (1)

- NASA started for exploration of extrasolar planets (since 2000)
- Formation control: Centralized methods difficult for large numbers
- System design through distributed control is necessary

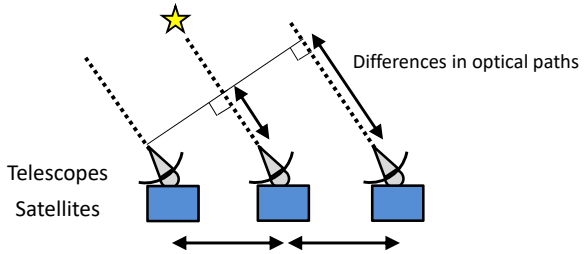


Courtesy NASA/JPL-Caltech
http://planetquest.jpl.nasa.gov/TPF-I/tpf-I_index.cfm

Astronomical Observation by Groups of Satellites (1)

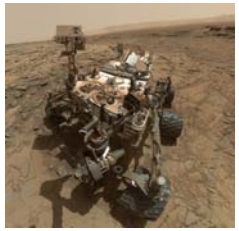
Astronomical Interferometer

- Resolution depends not on sizes of individual telescopes, but on distances between them.
- Using data from multiple telescopes, images are synthesized

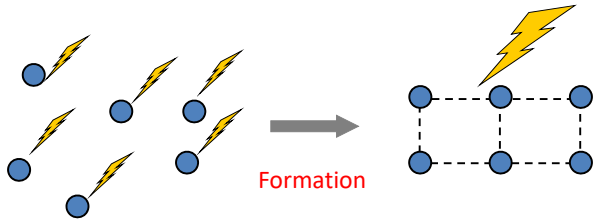


Vehicle Groups and Array Antennas

- Cluster of small robots for planetary exploration
  - High flexibility and reliability at lowcost
  - Communication is limited by on-board power
- Multiple antennas coupled for directed transmission
- Formation of robots based on distributed control laws

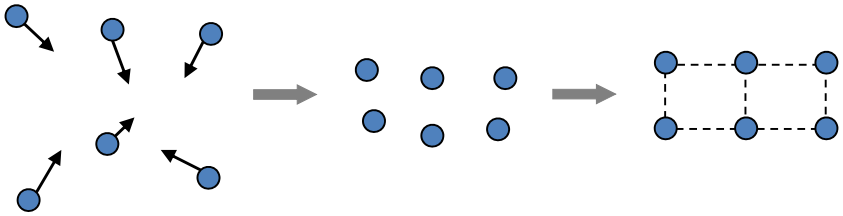


NASA Curiosity on Mars



Consensus Problem

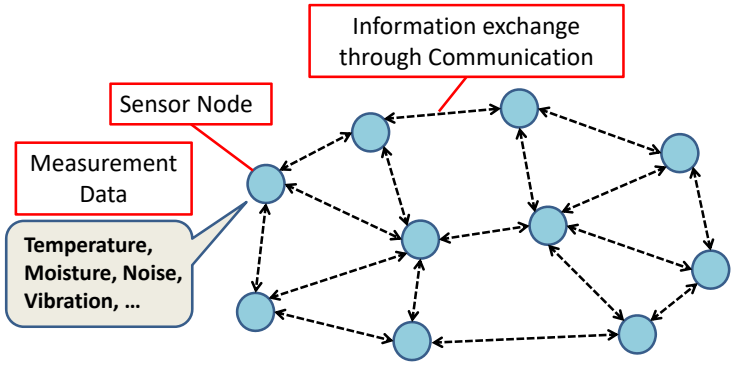
- Realization of Array Antennas
  1. Vehicles at various locations come together.
  2. They make desired formations and then maintain them.
- Based on local information, agents agree on their variables.
- One of the most fundamental problems in distributed control



Kiva Systems

Wireless Sensor Networks

Wireless Sensor Networks (WSNs)

