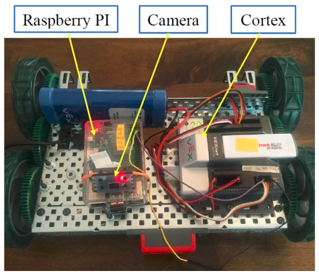
Cooperative Tracking of Multiple Targets in Flexible Formation Patterns



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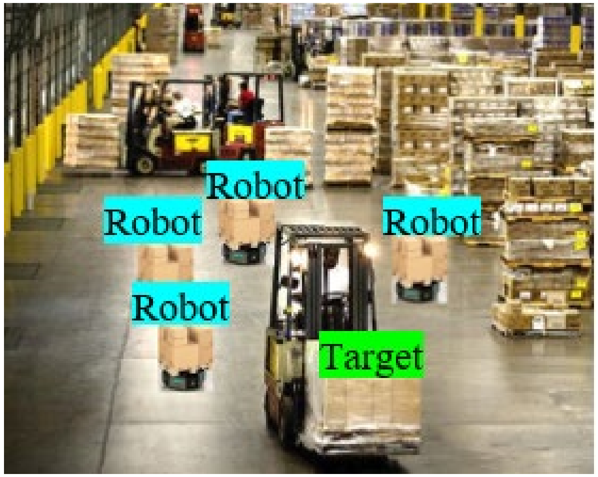
Motivation

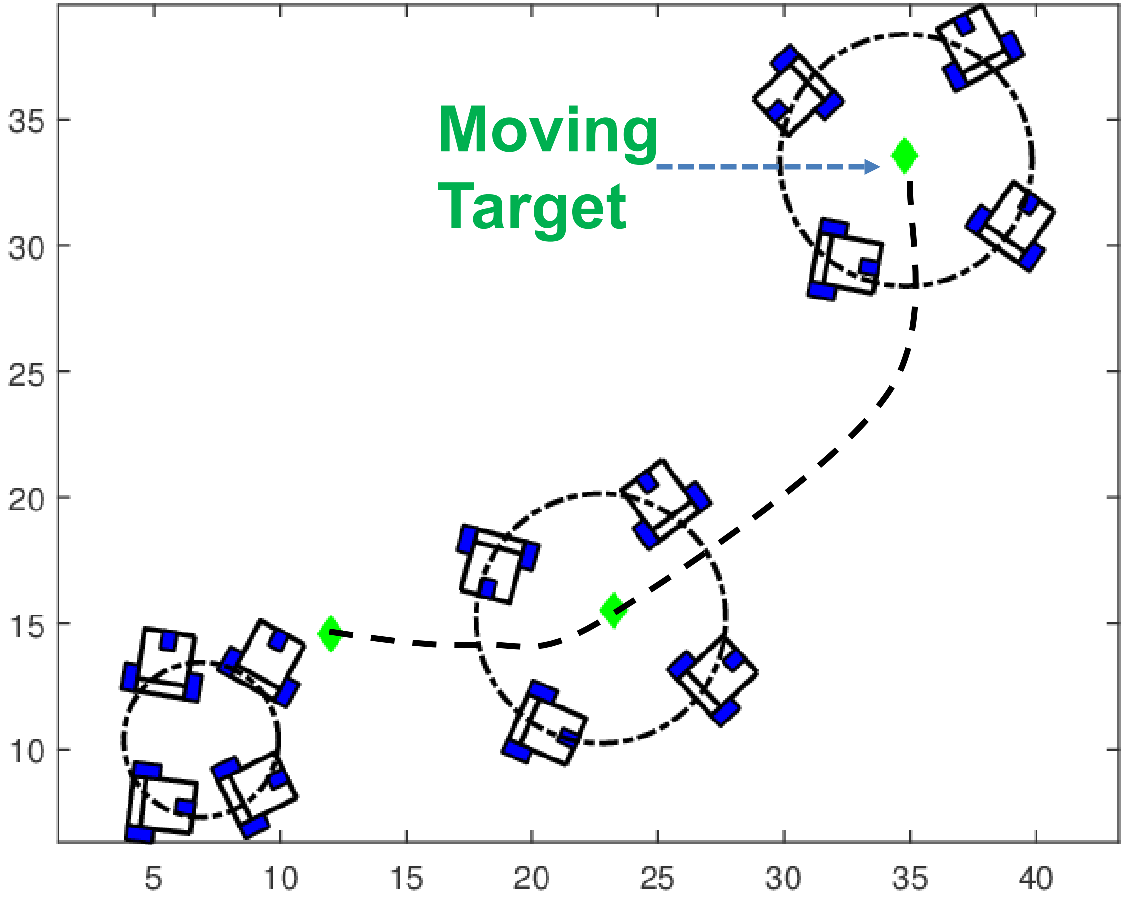
- Controlling a group of robots to achieve a common task has applications in areas such as warehouse or patrolling.



- **Cooperative target tracking:** control robots to follow a moving target (desired trajectory) as a group while maintaining certain formation locally within the group.
- **Benefits of Keeping Formation:**
  - Externally to the outside world, the robots' behaviors and trajectories are more predictable.
  - Internally the robots are more supportive to each other.

