Formation Adaptation in Obstacle-Cluttered Environments via MPC-Based Trajectory Planning

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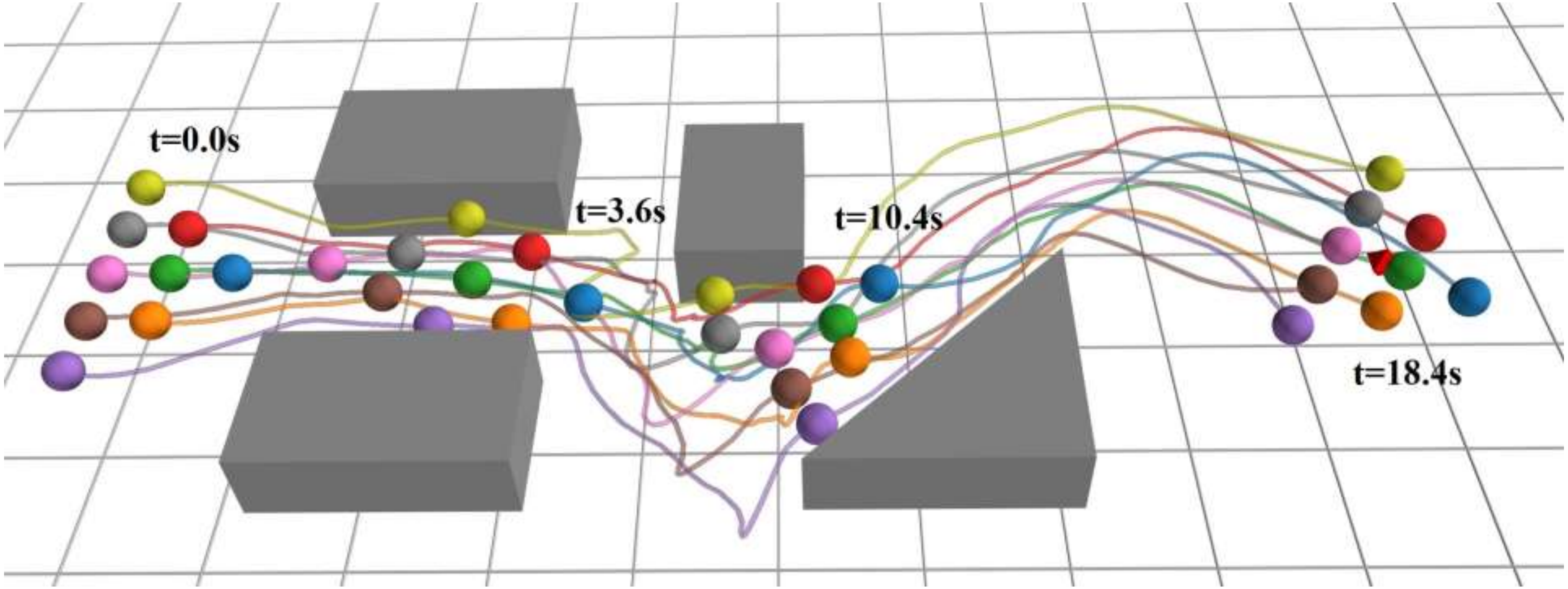
Motivation

- Formation is a typical collective behavior in multi-agent system, which has applications in inspection, surveillance, transportation.
- Current formation methods includes: virtual structure, consensus-based methods and affine formation.
- Though these feedback control methods have high robustness and low computation cost, yet they neglect the obstacle-cluttered environment.

Motivation



More specifically, the agents need to adapt their formation structure to safely pass some narrow passages or corners likes the above figure.

Motivation

Current works:

Recent works [1,2] propose an interesting idea of adopting trajectory planning to achieve formation and meanwhile avoid obstacle collisions. Specifically, they reformulate the planning as numerical optimization problems and enforce soft or hard constraints to avoid obstacles and inter-agent collision.

[1] Javier A, Stuart B, Daniela R. Multi-agent formation control and object transport in dynamic environments via constrained optimization. The International Journal of Robotics Research, 2017, 36:1000-1021.
[2] Quan L, Yin L, Zhang T, et al. Robust and efficient trajectory planning for formation flight in dense environments. IEEE Transactions on Robotics, 2023, 1-20.

