UAV Route Planning Strategies for Efficient Coverage Search in Complex Environments

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Università degli Studi di Padova

Dipartimento Matematica

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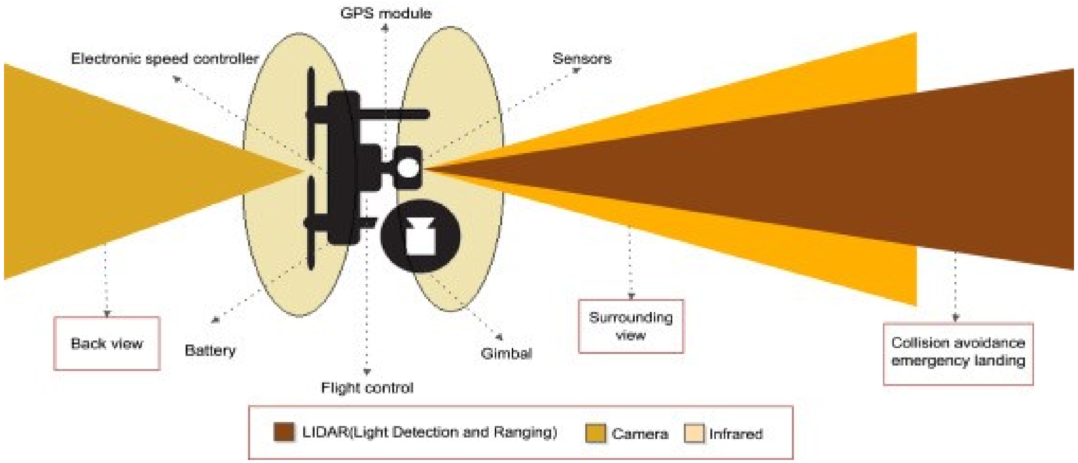
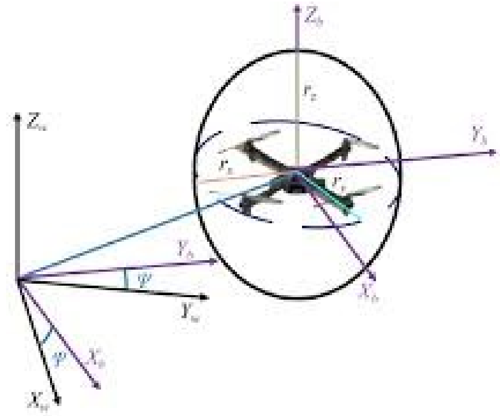
UAV Route Planning





Reference: https://www.sciencedirect.com/science/article/pii/S0140366419308539

Overview of approaches

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- Classical algorithms
- Probabilistic methods
- Nature-inspired algorithms
- Multi-UAV coordination
- Environment-specific approaches
- Military applications

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Classical approaches

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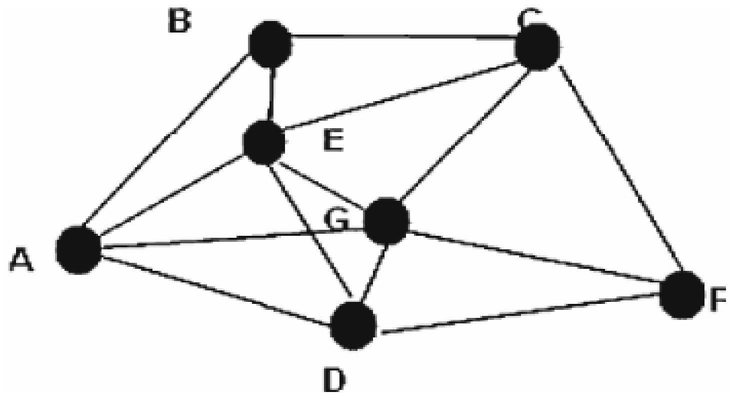
- Dijkstra's Algorithm
- A* Algorithm
- Bellman-Ford Algorithm
- Floyd-Warshall Algorithm



$$A[i]\,[j] = \begin{pmatrix} 0 & 1 & 0 & 1 & 1 & 0 & 0 \\ 1 & 0 & 1 & 0 & 1 & 0 & 1 \\ 0 & 1 & 0 & 0 & 0 & 1 & 1 \\ 1 & 0 & 0 & 0 & 1 & 1 & 1 \\ 1 & 1 & 0 & 1 & 0 & 0 & 1 \\ 0 & 0 & 1 & 1 & 0 & 0 & 1 \\ 0 & 1 & 1 & 1 & 1 & 1 & 0 \end{pmatrix}$$

