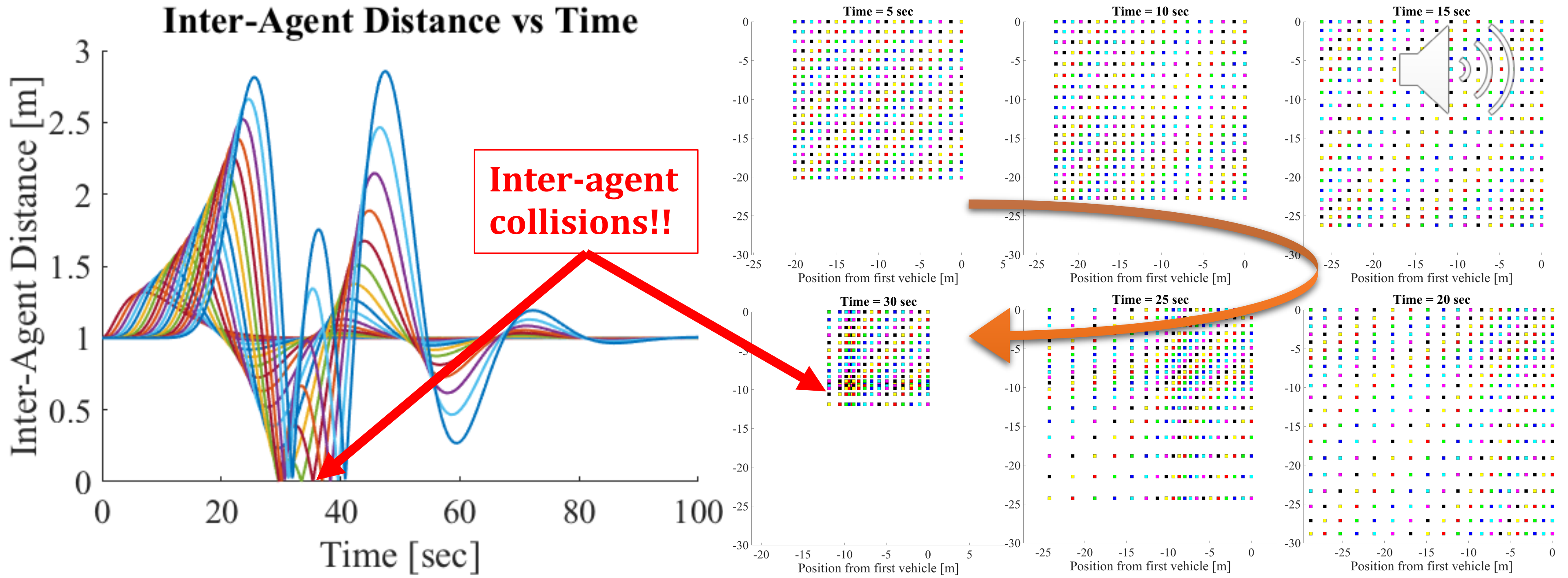

Transient Instabilities in Swarm Formations, Deployable Structures, and Robotic In-Space Assembly and the Development of Mitigation Strategies

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Program: Topical RTD

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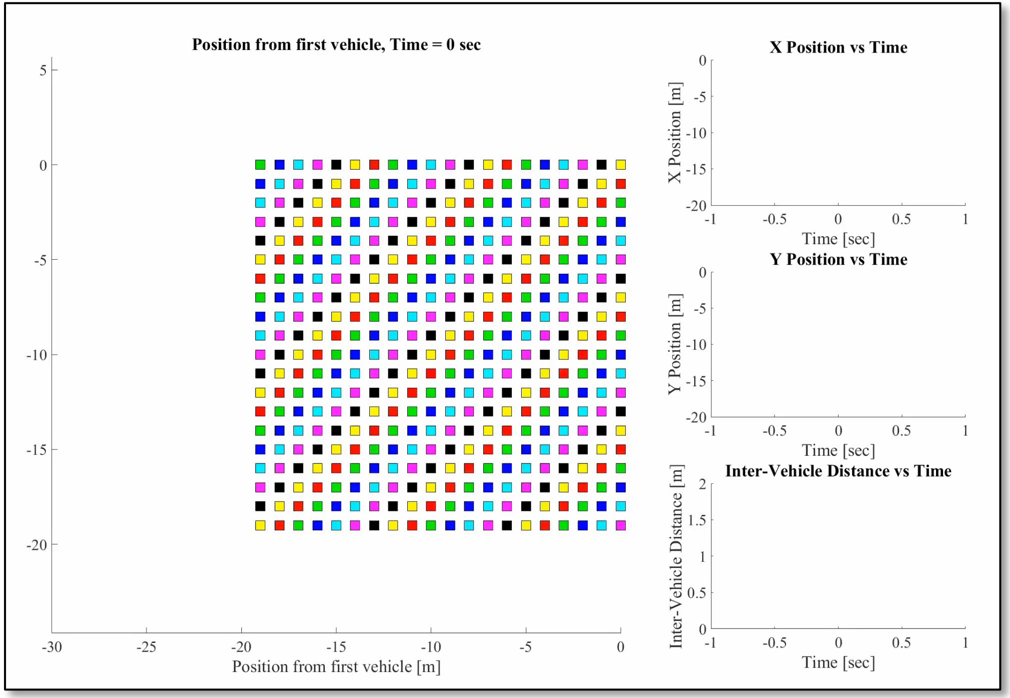
Jet Propulsion Laboratory
California Institute of Technology