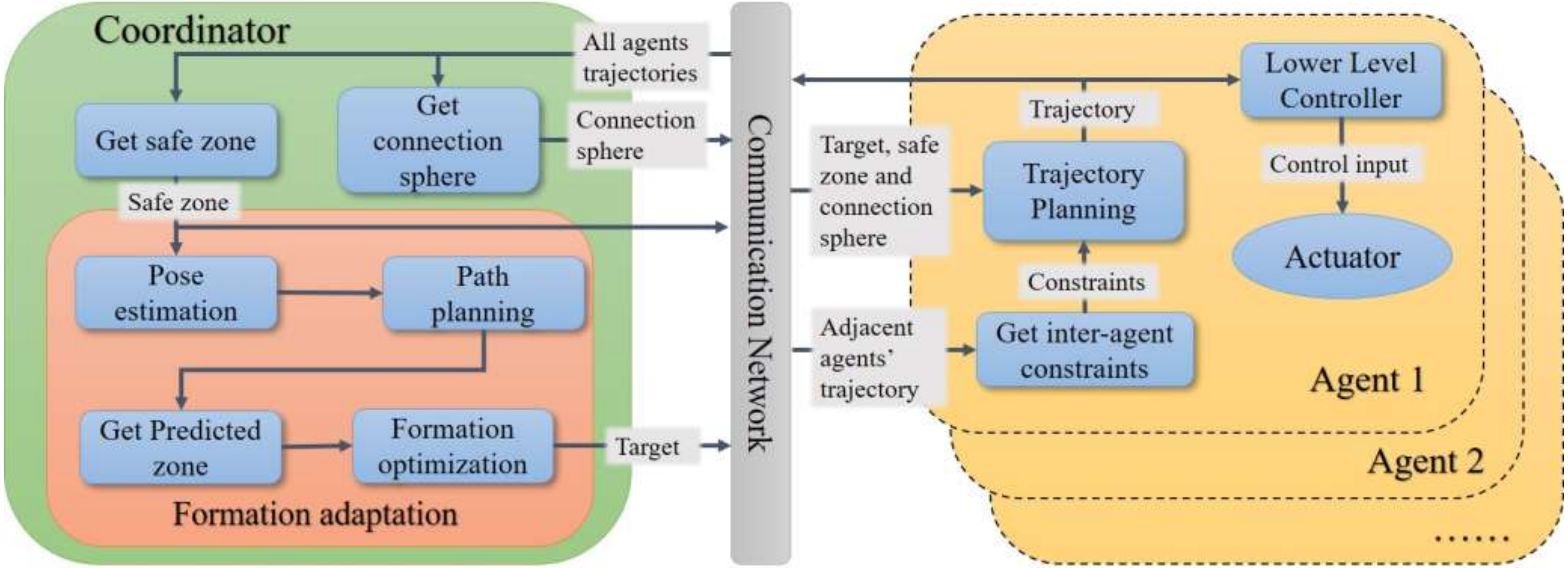
Motivation

The main difficulties of current works:

- The induced constrained optimization is not ensured to be feasible in the sense that the safety of the underlying agents in terms of agent-obstacle and inter-agent collision avoidance is not theoretically guaranteed.
- Inter-agent communication in the formation, e.g., the line-of-sight collision between agents, is not adequately concerned.

Therefore, we propose a novel formation adaption method via MPC (model predictive control)-based trajectory planning, with both collision avoidance and connectivity maintenance ensured. Formation adaptation is encoded to achieve adaptive deformation according to the obstacle distribution.

Proposed Method



The scheme of the proposed method.

Proposed Method

Safe zone:

$$a_m^{\mathrm{zone}\,T} p_k^i \geqslant b_m^{\mathrm{zone}}, m \in \mathcal{M}$$

where

$$\begin{aligned} \max_{a_m^{\mathrm{zone}}, b_m^{\mathrm{zone}}, \delta} \quad & \delta, \\ \text{s.t.} \quad & a_m^{\mathrm{zone}\,T} p \geqslant \delta + b_m^{\mathrm{zone}}, \; p \in \mathcal{P}^{\mathrm{free}} \\ & a_m^{\mathrm{zone}\,T} p \leqslant b_m^{\mathrm{zone}}, \; p \in \mathcal{P}_m^O, \\ & \left\| a_m^{\mathrm{zone}} \right\|_2 = 1, \end{aligned}$$

Inter-agent constraints:

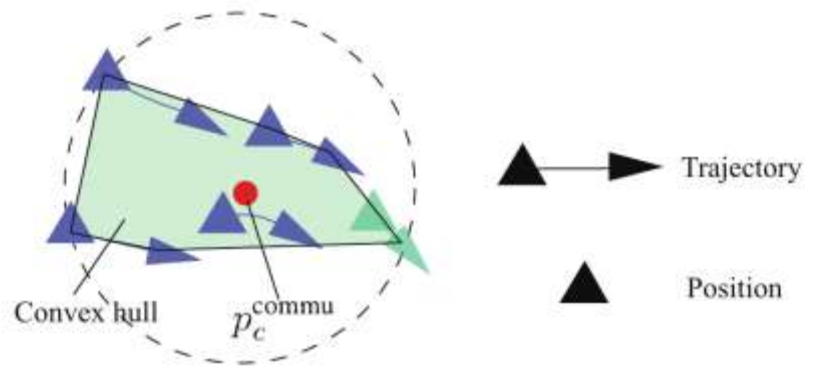
$$a_k^{ij\,\mathrm{T}} p_k^i \geqslant b_k^{ij}, \; \forall j \neq i, \; \forall k \in \mathcal{K}$$

where

$$a_k^{ij} = \frac{\overline{p}_k^i - \overline{p}_k^j}{\| \overline{p}_k^i - \overline{p}_k^j \|_2}, \; b_k^{ij} = a_k^{ij\,\mathrm{T}} \frac{\overline{p}_k^i + \overline{p}_k^j}{2} + \frac{r'_{\min}}{2}$$

$$r'_{\min} = \sqrt{4{r_a}^2 + h^2 v_{\max}^2}$$

Communication sphere:



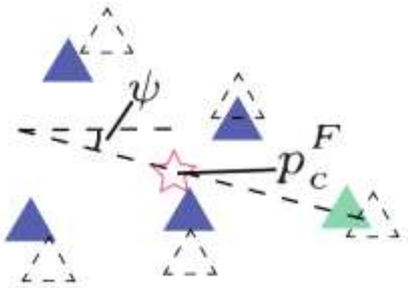
$$\left\| \overline{p}_k^i - p_c^{\mathrm{commu}} \right\|_2 \leqslant d_c$$

where

$$\begin{aligned} \min_{d, \; p_c^{\mathrm{commu}}} \quad & d, \\ \text{s.t.} \quad & \left\| p_c^{\mathrm{commu}} - \overline{p}_k^i \right\|_2 \leqslant d \end{aligned}$$

Proposed Method

Pose estimation:



$$\min_{\psi, p_c^F} \sum_{i=1}^{N} ||R^i(\psi) r^i + p_c^F - p_K^i||_2^2$$

$$\text{s.t. } |\psi(\mathrm{t}-\mathrm{h}) - \psi| \leqslant \delta\psi_{\max}$$

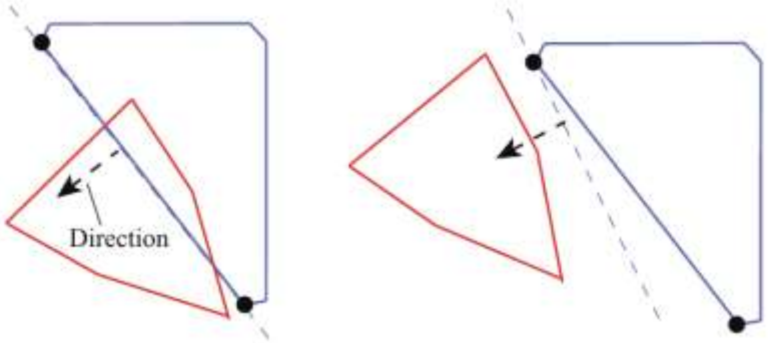
where $\mathcal{R}(\psi) = \mathcal{R}(\psi(t-h)) + \frac{\partial \mathcal{R}(\theta)}{\partial \theta}|_{\theta=\psi(t-h)}(\psi - \psi(t-h))$

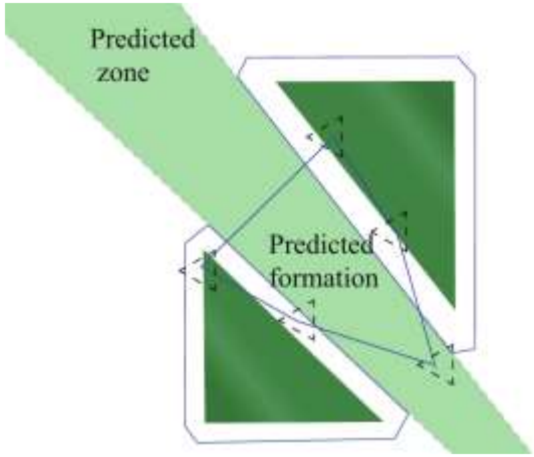
Path planning:

Inflate obstacles and, then, plan a path via RRT* based method.

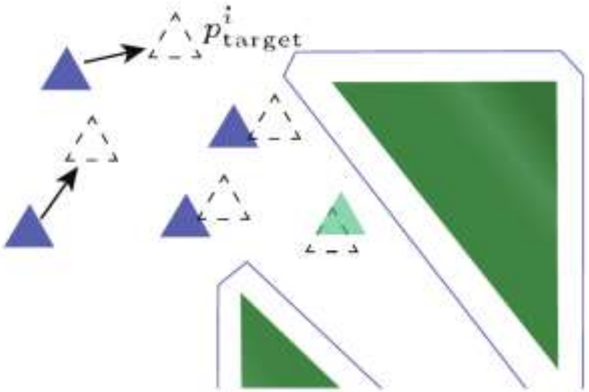
Proposed Method

Predicted zone derivation:





Formation optimization:



$$
\begin{aligned}
\min_{\overline{\psi},\, p^{i}_{\text{target}},\, w} \quad & \|p^{0}_{\text{target}} - p_{\text{tractive}}\|_2^2 + \alpha_w w^2 \\
& + \sum_{i=1}^{N} \|\mathcal{R}(\overline{\psi}) r^{i} + p^{0}_{\text{target}} - p^{i}_{\text{target}}\|_2^2 \\
\text{s.t.} \quad & a_m^{\text{zone}\,\mathrm{T}} p^{i}_{\text{target}} + b_m^{\text{zone}} + w \geqslant 0,\ m \in \mathcal{M} \\
& a_m^{\text{pre}\,\mathrm{T}} p^{i}_{\text{target}} + b_m^{\text{pre}} + w \geqslant 0,\ m \in \mathcal{M} \\
& w \geqslant 0,
\end{aligned}
$$

