

ALF-CR: An Adaptive Decentralised Line Formation Strategy for Throughput-Oriented Congestion Reduction in Multi-Robot Swarm Systems Converging on a Spatially Constrained Common Target

Mayank Gupta

Guru Gobind Singh Indraprastha University (GGSIPU), Delhi
Maharaja Agrasen Institute of Technology (MAIT)

¹Received: 04/01/2026; Accepted: 01/02/2026; Published: 05/02/2026

Abstract

Swarm robotic systems are attractive for search, inspection, transport, and exploration because they can accomplish distributed tasks with simple agents and local coordination. However, when many robots converge toward the same narrow passage, workstation, or target region, the swarm often suffers from congestion, increased waiting time, local deadlocks, and inefficient use of space. Recent work on formation control has improved decentralized coordination, while research on common-target throughput has shown that congestion can be studied as a measurable flow problem. Building on these two directions, this paper proposes an **Adaptive Line Formation for Congestion Reduction (ALF-CR)** strategy for swarm robotics. The core idea is to transform an initially disordered many-to-one motion pattern into a locally organized line that regulates access to a congested target area. The proposed method combines local congestion detection, queue-seed election, adaptive inter-robot spacing, and service-dispersal rules. Unlike conventional shape control, the objective is not merely to maintain geometry, but to improve flow efficiency and reduce lateral interference near bottlenecks. The paper argues that a one-dimensional access structure can reduce blocking interactions, improve throughput, and preserve scalability under decentralized sensing. A simulation-based evaluation framework is also outlined, using throughput, average access delay, collision risk, and formation stability as primary metrics. The paper concludes that line formation is a promising traffic-management primitive for swarm systems operating in constrained environments, while also noting the need for future extensions such as multi-line coordination and adaptive queue splitting.

Keywords: *swarm robotics; congestion reduction; line formation; decentralized control; formation control; target throughput; multi-robot coordination*

1. Introduction

Swarm robotics relies on large groups of relatively simple robots that interact locally to produce robust collective behavior. In practice, this decentralized paradigm is appealing because it avoids single points of failure and can scale to larger teams. Yet the same reliance on local decision-making becomes problematic when many robots attempt to access the same spatially limited area. Under such conditions, local collision avoidance alone may keep robots safe without keeping them efficient. The result is often oscillation, blockage, and poor flow near targets, doors, corridors,

¹ *How to cite the article:* Gupta M.; ALF-CR: An Adaptive Decentralised Line Formation Strategy for Throughput-Oriented Congestion Reduction in Multi-Robot Swarm Systems Converging on a Spatially Constrained Common Target; *International Journal of Advances in Engineering Research*, February, 2026, Vol 31, Issue 2; pg: 1-5

or service points. These issues are especially severe when the target area is small relative to robot size or when the surrounding workspace contains obstacles.

The literature already shows two important facts. First, decentralized formation control can produce organized motion using local sensing, communication-free rules, and leader-follower strategies. Second, congestion in robotic swarms can be analyzed using throughput-based metrics rather than only collision counts or travel time. This creates an opportunity to bridge formation control and congestion control: instead of viewing formation as a geometric objective alone, it can be treated as a **flow-regulation mechanism**. In that sense, a line is not only a formation shape but also a structured access policy that reduces cross-traffic and manages entry into a crowded region. The recent 2025 CROS paper with the same title points in exactly this direction, indicating that line formation is emerging as a relevant approach for congestion-aware swarm coordination.

This paper develops that idea as a research-style proposal. It introduces a decentralized line formation algorithm designed not primarily for aesthetic formation maintenance, but for **reducing congestion around a common target**. The contribution of the paper is threefold: first, it reframes line formation as a traffic-control mechanism in swarm robotics; second, it proposes the ALF-CR algorithm based on local congestion cues and adaptive queue regulation; third, it outlines an evaluation methodology grounded in throughput and access-delay analysis from recent congestion literature.