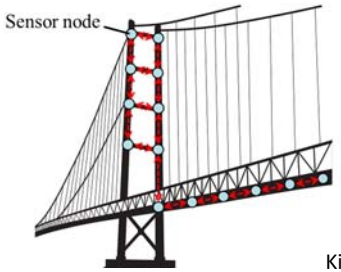


- Spatially distributed autonomous sensors with wireless communication capability
- Cost reduction for implementation and wide-area measurements
- Various application areas

Application Example of WSNs (1)

Health monitoring of large-scale structures

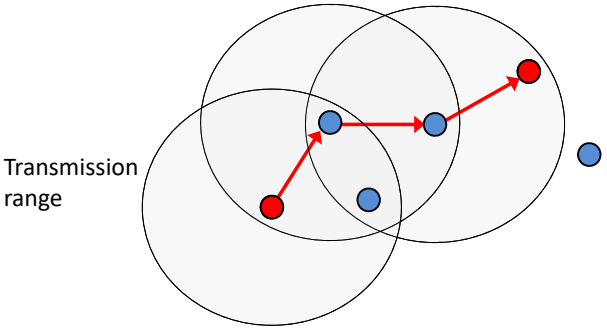
- To prevent accidents in buildings and bridges from aging
- Vibration is measured at multiple locations and then the data is analyzed.



Kim et al. (2007)

Multi-hop Communication

- Without any data center, nodes communicate with each other
- Autonomously routes are constructed
- Battery driven: Most power is used for wireless communication

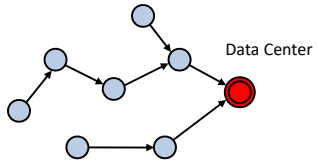


System Structures

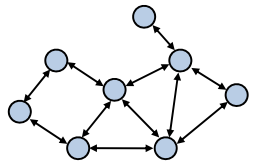
- Centralized: All data is collected at a data center
  - Possible to make global decisions
  - Data center has high load, and vulnerable against failures
- Distributed: Nodes make local decisions via info exchanges
  - When all nodes should share a specific value (average, etc)

Multi-agent systems approach

Centralized



Distributed

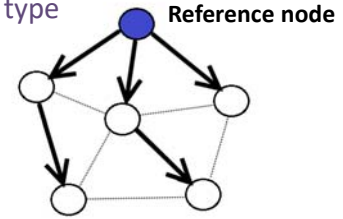


Application Example of WSNs (2)

Clock Synchronization

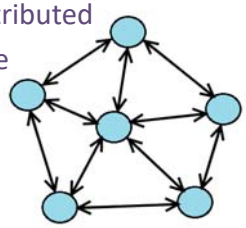
- Consistency in time among data is critical.
- Clocks in sensors have different speeds.
  - Error in time may occur among sensor nodes

Tree type



Vulnerable to node failures

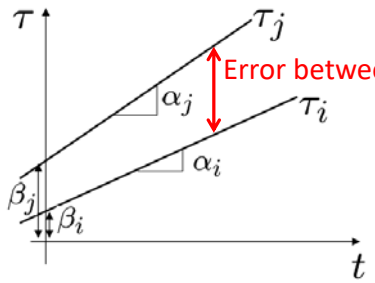
Distributed type



Protocol based on consensus problem

High precision and robustness

Clock Model in Sensor Nodes



- Clock of the ith sensor $\tau_i(t) = \alpha_i t + \beta_i$
- Modified clock with parameters $\hat{\alpha}_i$, $\hat{\beta}_i$

$$\hat{\tau}_i(t) = \hat{\alpha}_i \tau_i(t) + \hat{\beta}_i = \underbrace{\alpha_i \hat{\alpha}_i}_{\text{Adjusted drift}} t + \underbrace{\hat{\beta}_i + \beta_i \hat{\alpha}_i}_{\text{Adjusted offset}}$$

α_i : Drift
β_i : Offset
t : Absolute time

All sensors share a clock = Clock synchronization

Modeling of Agent Systems

Information Exchanges among Agents (1)

Characteristics of agent systems

- Each agent has dynamics, and autonomously makes decisions
- Data is exchanged for collaboration
  - Different information is physically distributed.