Tutorial Introduction

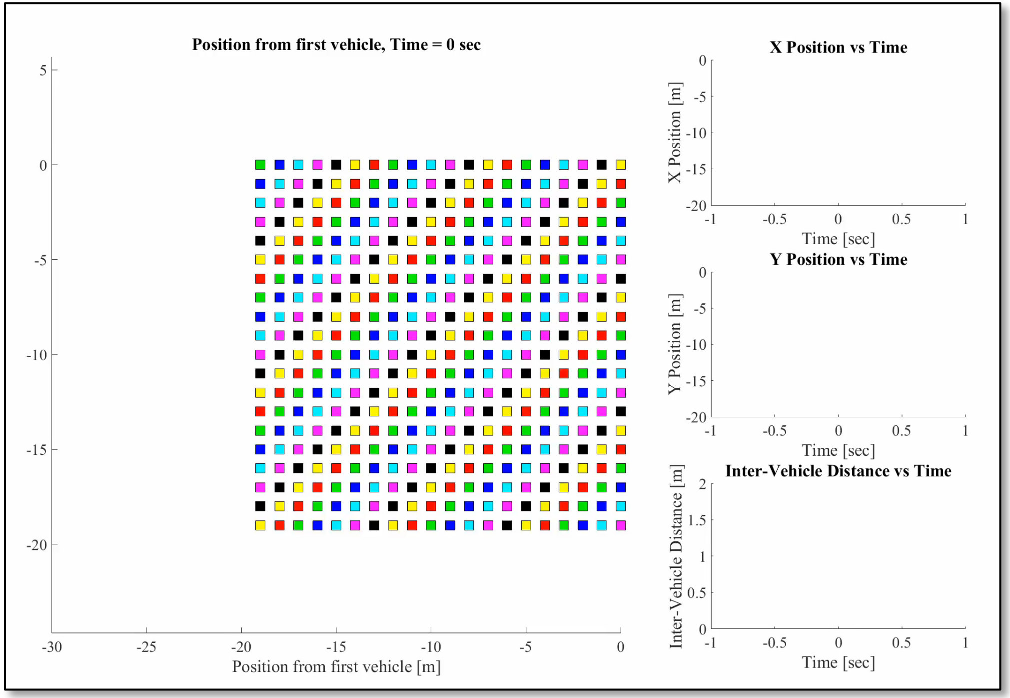
Abstract

- We address a ***fundamental control-theoretic challenge*** in swarms and advanced deployable structures, namely ***detection of transient instabilities and their mitigation***; and leverage these results for robotic in-space assembly.
- ***In Year 1***, we developed a rigorous mathematical framework to identify transient instabilities in swarms and developed mitigation strategies for swarms and validate them using many numerical simulations.
- ***In Year 2***, we will focus on applying these results to deployable structures and robotic in-space assembly.



Problem Description

- ***Our Discovery:*** There exists desired shapes and naïve feedback control laws that can lead to multiple inter-agent collisions within 2D/3D swarms!
- We define ***"transient instability"*** as the phenomenon of increasing-amplitude oscillations within the swarm that leads to inter-agent collisions. This instability is dominant in the transient phase of the system and it does not appear in the steady-state behavior.
- Since each agent's motion is asymptotically stable, all stability techniques in traditional control theory (like Lyapunov theory for nonlinear systems) cannot detect these transient instabilities because each agent's motion is technically "stable" according to the standard stability definition used in control theory. ***There is no technique in control theory that can detect these transient instabilities!***



Problem Description

- ***Deployable structures are analogous to swarms:*** Finite element analysis describes connections between point-masses using partial differential equations. Hence analogous transient instabilities must exist in deployable structures too!
- ***Current paradigm (large damping, large deployment time, essentially quasi-static deployment)***:
    - Uses non-optimized / over-designed structures
    - Not suitable for dynamic deployments or reconfiguration
    - Not suitable for rapid-prototyping and optimization
    - Spacecraft attitude control is switched off!
- We believe that the ***current paradigm effectively dissipates the energy in the transient instabilities***, but some behaviors have been observed that cannot be satisfactorily explained (e.g., SMAP deployment). Therefore, we need a theoretical framework to analyze deployable structures, address these limitations, and detect and mitigate transient instabilities.
- ***Why this is important to JPL:*** JPL, Caltech, and NASA are extremely interested in the development of technologies in these areas. Solving them is necessary for the success of future missions!

Results

We developed a rigorous mathematical framework to identify transient instabilities in swarm formations.

- Norm-based tool for transient stability that applies for both linear and nonlinear systems: $\sup_{\tau} \frac{\|x_i\|_{\mathcal{L}_2(\tau)}}{\|x_i\|_{\mathcal{L}_2(\tau)}} \leq 1,\ \forall i \in \{1, \dots, N\}$,

  where x_i is the multi-dimensional state of the ith agent, $\bar{x}_i$ is the equilibrium state, and $\mathcal{L}_2$-norm is in the extended space.

- *For linear systems*, the above mathematical framework reduces to $\max_{\omega} \left|\frac{X_i(j\omega)}{X_i(j\omega)}\right| \leq 1,\ \forall i \in \{1, \dots, N\}$ [1,2].

- ***Definition:*** Transient instability is the phenomenon of increasing-amplitude oscillations in the inter-agent distances within the Lyapunov-stable swarm that leads to inter-agent collisions, such that:

$$\sup_{\tau}\left(\|x_i\|_{\mathcal{L}_2(\tau)} - \|x_{i-1}\|_{\mathcal{L}_2(\tau)}\right) < \sup_{\tau}\left(\|x_{i+1}\|_{\mathcal{L}_2(\tau)} - \|x_i\|_{\mathcal{L}_2(\tau)}\right), \qquad \forall i \qquad (1)$$

- ***Theorem:*** In a leader-follower swarm, where each agent starts from a constant distance D from its preceding agent and wants to maintain a constant distance D from its preceding agent, and the swarm satisfies the condition:

$$\sup_{\tau} \frac{\|x_i\|_{\mathcal{L}_2(\tau)}}{\|\bar{x}_i\|_{\mathcal{L}_2(\tau)}} \leq 1, \qquad \forall i \in \{1, \dots, N\}$$

  then the swarm wont suffer from increasing-amplitude oscillations in inter-agent distance shown in Eq (1).

