Control of Multi-Agent System (YSEP)
Collision Avoidance
Teleoperation with Delay

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2011年6月15日

Outline

- Introduction
- Overview of the year in Fujita laboratory
  - Synchronization of Omnidirectional Robots
  - Control of Oscillating Robots
  - Collision Avoidance
  - Teleoperation with Constant Delay
- New topics more closely
  - Collision Avoidance
  - Teleoperation with Constant Delay
- Conclusion

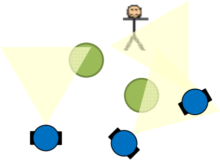
Introduction

Multi-Agent System

•What?
- Group of robots that try to achieve specified tasks with limited knowledge of the environment

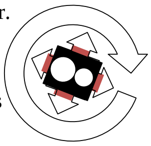
•Why?
- Scalable
- Robust to failures

•Applications?
- Exploration and survey
- Search and rescue



Synchronization of Omnidirectional Robots

- Robots: Move any direction, attitude and movement decoupled. See neighbor.
- Goal: 1. Attitude synchronization
  2. Pose synchronization
- Motivation: Basis of more complicated systems

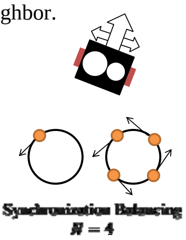


Attitude Synchronization

T. Ibuki, ”Research on Pose Synchronization Control of Wheeled Mobile Robots”

Control of Oscillating Robots

- Robots: Move forward, can turn. See neighbor. Movement periodical.
- Goal: 1. Phase and spatial control
  → Synchronization/balancing
  2. Human control
- Motivation: Study on movement of fishes

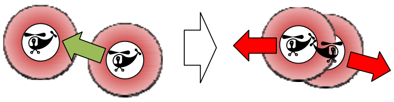


No Control Law

D. A. Paley, N. E. Leonard and J. K. Parrish, ”Oscillator Models and Collective Motion”

Collision Avoidance

- Robots: Omnidirectional
- Goal: 1. Avoid collisions with robots
  → Flocking
  2. Avoid collisions with environment
- Motivation: Robots are expensive
  Flocking of birds → flocking of spacecraft

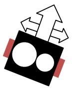


No Collision Avoidance

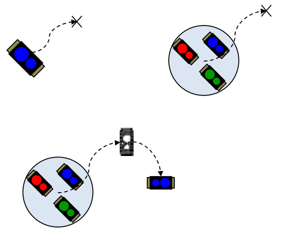
Y. Igarashi, T. Hatanaka, M. Fujita, M. W. Spong, ”Passivity-based Pose Synchronization and Flocking in Three Dimensions”

T. Hatanaka, ”3D上の群れ問題再考” (Revisit to Flocking in 3D)

Teleoperation with Constant Delay



- Robots: Move forward, can turn.
- Goal: 1. Teleoperation with delay
  2. Group based collision avoidance
- Motivation: Teleoperation over Internet, long distance



O. M. Palafox, M. W. Spong, "Bilateral Teleoperation of a Formation of Nonholonomic Mobile Robots Under Constant Time Delay"

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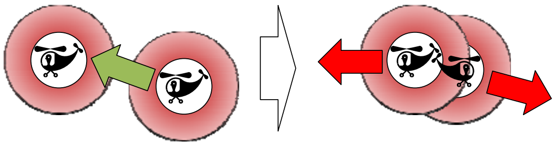
Collision Avoidance – Problem Setting

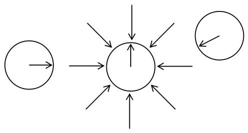
- Y. Igarashi, T. Hatanaka, M. Fujita, M. W. Spong, "Passivity-based Pose Synchronization and Flocking in Three Dimensions"
- Goal: Avoid collisions
- Idea: - Robots and obstacles have potential field
  → Field is stronger near the center
  - Sensed potential field dispels robot



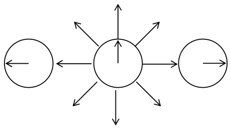
Collision Avoidance – Problem Setting

Rules of flocking (by C. W. Reynolds)

•Cohesion



•Separation



•Alignment

Collision Avoidance – Used Symbols

Passivity-based Pose Synchronization and Flocking in Three Dimensions

$p_i \in \mathcal{R}^3$, position of ith robot

$d_i \in \mathcal{R}^3$, bias of ith robot

$e^{\hat{\xi}_i\theta_i} \in \mathcal{R}^3$, rotation matrix of ith robot

$g_i = \begin{bmatrix} e^{\hat{\xi}_i\theta_i} & p_i \\ 0 & 1 \end{bmatrix}, i \in \{1, \cdots, n\}$

