Search-Based Footstep Planning

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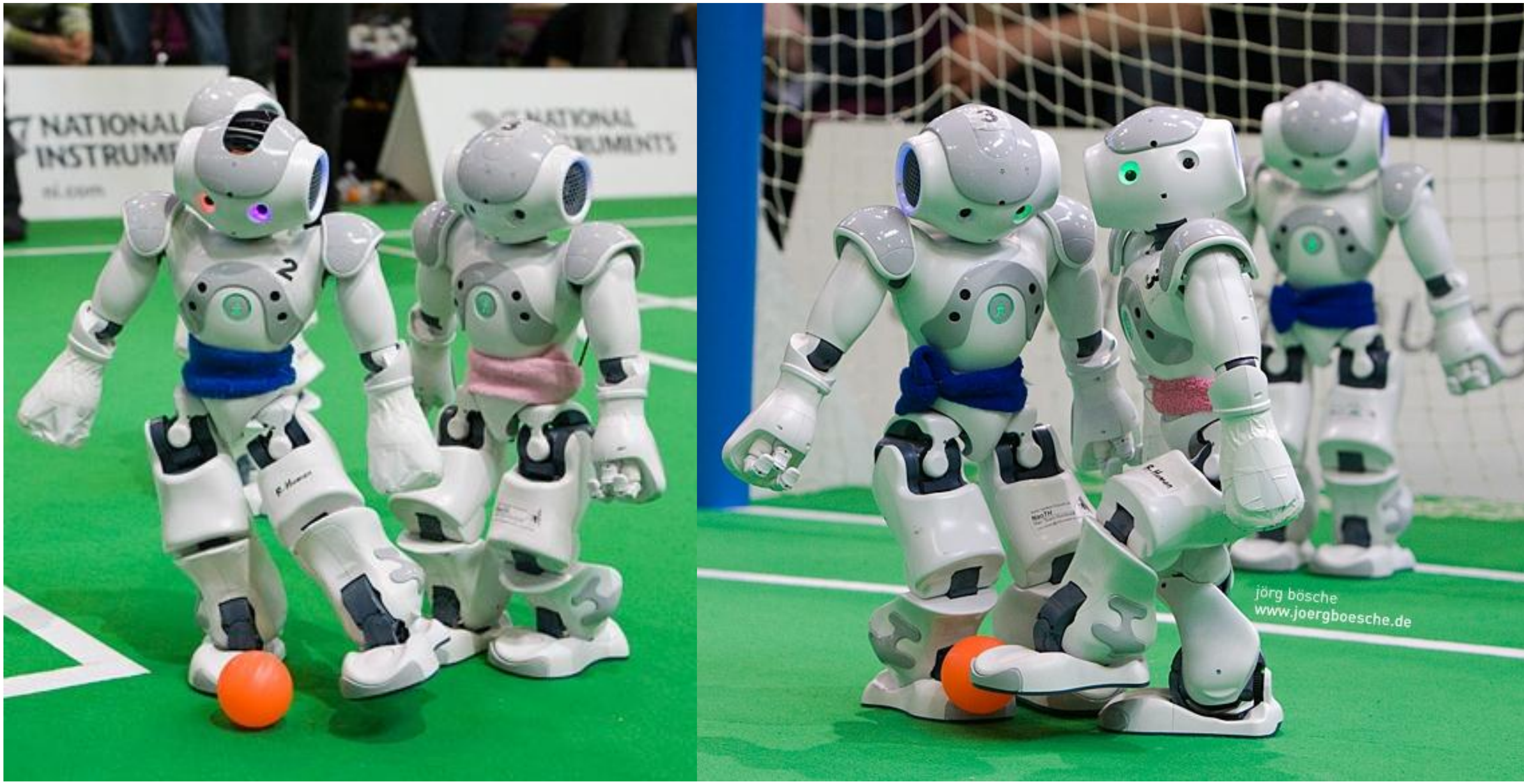
Motivation