[1] L. Peppard, “String stability of relative-motion PID vehicle control systems,” IEEE Transactions on Automatic Control, vol. 19, no. 5, pp. 579–581, 1974.
[2] Feng, Shuo, Yi Zhang, Shengbo Eben Li, Zhong Cao, Henry X. Liu, and Li Li. "String stability for vehicular platoon control: Definitions and analysis methods." Annual Reviews in Control (2019).

Results

We validated the theoretical tools and mitigation strategies using numerical simulations

- ***Mathematical tool with PID control***

PID Controller: $$u_i(t) = -h_1(p_i(t) - p_{i-1}(t) + D) - h_2\big(v_i(t) - v_{i-1}(t)\big)$$

$$-h_3 \int_0^t (p_i(\tau) - p_{i-1}(\tau) + D)d\tau$$

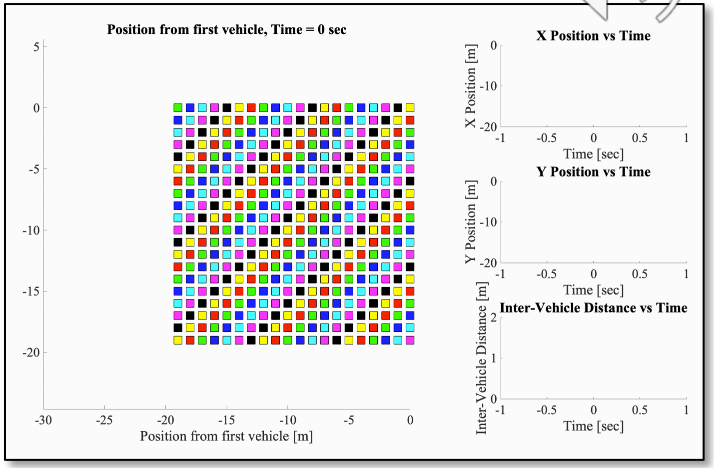
Mathematical tool: $$\frac{P_i(s)}{P_i(s)} = \frac{h_2 s^2 + h_1 s + h_3}{s^3 + (\mu + h_2)s^2 + h_1 s + h_3}$$

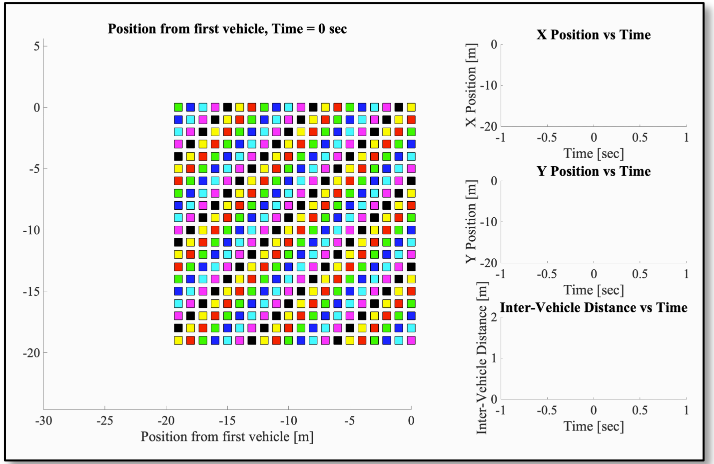
- ***Mathematical tool with Li-Slotine robust controller for Euler-Lagrange systems***

Robust controller: $$u_i(t) = \dot{\Omega}_i(t) + \mu\Omega(t) + h_2(\Omega_i(t) - v_i(t))$$

$$\Omega_i(t) = \dot{\bar{p}}_i(t) + h_1(\bar{p}_i(t) - p_i(t))$$

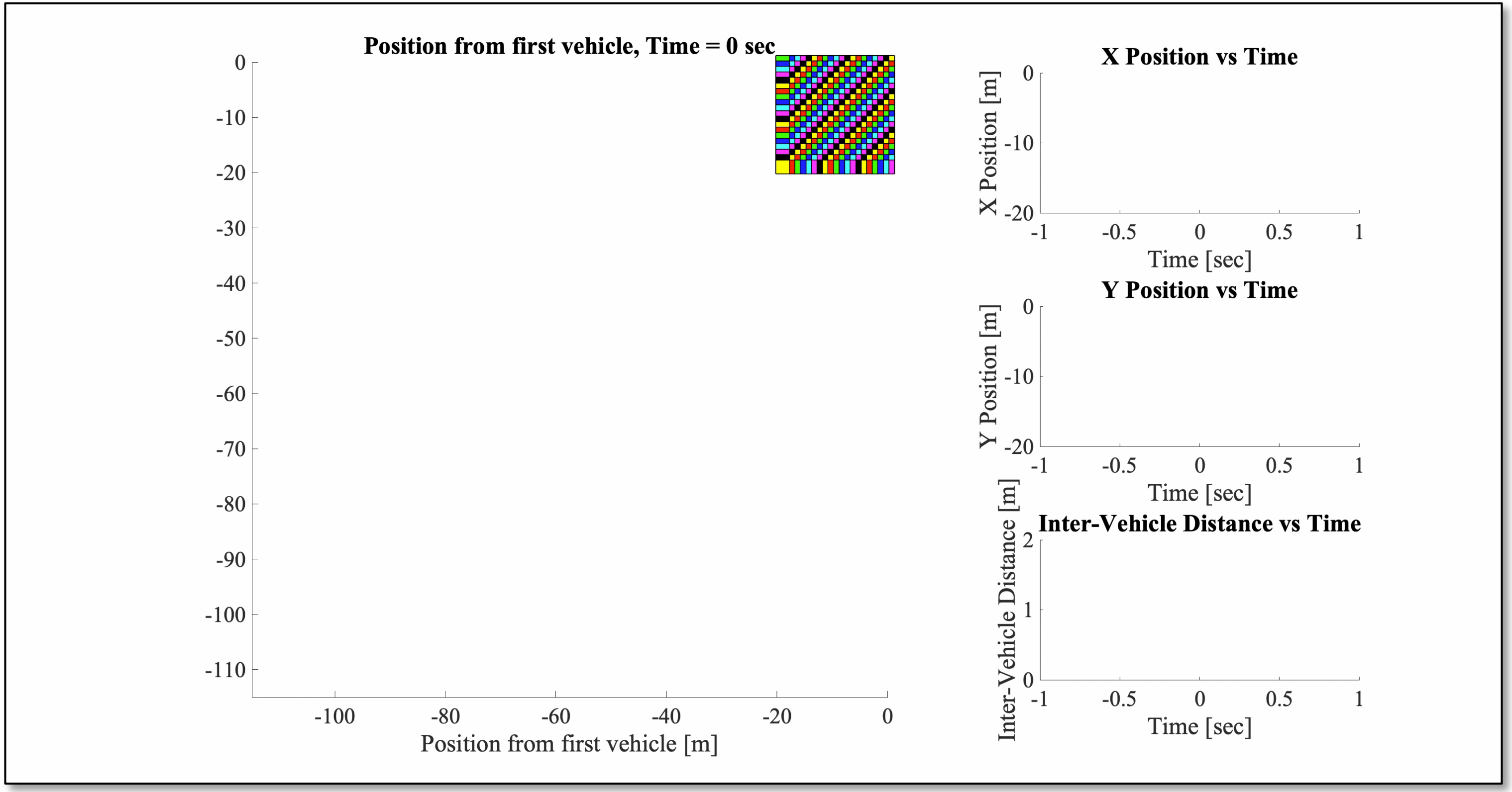
Mathematical tool: $$\frac{P_i(s)}{P_i(s)} = \frac{s^2 + (h_2 - \mu + h_1)s + (\mu h_1 + h_2 h_1)}{s^2 + (h_2 - \mu + h_1)s + (\mu h_1 + h_2 h_1)} = 1$$





