Path Planning in Dynamic Environments

A hierarchical global+local planning framework on gridworlds

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Outline

1. Motivation
2. Problem Formulation
3. Methodology
4. Experiments & Results

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Why Dynamic Environments Are Hard

- **Time-varying feasibility:** free space changes over time.
- **Partial observability:** agent only sees a local neighborhood.
- **Real-time constraint:** replanning from scratch can be too slow.
- **Safety:** must avoid both static and moving obstacles online.

Idea: combine long-horizon structure (global) with short-horizon reaction (local).

Scope & Contributions

Setting: single holonomic agent on a 2D discrete grid with static + moving obstacles.

Contributions

- Hierarchical planner: **global waypoint path** + **local reactive navigation**.
- Unified evaluation across 24 combinations of 4 global planners and 6 local planners.

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Gridworld Model

State space: $S = \{(x, y) \mid x, y \in \mathbb{N},\ 0 \leq x \leq X_{\mathsf{dim}},\ 0 \leq y \leq Y_{\mathsf{dim}}\} \subset \mathbb{N}^2,$

Action space: $A = \{(0, 1),\ (0, -1),\ (-1, 0),\ (1, 0),\ (0, 0)\} \subset \mathbb{Z}^2,$

Observation space: $G \in \{0, 1\}^{5\times5},$

Static obstacles: $O \subset S.$

Dynamic obstacles: $M_t \subset S$ at time t.

Transition function: $f : S \times A \to S.$

Planning Objective

Find a trajectory $T = \{S_0, S_1, \ldots, S_{N-1}\}$ such that:

- S_0 is start and S_{N-1} reaches the goal.
- For each step, $\exists a \in A$ with $f(S_i, a) = S_{i+1}$.
- Safety constraints: $S_i \notin O$ and $S_i \notin M_i$.

Challenge: M_i changes online, so the planner must react during execution.

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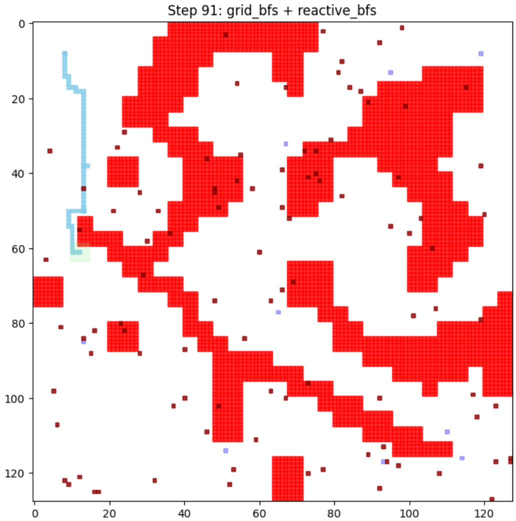
Two-Level Hierarchical Architecture

Global layer (static map)

- Computes a waypoint route from start to goal.
- Enforces safety margin via clearance map.
- Post-process: line-of-sight sparsification, wall-pushing.

Local layer (online, reactive)

- Plans inside observation window ($r = 2 \Rightarrow 5 \times 5$).
- Avoids moving obstacles, tracks current global waypoint.
- Triggers global replanning when stuck.



Global Planners (Waypoints)

- **Grid BFS**: shortest in number of grid steps (8-connected), with safety margin.
- **Grid DFS**: lower memory; not guaranteed shortest.
- **A***: $f(n) = g(n) + h(n)$; uses Manhattan heuristic with diagonal moves enabled.
- **Dijkstra**: optimal distances; slower.

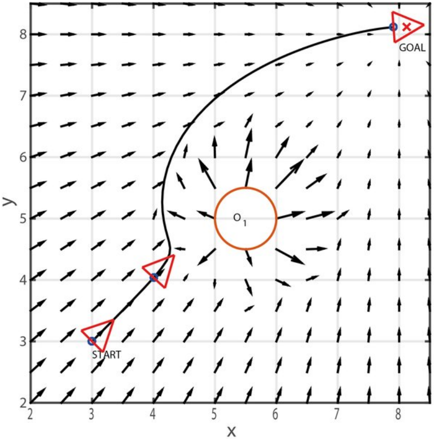
Post-processing: clearance map, Bresenham line-of-sight sparsification, wall pushing.

