Introduction to Multi-agent Systems and Applications

Masaaki Nagahara*

*The University of Kitakyushu

SICE Annual Conference 2021
7 September 2021

What is a multi-agent system? (definition)

Multi-agent system (MAS)

- A system consisting of multiple agents that can autonomously make decisions
- A system in which global tasks are achieved through local interactions

Smoke, which is a collection of gas particles, is not a MAS.
A flock of birds is a MAS.


The pictures are borrowed from wikipedia

What is a multi-agent system? (examples)

Examples of multi-agent systems:

- humans (collective behavior in human crowds, viral spreading, human social networks)
- creatures (ant's nest, flock of birds and fish)
- sensor network, antenna array
- robots, drones, autonomous cars
- smart grid, smart society, smart factory, etc.

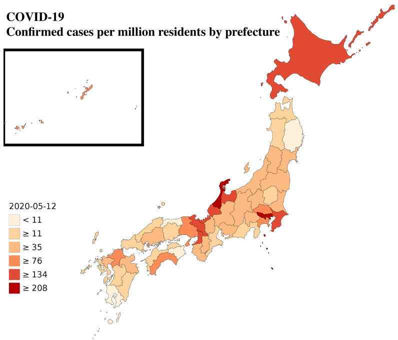
What is a multi-agent system? (examples)

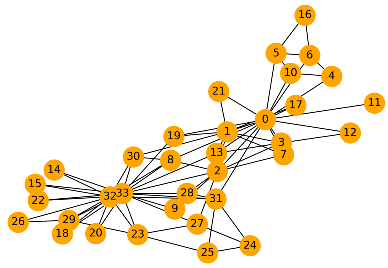
Examples of multi-agent systems:

- humans (collective behavior in human crowds, viral spreading, human social networks)
- creatures (ant's nest, flock of birds and fish)
- sensor network, antenna array
- robots, drones, autonomous cars
- smart grid, smart society, smart factory, etc.

MAS of humans

- collective behavior in human crowds
- viral spreading (COVID-19)
- human social networks
- control viewpoint: how to control human behaviors?
  - Cyber-physical-human systems

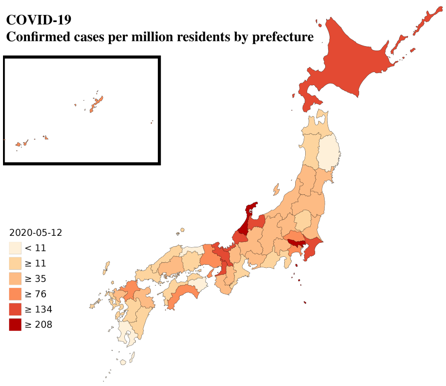


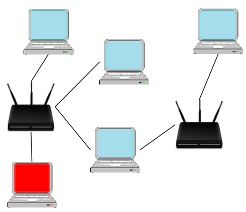


The left and center pictures are borrowed from wikipedia; the right graph is Zachary's Karate Club network.

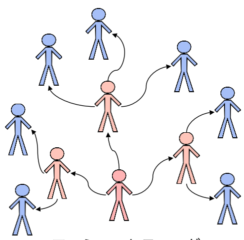
Viral spreading processes over networks

- COVID-19 outbreak





コンピュータウイルス

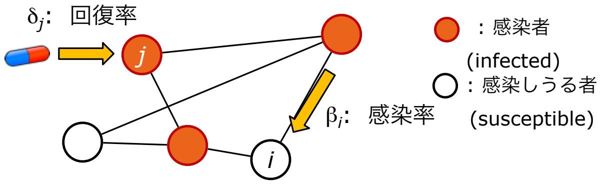


口コミマーケティング
Viral marketing

- How can we control them?
- You can use control theory for multi-agent systems!
  - *IEEE Control Systems Magazine*, Feb. 2016
  - "Control of Spreading Process"

