# 2022

# Consensus-based Communication-aware Formation Control

Sang Xing
(ERAU)
Dr. Yang
(ERAU)

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4 Simulation

5 Conclusion

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.

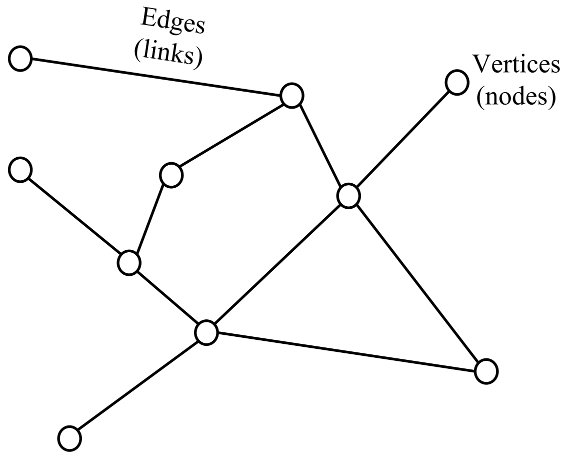
## Communication-aware Formation Control

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

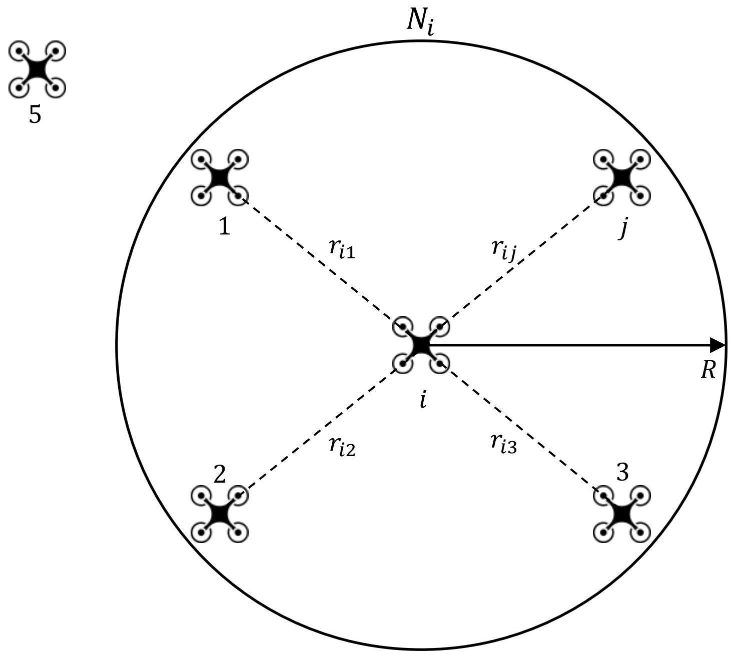
The formation of groups of mobile agents in which all inter-agent distances remain constant is called **rigid**.

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

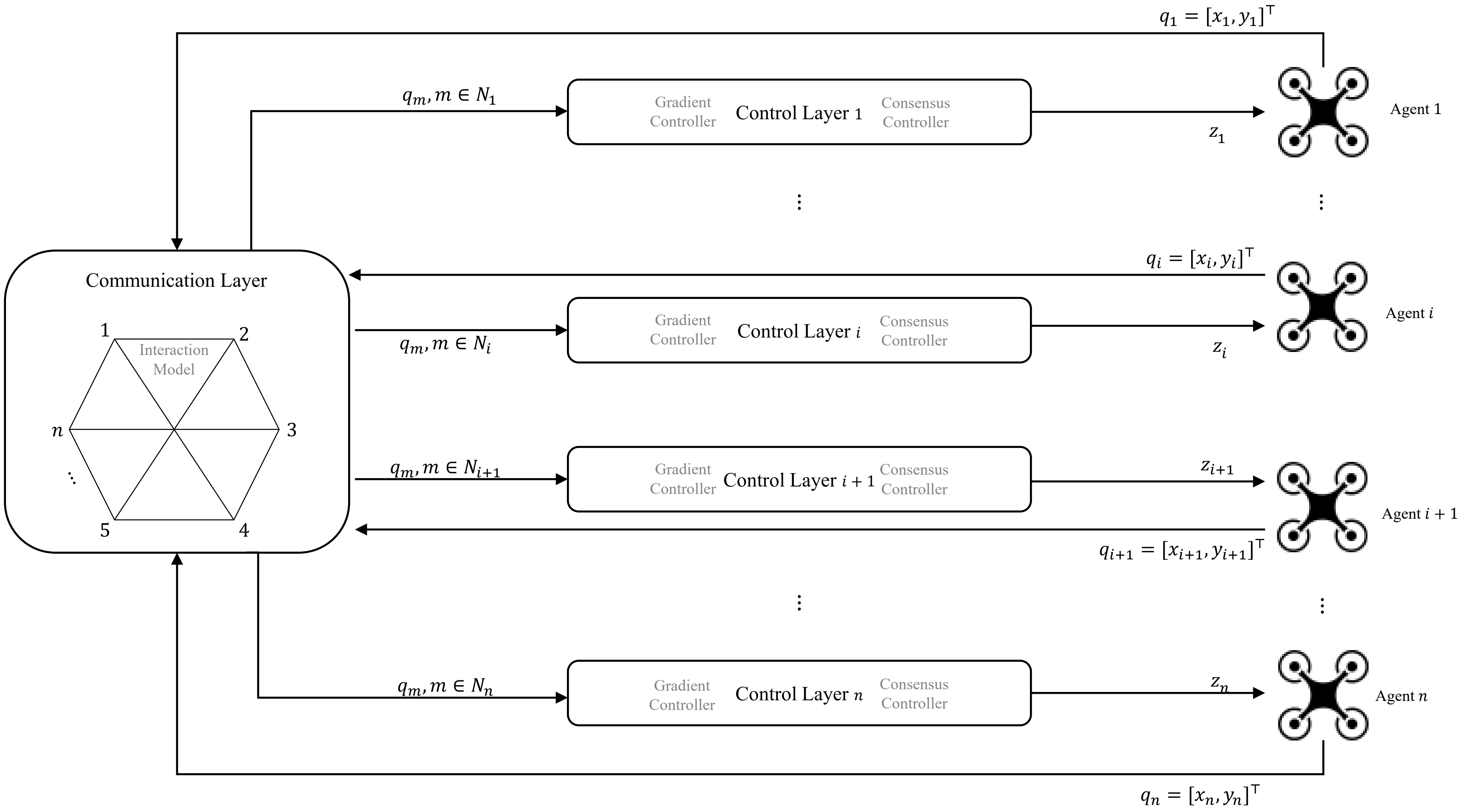
$$r_{ij} = \sqrt{\left(x_i - x_j\right)^2 + \left(y_i - y_j\right)^2} = \|q_i - q_j\|.$$

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.

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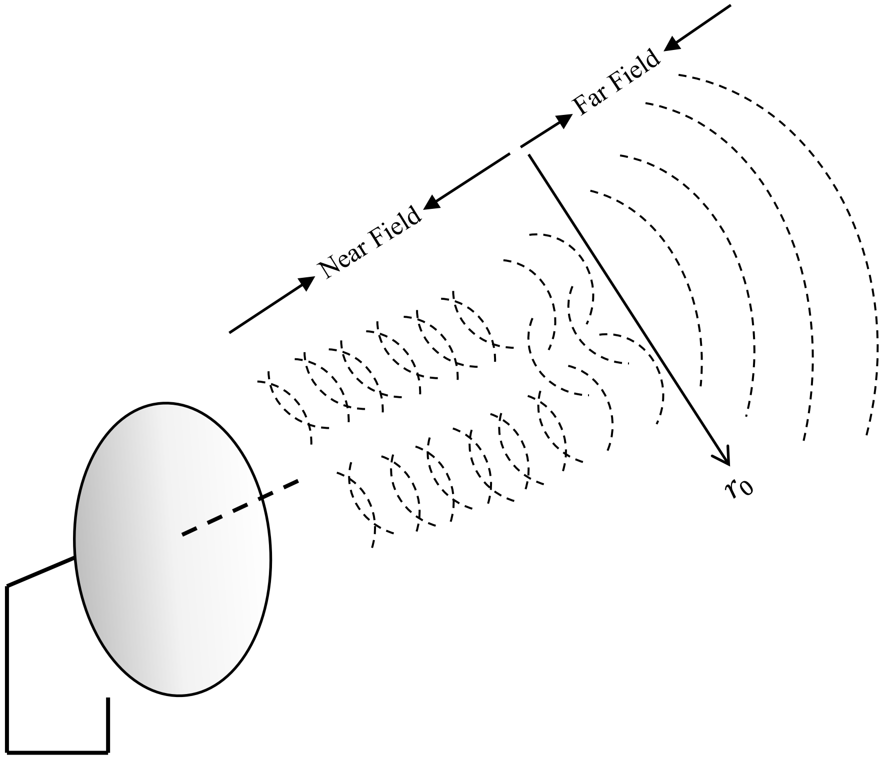
# Communication Layer

- ❑ 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

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

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:

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

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

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

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# 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

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

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

We find that interaction model has the best communication performance $\phi^*$ 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 $e_{ij} = (q_i - q_j)/\sqrt{r_{ij}}$.

# Gradient Controller

```
for iter=1:max_iter
    fprintf("Iteration %d\n", iter);
    for i=1:swarm_size
        for j=setdiff(1:swarm_size, i)
            rij = helper.calculate_rij(swarm(i, :), swarm(j, :));
            aij = helper.calculate_aij(rij, alpha, delta, r0, v);
            gij = helper.calculate_gij(rij, r0);
            if aij>=PT
                rho_ij = helper.calculate_rho_ij(rij, r0, v, beta);
            else
                rho_ij=0;
            end

            qi = [swarm(i,1), swarm(i,2)];
            qj = [swarm(j,1), swarm(j,2)];
            eij = (qi-qj) / sqrt(norm(qi - qj));

            %%%%%%%%%%%%%%%%%%%%%%%%%%%
            % Formation control input %
            %%%%%%%%%%%%%%%%%%%%%%%%%%%
            swarm_control_ui(i,1) = swarm_control_ui(i,1) + rho_ij*eij(1);
            swarm_control_ui(i,2) = swarm_control_ui(i,2) + rho_ij*eij(2);
```

**Proposed Formation Control Algorithm**

**Data:** $itr \leftarrow 1000$ // Number of Iterations
$n \leftarrow 8$ // Number of Agents
$J \leftarrow N_i$ // Number of Neighbors
$a_{ij}$ // Communication Near-field Model
$P_T \leftarrow 0.94$ // Reception Threshold
$\varphi_{ij}$ // Interaction Model
$\mathcal{G}_i$ // Gradient-term Controller
$\dot{q}$ // Dynamics of Multi-agent System

**Result:** Desired Swarm Formation Control (see Fig. 4.)

**for** $1 : itr$ **do**
  **for** $1 : n$ **do**
    **for** $J = N_i$ ; **do**
      **if** $a_{ij} \geq P_T$ **then**
        $\varphi(r_{ij}) = (21)$;
      **else**
        $\varphi(r_{ij}) = 0$;
      **end**
    **end**
  **end**
  $z_i = \varphi(r_{ij}) \cdot e_{ij}$;
  $\dot{q} = z_i$
**end**

# Gradient Controller

```
for iter in range(max_iter):
    print('Iteration: ', iter)
    for i in range(swarm_size):
        # print('Agent: ', i)
        for j in [x for x in range(swarm_size) if x != i]:
            # print('Neighbor: ', j)
            rij = utils.calculate_distance(swarm_position[i], swarm_position[j])
            aij = utils.calculate_aij(alpha, delta, rij, r0, v)
            gij = utils.calculate_gij(rij, r0)
            if aij >= PT:
                rho_ij = utils.calculate_rho_ij(beta, v, rij, r0)
            else:
                rho_ij = 0

            qi = swarm_position[i, :]
            qj = swarm_position[j, :]
            eij = (qi - qj) / np.sqrt(rij)

            ###########################
            # Formation control input #
            ###########################
            swarm_control_ui[i, 0] += rho_ij * eij[0]
            swarm_control_ui[i, 1] += rho_ij * eij[1]
```

**Proposed Formation Control Algorithm**

**Data:** $itr \leftarrow 1000$ `// Number of Iterations`
$n \leftarrow 8$ `// Number of Agents`
$J \leftarrow N_i$ `// Number of Neighbors`
$a_{ij}$ `// Communication Near-field Model`
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**Result:** Desired Swarm Formation Control (see Fig. 4.)

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        $\varphi(r_{ij}) = (21)$;
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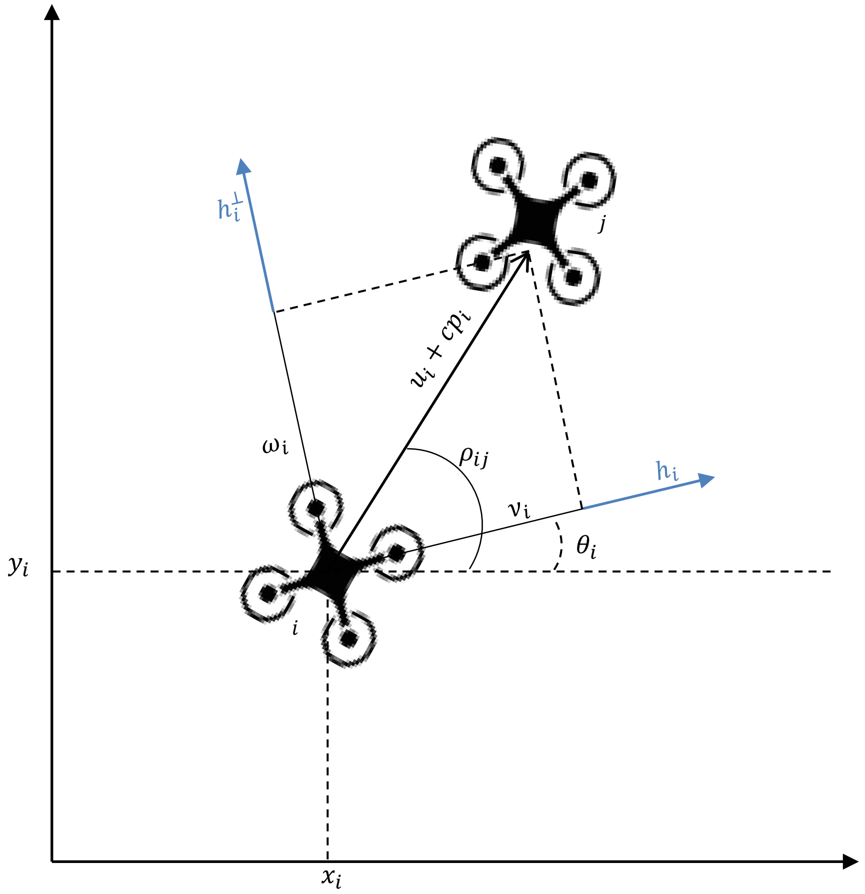
        $\varphi(r_{ij}) = 0$;
      **end**
    **end**
  **end**
  $z_i = \varphi(r_{ij}) \cdot e_{ij}$;
  $\dot{q} = z_i$
**end**

# 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 $\begin{bmatrix} -\sin(\theta_i) \\ \cos(\theta_i) \end{bmatrix}$

$\theta_i$: Heading angle

$\nu_i$: Linear velocity vector

$\omega_i$ : Angular velocity vector

$\rho_{ij}$: Line of sight, defined as $\arctan2(q_i - q_j)$

$u + cp_i$: 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

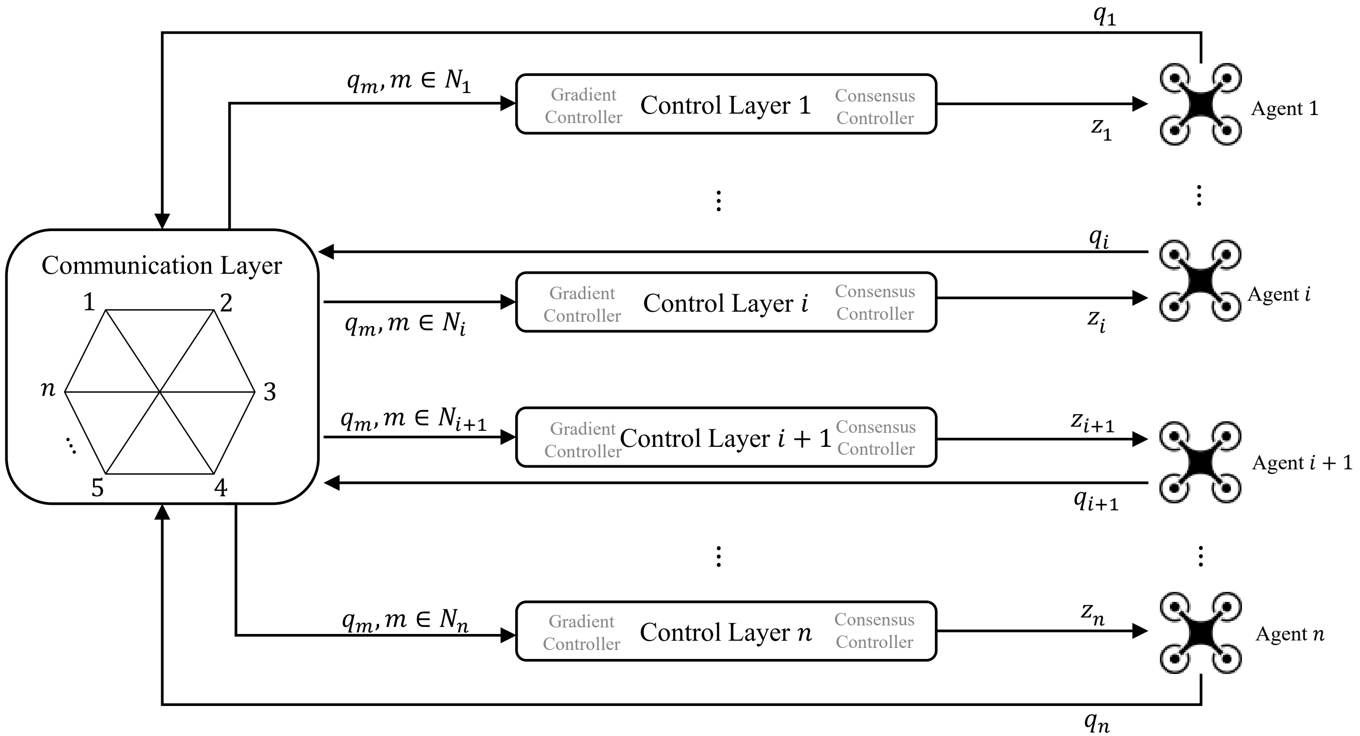
## Consensus Control Model

The projections of consensus control vector $u + cp_i$ 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

