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Behavior-based Communication-aware Formation Control

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ERAU NSF REU

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Introduction

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- Preliminaries
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Formation Control

Tasks

1. How to navigate a swarm towards a destination?
2. How to avoid a jamming area without prior knowledge of its position?
3. How to achieve the above 2 tasks while maximizing communication quality?

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.

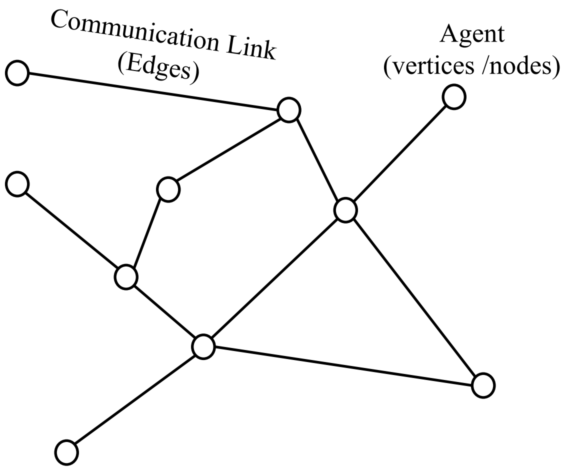
Communication-aware Formation Control

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

Behavior-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 adopt a flexible formation control model that adapts to complex and changing environments. Specifically, the investigation of a jamming area, where communication between agents is impaired.

Preliminaries



Graph Theory

A **graph** G is a pair of $(\mathcal{V}, \mathcal{E})$ consisting of a set of **vertices** $\mathcal{V} = \{1,2, \ldots, \mathrm{i}, \ldots, j, \ldots n\}$ 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

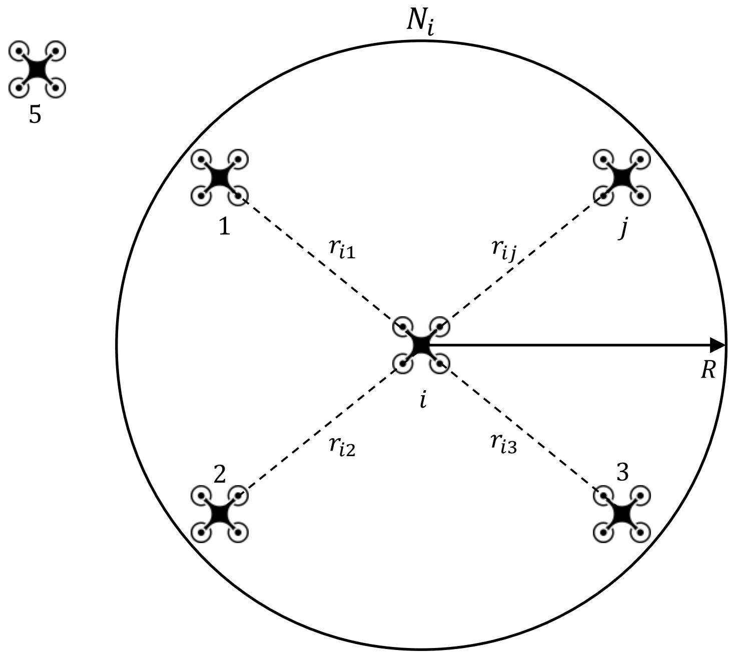
The formation of groups of mobile agents in which all inter-agent distances remain constant is called **rigid**.

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

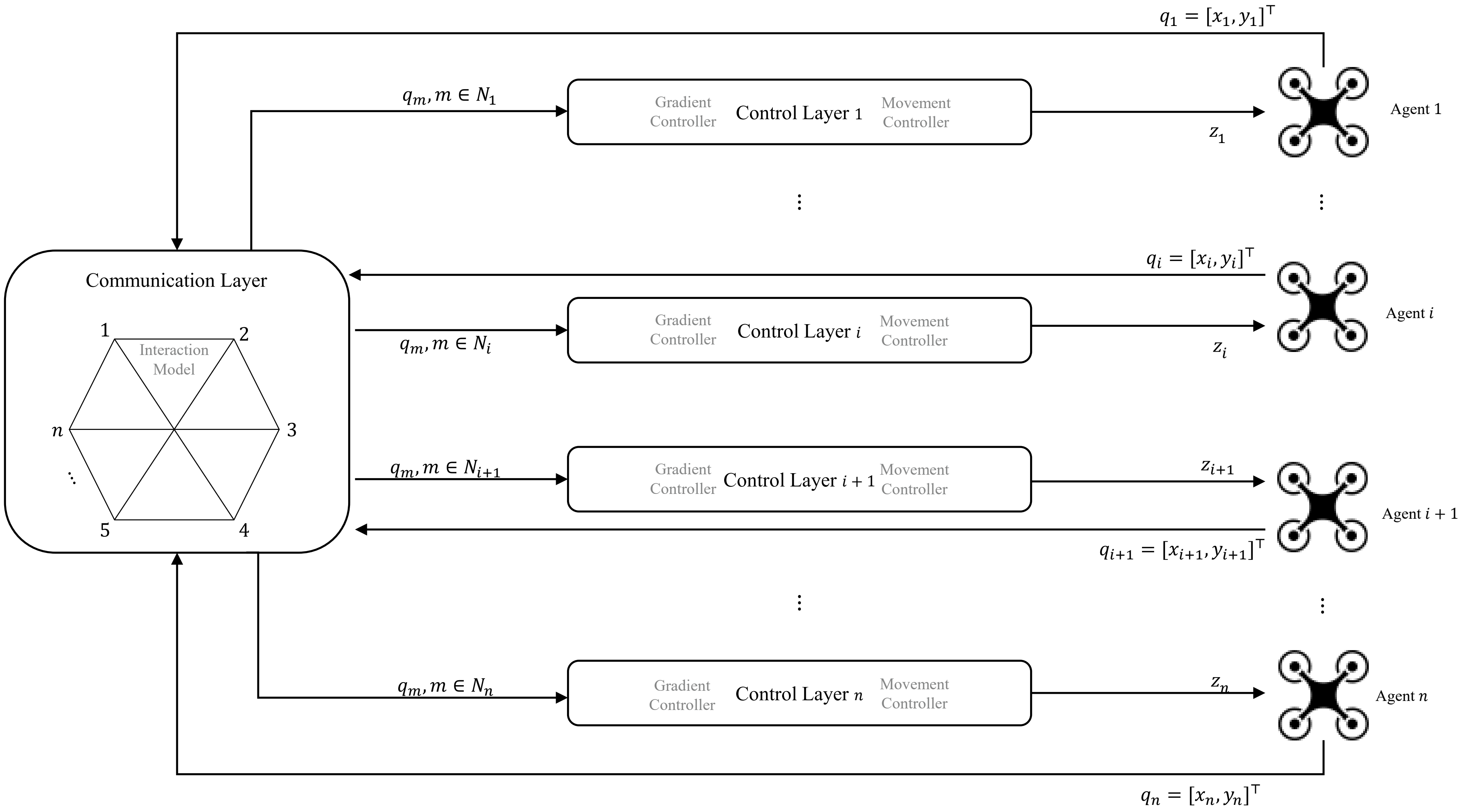
$$r_{ij} = \sqrt{\left(x_i - x_j\right)^2 + \left(y_i - y_j\right)^2} = \|q_i - q_j\|.$$