Cooperative Target Tracking

A group of agents reach desired relative positions & orientations with respect to a moving target



Flexible Formation Patterns: Examples

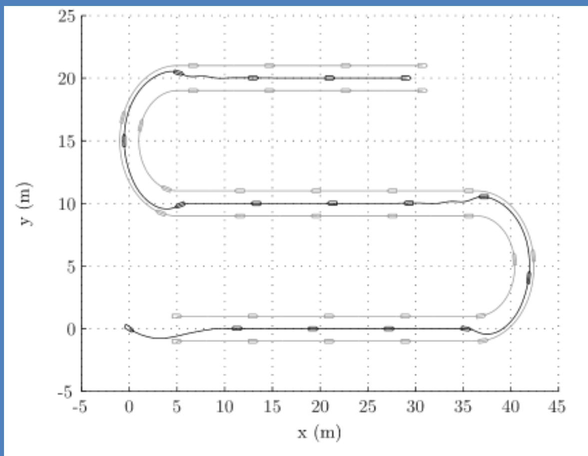
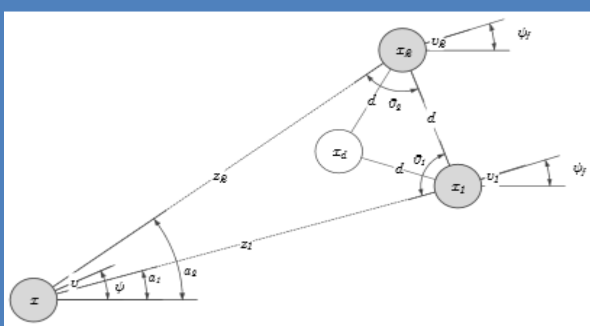
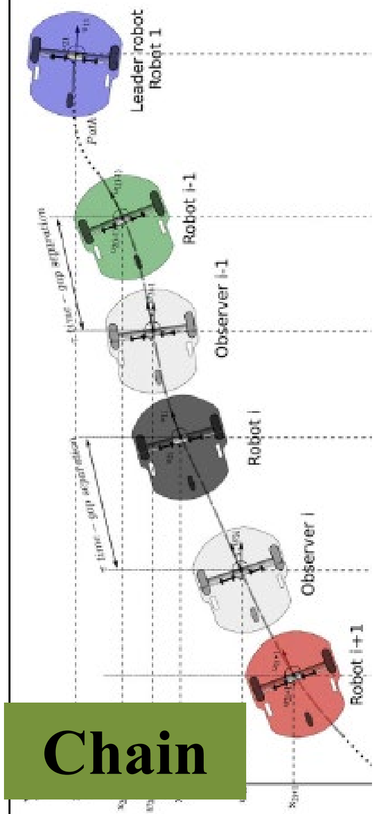


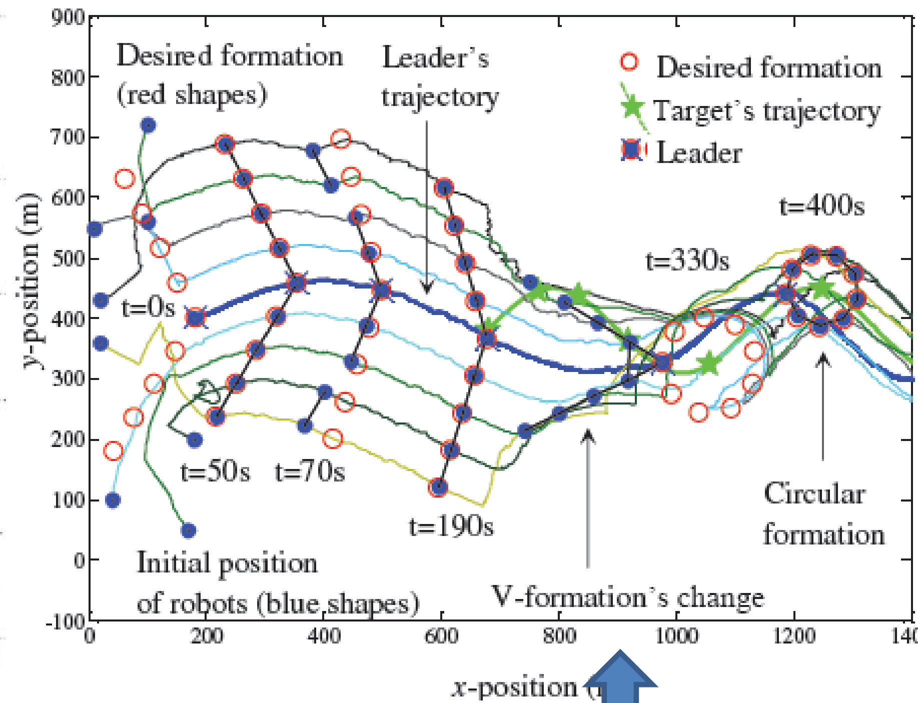
Fig. 5.1. Vehicle Paths. The maneuver starts on the lower left corner. The leader vehicles and the follower vehicle are shown in light and dark colours, respectively.

