(partially) Vision-Based Pose Synchronization FL08_15_1

Naoto Kobayashi

Outline

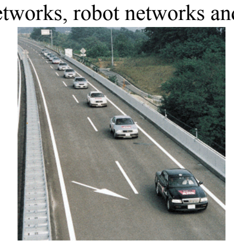
- **Introduction**
- (Partially) Vision-based Pose Synchronization
  - Problem Formulation
  - Control Laws
  - Experiment / Simulation
- Conclusion / Future Works

Introduction

Cooperative Control

- Cooperative control is a distributed control strategy that achieves specified tasks in multi-agent systems.
- It's been motivated by interests in group behavior of animals, formation control of multi-vehicle systems and so on.
- It is hoped to be applied to sensor networks, robot networks and many other multi-agents systems.

School of Fish
http://www.yunphoto.net/

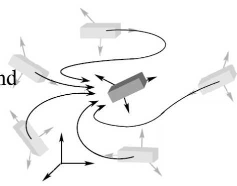


Automated Highway System
http://www.its.go.jp/ITS/

Introduction

Cooperative Control

- Consensus Problem
  : to reach an agreement regarding a certain quantity of interest that depends on the state of all agents.
- Flocking Problem
  : to make all of agents' speeds be the same.
- Coverage Problem
- Formation Control Problem
  :
- Pose Synchronization
  : to make all of the agents' positions and attitudes be the same.



Pose synchronization

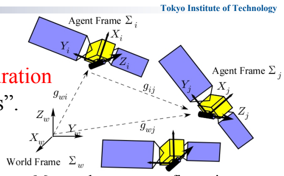
Introduction

Vision-based Cooperative Control

Mounted camera (local camera) configuration

- Each agent can have its own "eyes".

→ autonomous agents system

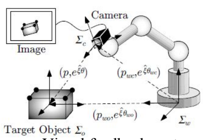


Mounted camera configuration

We have to get necessary information (neighbor's relative positions and attitudes) from camera images to achieve pose synchronization.

Visual Observer [4]

- Visual observer proposed in [4] can estimate relative positions and attitudes between camera and target objects.



Visual feedback system with visual observer

Introduction

Last Seminar(FL08_09_1)

- Simulations (mounted camera configuration - leader following -)
- Experiments (mounted camera configuration - leader following -)

This Seminar (FL08_15_1)

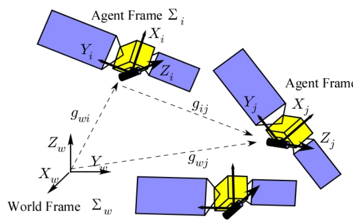
- Problem formulation (partially vision-based pose synchronization)
- Experiments (some kinds of partially vision-based pose synchronization)
- Simulations (some kinds of partially vision-based pose synchronization)

Outline

- Introduction
- **(Partially) Vision-based Pose Synchronization**
  - **Problem Formulation**
  - **Control Laws**
  - **Experiment / Simulation**
- Conclusion / Future Works

Problem Formulation

Partially vision-based pose synchronization



p : position
$R\ (= e^{\hat{\xi}})$: attitude
v : linear velocity
ω : angular velocity

subscript ij : from frame i to frame j
superscript i : see from frame i
w : world frame
$i\ j$: agent frame

$\wedge$:

$$\begin{bmatrix}\omega_x\\ \omega_y\\ \omega_z\end{bmatrix}^{\wedge} = \begin{bmatrix}0 & -\omega_z & \omega_y\\ \omega_z & 0 & -\omega_x\\ -\omega_y & \omega_x & 0\end{bmatrix}$$

$\vee$: inverse operator to $\wedge$

- Agents' kinematics

$$\begin{cases}\dot{p}^w_{wi} &= R_{wi} v^i_{wi}\\ \dot{R}_{wi} &= R_{wi}\hat{\omega}^i_{wi}\end{cases} \quad i = 0, 1, 2, \ldots, n \qquad \text{...(1)}$$

Problem Formulation

Define 2 kinds of neighbors $\mathcal{N}_{ic}$ and $\mathcal{N}_{iv}$.