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

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

where

q: positions of agents,

z: controls of agents.

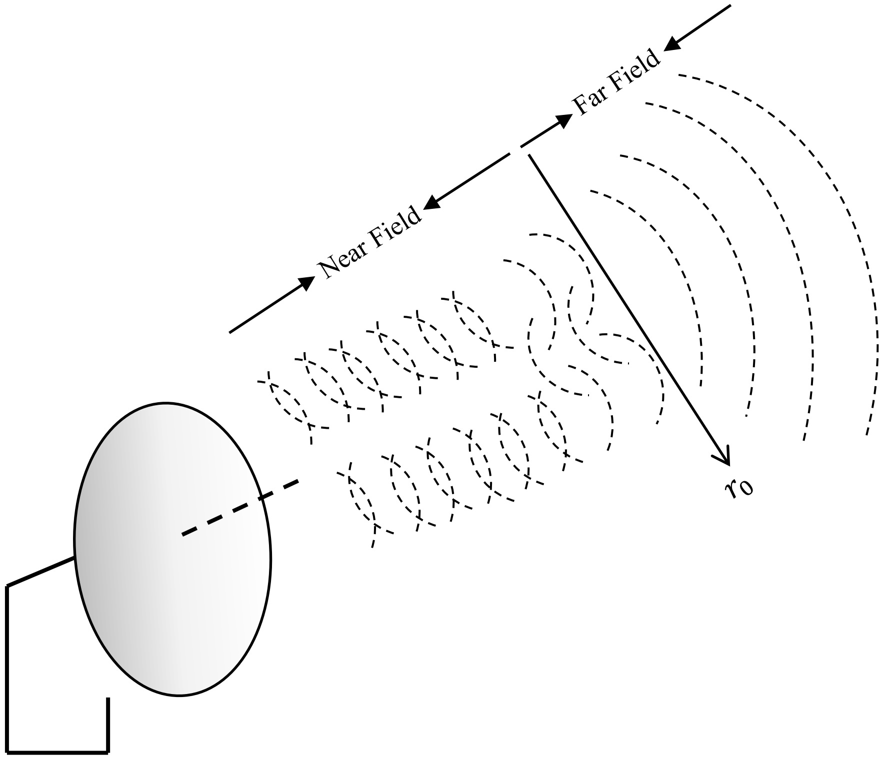
02

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

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

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

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

03

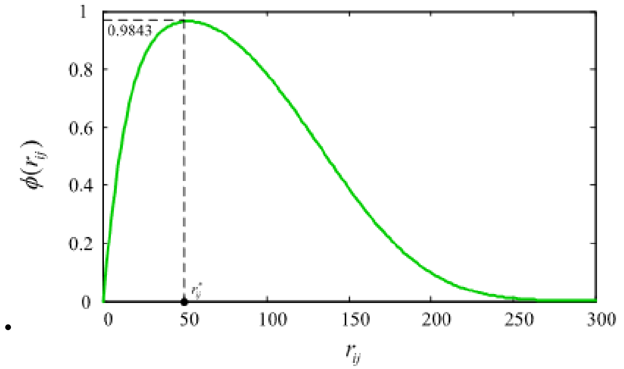
Control Layer

- ❑ Gradient Controller
- ❑ Movement Controller
  - ▪ Reach Goal Behavior
  - ▪ Jamming Avoidance Behavior
  - ▪ Edge Following Behavior

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

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



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

Movement Controller: Reach Goal Behavior

Description

Navigating the agents towards the destination.

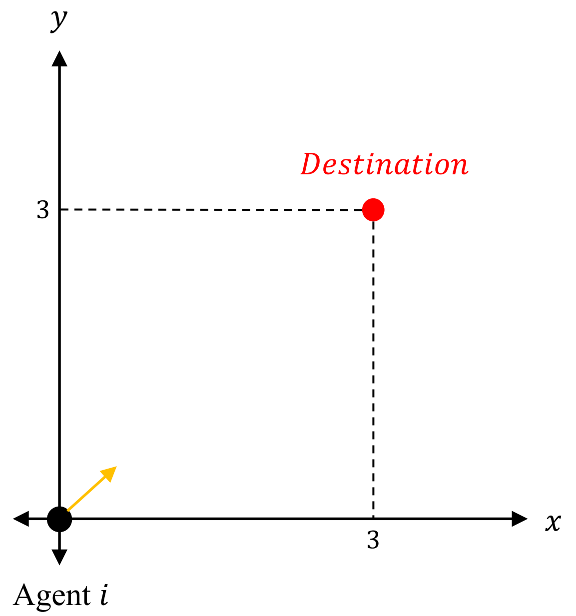
The behavior vector is calculated based on the current agent's coordinates and the destination coordinates.