Reference: [Multiple UAVs path planning algorithms: a comparative study]() (Paper 1)

Classical approaches

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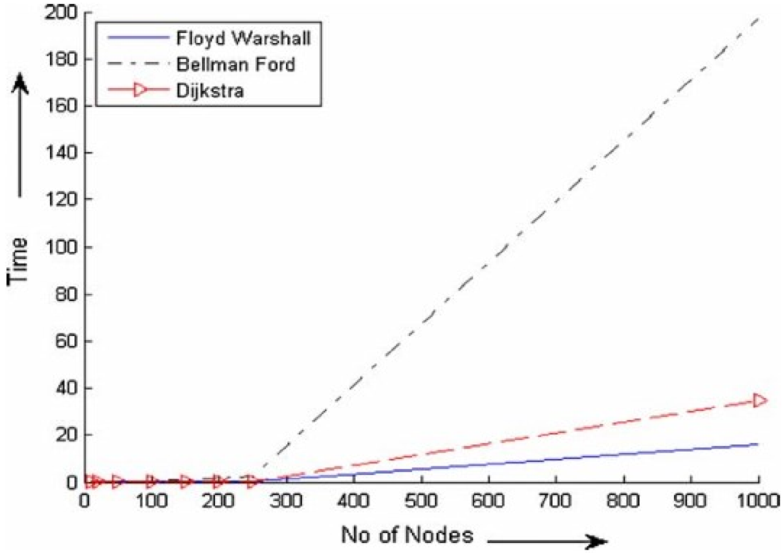


Fig. 5 Computation efficiency of search algorithms

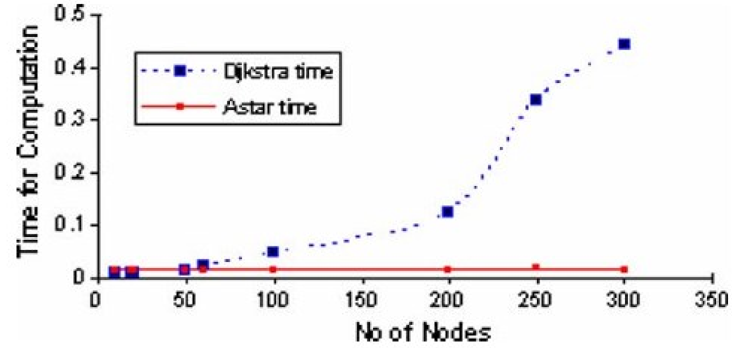
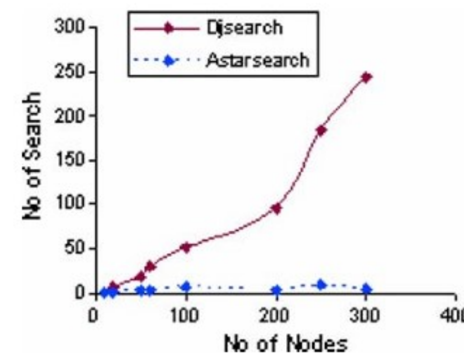


Fig. 6 Astar versus Dijkstra search

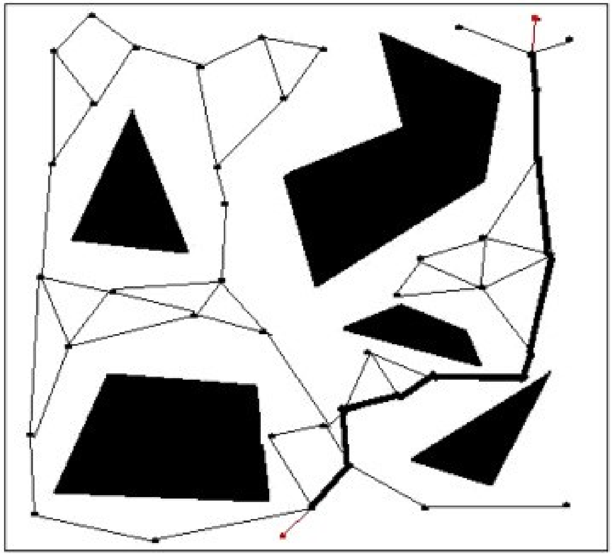
Fig. 7 Dijkstra versus astar



Reference: [Multiple UAVs path planning algorithms: a comparative study]() (Paper 1)