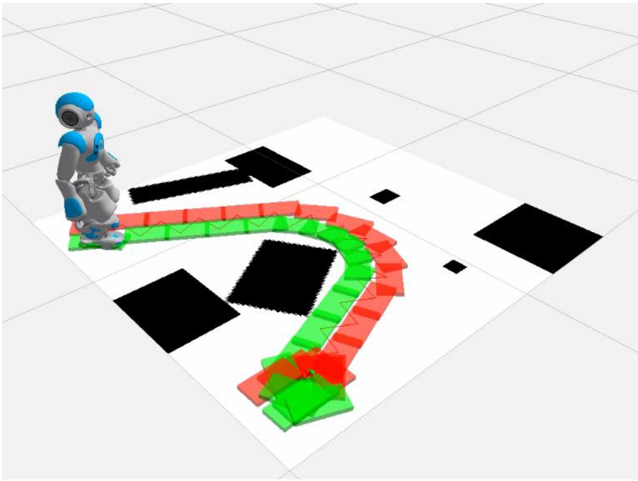


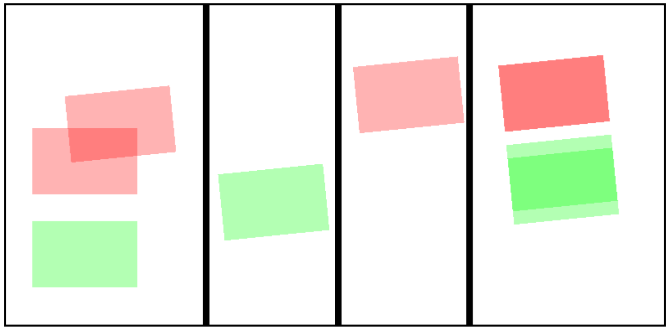
BHuman vs. Nimbro, RoboCup German Open 2010

Photo by J. Bösche, www.joergboesche.de

Path Planning for Humanoids

- Humanoids can avoid obstacles by stepping over or close to them
- However, planning whole-body motions has a high computational complexity
  [Hauser et al. ‘07, Kanoun ’10, …]
- Footstep planning given possible foot locations reduces the planning problem