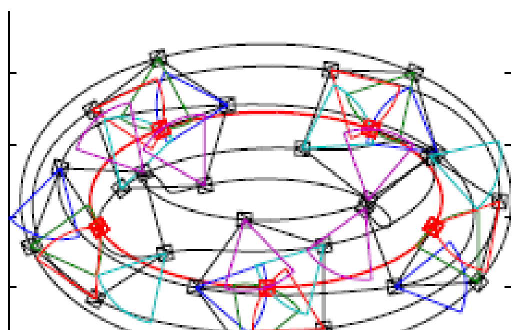


Triangular Formation



Chain





Concentric

With flexible formation patterns suitable to the task and environment

Pictures are from various research papers. These are not the speaker's own research results.

Simultaneous Tracking & Formation

The control input to each robot includes **two** components:

$$u_i(t) = u_{it}(t) + u_{ic}(t)$$

Dedicated for **Tracking**

Dedicated for **Formation**

Simultaneous Tracking & Formation with Obstacle/Collision Avoidance

The control input to each robot includes **three** components:

$$u_i(t) = u_{it}(t) + u_{ic}(t) + u_{ia}(t)$$

Dedicated for **Tracking**

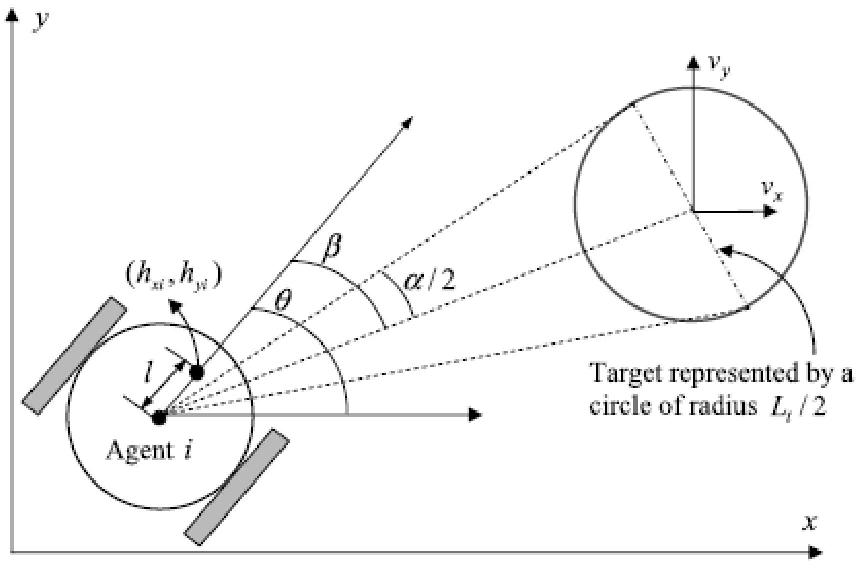
Dedicated for **Formation**

Dedicated for **Avoidance**

Traditional Approaches

- Traditional approaches are based on graph theory and classic control theory.
- **They typically requires relatively precise modeling of the environment and the robots.**
- They are thus hard to be generalized to new environments directly.

<u>Examples</u> of Relatively More Precise Modeling



Modeling of the **Target**

$$\begin{bmatrix} \dot{x}_i(t) \\ \dot{y}_i(t) \\ \dot{\theta}_i(t) \\ \dot{v}_i(t) \\ \dot{\omega}_i(t) \end{bmatrix} = \begin{bmatrix} v_i(t)\cos(\theta_i(t)) \\ v_i(t)\sin(\theta_i(t)) \\ \omega_i(t) \\ 0 \\ 0 \end{bmatrix} + \begin{bmatrix} 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 1/m & 0 \\ 0 & 1/J \end{bmatrix} \begin{bmatrix} F_i(t) \\ \tau_i(t) \end{bmatrix}$$

Modeling of the **Robot**

Modeling of the **Environment**

- Region-Based
- Graph-Based
- Polygon-Based

Example of Control Inputs

Tracking

$$\begin{cases} u_{it}(t) = \dfrac{V_{g,i}(t)\cos\eta_i(t) - \hat{V}_{ti}(t)\cos[\hat{\psi}_{ti}(t) - (\psi_i(t) - \eta_i(t))]}{\rho_i(t)} - k_2(\eta_i(t) - \eta_{di}(t)) \\ \eta_{di}(t) = \sin^{-1}\left(\frac{-k_1(\rho_i(t)-\rho_d)}{\zeta_{1i}(\omega_{ei}(t))}\right) - \zeta_{2i}\left(\omega_{ei}(t)\right) \end{cases}$$

Formation

$$u_{ic}(t) = \begin{cases} 0, & i = k \\ -k_v\beta_{i(i+1)}(t)\ln\left(\frac{(c_v-1)d_{i(i+1)}(t)+d_s}{c_v d_s}\right), & i \neq k \end{cases}$$

Avoidance

$$u_{ia}(t) = -K_r \sum_{j\in\mathcal{N}(r_i)} \frac{d_{\min}}{d_{ij}} \sin\beta_{ij}$$

Investigating MARL-Assisted Approaches (Multiple-Agent Reinforcement Learning)

- This research aims to achieve versatile and re-configurable formations with human awareness by resorting to multi-agent reinforcement learning (MARL)-assisted approaches.
- The objective is to provide EdgeRobot with learning capabilities to work in dynamic and human-populated environments.
- The designed robotic control algorithms will integrate traditional graph theory-based control solutions with MARL-based learning, estimation of motion intentions of people, adaption, and decision making.