The controlling parameter adjusts the agent's movement speed based on the distance between the agent and the target point.

Formula

$$V_{navigation} = \frac{1}{\sqrt{(x_{dest} - x_i)^2 + (y_{dest} - y_i)^2}} \begin{bmatrix} x_{dest} - x_i \\ y_{dest} - y_i \end{bmatrix}$$

$$f_1(d) = \begin{cases} a_m, & d > b_m \\ a_m \dfrac{d}{b_m}, & d \in [0, b_m] \end{cases}$$



$$V_{navigation} = \frac{1}{\sqrt{(x_{dest} - x_i)^2 + (y_{dest} - y_i)^2}} \begin{bmatrix} x_{dest} - x_i \\ y_{dest} - y_i \end{bmatrix}$$

$$= \frac{1}{\sqrt{(3-0)^2 + (3-0)^2}} \begin{bmatrix} 3-0 \\ 3-0 \end{bmatrix} = \frac{1}{\sqrt{18}} \begin{bmatrix} 3 \\ 3 \end{bmatrix} = \begin{bmatrix} 3/\sqrt{18} \\ 3/\sqrt{18} \end{bmatrix} = \begin{bmatrix} 0.707 \\ 0.707 \end{bmatrix}$$

Movement Controller: Reach Goal Behavior

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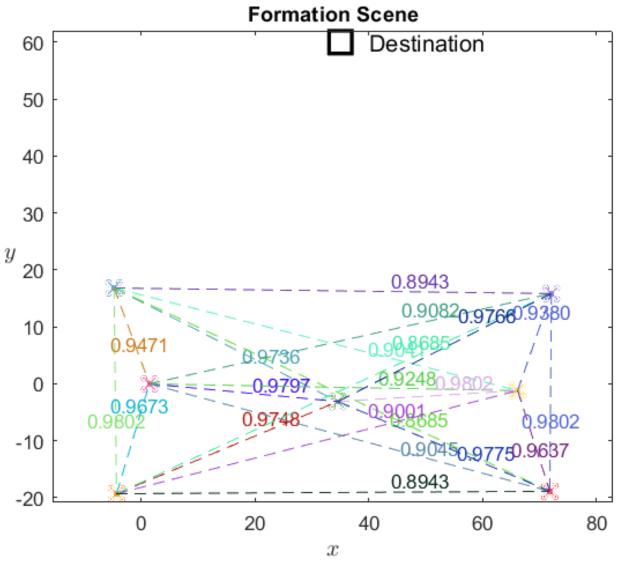
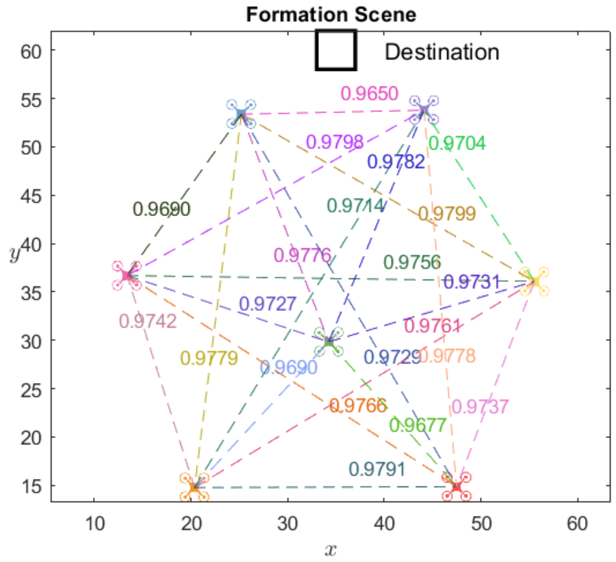
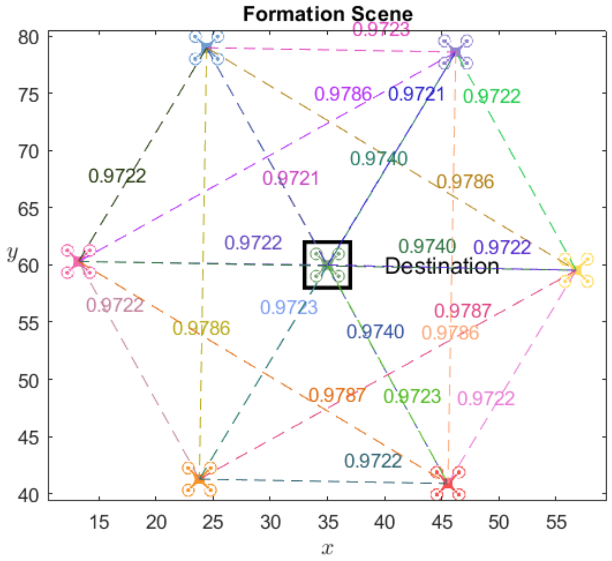


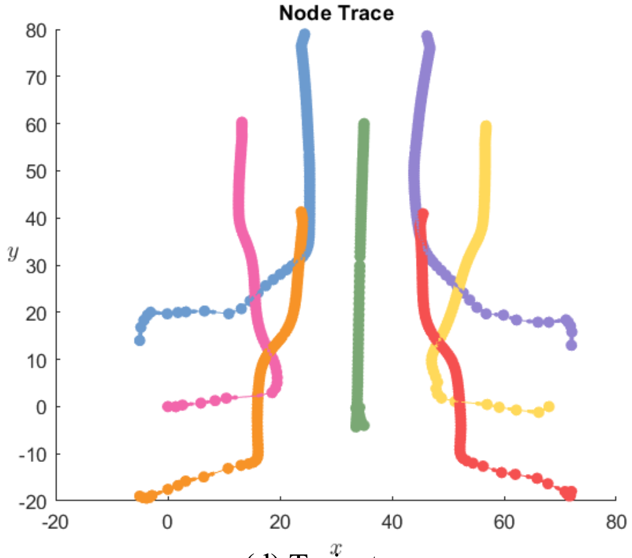
(a) Initial



(b) Halfway



(c) Final



(d) Trajectory

Movement Controller: Jamming Avoidance Behavior

Description

Enables agents to avoid jamming area in its path.