1. Wireless communication

- Speed/distance: Constrained by power consumptions
  - 10kbps～100 kbps, a few meters ～a few hundred meters
- Reliability/quality: More interference in large-scale systems
  - Low realtime capabilities influence sensing and control

Information Exchanges among Agents (2)

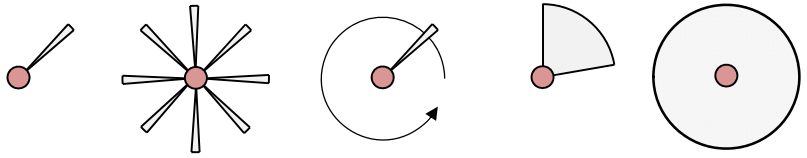
2. Interactions via sensors ⇨ Agents determine neighbors' positions

Distance sensors

- Ultra-sonic:
  - Short distance (a few meters)
  - Devices are small/inexpensive
- Lazer and infrared light:
  - ～a few 10 m, Very accurate

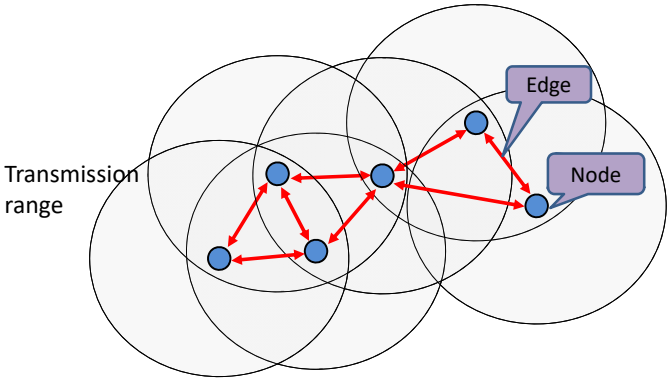
Vision sensors (Camera)

- Marking on objects to be measured
- Image processing
- Wide area in one image but in 2D



Modeling of Network Structure (1)

- At system level, important to know presence of data exchanges
- Mathematical description by graphs
- We can employ notions/tools from graph theory



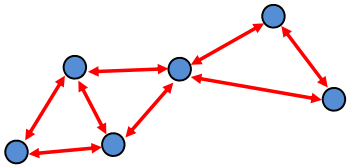
Modeling of Network Structure (1)

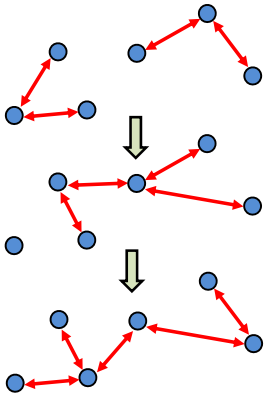
Static networks

- Vehicles measure each other's locations at all times

Dynamic networks

- Network changes depending on states and environment.





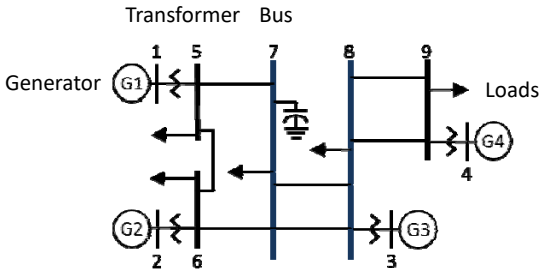
Multi-Agent Systems in Related Areas

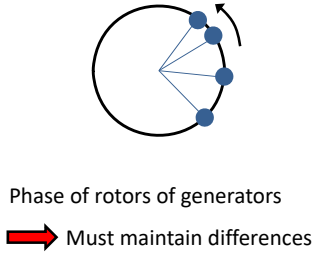
Power Systems

- Large-scale system connecting various generators to consumers
- In Smart Grids, communication and distributed control become critical.