Integrating MARL in Cooperative Target Tracking

Recall that so far, our control input to each robot includes **three** components:

$$u_i(t) = u_{it}(t) + u_{ic}(t) + u_{ia}(t)$$

When resorting to MARL-methods, the overall reward function will be designed similarly as a sum of **three** objectives: enforcing tracking, formation, and avoidance, respectively.

The MARL may be integrated as a substitute term of the three control inputs listed above, or as an extra decision layer selecting the most-rewarded

Tasks

Achieving **more formation patterns**: triangular, chain/platoon, concentric, geometrically specified.

Integrating **MARL** into the control laws and/or decision making.

Integrating dynamic scheduling for cooperative tracking of **multiple** targets.

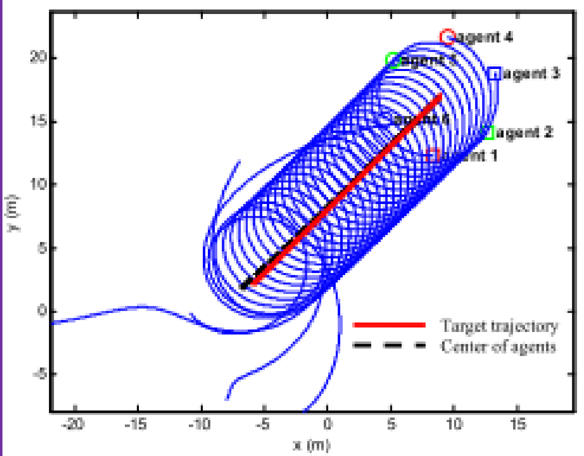
Eventually we need to answer the question of "**which robots tracking which target(s) in which formation**".

Existing Work

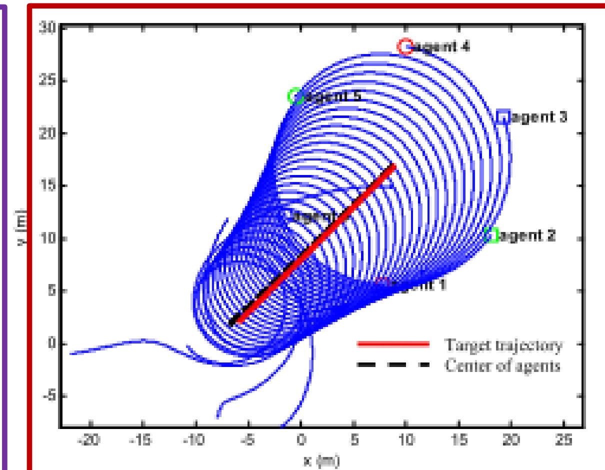
Achieved Formation Patterns (1)

Cooperative target tracking in:

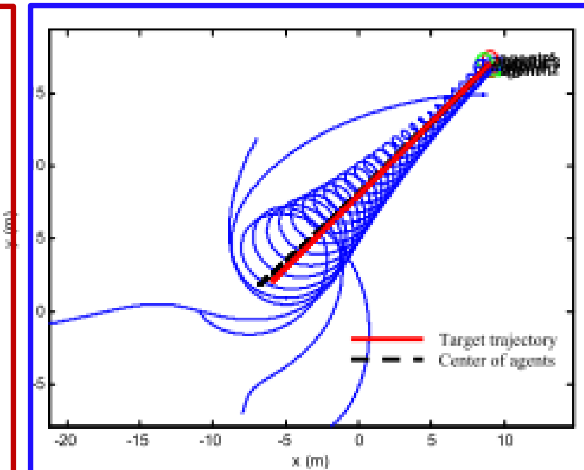
- Balanced **circular** formation
- Logarithmic **spirals**
- **Rendezvous** at a point