$q_i = p_i + d_i$

n, amount of robots

$\|x\|_F$, Frobenius matrix norm

$J = \begin{bmatrix} \frac{1}{2} I_3 & 0 \\ 0 & \frac{1}{\sqrt{2}} \end{bmatrix}$

$\phi(x) = \|J(I_4 - y_i)\|_F^2$

v_d, ω_d, desired velocities

K_i, gain matrix of ith robot

$\mathcal{V} = \{1, \cdots, n\}$, set of nodes

$\varepsilon \subset \mathcal{V} \times \mathcal{V}$, set of edges

W, set of weights

$G_O, G_C = (\mathcal{V}, \varepsilon, W)$, sensing graphs

$\mathcal{N}_O, \mathcal{N}_C$, set of neighbors

$\mathrm{sk}(x)$, skew-symmteric part of x

$x^\vee$, operator that transforms space of 3×3 skew-symmetric matrices to $\mathcal{R}^3$

r, minimum radius where collision avoidance is applied

R, maximum radius where collision avoidance is applied

3D上の群れ問題再考

Revisit to Flocking in 3D

R_i, rotation matrix of ith robot

$g_{wi} = (p_{wi}, R_{wi})$

$e_R(g) = \begin{bmatrix} p \\ \mathrm{sk}(R)^\vee \end{bmatrix}$

Collision Avoidance – Pose Control

1. Kinematic model

$$\dot{g}_i = g_i \hat{V}_i^b,$$
$$y_i = \begin{bmatrix} e^{\hat{\xi}_i\theta_i} & q_i \\ 0 & 1 \end{bmatrix}, i \in \{1, \cdots, n\}$$

2. Definition: Pose synchronization, if

$$\lim_{t \to \infty} \phi(y_i^{-1} y_j) = 0 \; \forall i, j (i \neq j) \in \{1, \cdots, n\}$$

3. Velocity control law

$$V_i^b = \begin{bmatrix} e^{-\hat{\xi}_i\theta_i} & 0 \\ 0 & e^{-\hat{\xi}_i\theta_i} \end{bmatrix} \begin{bmatrix} v_d \\ \omega_d \end{bmatrix}$$
$$- K_i \begin{bmatrix} e^{-\hat{\xi}_i\theta_i} & 0 \\ 0 & I \end{bmatrix} \left(\sum_{j \in \mathcal{N}_{Oi}} w_{ij} \begin{bmatrix} q_i - q_j \\ \mathrm{sk}\left(e^{-\hat{\xi}_j\theta_j} e^{\hat{\xi}_i\theta_i}\right)^\vee \end{bmatrix} \right), i \in \{1, \cdots, n\}$$

- Movement with desired velocities
- Synchronization and formations

Collision Avoidance – Pose Control

- **Theorem:** Consider n rigid bodies represented by (1) and suppose that v_d and ω_d represent desired group trajectories. Then, under the assumption that there exists $e^{-\hat{\xi}_{\kappa}\theta_{\kappa}}$ such that $e^{-\hat{\xi}_i\theta_i} = e^{-\hat{\xi}_d\theta_d} e^{-\hat{\xi}_{\kappa}\theta_{\kappa}} e^{\hat{\xi}_i\theta_i}$ are positive definite and the interconnection graph G_O is fixed and strongly connected, the velocity input (3) achieves pose synchronization in the sense of (2).
  - Proof: see report or original paper

Collision Avoidance – Algorithm

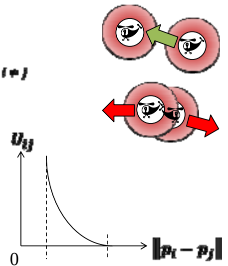
- Potential function

$$U_{ij}(p_i,p_j) = \left(\min\left\{0, \frac{\|p_i-p_j\|^2-R^2}{\|p_i-p_j\|^2-r^2}\right\}\right)^2, i \neq j$$

- Partial derivative

$$\frac{\partial U_{ij}}{\partial p_i} = \begin{cases} 0 & \text{if } R \le \|p_i-p_j\| \\ s_{ij} & \text{if } r < \|p_i-p_j\| < R \\ \text{not defined} & \text{if } \|p_i-p_j\| = r \\ 0 & \text{if } \|p_i-p_j\| < r \end{cases}$$

$$s_{ij} = 4\frac{(R^2-r^2)(\|p_i-p_j\|^2-R^2)}{(\|p_i-p_j\|^2-r^2)^3}(p_i-p_j)$$