Probabilistic methods

- **Probabilistic Roadmap Method (PRM)**
  - Efficient for high-dimensional configuration spaces
  - Two phases: learning phase and query phase
  - Handles complex 3D environments effectively
- **Key features**
  - Random sampling of configuration space
  - Creation of roadmap for path planning
  - Efficient for large/complex environments



Reference:
https://www.sciencedirect.com/science/article/pii/S0140366419308539

Probabilistic methods

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- **Enhancements for UAV Applications**
  - Octree-based environment representation
  - Safety-aware sampling
  - Bounding box array for focused sampling
  - Connectivity evaluation for feasible paths

- **Advantages**
  - Handling obstacle avoidance well
  - Computationally efficient for large environments
  - Adaptable to different types of environments

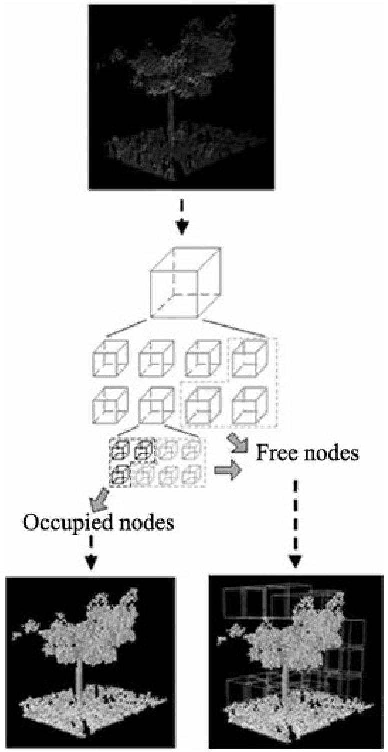

Fig. 1 The occupied voxels and free voxels are extracted from 3D data during octree building

Reference: [Path Planning in Complex 3D Environments Using a Probabilistic Roadmap Method]() – (Paper 2)

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Nature-inspired algorithms

- **Grey Wolf Optimization (GWO)**
  - Inspired by social hierarchy and hunting behavior or grey wolves
  - Balances exploration and exploitation effectively
- **Particle Swarm Optimization (PSO)**
  - Efficient for continuous optimization problems
  - Well-suited for dynamic UAV path plannig
  - Based on social behavior of bird flocking/fish schooling
- **Ant Colony Optimization (ACO)**
  - Effective for discrete optimization and adaptive path planning
  - Mimics foraging behavior of ant colonies