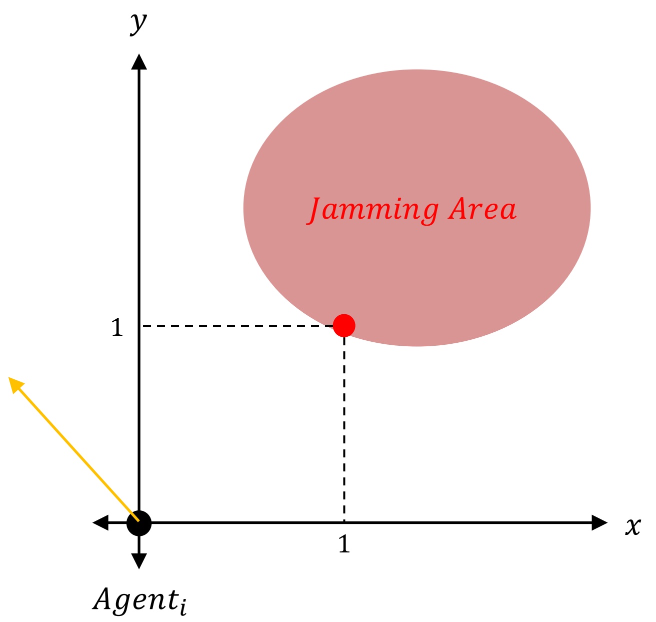
The behavior vector is determined by the distance between the agent and the nearest obstacle.

The controlling parameter adjusts the behavior to steer the agent away from the obstacle, with the sign of the vector determined by the obstacle's position relative to the agent.

Formula

$$V_{avoidance} = \frac{1}{\sqrt{\left(x_{jam} - x_i\right)^2 + \left(y_{jam} - y_i\right)^2}} \begin{bmatrix} \pm y_{jam} - y_i \\ \mp x_{jam} - x_i \end{bmatrix}$$

$$f_2(d) = \begin{cases} a_0 \left(\dfrac{d}{b_f - b_0} + \dfrac{b_0}{b_0 - b_f} \right), & d \in [b_f, b_0] \\ 0, & otherwise \end{cases}$$



$$V_{avoidance} = \frac{1}{\sqrt{\left(x_{jam} - x_i\right)^2 + \left(y_{jam} - y_i\right)^2}} \begin{bmatrix} \pm y_{jam} - y_i \\ \mp x_{jam} - x_i \end{bmatrix}$$

$$= \frac{1}{\sqrt{(1-0)^2 + (1-0)^2}} \begin{bmatrix} +(1-0) \\ -(1-0) \end{bmatrix} = \frac{1}{\sqrt{2}} \begin{bmatrix} 1 \\ -1 \end{bmatrix} = \begin{bmatrix} 0.707 \\ -0.707 \end{bmatrix}$$

Movement Controller: Jamming Avoidance Behavior

Description

Enables agents to avoid jamming area in its path.

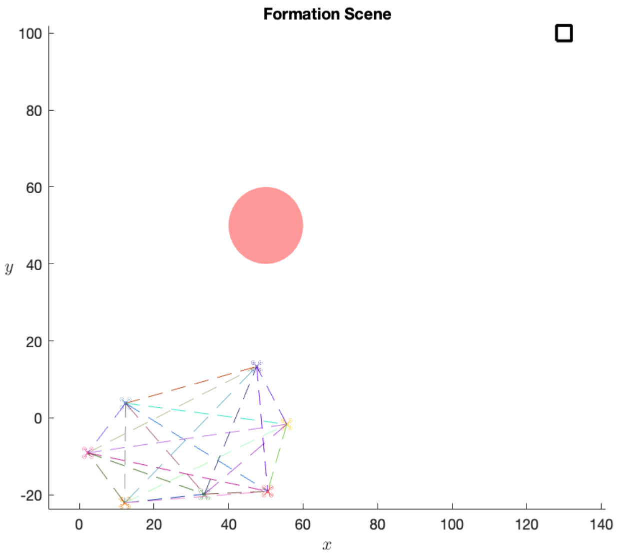
The behavior vector is determined by the distance between the agent and the nearest obstacle.

The controlling parameter adjusts the behavior to steer the agent away from the obstacle, with the sign of the vector determined by the obstacle's position relative to the agent.

Formula

$$V_{avoidance} = \frac{1}{\sqrt{\left(x_{jam} - x_i\right)^2 + \left(y_{jam} - y_i\right)^2}} \begin{bmatrix} \pm y_{jam} - y_i \\ \mp x_{jam} - x_i \end{bmatrix}$$

$$f_2(d) = \begin{cases} a_0\left(\dfrac{d}{b_f - b_0} + \dfrac{b_0}{b_0 - b_f}\right), & d \in [b_f, b_0] \\ 0, & otherwise \end{cases}$$



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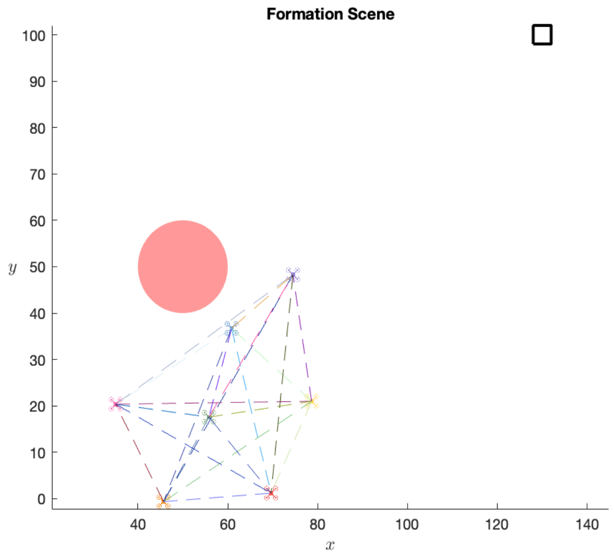