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

where

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

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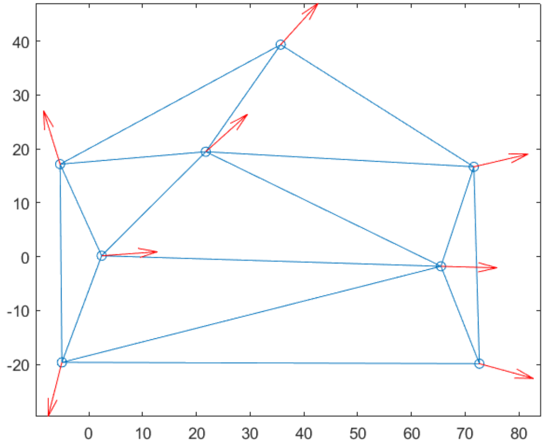
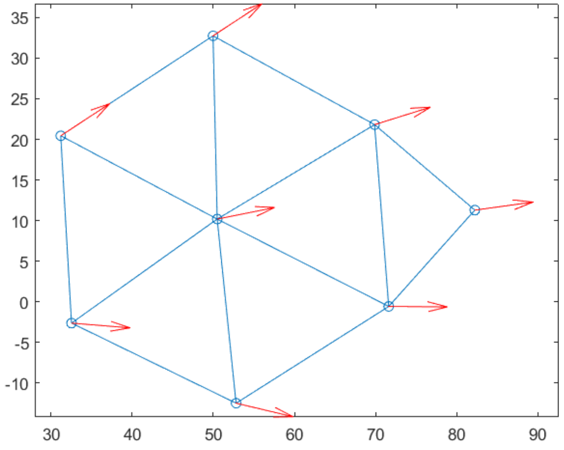
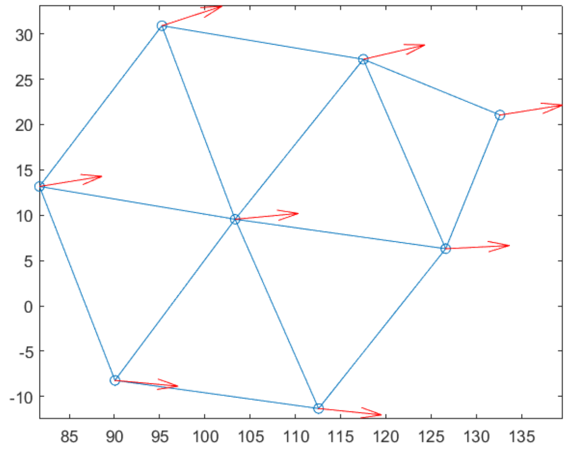
# Simulations



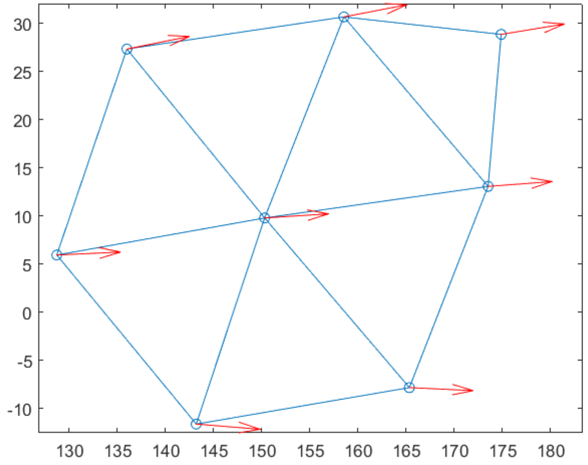

$t = 0s$



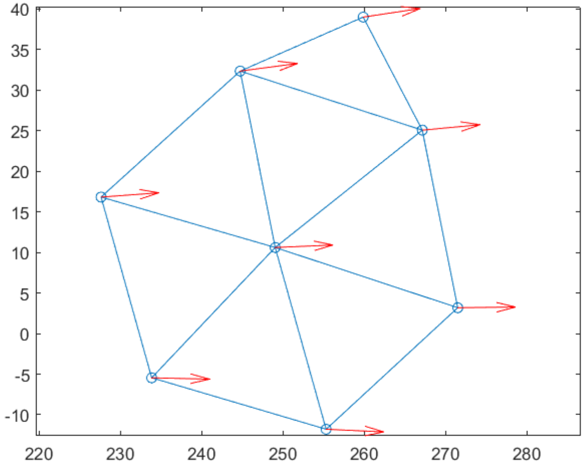

$t = 10s$



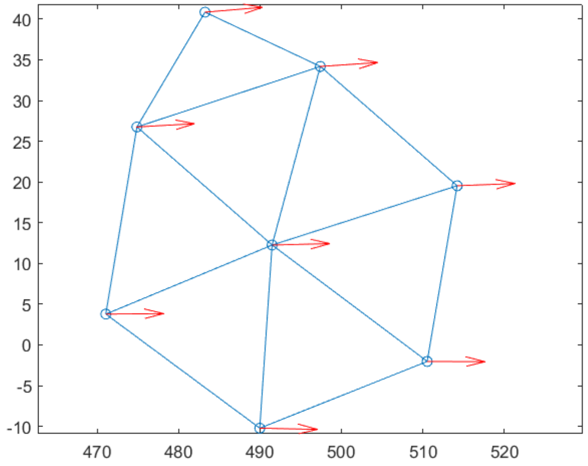

$t = 30s$



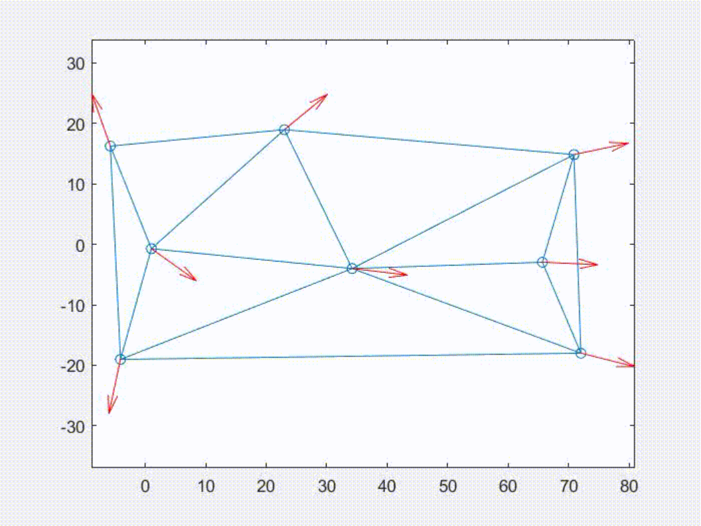

$t = 60s$



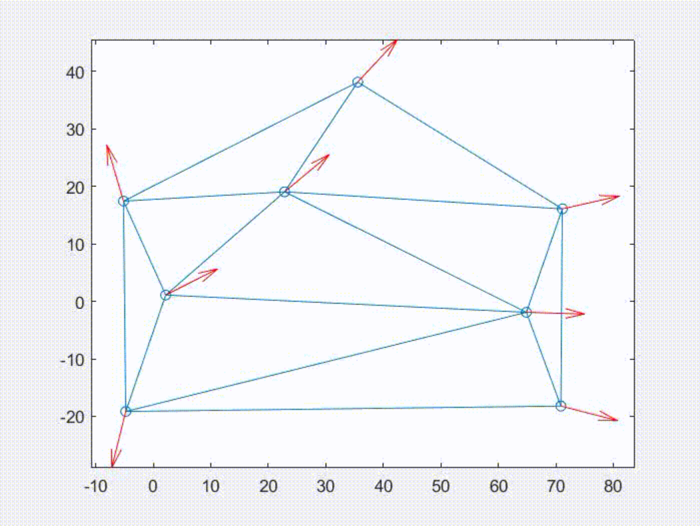

$t = 90s$



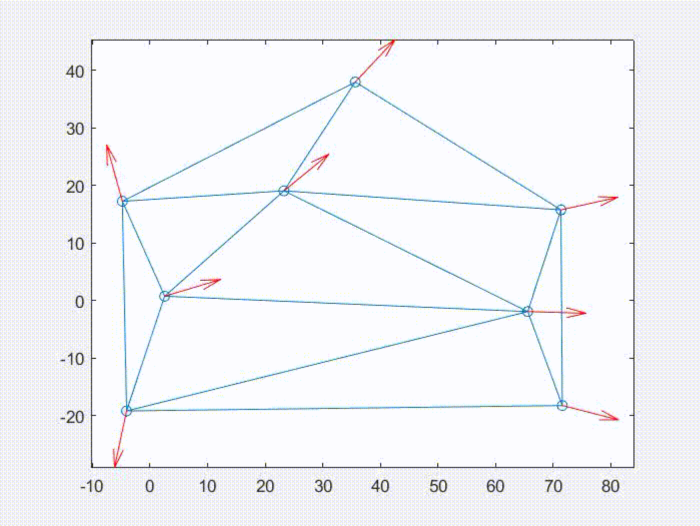

$t = 180s$




Before proposed

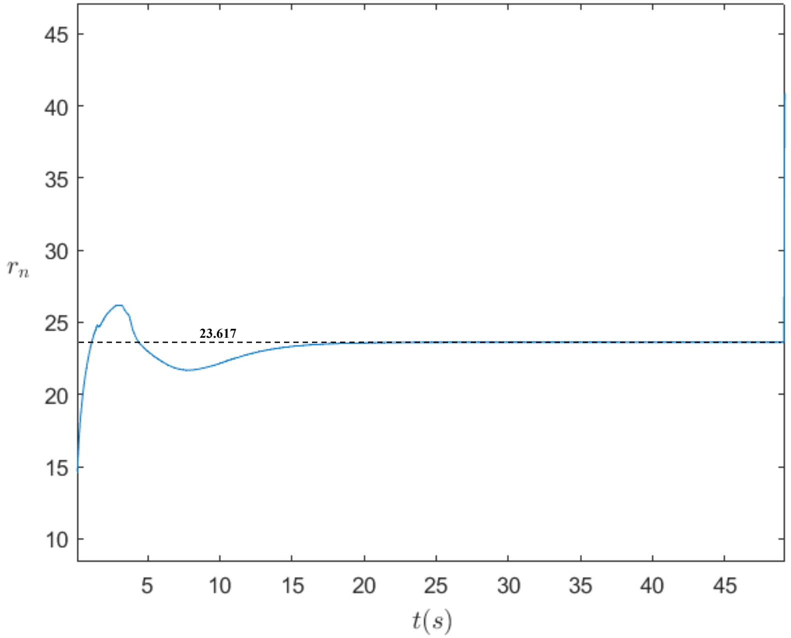



After Proposed
Traveling in NE direction

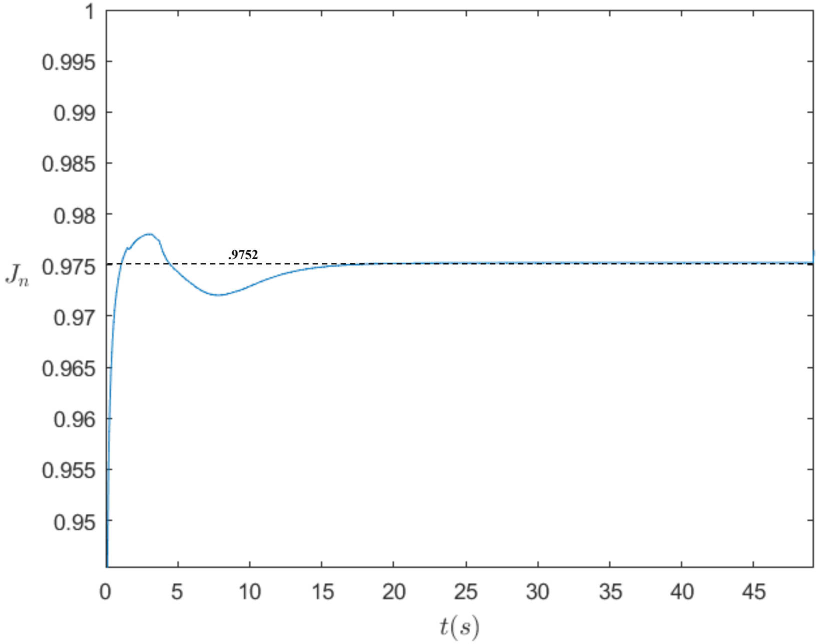



After Proposed
Traveling in in E direction

Agents Traveling in NE Direction




Before Proposed

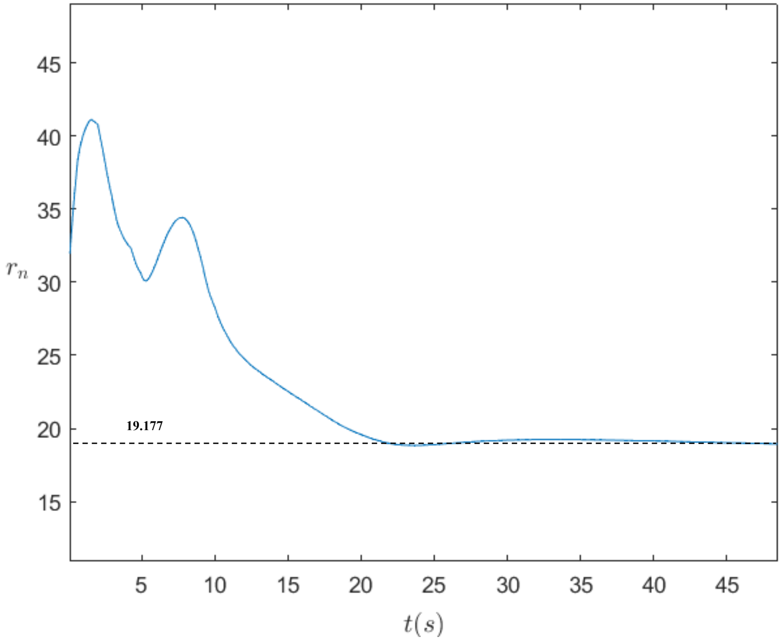



$J_n$: Average Communication Performance Indicator

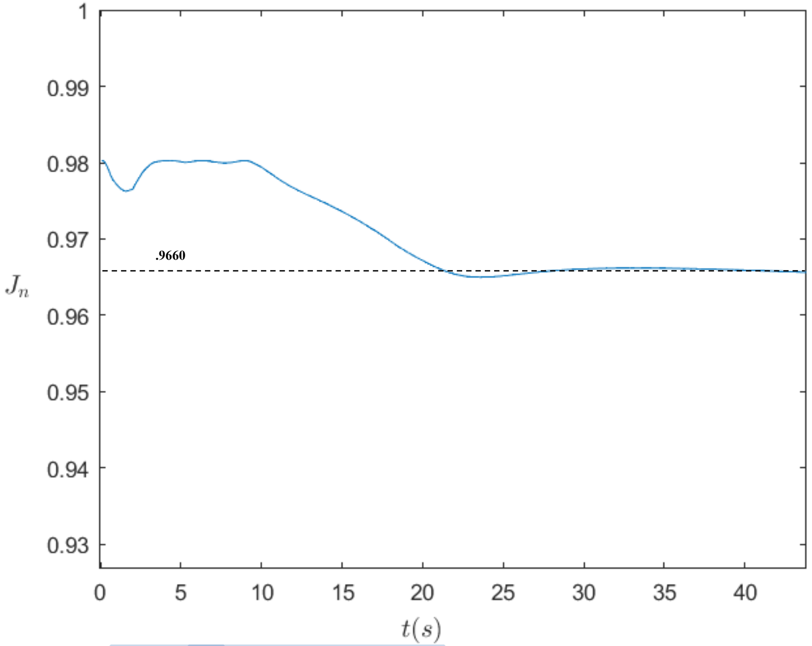
$$J_n = \frac{\sum_{i=1}^{n} \sum_{j \in N_i} \phi(r_{ij})}{2n|N_i|}$$

$r_n$: Average Neighboring Distance Indicator

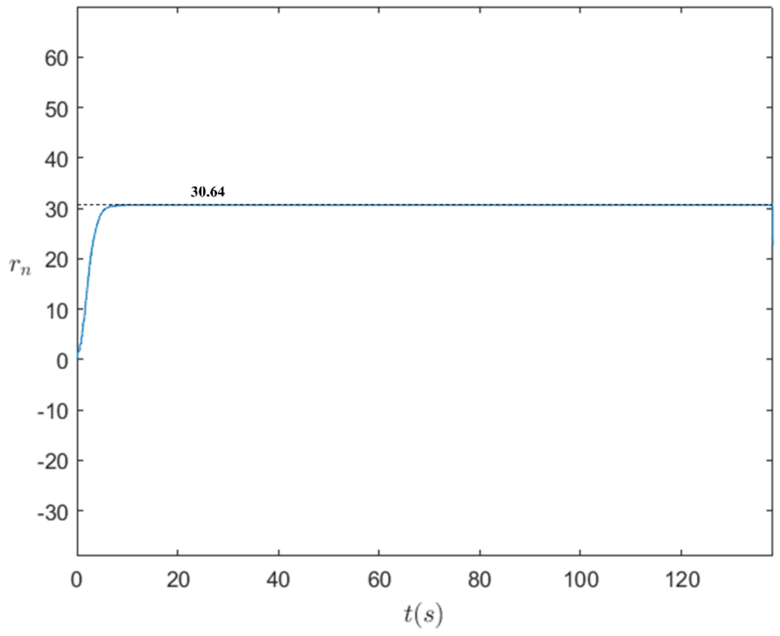
$$r_n = \frac{\sum_{i=1}^{n} \sum_{j \in N_i} r_{ij}}{2n|N_i|}$$