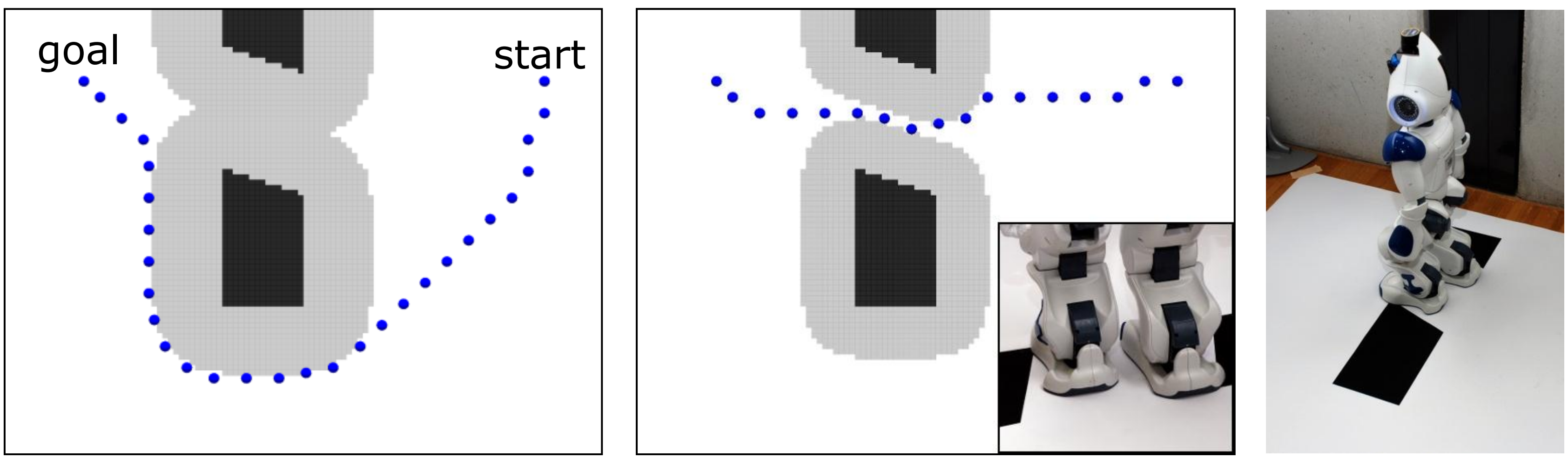


Previous Approaches

- Compute collision-free 2D path first, then footsteps in a local area

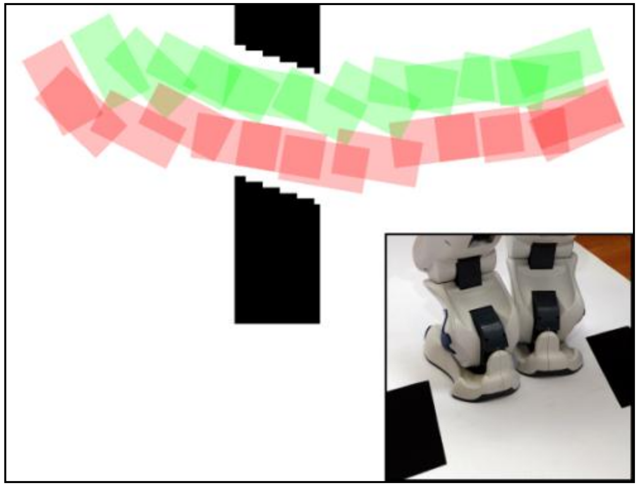
  [Li et al. ‘03, Chestnutt & Kuffner ‘04]

- Problem: 2D planner cannot consider all capabilities of the robot

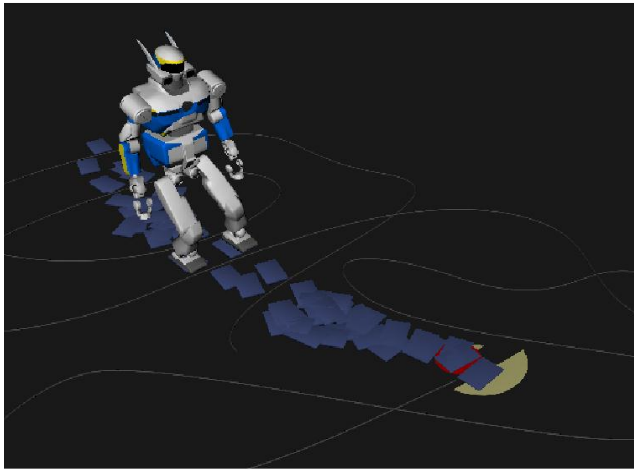


Previous Approaches

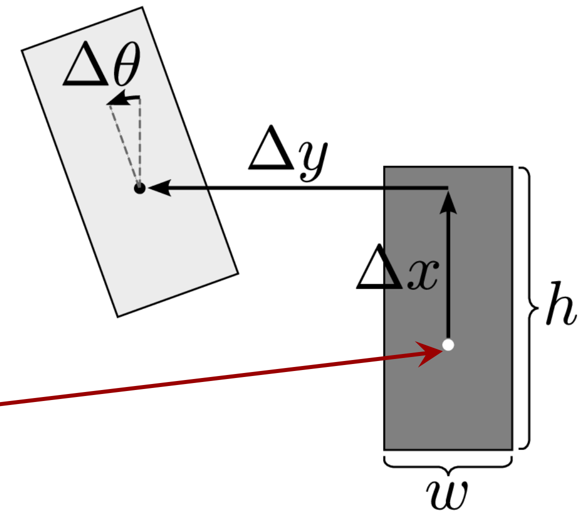
- Footstep planning with A*
  [Kuffner ‘01, Chestnutt et al. ‘05, ‘07]
  - Search space: (x,y,θ)
  - Discrete footstep set
  - Optimal solution with A*



- Probabilistic Footstep Planning
  [e.g. Perrin et al. ‘11]
  - Search space of footstep actions with RRT / PRM
  - Fast planning results
  - No guarantees on optimality or completeness



