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Consensus-based Communication-aware Formation Control

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Table of Contents

01

Introduction

- Formation Control
- Preliminaries
- Schematic Diagram

Formation Control

Classical Formation Control

Agents typically perceive their absolute position relative to the global coordinate system and achieve their desired formation by actively controlling the absolute position.

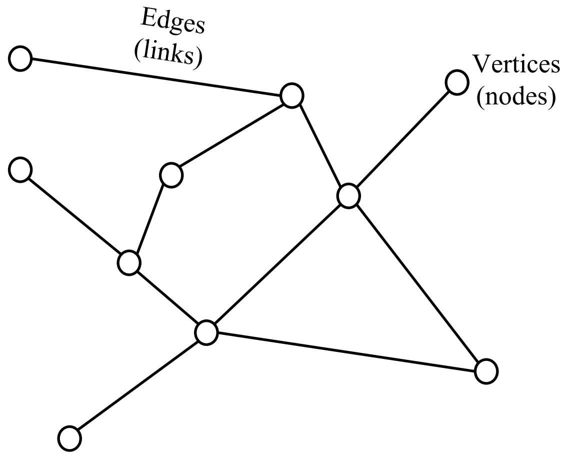
Communication-aware Formation Control

Wireless channel has been used in formation control since communications between agents are usually assumed to be ideal within a certain communication range.

Consensus-based Communication-aware Formation Control

In our research, we adopted ideas from [1], where author Li constructs a communication-aware formation controller that uses the communication channel quality, which is measured locally by agents to guide agents into a desired formation. Thus, it also optimizes the quality of communication of the formation system. Inspired by [2], We further constrains this formation control to reach a consensus between any pair of connected agents.

Preliminaries



Graph Theory

A **graph** G is a pair of $(\mathcal{V}, \mathcal{E})$ consisting of a set of **vertices** $\mathcal{V} = \{1,2,\dots,\mathrm{i},\dots,j,\dots n\}$ and a set of ordered pairs of the vertices called **edges** $\mathcal{E} \subseteq \mathcal{V} \times \mathcal{V}$. I.e., $\mathcal{E} = \{(i,j) | i,j \in \mathcal{V},\ i \neq j\}$. Here, we assume that G has no **self-edges** and **undirected**.

Rigid Formation

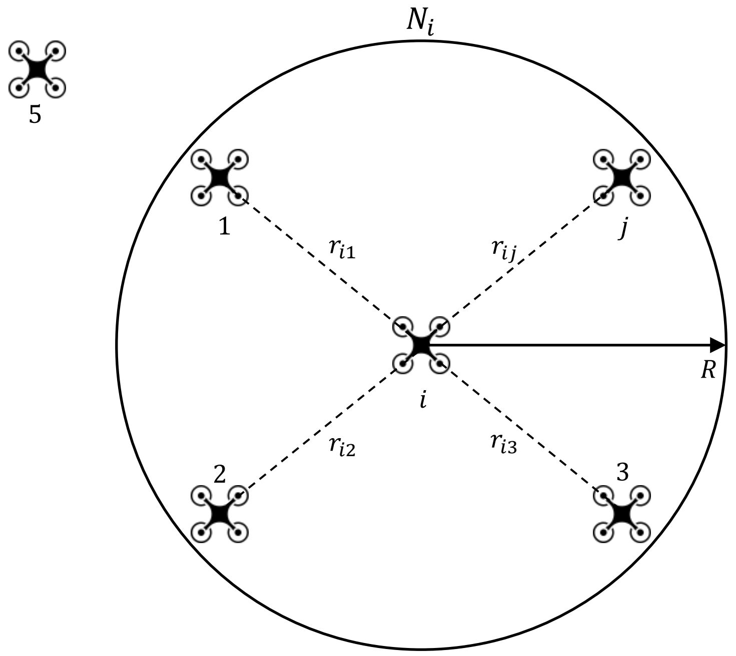
The formation of groups of mobile agents in which all inter-agent distances remain constant is called **rigid**.

