Real-Time Control of Multi-Robot Platooning Using Distributed Guiding Vector Fields

Gonzalo Valero-Domingo, Leyre Remartinez, Rosario Aragues
842392@unizar.es, 839995@unizar.es, raragues@unizar.es
Instituto de Investigación en Ingeniería de Aragón (I3A) - Universidad de Zaragoza

Universidad Zaragoza 1474
Instituto Universitario de Investigación en Ingeniería de Aragón Universidad Zaragoza
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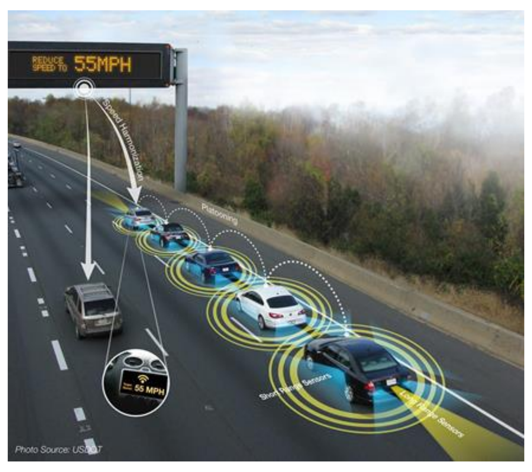
Motivation

Multi-robot coordination is vital for applications like surveillance and transportation. Achieving this requires overcoming key challenges:



Source: Wikipedia

- Maintaining **accurate formations** while following a target path.
- Optimizing vehicle platoons to improve safety, traffic flow and efficiency.
- Ensuring precise **inter-robot coordination** and trajectory tracking.

Contribution

This work extends the existing DGVF platooning framework [1] and [2] by introducing:

- **Advanced Trajectory Generation:** Supports complex geometries (rhodonea, astroid, limaçon) and user-defined cubic splines.
- **Repulsive Obstacle Avoidance:** Integrates a smooth, distance-dependent repulsive term to prevent collisions while ensuring safe path recovery.
- **Interactive Tuning:** Introduces a real-time, interactive simulation environment that allows users to dynamically adjust control parameters on the fly.
- **Hardware Validation:** Validates the strategy on physical hardware (Robotarium), confirming stable path following and accurate inter-robot spacing.

Method

A. Path representation and robot model

- **Robot state representation:**
  Each robot i operates in the planar augmented state

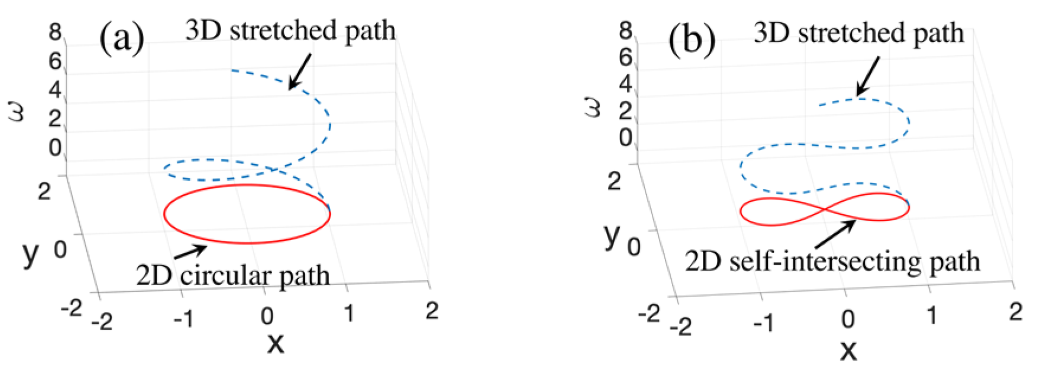
$$\xi_i = [x_{i,1},\ x_{i,2},\ \omega_i]^\top,$$

  where ω_i is a virtual coordinate that parametrizes the robot's progress along the path.
- **Path-following error:**
  The track… defined as:

$$\phi_{i,j}(\xi_i) := x_{i,j} - f_j(w_i)$$

- **Robot dynamics:**
  Robots are … systems:

$$\dot{x}_{i,j} = u_{i,j}, \quad \dot{w}_i = u_i^{\omega}$$



Source: [1]

B. Distributed Guiding Vector Field

- **Spatial control law** combines a tangential component and a corrective convergence term:

$$u_{i,j} = \frac{\partial f_j(w_i)}{\partial w_i} - k_j \phi_{i,j}$$

- **Virtual coordinate** evolves according to:

$$u_i^{\omega} = 1 + \sum_{j=1}^{2} k_j \phi_{i,j} \frac{\partial f_j(w_i)}{\partial w_i} - C(w_i - w^*) + D\,\eta_i$$

Where:
- w^* is the virtual leader.
- C and D attraction/repulsion gains.
- η_i captures inter-robot interactions.