Nature-inspired algorithms

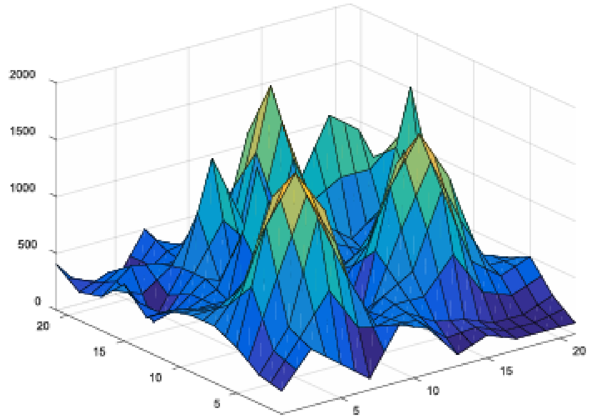


FIGURE 1. **Environmental model for three-dimensional planning.**

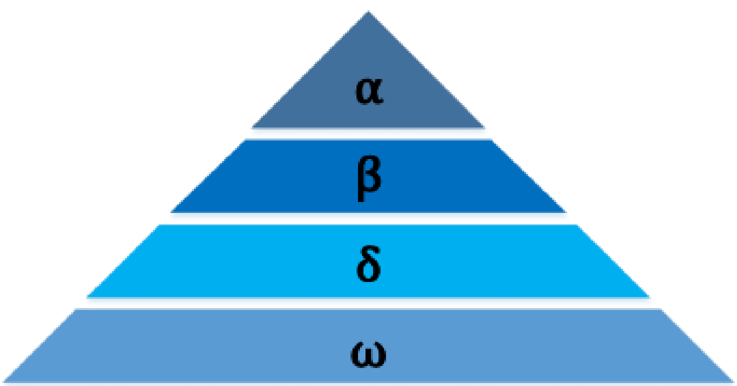


FIGURE 4. **The social hierarchy of the grey wolf.**

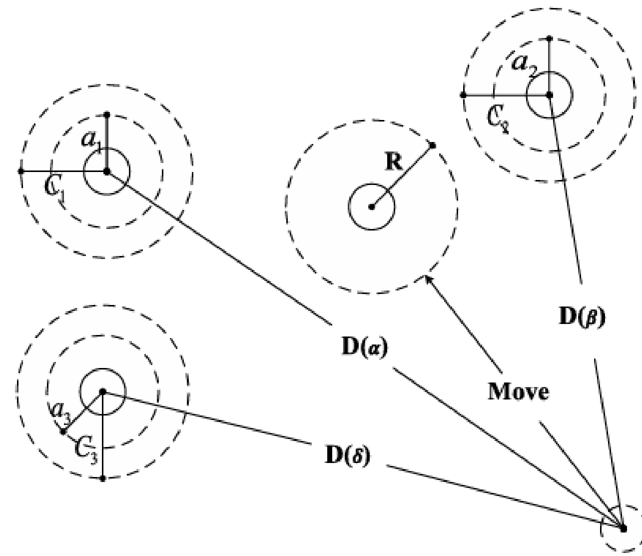


FIGURE 5. **Grey wolf population location update process.**

Reference: [Path Planning of UAV Based on Improved Adaptive Grey Wolf Optimization Algorithm]() – (Paper 4)

