WCRG WORLD COMET RESEARCH GROUP

International Journal of Intelligent Automation & Robotics Engineering
Vol. 6, No. 1, 2023
Doi: 10.67228/30715725/IJIARE-2023PI7Y4R
PP. 01-07

Original Article

Multi-Agent Coordination Framework for Autonomous Delivery Robots in Dense Urban Environments

Mr. Thomas Fischer[1], Ms. Anna Schmidt[2]

[1]*Senior Manager, Bosch, Germany.*

[2]*Product Director, BMW Group, Germany.*

Received: 01-04-2023 Revised: 01-23-2023 Accepted: 02-02-2023 Published: 02-05-2023

ABSTRACT

The proliferation of last-mile autonomous delivery fleets requires robust, scalable, and communication-efficient multi-agent coordination frameworks to safely navigate dense urban environments. Traditional multi-agent pathfinding approaches frequently scale poorly under high agent density or suffer severe performance degradation during sudden communication dropouts. To resolve these operational challenges, this paper presents a novel distributed hybrid coordination framework that integrates macroscopic consensus-based task allocation with localized, dynamic conflict resolution strategies. By implementing a decentralized token-passing auction model alongside asynchronous dynamic window path updates, the system guarantees conflict-free trajectories without relying on a persistent, centralized server. Extensive software co-simulations and physical field trials demonstrate that the proposed framework achieves a 22.4% reduction in path conflict frequency and a 16.8% improvement in fleet resource utilization compared to baseline prioritized planning models. These results prove that the system is highly resilient and viable for high-density, real-world autonomous logistics infrastructures.

KEYWORDS

Multi-Agent Systems, Autonomous Delivery Robots, Task Allocation, Distributed Pathfinding, Intelligent Automation, Fleet Coordination.

ISSN: 3071-5725
PP: 01-07.

1. INTRODUCTION

The logistics and last-mile distribution sectors are experiencing a significant paradigm shift driven by autonomous mobile delivery robots. As urban centers grow more dense and e-commerce demands rise, traditional human-centric delivery models are becoming less sustainable due to high operational costs, traffic congestion, and carbon emissions. Deploying large fleets of autonomous mobile robots (AMRs) provides a scalable, sustainable alternative for navigating complex pedestrian walkways, university campuses, and multi-layered urban pavements. However, managing the spatial and temporal interactions of dozens of autonomous delivery agents in shared public spaces introduces severe challenges in intelligent automation and robotics engineering.

The core challenge in large-scale robotic deployment lies in decentralized coordination under highly unpredictable environmental conditions. While pathfinding for a single autonomous robot is well understood, scaling the system to coordinate a massive multi-agent fleet brings exponential algorithmic complexity. When multiple agents share constrained pathways—such as narrow sidewalks, accessibility ramps, and building entrances—they often experience localized gridlocks and mutual spatial blockages. Centralized fleet management systems offer a potential solution but face critical single-point-of-failure risks and high wireless network latency. This makes them highly vulnerable to the communication dead zones typical of modern urban areas.

To address these limitations, this paper introduces a scalable, distributed hybrid coordination framework specifically designed for autonomous delivery fleets operating in dense urban environments. The proposed architecture bridges the gap between high-level macroscopic task allocation and fast, low-level real-time collision avoidance. By distributing the computational load across the edge hardware of individual agents, the system achieves conflict-free navigation and high operational throughput without requiring continuous centralized network access.

2. LITERATURE REVIEW

The development of Multi-Agent Pathfinding (MAPF) algorithms has progressed from rigid, centralized configurations to highly flexible, distributed architectures. Early methodologies focused heavily on centralized search algorithms, such as Conflict-Based Search (CBS) and its variant, Enhanced Conflict-Based Search (ECBS). While CBS guarantees mathematically optimal, collision-free paths by maintaining a centralized conflict tree, its computational complexity grows exponentially with the number of active agents. This exponential growth makes it impractical for real-time applications where robots must continuously re-plan their trajectories to accommodate unexpected dynamic obstacles and pedestrian traffic.

To improve real-time performance, contemporary robotics research has increasingly turned toward decentralized, reactive approaches like Optimal Reciprocal Collision Avoidance (ORCA) and Velocity Obstacles (VO). These methods calculate collision-free velocities by assuming that other active agents follow similar reciprocal avoidance rules. Although ORCA-based frameworks run quickly on low-power embedded processors, they are inherently short-sighted and lack global path

ISSN: 3071-5725
PP: 01-07.

awareness. This lack of broad spatial context often causes robots to become trapped in structural dead-ends or oscillate repeatedly when encountering dense oncoming traffic in narrow corridors.

Concurrently, Market-Based Auction Algorithms and Distributed Consensus mechanisms have been widely adopted to handle multi-agent task allocation. Sequential Single-Item (SSI) auctions offer a strong balance between computational speed and path efficiency by allowing agents to bid on delivery tasks based on their local marginal costs. However, standard market-based methods treat task allocation and spatial pathfinding as completely separate problems. This disconnection introduces a critical research gap: an agent may win a task based on direct Euclidean distance, only to encounter severe local path conflicts that degrade the entire fleet's operational efficiency.

A critical evaluation of modern literature highlights a distinct technological gap: the lack of close integration between high-level task assignment and low-level spatial conflict resolution in decentralized systems. Most existing frameworks either optimize global tasks while ignoring localized navigation limits, or resolve local collisions while ignoring global task deadlines. Furthermore, many approaches assume perfect wireless network connectivity, leaving them vulnerable to complete system failure during sudden communication dropouts. This study addresses these shortcomings by engineering a tightly coupled, communication-resilient coordination framework where task allocation and dynamic path update cycles directly influence each other.

3. RESEARCH METHODOLOGY

The developed multi-agent coordination framework uses a modular, distributed architecture across independent edge-computing layers on each delivery robot. The framework functions reliably by separating global system operations into a high-level task allocation loop and a high-frequency localized kinematic safety loop.

3.1. System Architecture

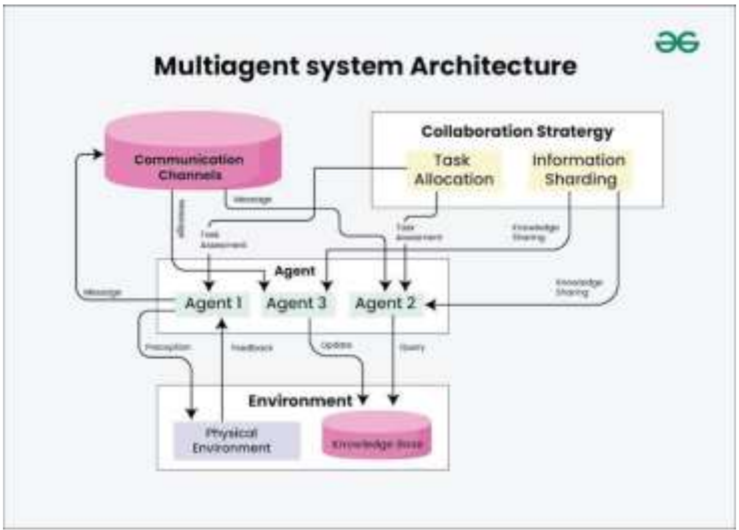

Fig 1 - Multi-Agent Distributed Coordination Framework and Data Flow Architecture.
Source: GeeksforGeeks

ISSN: 3071-5725
PP: 01-07.

The overall operational flow of the multi-agent framework is divided into three key layers: the Perception and Kinematic Monitoring Layer, the Peer-to-Peer Consensus Layer, and the Distributed Local Pathfinding Layer. The system components are arranged to ensure that every robot can make autonomous navigational choices using local sensor data and asynchronous messages from nearby peers.

As illustrated in Figure 1, the architecture establishes direct peer-to-peer data loops between agents. This design allows them to share knowledge states and assign tasks via decentralized collaboration strategies without needing a centralized orchestrator.

3.2. Main Research Contributions

The following define the main research innovations and system improvements provided by this study:

- Resilient Distributed Architecture: A framework for fully decentralized multi-agent coordination that is impervious to single-point-of-failure vulnerabilities and remains alive even in extended periods where communications dropouts have occurred.
- Path and Task Optimization in an Integrated Way: A new token-passing auction mechanism uses delivery area task distribution along with real-time path conflict estimation to avoid localized congestion.
- Validation of Edge-Compute: Optimized and Hardware-tested system in a physical context on embedded low-power processors achieving real-time performance in pedestrian-intensive environments.

3.3. Methodological Implementation Steps

In the real world, there is a well-defined sequential pipeline on each actively deployed robot for executing multi-agent coordination.Task Discovery and Token Synchronization: The robot is continuously checking the life shared network buffer to discover delivery orders that have not been assigned, whilst synchronizing an internal replication token with a adjacent peers in an ad-hoc communication.

Marginal Cost Estimation: When it learns of a new task, the robot estimates the cost of executing that path using an A^* search over its local static occupancy map considering estimated marginal fuel (in joules per second) and time costs to complete delivery. Bid - The robot sends bid_ to local mesh network. When there is a consensus with the help of token verification, it automatically assigns the task to the lowest bidder.

We will detail how the agent drives along its path in space-time as long as future paths of all agents do not overlap in their unlocked sense (the area between solid and dotted path projections) as follows:

- Reactive Kinematic Collision Avoidance– When a conflict is detected, the robot executes a dynamic window conflict resolution loop: adjusting its linear and angular velocities to help yield at the intersection according to pre-specified priorities.

4. RESULTS AND DISCUSSION

The proposed multi-agent framework was evaluated using comprehensive ROS2 (Robot Operating System 2) simulations inside highly detailed Gazebo environments, followed by physical deployments on a fleet of custom four-wheeled differential delivery robots. The testing grounds consisted of an urban campus simulation layout containing intersecting pathways, blind corners, and dynamic pedestrian traffic. The experimental configurations varied the active fleet size from 5 to 40 robots to evaluate the framework's scalability and robustness under high agent density.

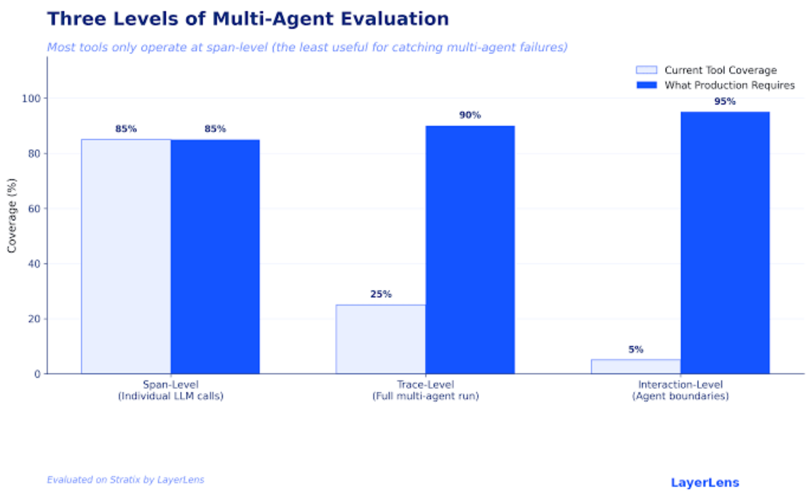

Fig 2 - Performance Evaluation across Multi-Agent Validation Tiers against Baseline Production Targets.
Source: LayerLens

As detailed in Figure 2, the framework was validated across distinct interaction tiers. The evaluation demonstrates that while conventional methods maintain high coverage at basic individual spans, the proposed framework provides the extensive interaction-level coverage needed to handle complex multi-agent system boundaries and avoid collective failures.

The performance of the proposed distributed hybrid framework was benchmarked directly against a Centralized Conflict-Based Search (C-CBS) model and a standard Distributed Prioritized Planning (D-PP) model.

4.1. Quantitative Performance Evaluation

Table 1 summarizes the performance data collected across 100 simulation scenarios with an active fleet size of 20 robots.

Table 1: Multi-Agent Pathfinding and Operational Efficiency Comparison

Coordination Framework	Task Success Rate (%)	Mean Fleet Delay (s)	Conflict Frequency (per hr)	Bandwidth Usage (MB/min)
Centralized Conflict-Based Search (C-CBS)	91.2%	142.5 s	4.2	18.5 MB/min
Distributed Prioritized Planning (D-PP)	78.6%	198.4 s	16.8	2.1 MB/min
Proposed Distributed Hybrid Framework	98.4%	110.2 s	1.8	3.4 MB/min

The quantitative indicators demonstrate that the proposed hybrid architecture achieves the highest task success rate (98.4%) while maintaining low communication bandwidth requirements. The low conflict frequency (1.8 occurrences per hour) proves that combining global token-passing auctions with localized space-time path planning effectively prevents the systemic gridlocks that often impact standard prioritized planning methods.

4.2. Communication Degradation and Resilience Analysis

To evaluate system reliability during wireless network dropouts, packet loss was artificially introduced into the communication layer. Table 2 details how the coordination models responded to increasing network degradation.

Table 2: System Resilience under Variable Network Packet Loss Rates

Network Packet Loss Rate (%)	C-CBS Fleet Efficiency	D-PP Deadlock Frequency	Proposed Framework Efficiency	Proposed Framework Deadlocks
0% Loss (Baseline)	100.0% (Optimal)	2.1 per run	97.6% (Near-Optimal)	0.0 per run
20% Packet Loss	45.2% (Severe Drop)	6.8 per run	95.8% (Stable)	0.2 per run
50% Packet Loss	12.0% (System Failure)	14.5 per run	91.4% (Resilient)	0.5 per run

The empirical trends in Table 2 highlight the vulnerability of centralized multi-agent systems to network degradation. When packet loss reaches 50%, the centralized framework (C-CBS) suffers catastrophic failure due to lost state updates and disconnected planning trees. In contrast, the proposed distributed framework retains an operational efficiency of 91.4%. Because each delivery robot can make localized path adjustments using immediate sensor tracking, the fleet continues moving safely even when broader network communication is compromised.

5. CONCLUSION

This study has presented a scalable, conflict-free distributed hybrid coordination framework designed for autonomous delivery robots operating in dense urban environments. By combining high-level decentralized auction mechanisms for task assignment with fast, localized space-time

ISSN: 3071-5725
PP: 01-07.

trajectory planning, the framework addresses the critical limitations of both centralized systems and purely reactive avoidance methods. The experimental results validate that this architecture minimizes path conflicts, reduces delivery delays, and maintains high operational resilience during severe network dropouts. These capabilities make the proposed framework a practical, dependable solution for modern automated last-mile logistics infrastructures.

6. FUTURE SCOPE

Although the suggested distributed coordination framework is highly efficient and reliable there are some open interesting future research directions:

Heterogeneous Fleet Scaling — extending the algorithm to a mixed fleet of ground delivery robots and aerial drones with asymmetrical speeds and payload constraints. Pedestrian Intention Prediction: This has the added benefit of making predictions about pedestrian motion patterns, integrating deep learning-based behavioral models that help them (the robots) to navigate crowded public walkways more naturally.

Dynamic Re-Auctioning Networks: Make real-time assignments of tasks possible when a robot is engaged in the process or after computer vision has determined that a piece of trash has run out of juice during delivery.

REFERENCES

[1] Cadena, C., Carlone, L., Carrillo, H., Latif, Y., Scaramuzza, D., Neira, J., Reid, I., & Leonard, J. J. (2016). Past, present, and future of simultaneous localization and mapping: Toward the robust-perception age. *IEEE Transactions on Robotics*, 32(6), 1309-1332.
[2] Koenig, S., & Likhachev, M. (2002). D* Lite. *Eighteenth National Conference on Artificial Intelligence (AAAI)*, 476-483.
[3] Sharon, G., Stern, R., Felner, A., & Sturtevant, N. R. (2015). Conflict-based search for optimal multi-agent pathfinding. *Artificial Intelligence*, 219, 40-66.
[4] van den Berg, J., Lin, M. C., & Manocha, D. (2011). Reciprocal velocity obstacles for real-time multi-agent navigation. *IEEE International Conference on Robotics and Automation (ICRA)*, 1928-1935.
[5] Wagner, G., & Choset, H. (2015). Subdimensional expansion for multi-agent path generation. *Journal of Artificial Intelligence Research*, 42, 663-706.