Local Planners (Reactive Navigation)

- **Reactive BFS**: BFS in local observation graph.
- **Reactive DFS**: DFS locally.
- **Potential Field**: attractive + repulsive forces.
- **Greedy**: choose locally improving action.
- **DWA**: simulate short trajectories, pick best.
- **Evolutionary**: optimizes a sequence of actions $\pi = (a_0, \ldots, a_{H-1})$ over a 5-action set.

Local Planner: Potential Field

- Computes an attractive force toward the projected waypoint and repulsive forces away from obstacles.
- Net force: $\boldsymbol{F} = \boldsymbol{F}_{att} + \boldsymbol{F}_{rep}$.
- Maps $\boldsymbol{F}$ to a **4-connected** action (dominant axis) while respecting the margin constraint.



Local Planner: Dynamic Window Approach (DWA)

- Samples discrete velocity commands within a **window** around the previous action

$$v_x \in [v_{x,t-1} - a_{max},\ v_{x,t-1} + a_{max}], \quad v_y \in [v_{y,t-1} - a_{max},\ v_{y,t-1} + a_{max}], \tag{1}$$

- Simulates short trajectories (prediction horizon).

$$\vec{p}_k = \vec{p}_0 + k\vec{v}, \quad k = 1, \dots, N \tag{2}$$

- Scores candidates by goal heading, obstacle clearance, and speed.

$$J(\vec{v}) = w_h\, S_{heading} + w_c\, S_{clearance} + w_s\, S_{speed} \tag{3}$$

$$S_{heading} = \frac{1}{\|\vec{p}_{final} - \vec{p}_{goal}\| + 1} \quad S_{clearance} = \frac{\min(c_{min}, c_{cap})}{c_{cap}} \quad S_{speed} = \frac{k\|\vec{v}\|}{v_{max}}$$

Local Planner: Rolling-Horizon Evolutionary

- Optimizes a short sequence of actions $\pi = (a_0, \ldots, a_{H-1})$ over a 5-action set.
- Fitness combines distance-to-goal terms, clearance risk, turn/stall penalties, and unknown-space penalty.

$$d_t = |x_t - x_g| + |y_t - y_g|, \quad d_{final} = d_H, \quad d_{min} = \min_{1 \le t \le H} d_t, \quad \bar{d} = \frac{1}{H} \sum_{t=1}^{H} d_t$$

$$T = \sum_{t=1}^{H-1} \mathbb{I}[a_{t-1} \neq \texttt{NONE} \wedge a_t \neq \texttt{NONE} \wedge a_{t-1} \neq a_t], \quad S = \sum_{t=0}^{H-1} \mathbb{I}[a_t = \texttt{NONE}]$$

- Evolves a population via elitism, tournament selection, crossover, and mutation.