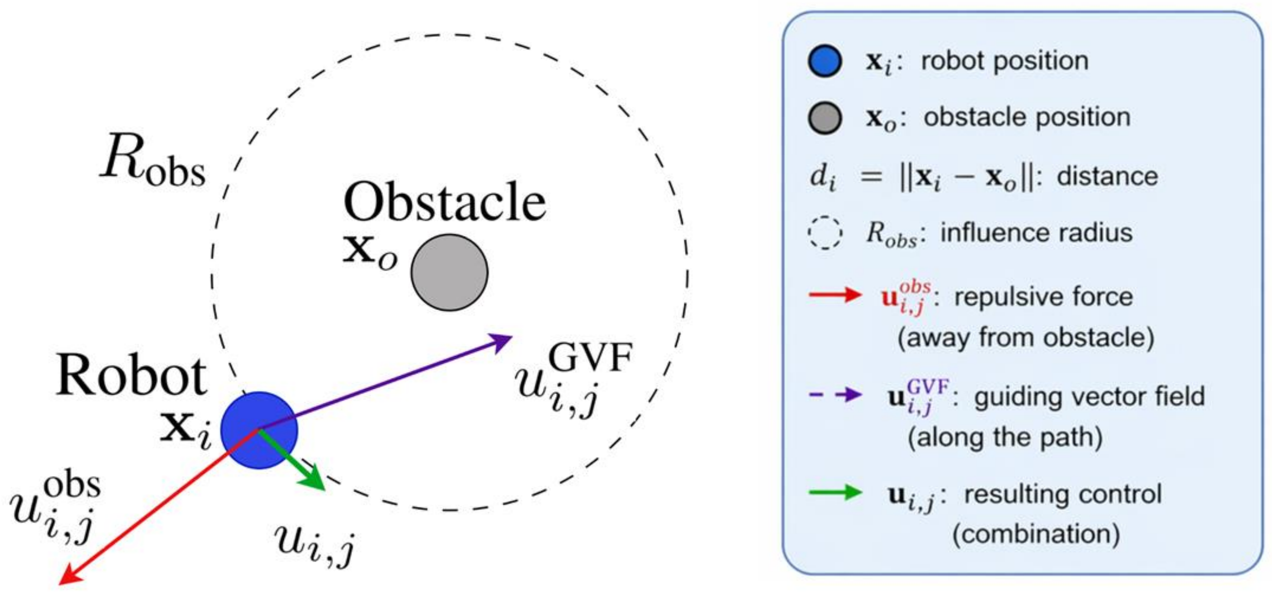
C. Obstacle avoidance

A repulsive control term is added to the spatial input to avoid obstacles.

$$u_{i,j} = u_{i,j}^{\mathrm{GVF}} + u_{i,j}^{\mathrm{obs}}$$

$$u_{i,j}^{\mathrm{obs}} = \begin{cases} k_{\mathrm{obs}}\left(\frac{1}{d_i} - \frac{1}{R_{\mathrm{obs}}}\right)\frac{1}{d_i^2}\frac{\mathbf{x}_i - \mathbf{x}_o}{d_i}, & d_i < R_{\mathrm{obs}} \\ 0, & d_i \geq R_{\mathrm{obs}} \end{cases}$$

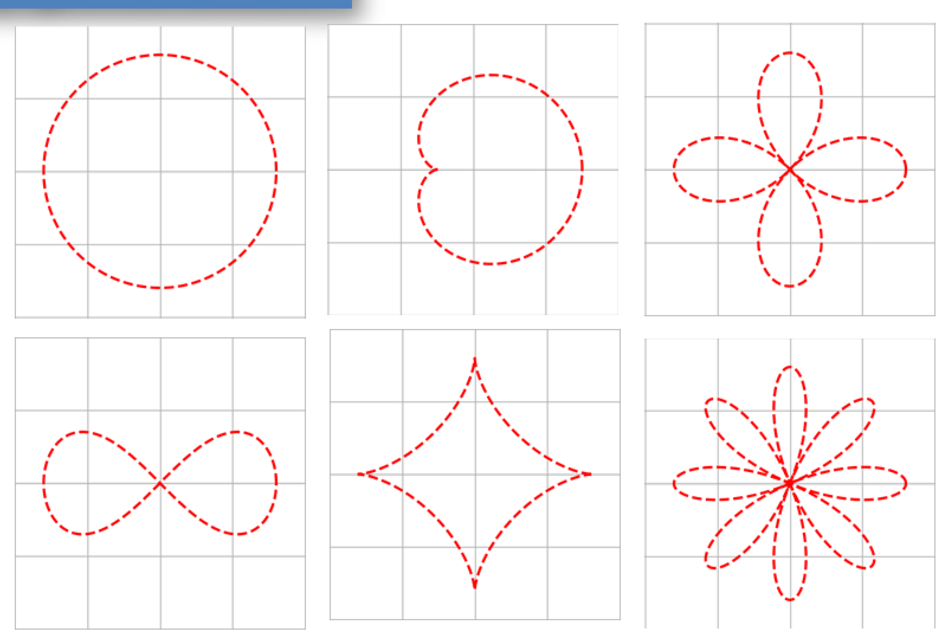
Behavior:
- Vanishes at the influence boundary.
- Increases as the robot approaches the obstacle.
- Ensures safe navigation near obstacles.