$\mathcal{N}_{ic}$: neighbors which can transmit pose information to agent i

➡ Agent i can get exact value of relative pose with $\mathcal{N}_{ic}$ neighbors by receiving the information transmitted by agent j .

communication-based (ordinary case)

➕

$\mathcal{N}_{iv}$: neighbors seen by agent i 's mounted camera

➡ Agent i can get only **estimated value** of relative pose with $\mathcal{N}_{iv}$ neighbors using visual feedback observer.

vision-based

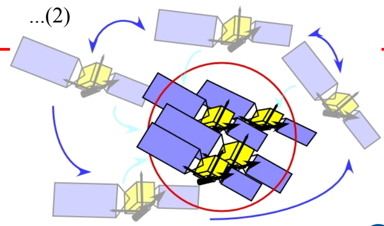
Problem Formulation

- Control Objective

Pose Synchronization in SE(3)

: Make all of the agents' positions converge to a certain region near their neighbors and make their attitudes be the same.

$$\begin{cases}||p^w_{wj} - p^w_{wi}|| \le L, \quad L > 0\\ R_{wi} = R_{wj}\end{cases} \quad \forall i \qquad \text{...(2)}$$



Velocity Input

Partially vision-based pose synchronization

Velocity Input

$$\begin{bmatrix}v^i_{wi}\\ \omega^i_{wi}\end{bmatrix} = \sum_{j\in\mathcal{N}_{ic}} \begin{bmatrix}k_v(p^i_{ij} - d^i_{ij})\\ k_\omega \mathrm{sk}(R_{ij})^{\vee}\end{bmatrix} + \sum_{j\in\mathcal{N}_{iv}} \begin{bmatrix}k_v(\bar{p}^i_{ij} - \bar{d}^i_{ij})\\ k_\omega \mathrm{sk}(\bar{R}_{ij})^{\vee}\end{bmatrix}$$

communication-based **vision-based**

$$d^i_{ij} := \frac{l}{||p^i_{ij}||} p^i_{ij}$$

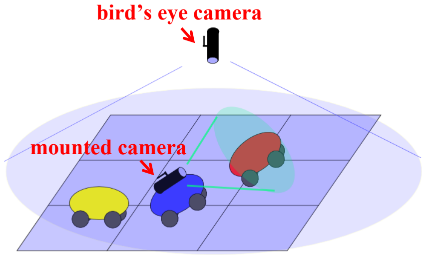
: safety distance (for collision avoidance and guarantee of visibility of camera)

$\bar{(\cdot)}$: estimated value

Experiment / Simulation

Experimental system

- Bird's eye camera can sense each agent's exact position and attitude.
- These information is transmitted to the neighbors $\mathcal{N}_{ic}$.

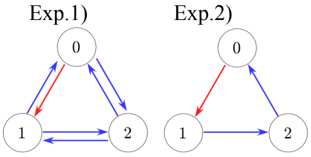


- With mounted camera, we can get estimated values of relative position and attitude of neighbors $\mathcal{N}_{iv}$ using visual feedback observer.

Experiment / Simulation

- **Graph**

Exp.1) Exp.2)



: exact relative pose (from bird's eye camera)

: estimated relative pose (using mounted camera and visual feedback observer)

- **Velocity input**

$$\begin{bmatrix} v_{wi}^i \\ \omega_{wi}^i \end{bmatrix} = \sum_{j\in\mathcal{N}_{ic}} \begin{bmatrix} k_v(p_{ij}^i - d_{ij}^i) \\ k_\omega \mathrm{sk}(R_{ij})^\vee \end{bmatrix} + \sum_{j\in\mathcal{N}_{iv}} \begin{bmatrix} k_v(\bar{p}_{ij}^i - \bar{d}_{ij}^i) \\ k_\omega \mathrm{sk}(\bar{R}_{ij})^\vee \end{bmatrix}$$

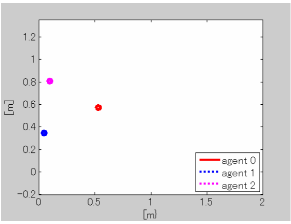
$$d_{ij}^i := \frac{l}{||p_{ij}^i||} p_{ij}^i \qquad l = 0.40[\mathrm{m}]$$

Experiment / Simulation

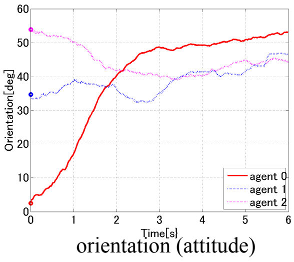
■ **Exp. 1)**

Experiment / Simulation

■ **Exp. 1)**



position



orientation (attitude)

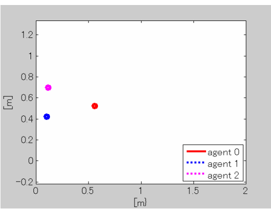
- Pose synchronization (2) is almost achieved.
- I have to raise the precision of experiment.