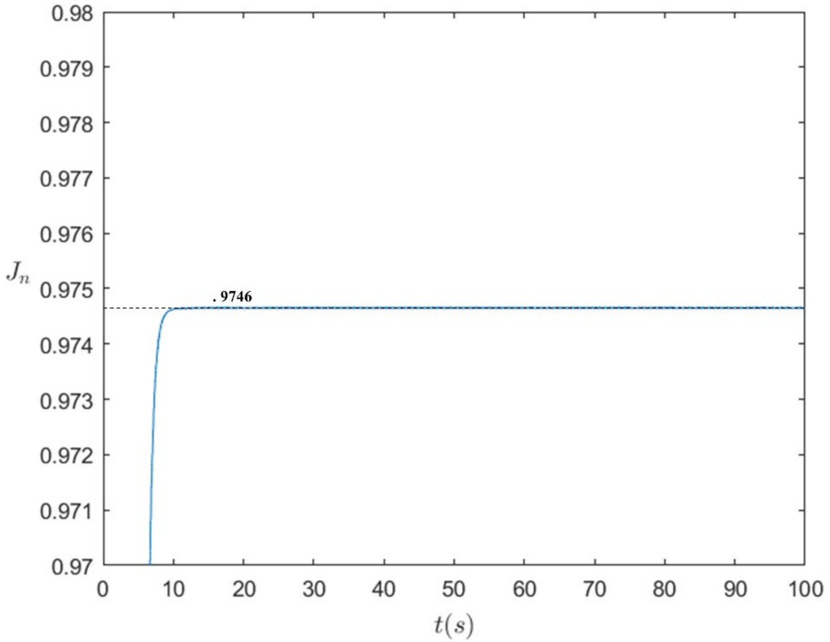

After Proposed



Agents Traveling in E Direction




Before Proposed




$J_n$: Average Communication Performance Indicator

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

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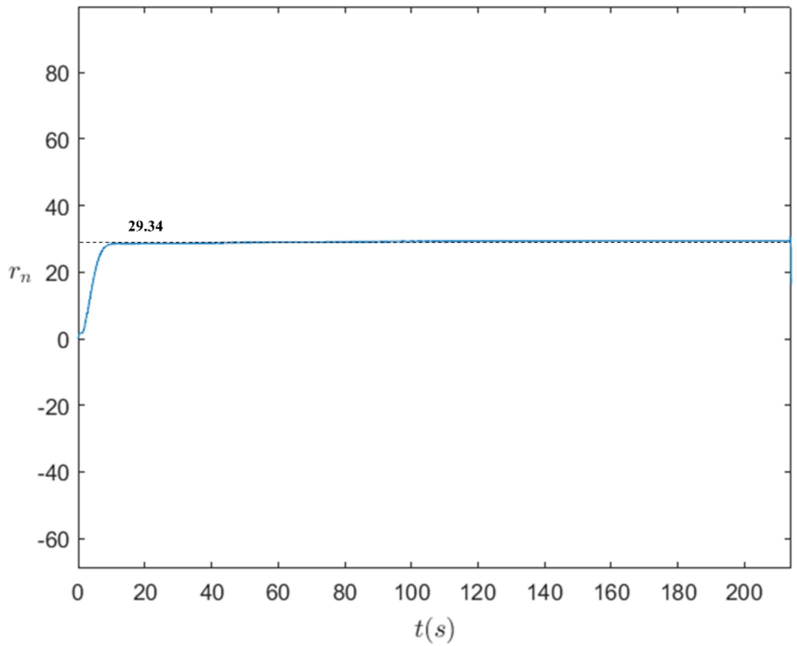
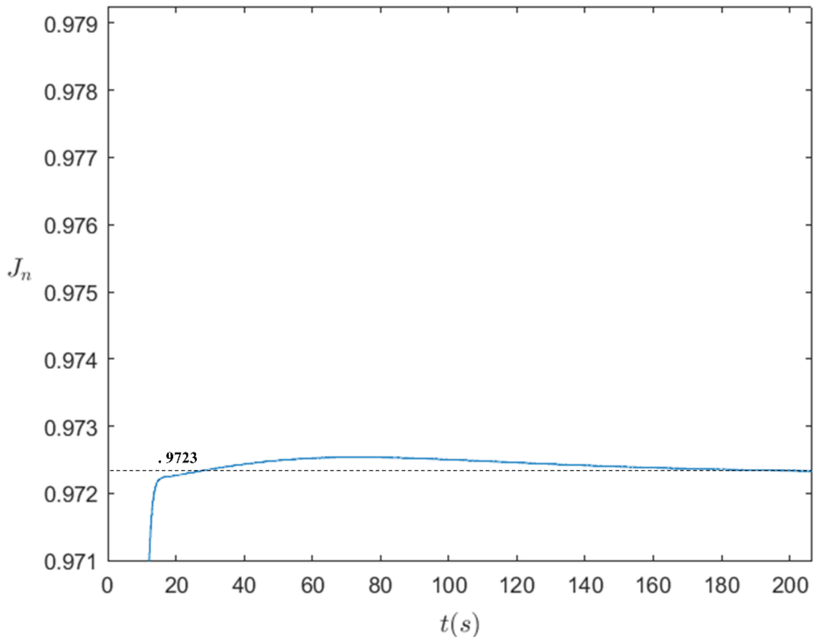



After Proposed



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 $r_n$

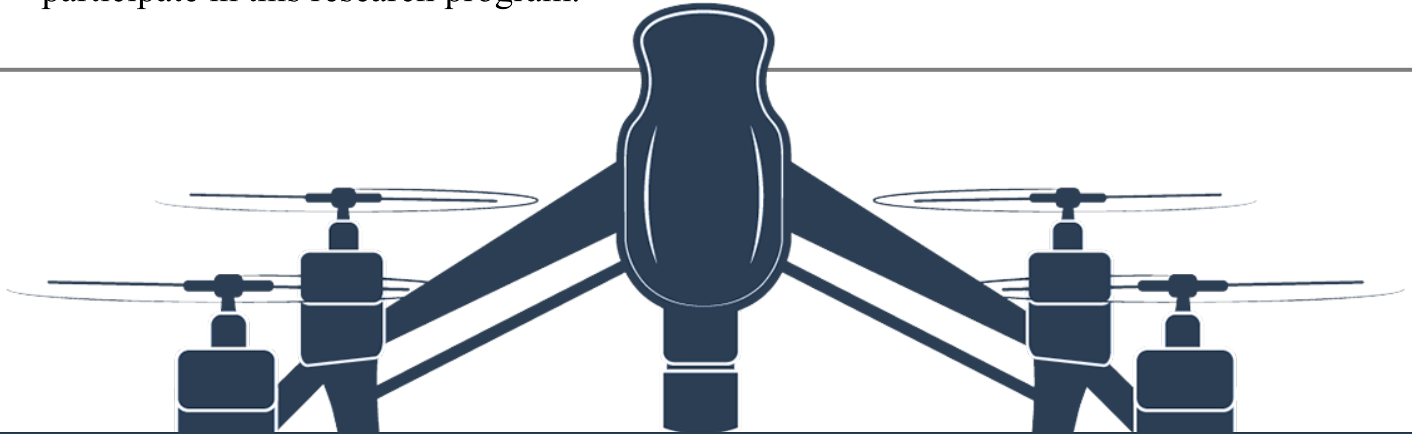
Outro

## Significance

- Formation control is communication-aware.
- Formation control is consensus-based.
- Maintained a similar average neighboring distance.
- Achieved sufficient average communication performance.

## Acknowledgements

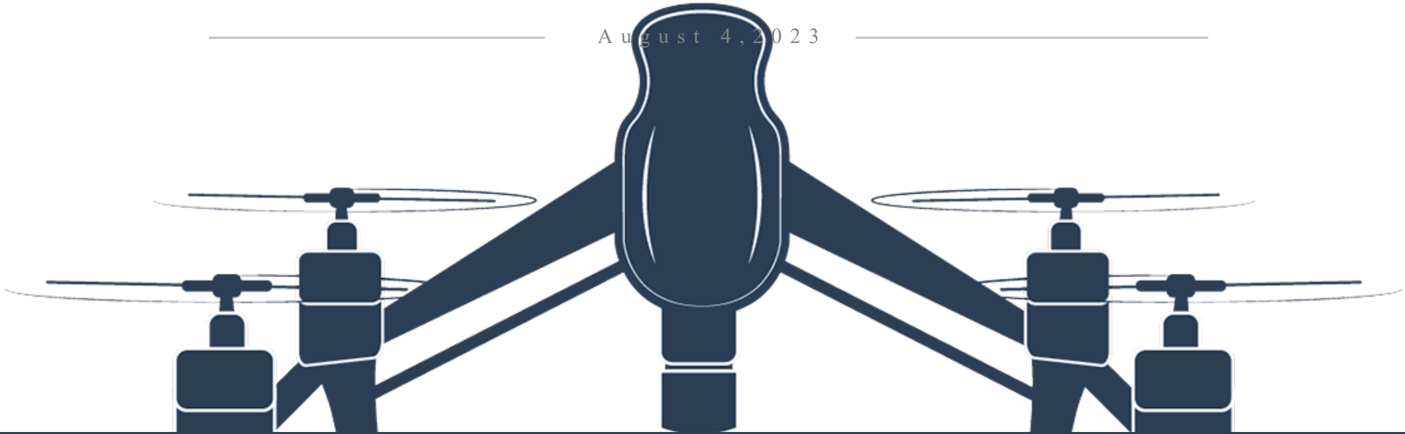

- This research was supported by the National Science Foundation under Grant No. 2150213.
- I'd like to thank you Dr. Song and Dr. Stansbury for considering me into this research program.
- I'd also like to thank you Dr. Yang's guidance throughout the project.
- Last but not the least, I would thank to Dr. Jayasena Dr. Ofori-Boateng, and Dr. Taylor-Rodriguez for taking the time to write me a letter of recommendation which allowed me to participate in this research program.

# THANKS

Questions?

August 4, 2023



# 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.

# 2023

# Behavior-based Communication-aware Formation Control


Samuel Peccoud (CSU)

Sang Xing (PSU)

Dr. Yang (ERAU)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# Introduction

- Formation Control
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- Schematic Diagram

# 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.

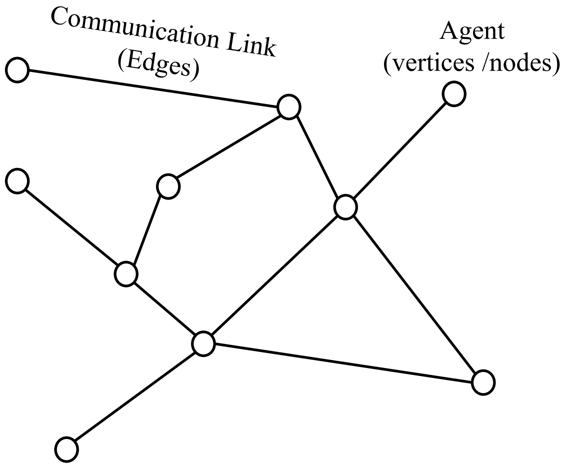
## Communication-aware Formation Control

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

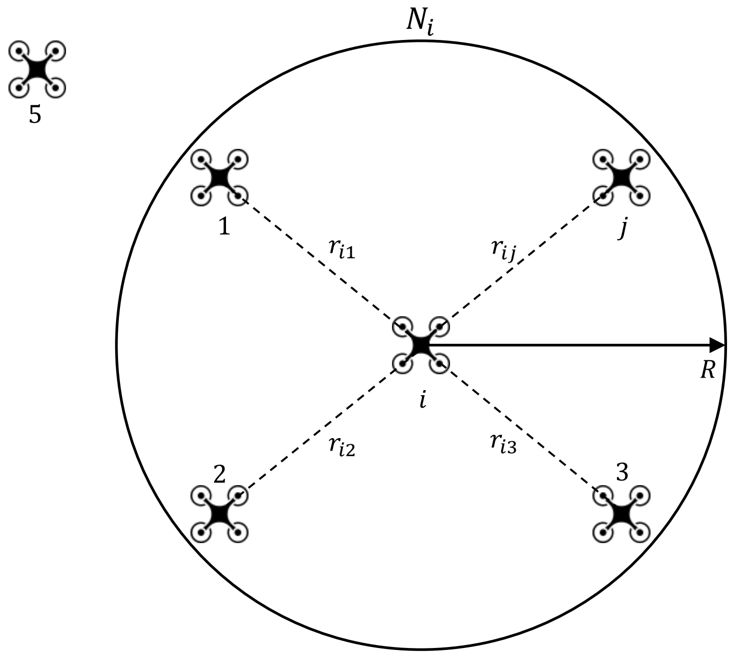
The formation of groups of mobile agents in which all inter-agent distances remain constant is called **rigid**.

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

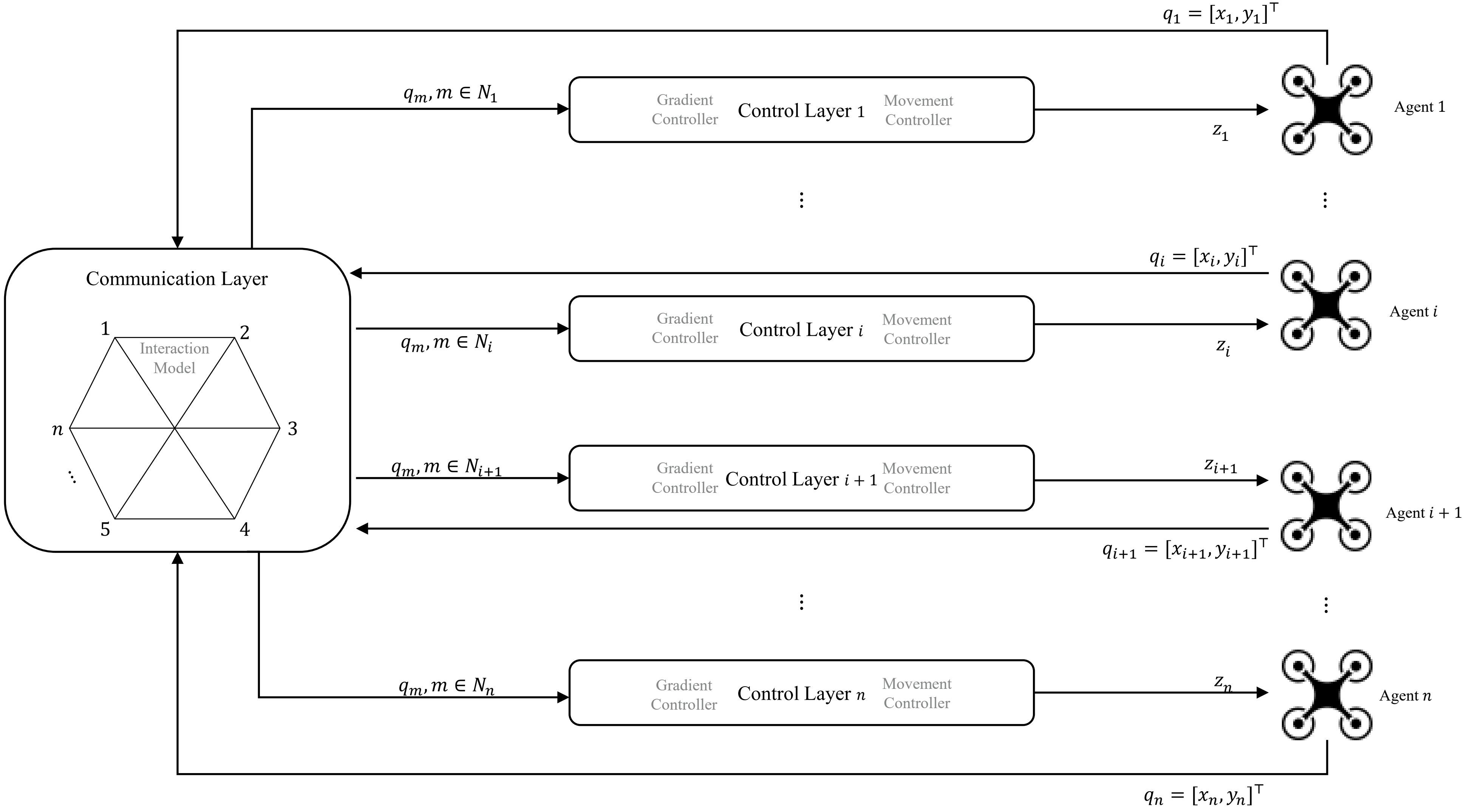
$$r_{ij} = \sqrt{(x_i - x_j)^2 + (y_i - y_j)^2} = \|q_i - q_j\|.$$

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

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02

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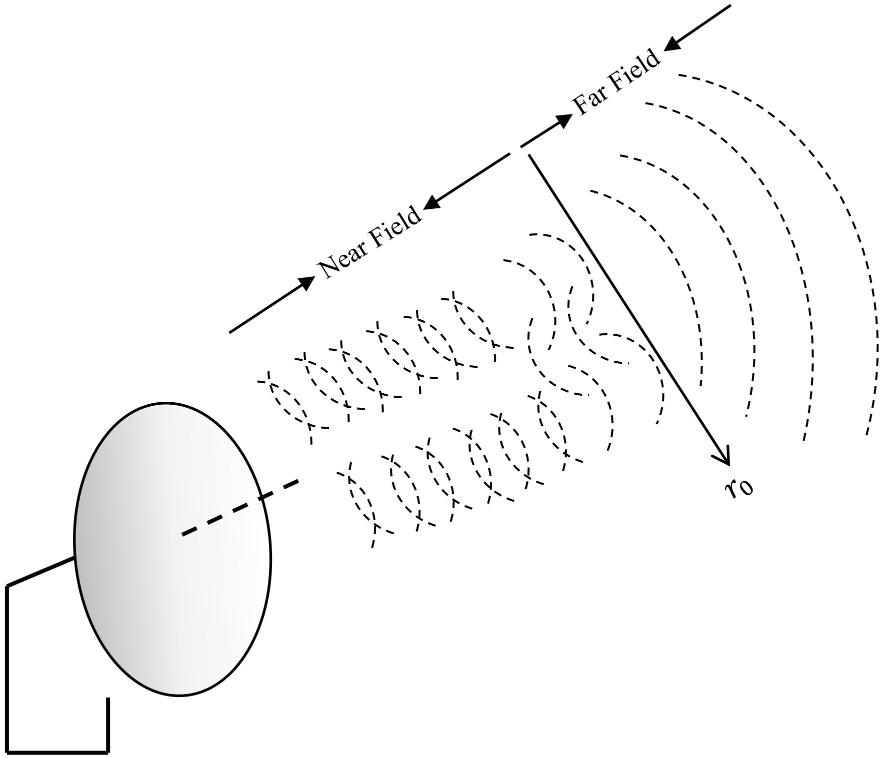



## Far-field

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

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

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

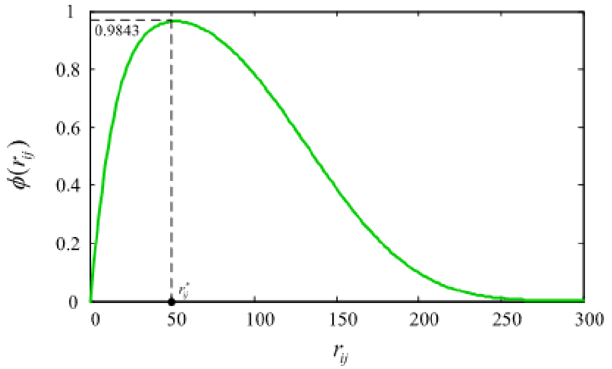
- ❑ Gradient Controller
- ❑ Movement Controller
  - Reach Goal Behavior
  - Jamming Avoidance Behavior
  - Edge Following Behavior

# 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

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

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




We find that interaction model has the best communication performance $\phi^*$ 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.

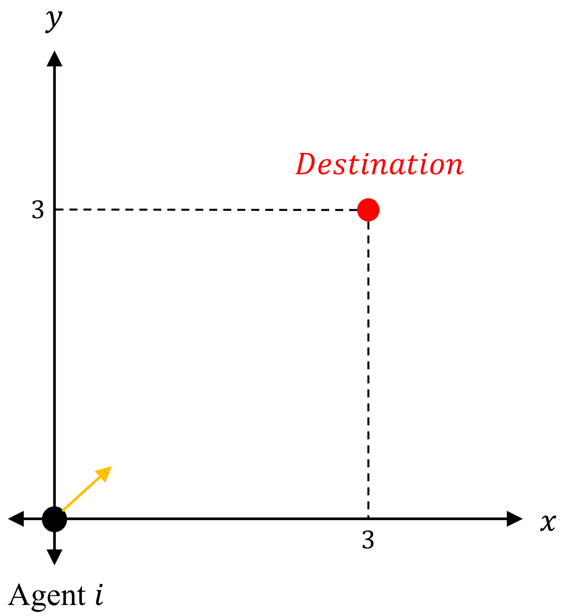
The behavior vector is calculated based on the current agent's coordinates and the destination coordinates.

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

## Description

Navigating the agents towards the destination.