The **relative distance** between agent i and agent j is denoted by

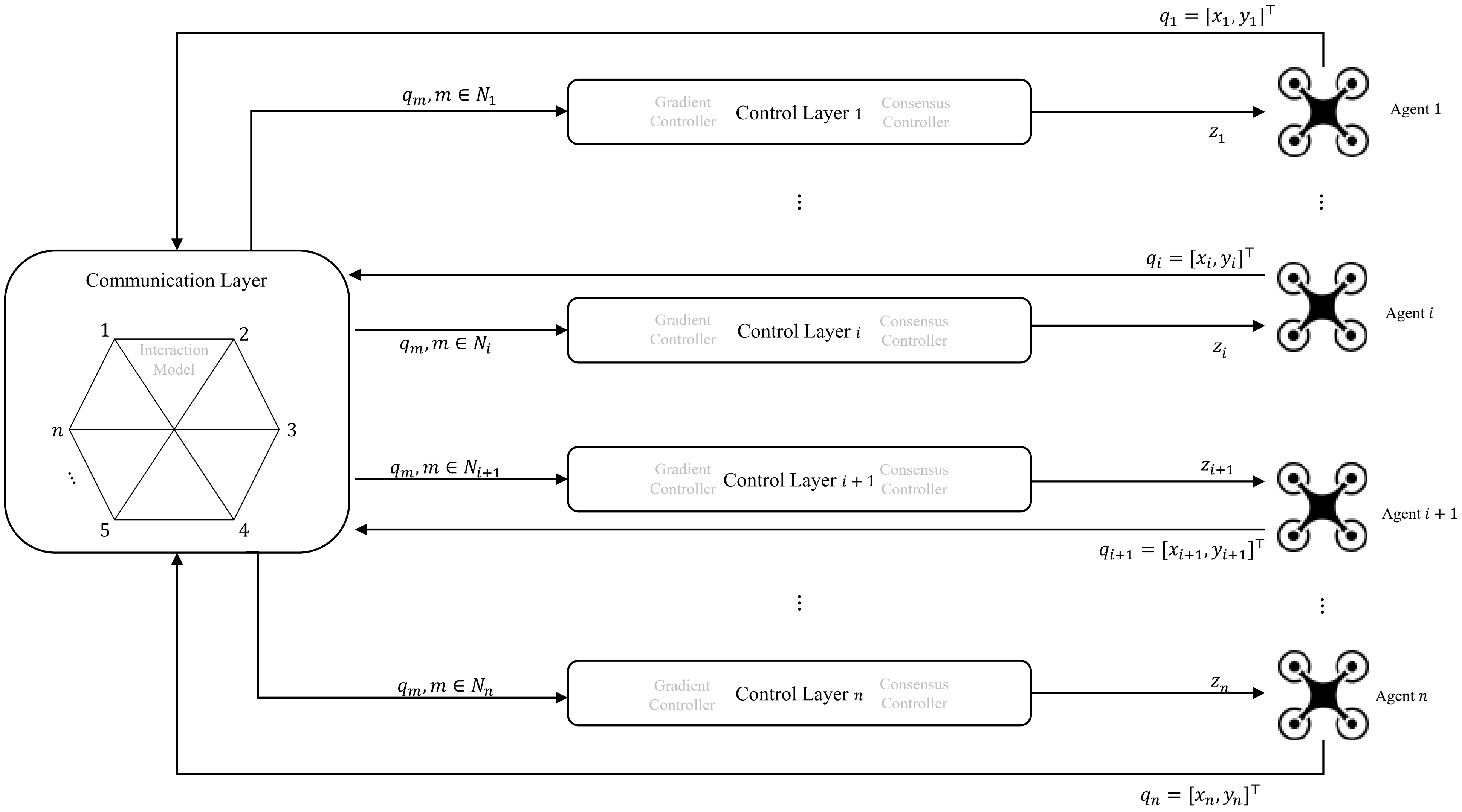
$$r_{ij} = \sqrt{\left(x_i - x_j\right)^2 + \left(y_i - y_j\right)^2} = \|q_i - q_j\|.$$

Let $R > 0$ denote the **communication range** between two agents. The neighboring set of agent i can be denoted by

$$N_i = \{j \in \mathcal{V} \mid r_{ij} \leq R\}.$$



Schematic Diagram



System Dynamics

The **dynamics** of this multi-agent system is denoted by

$$\dot{q}_i = z_i, \quad i = 1,2,\dots,n,$$

where

q: positions of agents,

z: controls of agents.

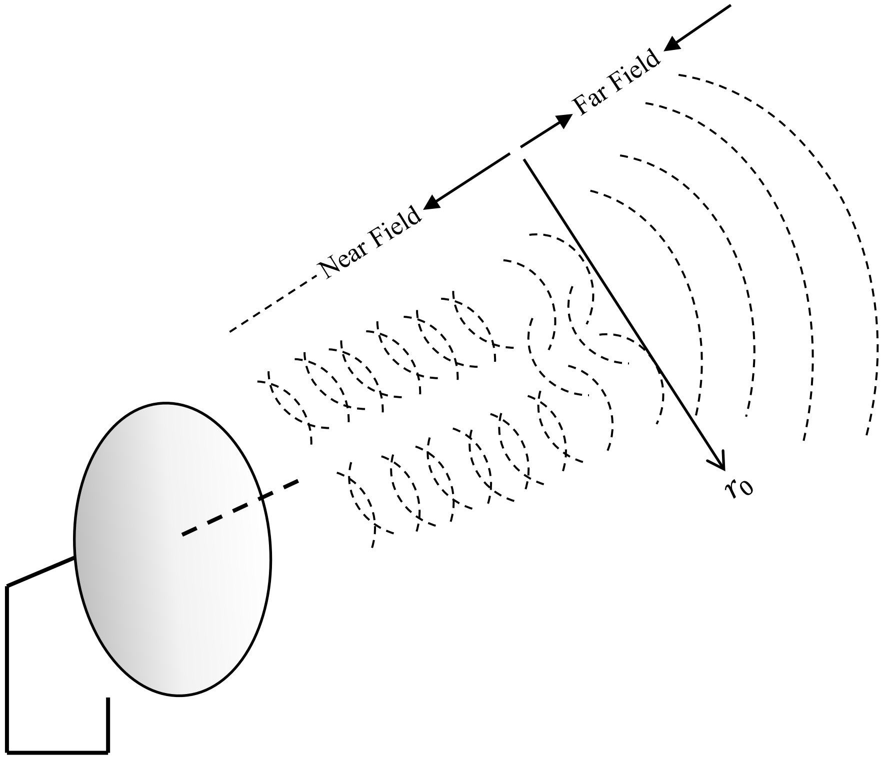
02

Communication Layer

- ❑ Antenna Near-field and Far-field
- ❑ Interaction Model

Antenna Near-field and Far-field

The antenna far field is the area away from the antenna. The boundary between antenna near-field and far-field is vaguely defined by the reference distance r_0 .



Far-field

The communication channel quality in antenna far-field is denoted by

$$f_{ij} = \exp\left(-\alpha(2^{\delta}-1)\left(\frac{r_{ij}}{r_0}\right)^{\upsilon}\right),$$

where
r_0: reference distance for antenna near-field,
r_{ij}: Euclidean distance between agent i and agent j.

Near-field

A simple model of antenna near-field communication quality is:

$$n_{ij} = \frac{r_{ij}}{\sqrt{r_{ij}^2 + r_0^2}}$$

where
r_0: reference distance for antenna near-field,
r_{ij}: Euclidean distance between agent i and agent j.

