Revisiting Bounded-Suboptimal Safe Interval Path Planning

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1. Problem Statement

Environment – a graph (grid with 2^k connectedness or a roadmap)

Agent – an open disk of radii $\boldsymbol{r}$ that is allowed to:
a) **move** with constant speed
b) stay and **wait** any arbitrary amount of time
c) **rotate** in place

Dynamic obstacles – $\boldsymbol{N}$ disks of radii $\boldsymbol{r}$ that move inside the environment along the known trajectories

Trajectory – a sequence of actions:

$$\pi = \{a_1, a_2, \ldots, a_k\}$$

Task – having the given graph, a set of dynamic obstacles, start and goal agent's locations, find a trajectory that avoids static and dynamic obstacles.

Solution quality is determined by the cost(duration) of the agent's trajectory.

Cost – sum of actions' durations:

$$c(\pi) = \sum_{i=1}^{k} dur(a_i)$$

Optimal Solution:

π^*= Plan with the minimal cost

Bounded-suboptimal solution

π: $c(\pi) \leq w \cdot c(\pi^*)$, $w \geq 1.0$

2. Safe Interval Path Planning

SIPP [Phillips and Likhachev, 2011] – A* in a different search space.

SIPP is complete and optimal

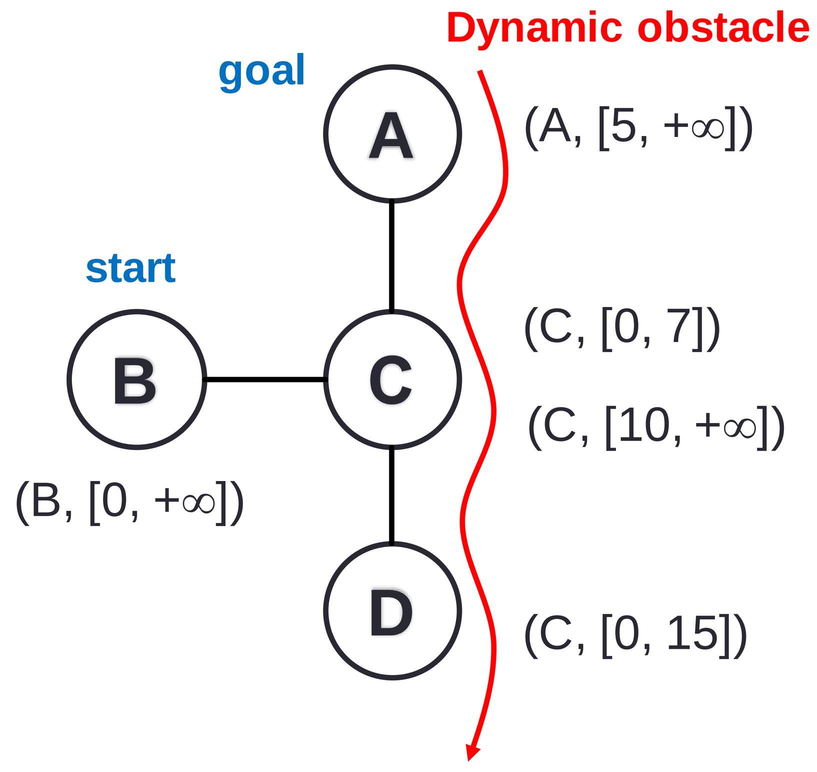
Each vertex has a corresponding **safe intervals** computed with respect to the trajectories of dynamic obstacles

SIPP state – (graph vertex, safe interval)

$n = (v, [t_i, t_j])$

$g(n)$ – the earliest possible arrival time to n
$h(n)$ – estimate of the plan cost to the goal
- Admissible
- Consisitent

When SIPP expands a node $n = (v, [t_i, t_j])$, then $g(n)$ is the earliest possible arrival time to v in $[t_i, t_j]$.



