

RESEARCH ARTICLE

Graph Laplacian-Based Modeling of Distributed Consensus and Cooperative Control in Multi-Agent Engineering Systems

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Graph Laplacians provide a compact mathematical bridge between communication topology and closed-loop behavior in distributed engineering systems. This paper develops a reproducible Laplacian-based framework for first-order consensus, discrete-time stability, switching communication graphs, link-loss robustness, and leader-follower cooperative formation control. For a 12-agent study, four canonical weighted topologies show a strong spectral ordering: algebraic connectivity λ_2 increases from 0.068 for a path to 0.254 for a ring, 0.861 for a small-world mesh, and 12 for a complete graph, while measured 2% consensus settling time decreases from 19.76 s to 5.50 s, 2.53 s, and 0.33 s, respectively. Across 72 additional connected random graphs, log settling time versus log λ_2 has slope -0.887 and $R^2 = 0.931$, empirically supporting inverse spectral scaling. For the small-world mesh, the discrete consensus stability boundary is $\alpha < 2/\lambda_{\max} = 0.2720$. Edge-removal tests reveal up to 29.26% loss of algebraic connectivity, and a Fiedler-vector edge sensitivity proxy correlates 0.956 with the measured λ_2 loss. A switching-topology protocol settles in 2.56 s, while an eight-follower second-order leader-follower system reaches 0.1 position-RMSE in 4.34 s. The study emphasizes spectral interpretation, limitations of topology-only modeling, and engineering tradeoffs among connectivity, communication burden, robustness, and control speed.

Keywords: Graph Laplacian, Algebraic connectivity, Consensus control, Multi-agent systems, Cooperative formation control.

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This is an open-access article distributed under the terms of the [Creative Commons Attribution-NonCommercial 4.0 International License \(CC BY-NC 4.0\)](https://creativecommons.org/licenses/by-nc/4.0/).**1. Introduction**

Distributed engineering systems increasingly rely on groups of locally communicating agents rather than a single centralized controller. Vehicle platoons, mobile robots, unmanned aerial vehicles, sensor networks, spacecraft formations, microgrids, and cooperative manipulators all share a common architectural question: how does the communication graph constrain what the closed-loop system can achieve? Algebraic graph theory provides one of the most direct mathematical answers. Fiedler's algebraic connectivity identifies the second-smallest Laplacian eigenvalue as a quantitative measure of connectedness [1]; Laplacian

matrix theory subsequently established a broad spectral vocabulary for relating graph structure, cuts, connectivity, and eigenmodes [2]. In distributed control, these spectral quantities enter directly into convergence and stability conditions rather than serving only as descriptive graph statistics.

The modern consensus literature made this connection operational. Jadbabaie, Lin, and Morse showed how local nearest-neighbor interaction can coordinate mobile agents under changing neighborhoods [3]. Fax and Murray explicitly related information-flow topology and Laplacian eigenvalues to multivehicle formation stability [4]. Ren and Beard established consensus conditions under dynamically changing directed interaction topologies [5]. Olfati-Saber, Fax, and Murray then unified matrix, graph, and control viewpoints and highlighted a direct relationship between network spectra and the speed of information diffusion [6]. These works motivate a modeling philosophy in which the

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List of acronyms and mathematical symbols