Results

Swarm Reconfiguration (analogous to Deployment) using Li-Slotine robust controller for Euler-Lagrange systems



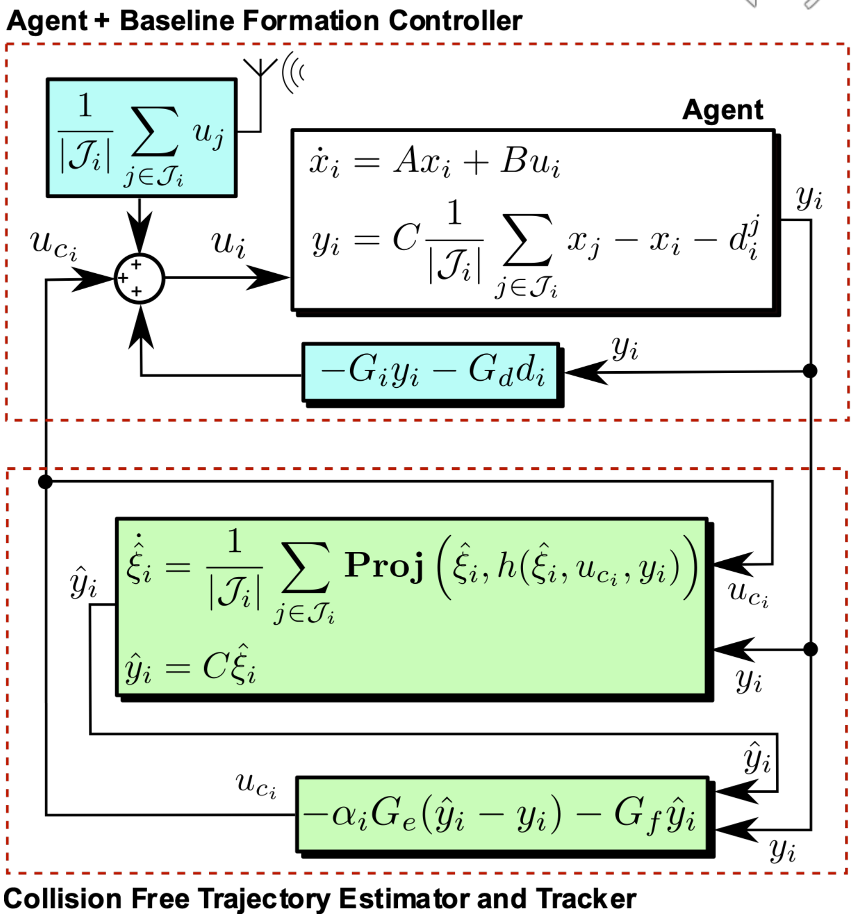
Results

We developed mitigation strategies to combat transient instabilities in swarm formation.

The control mitigation architecture consists of:

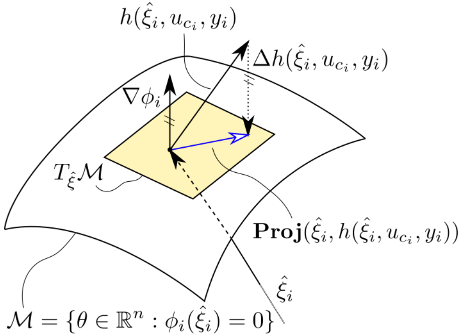
- The ***baseline controller***, which is responsible for formation maintenance.
- The ***projection based estimator*** that estimates the relative error vector and guarantees that the estimates will never violate the constraint cell.
- The ***tracking controller***, which drives the agent's relative error trajectory to the collision-free trajectory generated by the projection estimator.

Together, the projection based estimator and the tracking controller accomplish the task of collision avoidance in geometric formations of multi-agent systems.