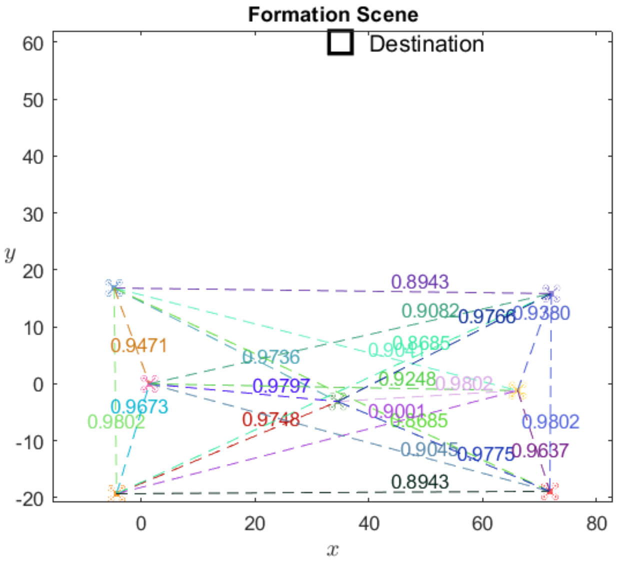
The behavior vector is calculated based on the current agent's coordinates and the destination coordinates.

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

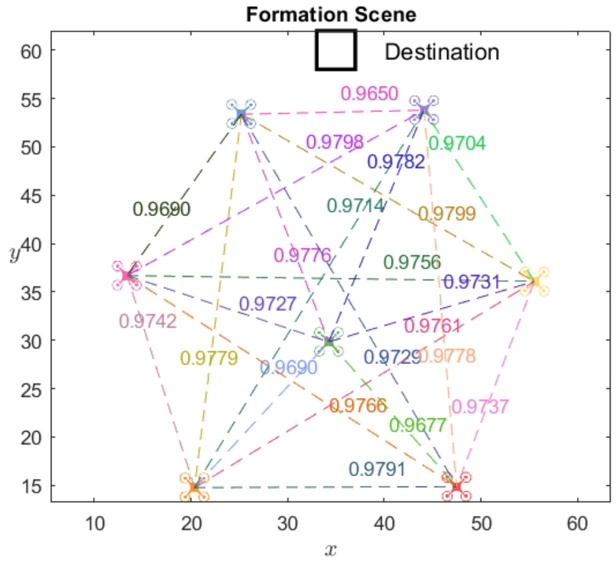
## Formula

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

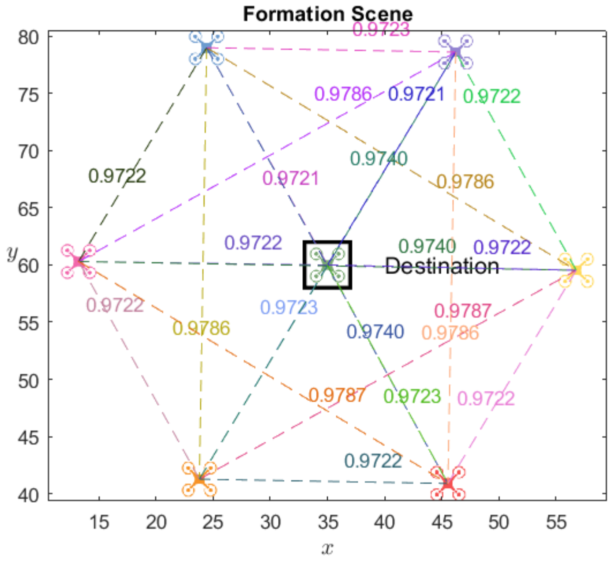
$$f_1(d) = \begin{cases} a_m, & d > b_m \\ a_m \dfrac{d}{b_m}, & d \in [0, b_m] \end{cases}$$



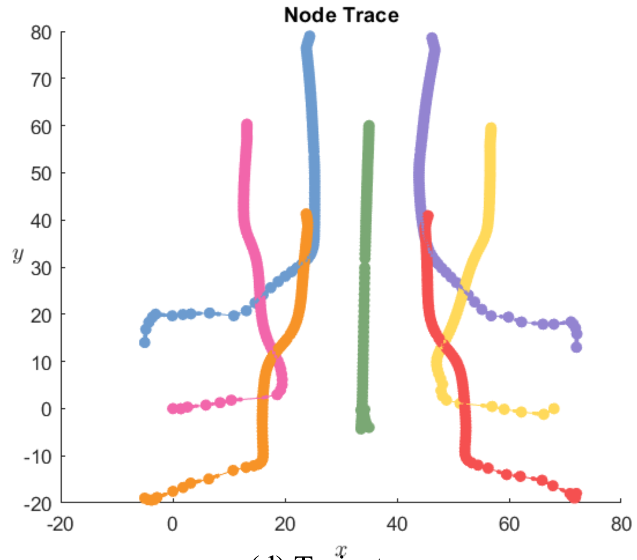

(a) Initial




(b) Halfway




(c) Final




(d) Trajectory

# Movement Controller: Jamming Avoidance Behavior

## Description

Enables agents to avoid jamming area in its path.

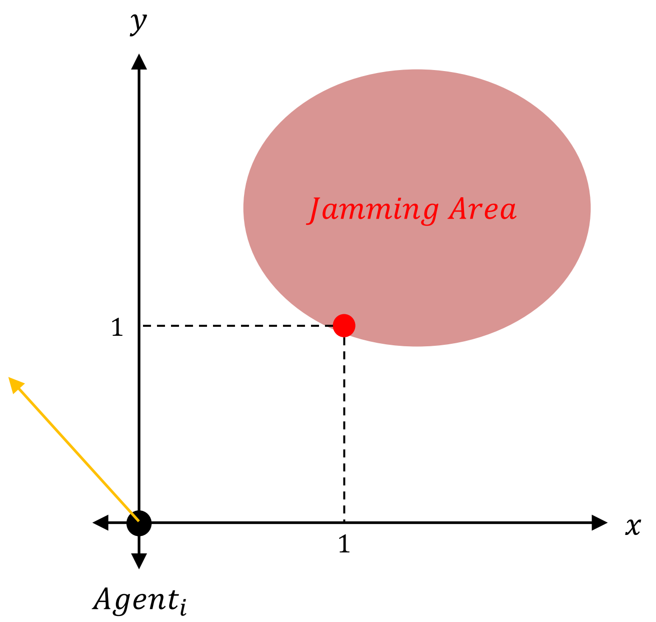
The behavior vector is determined by the distance between the agent and the nearest obstacle.

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.

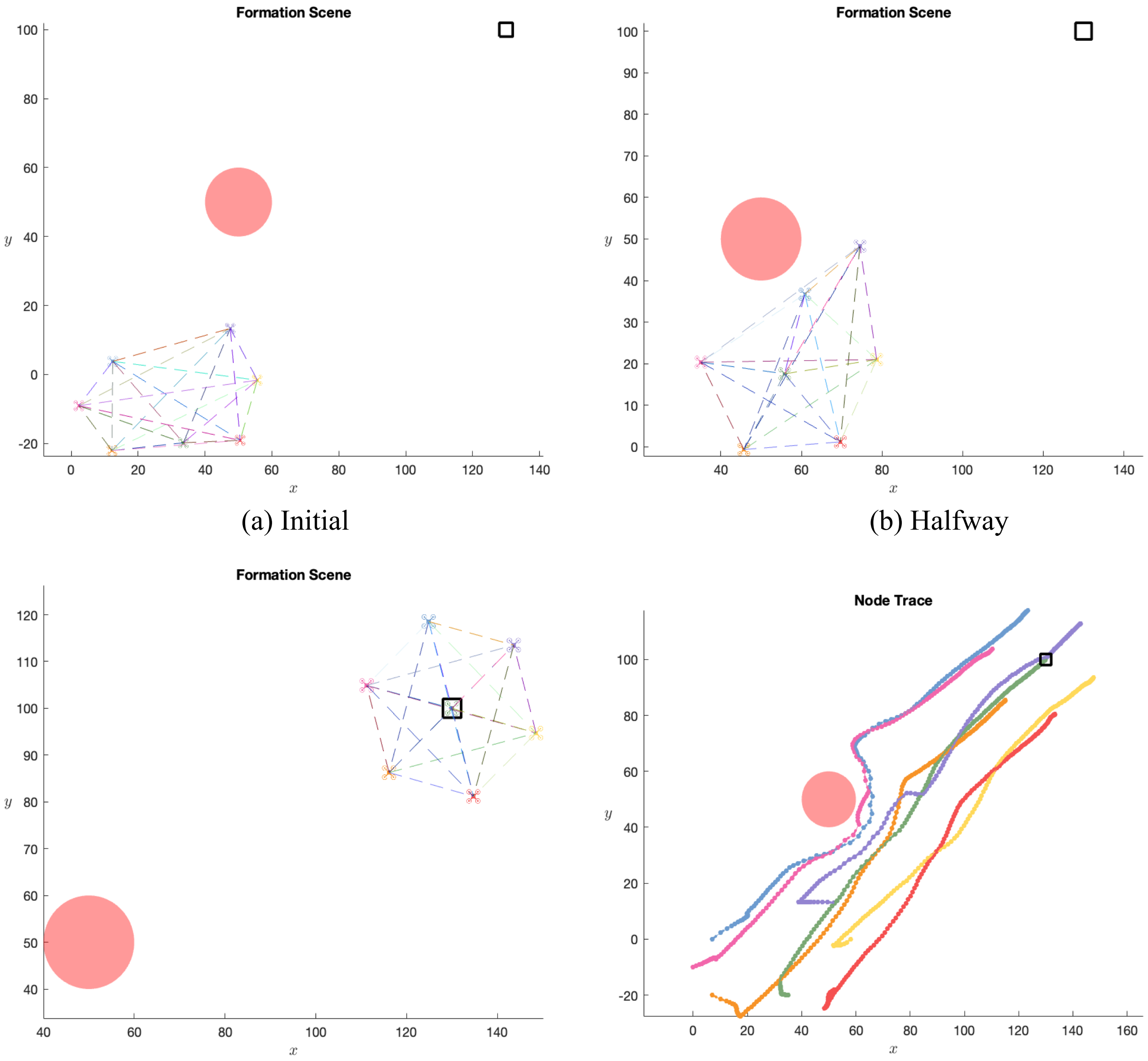
The behavior vector is determined by the distance between the agent and the nearest obstacle.

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

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

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




(a) Initial (b) Halfway (c) Final (d) Trajectory

# Movement Controller: Edge Following Behavior

## Description

Helps the agents navigate by following jamming area edges.

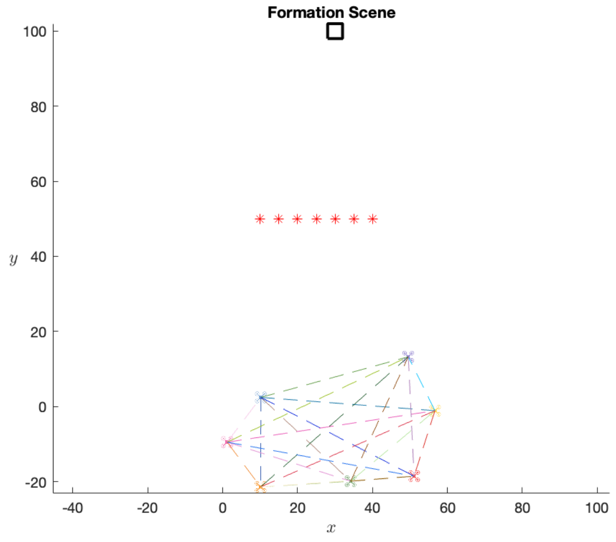
The behavior vector is calculated based on the coordinates of the nearest obstacle and the agent's current position.

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

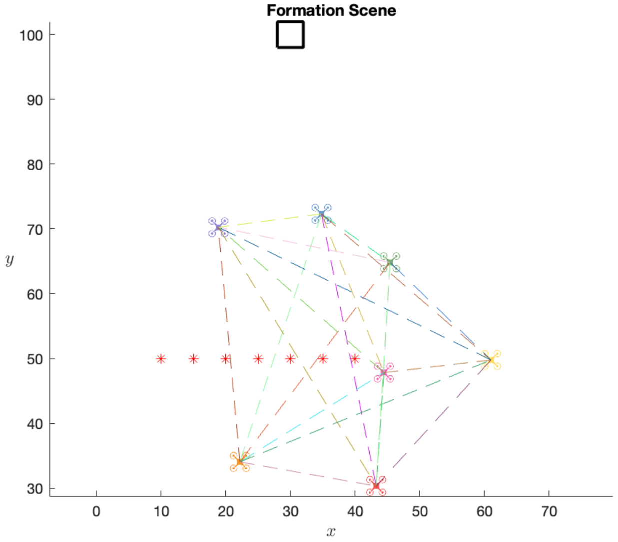
## Formula

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

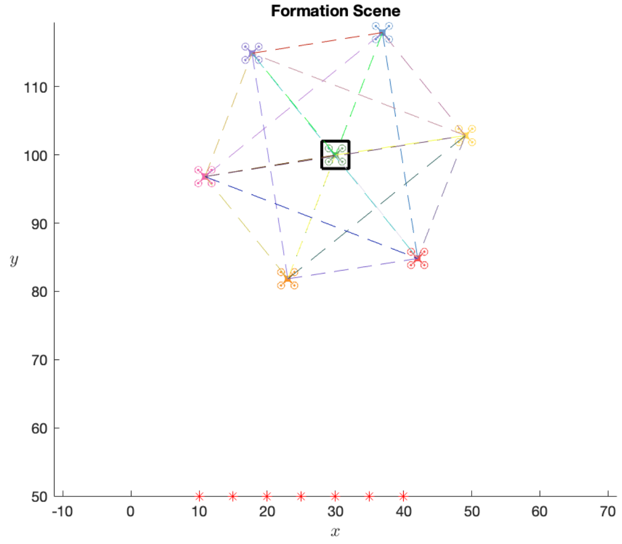
$$f_3(d) = \begin{cases} a_f, & d \in [0, e_f] \\ 0, & otherwise \end{cases}$$



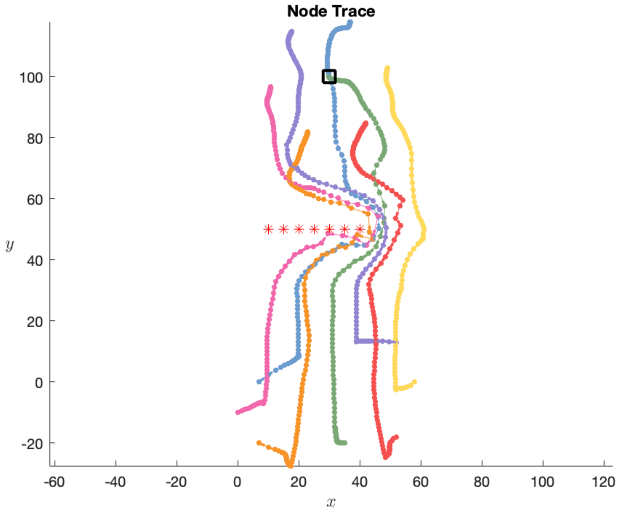

(a) Initial




(b) Halfway




(c) Final




(d) Trajectory

# Final Controller

## System Dynamics

The dynamics of this multi-agent system is denoted by

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

where

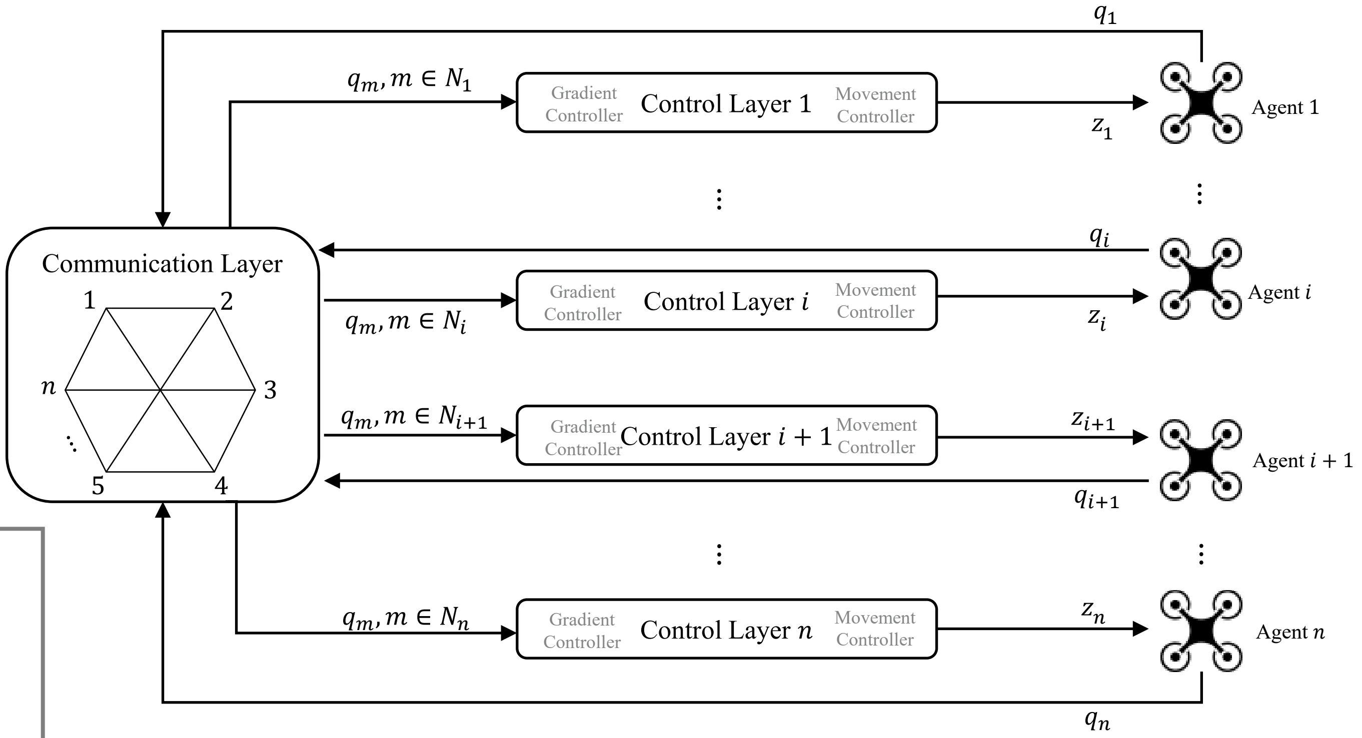
$q$: position input of agents,

$z$: control input of agents.