Acronym/ symbol	Meaning	Acronym/ symbol	Meaning
MAS	Multi-agent system	UAV	Unmanned aerial vehicle
RMS	Root mean square	RMSE	Root mean squared error
MPC	Model predictive control	CSV	Comma-separated values
JSON	JavaScript Object Notation	ER	Erdős–Rényi
$\mathcal{G}$	Weighted communication graph	$\mathcal{V}$	Set of graph vertices or agents
$\mathcal{E}$	Set of communication edges	A	Weighted adjacency matrix
D	Degree matrix	L	Graph Laplacian, $L = D - A$
n	Number of agents	λ_i	i th Laplacian eigenvalue
λ_2	Algebraic connectivity	λ_n	Largest Laplacian eigenvalue
$\mathbf{1}$	All-ones vector	J	Consensus projection matrix
$\mathbf{x}$	Stacked agent-state vector	$\mathbf{z}$	Disagreement-state vector
κ	Continuous-time consensus gain	ε	Relative settling tolerance
t_ε	Settling-time estimate	α	Discrete-time consensus step size
$\rho_\perp$	Disagreement spectral radius	$L_{\sigma(t)}$	Active switching Laplacian
p_i	Position of follower i	v_i	Velocity of follower i
u_i	Distributed control input	B	Leader-pinning matrix
L_f	Follower-graph Laplacian	H	Grounded Laplacian, $H = L_f + B$
e_p	Formation position error	e_v	Formation velocity error
k_p	Position-feedback gain	k_v	Velocity-feedback gain
μ_i	i th grounded-Laplacian eigenvalue	r_i	Desired formation offset

graph is not an auxiliary diagram attached to a controller: it is part of the dynamical system.

That viewpoint is especially useful in engineering design because topology has competing effects. Additional communication links can increase algebraic connectivity and accelerate consensus, but they also consume bandwidth, energy, and scheduling resources. A dense graph can be fast yet impractical. A sparse graph can be efficient yet fragile to a single critical link. In multivehicle settings, information consensus is therefore inseparable from communication architecture [7]. Delays further complicate the spectral picture because otherwise stable consensus protocols can lose robustness when input or communication latency interacts with Laplacian modes [8]. For more general linear agent dynamics, consensus can be interpreted through synchronization and modal stability of graph-induced subsystems [9]. Coordinated-control frameworks similarly emphasize that local continuous control and higher-level cooperation must be designed together [10].

Despite this mature theory, many applied multi-agent studies use the Laplacian only to define a control law and then report one simulation. Such a presentation can obscure the most useful engineering questions. How closely does measured convergence follow the $1/\lambda_2$ spectral scaling? Where does the discrete-time step-size boundary predicted by $\lambda_{\max}$ actually occur? Which edges cause the greatest degradation when removed? Can Fiedler-vector structure anticipate those critical links? How does switching between connected graphs alter the disagreement energy? In leader–follower formation control, how does pinning transform the singular Laplacian into a positive-definite grounded operator? These questions are mathematical-modeling questions, and answering them requires experiments that vary graph structure systematically rather than changing the controller and topology simultaneously.

This paper develops such a study. The agents are normalized single- or double-integrator engineering models so that topology and spectral effects remain identifiable. The purpose is not to claim hardware-specific performance; rather, it is to isolate how Laplacian structure governs distributed coordination. Four canonical 12-agent graphs are compared, followed by a 72-graph spectral sweep, a discrete-time stability study, a switching-topology experiment, exhaustive single-edge removal on a small-world mesh, and second-order leader–follower formation tracking. All experiments are generated by one deterministic Python script, and all numerical tables and plot coordinates are included in the project.

The main contributions are: (1) a common Laplacian formulation connecting continuous consensus, discrete consensus, switching systems, link robustness, and grounded leader–follower dynamics; (2) an empirical spectral-scaling audit showing a -0.887 log–log slope between λ_2 and settling time across 72 connected graphs; (3) a robustness study showing that single-edge removals can reduce λ_2 by 29.26%, with a Fiedler-edge proxy correlating 0.956 with the measured loss; (4) verification of the discrete stability boundary $\alpha < 2/\lambda_{\max}$ and a switching protocol that converges without centralized state feedback; and (5) a leader–follower formation example in which grounded-Laplacian eigenvalues provide a direct modal explanation of tracking convergence.