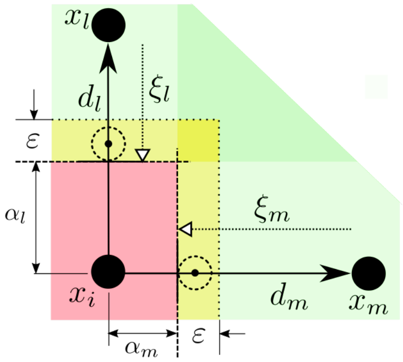


Results

Control Architecture For Mitigating Transient Instability in Arbitrary Formations in N-Dimensional Formation Dynamics

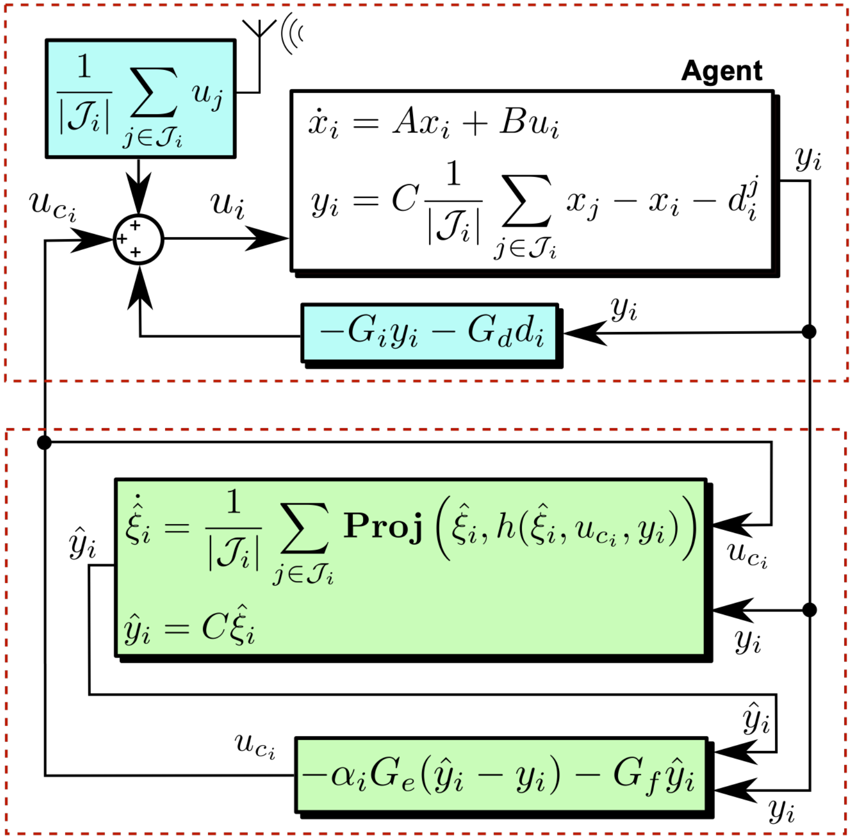


Multi-Dimensional Projection Dynamics



Voronoi Cell Inspired Constraint Cell

Agent + Baseline Formation Controller

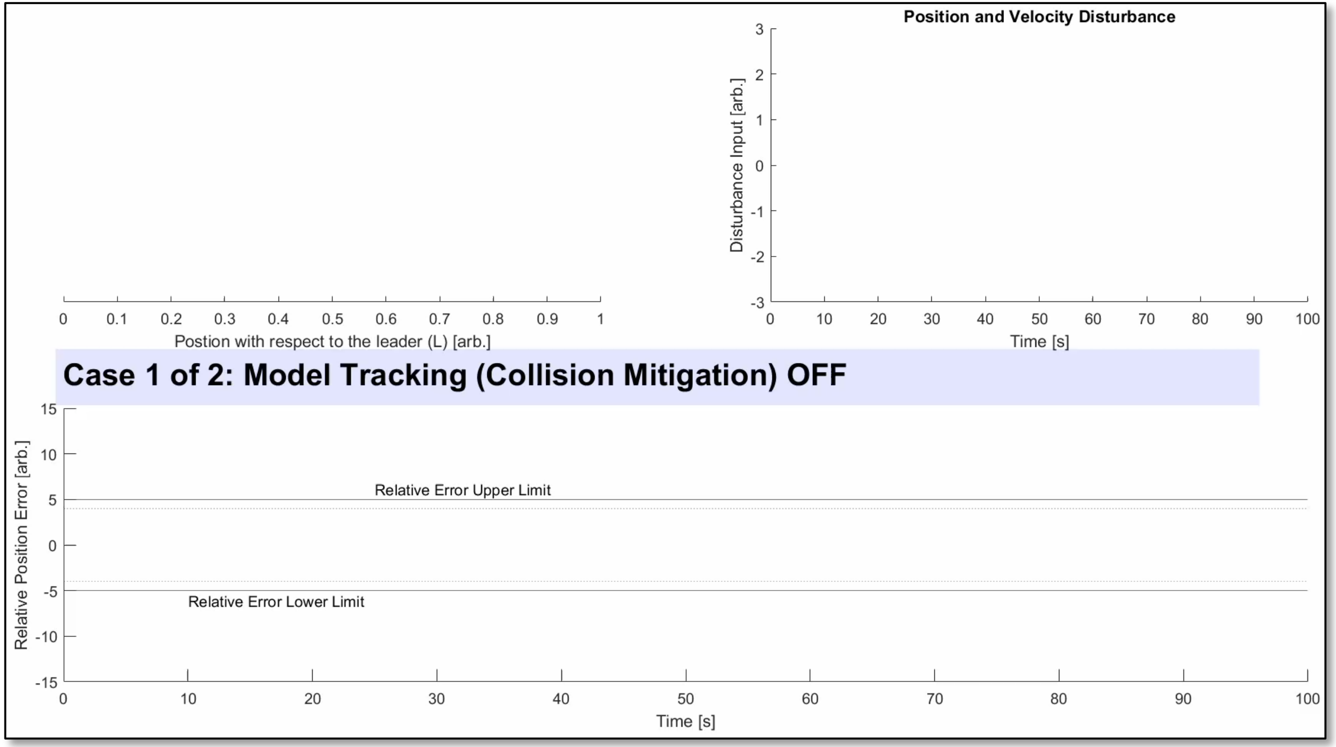


Collision Free Trajectory Estimator and Tracker

Results

We validated the theoretical tools and mitigation strategies using numerical simulations

