RITSUMEIKAN UNIVERSITY

Intelligent Robotic Systems Laboratory

「Non-circular Control Barrier Function Technique for Mobile Robots Collision Avoidance in Complex Environments」

立命館大学 ISSE
JIA Shucheng-26002104600

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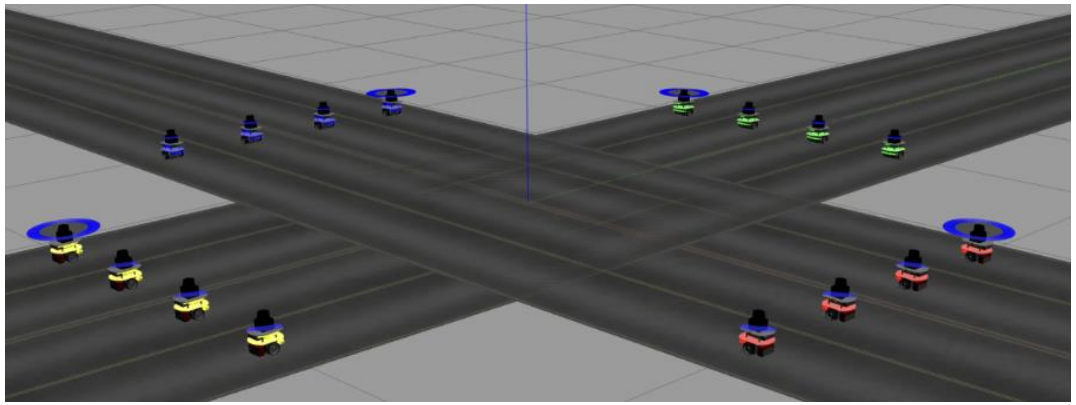
Agenda

- Background
- Related work
- Problem formulation
- Research goal
- Algorithm
- Experiment
- Summary

Background

The development of automation and robotics

- Autonomous vehicles
- Robotic delivery



Key challenges:

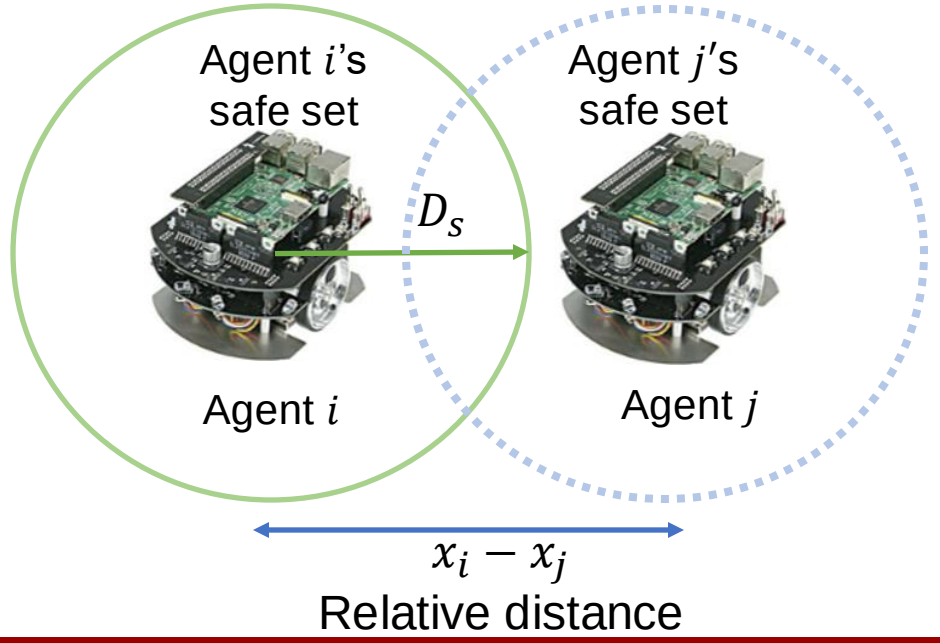
- Navigate through crowded environments
- Obstacle avoidance

Related work

Control barrier functions (CBF): Theory and applications(Ames, A. D,2019)

- Mathematical tools ensure system safety
- Ensure agents maintain safety distances
- A ‘safe set’ represents constraints
- $C_{ij} = \{x_i \in \mathbb{R}^2 \mid h_{ij}(x) = ||x_i - x_j||^2 - D_S^2 \geq 0\}$

D_s -Minimum safety distance between agents
C_{ij}- safe set of states for agents i and j
x_i , x_j- Position of agent i and agent j in 2D space
h_{ij}- Control Barrier Function (CBF)



Related work

Hierarchical consensus-based multi-agent reinforcement learning for multi-robot cooperation tasks (Feng, P, 2019)

- CBF's multi-agent reinforcement learning framework
- Safety and cooperation in robotic systems
- Excessive space usage

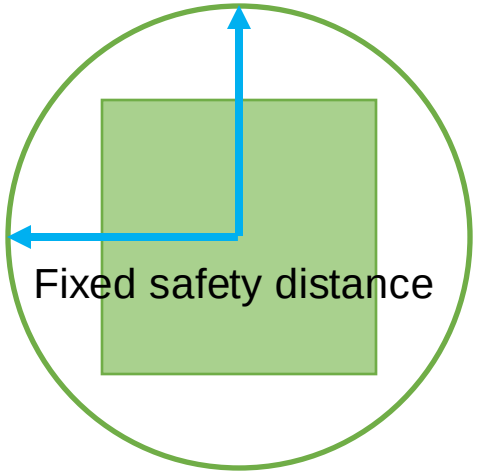
Extent-compatible Control Barrier Functions (Mohit Srinivasan, 2020)

- Physical volume incorporated into safety modeling
- Improved performance in complex environments
- Unable to adapt to irregular shapes

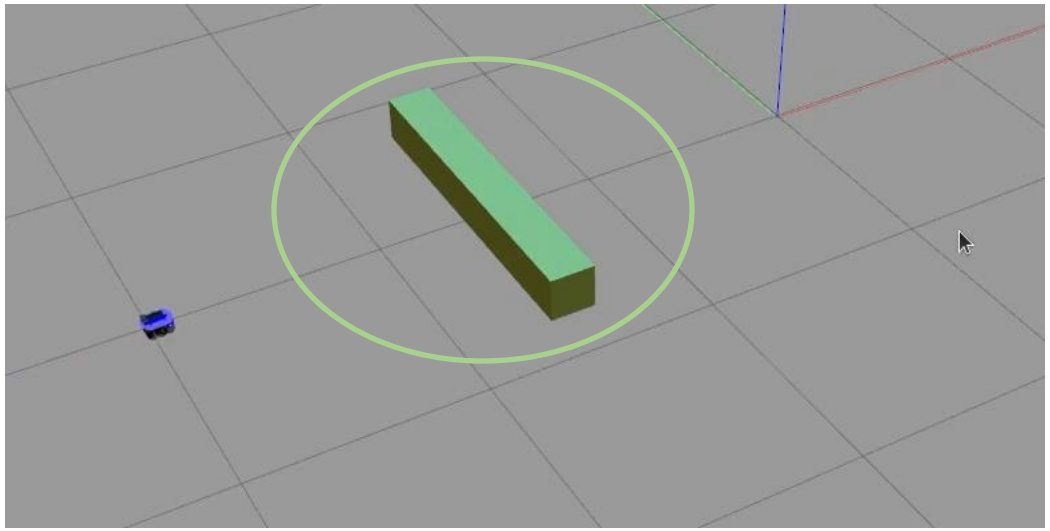
Problem statement

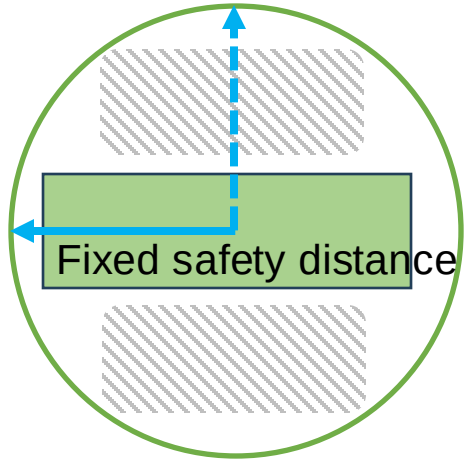
Limitations in control barrier function

- Fixed safety distance and safe set
- Excessive space usage
- Limited applications in high-precision requirements scenarios



Equal sides object





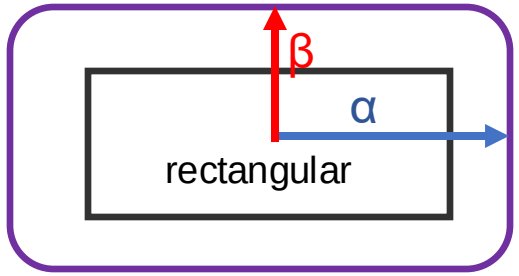
Unequal sides object

Research Goal

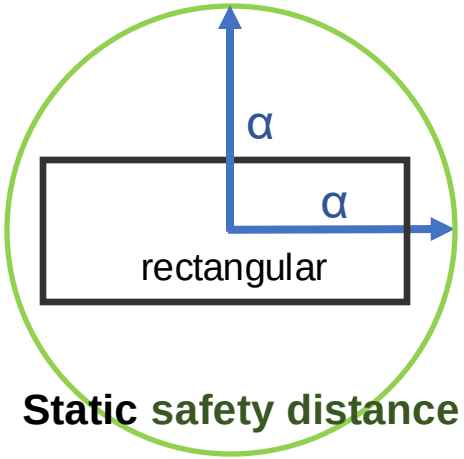
1. Improving barrier function for complex scenarios
   - Flexible safety distance for irregularly shaped
   - Optimize collision avoidance space for efficient execution
   - Achieve greater adaptability for different situations
2. Evaluate method efficacy across scenarios
   - Test the new collision avoidance technique in complex environments