## Final Formation Controller

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

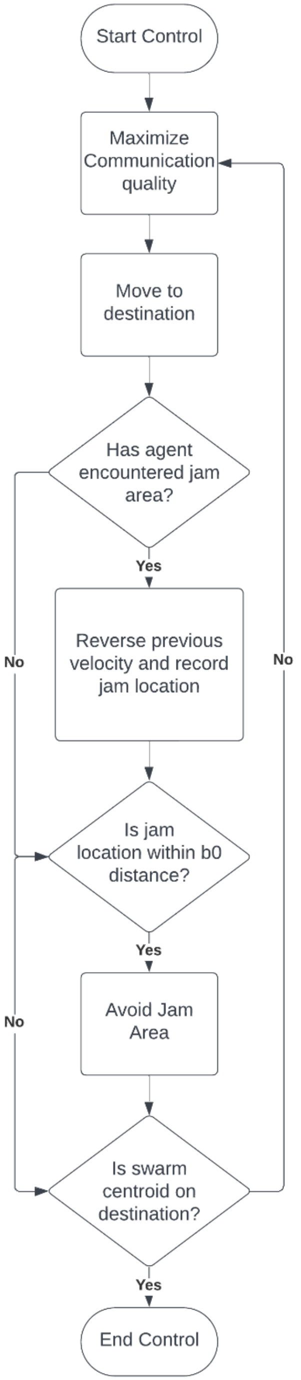
$$= \sum_{j\in N_i}\left[\varphi(r_{ij})\cdot e_{ij}\right] + \left[f_1(\cdot)\quad f_2(\cdot)\quad f_3(\cdot)\right]\begin{bmatrix}V_{navigation}\\ V_{avoidance}\\ V_{edge-following}\end{bmatrix}$$

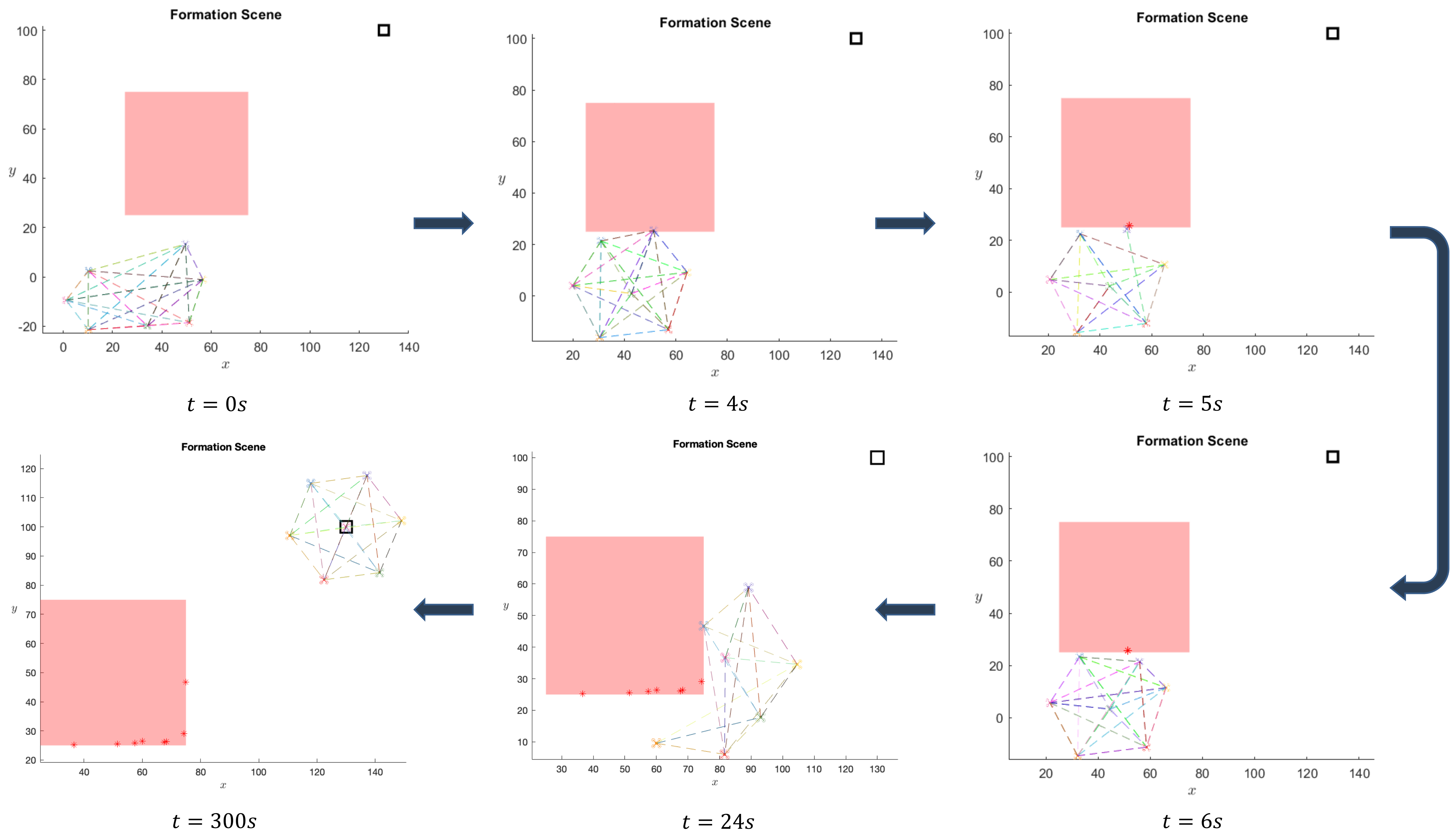


04

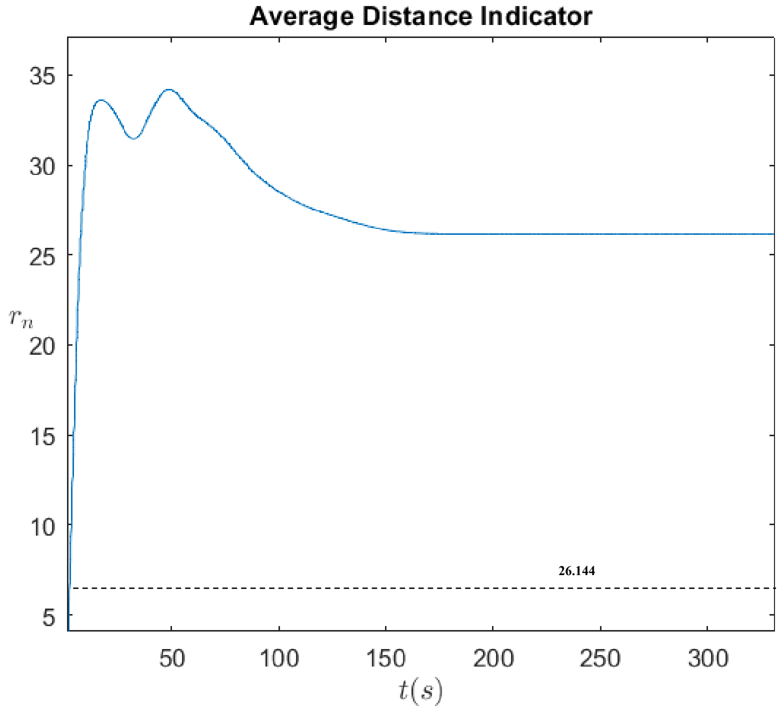
# Simulations

# Workflow


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



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

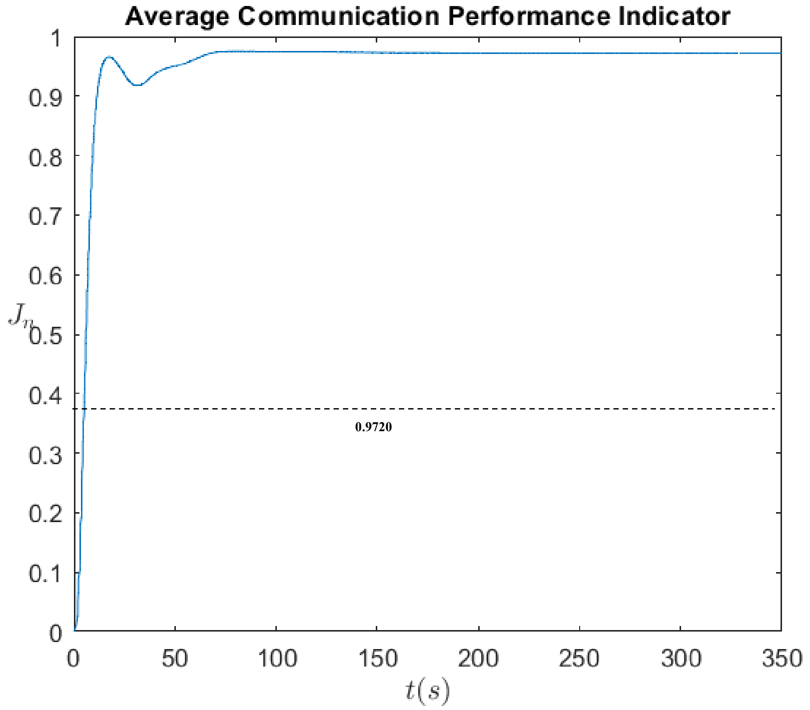



$J_n$: Average Communication Performance Indicator

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

$r_n$: 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.

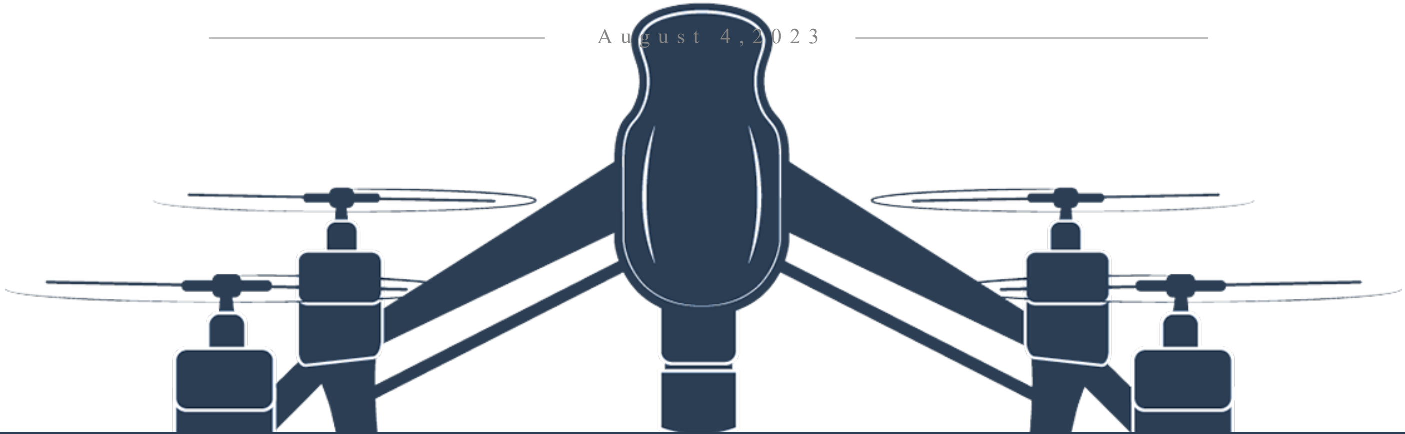
## Acknowledgement

- 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?

August 4, 2023



# 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

2023

# Robust Communication-aware Jamming Detection and Avoidance

Samuel Peccoud (CSU)

Sang Xing (PSU)

Dr. Yang (ERAU)

ERAU NSF REU

# Table of Contents


1. Introduction
2. Communication Model
3. Control Layer
4. Simulation
5. Conclusion

01

# Introduction

- ❑ Research Questions
- ❑ Background
- ❑ Preliminaries
- ❑ Schematic Diagram

# Research Questions

## Tasks

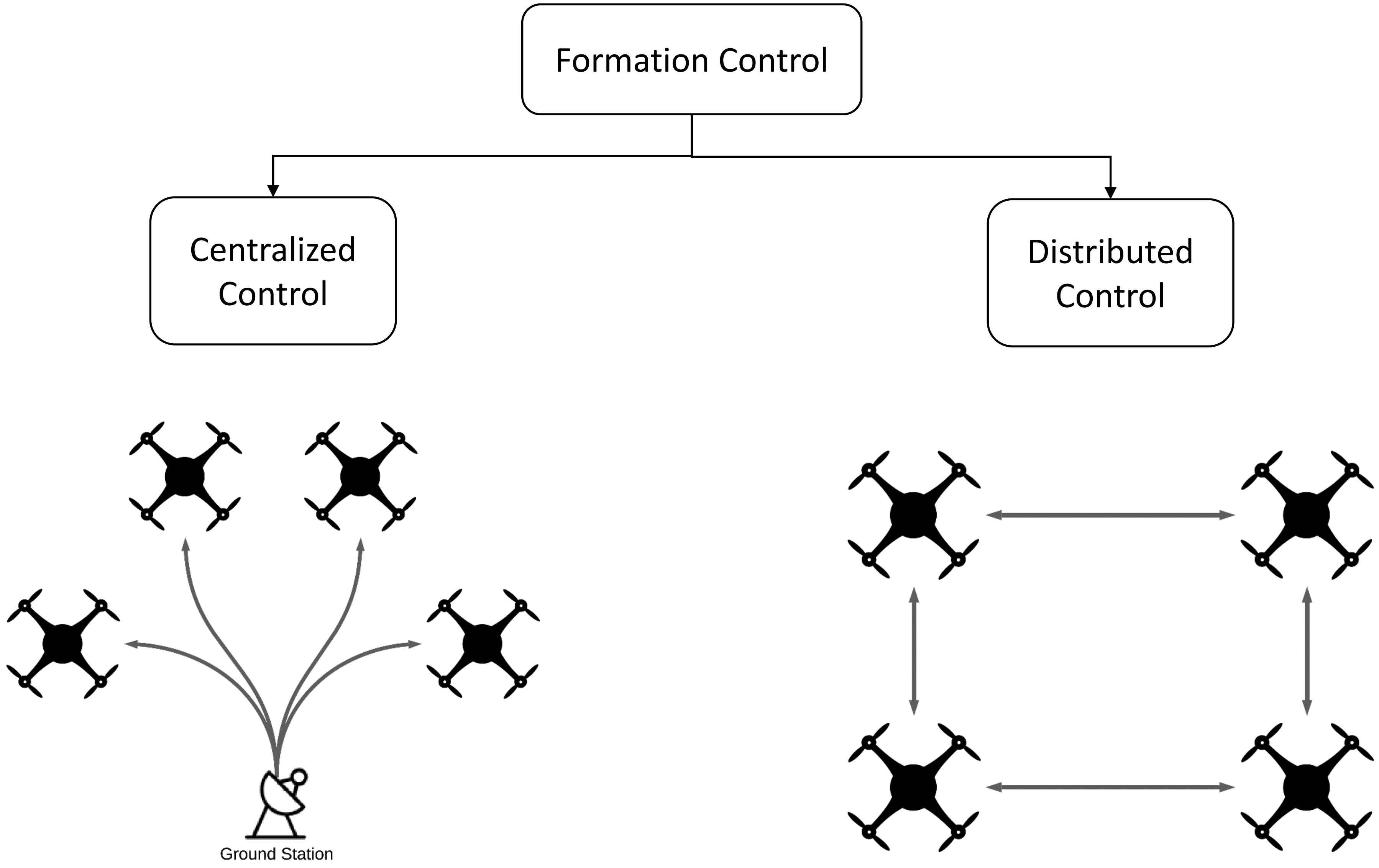
1. How to navigate a swarm around jamming areas?

   Particle Swarm Optimization (PSO) Algorithm + Path Planning Algorithm

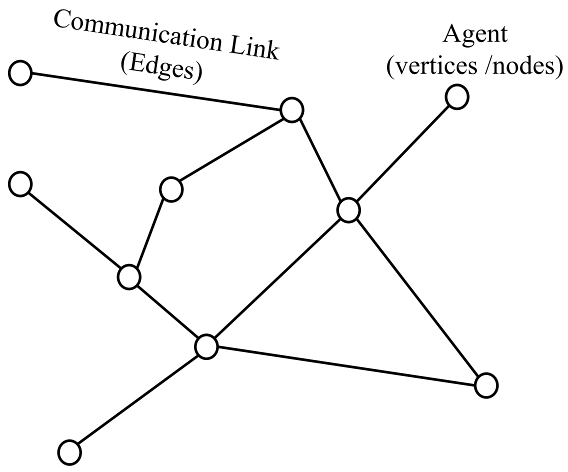
2. How to maximizing communication quality between agents?

   Communication-aware formation control

# Background


Formation Control
Centralized Control
Distributed Control
Ground Station

# 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

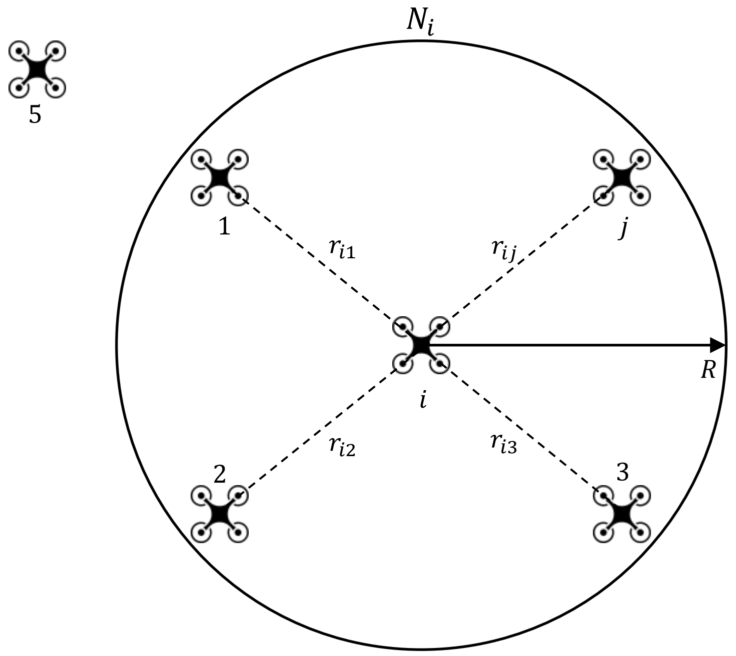
The formation of groups of mobile agents in which all inter-agent distances remain constant is called **rigid**.