Experiment / Simulation

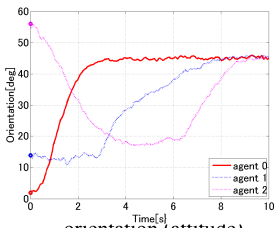
■ **Exp. 2)**

Experiment / Simulation

■ **Exp. 2)**

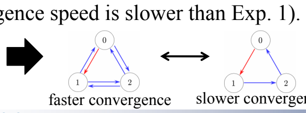


position



orientation (attitude)

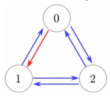
- Pose synchronization (2) is almost achieved.
- Convergence speed is slower than Exp. 1).



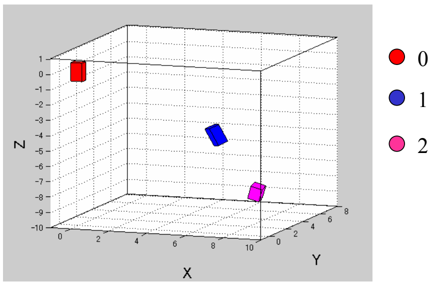
faster convergence ⟷ slower convergence

Experiment / Simulation

■ **Sim. 1)**



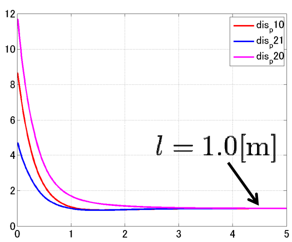
$$\begin{bmatrix} v_{wi}^i \\ \omega_{wi}^i \end{bmatrix} = \sum_{j\in\mathcal{N}_{ic}} \begin{bmatrix} k_v(p_{ij}^i - d_{ij}^i) \\ k_\omega \mathrm{sk}(R_{ij})^\vee \end{bmatrix} + \sum_{j\in\mathcal{N}_{iv}} \begin{bmatrix} k_v(\bar{p}_{ij}^i - \bar{d}_{ij}^i) \\ k_\omega \mathrm{sk}(\bar{R}_{ij})^\vee \end{bmatrix}$$



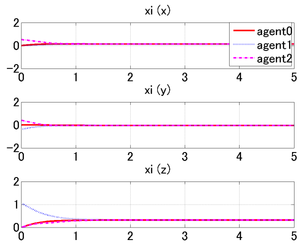
position and attitude

Experiment / Simulation

■ **Sim. 1)**



relative distance

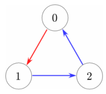


attitude vector ξ_i

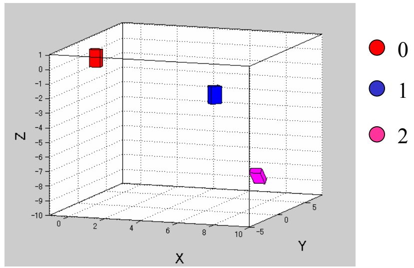
- Pose synchronization (2) is achieved.

Experiment / Simulation

■ **Sim. 2)**



$$\begin{bmatrix} v_{wi}^i \\ \omega_{wi}^i \end{bmatrix} = \sum_{j\in\mathcal{N}_{ic}} \begin{bmatrix} k_v(p_{ij}^i - d_{ij}^i) \\ k_\omega \mathrm{sk}(R_{ij})^\vee \end{bmatrix} + \sum_{j\in\mathcal{N}_{iv}} \begin{bmatrix} k_v(\bar{p}_{ij}^i - \bar{d}_{ij}^i) \\ k_\omega \mathrm{sk}(\bar{R}_{ij})^\vee \end{bmatrix}$$



position and attitude

Experiment / Simulation

■ **Sim. 2)**

- Agent 1 goes infinity when it comes not to be able to see agent 0 anymore.

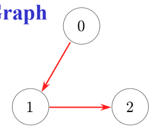
⬇

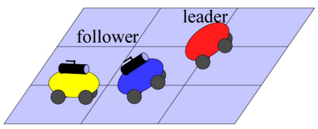
We have to maintain visibility.