Super-Ellipse CBF(SE-CBF)

1. Apply Super-Ellipse curve
   - Flexible Mathematical curve
2. Dynamic distance calculation
   - Direction-Dependent safety distance
3. Adaptive various boundary
   - Optimize collision avoidance space

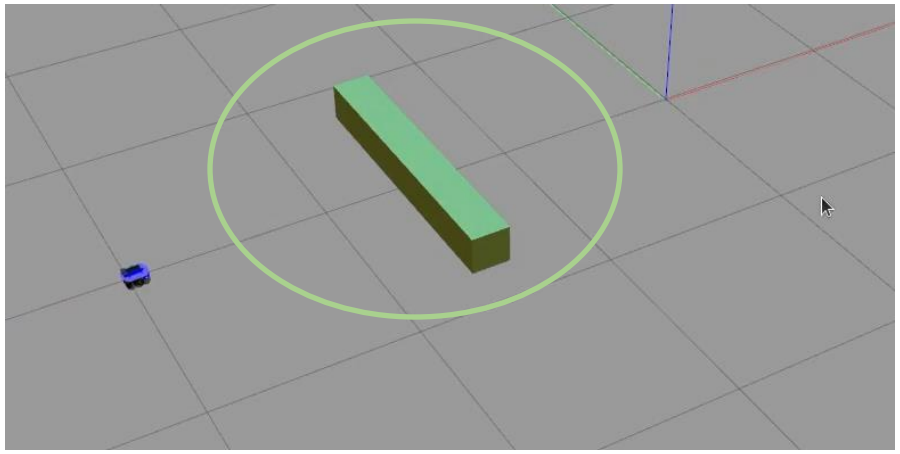


Dynamic safety distance

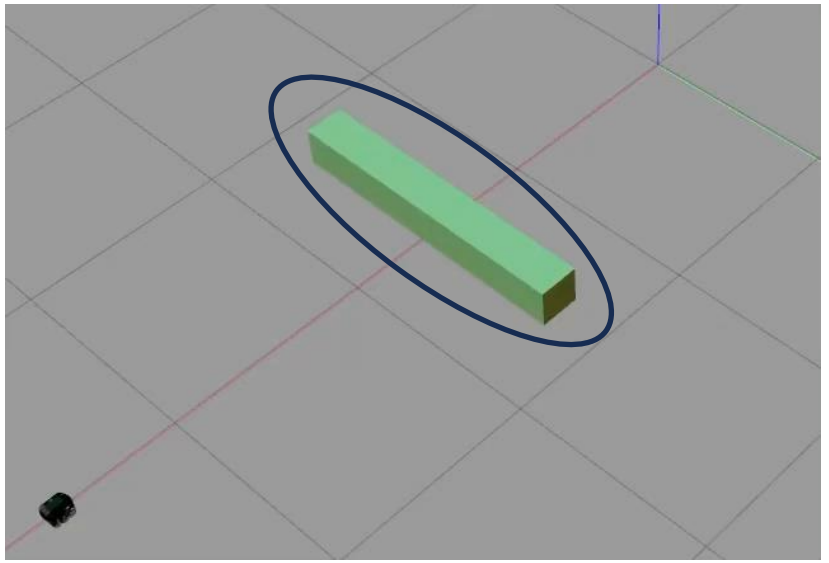


Static safety distance