2. Related work and modeling gap

2.1. Consensus, sampling, and communication constraints

Consensus theory has expanded from continuous first-order integrators to sampled, delayed, nonlinear, and constrained systems. Sampled-data second-order consensus

studies show that sampling interacts explicitly with Laplacian eigenvalues and can create critical stability regions [11]. Event-triggered consensus replaces periodic communication with state-dependent updates and thereby exposes a tradeoff between communication rate and convergence quality [12]. Dynamic event-triggered leader–follower protocols extend this idea to switching graphs and cooperative tracking while excluding Zeno behavior [13]. These results reinforce a central engineering lesson: graph connectivity alone is insufficient; the control and communication clocks determine how graph information enters dynamics.

Recent work extends cooperative control to constrained heterogeneous agents. Distributed model predictive control can coordinate agents through local optimization and communicated artificial references while preserving closed-loop consensus and formation objectives [14]. Safe formation control now incorporates prescribed performance, input constraints, and collision avoidance in explicitly cooperative architectures [15].

2.2. Modeling gap

The modeling gap is not a lack of consensus theorems. It is a lack of compact reproducible studies that connect several engineering consequences to the *same* Laplacian objects. In many simulations, topology, control gain, sampling interval, dynamics, and initial conditions change together. Consequently, a faster response cannot be attributed cleanly to algebraic connectivity, control gain, or model order. Here, topology is varied while the state protocol and initial condition are held fixed for the spectral study. The same weighted mesh is then reused for discrete-time stability and edge-loss experiments. Leader–follower formation uses a related sparse follower graph but introduces pinning explicitly through a grounded Laplacian. This design turns classical theory into a traceable modeling workflow.

3. Graph-Laplacian mathematical model

3.1. Weighted communication graph

Let $\mathcal{G} = (\mathcal{V}, \mathcal{E}, A)$ be a weighted graph with n agents, adjacency matrix $A = [a_{ij}]$, degree matrix $D = \text{diag}(\sum_j a_{ij})$, and Laplacian (1):

$$L = D - A. \quad (1)$$

For an undirected connected graph, $L = L^\top \succeq 0$ and its eigenvalues satisfy Equation (2).

$$0 = \lambda_1 < \lambda_2 \leq \dots \leq \lambda_n. \quad (2)$$

The eigenvector associated with λ_1 is $\mathbf{1}$. The value λ_2 is the algebraic connectivity and governs the slowest non-consensus mode; λ_n governs the fastest mode and enters discrete-time stability limits.

3.2. Continuous-time consensus and spectral rate

For normalized single-integrator agents $\dot{x}_i = u_i$, use the distributed protocol (3):

$$u_i = -\kappa \sum_{j=1}^n a_{ij}(x_i - x_j), \quad \dot{\mathbf{x}} = -\kappa L \mathbf{x}. \quad (3)$$

Define $J = \frac{1}{n} \mathbf{1} \mathbf{1}^\top$ and disagreement $\mathbf{z} = (I - J)\mathbf{x}$. Because $LJ = JL = 0$ for the undirected case,

$$\|\mathbf{z}(t)\|_2 \leq e^{-\kappa \lambda_2 t} \|\mathbf{z}(0)\|_2. \quad (4)$$

Thus a conservative relative- ε settling estimate is written by (5).

$$t_\varepsilon \leq \frac{\ln(1/\varepsilon)}{\kappa \lambda_2}. \quad (5)$$

Equation (5) predicts inverse scaling with λ_2 without requiring a specific initial state.

3.3. Discrete-time consensus

A forward-Euler or sampled consensus update has the form (6).

$$\mathbf{x}_{k+1} = (I - \alpha L) \mathbf{x}_k. \quad (6)$$

For a connected undirected graph, disagreement converges if every nontrivial eigenmode satisfies $|1 - \alpha \lambda_i| < 1$, yielding (7):

$$0 < \alpha < \frac{2}{\lambda_n}. \quad (7)$$

The disagreement spectral radius is $\rho_\perp = \max_{i \geq 2} |1 - \alpha \lambda_i|$. Equation (7) exposes a design tension: higher connectivity usually raises λ_2 , but may also raise λ_n , reducing the admissible step size for an explicit discrete update.