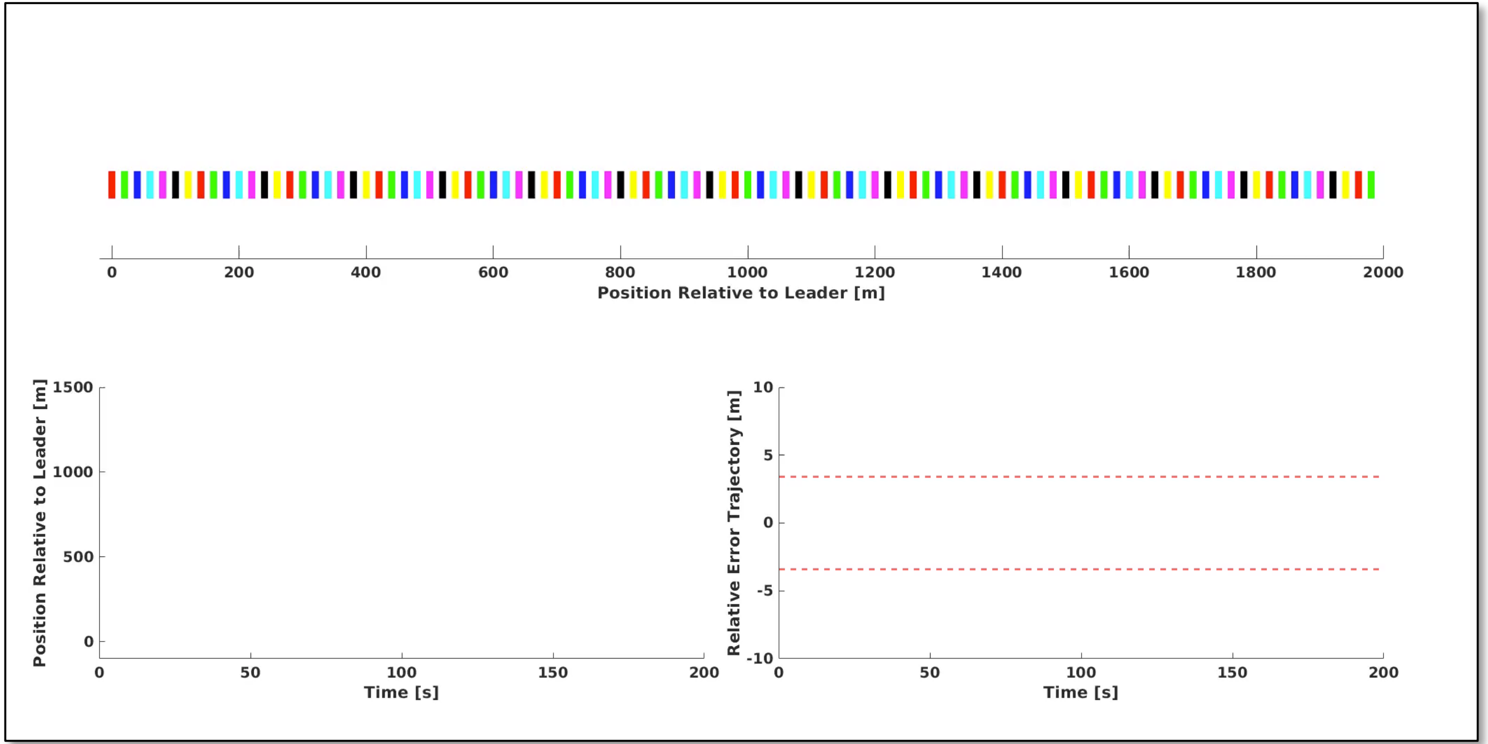
- Simple 2 agent leader-follower system



Results

We validated the theoretical tools and mitigation strategies using numerical simulations

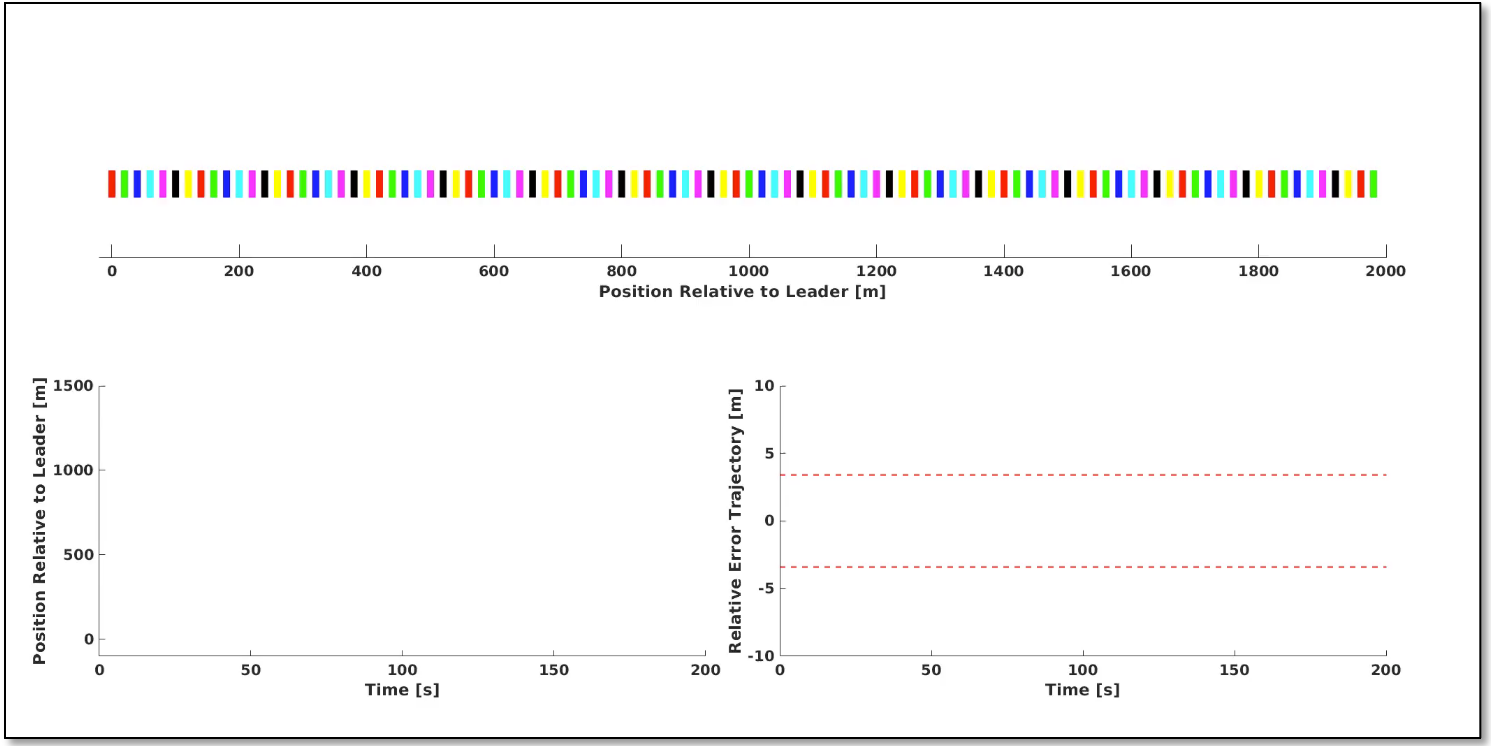
- 100 Agent video, without collision avoidance.