Mathematical model of spreading processes

SIS (susceptible-infected-susceptible) model



Prevention of epidemic outbreak by distributing resources over networks

- Antidote allocation in node j increases δ_j
- Vaccinating node i decreases β_i

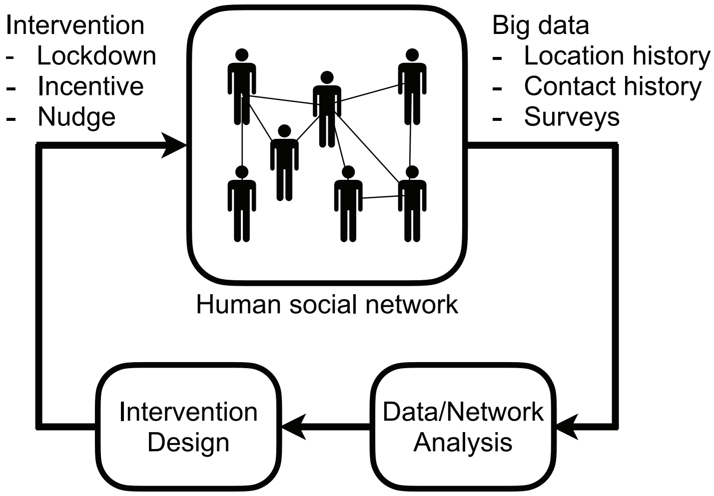
Cost-optimal distribution of medical resources?

Optimal resource allocation

- Time-invariant and closed networks $\rightarrow$ convex optimization [Preciado et al. 2014]
- Time-varying network with infection from outside of the network $\rightarrow$ geometric programming [Ogura, Nagahara, Preciado, 2015]

Cyber-Physical-Human Systems (CPHS)

A “feedback control” system to suppress COVID-19 epidemics in a human social network.



[Nagahara et al. *Advanced Robotics*, 2021]

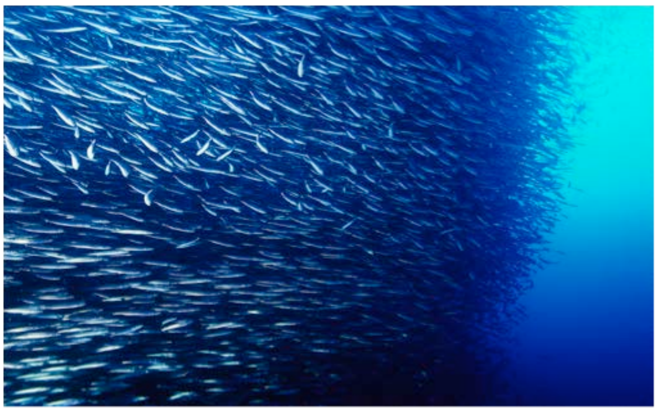
Cyber-Physical-Human System: we will discuss this later.

What is a multi-agent system? (examples)

Examples of multi-agent systems:

- humans (collective behavior in human crowds, viral spreading, human social networks)
- creatures (ant's nest, flock of birds and fish)
- sensor network, antenna array
- robots, drones, autonomous cars
- smart grid, smart society, smart factory, etc.

Flocking of birds and fish



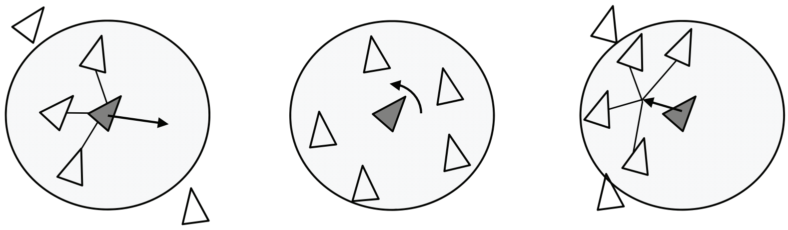
Kilobot 

All pictures are taken from Wikipedia

Boids

Craig Reynolds has proposed in 1987
Computer simulation of flocking of birds or fish
Rules for simulation:

- Separation: steer to avoid crowding local flockmates
- Alignment: steer towards the average heading of local flockmates
- Cohesion: steer to move toward the average position (center of mass) of local flockmates