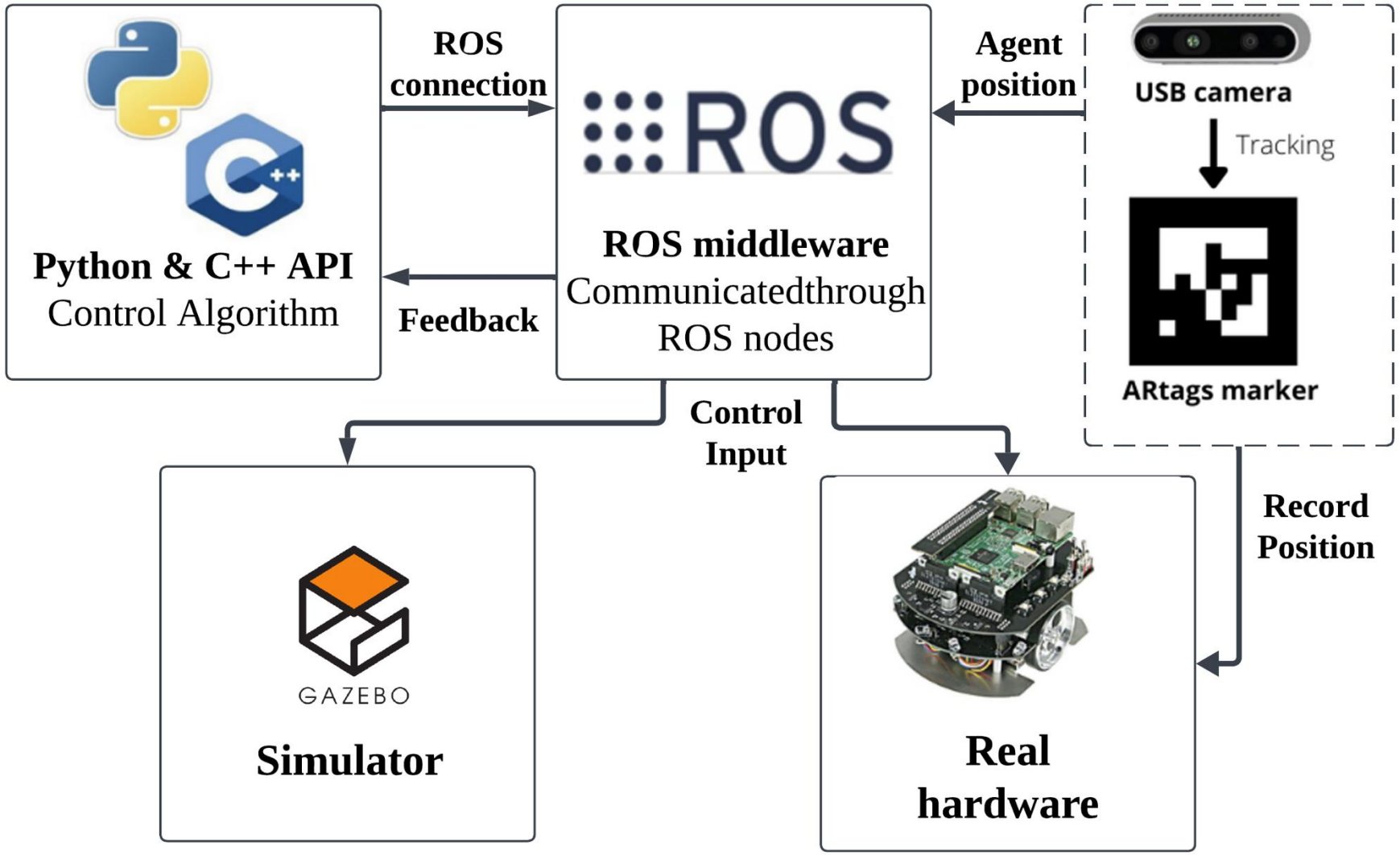
Static safety distance



Dynamic safety distance

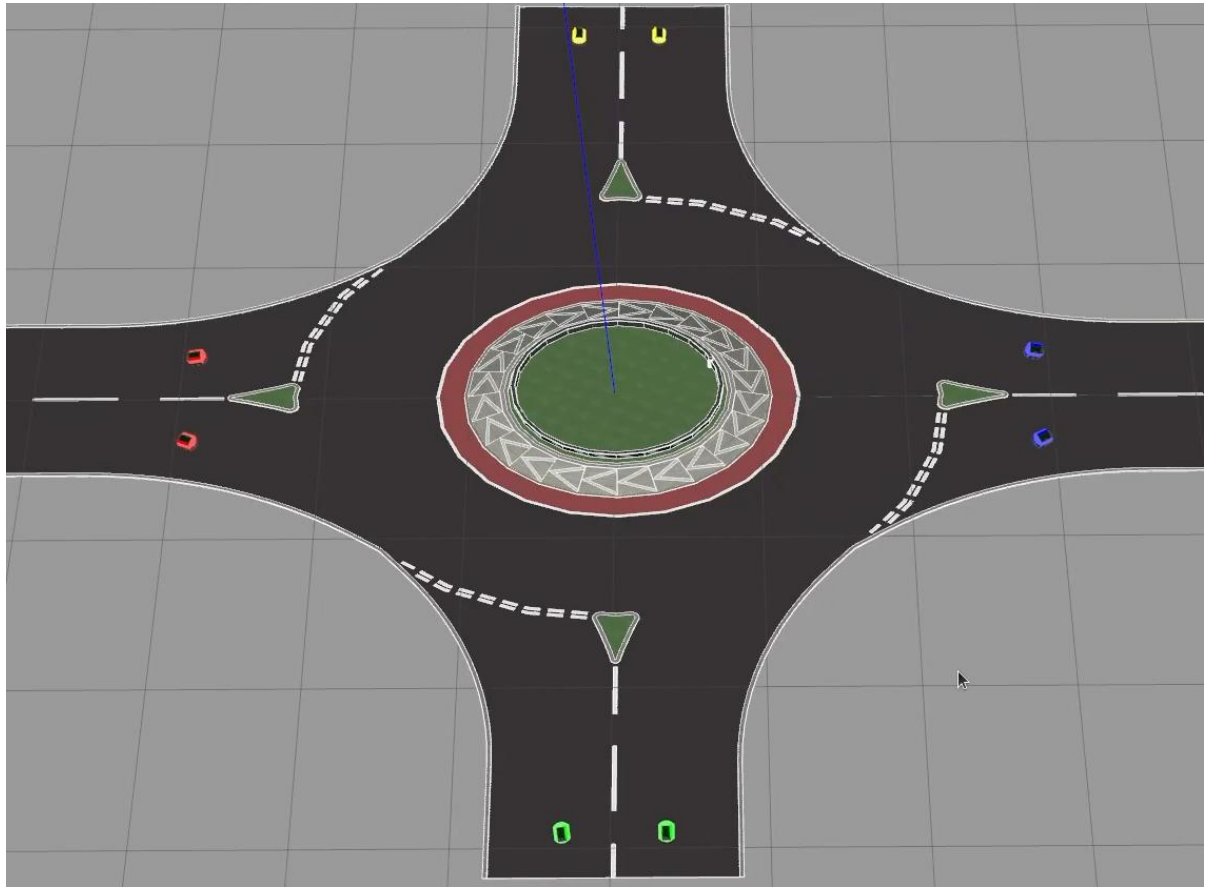


System Architecture



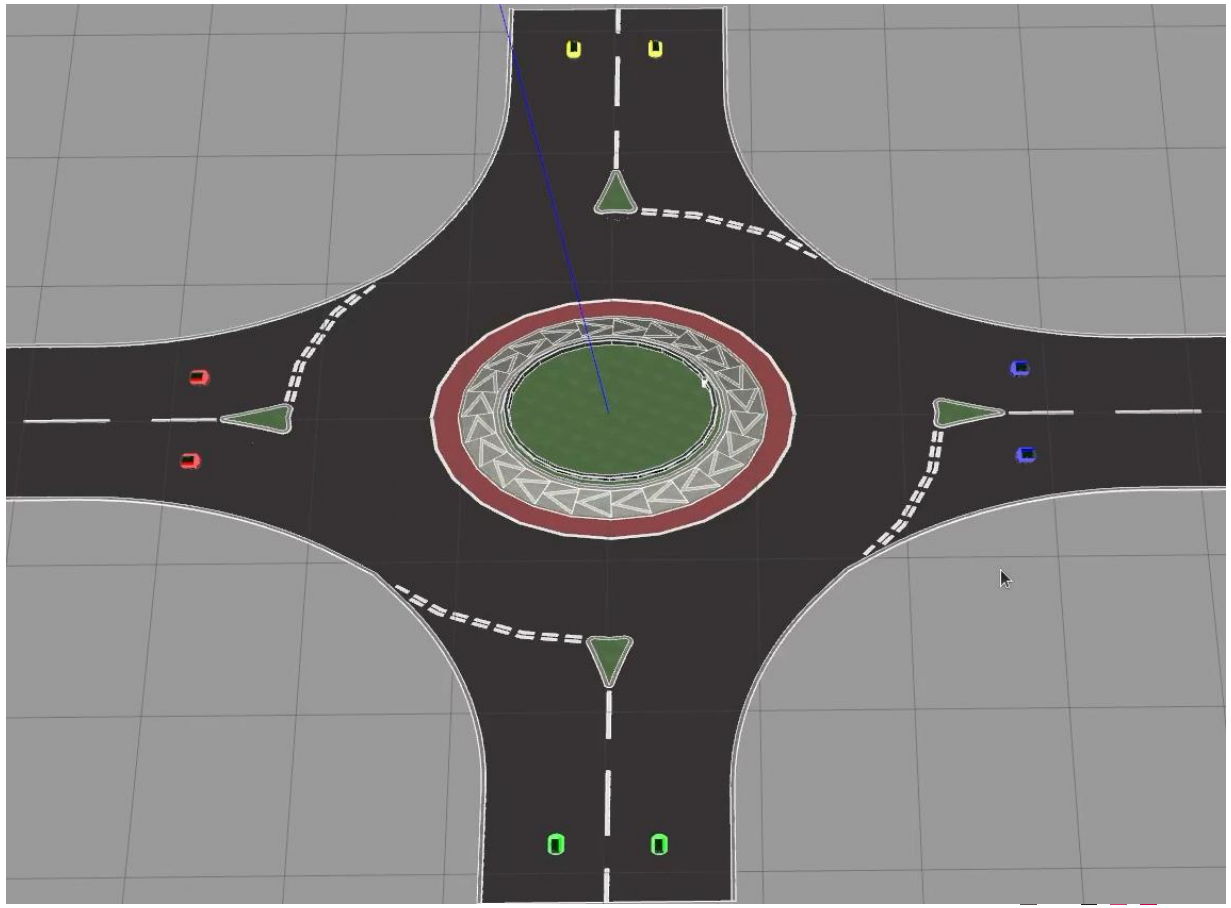
Intersection Simulation

Dynamic safety distance



Super-Ellipse Control Barrier Function (SE-CBF)

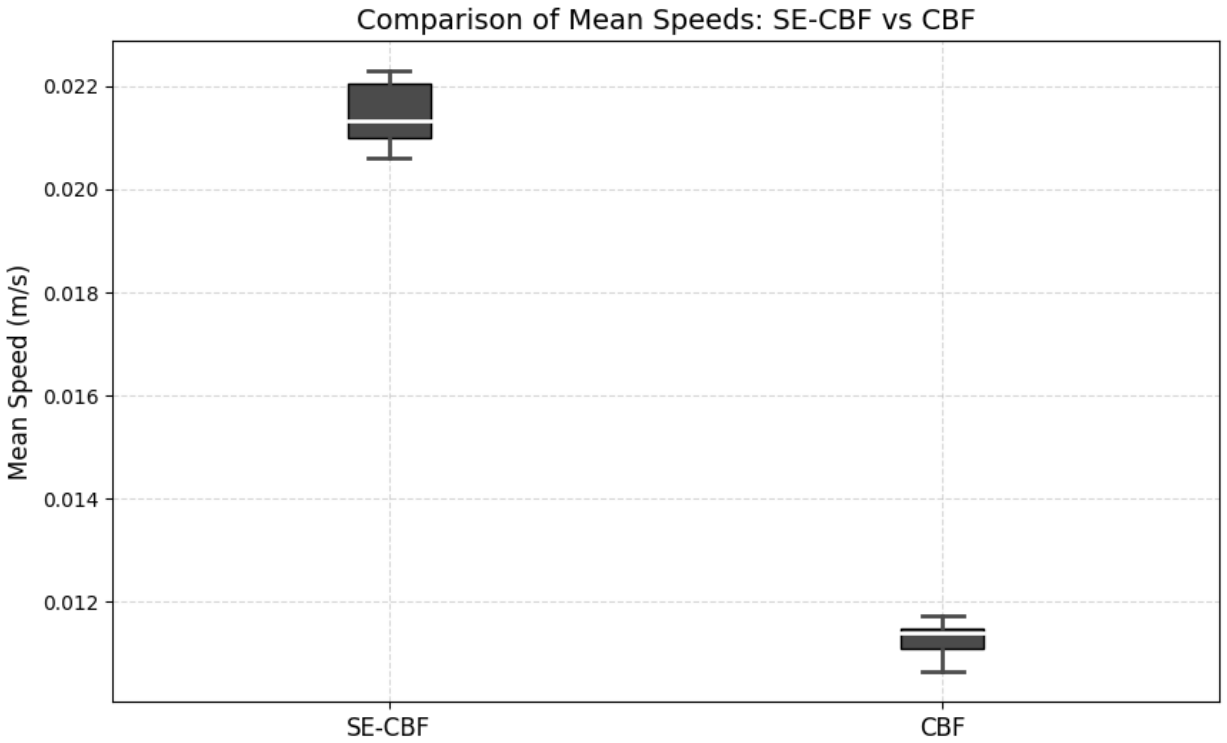
Static safety distance



Control Barrier Function (CBF)