(a) Circular Formation



(b) Logarithmic Spiral



(c) Rendezvous to a Point

Balanced Circular

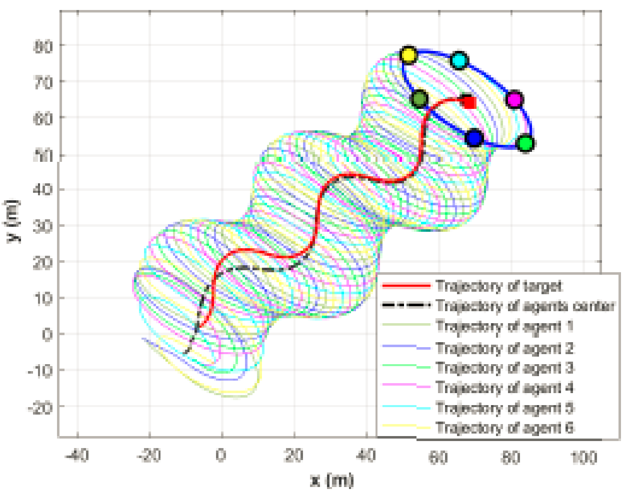
Logarithmic Spiral

Rendezvous to Point

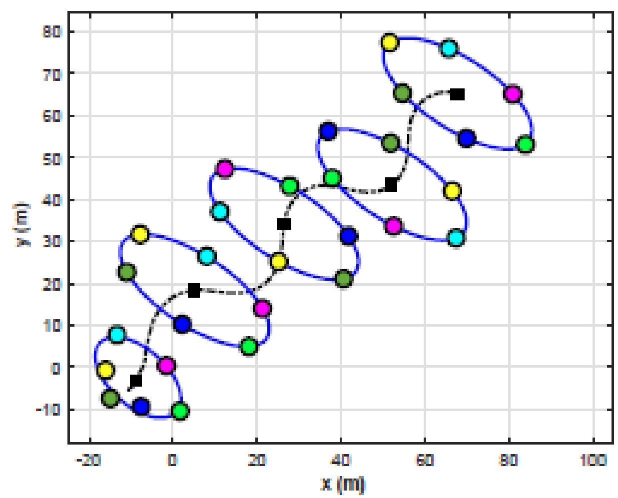
Achieved Formation Patterns (2)

Cooperative target tracking in:

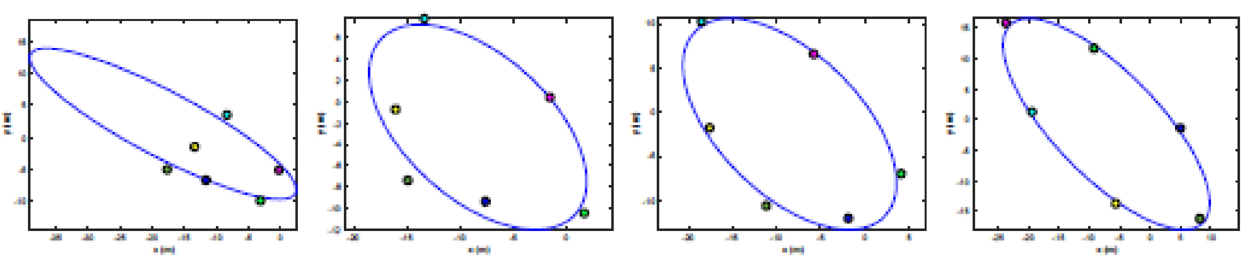
- **Elliptical** formations of different orientations and shape/roundness



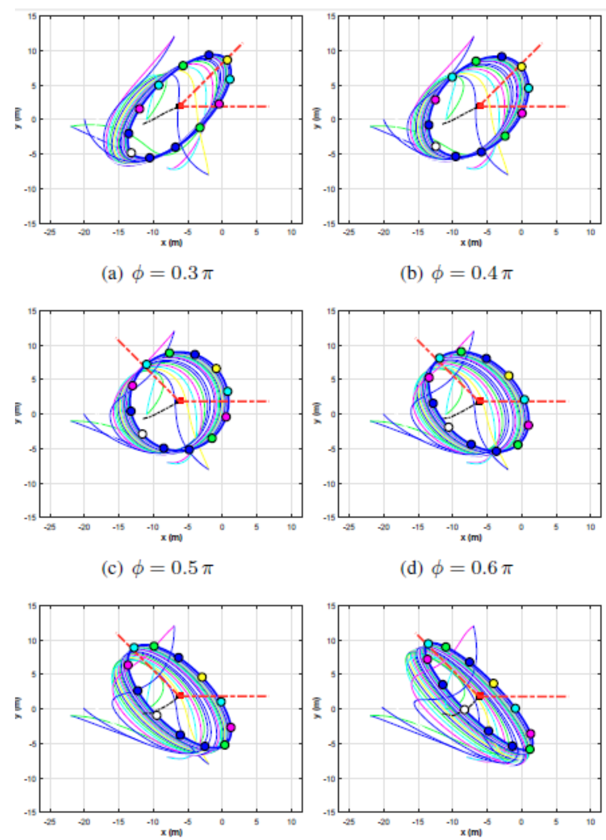
(a) Trajectories



(b) Snapshots



(c) $t = 2$ (sec.) (d) $t = 2.5$ (sec.) (e) $t = 3$ (sec.) (f) $t = 4.5$ (sec.)