3. Bounded Suboptimal SIPP

Weighted SIPP with re-expansions (WSIPP$_r$)

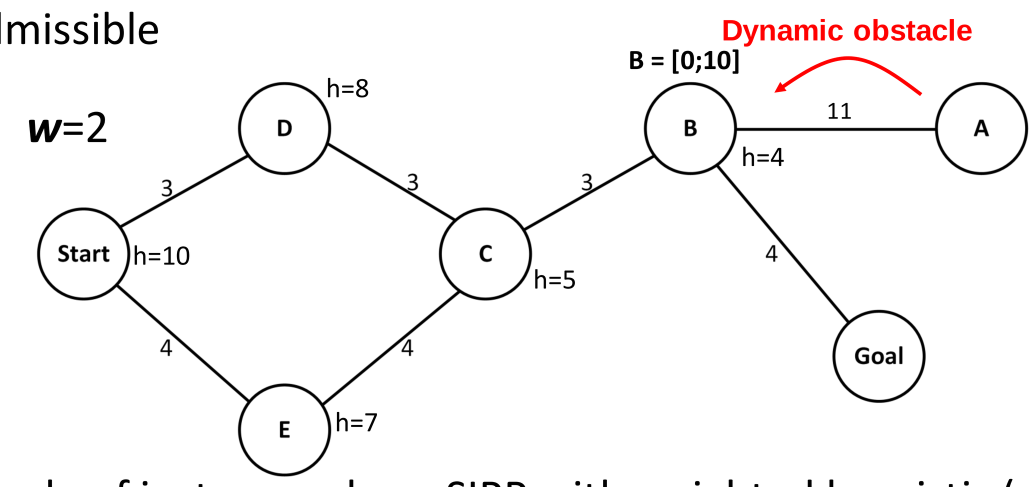
- h-values are multiplied by factor w (like in WA*)
- Each state can be re-expanded multiple times
- Without allowed re-expansions loses the property of completeness (see example below)

Weighted SIPP with Duplicate States (WSIPP$_d$)

- Suggested by authors of SIPP in [Narayanan et. al, 2012]
- Each successor is duplicated:
  Suboptimal version with f-value = $g + w \cdot h$
  Optimal version with f-value = $w \cdot (g + h)$
- Each successor is expanded at most once

SIPP with FOCAL list (FocalSIPP)

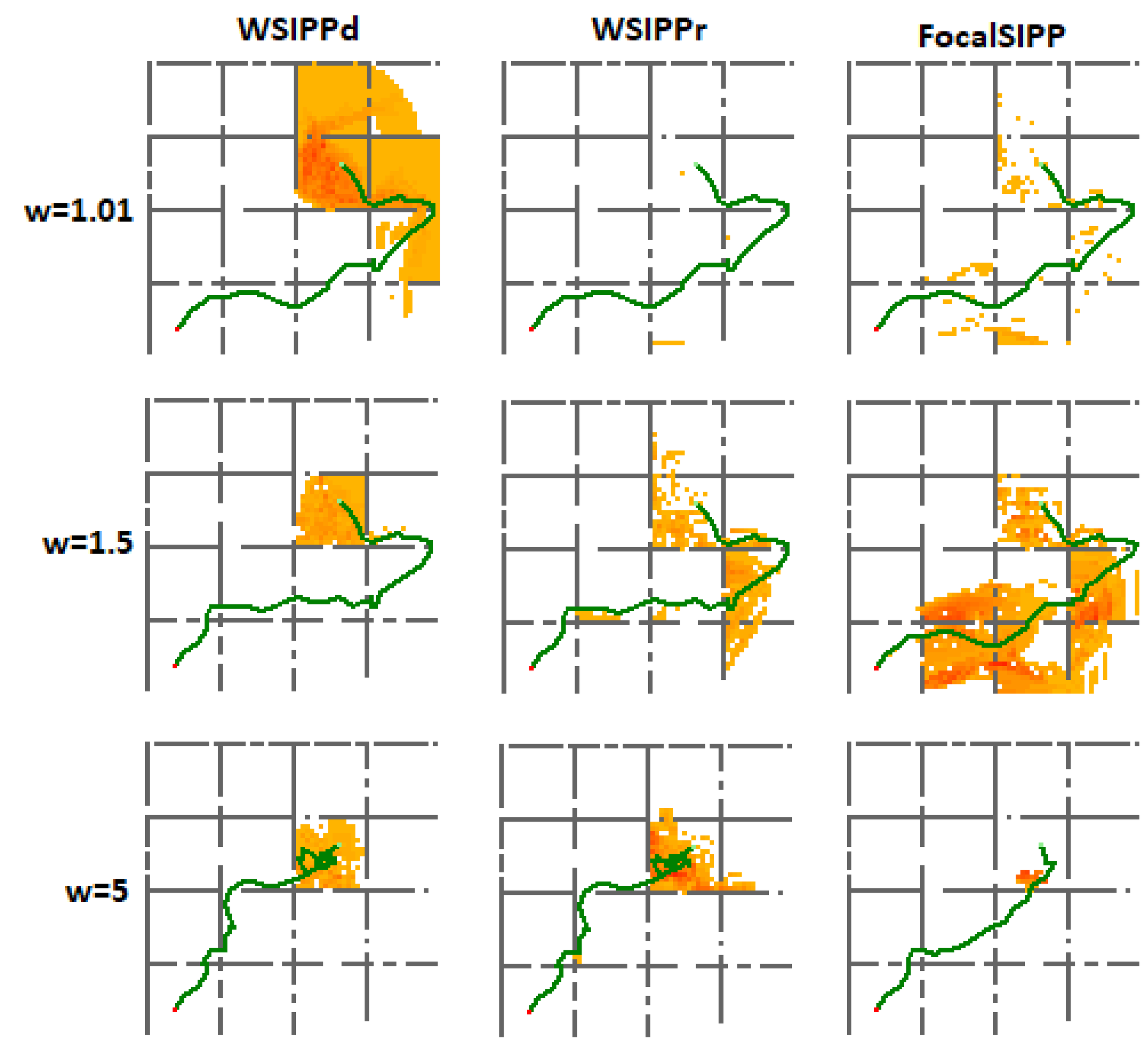
- Each state can be re-expanded multiple times
- Contains additional list – FOCAL [Pearl and Kim, 1982]
- FOCAL is a subset of OPEN list: $\{n | n \in OPEN, g(n)+h(n) \leq w \cdot f_{min}\}$
- Auxiliary heuristic function $h_{FOCAL}(n)$ for choosing a node from FOCAL does not have to be consistent, admissible