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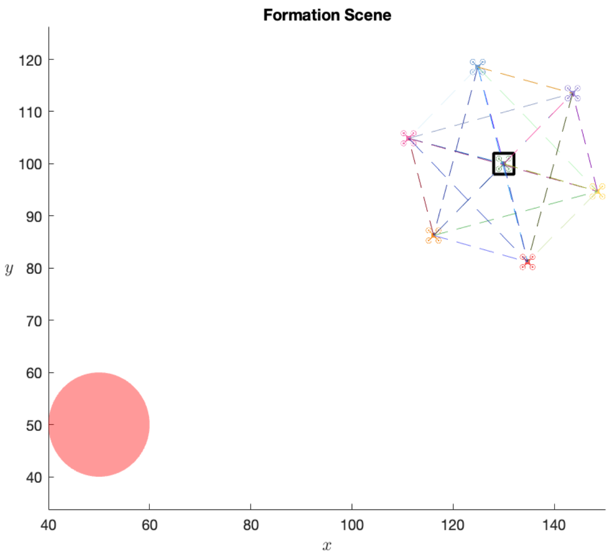

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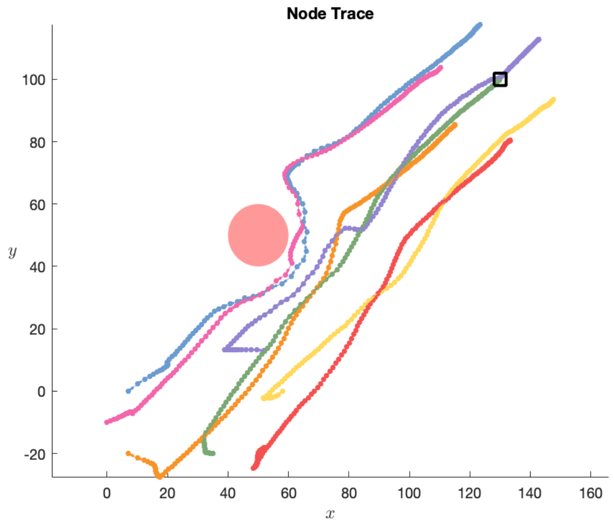


(d) Trajectory

Movement Controller: Edge Following Behavior

Description

Helps the agents navigate by following jamming area edges.

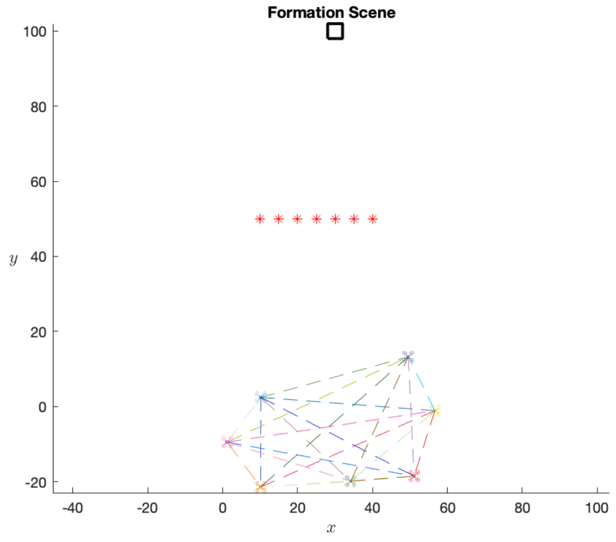
The behavior vector is calculated based on the coordinates of the nearest obstacle and the agent's current position.

The controlling parameter activates the behavior and determines the direction of edge following based on the obstacle's position relative to the agent.

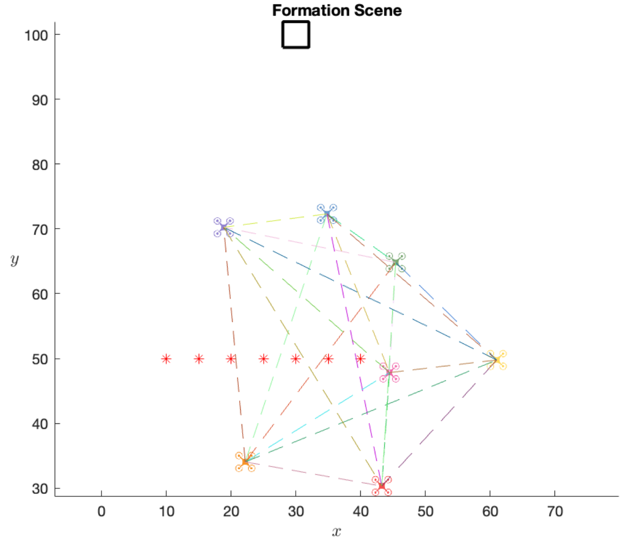
Formula

$$V_{edge-following} = \frac{1}{\sqrt{(x_{jam} - x_i)^2 + (y_{jam} - y_i)^2}} \begin{bmatrix} \pm y_{jam} - y_i \\ \mp x_{jam} - x_i \end{bmatrix}$$