(a) $\phi = 0.3\,\pi$ (b) $\phi = 0.4\,\pi$

(c) $\phi = 0.5\,\pi$ (d) $\phi = 0.6\,\pi$

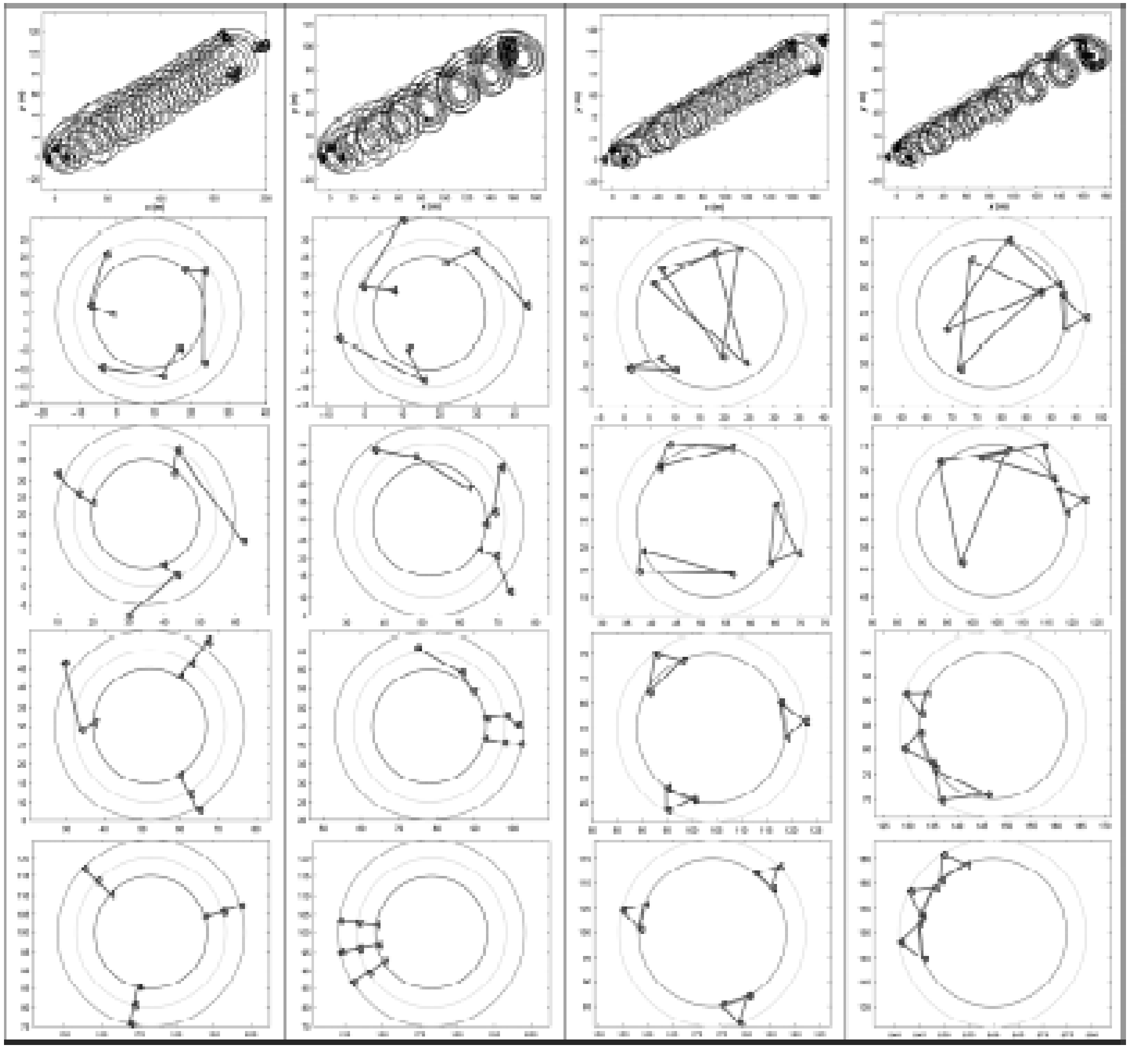
(e) $\phi = 0.7\,\pi$ (f) $\phi = 0.8\,\pi$

Existing Work

Achieved Formation Patterns (3)

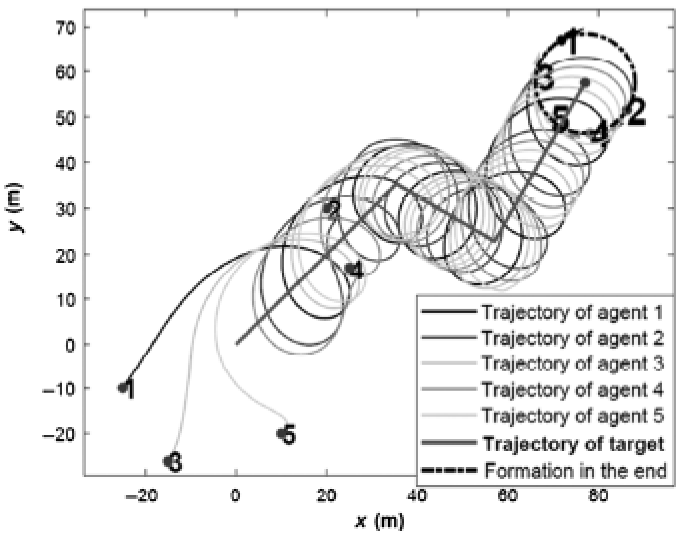
Cooperative target tracking in:

- **Concentric formations with local geometric shapes**

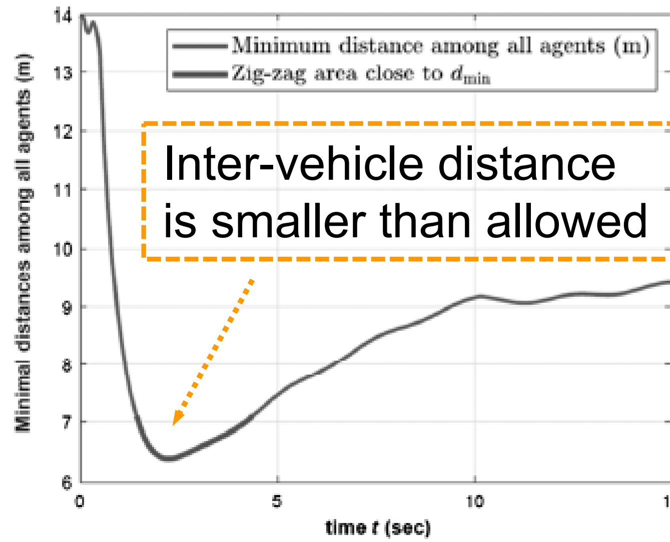


Existing Work

With/Without Collision Avoidance



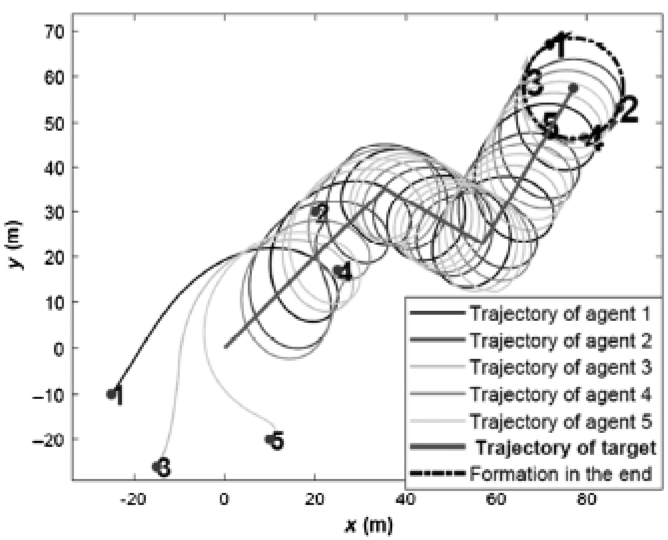
(a)



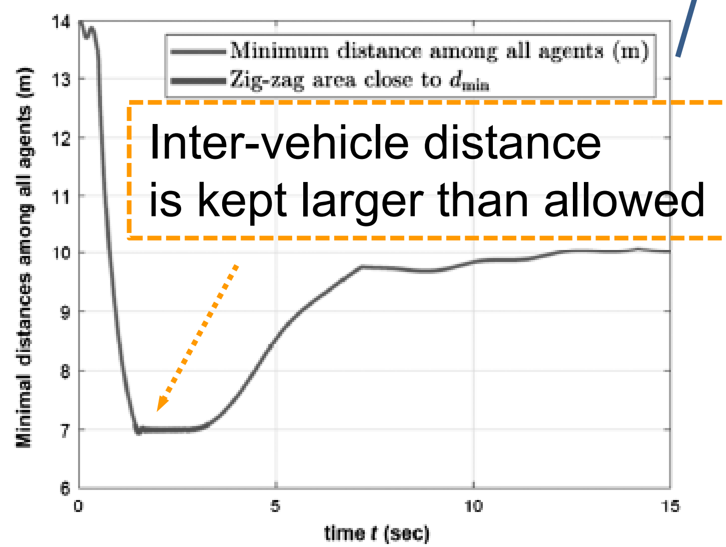
(b)

Without Collison Avoidance

With Collison Avoidance in Place



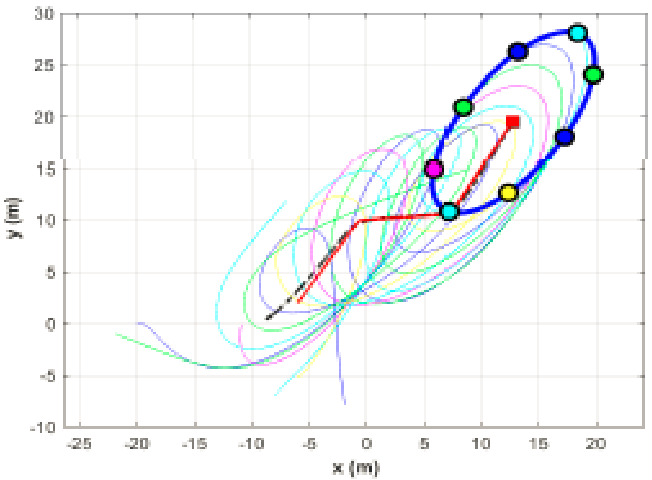
(c)