(1) Separation (2) Alignment (3) Cohesion

Boids

http://www.red3d.com/cwr/boids/

Swarm Robotics

https://spectrum.ieee.org/a-thousand-kilobots-self-assemble

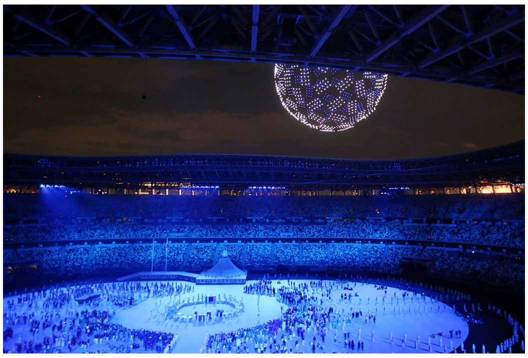
What is a multi-agent system? (examples)

Examples of multi-agent systems:

- humans (collective behavior in human crowds, viral spreading, human social networks)
- creatures (ant's nest, flock of birds and fish)
- sensor network, antenna array
- robots, drones, autonomous cars
- smart grid, smart society, smart factory, etc.

Drone (UAV, Unmanned Aerial Vehicle)

- A drone=a flying computer
- A sensor network with multiple drones
- Drone light show by Intel (Tokyo2020 Olympic Games)
- Each drone works autonomously and achieves a global task



The left picture was borrowed from wikipedia.

Intel Drone Light Show

https://inteldronelightshows.com/

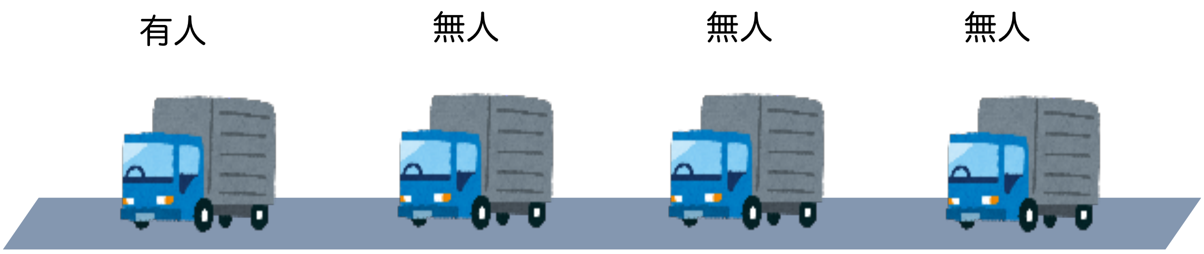
What is a multi-agent system? (examples)

Examples of multi-agent systems:

- humans (collective behavior in human crowds, viral spreading, human social networks)
- creatures (ant's nest, flock of birds and fish)
- sensor network, antenna array
- robots, drones, autonomous cars
- smart grid, smart society, smart factory, etc.

Autonomous Cars

- Truck platooning
- Leader truck: manual operation by a driver
- Follower trucks: autonomous operation
  - Labor cost reduction, congestion elimination, energy saving



Stability: *string stability*

J. Ploeg, N. van de Wouw, and H. Nijmeijer, *IEEE TCST*, 22(2), 2014

Truck platooning

https://www.volvogroup.com/en/future-of-transportation/innovation/automation.html

Smart vehicle community

What if all the cars on the road become autonomous vehicles...?

- Each car communicates with neighboring cars.
- Each acts estimating the environment based on artificial intelligence.
- All cars achieve global tasks such as
  - saving energy
  - eliminating congestion and accidents
  - improving the quality of human life

What we will not need

- drivers
- car insurance
- traffic lights, road signs, and lanes
- railway stations

Is it the next big business?

MAS of autonomous vehicles (experiment)

https://www.preferred.jp/en/projects/transportation/

- An experiment by Preferred Networks, Toyota, and NTT.
- The toy cars learn smooth and safe driving by deep Q learning (DQN).