- Included in the input

$$V_i^b = \begin{bmatrix} e^{-\hat{\xi}\theta_i} & 0 \\ 0 & e^{-\hat{\xi}\theta_i} \end{bmatrix}\begin{bmatrix} v_d \\ \omega_d \end{bmatrix} - K_i \begin{bmatrix} e^{-\hat{\xi}\theta_i} & 0 \\ 0 & I \end{bmatrix}\left(\sum_{j\in N_{oi}} \omega_{ij}\begin{bmatrix} p_i - p_j \\ \mathrm{sk}(e^{-\hat{\xi}\theta_j} e^{\hat{\xi}\theta_i})^{\vee} \end{bmatrix} + \sum_{j\in N_{ci}} \begin{bmatrix} \frac{\partial U_{ij}}{\partial p_i} \\ 0 \end{bmatrix}\right), i \in \{1,\cdots,n\}$$

  - Collision avoidance

Collision Avoidance – Body Frame

- T. Hatanaka, "3D上の群れ問題再考", Revisit to Flocking in 3D
- Improvement for the previous control law
  - Common velocity in world frame → common velocity in body frame
- New velocity input

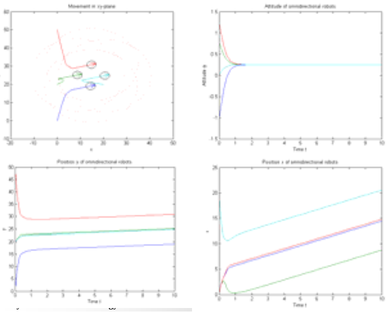
$$V_{wi}^b = V_d^b + \sum_{j\in N_i} E_R(g_{wi}^{-1} g_{wj}), E_R(g) = (p, e_R(R)), V_d^b = (v_d, \omega_d)$$

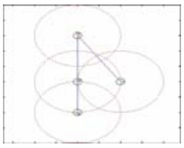
  - Movement with desired velocities
  - Synchronization

Collision Avoidance – Simulations

- Flocking (no set formation)
- Simulation and experiments in 2D

- $\theta_0 = \begin{bmatrix} -\frac{\pi}{3} & \frac{\pi}{4} & \frac{\pi}{2.5} & 0 \end{bmatrix}^T$
- $x_0 = \begin{bmatrix} 0 & 0 & 0 & 20 \end{bmatrix}^T$
- $y_0 = \begin{bmatrix} 0 & 20 & 50 & 20 \end{bmatrix}^T$
- $K_i = 1$





Collision Avoidance – Experiments

- Omnidirectional robots
- Obstacles made from paper
- Videos available on laboratory's homepage

Collision Avoidance

Human controls the formation and the pose of the group.

When robots are going to collide they will start to avoid each other.

Collision Avoidance and Flocking

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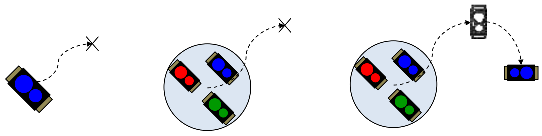
Teleoperation with Constant Delay – Problem Setting

- O. M. Palafox, M. W. Spong, "Bilateral Teleoperation of a Formation of Nonholonomic Mobile Robots Under Constant Time Delay"
- Robots: Unicycles
- Goal: Teleoperation of a system with delay
- Idea: 1. Robot to point
  2. Formation ≈ robot → Formation to point
  3. Delayed formation information to robots



Teleoperation with Constant Delay – Used Symbols

- ϕ, angle
- x_d, y_d, desired position
- d = distance between center and front of a robot
- k_x, k_y, constant gains
- x_i^d, y_i^d, desired position for ith robot
- x_f^d, y_f^d, desired position for formation
- l_i, bias of ith robot
- ϕ_f, angle of formation
- $\phi(0)_i$, initial angle of ith robot w. r. t. angle of the formation
- x_{obs}, y_{obs}, position of an obstacle

Teleoperation with Constant Delay – Single Robot

- Kinematic model

$$\begin{bmatrix} \dot{x} \\ \dot{y} \\ \dot{\phi} \end{bmatrix} = \begin{bmatrix} \cos(\phi) & 0 \\ \sin(\phi) & 0 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} v \\ \omega \end{bmatrix}$$

- Control law to move robot to (x_d, y_d)