Interaction Model

Signal Scattering Effect

When a traveling wave encounters a change in the wave impedance, it will reflect, at least partially. If the reflection is not total, it will also partially transmit into the new impedance.

Path Loss Effect

The reduction in power density (attenuation) of an electromagnetic wave as it propagates through space. As a result, the received signal power level is several orders below the transmitted power level.

Interference Effect

When a signal is disrupted as it travels along the communication channel between its source and receiver. It may cause only a temporary loss of a signal and may affect the quality of the communication.

Interaction Model

The interaction model is denoted by

$$\phi(r_{ij}) = n_{ij} \cdot f_{ij} = \frac{r_{ij}}{\sqrt{{r_{ij}}^2 + {r_0}^2}} \cdot \exp\left(-\alpha\left(2^{\delta} - 1\right)\left(\frac{r_{ij}}{r_0}\right)^{v}\right).$$

03

Control Layer

- ❑ Gradient Controller
- ❑ Unicycle Kinematic Model
- ❑ Consensus Controller

Gradient Controller

In order to optimize the communication performance, the interaction model is designed to maximize its communication performance by taking the first-order derivative of interaction model we denote

$$\frac{d\phi}{dr_{ij}} = \varphi(r_{ij}) = \frac{-\beta v (r_{ij})^{v+2} - \beta v r_0^2 (r_{ij})^{v} + r_0^{v+2}}{\sqrt{\left(r_{ij}^2 + r_0^2\right)^3}} \cdot \exp\left(-\beta \left(\frac{r_{ij}}{r_0}\right)^{v}\right),$$

where $\beta = \alpha(2^{\delta} - 1)$.

We find that interaction model has the best communication performance ϕ^* at r_{ij}^*.

A gradient controller can be designed for agents converge in the formation with the maximized communication performance of function $\phi(r_{ij})$.

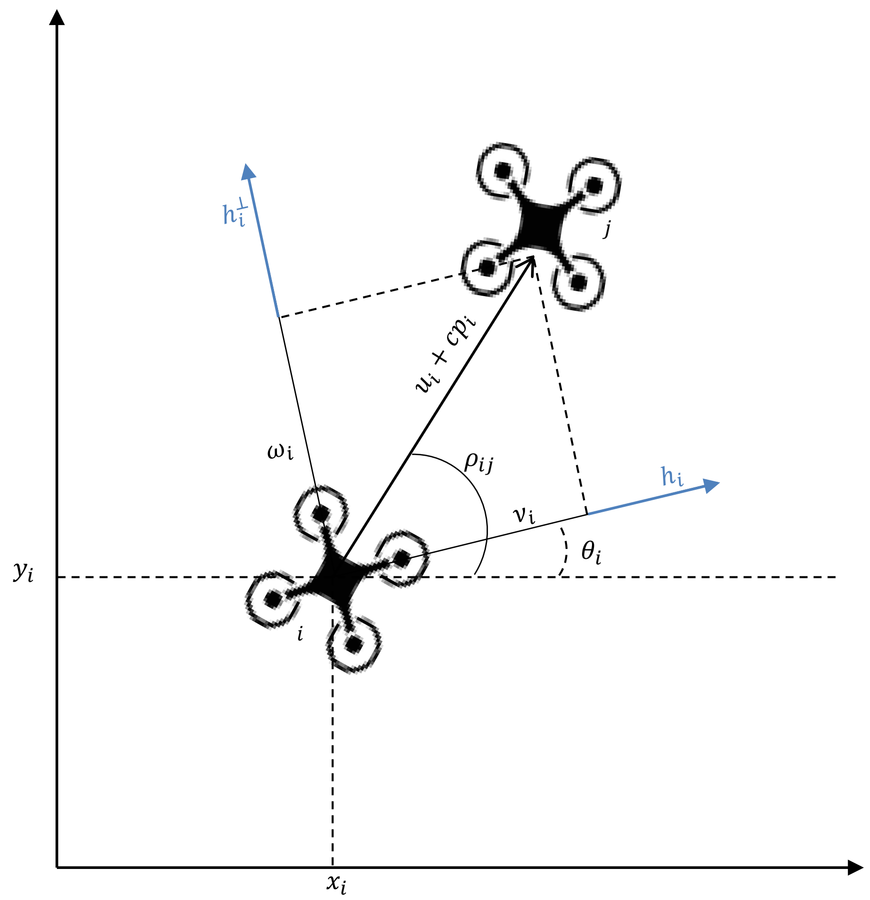
Gradient Control Model

The gradient control model of agent i is denoted by

$$\mathcal{G}_i = \sum_{j \in N_i} [\nabla_{q_i} \phi(r_{ij})] = \sum_{j \in N_i} [\varphi(r_{ij}) \cdot e_{ij}]$$

where $e_{ij} = (q_i - q_j)/\sqrt{r_{ij}}$.

Unicycle Kinematic Model



Unicycle Kinematic Model

The unicycle kinematic model of agent i is denoted by

$$\dot{x}_i = \nu_i \cos(\theta_i)$$
$$\dot{y}_i = \nu_i \sin(\theta_i)$$
$$\dot{\theta}_i = \omega_i,$$

h_i: Heading vector, defined as $\begin{bmatrix}\cos(\theta_i)\\ \sin(\theta_i)\end{bmatrix}$

$h_i^\perp$: Perpendicular heading vector, defined as $\begin{bmatrix}-\sin(\theta_i)\\ \cos(\theta_i)\end{bmatrix}$

θ_i: Heading angle
ν_i: Linear velocity vector
ω_i : Angular velocity vector
ρ_{ij}: Line of sight, defined as $\mathrm{arctan2}(q_i - q_j)$
$u + cp_i$: consensus control vector