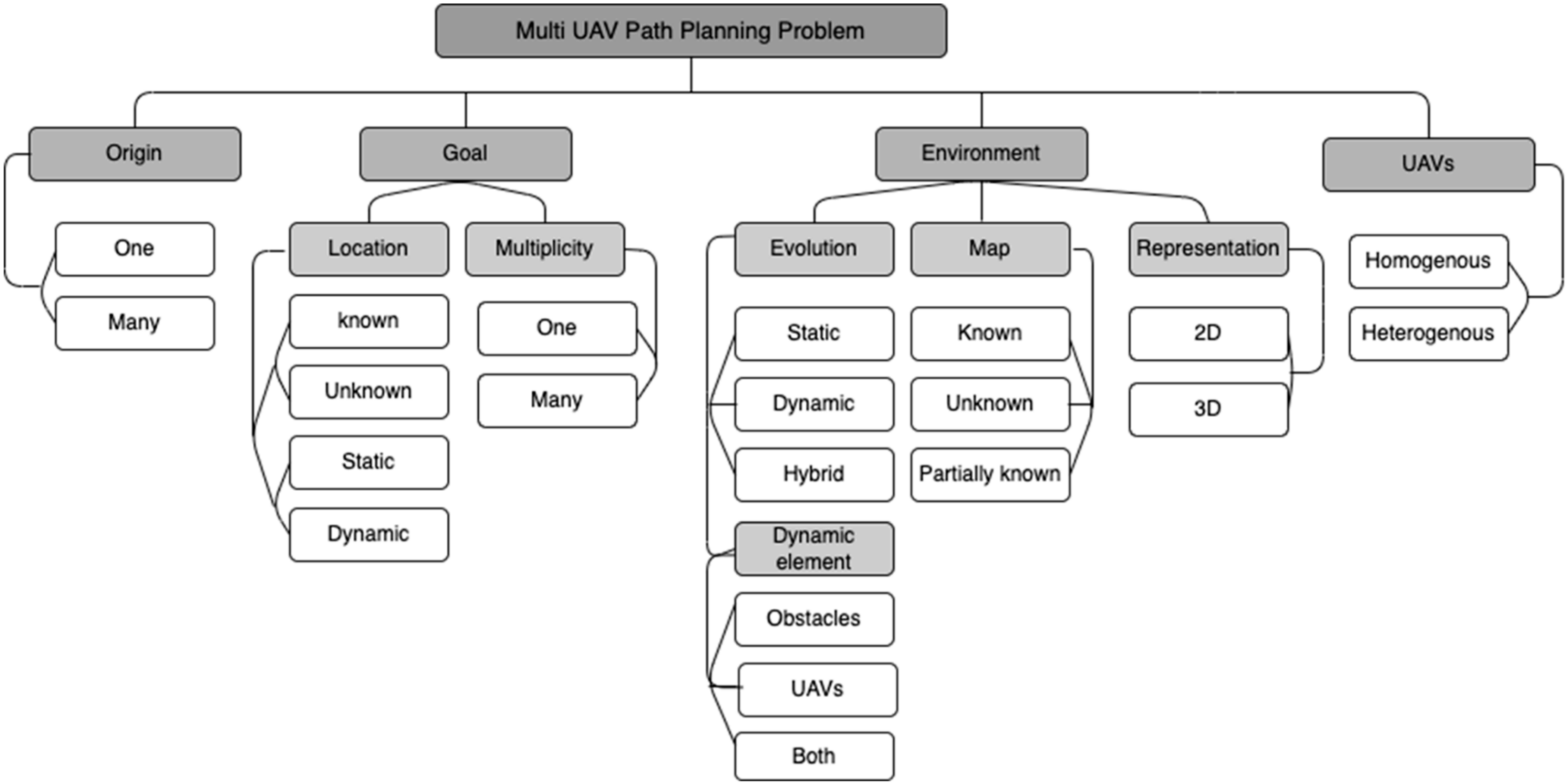
Multi-UAV coordination

- **Extended from single-agent to multi-agent planning**
  - Multiple Traveling Salesman Problem (MTSP)
  - Vehicle Routing Problem (VRP)

- **Key challenges**
  - Grouping and task allocation among UAVs
  - Multi-objective optimization (e.g. distance, energy, risk)
  - Dynamic environments (e.g., synchronization precedence)

- **Solution methods**
  - Meta-heuristic algorithms
  - Neural Networks (NN) for complex pattern learning
  - Hybrid approaches combining multiple algorithms

Multi-UAV coordination



Reference: https://www.mdpi.com/2227-7390/11/10/2356

Environment-specific approaches

- **Focus**
  - River search scenarios (Yao et al.)

- **Key components**
  - Gaussian Mixture Model (GMM) for probability distribution
    - Identifies high-value river segments and adjusts greedily
  - Approximation Insertion (AI) method for prioritization
    - Constructs search route iteratively

- **Innovative aspects**
  - Uses prior information to estimate target locations
  - Adapts to river geometry and probability distributions
  - Balances detection probability and travel time

Environment-specific approaches

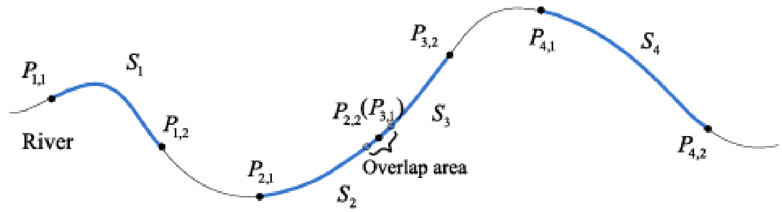


Fig. 2. Illustration of extracted river subregions.