Proposed Method

Finally, the following optimization problem is carried out in each agent

$$
\begin{aligned}
&\min_{\mathrm{u}_{k-1}^i, x_k^i, k\in\mathcal{K}} \quad C^i \\
\text{s.t.}\ & x_k^i = \mathbf{A}x_{k-1}^i + \mathbf{B}u_{k-1}^i,\ k\in\mathcal{K}, \\
& \|\Theta_a u_{k-1}^i\|_2 \leqslant a_{\max},\ k\in\mathcal{K}, \\
& \|\Theta_v v_k^i\|_2 \leqslant v_{\max},\ k\in\mathcal{K}, \\
& a_k^{ij\,\mathrm{T}} p_k^i \geqslant b_k^{ij},\ \forall j\neq i,\ k\in\mathcal{K}, \\
& a_m^{\mathrm{zone}\,T} p_k^i \geqslant b_m^{\mathrm{zone}}, m\in\mathcal{M}, k\in\mathcal{K}, \\
& \left\|\overline{p}_k^i - p_c^{\mathrm{commu}}\right\|_2 \leqslant d_c, k\in\mathcal{K}, \\
& v_K^i = \mathbf{0}_d.
\end{aligned}
$$

Objective function

Dynamic constraints

Inter-agent collision constraints

Obstacle collision constraints

Connectivity constraints

Terminal constraints

The objective function is determined as follows:

$$
\frac{1}{2}Q_K\|p_K^i - p_{\mathrm{target}}^i\|_2^2 + \frac{1}{2}\sum_{k=1}^{K-1} Q_k\|p_{k+1}^i - p_k^i\|_2^2
$$

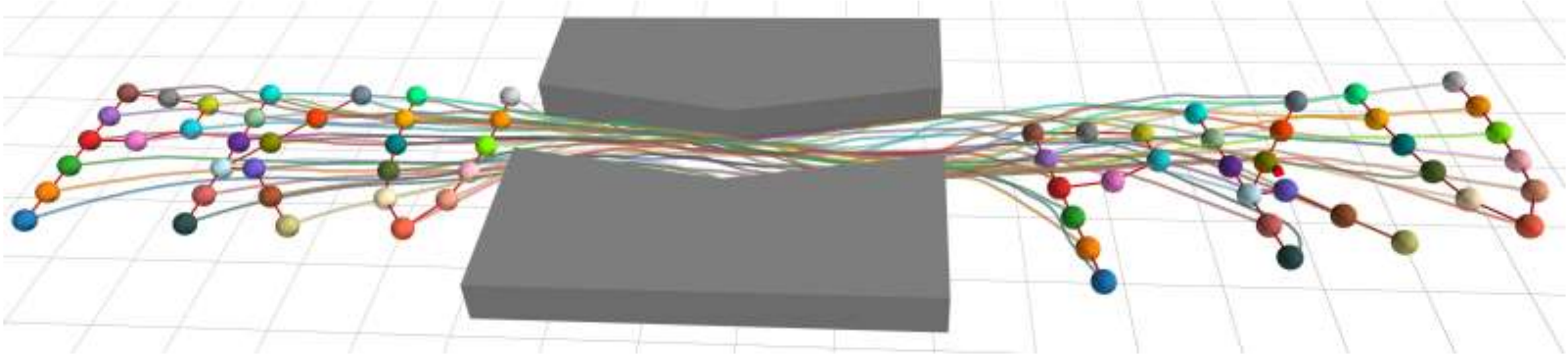
Results

Property:

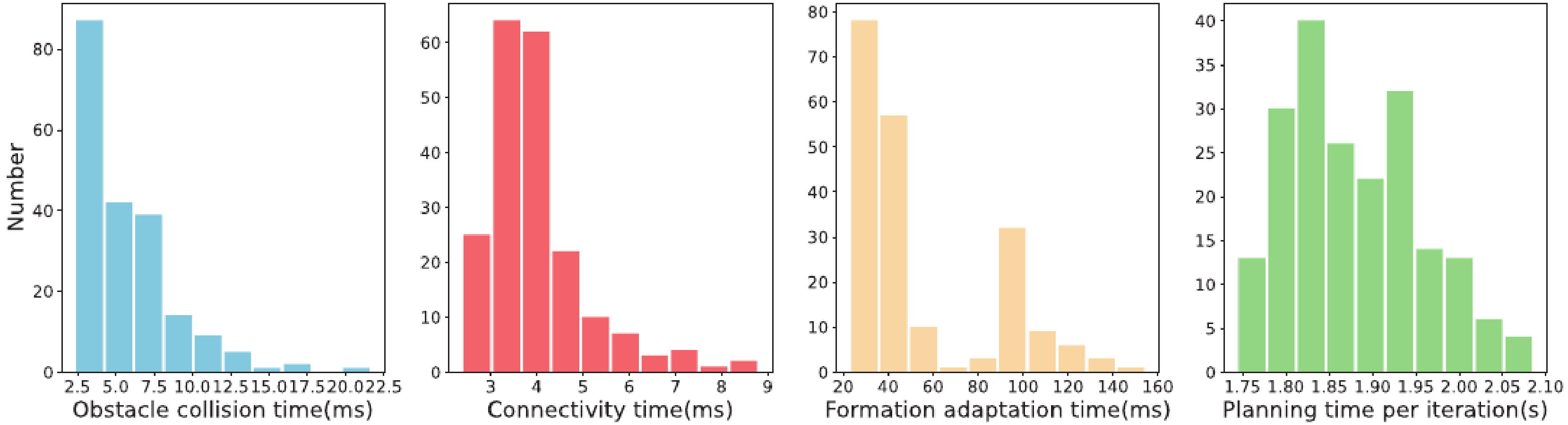
By adopting the proposed method, if the agents are initially connected and collision-free, then they can maintain connectivity and be collision-free thereafter.