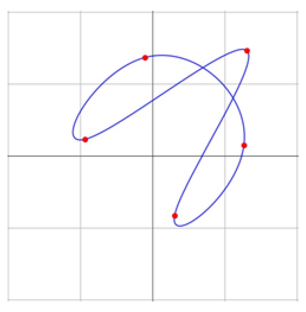
D. New trajectory generation

- **Analytical curves:**
  Baseline:
  - Circle.
  - Lissajous.

  New additions:
  - Rhodonea.
  - Astroid.
  - Limaçon.

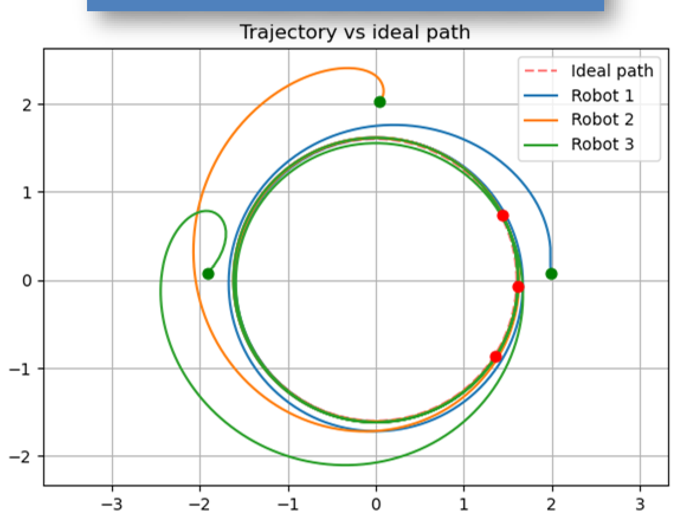


- **Spline curves:**
  To support arbitrary closed paths, a C² cubic spline is fitted through user-defined waypoints. On each segment the trajectory is a cubic polynomial.