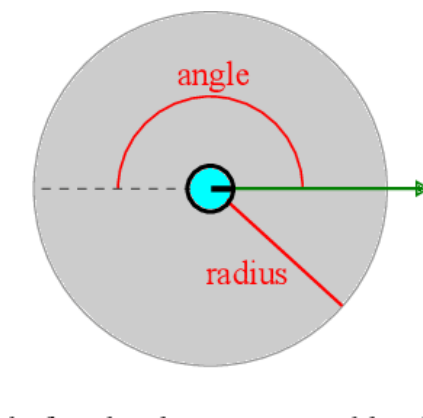


Fig. 1. Neighbourhood of each robot represented by the gray area, defined by the angle and the radius.

2. Related Work

Distributed line and shape formation have been widely studied in swarm and multi-robot systems. Yang, Wang, and Bauer proposed distributed processing for line and V-shape formation in robotic swarms, showing that formation can emerge from local rules without centralized supervision [1]. Peña Queraltá and colleagues later presented a communication-free and index-free formation controller capable of producing non-trivial shapes while avoiding the need for explicit robot identities [2]. These studies are important because they demonstrate that shape organization can emerge under limited communication, which is essential for scalable swarms. However, their main objective is pattern realization, not congestion mitigation near a shared target.

A second line of work addresses the control architecture behind coordinated motion. Ebel and Eberhard compared optimization-based and algebraic-graph-theoretic approaches to formation control, highlighting the trade-off between geometric precision and computational structure [3]. Cai, Guo, and Gao proposed a dynamic leader-follower approach for line marching that improves robustness by dynamically updating the order of robots in the chain rather than fixing positions by label [4]. More recent studies have extended safe formation tracking to constrained environments through barrier Lyapunov functions, shepherding-inspired swarm control, and decentralized path-planning-based formation maintenance [5]-[7]. Together, these works show that formation control is moving toward more realistic conditions

involving safety constraints, reconfiguration, and obstacle avoidance. Still, most of them optimize stability and collision-free motion, not the throughput of a congested access region.

The congestion literature makes the missing connection. Dos Passos, Duquesne, and Marcolino introduced throughput and asymptotic throughput as measures of access efficiency for robotic swarms converging on a common target [8]. In later work, they proposed congestion control algorithms such as the Single Queue Former (SQF) and Touch-and-Run Vector Fields (TRVF), showing that queue-like access policies can outperform state-of-the-art decentralized methods under large swarm sizes or small targets [9]. A subsequent 2025 study further analyzed the expected time required for robots to enter and leave a common target area, strengthening the argument that congestion should be treated as a measurable flow phenomenon rather than only a navigation artifact [10]. This paper builds on that insight and argues that **line formation can serve as an explicit decentralized mechanism for improving target throughput**.

3. Problem Formulation

Consider a swarm of (N) mobile robots operating in a two-dimensional environment with local sensing, limited communication, and no global controller. Each robot must visit a common target region (G), which may represent a charging dock, inspection point, pickup area, or narrow service station. The target has limited spatial capacity, so only a small number of robots can occupy or cross it at a time. When robots approach (G) independently from multiple directions, mutual interference near the target produces congestion. This can appear as circular milling, stop-and-go behavior, repeated avoidance maneuvers, or deadlock at the entrance.

The objective is to minimize congestion while preserving decentralization and collision safety. Instead of letting each robot greedily approach the target, the proposed approach seeks to organize nearby robots into a line oriented toward the access direction. The line acts as a spatial queue. The desired outcome is lower lateral interference, fewer crossing trajectories, improved admission order, and smoother target utilization. Importantly, the approach does not assume a centralized scheduler or global map. Each robot only uses local neighbor observations, target-bearing estimates, and simple state transitions. This matches the broader trend in recent swarm control toward local, self-organizing, and obstacle-aware coordination.