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

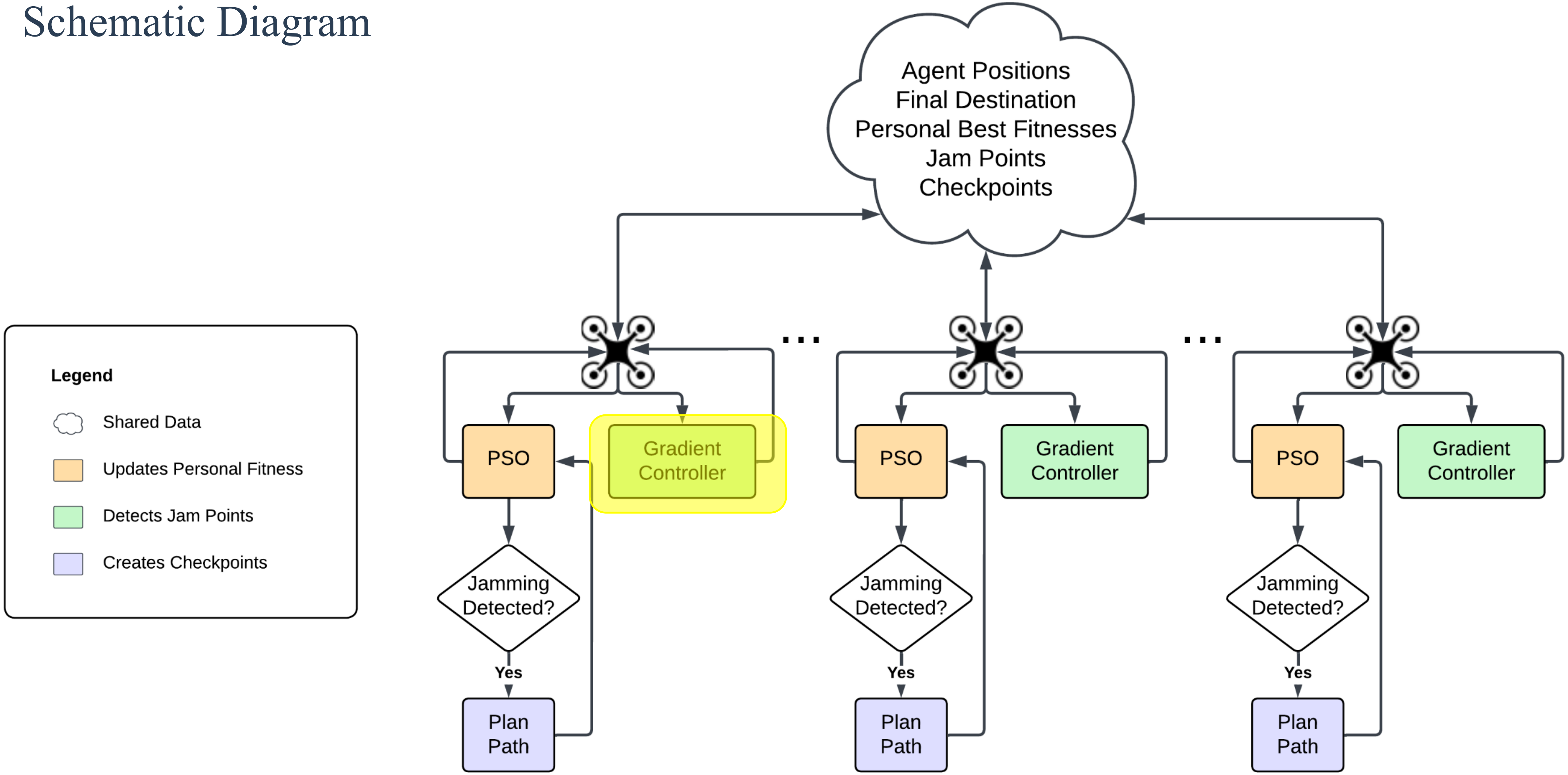
$$r_{ij} = \sqrt{\left(x_i - x_j\right)^2 + \left(y_i - y_j\right)^2} = \|q_i - q_j\|.$$

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

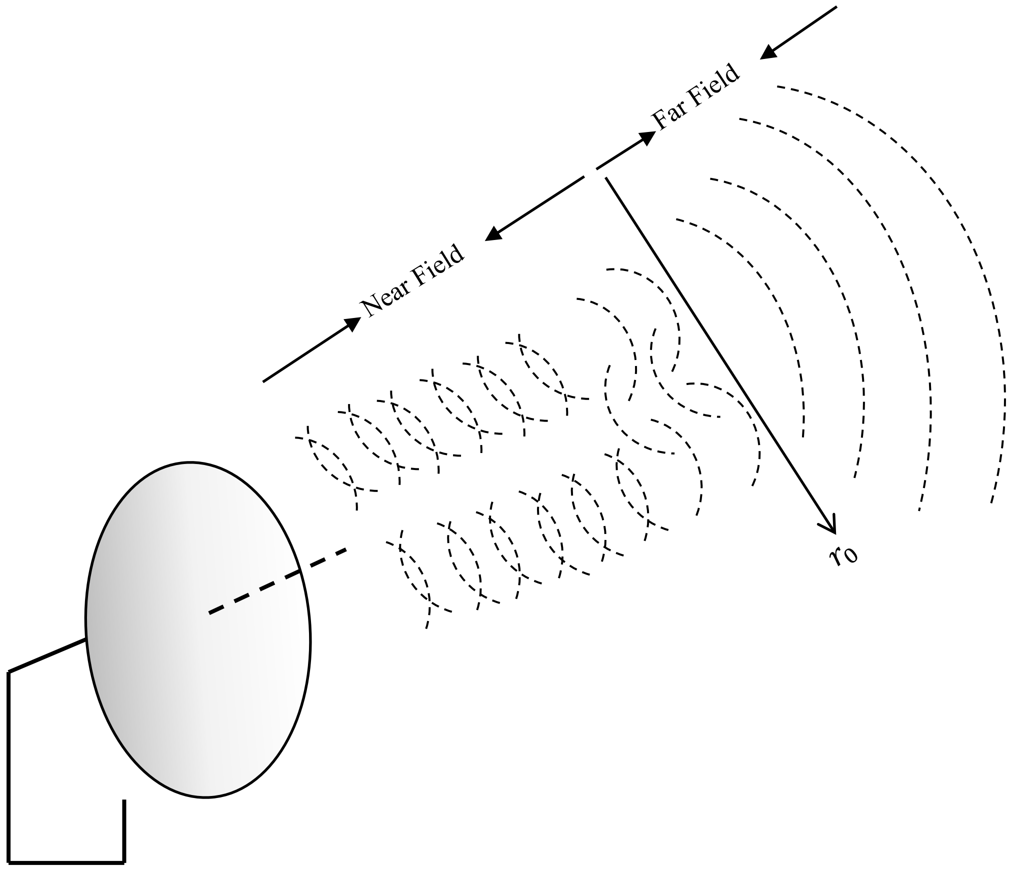


02

# Communication Model

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

# Antenna Near-field and Far-field




## Far-field

The communication channel quality in antenna far-field is:

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

## 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

$r_0$: antenna field separator,

$r_{\mathrm{ij}}$: 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.

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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

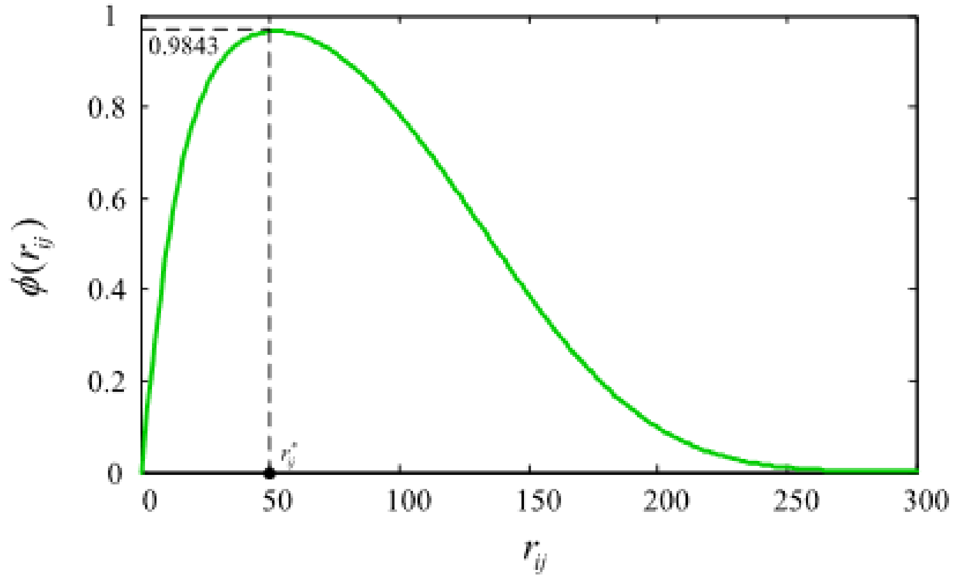
# Control Layer

- ❑ Gradient Controller
- ❑ Movement Controller
  - Particle Swarm Optimization (PSO)
  - Path Planning

# Gradient Controller

To maximizes the communication performance, we take the first-order derivative of the interaction model,

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




A gradient controller moves agents to maximize communication performance.

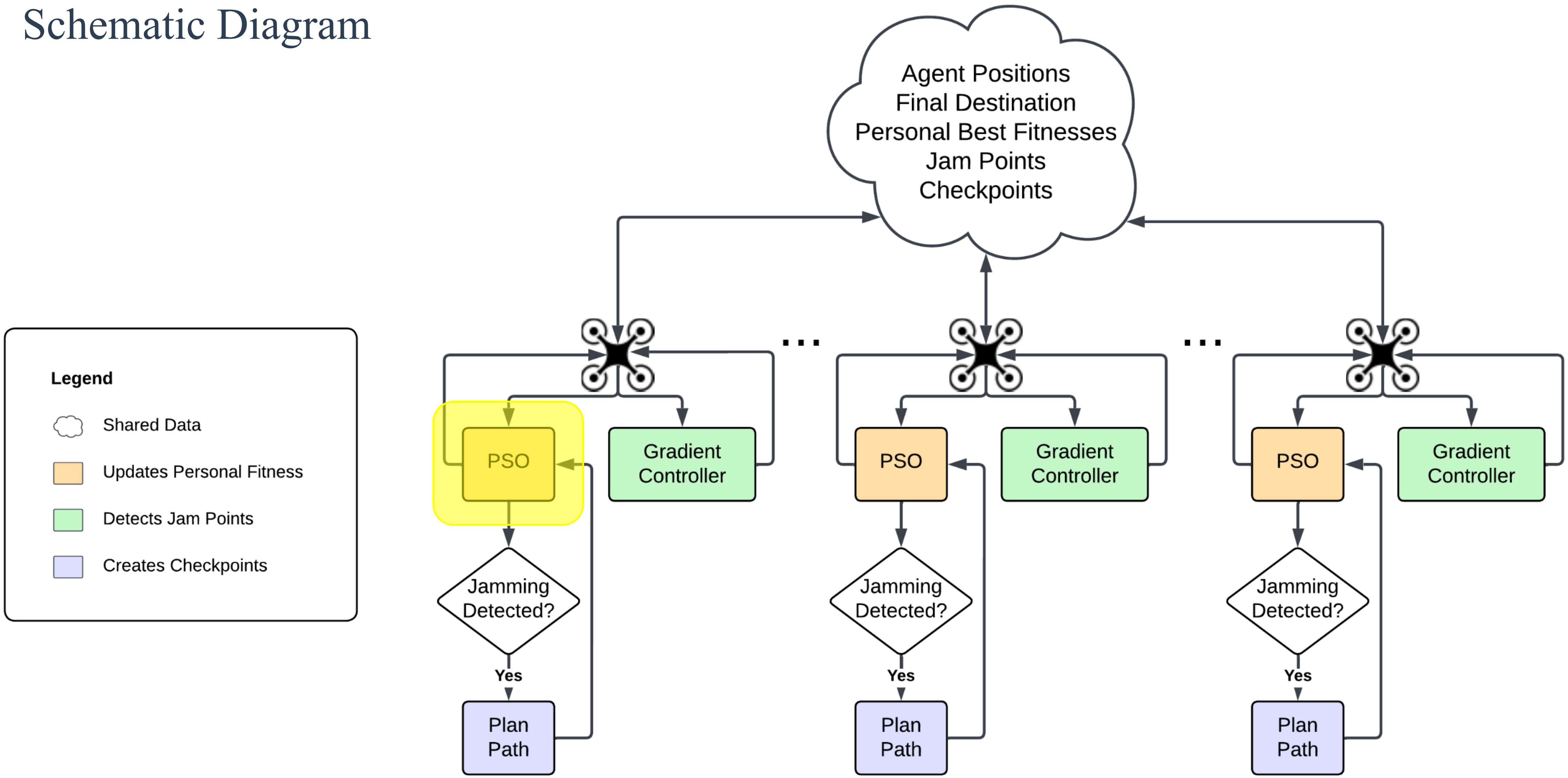
**Gradient Control Model**

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

# Schematic Diagram

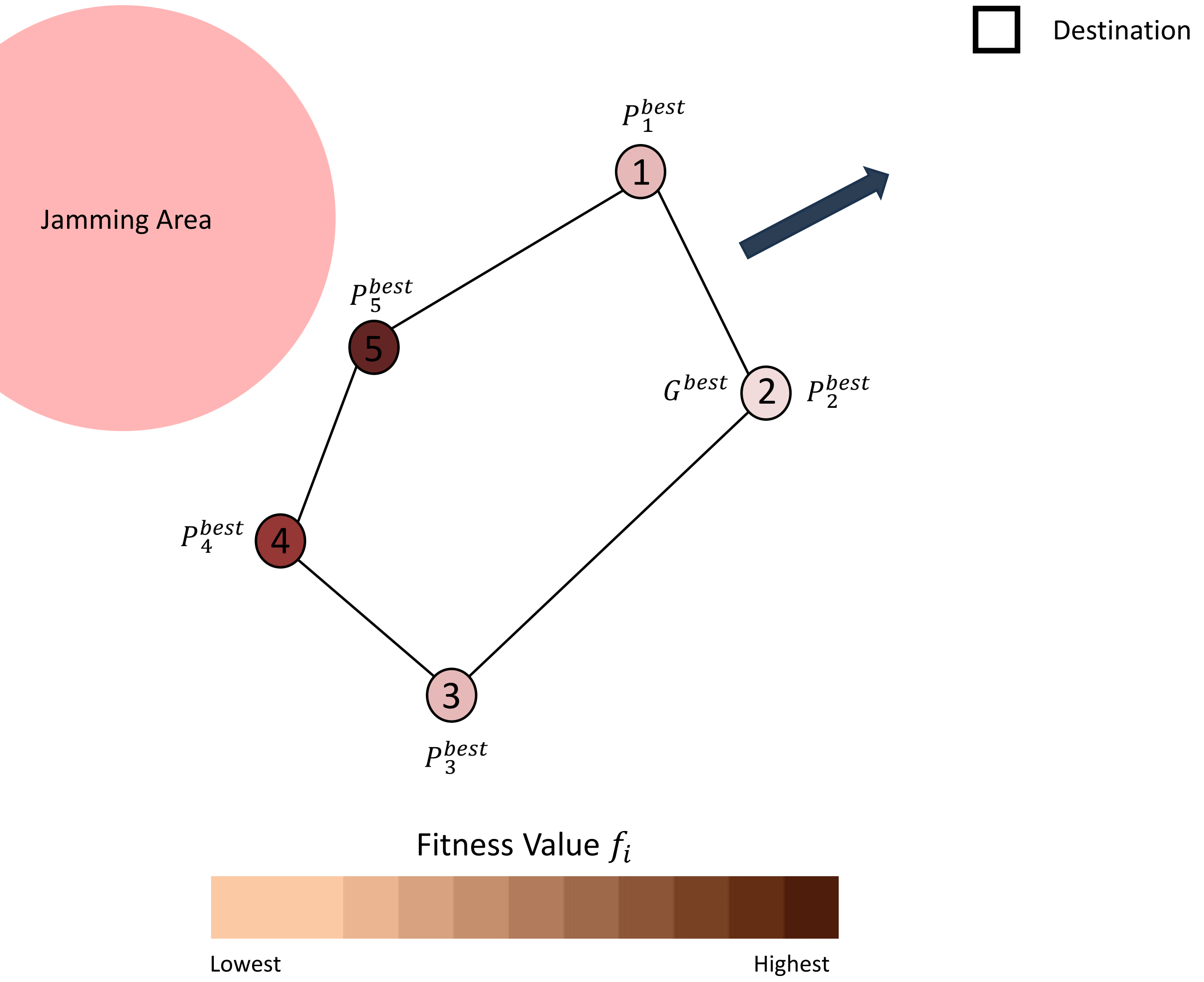


# Particle Swarm Optimization

Particle Swarm Optimization (PSO) is a biology inspired algorithm.

It is commonly used in multi-robot path planning.

# Particle Swarm Optimization




## Fitness Function

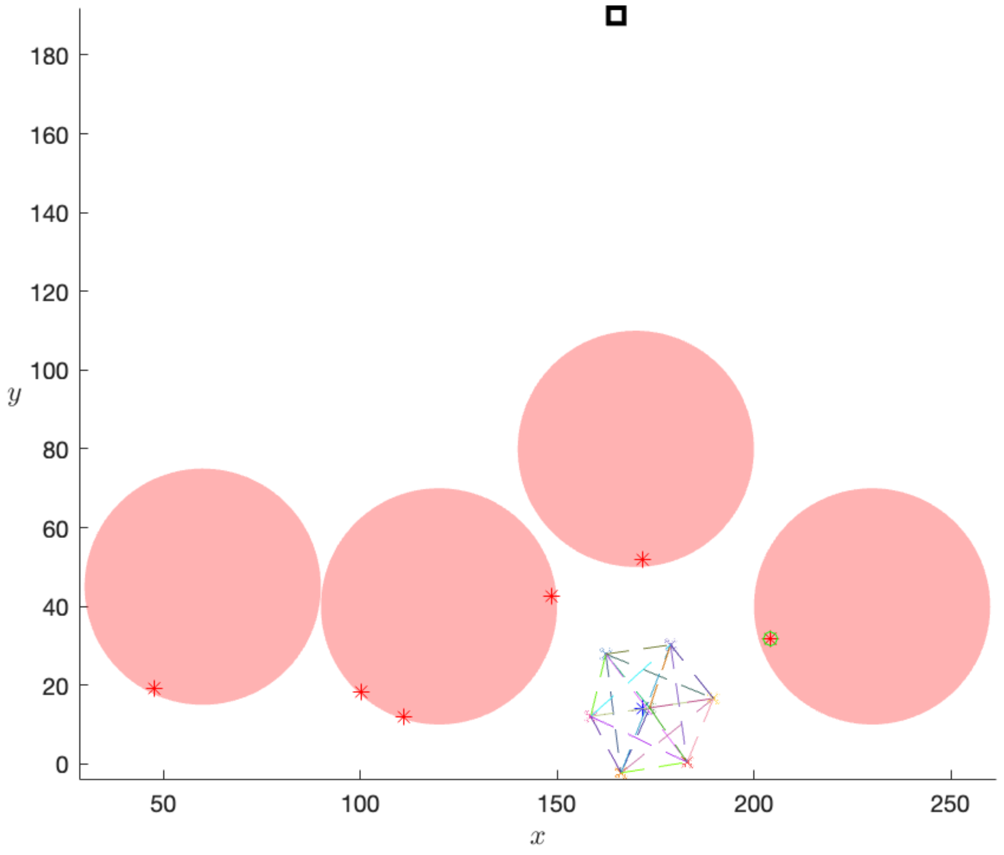
The fitness value of agent $i$ is:

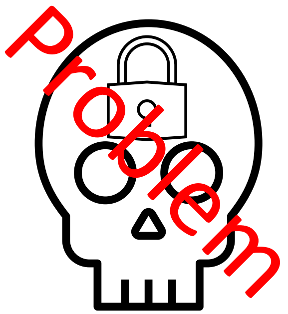
$$f_i = d_{\text{dest}} \cdot w_{\text{dest}} - \log_{10}\left(h_{\text{jam}}\right) \cdot w_{\text{jam}},$$

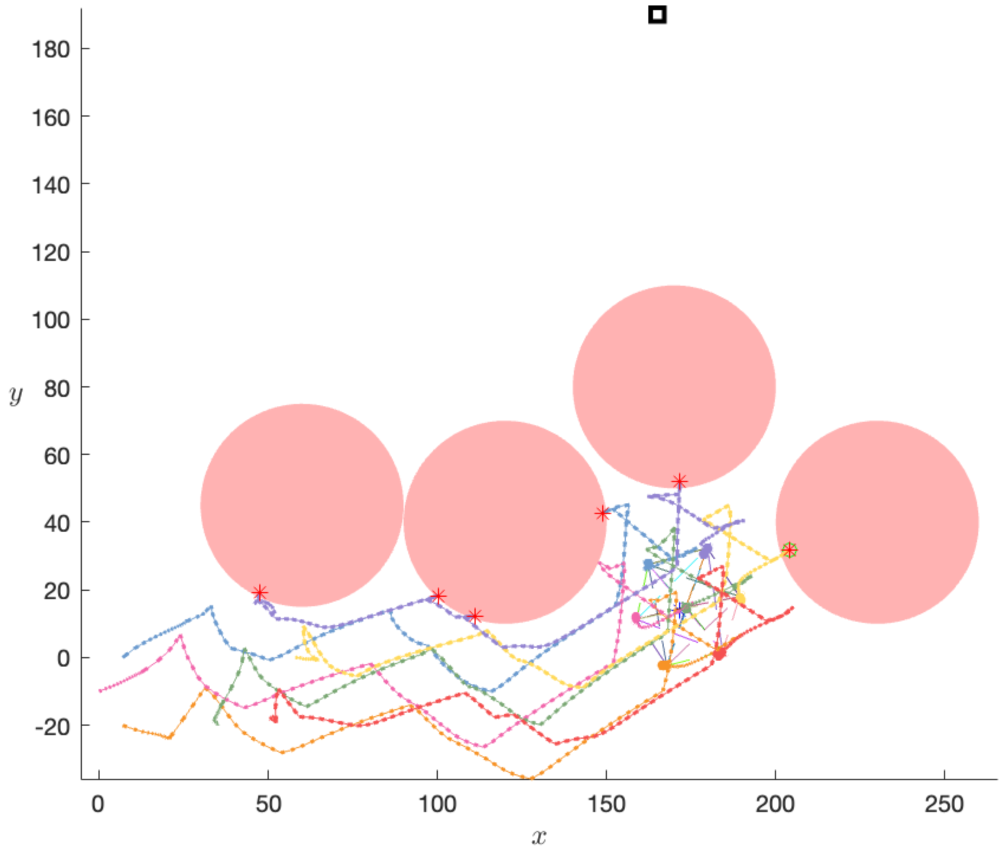
where

- $d_{\text{dest}}$ is the distance from agent to destination.
- $h_{\text{jam}}$ is the distance from agent to jam point.
- $w_{\text{dest}}$ and $w_{\text{jam}}$ are adjustable weight to the distance vector.