An example of instance where SIPP with weighted heuristic (w=2) and disallowed re-expansions cannot find a solution. Safe-interval in B = [0;10]

4. Re-expansions Analysis

Re-expanded* states are shown in yellow. The more states corresponding to the grid cell were re-expanded – the darker this cell is (remember that in SIPP numerous states corresponding to the same cell might exist). It is clearly seen that when w is close 1 the lowest number of re-expansions is achieved by **WSIPP$_r$**, when w is large – by **FocalSIPP**, when w is "medium" – by **WSIPP$_d$**



*If **WSIPP$_d$** expands both versions of some state, we consider it as a re-expansion

5. Experimental evaluation

Maps:
- Empty 64x64
- Warehouse 64x64
- Rooms 64x64
- Den520d 257x256

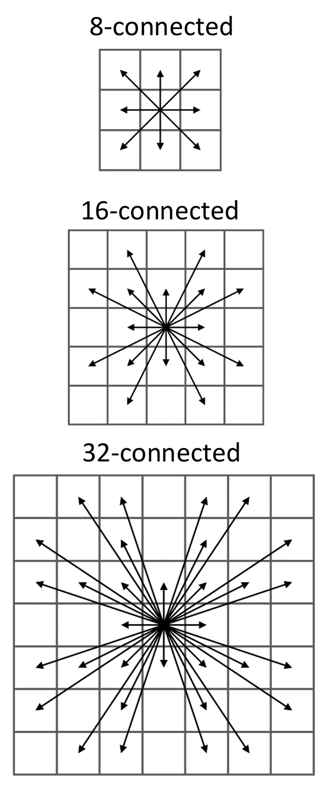
Action model:
w/o (without) rotations
w (with) rotations