Experiment / Simulation

■ **Exp. 3) Vision-based leader following**

- **Graph**





- **Velocity input**

leader $\begin{bmatrix} v_{w0}^0 \\ \omega_{w0}^0 \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ k_v \\ 0 \\ 0 \\ 0 \end{bmatrix}$

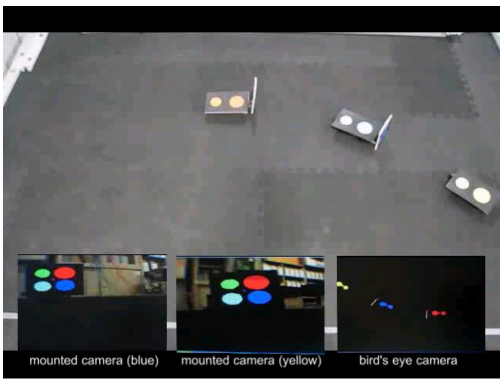
agent 1 $\begin{bmatrix} v_{w1}^1 \\ \omega_{w1}^1 \end{bmatrix} = \begin{bmatrix} k_v(\bar{p}_{10}^1 - \bar{d}_{10}^1) \\ k_\omega \mathrm{sk}(\bar{R}_{10})^\vee \end{bmatrix}$

agent 2 $\begin{bmatrix} v_{w2}^2 \\ \omega_{w2}^2 \end{bmatrix} = \begin{bmatrix} k_v(\bar{p}_{21}^2 - \bar{d}_{21}^2) \\ k_\omega \mathrm{sk}(\bar{R}_{21})^\vee \end{bmatrix}$

$d_{ij}^i := \frac{l}{||p_{ij}^i||} p_{ij}^i \quad l = 0.30$[m]

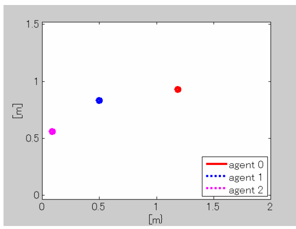
Experiment / Simulation

■ **Exp. 3)**

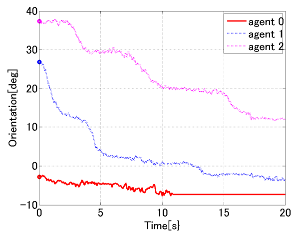


Experiment / Simulation

■ **Exp. 3)**



position

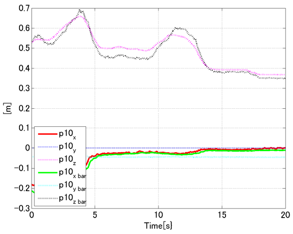


orientation (attitude)

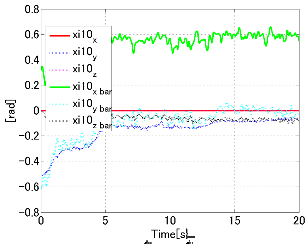
- Due to luck of space, leader following is not completely achieved. But they would achieve it if there were sufficient space or by making angular velocity gain large.

Experiment / Simulation

■ **Exp. 3)**



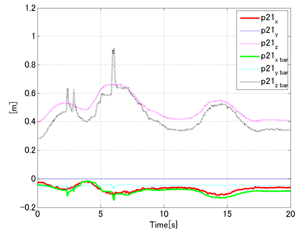
$p_{10}, \bar{p}_{10}$
(relative position)



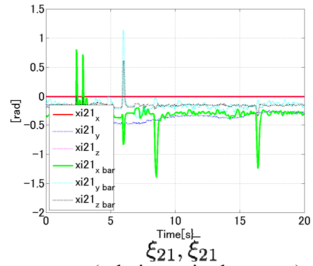
$\xi_{10}, \bar{\xi}_{10}$
(relative attitude vector)

Experiment / Simulation

■ **Exp. 3)**



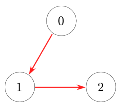
$p_{21}, \bar{p}_{21}$
(relative position)



$\xi_{21}, \bar{\xi}_{21}$
(relative attitude vector)

Experiment / Simulation

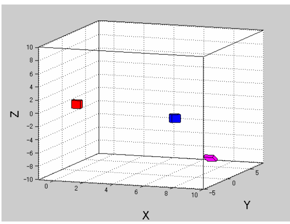
■ **Sim. 3) Vision-based leader following**



leader $\begin{bmatrix} v_{w0}^0 \\ \omega_{w0}^0 \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ k_v \\ 0 \\ 0 \\ 0 \end{bmatrix}$

agent 1 $\begin{bmatrix} v_{w1}^1 \\ \omega_{w1}^1 \end{bmatrix} = \begin{bmatrix} k_v(\bar{p}_{10}^1 - d_{10}^1) \\ k_\omega \mathrm{sk}(\bar{R}_{10})^\vee \end{bmatrix}$