3.4. Switching and directed extensions

For switching topology, L becomes $L_{\sigma(t)}$ and

$$\dot{\mathbf{x}} = -\kappa L_{\sigma(t)} \mathbf{x}. \quad (8)$$

If each active undirected graph is connected, average consensus is immediate under arbitrary switching; weaker joint-connectivity conditions can also suffice. For a directed graph, L is generally nonsymmetric. The zero eigenvalue and spanning-tree structure still determine consensus feasibility, but convergence is governed by real parts and left/right eigenvectors rather than the ordered real spectrum in (2). The numerical study keeps the principal spectral experiments undirected so that λ_2 retains its standard energy interpretation.

3.5. Grounded Laplacian for leader–follower control

Consider n_f second-order followers with position $p_i \in \mathbb{R}^2$ and velocity v_i (9):

$$\dot{p}_i = v_i, \quad \dot{v}_i = u_i. \quad (9)$$

Let $B = \text{diag}(b_i)$ indicate which followers receive leader information, and let $H = L_f + B$ be the grounded Laplacian. For desired formation offsets r_i and leader state (p_0, v_0) , define $e_p = p - (\mathbf{1} \otimes p_0 + r)$ and $e_v = v - \mathbf{1} \otimes v_0$. The distributed control law is expressed as in (10).

$$u = -k_p(H \otimes I_2)e_p - k_v(H \otimes I_2)e_v. \quad (10)$$

If the follower graph is connected and at least one follower is pinned, $H \succ 0$. Each modal coordinate with grounded eigenvalue $\mu_i > 0$ then obeys (11):

$$s^2 + k_v \mu_i s + k_p \mu_i = 0, \quad (11)$$

The Equation (11) is stable for $k_p, k_v > 0$. This makes the smallest grounded eigenvalue a leader-information analogue of algebraic connectivity.

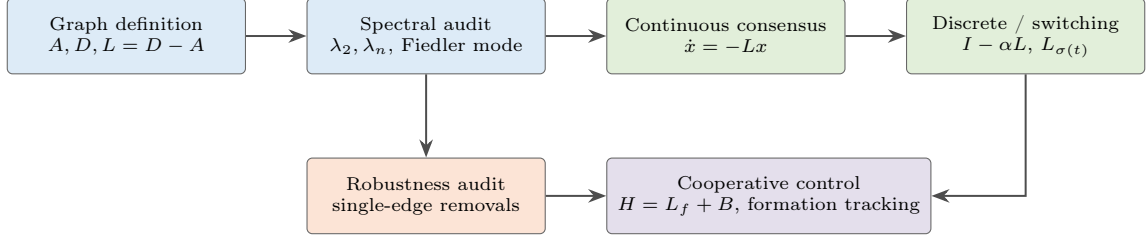


Figure 1: Unified Laplacian modeling workflow.

Algorithm 1 Laplacian modeling audit

Require: Graph set $\{\mathcal{G}_q\}$, common initial state, tolerance ε

- 1 **for** each graph $\mathcal{G}_q$ **do**
- 2 Build A_q, D_q, L_q and compute λ_2, λ_n
- 3 Simulate $\dot{x} = -L_q x$; record 2% settling time
- 4 **end for**
- 5 Fit $\log t_s = c + \beta \log \lambda_2$ on the 72-graph sweep
- 6 Sweep α and compute $\rho_\perp(I - \alpha L)$
- 7 **for** each edge e of the reference mesh **do**
- 8 Remove e ; recompute λ_2 and settling time
- 9 Record Fiedler proxy $(v_{2,i} - v_{2,j})^2$
- 10 **end for**
- 11 Simulate switching $L_{\sigma(t)}$ with fixed dwell time
- 12 Form $H = L_f + B$ and simulate second-order formation dynamics
- 13 Export every metric and plotting coordinate to CSV/JSON

4. Experimental design

The experiments use deterministic normalized systems rather than a physical dataset. This is intentional: the objective is to isolate graph structure and verify mathematical consequences without confounding hardware dynamics, sensing noise, or actuator limits. The complete script is included in the Overleaf package.