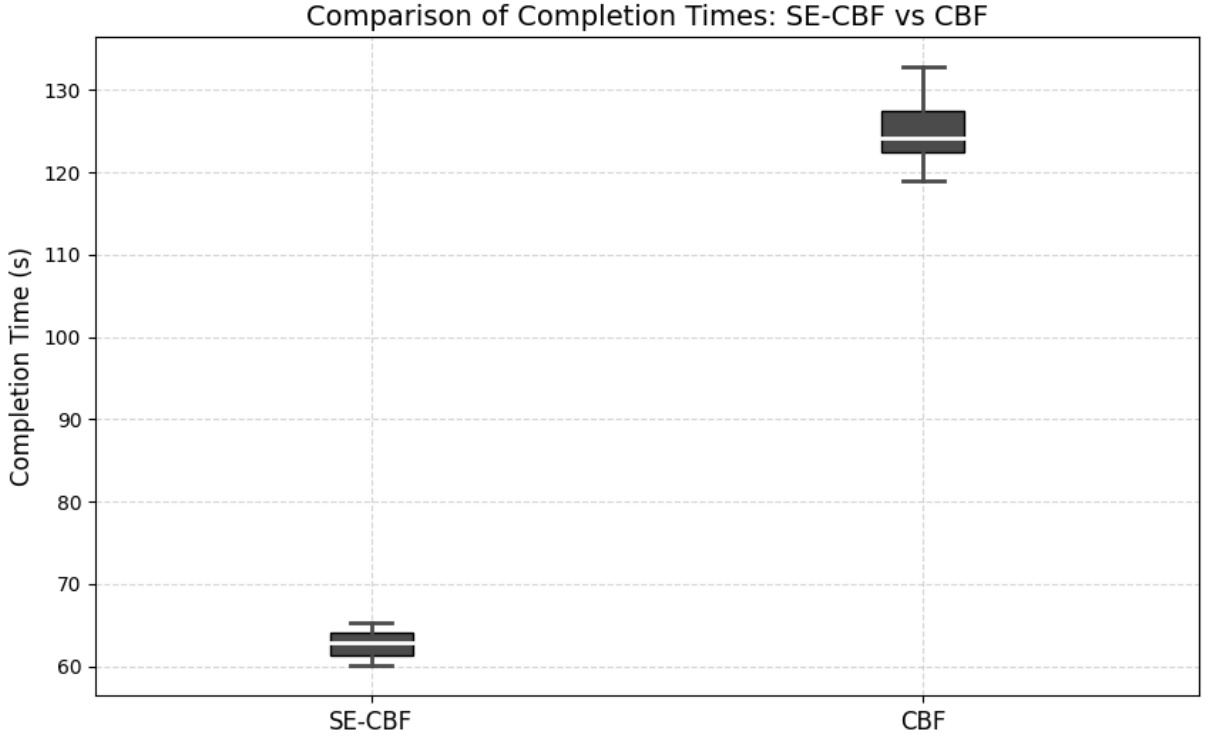
Simulation Results and Analysis

Mean Speed Boxplot



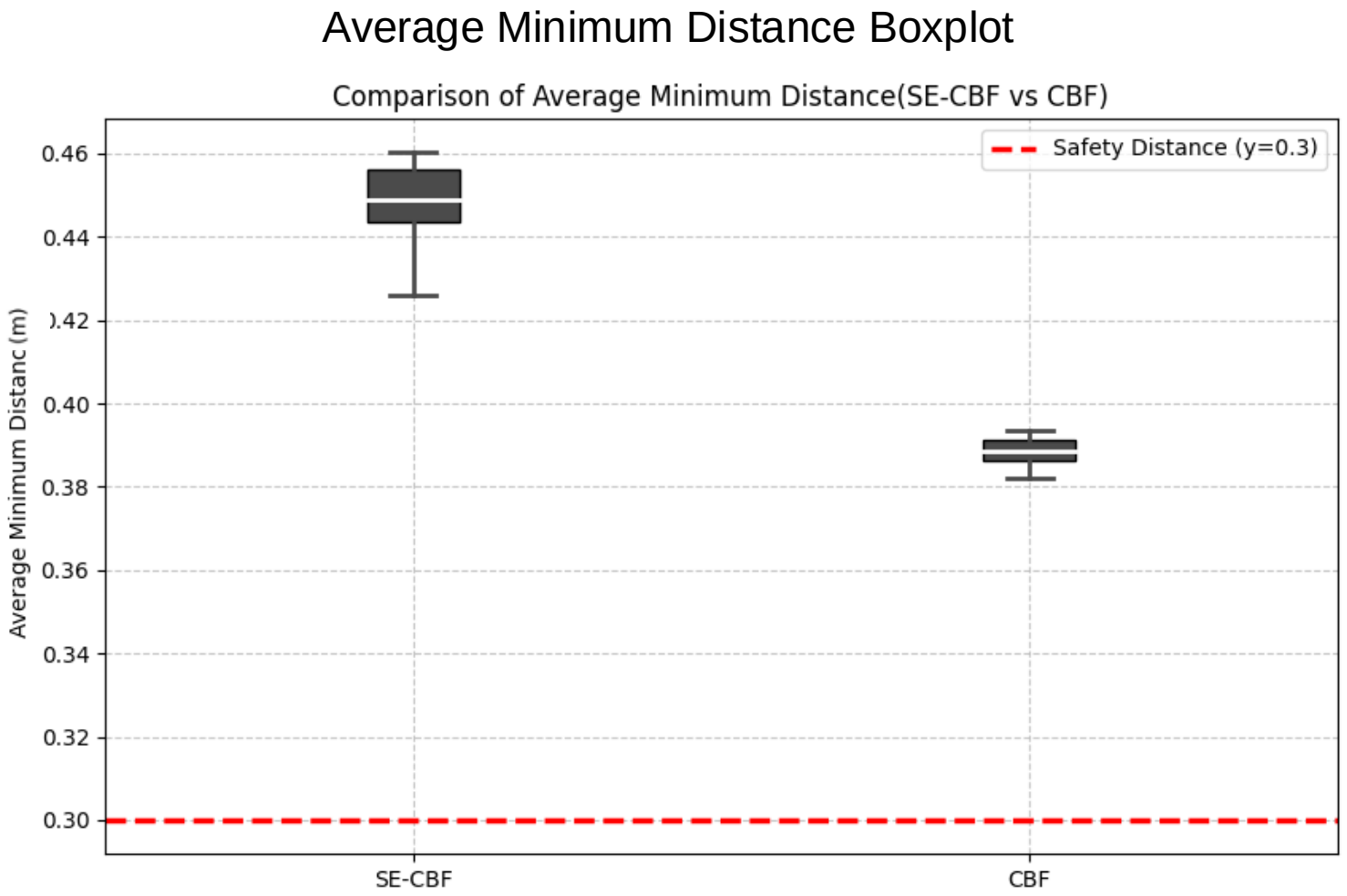
- SE-CBF robot operates at approximately twice the speed of the CBF robot
- SE-CBF significantly enhances operating speed

Completion Time Boxplot



- SE-CBF completes tasks in approximately half the time compared to the CBF robot
- SE-CBF method improves task efficiency

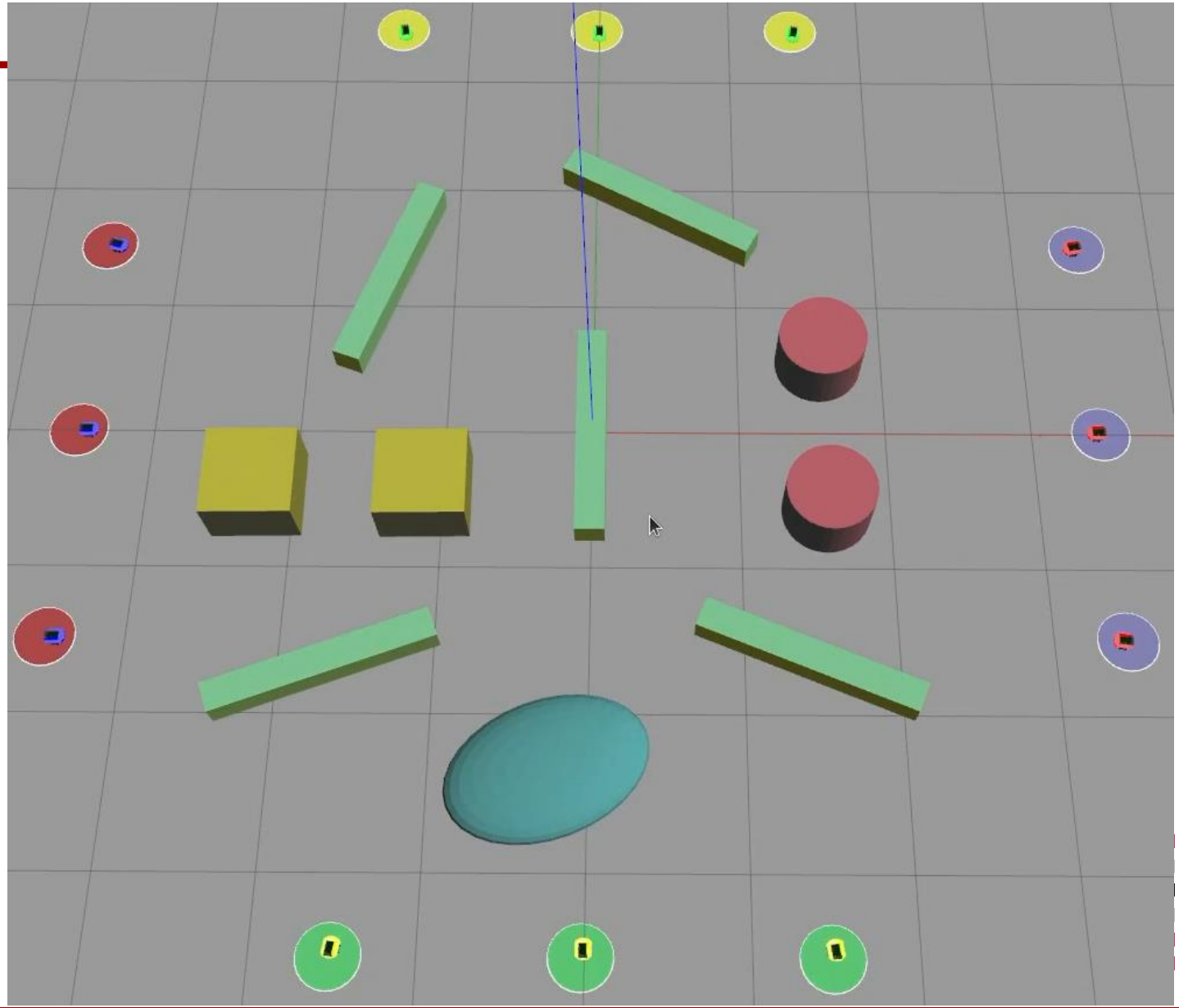
Simulation Results and Analysis



- The SE-CBF method maintains a higher average minimum distance (0.45 m) compared to the CBF method (0.35 m)
- SE-CBF consistently provides a larger safety margin
- SE-CBF method enhanced adaptability and reliability in maintaining safe trajectories