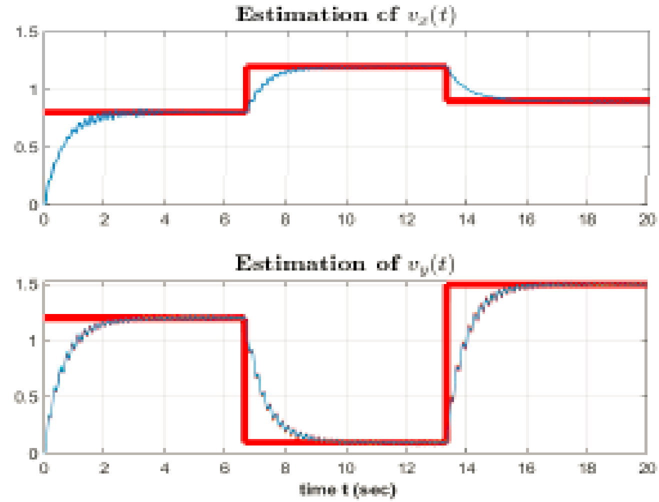
(d)

Existing Work

Estimation of Target Intensions

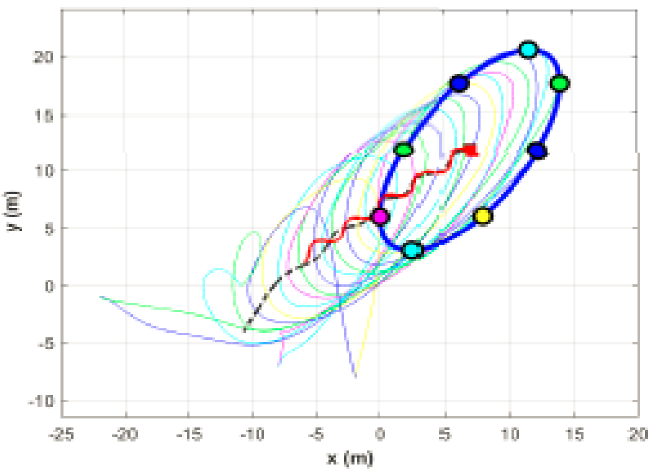


(a) Trajectories

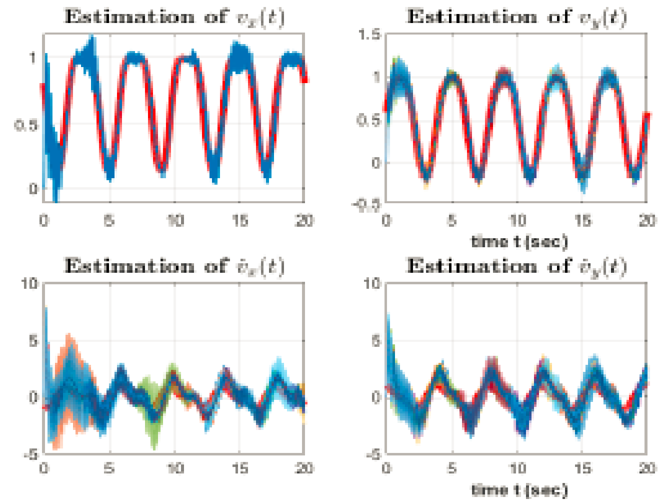


(b) Estimation

With estimated target information



(c) Trajectories



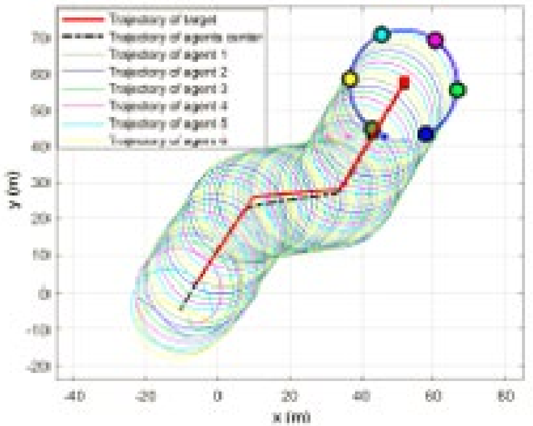
(d) Estimation

Cooperative Target Tracking for EdgeRobots

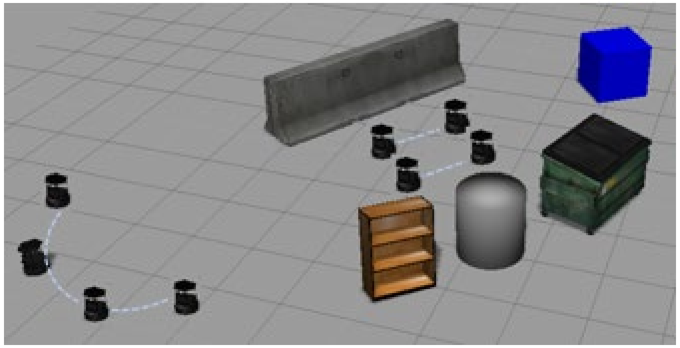
- **At the Robot-Level:**
  - Achieving tracking and simultaneous formation
  - Deciding the right/appropriate formation
- **At the Edge-Level:**
  - Dynamic scheduling and/or assignment of robots for tasks/targets
- **The Rule-of-Thumb: Do as much as we can locally on each robot; if can not, ask Edge.**

Three-Stage Algorithm Validation & Verification

- Via MATLAB simulation



- Via ROS simulation



- On physical robots