$$f_3(d) = \begin{cases} a_f, & d \in [0, e_f] \\ 0, & otherwise \end{cases}$$



(a) Initial



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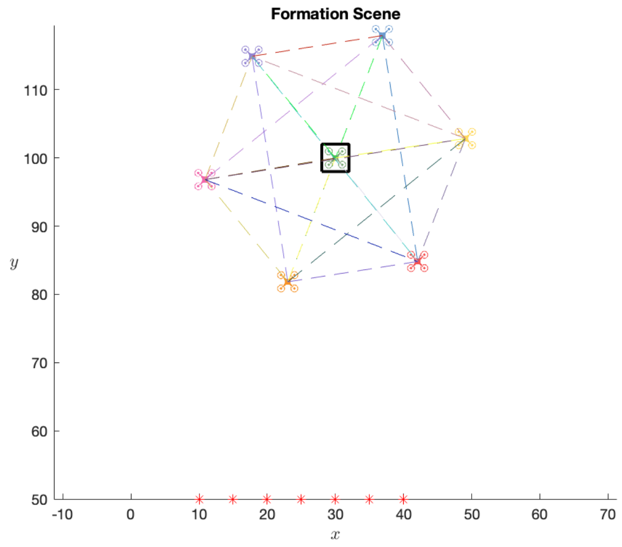
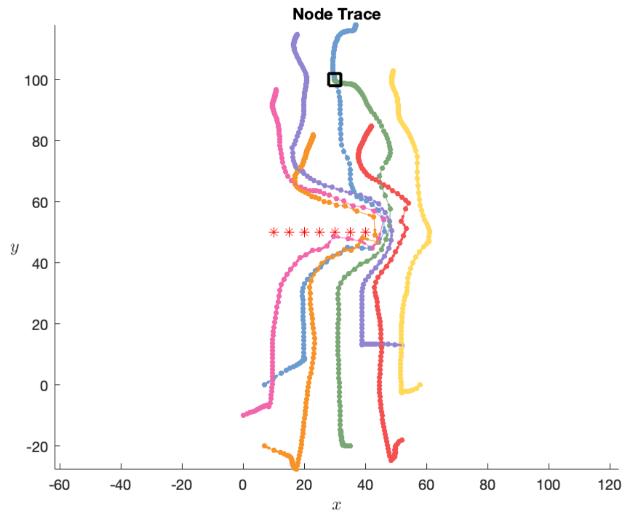


(c) Final



(d) Trajectory

Final Controller

System Dynamics

The dynamics of this multi-agent system is denoted by

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

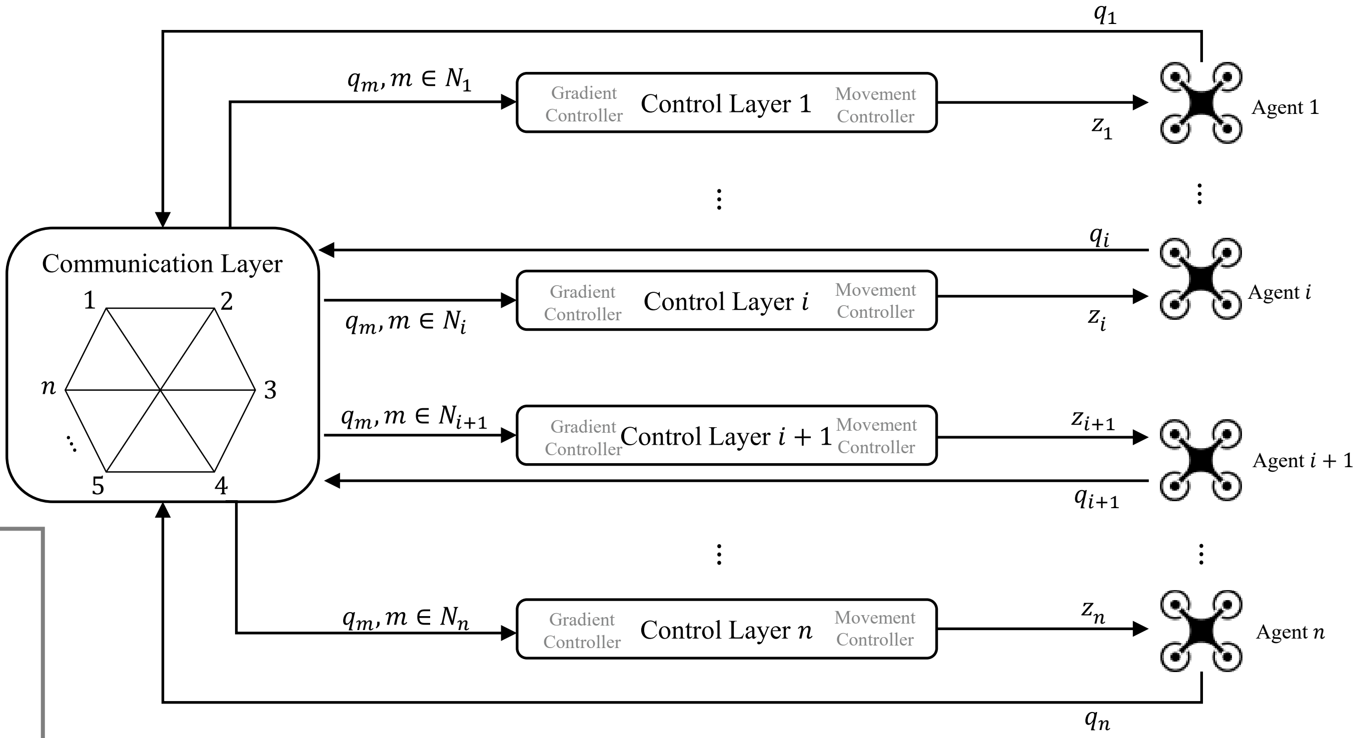
where

q: position input of agents,
z: control input of agents.

Final Formation Controller

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

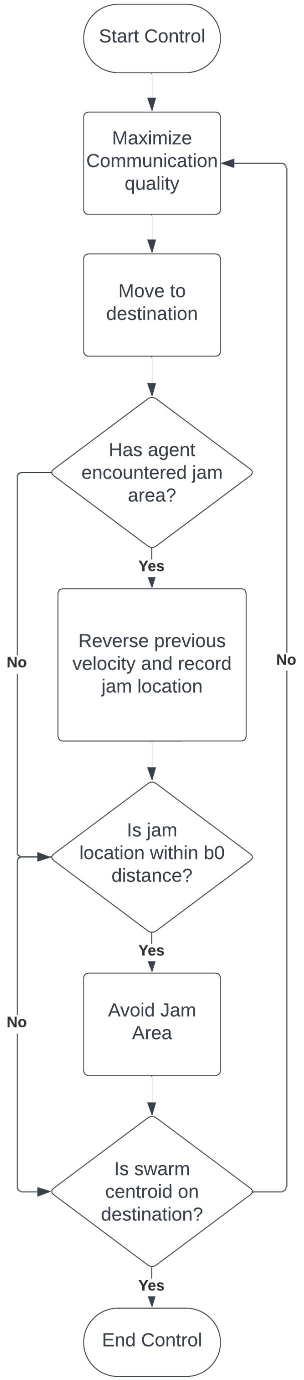
$$= \sum_{j \in N_i} \left[\varphi(r_{ij}) \cdot e_{ij} \right] + \left[f_1(\cdot) \quad f_2(\cdot) \quad f_3(\cdot) \right] \begin{bmatrix} V_{navigation} \\ V_{avoidance} \\ V_{edge-following} \end{bmatrix}$$