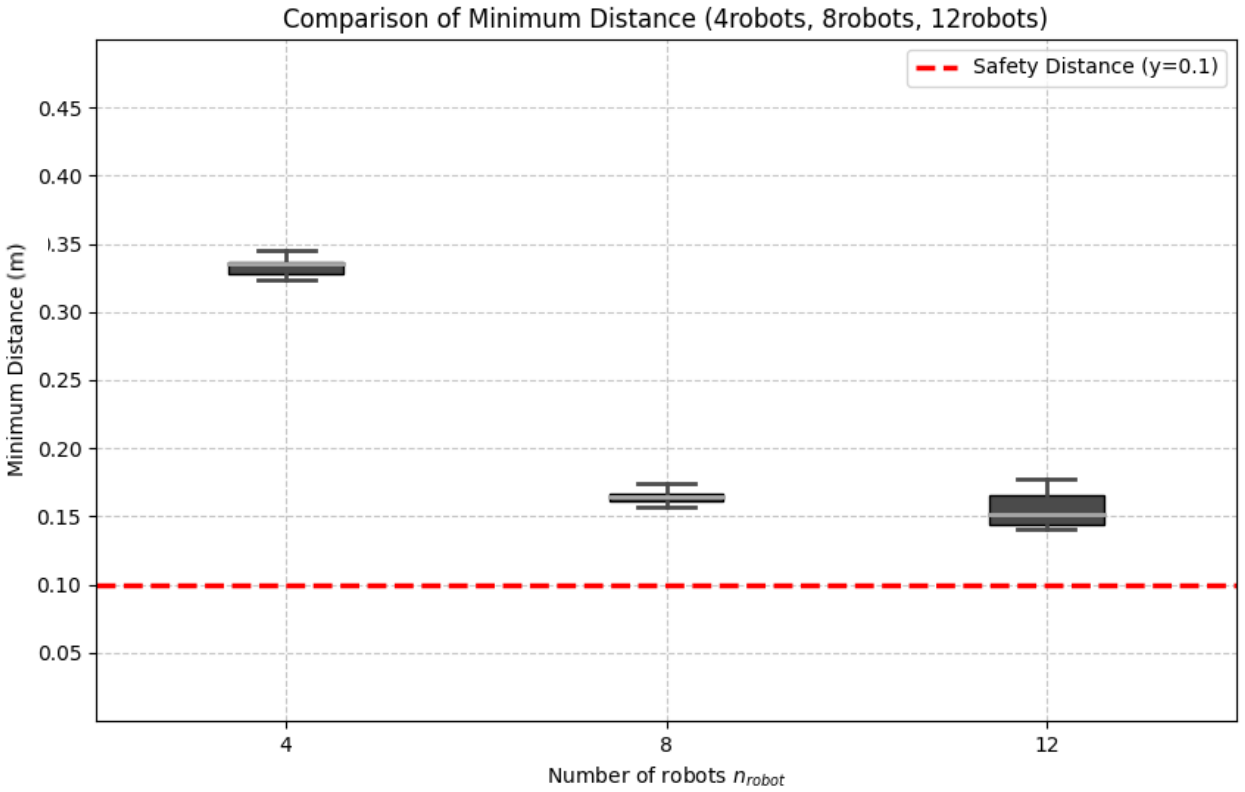
Unknown area exploration

- Obstacles are randomly placed in the central area
- Test the performance of path-planning and collision avoidance



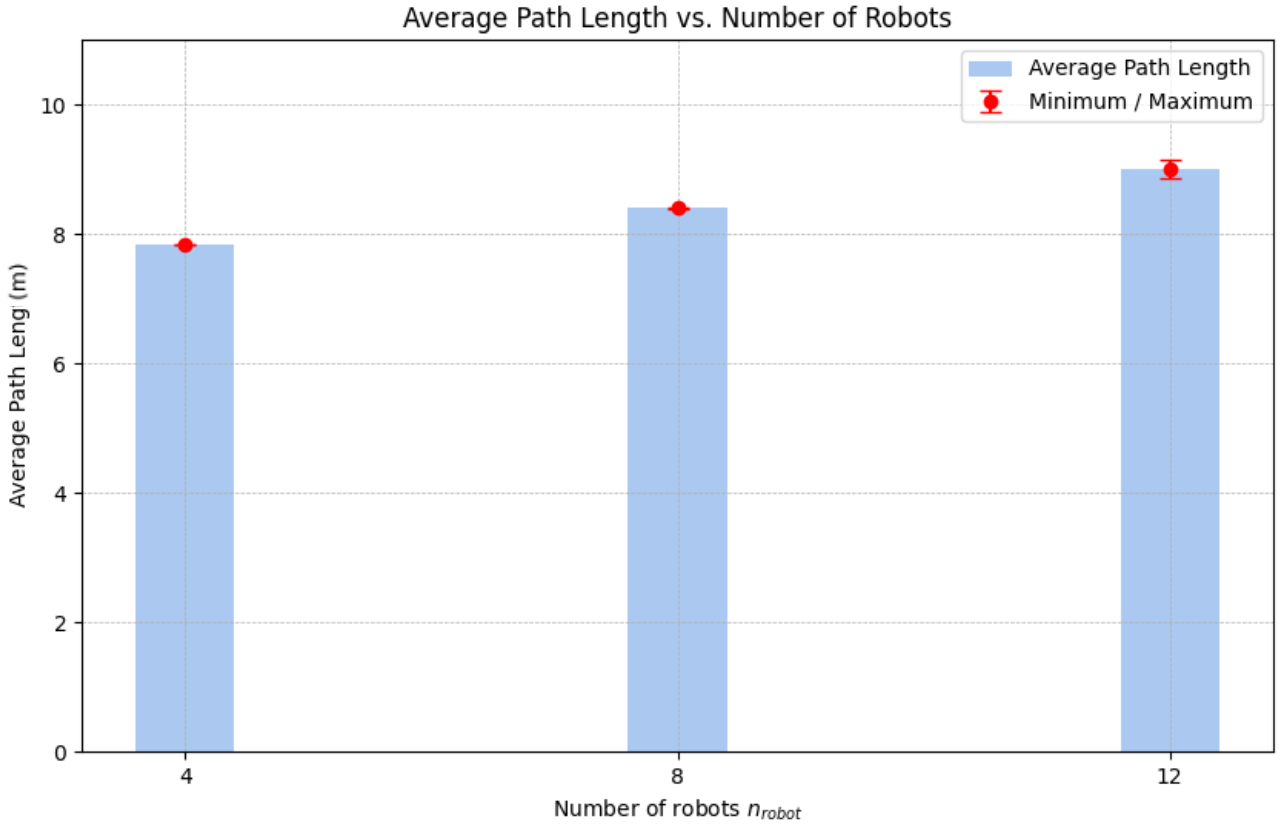
Simulation Results and Analysis

Minimum distance



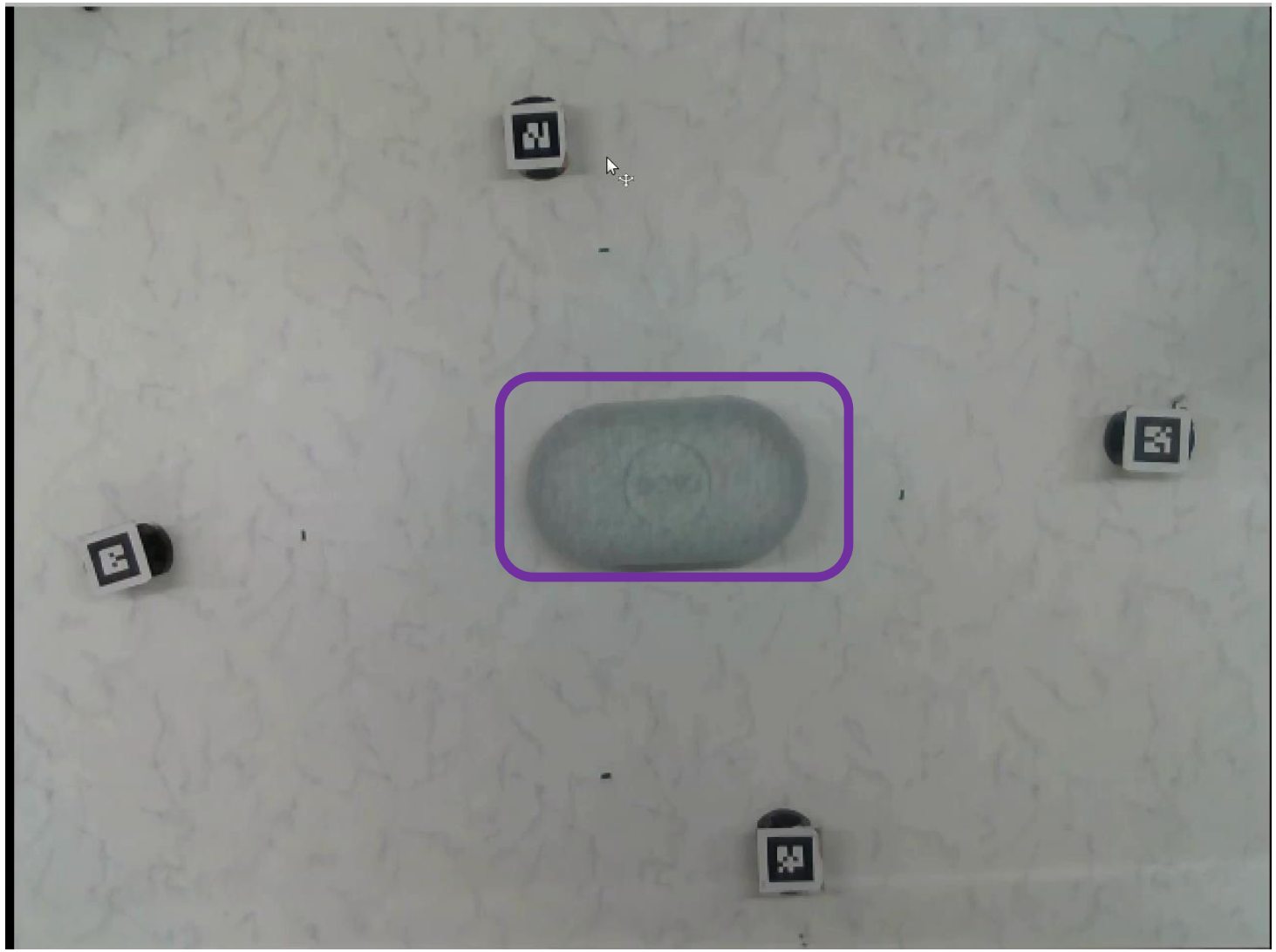
- SE-CBF demonstrates excellent adaptability while maintaining distances above the safety threshold.