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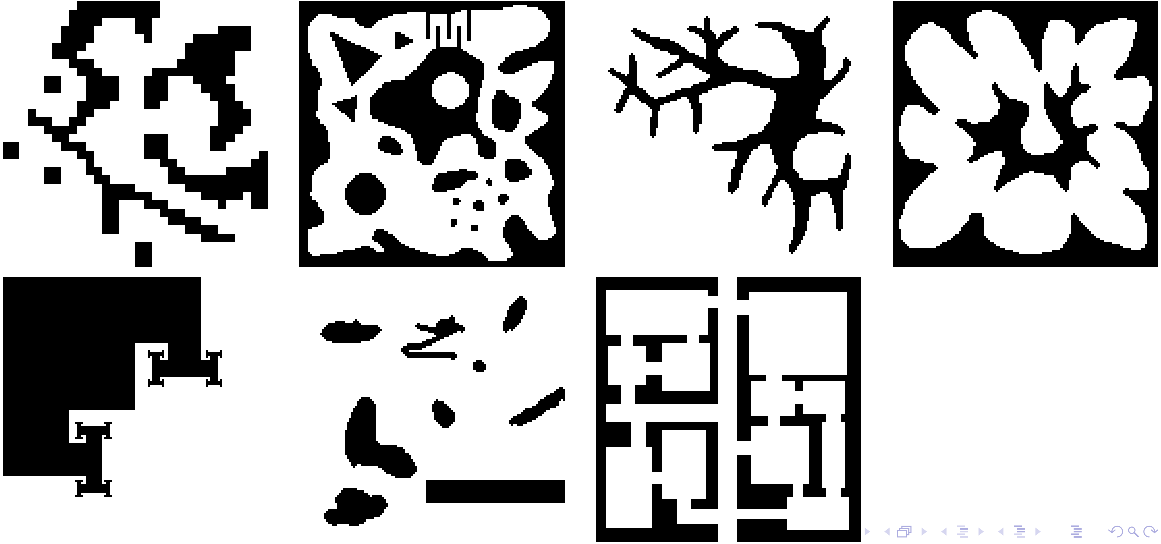
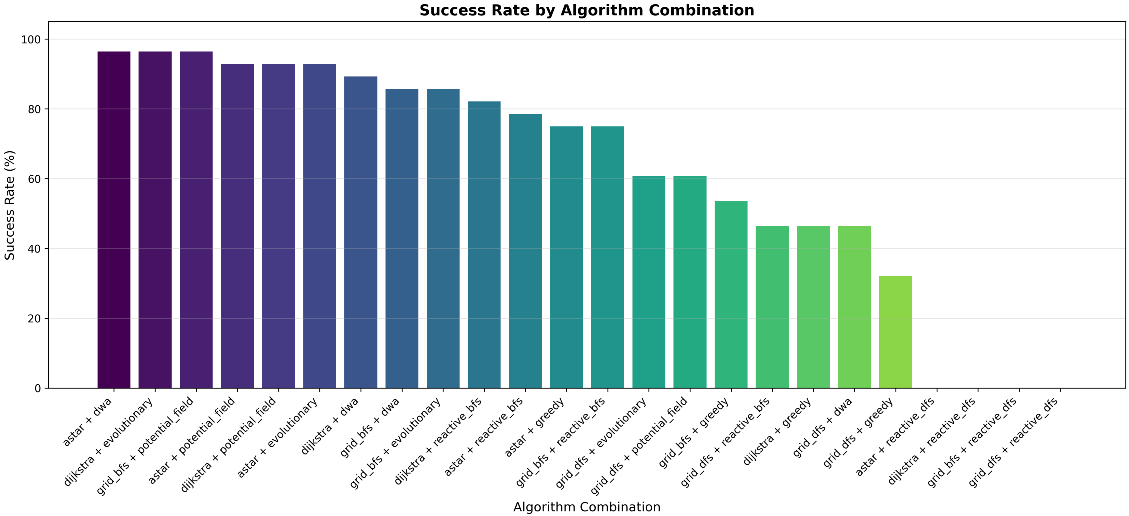
Benchmark Setup

- 7 maps, obstacle counts $\{0, 50, 100, 200\}$.
- 24 combinations: 4 global × 6 local planners $\Rightarrow 672$ runs.
- Observation radius $r = 2$ $(5 \times 5$ window); local inflation margin 1.
- Stop: 2000 steps or 100 seconds; success when Manhattan distance to goal ≤ 3.