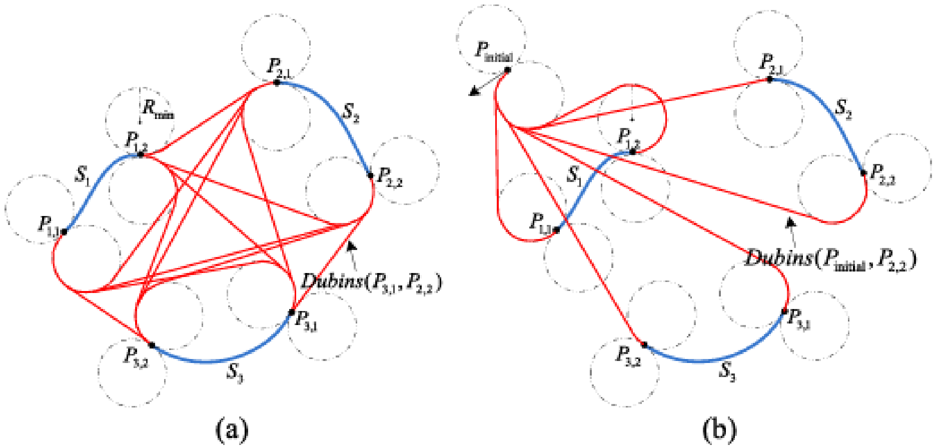


Fig. 3. Illustration of synthesized graph using Dubins connections. (a) Connecting nodes. (b) Connecting UAV initial point and nodes.

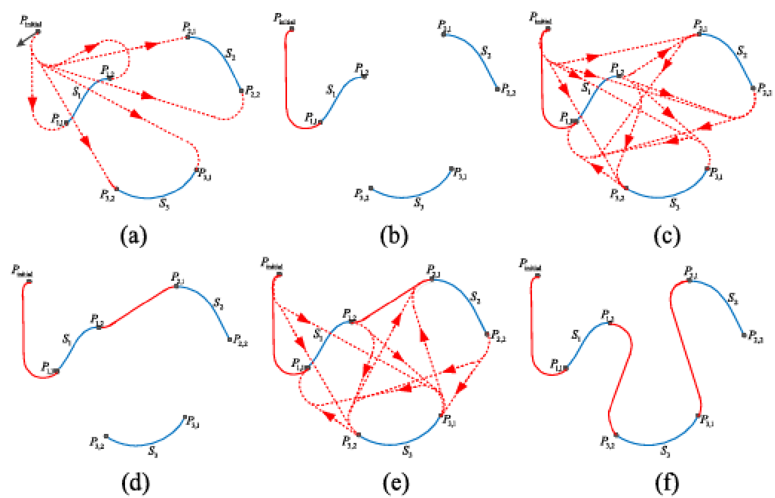


Fig. 4. Illustration of AI method. (a) Find the best edge. (b) First time (choose S_1). (c) Find the best edge. (d) Second time (S_2 is stacked after S_1). (e) Find the best edge. (f) Third time (S_3 is inserted between S_1 and S_2).

Reference: Optimal UAV Route Planning for Coverage Search of Stationary Target in River – (Paper 5)

Military applications

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- **Unique challenges**
  - Hostile environments with rapid changes
  - Multiple objectives and stringent constraints
  - Need for real-time planning and decision-making

- **Key approaches**
  - Constrained Shortest-Path (CSP) method (Royset et al.)
    - Minimizes risk while satisfying fuel and time constraints
    - Uses Lagrangian Relaxation and Enumeration (LRE) algorithm
  - Real-time network approach (Myers et al.)
    - Incorporates obstacles and flight dynamics
    - Uses pseudonodes for realistic aircraft behavior
    - Adapts Djikstra's algorithm for optimal paths