Four $n = 12$ canonical graphs are compared under the same scalar initial condition $\mathbf{x}(0)$. Path, ring, and small-world edges receive deterministic weights in $[0.8, 1.2]$; the complete graph is unit weighted. Continuous consensus uses $\kappa = 1$, and 2% settling time is the first time after which RMS disagreement remains below 2% of its initial value. A second experiment generates 72 connected Erdős–Rényi graphs over 12 edge-probability levels and fits a log–log model between λ_2 and settling time.

The small-world mesh is then held fixed for discrete-time and single-edge-removal studies. Discrete step size is swept beyond the theoretical boundary $2/\lambda_n$. Every one of the 24 mesh edges is removed independently; the graph is recomputed and simulated without retuning the controller. The Fiedler edge proxy $(v_{2,i} - v_{2,j})^2$ is compared against the actual fractional λ_2 loss.

Switching consensus alternates every 0.8 s between two connected graphs. Finally, eight double-integrator followers use a ring-plus-chords graph, with followers 1 and 5 pinned to a moving leader. Formation offsets form a radius-2 octagon, $k_p = 2.4$, and $k_v = 2.0$. No collision avoidance, saturation, packet loss, or unmodeled vehicle dynamics is included; the formation experiment is a Laplacian modal study rather than a claim of flight-ready control.

Table 1: Canonical 12-agent spectral and consensus results.

Topology	Edges	λ_2	λ_n	$t_{2\%}$ (s)
Path	11	0.0680	4.0348	19.76
Ring	12	0.2537	4.0314	5.50
Small-world mesh	24	0.8614	7.3534	2.53
Complete	66	12.0000	12.0000	0.33

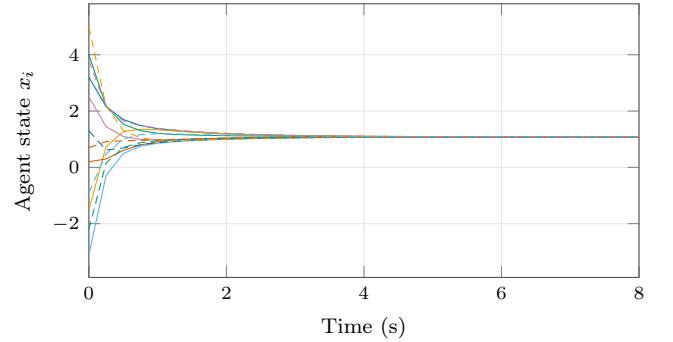


Figure 2: Continuous-time consensus trajectories on the weighted small-world mesh.

5. Results and discussion*5.1. Topology, algebraic connectivity, and consensus speed*

Table 1 exhibits the expected ordering. The weighted path is connected but weakly so; its $\lambda_2 = 0.0680$ produces a 19.76 s settling time. Adding one edge to close the ring raises λ_2 by a factor of 3.73 and reduces settling time to 5.50 s. The 24-edge small-world mesh raises λ_2 to 0.8614 and settles in 2.53 s. A complete graph is an intentionally communication-heavy upper reference: $\lambda_2 = 12$ and measured settling is 0.33 s.

The theoretical bound in (5) is conservative for the sparse graphs because the chosen initial condition does not lie entirely along the Fiedler mode. For the path, the 2% bound is 57.55 s while measured settling is 19.76 s. For the complete graph, all disagreement modes share eigenvalue 12, and the bound 0.326 s essentially equals the measured 0.33 s. This illustrates an important modeling point: λ_2 controls the worst disagreement direction, whereas a particular trajectory may converge faster if its projection onto that mode is small.