What is a multi-agent system? (examples)

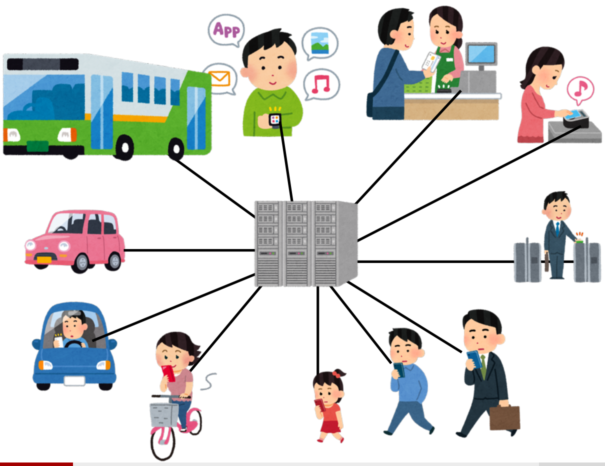
Examples of multi-agent systems:

- humans (collective behavior in human crowds, viral spreading, human social networks)
- creatures (ant's nest, flock of birds and fish)
- sensor network, antenna array
- robots, drones, autonomous cars
- smart grid, smart society, smart factory, etc.

Smart society by cyber-physical systems

Cyber-physical systems (CPS)

Physical systems, such as smartphones, wearable devices, cars, POS systems, and ticketing machines, form a communication network, by which we estimate and control the environment and the society from a large amount of data (aka big data) in the cyber space.

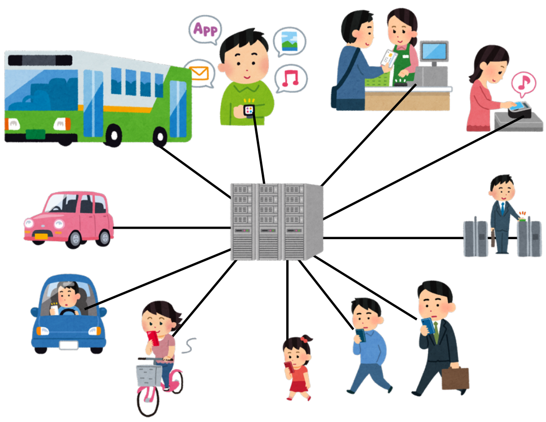


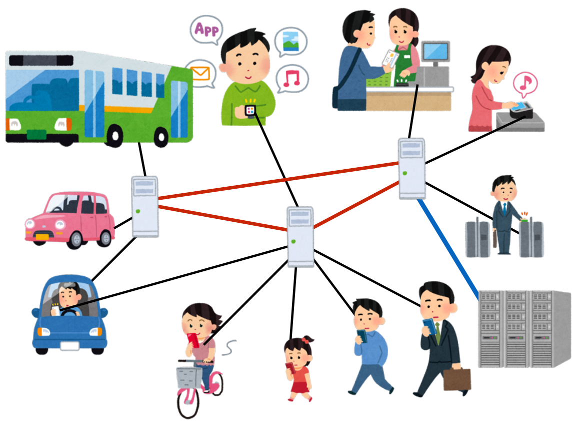
CPS: Cyber-Physical System

Cloud computing: Processes data with a centralized server

Edge computing: Processes data with edge (local) servers

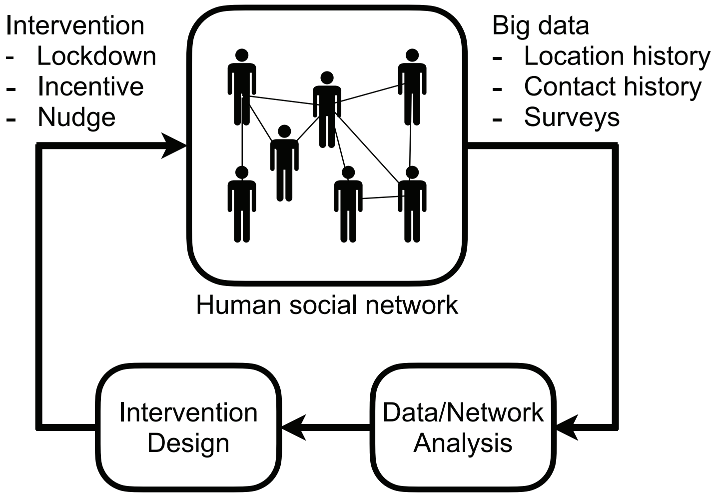
- reduction of energy consumption in the server
- saving the bandwidth in the communication network





CPHS: Cyber-Physical-Human System

A "feedback control" system to suppress COVID-19 epidemics in a human social network.