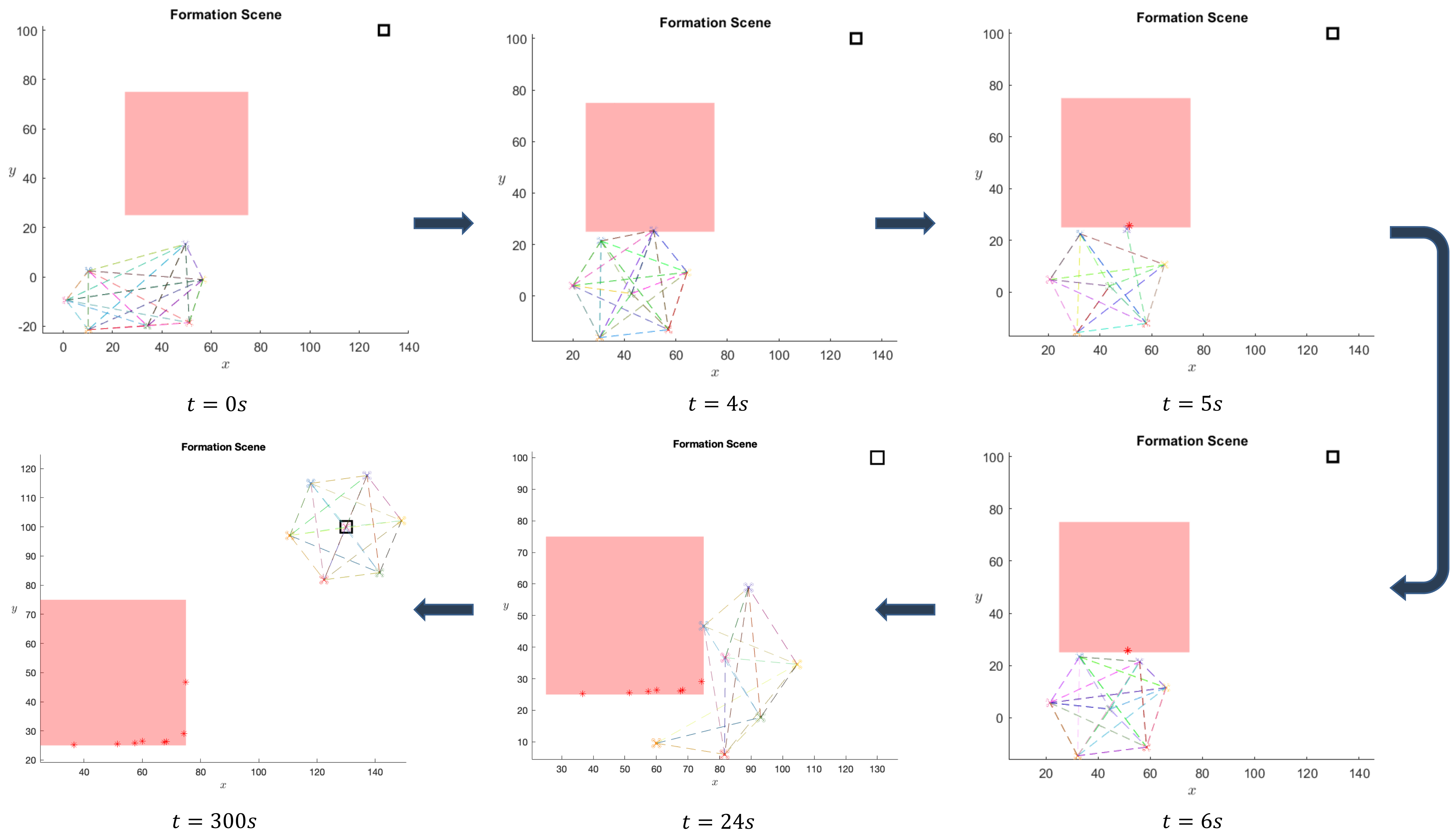
04

Simulations

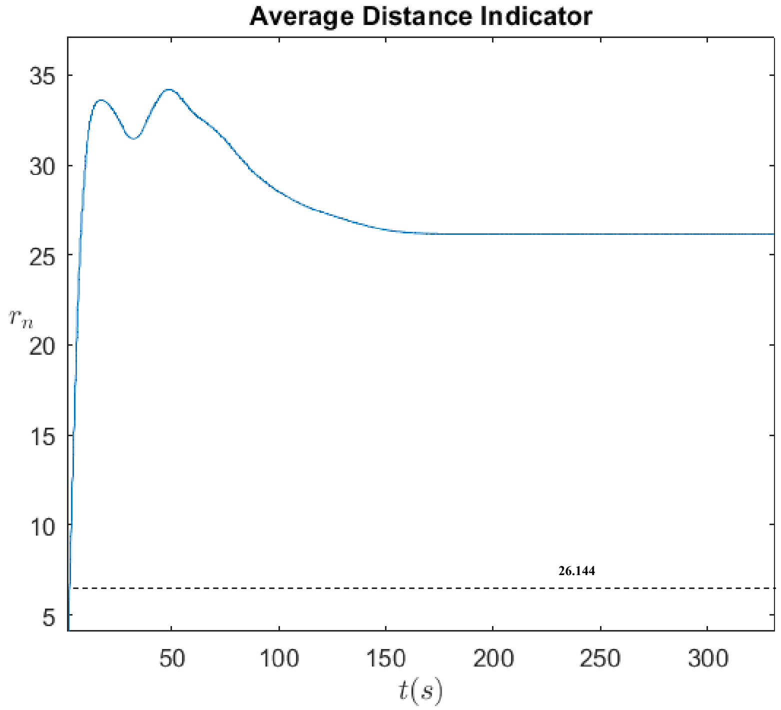
Workflow



Start Control
Maximize Communication quality
Move to destination
Has agent encountered jam area?
Yes
No
Reverse previous velocity and record jam location
Is jam location within b0 distance?
Yes
No
Avoid Jam Area
Is swarm centroid on destination?
No
Yes
End Control