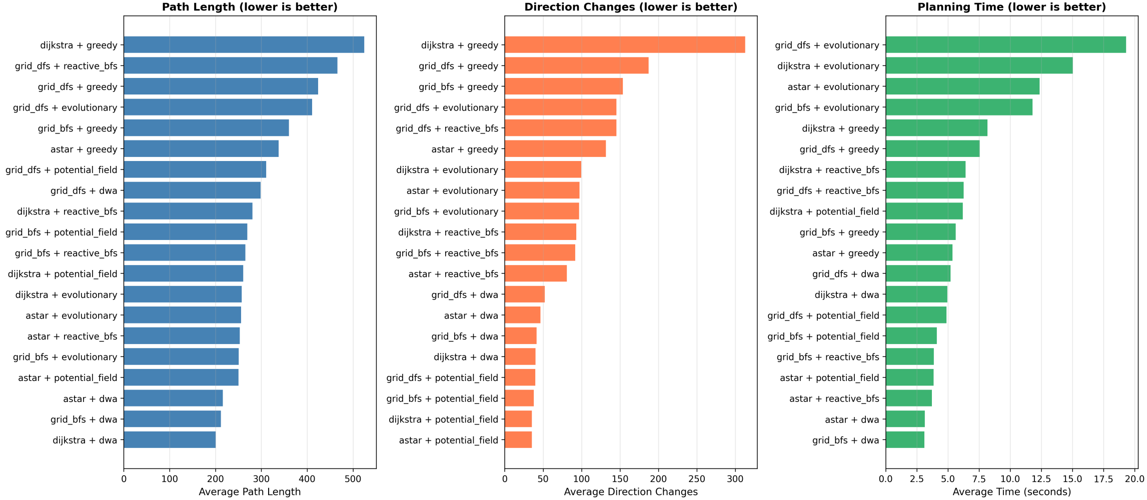
Benchmark Maps



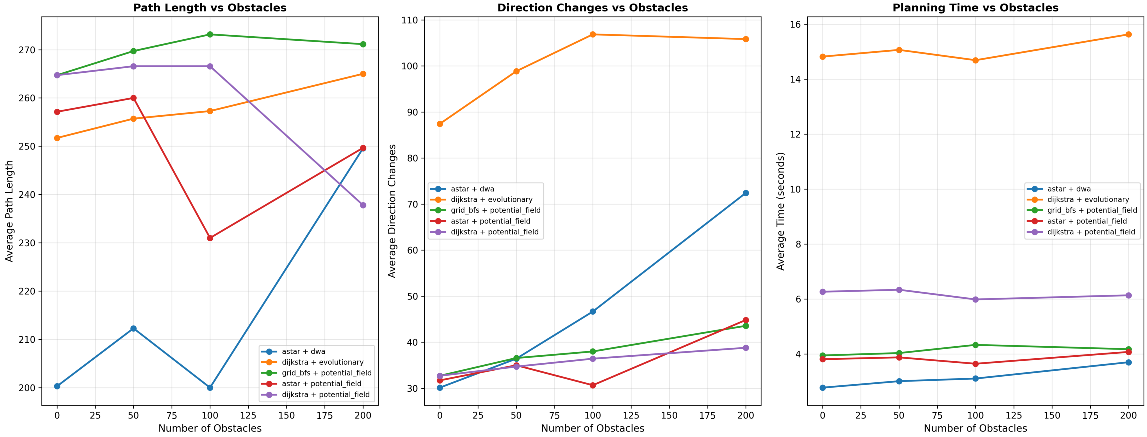
Overall Results (672 runs)



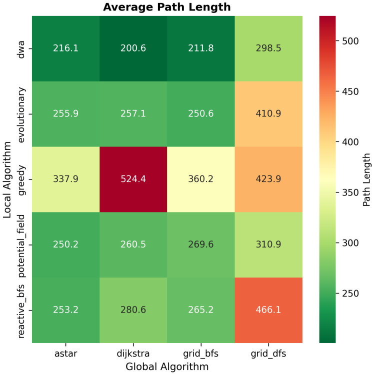
Path Quality & Runtime (Successful Runs)



Impact of Obstacle Density

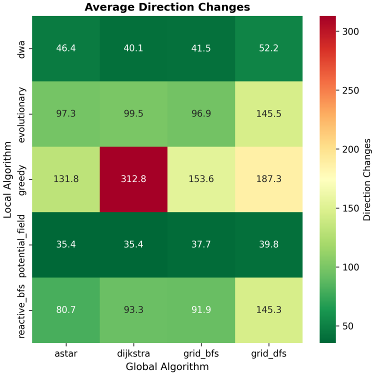


Heatmap Summary (Averages)



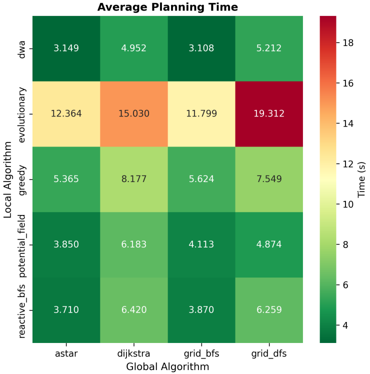
Average Path Length

Local Algorithm	astar	dijkstra	grid_bfs	grid_dfs
dwa	216.1	200.6	211.8	298.5
evolutionary	255.9	257.1	250.6	410.9
greedy	337.9	524.4	360.2	423.9
potential_field	250.2	260.5	269.6	310.9
reactive_bfs	253.2	280.6	265.2	466.1



Average Direction Changes

Local Algorithm	astar	dijkstra	grid_bfs	grid_dfs
dwa	46.4	40.1	41.5	52.2
evolutionary	97.3	99.5	96.9	145.5
greedy	131.8	312.8	153.6	187.3
potential_field	35.4	35.4	37.7	39.8
reactive_bfs	80.7	93.3	91.9	145.3



Average Planning Time

Local Algorithm	astar	dijkstra	grid_bfs	grid_dfs
dwa	3.149	4.952	3.108	5.212
evolutionary	12.364	15.030	11.799	19.312
greedy	5.365	8.177	5.624	7.549
potential_field	3.850	6.183	4.113	4.874
reactive_bfs	3.710	6.420	3.870	6.259

Q & A

Questions?