[Nagahara et al. *Advanced Robotics*, 2021]

Cyber-Physical-Human System

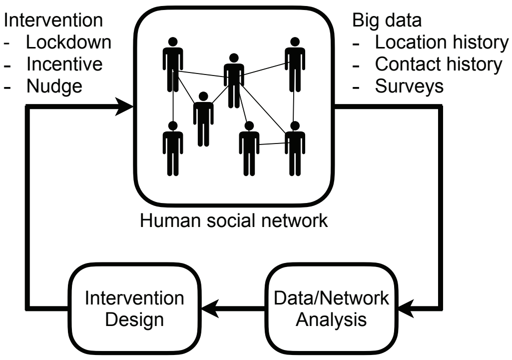
How to design effective interventions?

Is this is a control engineering problem?

Can we use our PID control for this purpose?

Maybe yes, but control of people is much more difficult than electric motors.

A cross-cutting research between control engineering and behavioral economics.



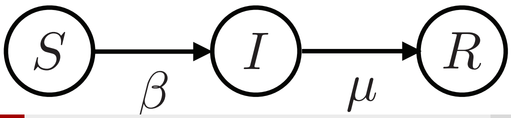
Wikipedia

SIR Model

SIR (Susceptible-Infected-Recovered) model of epidemics:

$$\begin{aligned}\dot{S}(t) &= -N^{-1}\beta\langle k\rangle S(t)I(t),\\ \dot{I}(t) &= N^{-1}\beta\langle k\rangle S(t)I(t) - \mu I(t),\\ \dot{R}(t) &= \mu I(t),\end{aligned}$$

$S(t)$: the number of susceptible people at time $t \geq 0$
$I(t)$: the number of infected people at time $t \geq 0$
$R(t)$: the number of recovered (or dead) people at time $t \geq 0$
$N = S(t) + I(t) + R(t)$: the total number of people
β: the average number of contacts per person per time
μ: the recovery rate
$\langle k\rangle$: the average degree of the human contact network

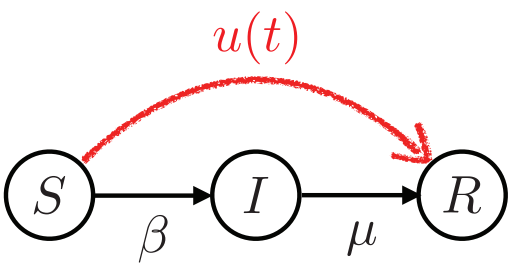


Control based-on SIR model

We consider the SIR model as a dynamical system (like a mechanical system), and compute a control.
Vaccination:

$$\begin{aligned}\dot{S}(t) &= -N^{-1}\beta\langle k\rangle S(t)I(t) - u(t)S(t),\\ \dot{I}(t) &= N^{-1}\beta\langle k\rangle S(t)I(t) - \mu I(t),\\ \dot{R}(t) &= \mu I(t) + u(t)S(t),\end{aligned}$$

Optimal control: minimize $I(T) + \lambda\|u\|_2^2$ (finite horizon control)
PID control: $u(t) = \mathrm{PID}(I(t))$ (feedback control)



Effective Interventions

- Once the control law $u(t)$ is obtained, *how to apply it to the human-social network?*
- Often, this is highly political (e.g. lockdown).
- We can find good strategies in behavioral economics
  - Incentive: e.g., offering free baseball game entry for those who get vaccine at a stadium
  - Nudge: e.g., showing the Vice President getting vaccine on TV
  - Effective intervention design is essential for control of human-social networks.

(left) https://www.mlb.com (right) wikipedia

Summary

- Multi-agent systems: definition and examples
- Control of multi-agent systems:
  - Swarm robots (homogeneous MAS)
  - Cyber-physical systems (heterogeneous MAS)
  - Cyber-physical-human systems (MAS with humans: challenging!)