The 72-graph sweep removes dependence on a single topology family. Figure 3 shows a strong monotone relationship between algebraic connectivity and settling time. A regression in logarithmic coordinates gives (12):

$$\log t_{2\%} = c - 0.887 \log \lambda_2, \quad R^2 = 0.931. \quad (12)$$

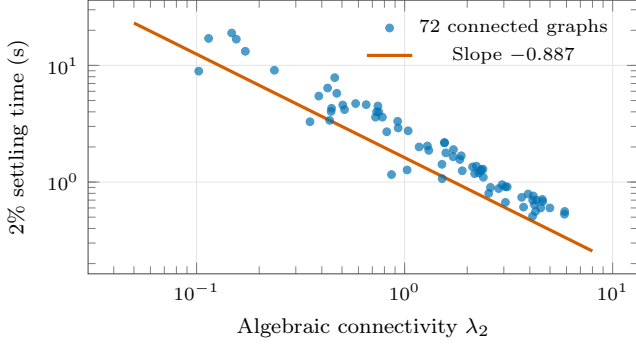


Figure 3: Spectral scaling over 72 additional connected weighted graphs.

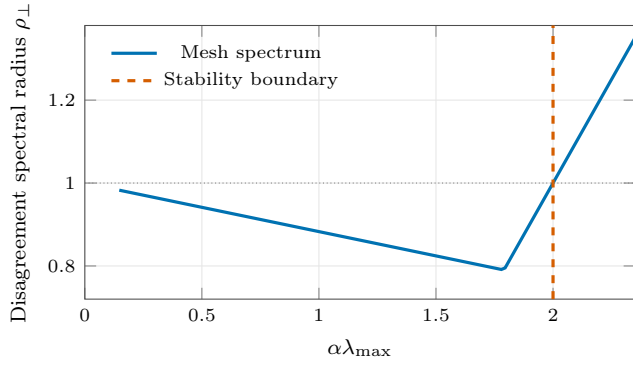


Figure 4: Discrete consensus stability sweep. The non-consensus spectral radius crosses one at the theoretical boundary $\alpha\lambda_{\max} = 2$.

The exponent is close to the ideal -1 scaling suggested by (5). Deviations arise from different eigenvalue distributions and different projections of the common initial condition onto graph eigenvectors. Thus λ_2 is an excellent first-order design indicator, but not a complete prediction of finite-time trajectory shape.

5.2. Discrete-time stability is governed by the opposite end of the spectrum

For the reference mesh, $\lambda_n = 7.3534$, so Equation (7) gives $\alpha < 0.27198$. Figure 4 plots the disagreement spectral radius as the normalized step $\alpha\lambda_n$ approaches and crosses 2. Stability is lost exactly when the largest Laplacian mode reaches -1 . The best point on the numerical sweep occurs at $\alpha = 0.24199$ ($\alpha\lambda_n = 1.7795$) with $\rho_{\perp} = 0.7915$.

This result complements the continuous-time λ_2 discussion. Increasing graph density often improves the slowest mode, yet a naive explicit discrete controller may require a smaller sampling gain because λ_n also grows. Engineering topology design must therefore consider spectral *spread*, not only algebraic connectivity.

5.3. Switching topology and link robustness

Alternating every 0.8 s between two connected graphs preserves convergence. The switching RMS disagreement reaches the 2% criterion in 2.56 s, close to the fixed-mesh 2.53 s result but with visibly changing decay rate in Figure 5. No global state or centralized correction is introduced; the change is solely the active Laplacian.

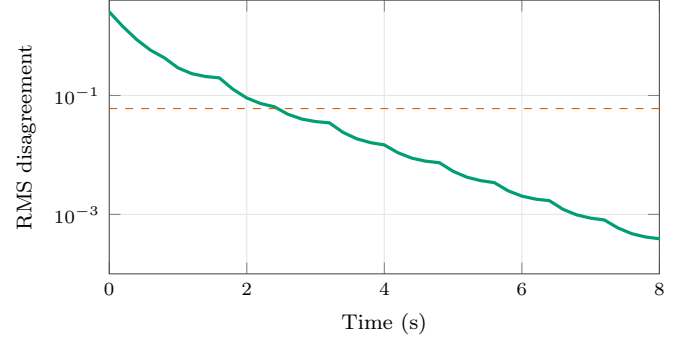


Figure 5: Consensus under 0.8-s topology switching.