Dubins Constraints

Due to its physical capabilities, the airspeed and heading angle of the UAV are limited. These physical limits can be represented by the constraints

$$\nu_{min} \le \nu_i \le \nu_{\max},$$
$$|\omega_i| \le \omega_{max},$$

Consensus Controller

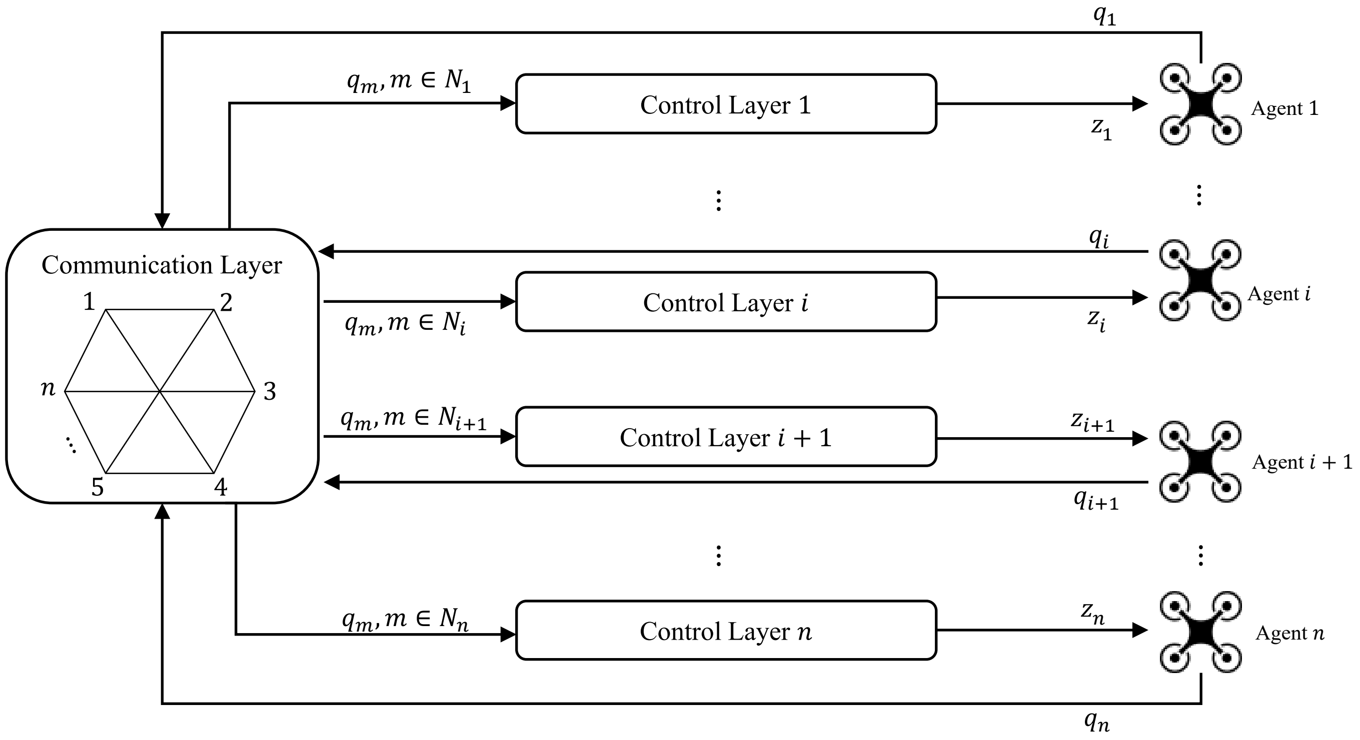
Consensus Control Model

The projections of consensus control vector $u + p_i$ along the heading direction h_i and its perpendicular vector $h_i^\perp$ are then calculated and used as the linear and angular velocity vectors, respectively. Specifically, the linear and angular velocity controls are given by

$$\nu_i = h_i^\top (u + cp_i)\cos(\rho_{ij} - \theta_i)$$
$$\omega_i = h_i^{\perp\top} (u + cp_i)\sin(\rho_{ij} - \theta_i).$$

And the consensus motion of agents i can be collectively expressed as

$$\mathcal{C}_i = h_i h_i^\top (u + cp_i)\cos(\rho_{ij} - \theta_i).$$



Final Formation Controller

$$z_i = \mathcal{G}_i + \mathcal{C}_i$$

$$= \sum_{j \in N_i} [\varphi(r_{ij}) \cdot e_{ij}] + \sum_{j \in N_i} [h_i h_i^\top (u + cp_i)\cos(\rho_{ij} - \theta_i)]$$

Dynamics

The dynamics of this multi-agent system is denoted by

$$\dot{q}_i = z_i, \quad i = 1,2,\ldots,n,$$

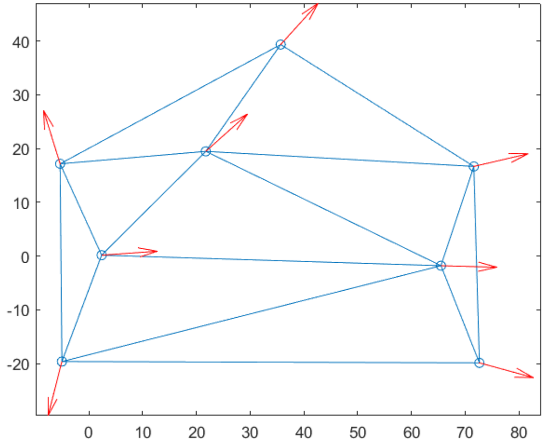
where

q: position input of agents,

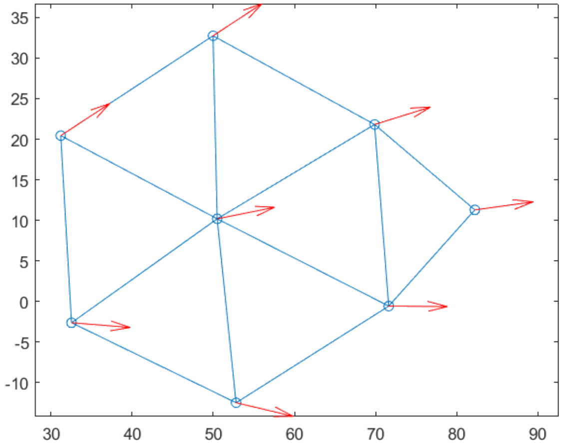
z: control input of agents.