Results

Simulation 1:



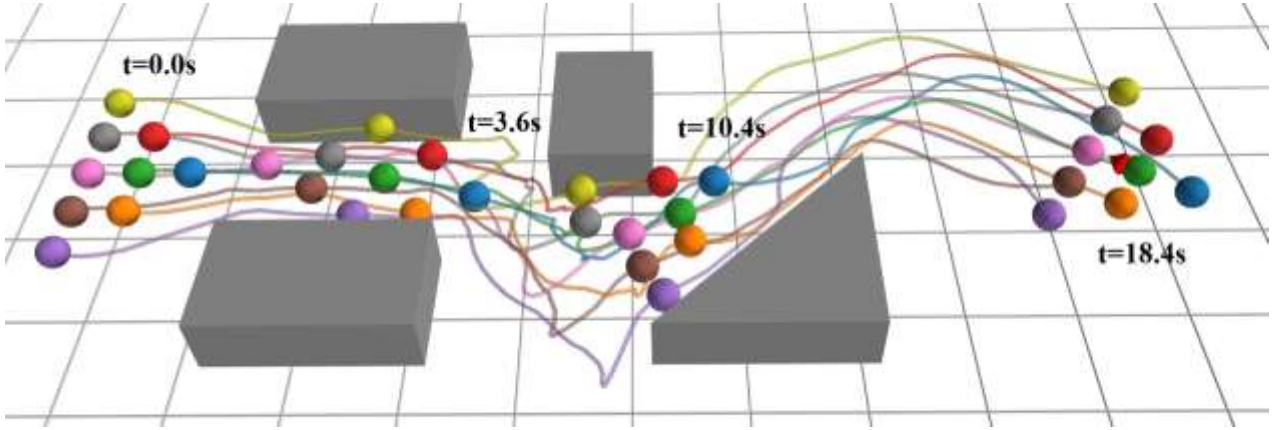
The trajectories of the underlying agents.



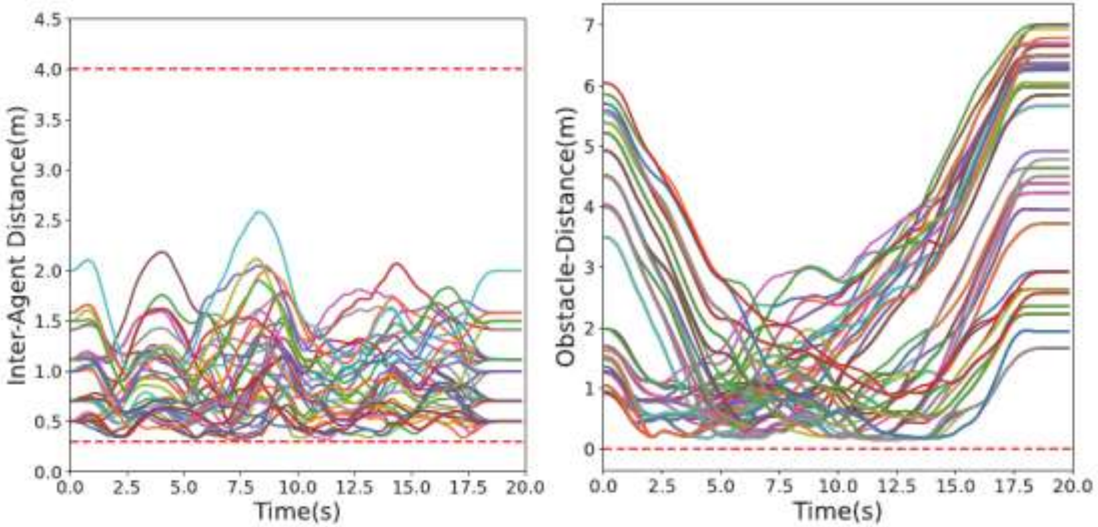
From left to right is the times of runtime w.r.t. different parts in a replanning.

Results

Simulation 2:



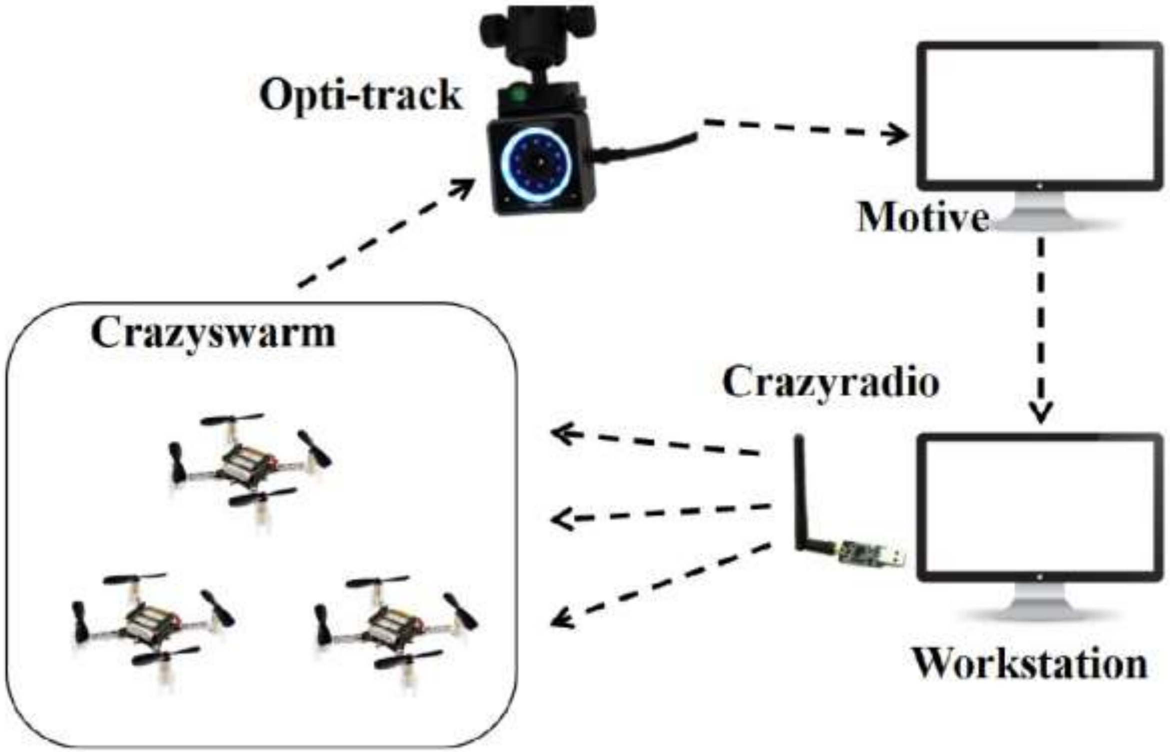
The trajectories of the underlying agents.



Left: the distance between each pair of agents. Right: the distance between LOS of each pair of agents and obstacles.

Results

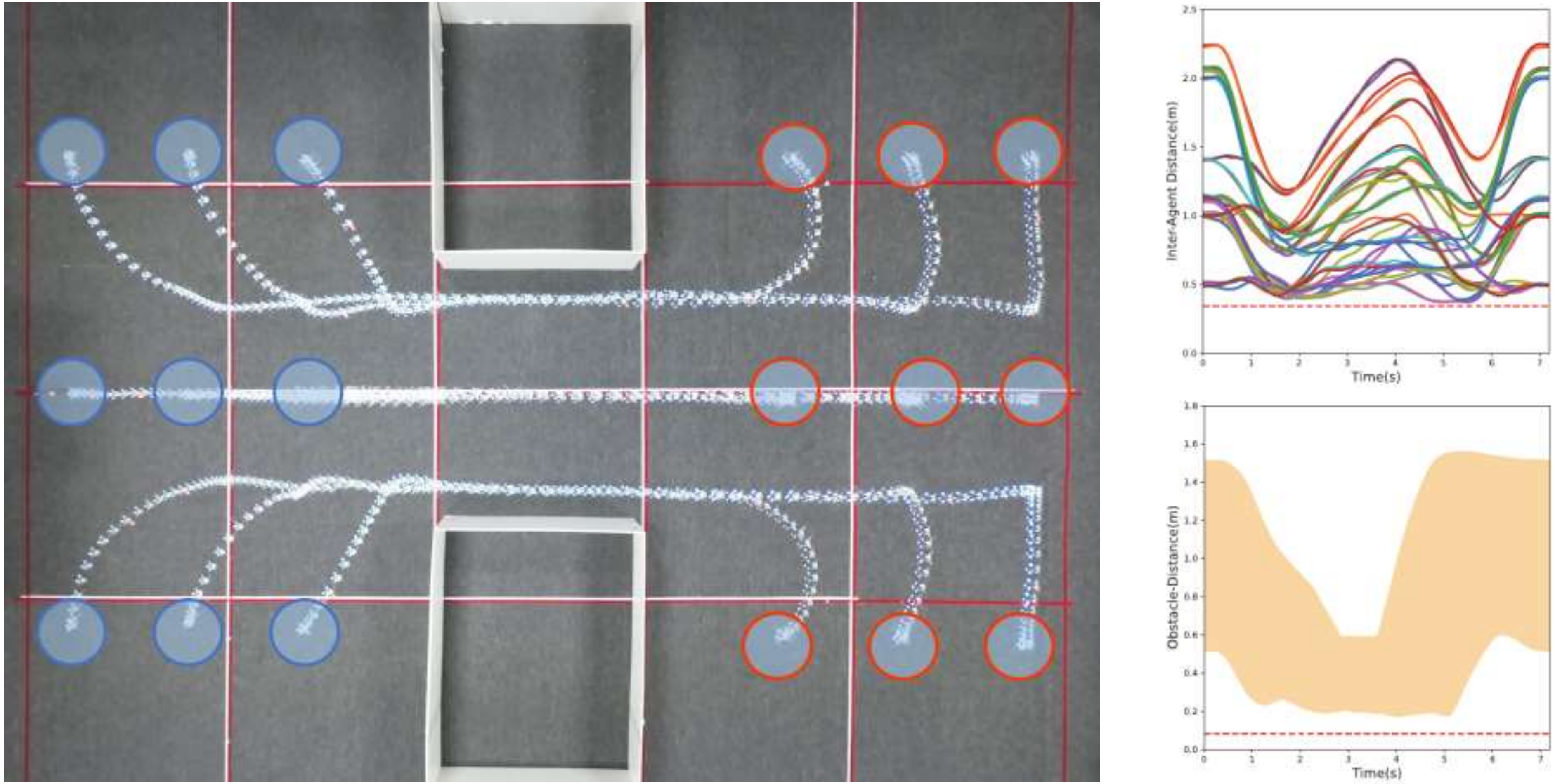
Experiment platform:



Left: The architecture of the hardware platform. Right: The testing ground.

Results

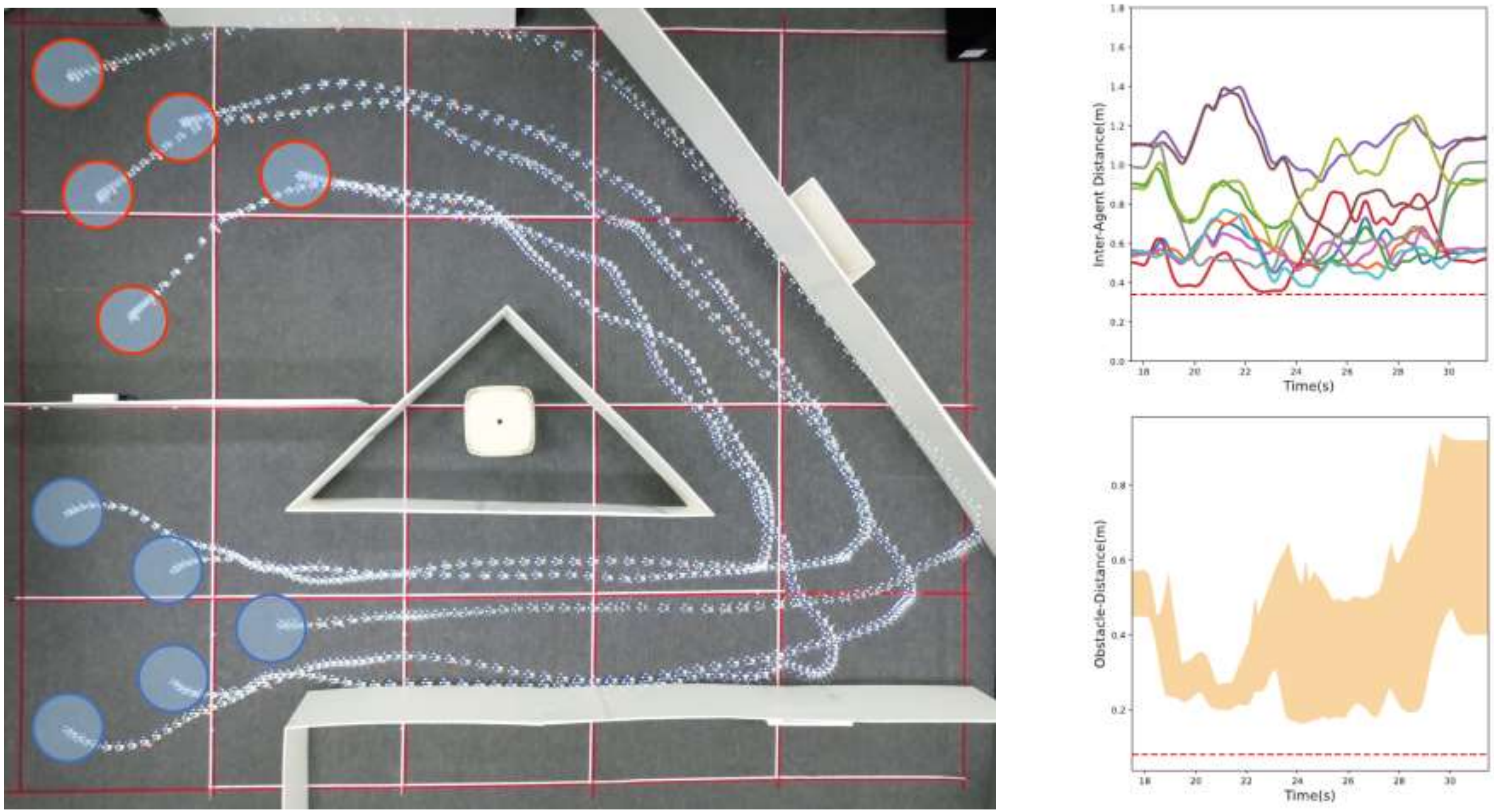
Experiment 1:



Left: The trajectories of agents. Right: The inter-agent and LOS-obstacles distance.