Table 2: Most spectrally critical mesh edges.

Removed edge	λ_2	Loss (%)	$t_{2\%}$ (s)
9–12	0.6094	29.26	3.53
3–4	0.6437	25.27	4.04
10–12	0.6582	23.59	2.88
3–5	0.6652	22.78	3.33
2–3	0.7359	14.57	2.09
1–3	0.7399	14.11	2.81
11–12	0.7436	13.68	3.30
4–6	0.7865	8.70	2.82

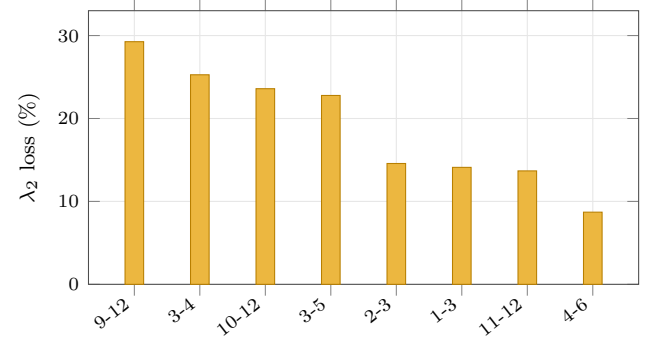


Figure 6: Eight most damaging single-edge removals in the reference mesh. The intact algebraic connectivity is 0.8614.

The single-edge audit demonstrates why edge count alone is not a robustness metric. Removing edge 9–12 reduces λ_2 by 29.26% and increases settling time from 2.53 s to 3.53 s; removing edge 3–4 produces a 25.27% spectral loss and a 4.04 s settling time. Other removals have much smaller effects. The Fiedler-vector proxy computed on the intact graph correlates 0.956 with the actual percentage loss in λ_2 across the 24 removals. This is useful because it provides a topology-only ranking before failures are simulated.

5.4. Grounded-Laplacian Leader–follower formation

The eight-follower ring-plus-chords graph is pinned to the leader at followers 1 and 5. The grounded Laplacian has $\lambda_{\min}(H) = 0.1864$ and $\lambda_{\max}(H) = 6.0$. With $k_p = 2.4$ and $k_v = 2.0$, every modal polynomial in (11) is Hurwitz. Starting from deliberately dispersed positions, position RMSE peaks at 2.9405 and falls below 0.1 at 4.34 s. At 25 s, position RMSE is 0.0703 and velocity RMSE is 0.0467.

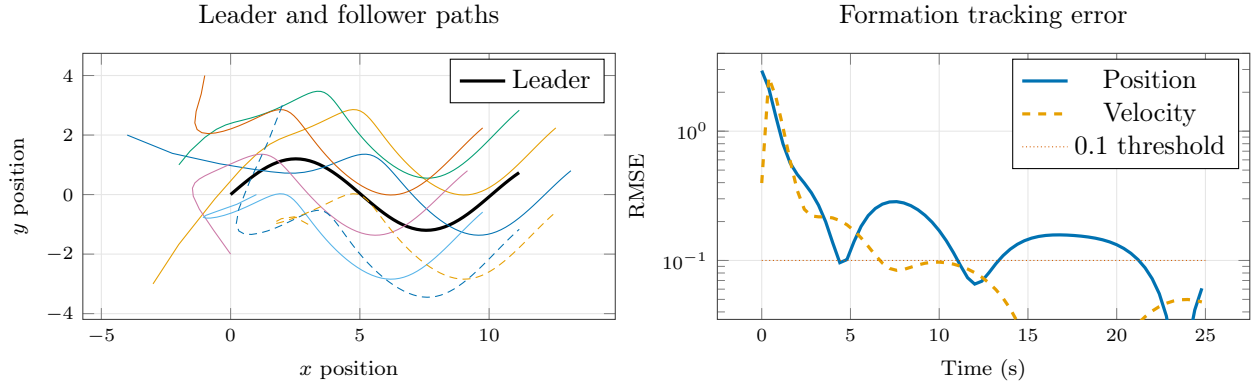


Figure 7: Second-order cooperative formation control. Left: leader trajectory and eight follower paths. Right: grounded-Laplacian position and velocity errors.