04

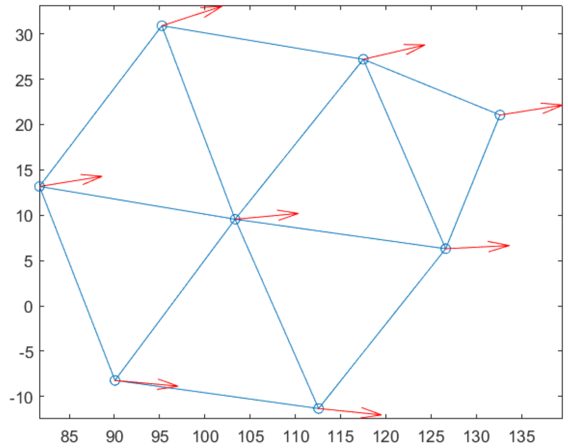
Simulations



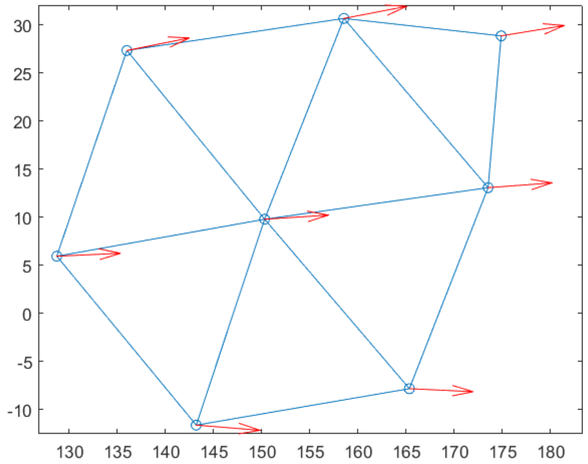
(a) $t = 0s$



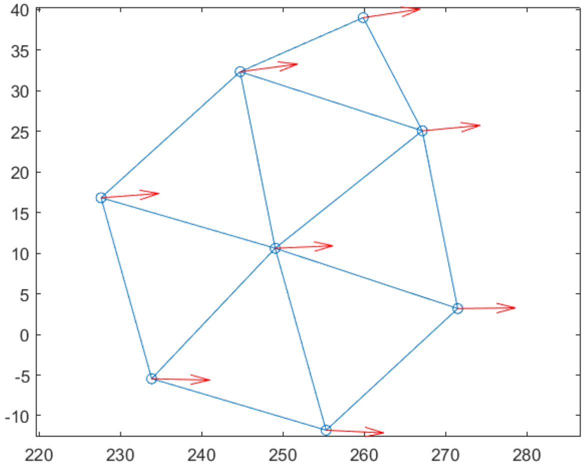
(b) $t = 10s$



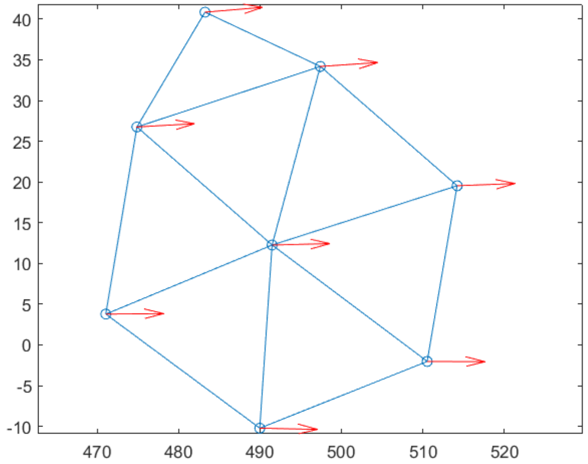
(c) $t = 30s$



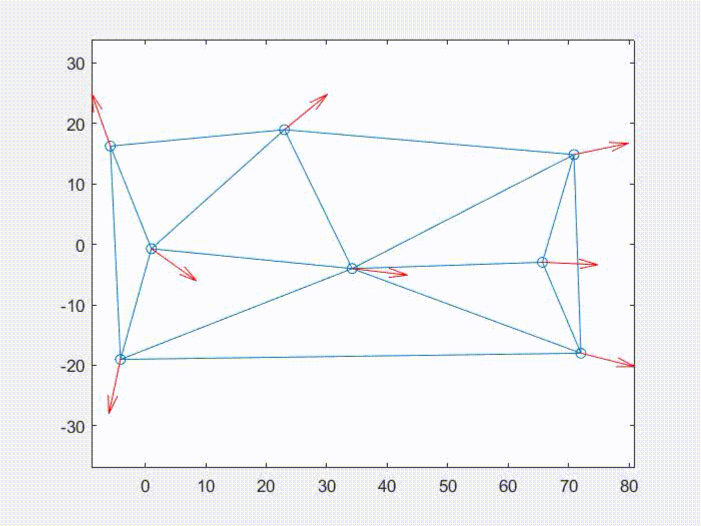
(d) $t = 60s$



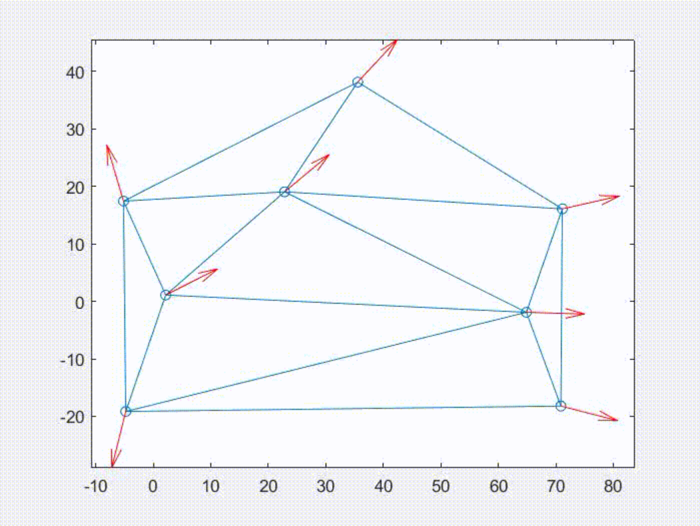