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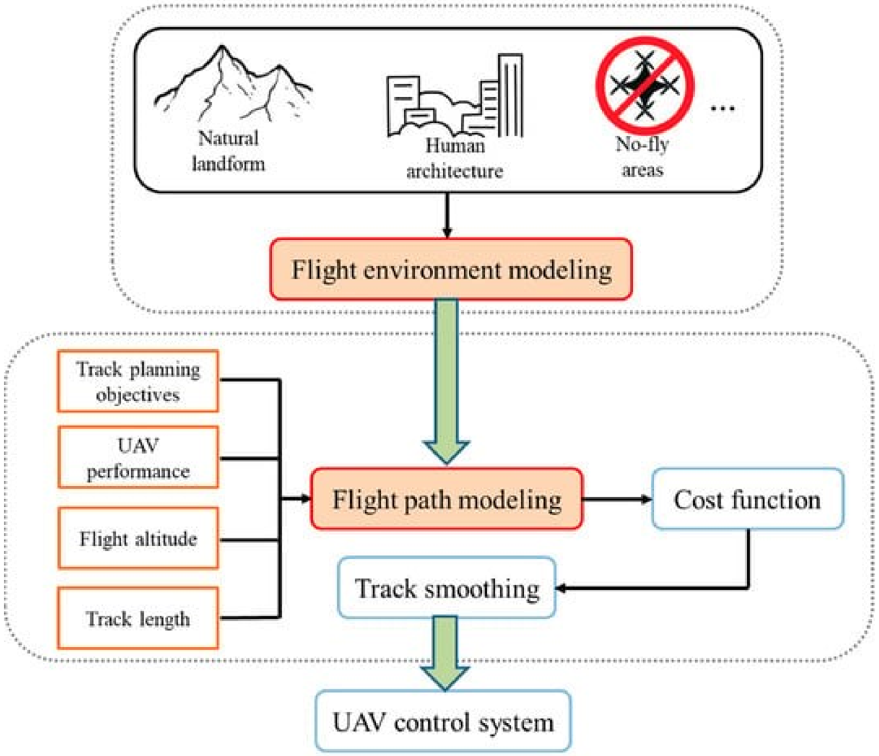
Military applications

- **Comparative strengths**
  - CSP method: handles multiple constraints, suitable for complex missions
  - Real-time approach: fast computation, adaptable to dynamic environments
- **Limitations**
  - Both focus on single-UAV routing
  - Limited handling of rapidly changing threat landscapes
  - Lack of multi-UAV coordination considerations



Reference: https://www.mdpi.com/2075-1680/12/7/702

Military applications

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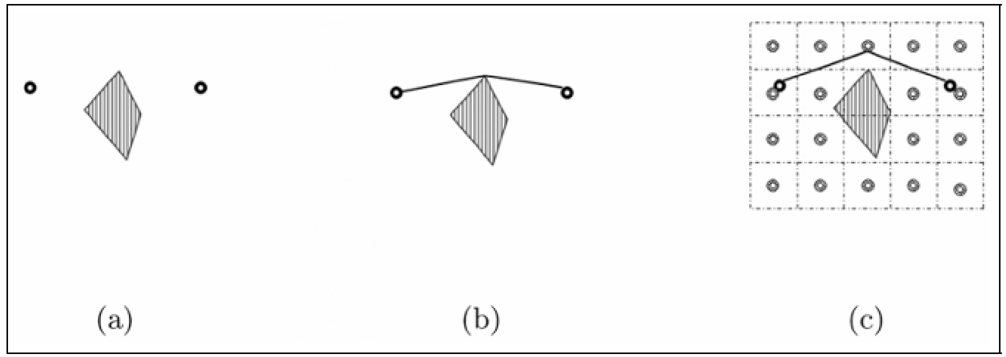

Figure 2. Discretization of airspace. (a) Example scenario. (b) Optimal path. (c) Grid path.

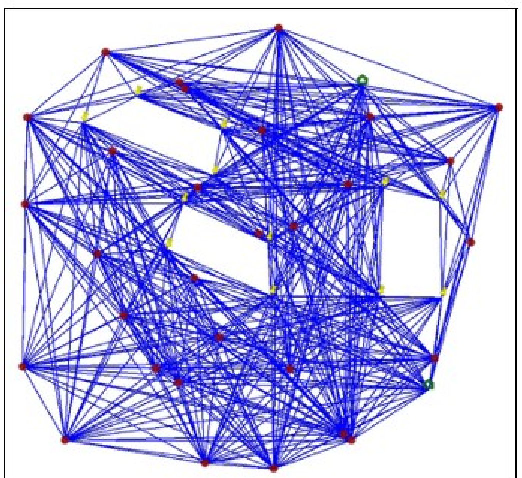

Figure 6. Test case network.