Results

We validated the theoretical tools and mitigation strategies using numerical simulations

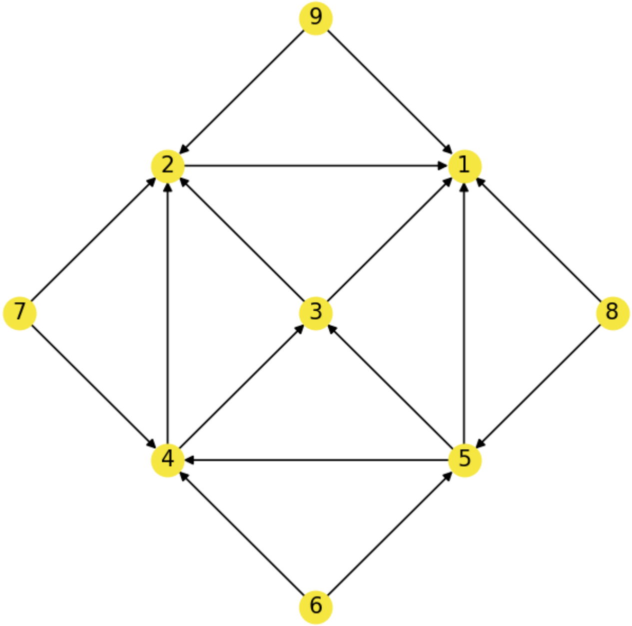
- 100 Agent video, with projection based collision avoidance.



Results

We validated the theoretical tools and mitigation strategies using numerical simulations

- ***Simulation of a 9-agent network***
- A 9-agent formation with 2 axis (x-y) double integrator agent dynamics.
- The formation choice is arbitrary, except that the graph topology is chosen to ensure structural rigidity, which ensures that the formations maintains its shape under reconfiguration.
- There are two 30 second simulations:
    - Simulation 1: Collision Avoidance disabled (i.e. tracking of projection based trajectories is turned off)
    - Simulation 2: All components of the controller are enabled, ensuring collision mitigation.
- For both the simulations, the following reconfiguration commands are issues:
    - At t=1s, a positive 90 deg. rotation reconfiguration command is issued.
    - At t=7s, two commands: 1) -90 deg. rotation, and 2) resize to 25% of original size, are issued.

