Distributed Constraint-Based Search using Multi-Hop Communication

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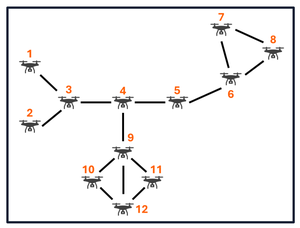
INTRODUCTION

- **Decentralized Multi-Agent Pathfinding (MAPF):** a distributed approach to MAPF, where each agent makes its own decisions to avoid conflicts
- **Advantages:** Improves scalability, robustness, and flexibility, especially in large-scale environments
- **Applications:** Warehouse Automation and Vehicle Routing
- **Challenges:** Multi-hop communication introduces complexities, such as ensuing accurate and timely data exchange
- **Solution:** *Hierarchical Composition for Multi-Hop Distributed Communication (HCMDC)*
  - Introduces a heuristic for creating subproblems in distributed settings that leverages network communication and greedy solution passing



Simple example of a decentralized drone swarm's communication network.

Edges indicate lines of communication between agents.

Agents are numbered for future examples

METHOD

- **HCMDC:** Extends Hierarchical-Composition Conflict-Based Search (HC-CBS)[1] to solve decentralized MAPF in multi-hop networks
- Two main components:
  - **Network Navigator**: Assigns roles to agents to optimize workload distribution and finds simple communication paths
  - **Pathfinder**: Solves MAPF subproblems along the communication paths

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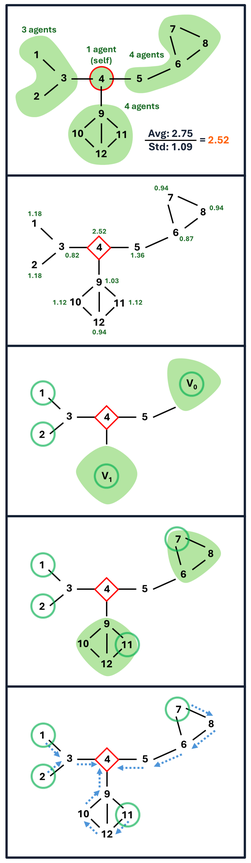
NETWORK NAVIGATOR

- **Role Assignment:** Assigns roles to manage communication efficiently
  - **Initiators**: start the search process by transmitting path information
  - **Intermediaries**: relay and merge information, ensure a consistent flow of data through the network
  - **Terminator**: receives and consolidates all paths to complete the search process
- **Workload balancing:** Selects the terminator based on the transmission ratio of transmitted agents to balance the computational load
- **Acyclic Reduction:** Transforms strongly connected components into virtual nodes to reduce the network to an acyclic structure, simplifying role assignment and communication paths
  - Simplifies role assignment: nodes in reduced graph with a single neighbor are assigned as initiators
- **Simple Communication Path:** Communication path is found such that each node is visited only once along a simple path
  - Optimizes communication efficiency
  - Reduces redundant transmission



For a given agent (drone 4, circled in red), subproblem sizes at each neighbor are counted. These counts calculate the average, standard deviation, and transmission ratio (2.52).

Calculations are repeated for all agents, and the agent with the lowest transmission ratio becomes the terminator (red diamond).

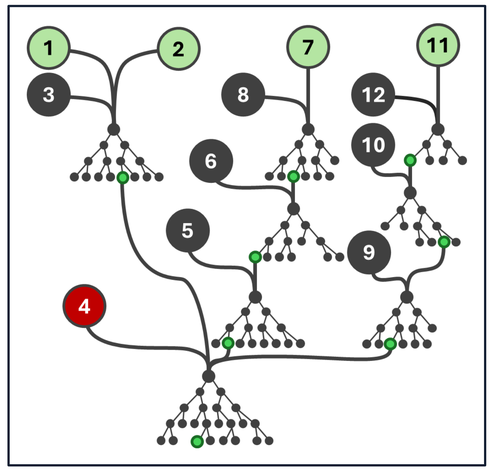
Graph is reduced to acyclic, and agents with a single neighbor become initiators (green double circle).

Virtual initiators are expanded, and the fewest necessary initiators are assigned within each virtual node to ensure all agents are covered efficiently.

Simple communication paths are found from initiators to the terminator (dotted blue arrows). These ensure each agent is visited once, with each transmitting only once.

PATHFINDER

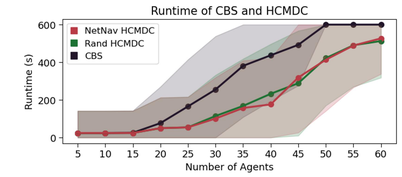
- **Incremental Path Solving:** Agents solve subproblems incrementally
  - Uses information received from prior agents
  - Ensures safe paths for agents in each subproblem
- **Greedy Solution Passing:** Only transmits solution nodes between agents
  - Minimizes network traffic and computation overhead
- **Gradual Problem Construction:** Each agent solves its part of the MAPF problem before passing it on to gradually construct the full MAPF problem
  - Leverages concepts from HC-CBS to hierarchically solve the full MAPF problem
- **Final Assembly:** At the terminator, the full MAPF problem is solved and the solution can be transmitted back to the agents along the same communication paths

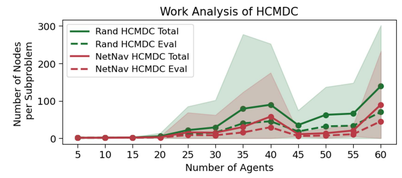


- *Search starts with initiators (green)*
- *Initiators pass path info to intermediaries (gray) to solve problems*
- *Subproblem solutions (green tree nodes) are passed along intermediaries until reaching the terminator (red)*
- *At the terminator, the full MAPF problem is solved.*

PRELIMINARY RESULTS

- **Experiment Setup:** Ran 25 scenarios in randomly generated environments comparing:
  - HCMDC using a network navigator (NetNav)
  - HCMDC with random agent roles (Rand)
  - Conflict-Based Search (CBS)[2]: centralized baseline





- **Results:** HCMDC improved scalability, with NetNav showing lower node counts, indicating better workload distribution compared to Rand
- **Plan Quality:** No significant degradation in plan quality, even with greedy solution passing
- **Future Work:** Further analysis needed on navigator heuristics across different environments, network topologies, and with heterogenous teams of agents

REFERENCES

[1] H. Lee, J. Motes, M. Morales, and N. M. Amato, "Parallel hierarchical composition conflict-based search for optimal multi-agent pathfinding," IEEE Robotics and Automation Letters, vol. 6, no. 4, pp. 7001–7008,2021.
[2] G. Sharon, R. Stern, A. Felner, and N. R. Sturtevant, "Conflict-based search for optimal multi-agent pathfinding," Artificial Intelligence, vol. 219, pp. 40–66, 2015.

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