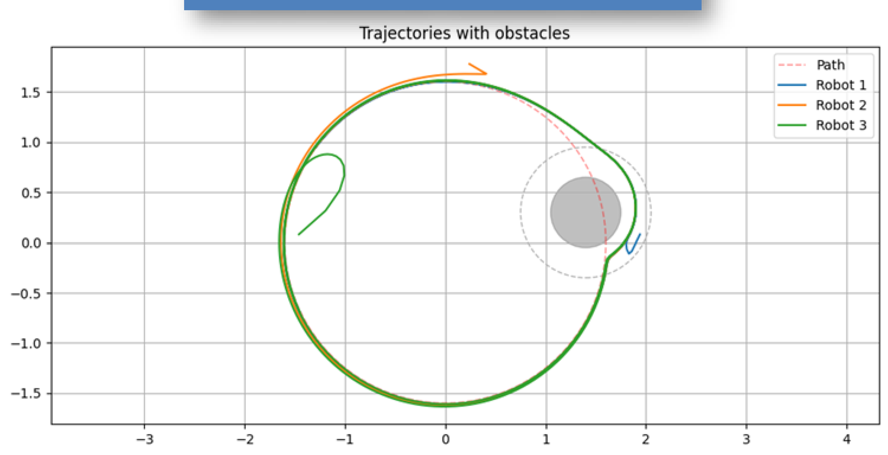


Simulation Results

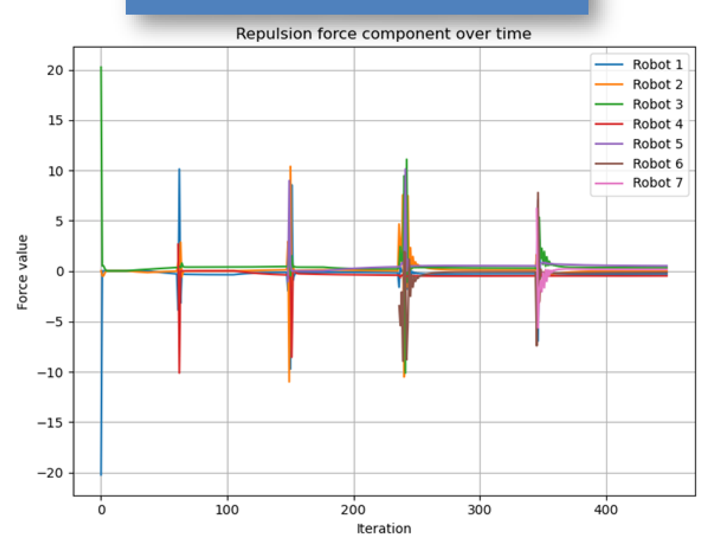
Normal Behavior



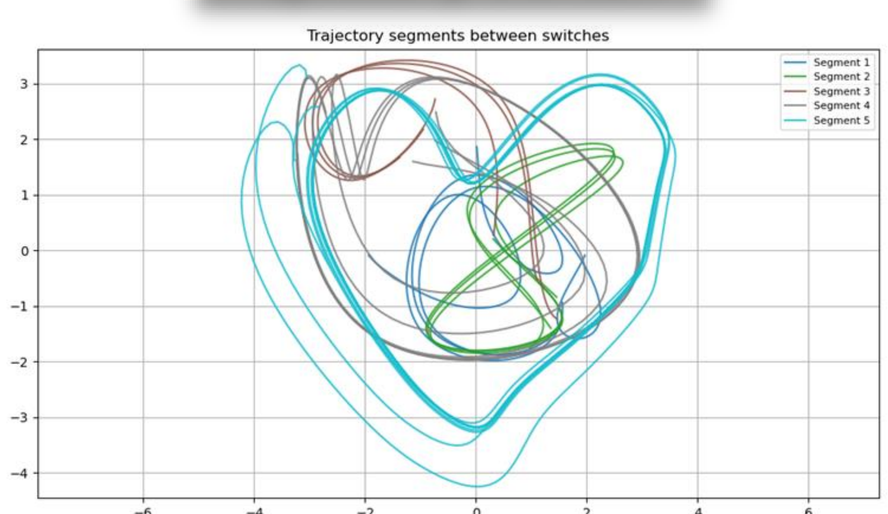
Obstacle insertion



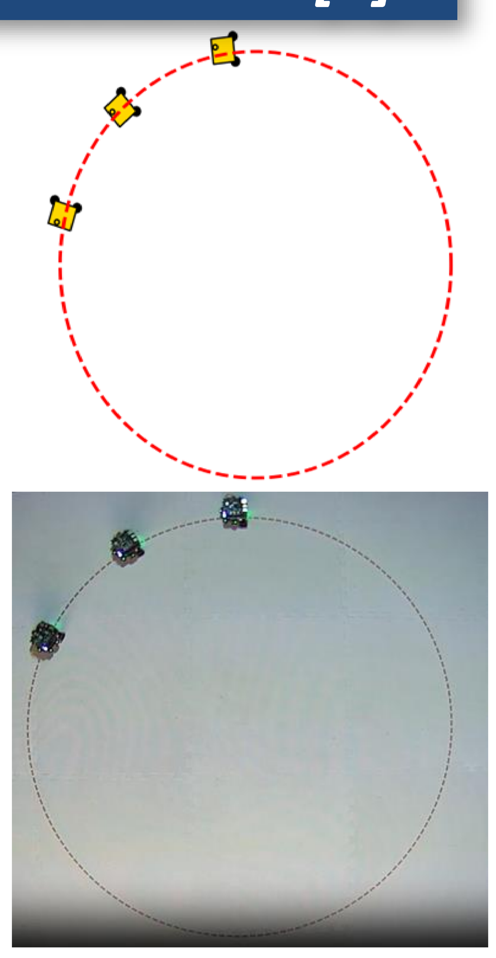
Robots insertion



Trajectory Switch



Robotarium [3]



Conclusions

This work extends the DGVF platooning framework of [1] in three directions:

1. A richer trajectory set (rhodonea, astroid, limaçon and spline-based custom paths).
2. Obstacle avoidance through repulsive fields.
3. Interactive real-time simulation tool for parameter tuning.

The approach was validated in simulation across multiple parameter configurations and in real experiments on the Robotarium platform, achieving stable path following and correct inter-robot spacing in both settings.

References

[1] HU, B.-B.; ZHANG, H.-T.; YAO, W.; DING, J. y CAO, M. Spontaneous-ordering platoon control for multirobot path navigation using guiding vector fields. IEEE Transactions on Robotics. 2023, vol. 39, n.º 4, pp. 2654–2668.
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Acknowledgments

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