# Particle Swarm Optimization



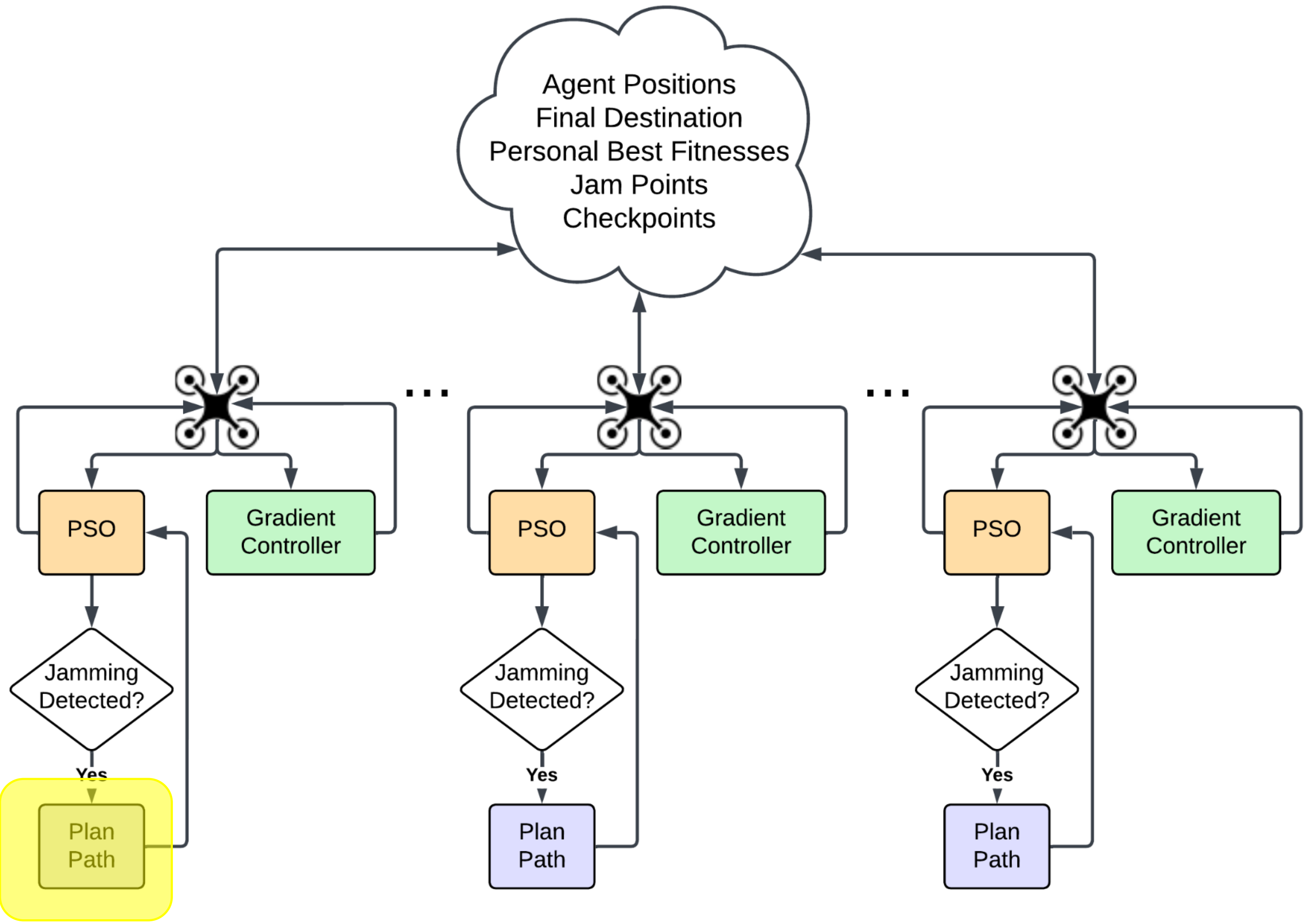



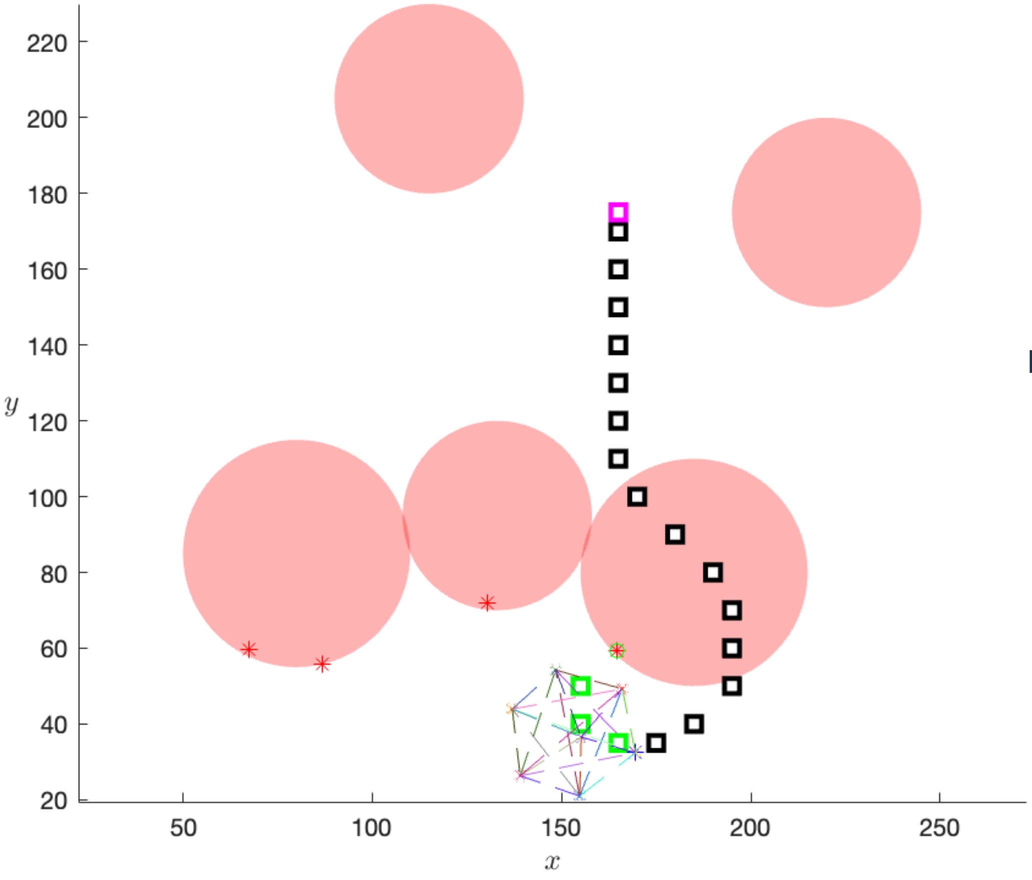
# Schematic Diagram

**Legend**

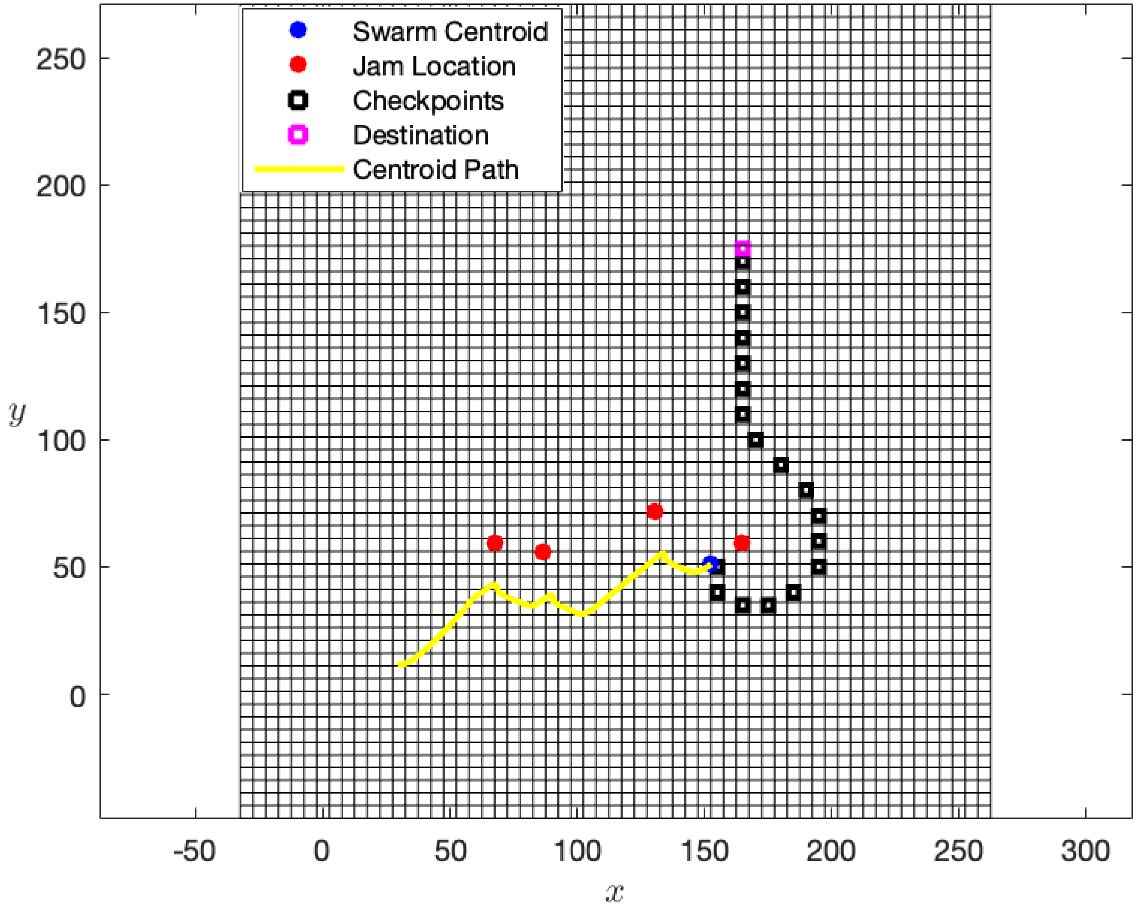
- Shared Data
- Updates Personal Fitness
- Detects Jam Points
- Creates Checkpoints



# Path Planning Algorithm




Discretized Environment



# Schematic Diagram

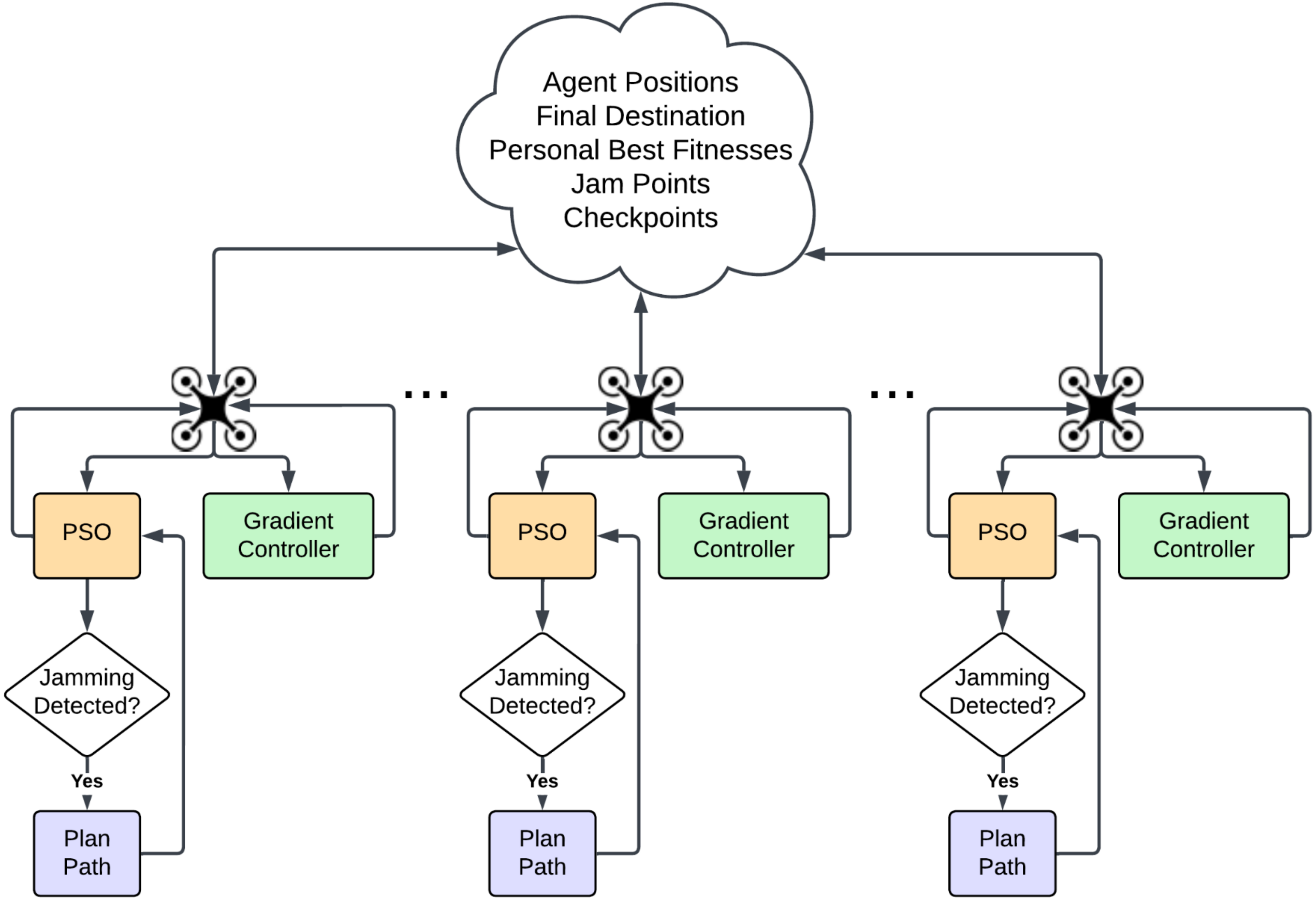
**Legend**

Shared Data

Updates Personal Fitness

Detects Jam Points

Creates Checkpoints

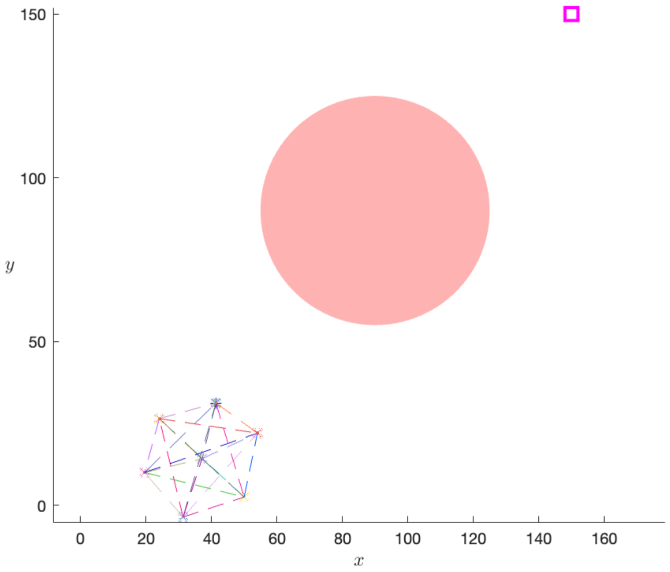


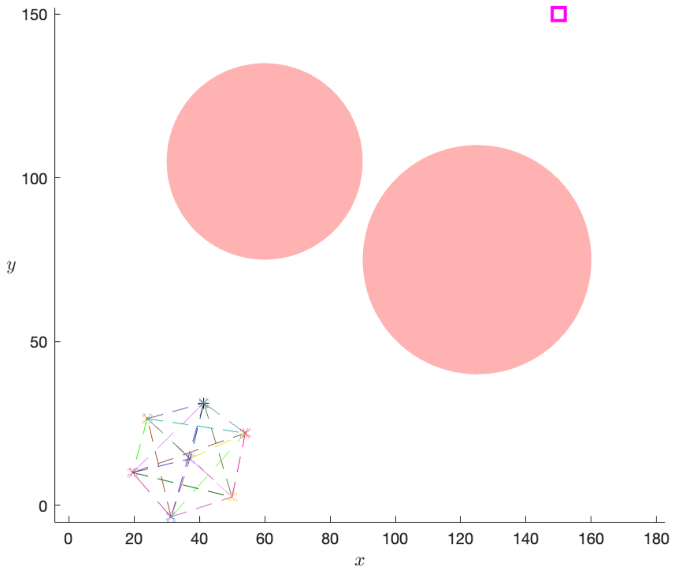
04

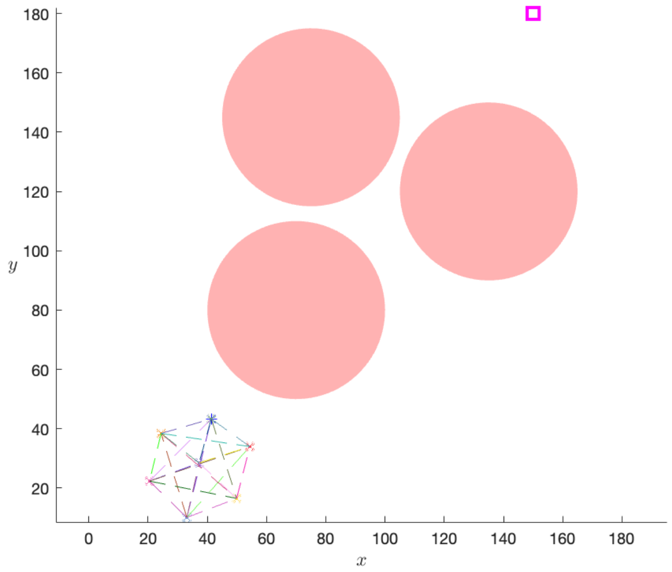
# Simulations

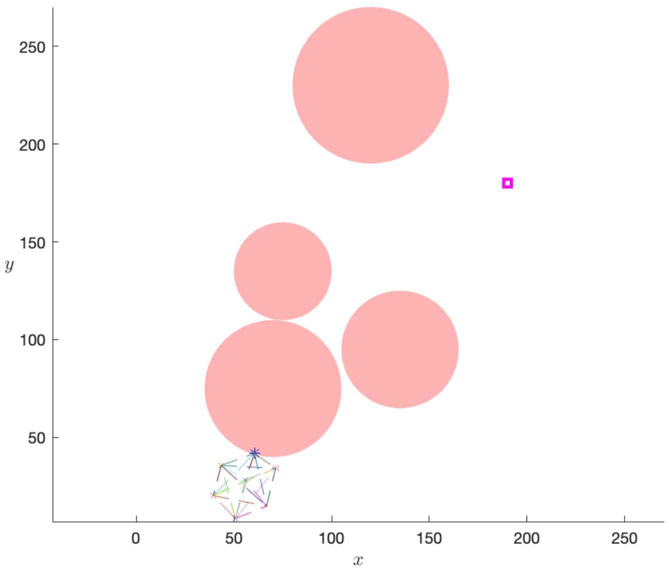
- Simulation Environments
- Simulation Results
- Simulation Evaluation