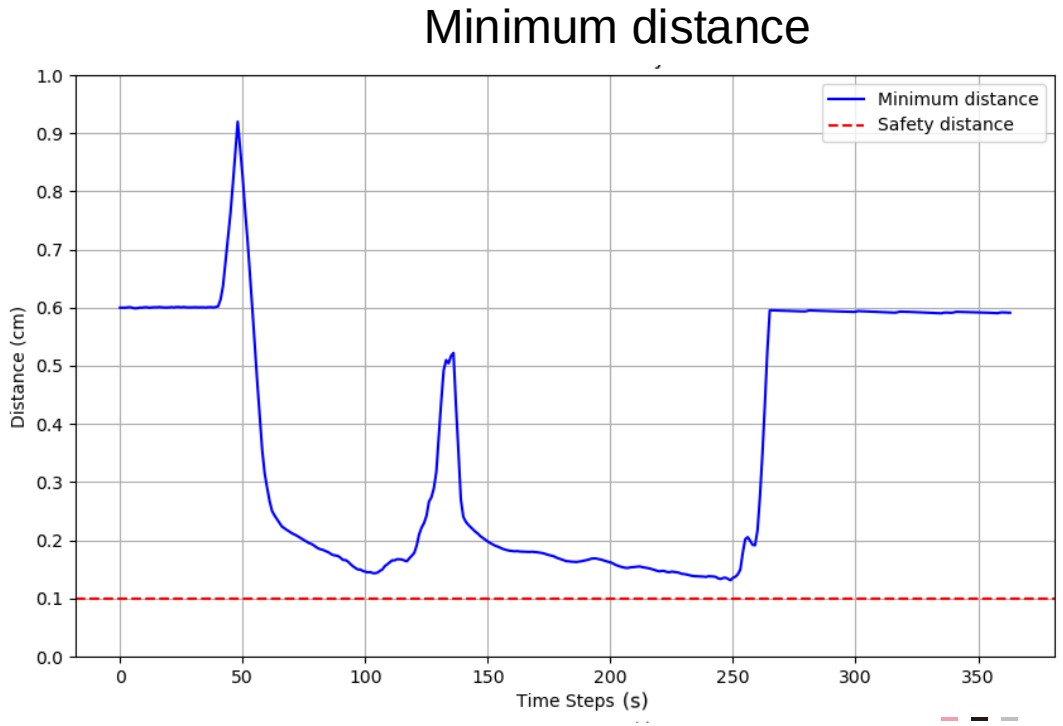
Average Path Length



- SE-CBF maintains a consistent average path length and demonstrates higher adaptability and efficient path planning

Real-world Experiment





Summary

- Introduced Super-Ellipse CBF collision avoidance technique
- Developed a dynamic safety distance framework
- Improved collision avoidance efficiency and system performance
- Enhanced the system applicability in various scenarios

Reference

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Reference:

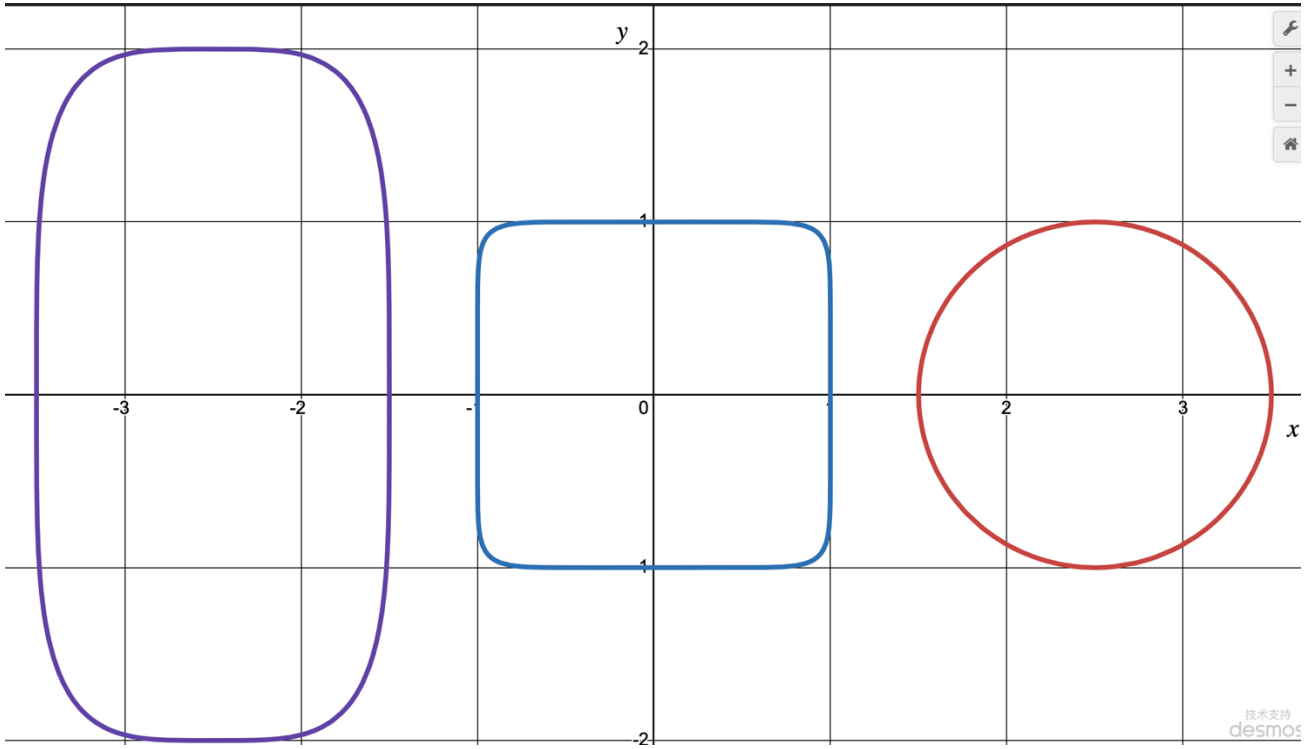
1. Ames, A. D., Coogan, S., Egerstedt, M., Notomista, G., Sreenath, K., & Tabuada, P. (2019). Control barrier functions: Theory and applications. arXiv. https://arxiv.org/abs/1903.11199
2. Feng, P., Liang, J., Wang, S., Yu, X., Ji, X., Chen, Y., Zhang, K., Shi, R., & Wu, W. (2024). Hierarchical consensus-based multi-agent reinforcement learning for multi-robot cooperation tasks. arXiv. https://arxiv.org/abs/2407.08164
3. Srinivasan, M., Abate, M., Nilsson, G., & Coogan, S. (2021). Extent-compatible control barrier functions. *Systems & Control Letters, 150*, 104895. https://doi.org/10.1016/j.sysconle.2021.104895

Algorithm

Super-ellipse :

- Mathematical curve
- Flexible in shape circle, oval, rectangular, square
- Respond to varying circumstances

$$\left(\frac{x}{\alpha}\right)^n + \left(\frac{y}{\beta}\right)^n = 1$$



$n = 4$
$\alpha = 1$
$\beta = 2$

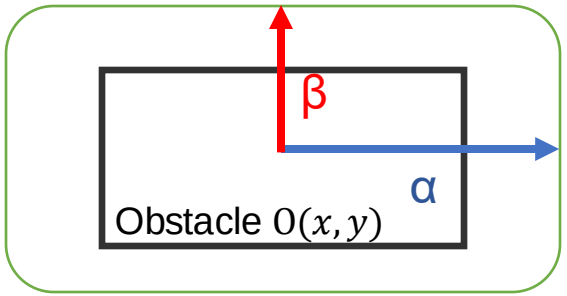
$n = 10$
$\alpha = 1$
$\beta = 1$

$n = 2$
$\alpha = 1$
$\beta = 1$

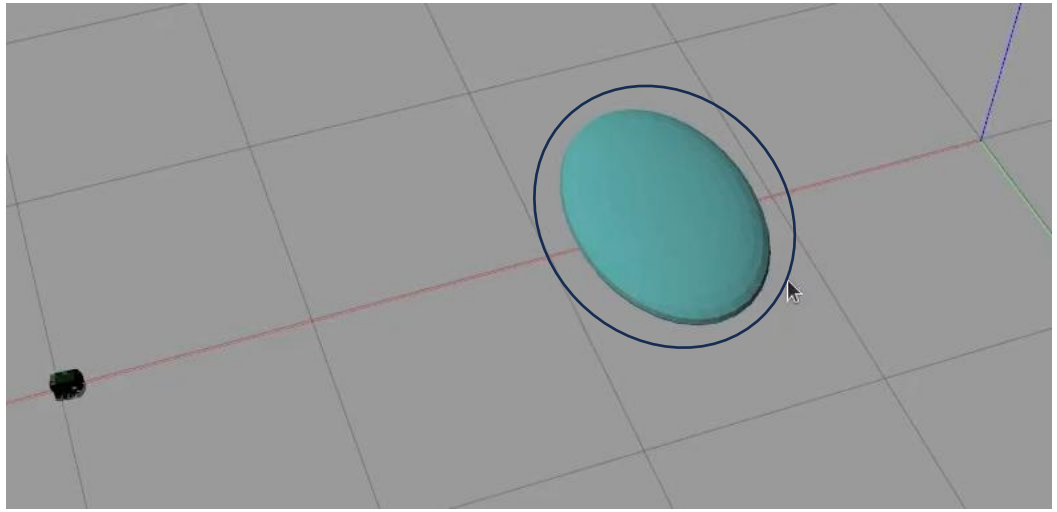
Appendix Super-Ellipse CBF:

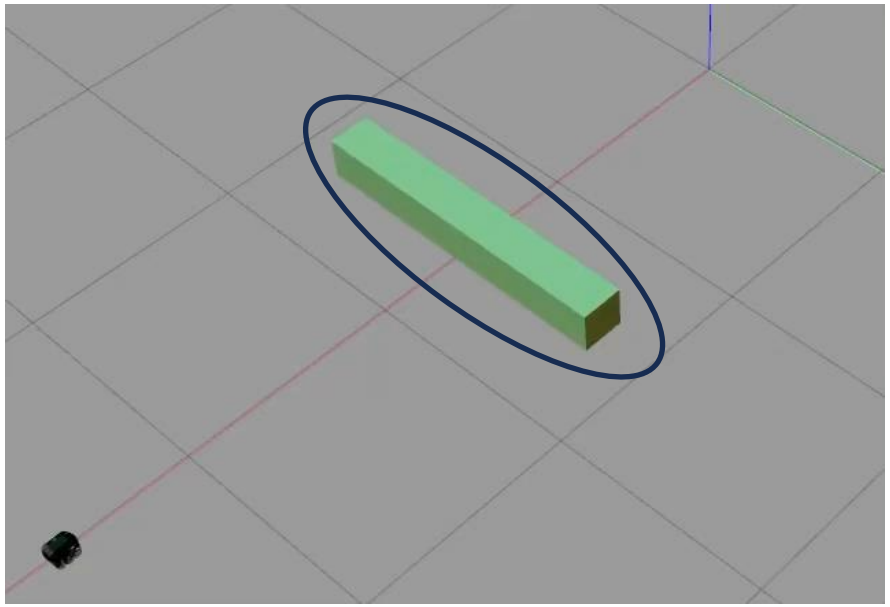
$$\left(\frac{\mathrm{P}_x - \mathrm{O}_x}{\alpha}\right)^n + \left(\frac{\mathrm{P}_y - \mathrm{O}_y}{\beta}\right)^n = 1$$

P_x and P_y: The position of robots
$\mathrm{O}_x$and O_y: The position of obstacle
α and β: Scaling factors in the x and y directions