Table 3: Leader–follower cooperative-control summary.

Quantity	Value
Followers / pinned followers	8 / 2
k_p / k_v	2.4 / 2.0
$\lambda_{\min}(H)$	0.1864
$\lambda_{\max}(H)$	6.0000
Initial/peak position RMSE	2.9405
Time to position RMSE ≤ 0.1	4.34 s
Final position RMSE	0.0703
Final velocity RMSE	0.0467

5.5. Engineering interpretation and limitations

The results separate four roles of the Laplacian spectrum. First, λ_2 sets the slowest continuous disagreement mode and is therefore a useful consensus-speed metric. Second, λ_n limits explicit discrete update gain. Third, Fiedler-mode edge differences identify links whose loss most damages algebraic connectivity. Fourth, leader pinning replaces the zero eigenvalue with a positive grounded spectrum, turning consensus-to-an-average into tracking-to-a-reference.

These spectral roles should not be overextended. A larger λ_2 is not automatically a better engineering network if it requires excessive communication, if the added links have delay or packet loss, or if sensing quality is heterogeneous. Directed information flow requires nonsymmetric spectral tools. Second-order or nonlinear agents introduce plant dynamics that can interact with graph modes. Collision avoidance, input constraints, actuator saturation, disturbance avoidance, asynchronous sampling, quantization, and cybersecurity are omitted from the numerical model. Recent distributed MPC and prescribed-performance formation work addresses several of those constraints [14], [15], but with correspondingly more complex closed-loop analysis.

6. Conclusion

This paper developed a unified Graph Laplacian model for distributed consensus and cooperative control. Holding agent dynamics and initial conditions fixed revealed a clear spectral hierarchy: as λ_2 increased from 0.0680 for a path to 12 for a complete graph, measured 2% settling time decreased from 19.76 s to 0.33 s. Across 72 additional connected graphs, the fitted spectral exponent was -0.887

with $R^2 = 0.931$, quantitatively supporting the inverse relationship between algebraic connectivity and convergence time.

The same mesh demonstrated the complementary role of the largest Laplacian eigenvalue: discrete consensus lost stability at the predicted boundary $\alpha = 2/\lambda_{\max} = 0.27198$. Edge-loss analysis showed that connectivity degradation is highly nonuniform; the worst edge removal reduced λ_2 by 29.26%, and a Fiedler-vector edge proxy correlated 0.956 with actual spectral loss. Switching between connected topologies preserved convergence, with 2% settling in 2.56 s. Finally, grounding the follower Laplacian through two leader pins produced a positive-definite cooperative operator and an eight-follower second-order formation that reached position RMSE below 0.1 in 4.34 s.

The principal conclusion is that graph design and control design should not be separated. Algebraic connectivity controls the slow mode, the largest eigenvalue constrains sampled gains, Fiedler structure exposes fragile links, and grounded eigenvalues govern leader-information penetration. Future work should place these spectral diagnostics inside hardware-constrained robot, UAV, vehicle-platoon, and microgrid models with packet delay, directed communication, event-triggering, nonlinear dynamics, and safety constraints.

Declarations and ethical statements

Conflict of interest: The authors declare that they have no conflicts of interest.

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Availability of data and materials: The data and/or materials that support the findings of this study are available from the corresponding author upon reasonable request.

CRediT authorship contribution statement

Sandhya B G: Conceptualization, methodology, Visualization & Writing—original draft. **Bhavana B:** Conceptualization & Writing—review and editing.

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