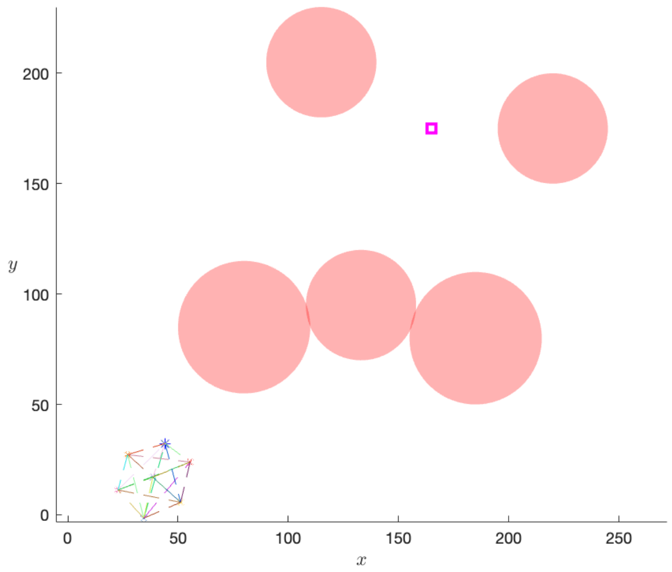
# Simulation Environments



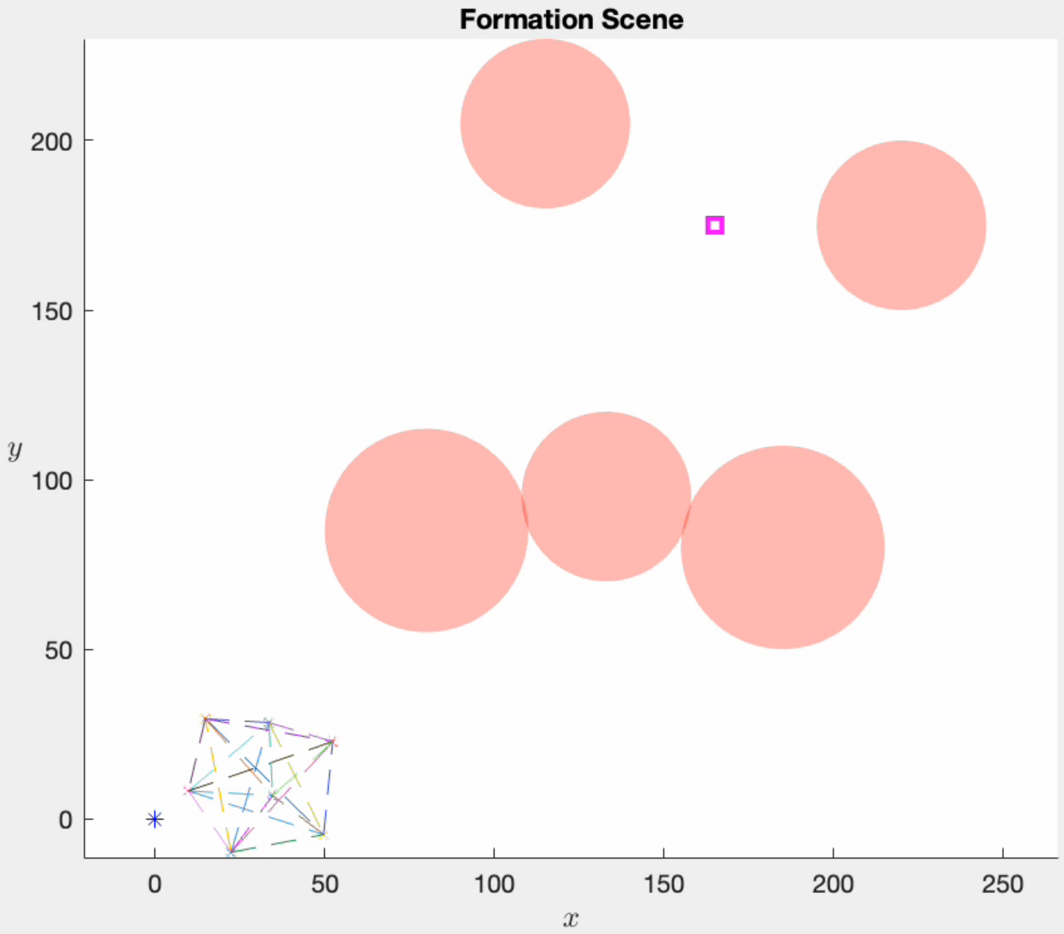



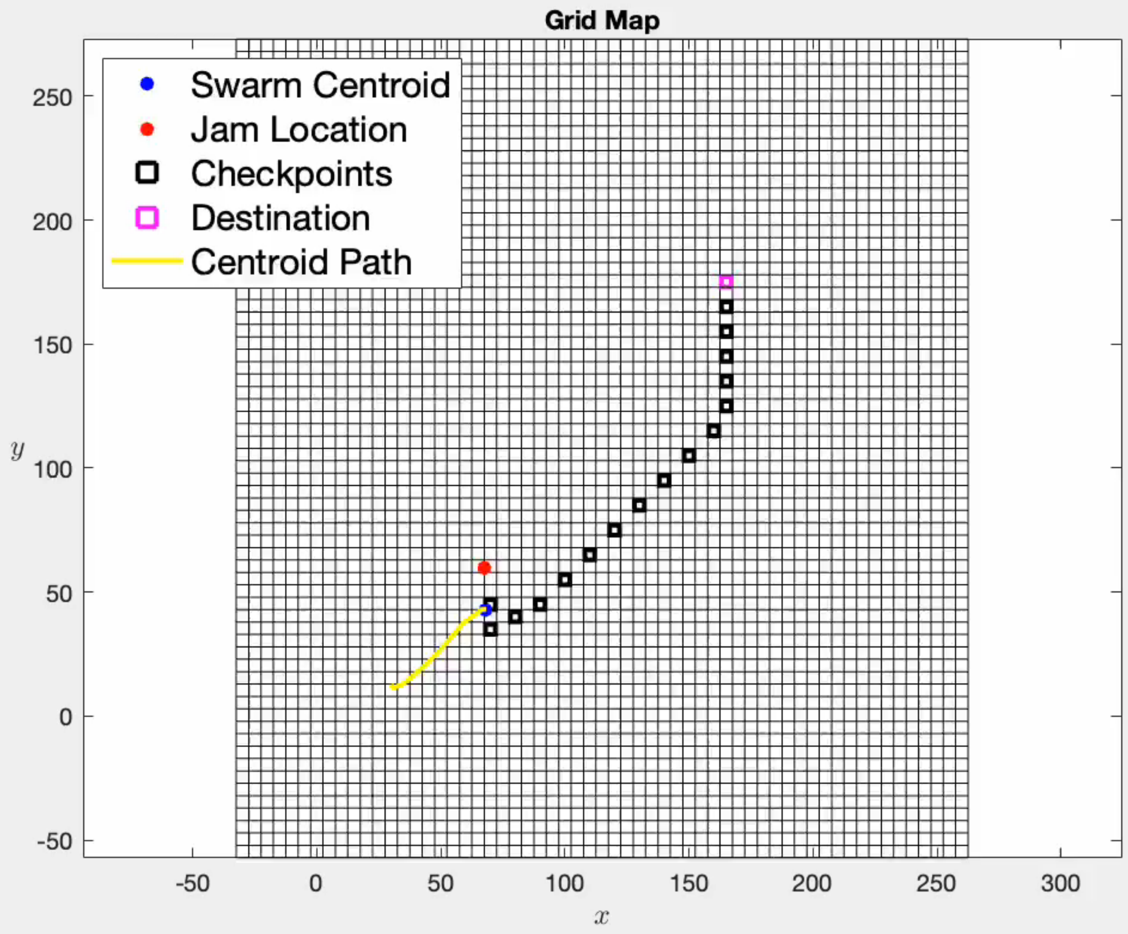



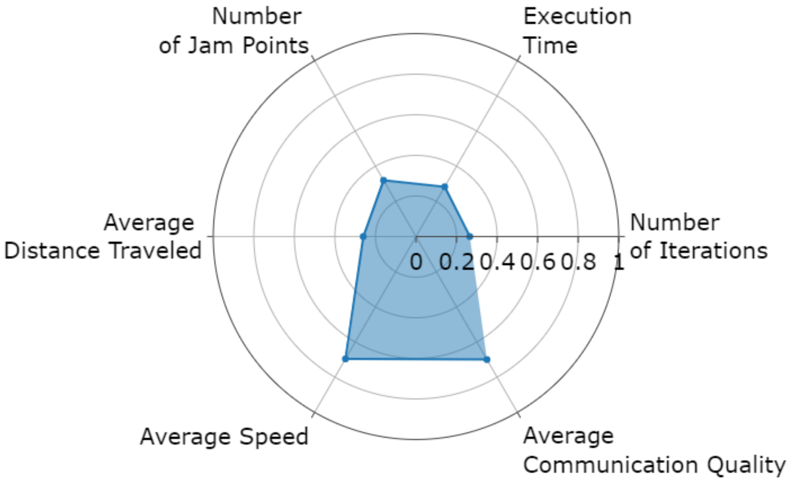
# Simulation Results



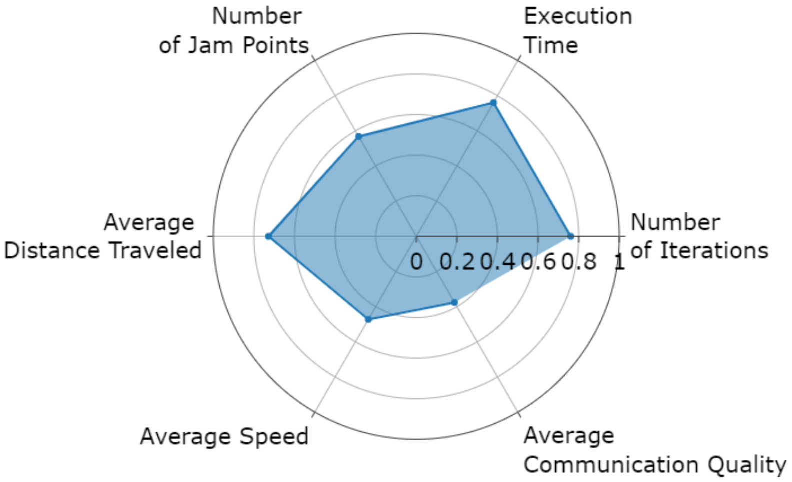



# Simulation Evaluation

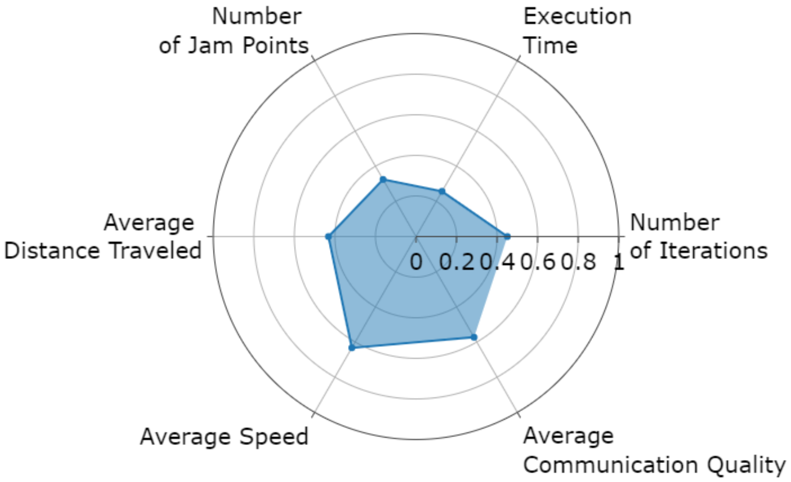
Theta*



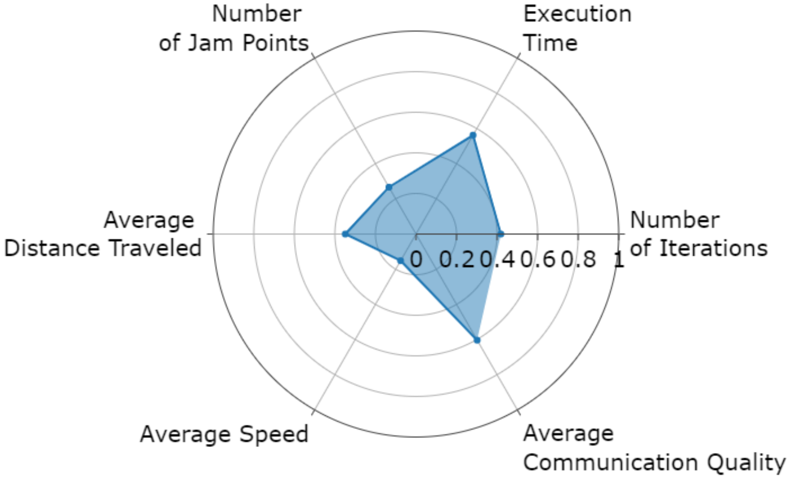

Jump Point Search



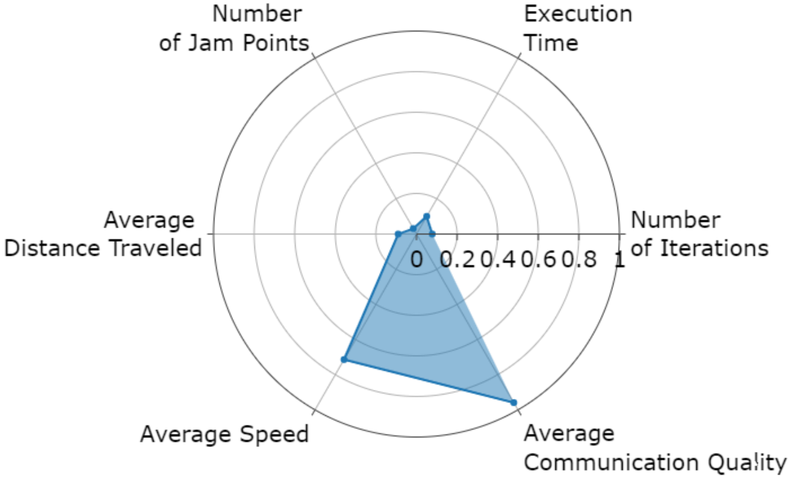

Breadth First Search



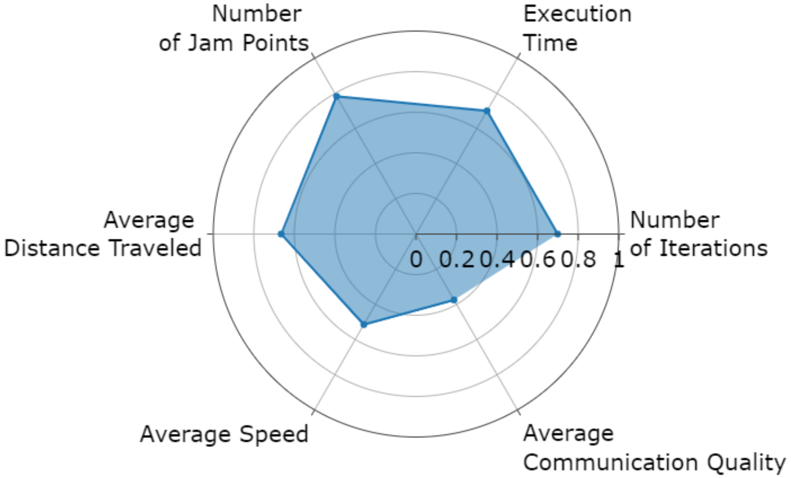

Greedy Best First Search




A*




Dijkstra



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# Conclusion

# Review

Intro

Preliminaries

- System Dynamics
- Graph Theory
- Rigid Formation

Communication Layer

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

Control Layer

- Gradient Controller
- PSO
- Path Planning Algorithm

Simulation

- Performance Metrics

Outro

## Results

- A* is identified as the most effective approach.
- Proposed a novel control strategy for swarm navigation in the presence of unknown jamming areas.
- Ensures efficient navigation, formation maintenance, and robust communication through extensive simulations in all 30 simulations.

# Final Project

### Project 1

- Add an agent.
- Remove an agent.
- Freeze an agent.

### Project 2

An obstacle avoidance strategy with at least one static obstacle while swarm are traveling to the destination.

# Project Strategies

## Obstacle Avoidance Approaches

- Reactive Control
- Potential Fields
- Voronoi Diagrams
- Evolutionary Algorithms
- Ant Colony Optimization (ACO)
- Path Planning Algorithms
- Model Predictive Control (MPC)
- Reinforcement Learning (RL)

You can find source code on my Github repo at: Here or via QR code above

## 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?

August 4, 2023