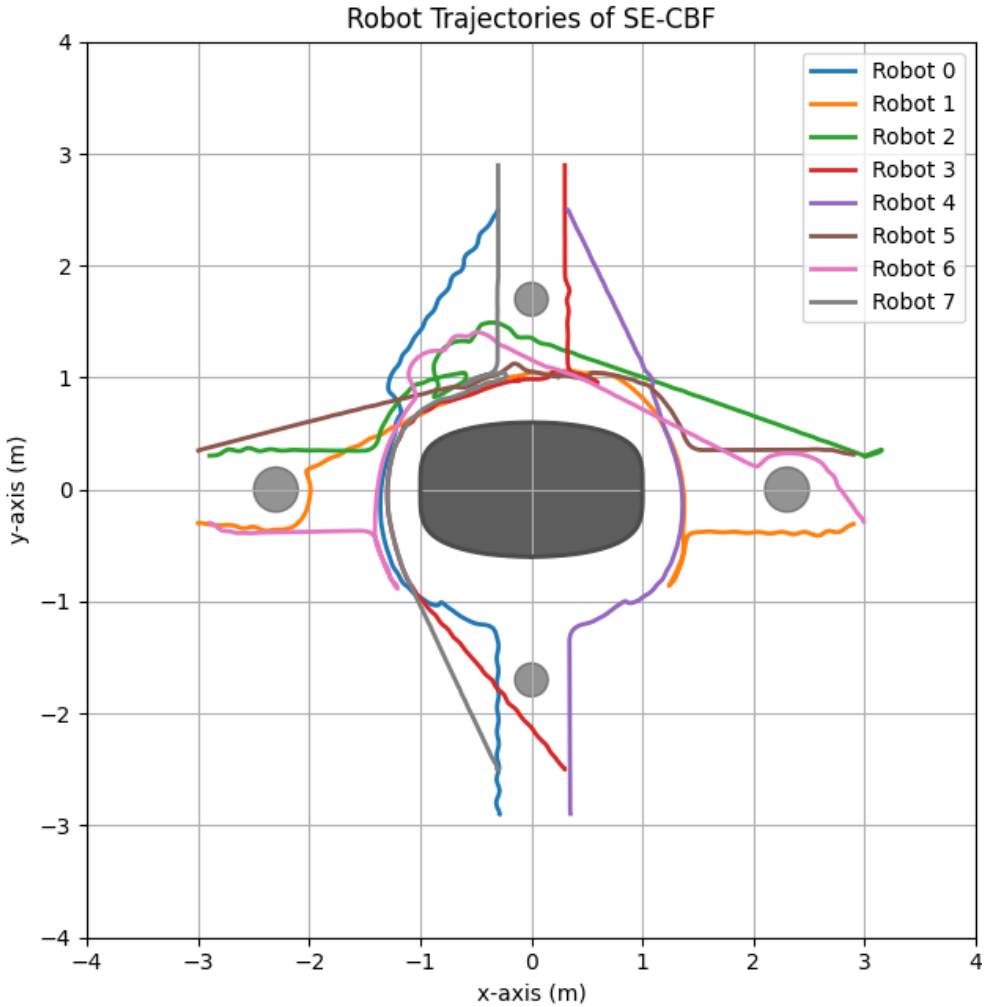
Agent
$\mathrm{P}(x, y)$



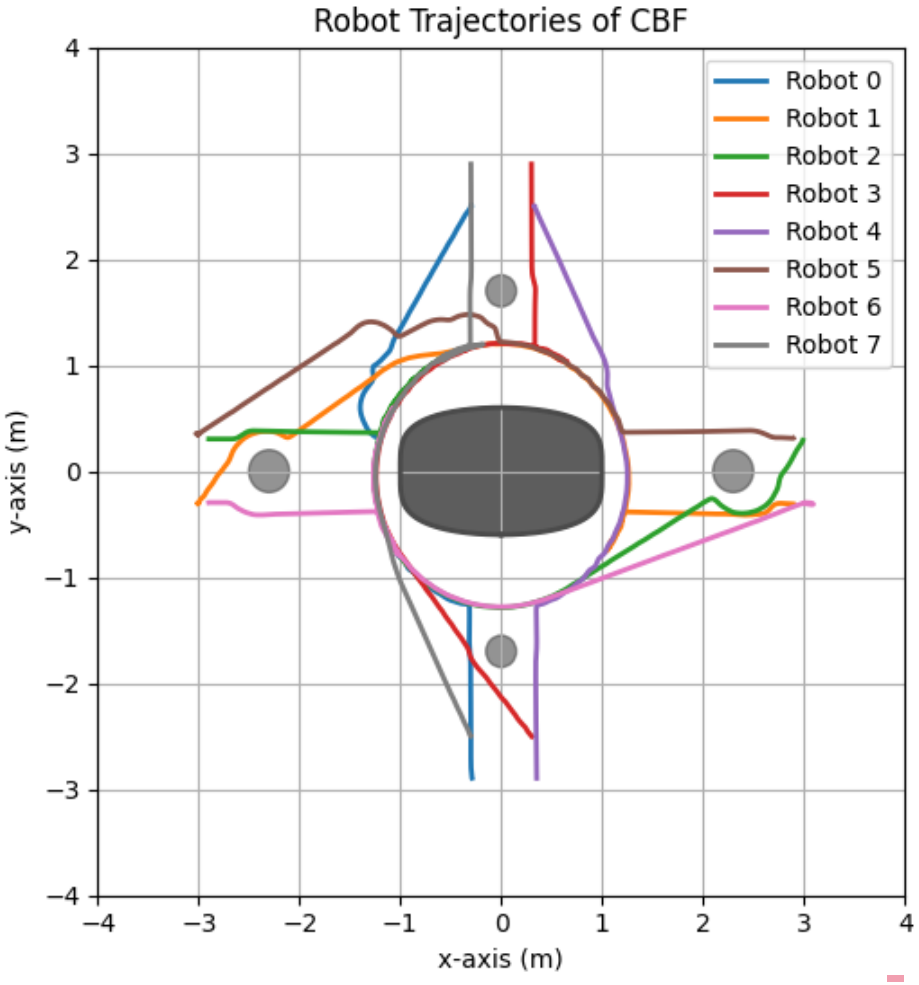


Simulation of Intersection

Path diagram of SE-CBF

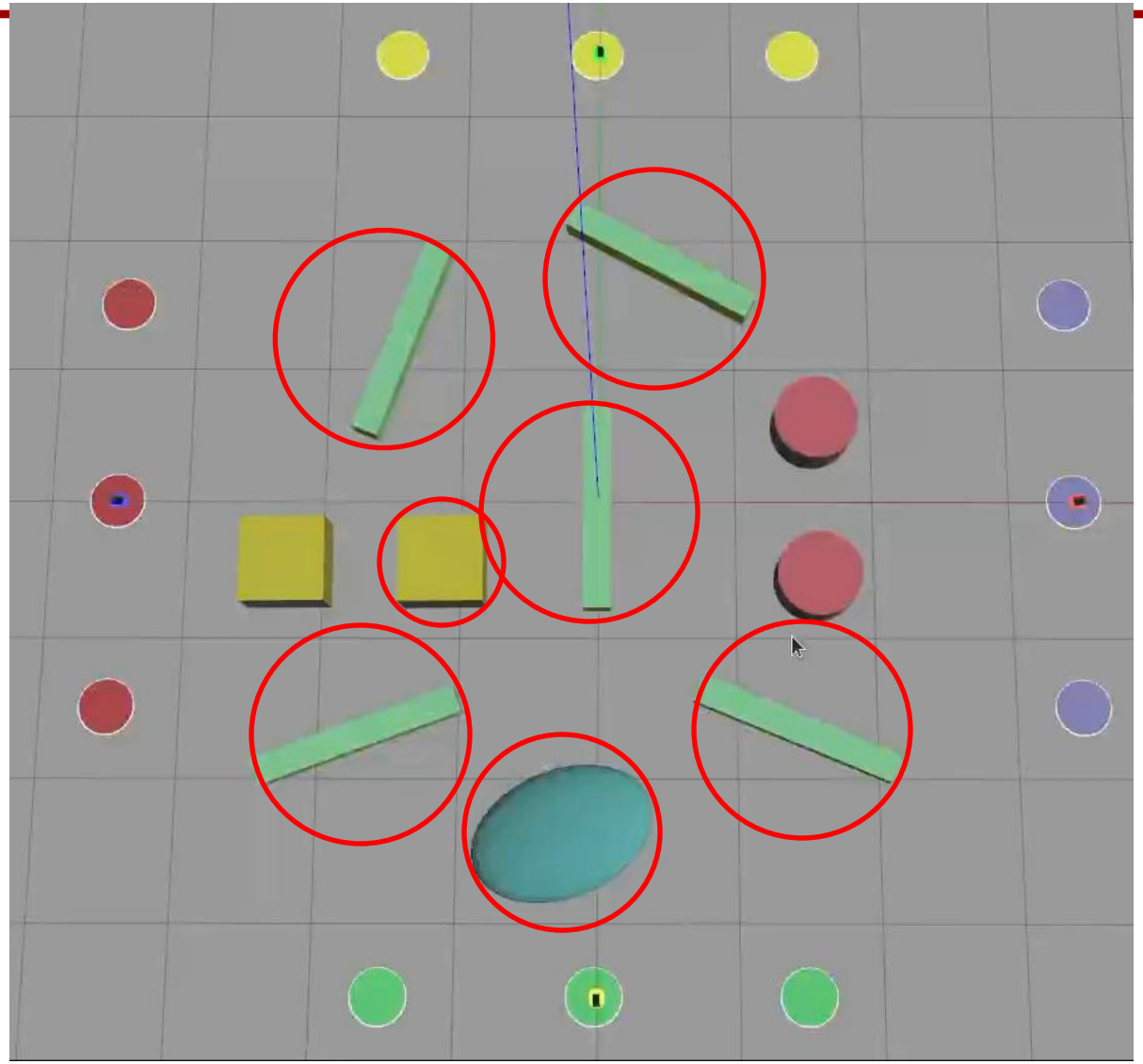


Path diagram of CBF



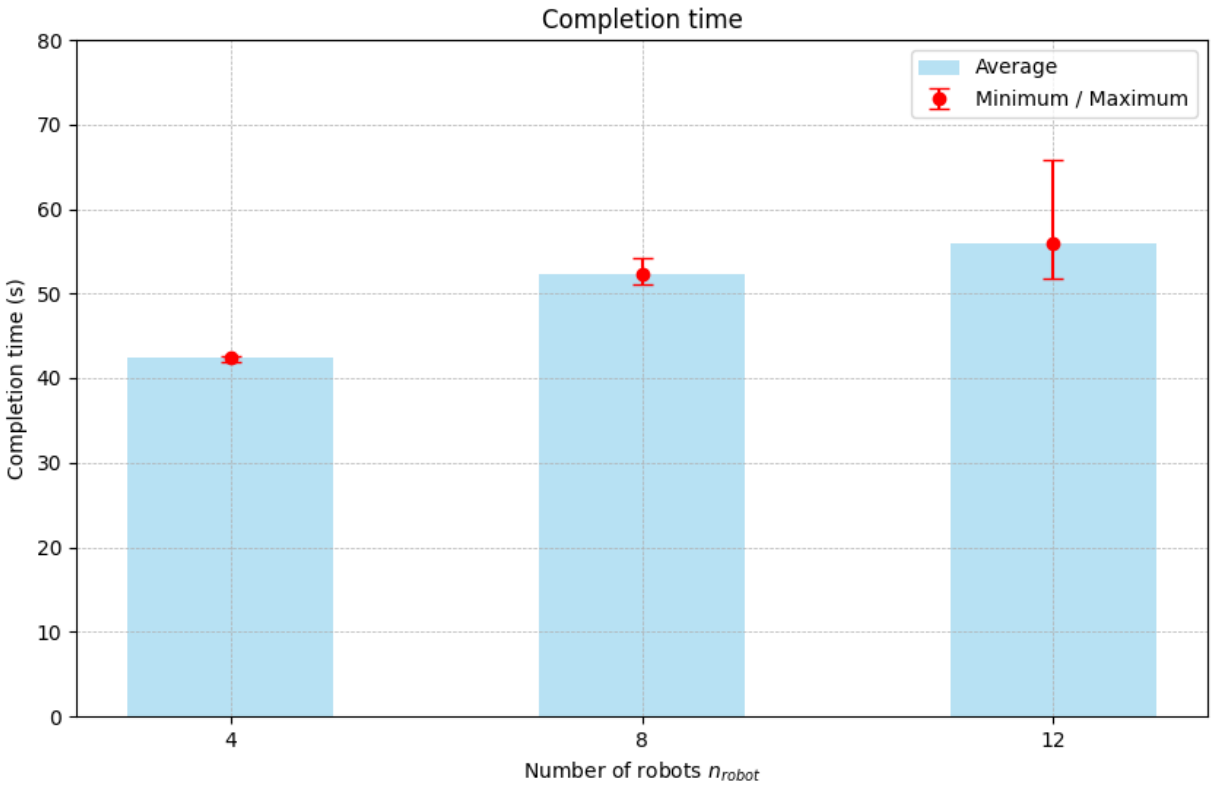
Unknown area exploration

- CBF can not work due to space limitation
- Robots do not have adequate space for safe movement

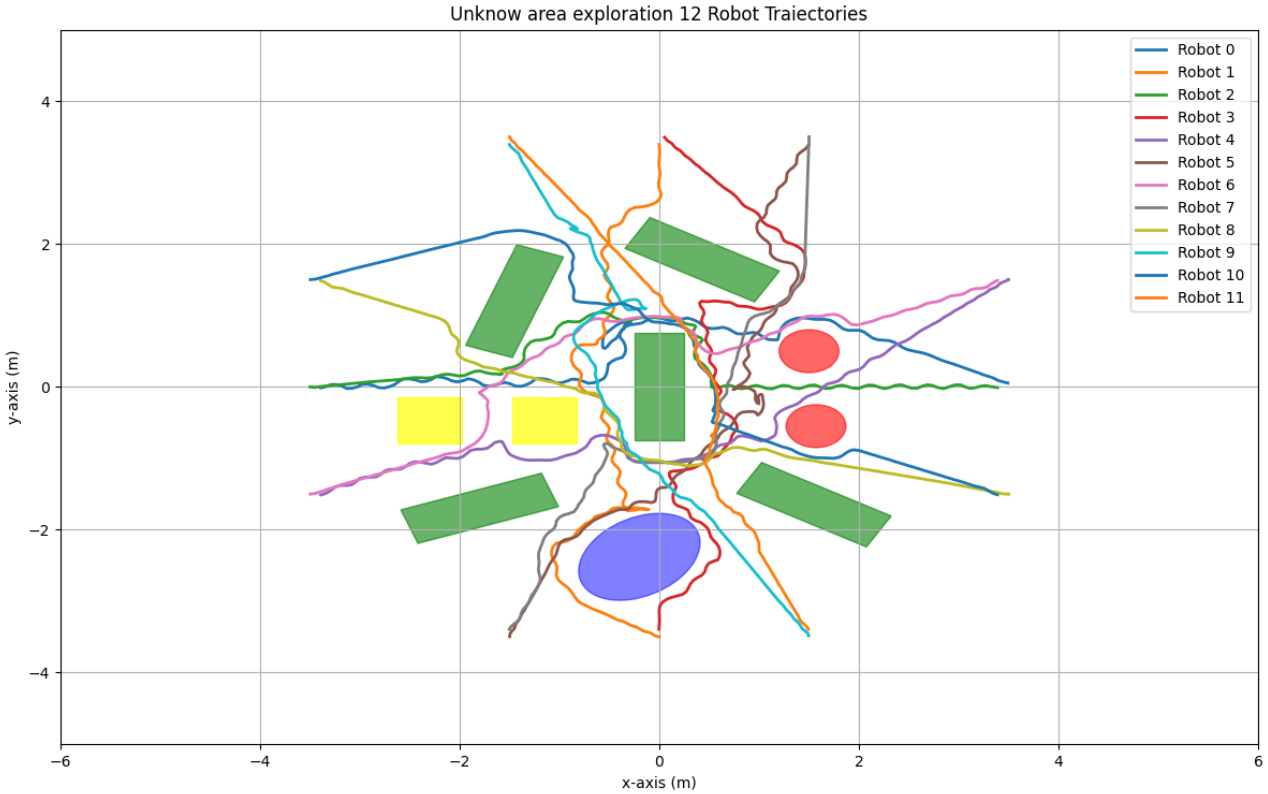


Simulation Results and Analysis

Task Completion Time



Path diagram



Appendix

Experiment setup: