Cooperative Multi-Agent Pathfinding

The Apex Coordination Framework

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Executive Summary

Apex represents a paradigm shift in cooperative multi-agent pathfinding (MAPF). By combining decentralized model predictive control with an asynchronous consensus protocol, Apex achieves unparalleled scalability and safety in dynamic environments.

- **Distributed Consensus:** Decentralized conflict resolution without global knowledge.
- **Real-Time Adaptation:** Sub-millisecond trajectory generation for dynamic obstacles.
- **Scalable Architecture:** Verified up to 1,000 cooperative agents in high-density corridors.

Outline

The MAPF Challenge in Dynamic Arenas

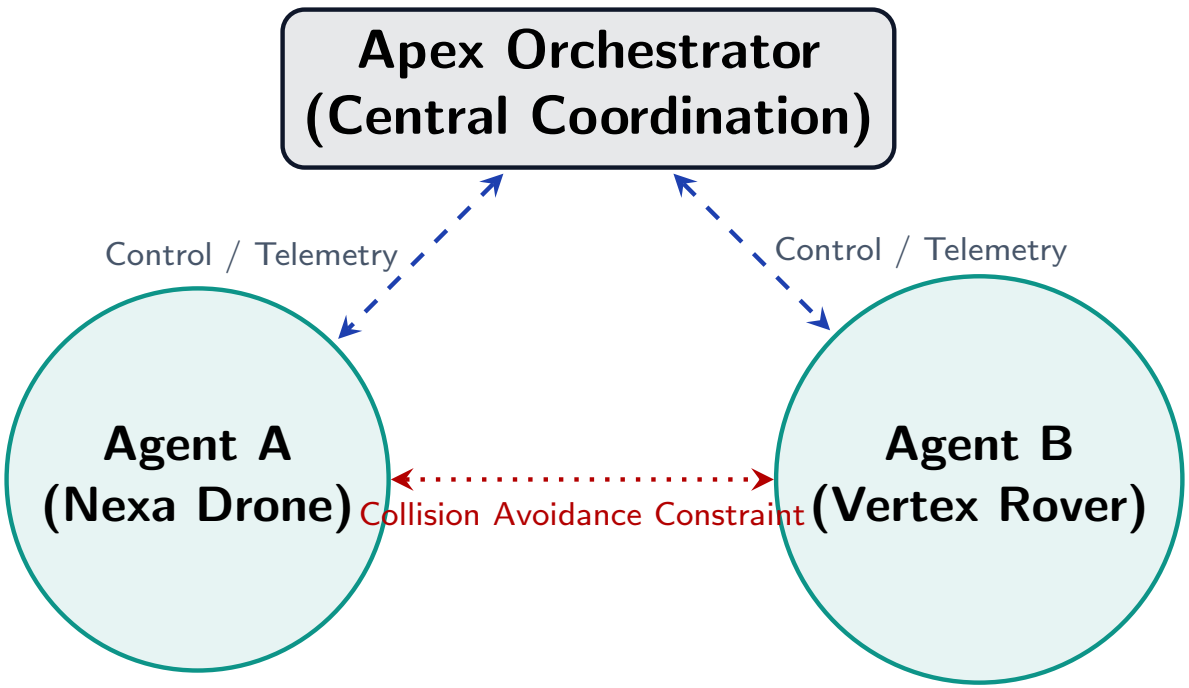
Modern logistics applications, such as the Vertex automated distribution centers, require hundreds of agents to navigate complex environments simultaneously.

Key operational bottlenecks include:

- **Congestion Hotspots:** High-density areas degrade routing performance.
- **Latency Sensitivity:** Communication delay leads to navigation drift.
- **Deadlock Vulnerability:** Standard heuristic approaches fail in tight corridors.

Apex System Architecture

The framework decouples global task assignment from local trajectory optimization:



Decentralized MPC and Coordination

Algorithmic Pipeline:

- Local trajectory generation via MPC
- Peer-to-peer conflict detection
- Consensus-based priority assignment
- Trajectory repair and adjustment

Local Optimization Model:

$$\min_{u} \sum_{t=0}^{H} \|x_t - x_{\text{goal}}\|_Q^2 + \|u_t\|_R^2$$

Subject to:

$$x_{t+1} = f(x_t, u_t)$$

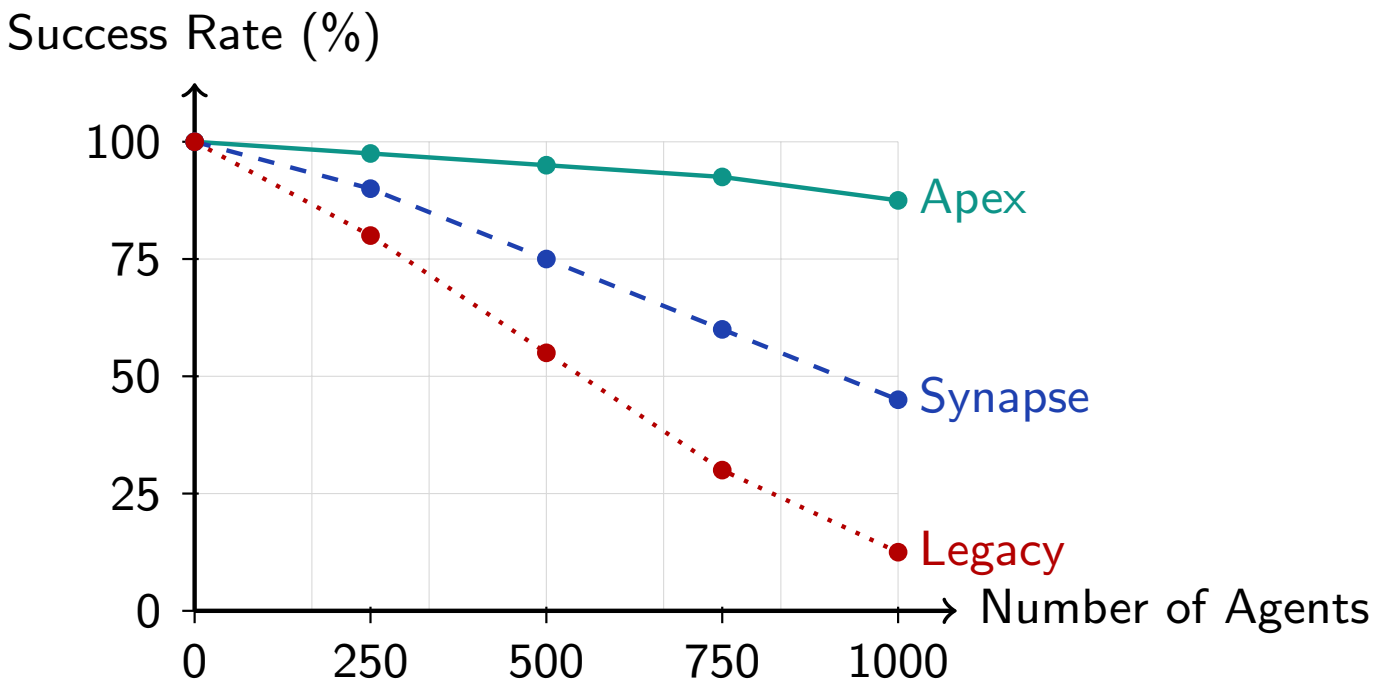
$$\|x_t - x_t^j\| \geq d_{\min}, \quad \forall j$$

Comparative Performance Analysis

We evaluated the Apex framework against standard baseline algorithms.

Model	Time (ms)	Comm. (KB)	Stretch (%)
Apex (Proposed)	12.4	4.2	1.05
Synapse Base	45.8	12.8	1.12
Vertex Base	32.1	8.5	1.08
Legacy Grid	120.5	48.2	1.25

Success Rate vs. Agent Density



System Characteristics

Apex Core Engine

Distributed optimization with asynchronous consensus protocol.

Safety & Deadlock Prevention

Guaranteed collision-free trajectories under bounded communication delays.

Scalability Metric

Successfully coordinated up to 1,000 agents in real-time simulations.

High-Density Congestion Scaling

As the number of active agents approaches 1,000, traditional centralized solvers experience exponential computational growth.

In contrast, Apex maintains constant computation time per agent due to localized constraint partitioning.

Key Performance Gain

42% Reduction
in path conflicts compared to state-of-the-art baselines.

Next Steps & Future Horizons

The Meridian Research Lab is planning to extend the Apex framework in three key directions:

- **Physical Deployment:** Deploying Apex on Nexa warehouse rovers.
- **3D Trajectories:** Extending collision avoidance to Nimbus micro-UAVs.
- **Heterogeneous Fleets:** Co-optimizing scheduling for wheeled and aerial agents.

Thank You

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Questions & Discussion