(e) $t = 90s$



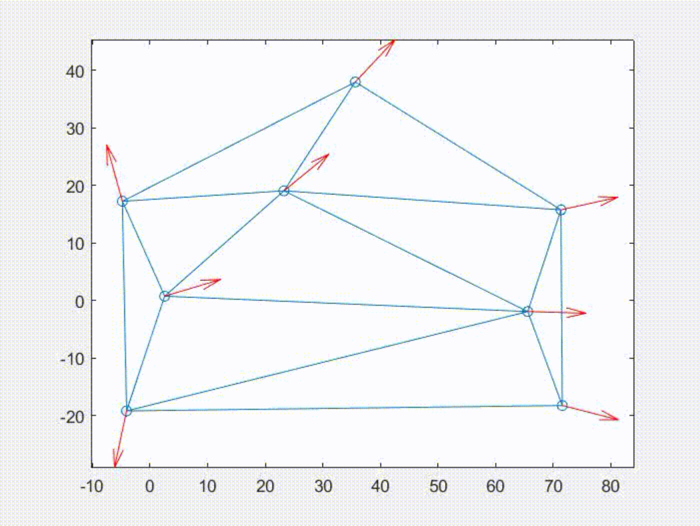
(f) $t = 180s$



Before proposed

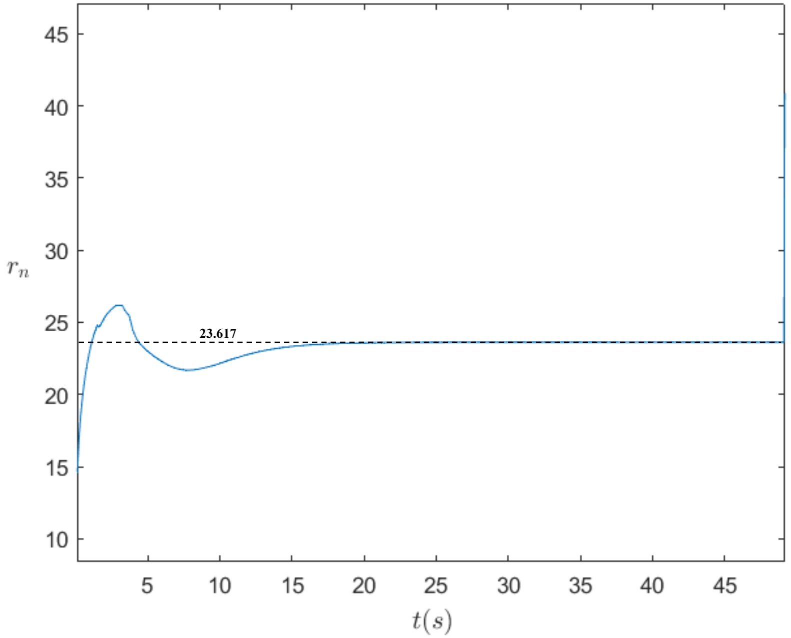


After Proposed
Traveling in NE direction

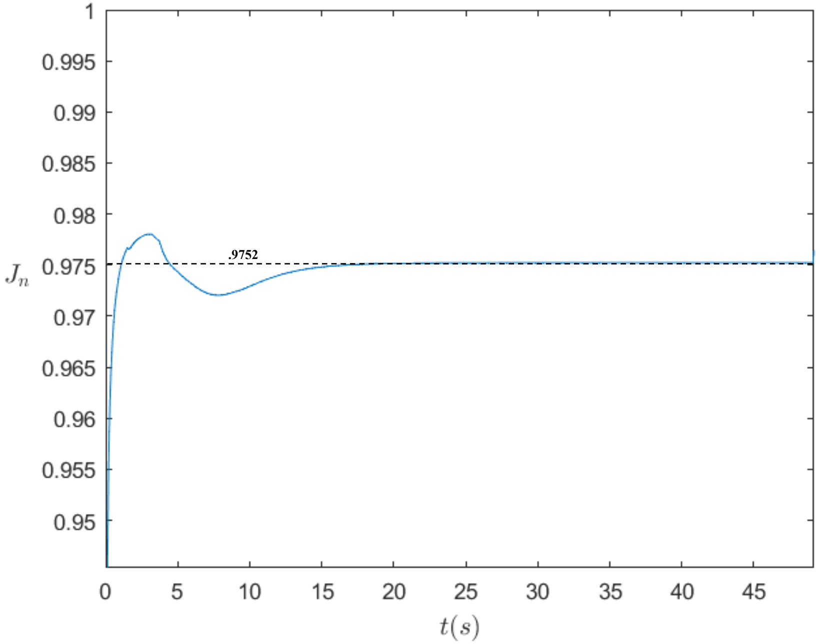


After Proposed
Traveling in in E direction

Agents Traveling in NE Direction



Before Proposed

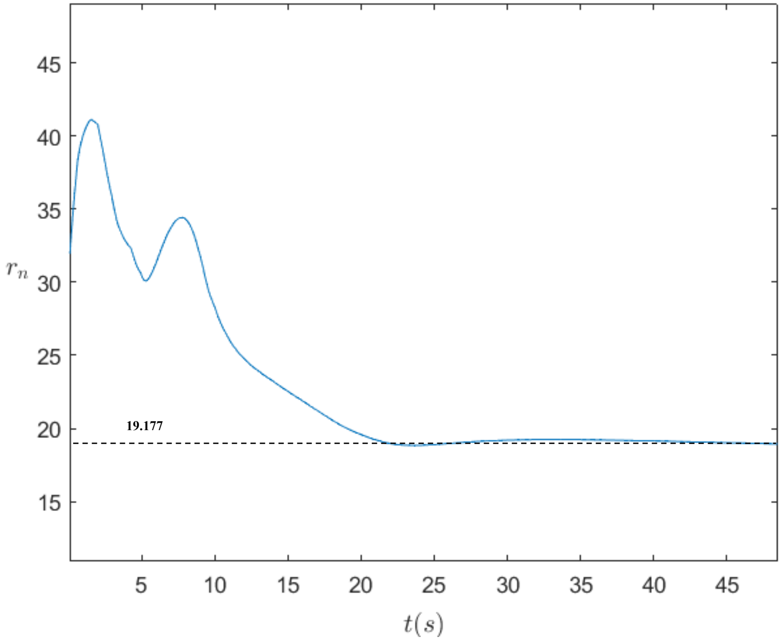