Synchronization in Power Grids

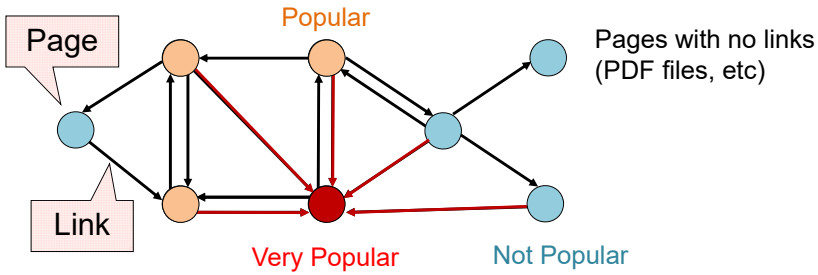
- Critical to synchronize output AC powers must synchronize
- Must consider network structures and nonlinear dynamics of various generators



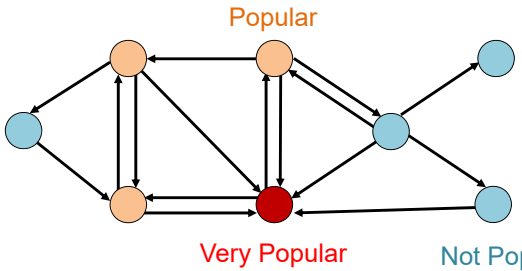


Search Engine Google

Network of Web Pages



PageRank Algorithm

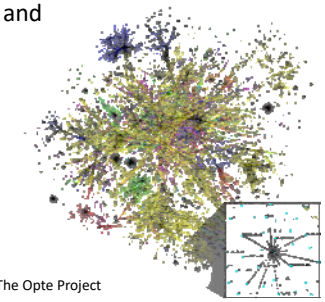


- Exploits the link structure among web pages
- Computes popularity/importance of pages: Used for ranking
- Based on agent systems' viewpoint, distributed computation has been developed

Brin & Page (1998), Ishii & Tempo (2014)

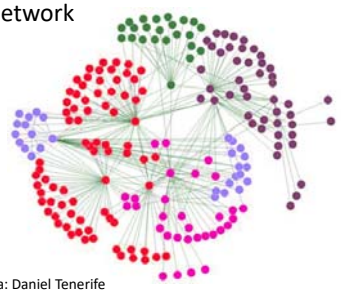
Network Science

Internet and Web



Wikipedia: The Opte Project

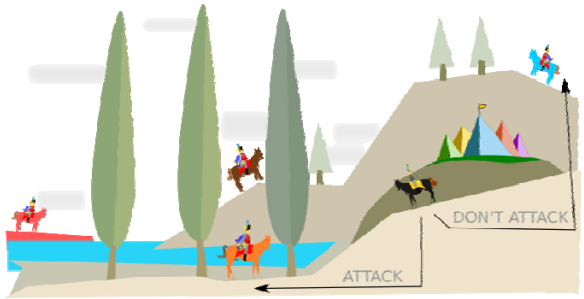
Social Network



Wikipedia: Daniel Tenerife

- Focus on network structures of complex systems
  - Traffic networks (roads and flight routes), Metabolic network of biological systems, Citation of academic papers, …
- Extracting common features: Scale free networks, Small world networks

Byzantine Agreement Problem in Comp. Science

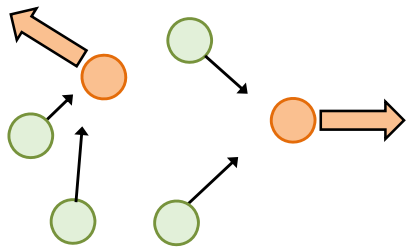


- Loyal generals vs Traitorous generals
- How can the loyal ones come to agreement?
- Robustness against faults in distributed algorithms

Rabin (1983), Motwani & Raghavan (1995), Lynch (1996)

Agents with Malicious Behaviors

- Some agents may misbehave due to noise, faults, adversaries…
- *Malicious* agents might attempt to deceive *normal* agents who work following a given protocol.



Vaidya, Tseng, & Liang (2012), LeBlanc, Zhang, Koutsoukos, & Sundaram (2013)
Dibaji & Ishii (2015)

Major Black Out due to Cyber Attacks

Conclusion

Conclusion

- Goals of “Control of multi-agent systems”
- Starting point: “Cooperation” & “distributed autonomous control” in nature
- Applications: Groups of autonomous vehicles, WSNs
- Modeling: Information exchanges and network structures
- New developments through interdisciplinary studies

Relations to Other Areas