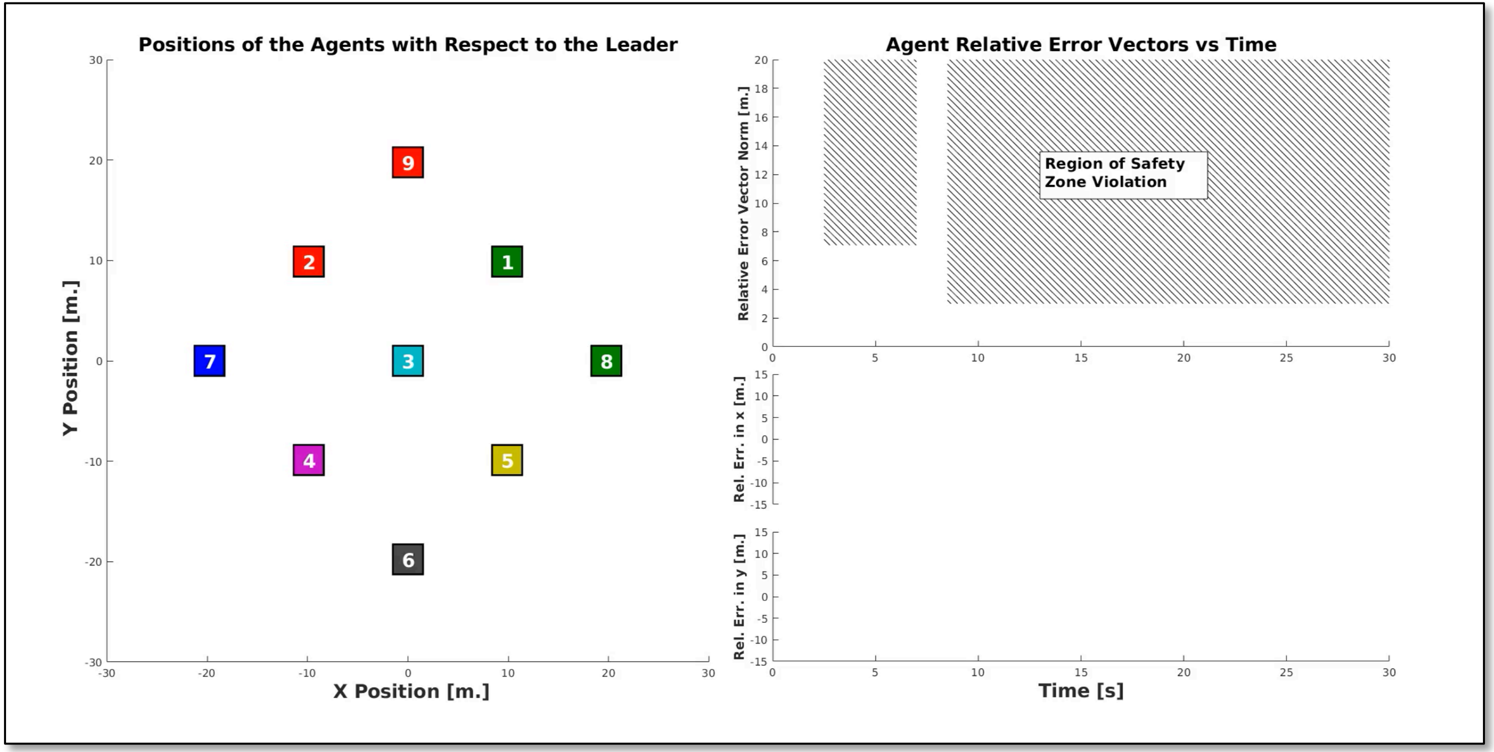


Simulation Formation/Graph

Results

We validated the theoretical tools and mitigation strategies using numerical simulations

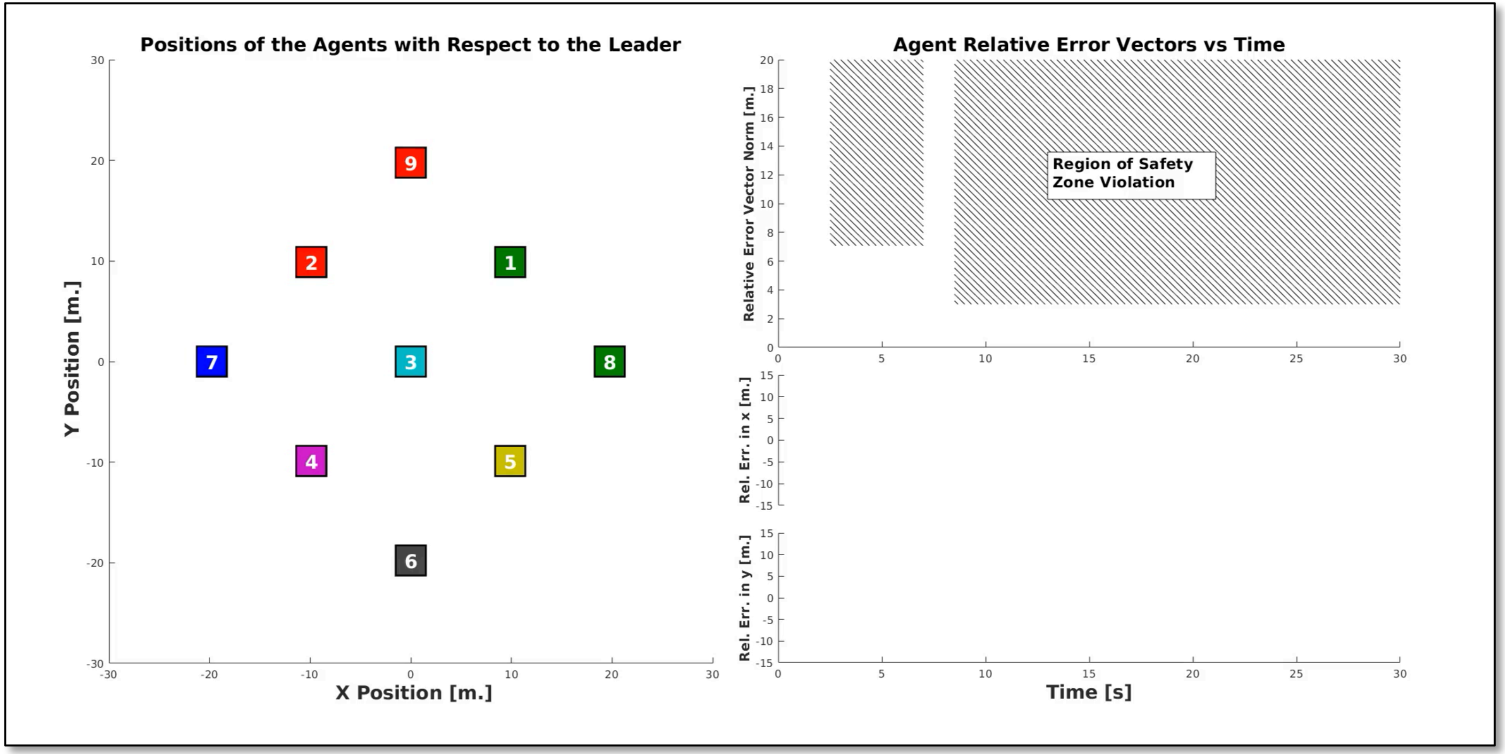
- Simulation of a 9-agent network: Collision Avoidance Turned Off



Results

We validated the theoretical tools and mitigation strategies using numerical simulations

- Simulation of a 9-agent network: Collision Avoidance Enabled



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3. S. Bandyopadhyay, V. Gehlot, M. Balas, M. Quadrelli, D. Bayard, “Detection and Mitigation of Transient Instabilities in Swarms”, International Symposium on Artificial Intelligence, Robotics and Automation in Space (iSAIRAS), Pasadena, CA, Oct. 2020, accepted.

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Thank you!

Acknowledgement

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If you have any questions or comments, please feel free to email Saptarshi.Bandyopadhyay@jpl.nasa.gov