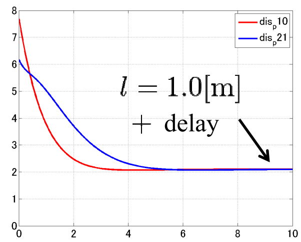
agent 2 $\begin{bmatrix} v_{w2}^2 \\ \omega_{w2}^2 \end{bmatrix} = \begin{bmatrix} k_v(\bar{p}_{21}^2 - d_{21}^2) \\ k_\omega \mathrm{sk}(\bar{R}_{21})^\vee \end{bmatrix}$



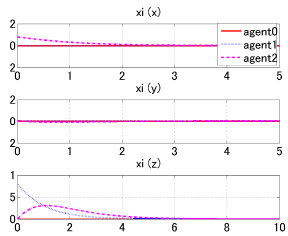
position and attitude

Experiment / Simulation

■ **Sim. 3)**



relative distance



attitude vector ξ_i

- If leader is moving, there exists some delay.
- If leader is moving along a certain line, followers will also move on the line.
- If leader is standstill, pose synchronization is achieved (no delay).

Outline

Conclusion / Future Works

■ **Conclusion**

- Problem formulation (partially vision-based pose synchronization)
- Simulations (some kinds of partially vision-based pose synchronization)
- Experiments / Simulations (some kinds of partially vision-based pose synchronization)

■ **Future Works**

- Visibility maintenance
- Other experiments

References

[1]Y. Igarashi, T. Hatanaka and M. Fujita, Output Synchronization in SE(3) -Passivity-based Approach- ,Proc. of the 36th SICE Symposium on Control Theory, 35/38, 2007.

[2]R. O. Saber, J. A. Fax and T. M. Murray, Consensus and Cooperation in Networked Multi-Agent Systems, Proc. of the IEEE, 95-1, 215/233, 2007.

[3]N. Moshtagh, N. Michael, A. Jadbabaie and K. Daniilidis, Vision-Based, Distributed Control Laws for Motion Coordination of Nonholonomic Robots, IEEE Trans. on Robotics, 2008(accepted).

[4] M. Fujita, H. Kawai and M. W. Spong, Passivity-based Dynamic Visual Feedback Control for Three Dimensional Target Tracking:Stability and L2-gain Performance Analysis, IEEE Trans. on Control Systems Technology, vol. 15, no. 1, 40/52, 2007.

Appendix

■ Comparison between my study and [3]

	my study	[3]
kinematics	$\begin{cases}\dot{p}^w_{wi} &= R_{wi}v^i_{wi}\\ \dot{R}_{wi} &= R_{wi}\hat{\omega}^i_{wi}\end{cases}$	$\dot{x}_i = \cos\theta_i$ $\dot{y}_i = \sin\theta_i$ $\dot{\theta}_i = \omega_i$
original control law	$\begin{bmatrix}v^i_{wi}\\ \omega^i_{wi}\end{bmatrix} = \sum_{j\in\mathcal{N}_i}\begin{bmatrix}k_v(p^i_{ij}-d^i_{ij})\\ k_\omega \mathrm{sk}(R_{ij})^\vee\end{bmatrix}$ • position and attitude • 3D space	$\omega_i = \kappa\sum_{j\in\mathcal{N}_i}\sin(\theta_i-\theta_j)$ $\kappa < 0$ • attitude only • planer space
necessary values for vision-based controller	• pixels of 4 feature point	• bearing angle, optical flow and time-to-collision (which can be gotten by image processing)

Appendix

■ Comparison between my study and [3]

	my study	[3]
vision-based control law	$\begin{bmatrix}v^i_{wi}\\ \omega^i_{wi}\end{bmatrix} = \sum_{j\in\mathcal{N}_{ic}}\begin{bmatrix}k_v(p^i_{ij}-d^i_{ij})\\ k_\omega \mathrm{sk}(R_{ij})^\vee\end{bmatrix} + \sum_{j\in\mathcal{N}_{iv}}\begin{bmatrix}k_v(\bar{p}^i_{ij}-\bar{d}^i_{ij})\\ k_\omega \mathrm{sk}(\bar{R}_{ij})^\vee\end{bmatrix}$ • using estimated values • affected by estimation error • position and attitude • 3D space	$\omega_i = \frac{-\kappa\sum_{j\in\mathcal{N}_i}(\frac{1}{\tau_{ij}}\sin\beta_{ij}+\dot{\beta}_{ij}\cos\beta_{ij})}{1+\kappa\sum_{j\in\mathcal{N}_i}\cos\beta_{ij}}$ $\kappa < 0$ • using exactly measurable values • equals to original control law •attitude only • planer space
	• estimated relative pose values can be used to many application (collision avoidance, coverage, etc.) but they are affected by estimation error.	