J_n: Average Communication Performance Indicator

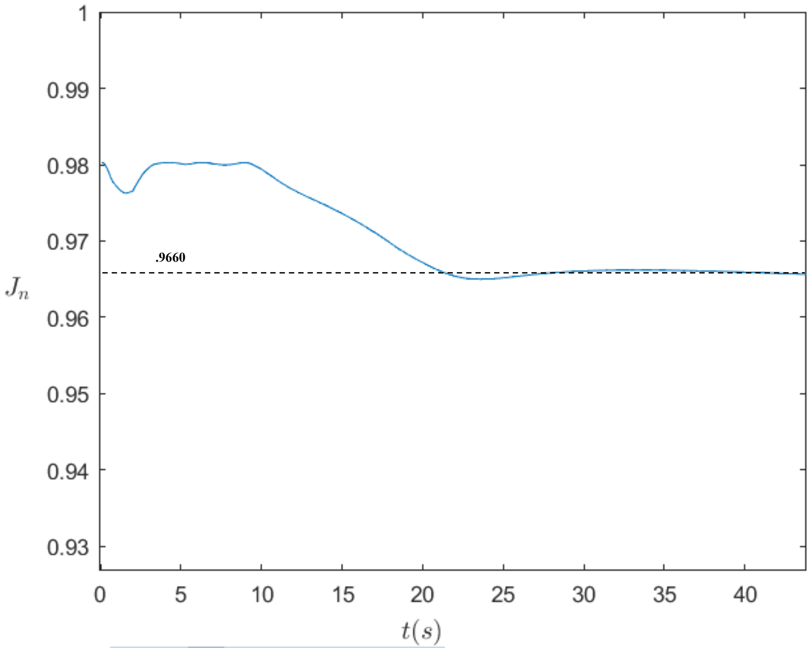
$$J_n = \frac{\sum_{i=1}^{n} \sum_{j \in N_i} \phi(r_{ij})}{2n|N_i|}$$

r_n: Average Neighboring Distance Indicator

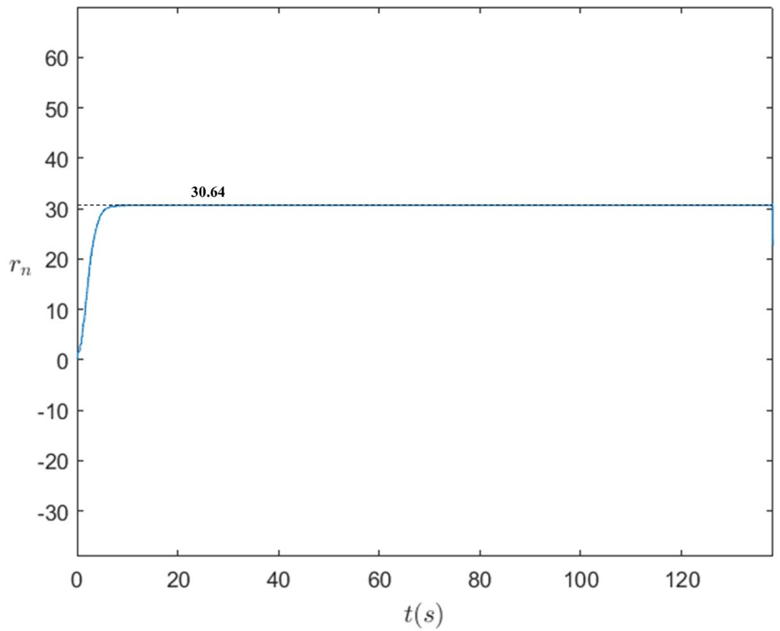
$$r_n = \frac{\sum_{i=1}^{n} \sum_{j \in N_i} r_{ij}}{2n|N_i|}$$