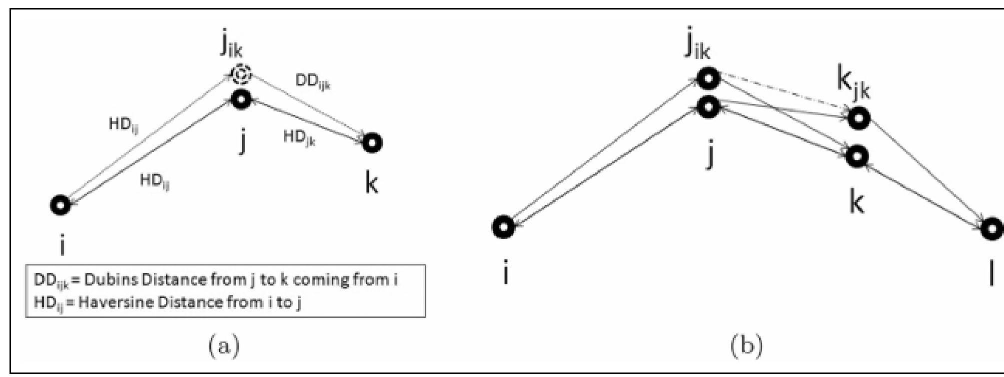

Figure 8. Psuedonode addition and connection. (a) Addition of a pseudonode. (b) Connection of pseudonodes.

Reference: https://www.acsu.buffalo.edu/~batta/myers.pdf

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Comparison of approaches (1)

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Approach	Key Algorithms	Complexity	Advantages	Disadvantages	Best Use Case
Classical	Dijkstra, A*, Bellman-Ford, Floyd-Warshall	Polynomial to cubic (O(V^2), O(VE))	Well-known, reliable, goal-directed for static environments	Poor performance in large or dynamic environments	Simple or static 2D/3D path planning, single UAV
Probabilistic	Probabilistic Roadmap (PRM), RRT	Depends on environment (sampling)	Efficient in complex 3D environments, good obstacle avoidance	May miss optimal paths, requires tuning	3D environments, obstacle avoidance, complex terrain
Nature-Inspired	PSO, ACO, Grey Wolf Optimization (GWO), GSA	Depends on algorithm, mostly heuristic	Adaptive, handles multiple objectives, works in dynamic environments	Premature convergence, sensitive to parameter settings	Dynamic environments, multi-objective optimization

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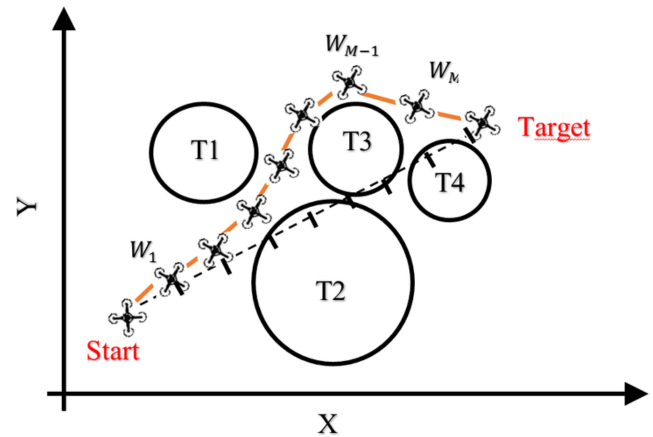
Comparison of approaches (2)

Multi-UAV Coordination	MTSP, VRP, Gravitational Search Algorithm (GSA), GA	NP-Hard	Suitable for complex task allocation, scalable to multi-UAV systems	Complex and computationally intensive	Logistics, multi-objective task allocation, large teams
Environment-Specific	Gaussian Mixture Models (GMM), Approximation Insertion	Depends on task complexity	Optimizes for specific environments, dynamic route adjustment	Limited applicability to other environments	River search, disaster relief, specific missions
Military Applications	CSP, Lagrangian Relaxation (LRE), real-time algorithms	Polynomial for constrained search	Robust real-time decision-making, threat avoidance	Limited multi-UAV coordination, single-agent focus	High-risk missions, military surveillance, real-time planning

Future challenges and research directions

- Integration with emerging technologies (e.g., 5G, IoT)
- Scalability improvements and real-time adaptability
- Multi-UAV coordination
- Human-swarm interaction
- Environmental considerations
- Ethical and regulatory challenges (e.g., AI, robotics)



Reference: https://www.researchgate.net/figure/UAV-path-planning-model-in-2D-space_fig1_329311458