Formation Scene
$t = 0s$
Formation Scene
$t = 4s$
Formation Scene
$t = 5s$
Formation Scene
$t = 300s$
Formation Scene
$t = 24s$
Formation Scene
$t = 6s$

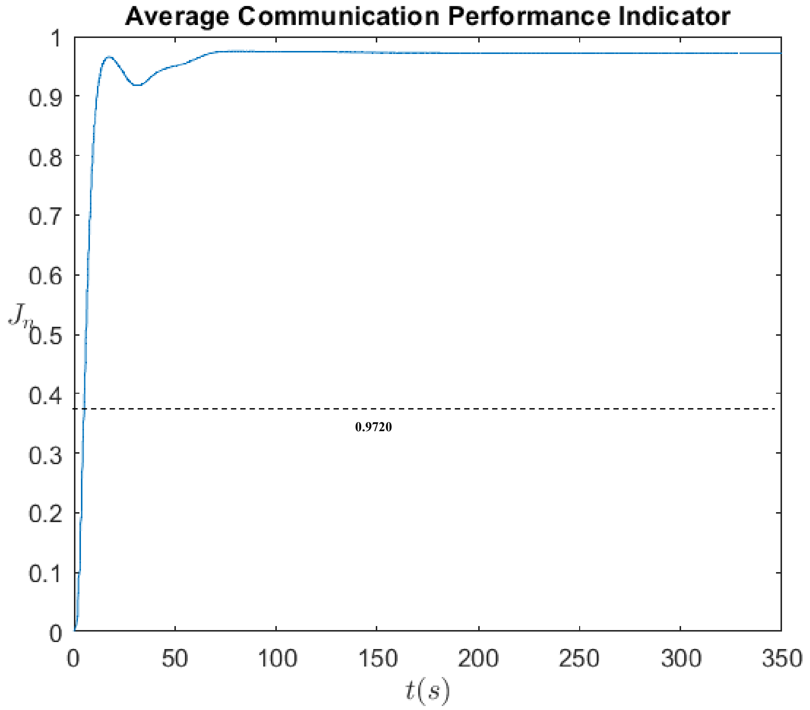


J_n: Average Communication Performance Indicator

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

r_n: Average Neighboring Distance Indicator

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



05

Conclusion

Review

Intro

Preliminaries

- Graph Theory
- Rigid Formation
- System Dynamics

Communication Layer

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

Control Layer

- Gradient Controller
- Movement Control

Simulation

- Average Communication Performance J_n
- Average neighboring Distance r_n

Outro

Results

- Formation control is communication-aware and behavior-based.
- Maintained a similar average neighboring distance. Achieved sufficient average communication performance.
- Enhanced resilience in complex environments, such as jamming area.

Acknowledgement

- This research was supported by the National Science Foundation under Grant No. 2150213.
- We’d like to thank you Dr. Stansbury for considering us into this research program.
- We’d like to thank you Dr. Yang’s guidance throughout this research project.

THANKS

Questions?

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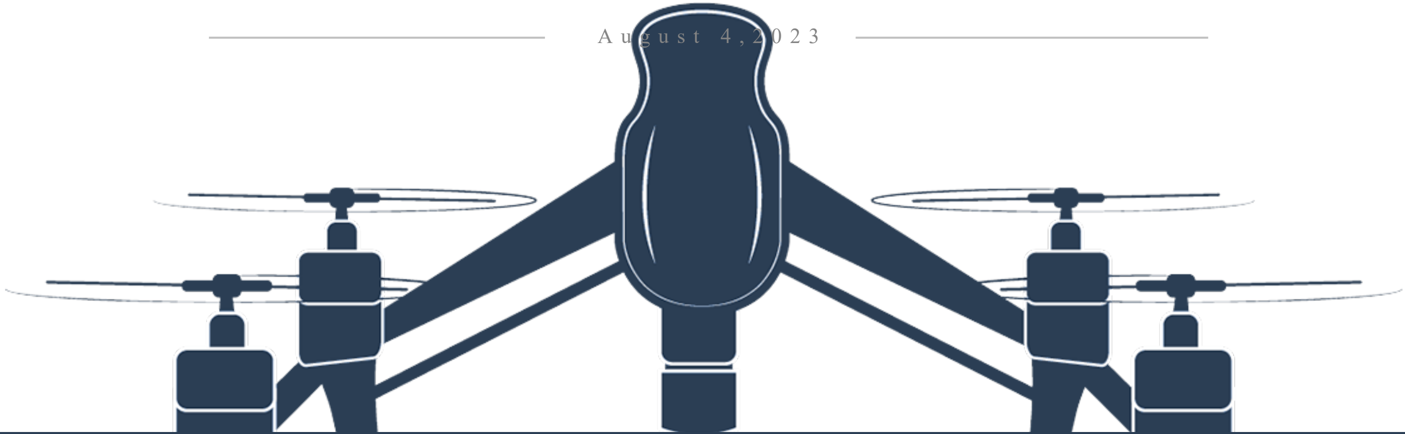

Reference

[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]: D. Xu, X. Zhang, Z. Zhu, C. Chen, and P. Yang, “Behavior-based formation control of Swarm Robots,” Mathematical Problems in Engineering, vol. 2014, pp. 1–13, 2014. doi:10.1155/2014/205759