Results

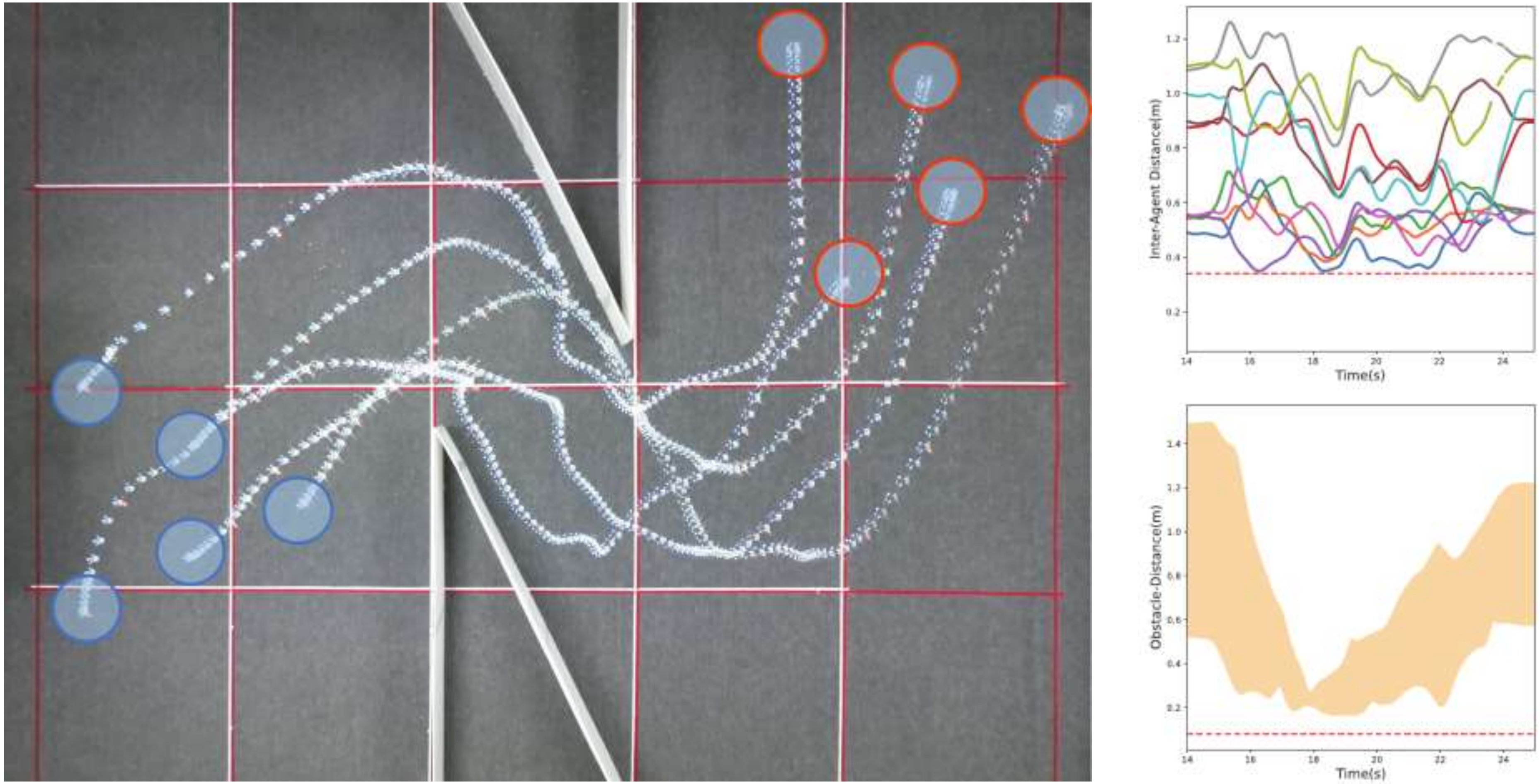
Experiment 2:



Left: The trajectories of agents. Right: The inter-agent and LOS-obstacles distance.

Results

Experiment 3:



Left: The trajectories of agents. Right: The inter-agent and LOS-obstacles distance.

Conclusions

- A formation adaptation method based on MPC-based trajectory planning, under which a swarms of agents can flexibly adjust the formation structure online to pass through narrow corridors and avoid obstacles

- Simulations and experiments are conducted to show the effectiveness and performance of the proposed scheme.

- Compared to previous related works, the advantages of the results in this paper are that the inter-agent connectivity can be maintained and the feasibility of the underlying optimizations is guaranteed in a recursive way.

Thank you!