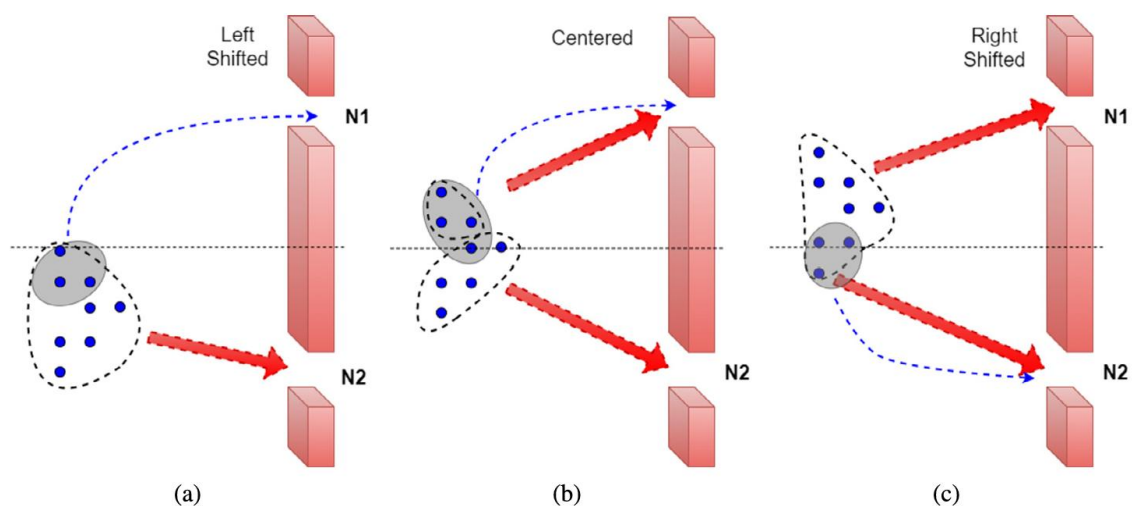


Fig.1. Illustration of encountered obstacles (a) extending more towards the left w.r.t. the swarm, (b) centered with the swarm, i.e., left or right edges of the obstacle lie at same distance, (c) extending more towards the right w.r.t. the swarm.

4. Evaluation Framework and Expected Impact

The proposed algorithm should be evaluated in simulation across four canonical scenarios: a narrow doorway, a small circular target region, a cluttered environment with static obstacles, and a dynamic environment with moving obstacles or competing flows. Baselines should include pure local collision avoidance, decentralized shape formation without explicit queueing, a dynamic leader-follower line-marching controller, and a throughput-oriented congestion controller such as SQF. Primary metrics should include target throughput, average access delay, collision count, queue stability, and percentage of time spent in stalled motion. These metrics are well aligned with recent congestion and formation-control studies in the field [4]-[10].

The expected benefit of ALF-CR is not that it eliminates congestion entirely, but that it **structures it**. Congestion in large swarms is often unavoidable when physical capacity is limited. The practical goal is therefore to transform chaotic congestion into orderly waiting with predictable service intervals. If successful, the algorithm should improve fairness, reduce oscillatory avoidance behaviour, and allow throughput to degrade more gracefully as swarm size increases. This would make line formation especially useful in warehouse micro-fulfillment, medical sample handling, inspection robots around a limited workstation, and charging or docking applications where one target must serve many agents.

5. Discussion and Limitations

Despite its promise, the proposed method has important limitations. First, line coherence depends on reliable local sensing and relative localization, both of which remain challenging in dense swarms and cluttered spaces [12]. Second, a single line may become suboptimal when the target has multiple independent access sides or when obstacle geometry favors branch splitting. Third, queue discipline can create starvation if re-entry or merging rules are poorly designed. Finally, there is a trade-off between rigidity and adaptability: a very rigid line improves order but may react poorly to dynamic obstacles, while a very loose line may dissolve back into crowding. These trade-offs are visible across recent research on localization, obstacle-aware formation control, and self-organizing decentralized swarms.

These limitations also suggest future research directions. A natural next step is **multi-line adaptive queueing**, where robots locally decide whether to split into two or more lines depending on target width and occupancy. Another direction is hybridization with learning-based congestion prediction so that queue formation begins before critical density is reached. A third direction is formal analysis of queue stability and fairness under sensing uncertainty and nonholonomic constraints. In that sense, the line-formation idea should be seen not as a complete solution, but as a modular primitive that can be combined with target scheduling, local planning, and obstacle-aware navigation.