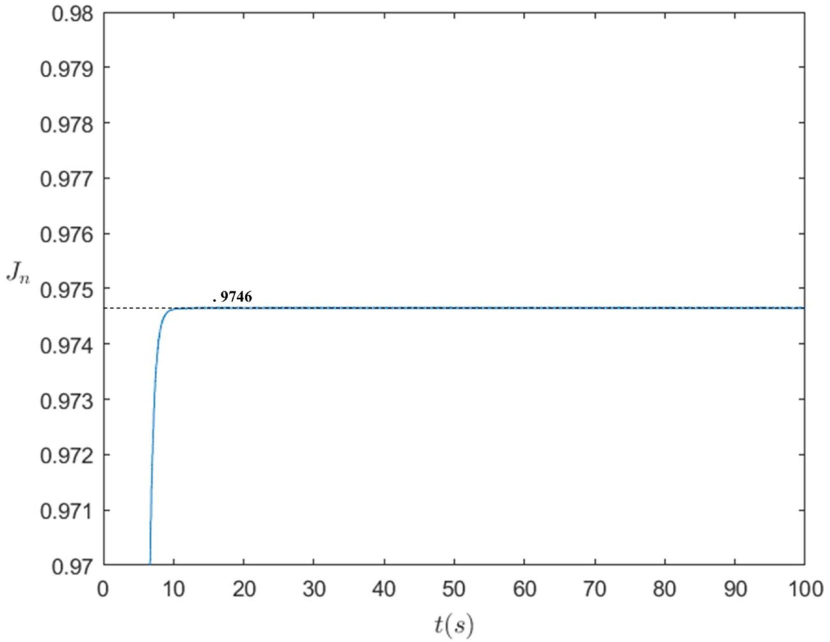
After Proposed



Agents Traveling in E Direction



Before Proposed



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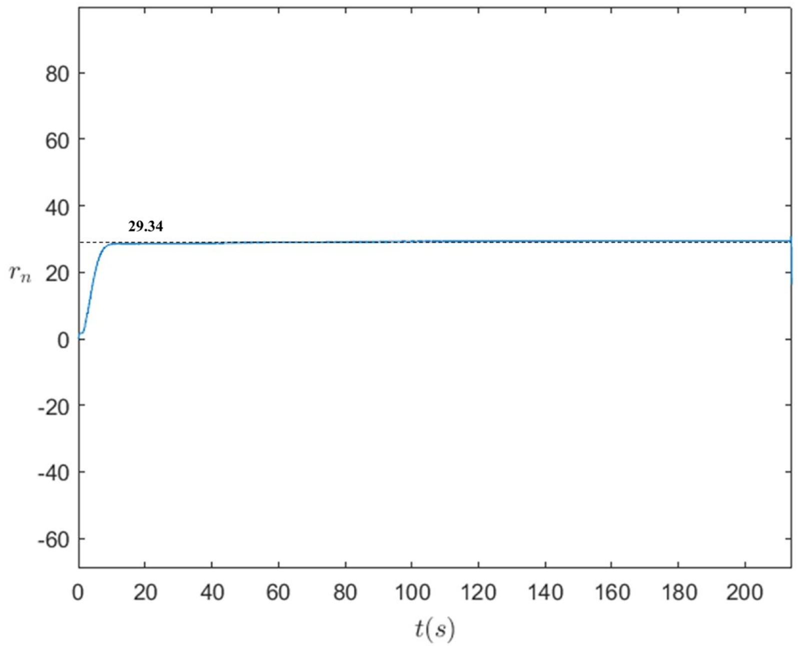
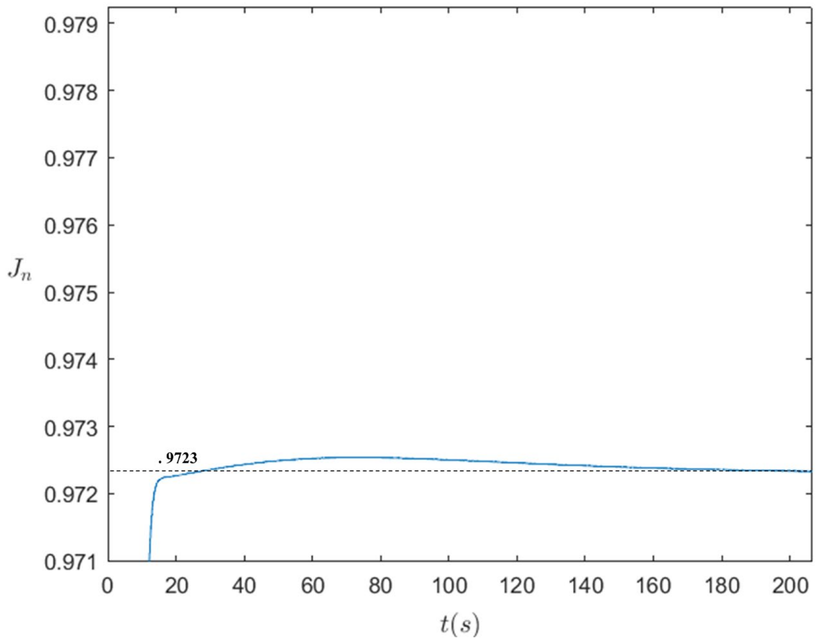


After Proposed



05

Conclusion

Outline

Intro

Preliminaries

- Graph Theory
- Rigid Formation
- System Dynamics

Communication Layer

- Antenna Far-field Model
- Antenna Near-field Model
- Interaction Model

Control Layer

- Gradient Controller
- Unicycle Kinematic Model
- Consensus Control

Simulation

- Average Communication Performance J_n
- Average neighboring Distance r_n

Outro

THANKS

Questions?

Reference

[1]: H. Li, J. Peng, W. Liu, K. Gao, Z. Huang, "A novel communication aware formation control strategy for dynamical multi-agent systems", Journal of the Franklin Institute 352 (2015), 3701-3715.

[2]: K. Fathian, T. H. Summers, and N. R. Gans, "Distributed formation control and navigation of fixed-wing UAVs at constant altitude," in 2018 International Conference on Unmanned Aircraft Systems (ICUAS), 2018.