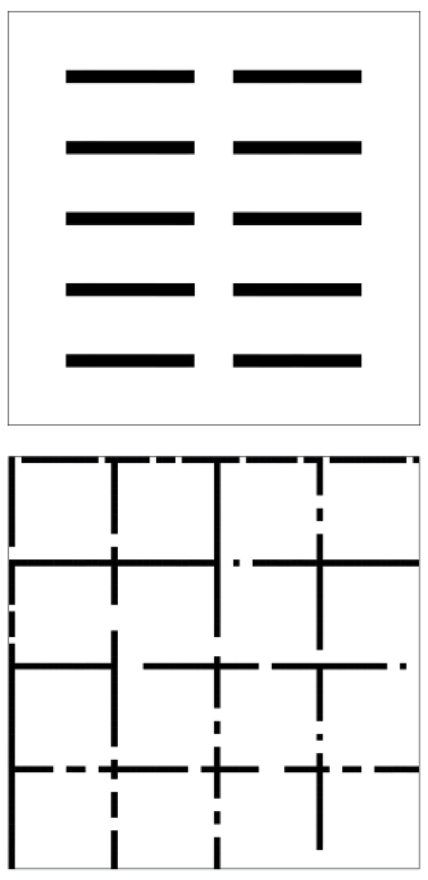
Grid connectivity: 8, 16, 32

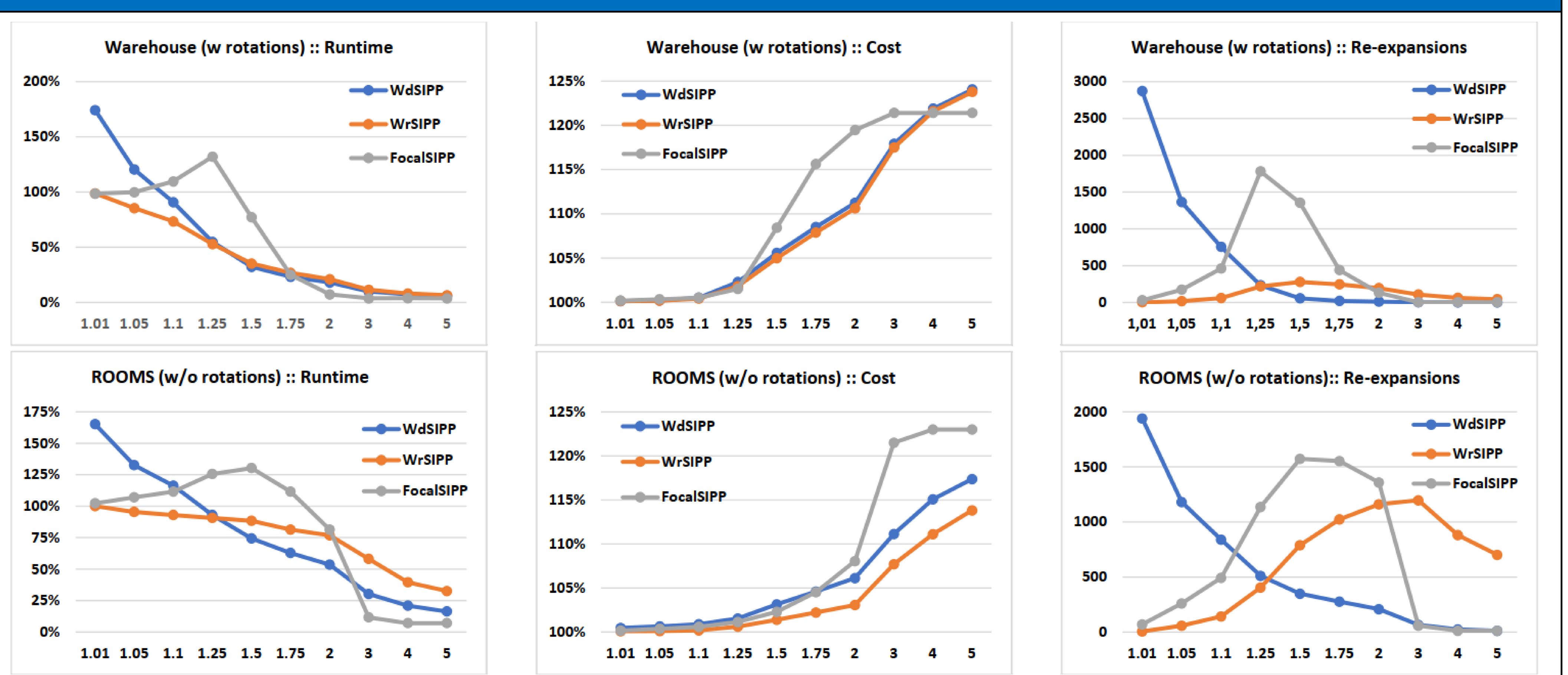
250 dynamic obstacles
100 instances per each map

Heuristic functions:
h – Euclidean distance;
h_{FOCAL} – hops-to-goal

Suboptimality factor: 1.01, 1.05, 1.1, 1.25, 1.5, 1.75, 2, 3, 4,5







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