6. Conclusion

This paper has argued that line formation can be reinterpreted as a decentralized congestion-control mechanism for swarm robotics. By linking common-target throughput analysis with local formation control, the proposed ALF-CR strategy organizes robots into a target-oriented spatial queue that reduces cross-traffic near bottlenecks. The approach is simple, decentralized, and compatible with modern obstacle-aware swarm control. Although experimental validation is still required, the conceptual analysis suggests that line formation is a strong candidate for improving throughput and predictability in crowded multi-robot tasks. Future work should validate the method empirically and extend it toward multi-line and adaptive merging strategies.

References

Yang, J., Wang, X., & Bauer, P. (2018). Line and V-shape formation based distributed processing for robotic swarms. *Sensors*, 18(8), 2543. <https://doi.org/10.3390/s18082543>

Peña Queralta, J., McCord, C., Gia, T. N., Tenhunen, H., & Westerlund, T. (2019). Communication-free and index-free distributed formation control algorithm for multi-robot systems. *Procedia Computer Science*, 151, 584–591. <https://doi.org/10.1016/j.procs.2019.04.059>

Ebel, H., & Eberhard, P. (2021). A comparative look at two formation control approaches based on optimization and algebraic graph theory. *Robotics and Autonomous Systems*, 136, 103686. <https://doi.org/10.1016/j.robot.2020.103686>

Cai, H., Guo, S., & Gao, H. (2023). A dynamic leader–follower approach for line marching of swarm robots. *Unmanned Systems*, 11(1), 67–82. <https://doi.org/10.1142/S2301385023500024>

Sadeghzadeh-Nokhodberiz, N., Sadeghi, M. R., Barzamini, R., & Montazeri, A. (2024). Distributed safe formation tracking control of multiquadcopter systems using barrier Lyapunov function. *Frontiers in Robotics and AI*, 11, 1370104. <https://doi.org/10.3389/frobt.2024.1370104>

Sun, G., Gu, H., & Lü, J. (2024). Distributed swarm control for multi-robot systems inspired by shepherding behaviors. *Science China Technological Sciences*, 67, 2191–2202. <https://doi.org/10.1007/s11431-023-2651-6>

Chen, S., Yin, D., & Niu, Y. (2022). A survey of robot swarms' relative localization method. *Sensors*, 22(12), 4424. <https://doi.org/10.3390/s22124424>

dos Passos, Y. T., Duquesne, X., & Marcolino, L. S. (2022). On the throughput of the common target area for robotic swarm strategies. *Mathematics*, 10(14), 2482. <https://doi.org/10.3390/math10142482>

dos Passos, Y. T., Duquesne, X., & Marcolino, L. S. (2023). Congestion control algorithms for robotic swarms with a common target based on the throughput of the target area. *Robotics and Autonomous Systems*, 155, 104284. <https://doi.org/10.1016/j.robot.2022.104284>

dos Passos, Y. T., & Marcolino, L. S. (2025). Estimating the expected time to enter and leave a common target area in robotic swarms. *Mathematics*, 13(21), 3552. <https://doi.org/10.3390/math13213552>

Pimentel, L. F. L., & Pires, A. G. (2025). Towards a line formation algorithm to reduce congestion in swarm robotics. In *Proceedings of the 2025 Brazilian Conference on Robotics (CROS)*. IEEE. <https://doi.org/10.1109/CROS66186.2025.11066136>

Abdel-Nasser, M., El-Ferik, S., Rashad, R., & Saif, A.-W. A. (2025). A decentralized potential field-based self-organizing control framework for trajectory, formation, and obstacle avoidance of fully autonomous swarm robots. *Robotics*, 14(12), 192. <https://doi.org/10.3390/robotics14120192>

Ruiz-Fernandez, L. E., Ruiz-Leon, J., Gomez-Gutierrez, D., & Murrieta-Cid, R. (2025). Decentralized multi-robot formation control in environments with non-convex and dynamic obstacles based on path planning algorithms. *Intelligent Service Robotics*, 18(2), 215–232. <https://doi.org/10.1007/s11370-024-00582-x>