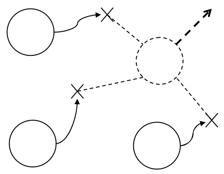
$$\begin{bmatrix} v \\ \omega \end{bmatrix} = \begin{bmatrix} \cos(\phi) & \sin(\phi) \\ -\frac{1}{d}\sin(\phi) & -\frac{1}{d}\cos(\phi) \end{bmatrix} \begin{bmatrix} k_x(x_d - x - d\cos(\phi)) \\ k_y(y_d - y - d\sin(\phi)) \end{bmatrix}$$

- Exponentially stable
  - For details, see report or original paper

Teleoperation with Constant Delay – Robot Group

- Formation is modeled as a single robot
  - Individual robots get desired positions from formation

$$x_i^d = x_f^d + l_i \cos(\phi_f + \pi + \phi(0)_i)$$
$$y_i^d = y_f^d + l_i \cos(\phi_f + \pi + \phi(0)_i)$$



Teleoperation with Constant Delay – Robot Group

- Collision avoidance is applied only to formation (not individual robots)

$$U = \left(\min\left\{0, \frac{\eta^2 - R^2}{\eta^2 - r^2}\right\}\right)^2$$

$$\eta = \sqrt{(x_f - x_{obs})^2 + (y_f - y_{obs})^2}$$

- Gradient of U

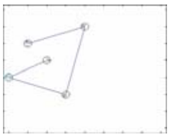
$$\nabla U = \begin{bmatrix} \frac{4(R^2 - r^2)(\eta^2 - R^2)(x_f - x_{obs})}{(\eta^2 - r^2)^3} \\ \frac{4(R^2 - r^2)(\eta^2 - R^2)(y_f - y_{obs})}{(\eta^2 - r^2)^3} \end{bmatrix}$$

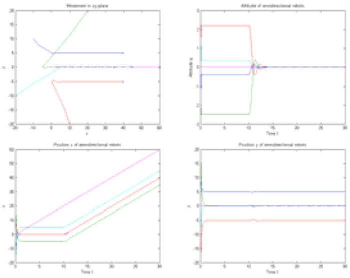
Teleoperation with Constant Delay – Full System

- System proven to be globally asymptotically stable even with delays
  - See report or original paper
- In free motion (no obstacles)
  - Master and formation positions converge as $t \to \infty$
  - Formation error converges to zero
- In constrained motion (obstacles)
  - Error is fed back to master

Teleoperation with Constant Delay – Simulations

- Teleoperation with constant delay (10 s)
- $\theta_0 = [-2.5287 \quad -1.3917 \quad 0.2946 \quad 2.8746]^T$
- $x_0 = [-10 \quad 20 \quad 10 \quad -20]^T$
- $y_0 = [10 \quad 20 \quad -20 \quad -10]^T$
- $\phi_0 = [\frac{\pi}{2} \quad 0 \quad \frac{\pi}{2} \quad \pi]$
- $l = [-5 \quad 5 \quad 5 \quad 5]$
- $k_x = k_y = 5$
- $\dot{x}_f = 2$
- $d = 1$





Teleoperation with Constant Delay – Main Point

(only my thoughts, nothing proven)

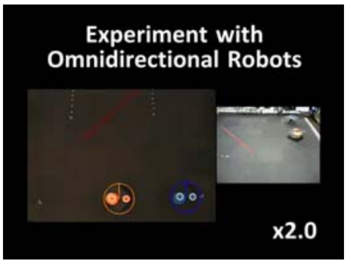
•The main reason this system works with even with delay is that it is based on position synchronization

→All systems capable of position synchronization should be capable of this

→Omnidirectional robot system should already be capable of this (pose synchronization includes position)

Teleoperation with Constant Delay – Main Point

- Experiments
  - No time to try bi-wheeled robots with given control laws
  - Omnidirectional robots work well with applying the usual pose synchronization



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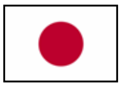

Future Works

Only 1 month left

•Write YSEP report

•Improve slides for final presentation

•Flocking experiment

- Make more user friendly and more robust (so that it could be demonstrated easily if required)
- Documentation
- Teach to Okazaki

Conclusion

- It has been a fun and educating year
  - Learned a lot about control engineering and related mathematics, simulation and experimenting
  - Learned what doing research is
    - In Finland only doctorate students do research
- Details about YSEP presentation later
  - July 15th, morning
  - Exact time announced later

- Thank you to everyone in Fujita laboratory for the past year