Footstep Planning



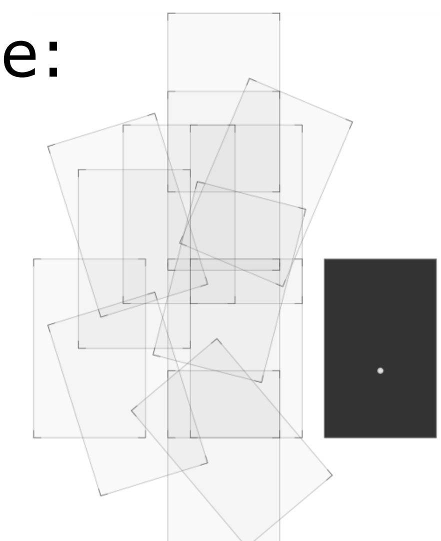
- State $s = (x, y, \theta)$
- Footstep action $a = (\Delta x, \Delta y, \Delta\theta)$
- Fixed set of footstep actions $F = \{a_1, \ldots, a_n\}$
- Successor state $s' = t(s, a)$
- Transition costs reflect execution time:

$$c(s, s') = \|(\Delta x, \Delta y)\| + k + d(s')$$

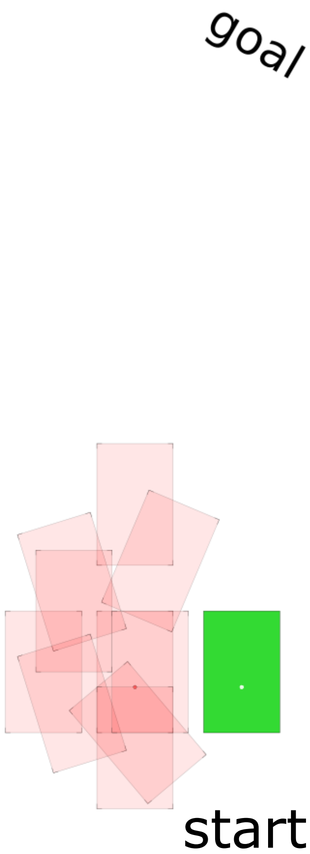
Euclidean distance

constant step cost

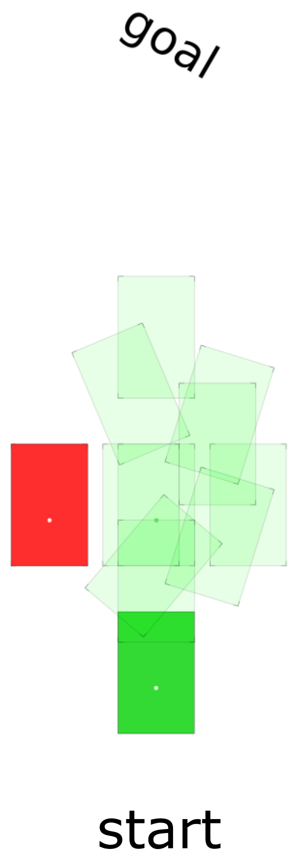
costs based on the distance to obstacles



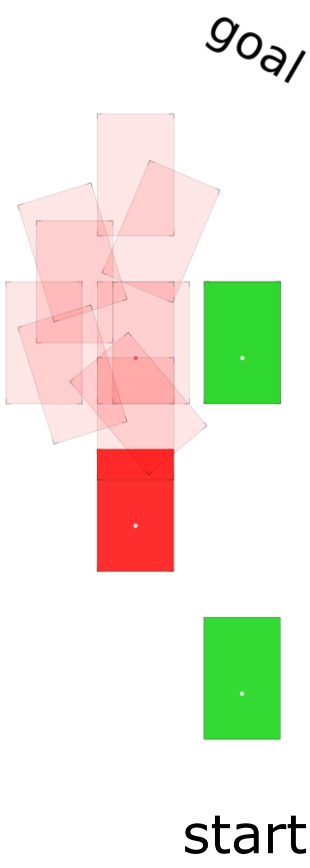
Footstep Planning



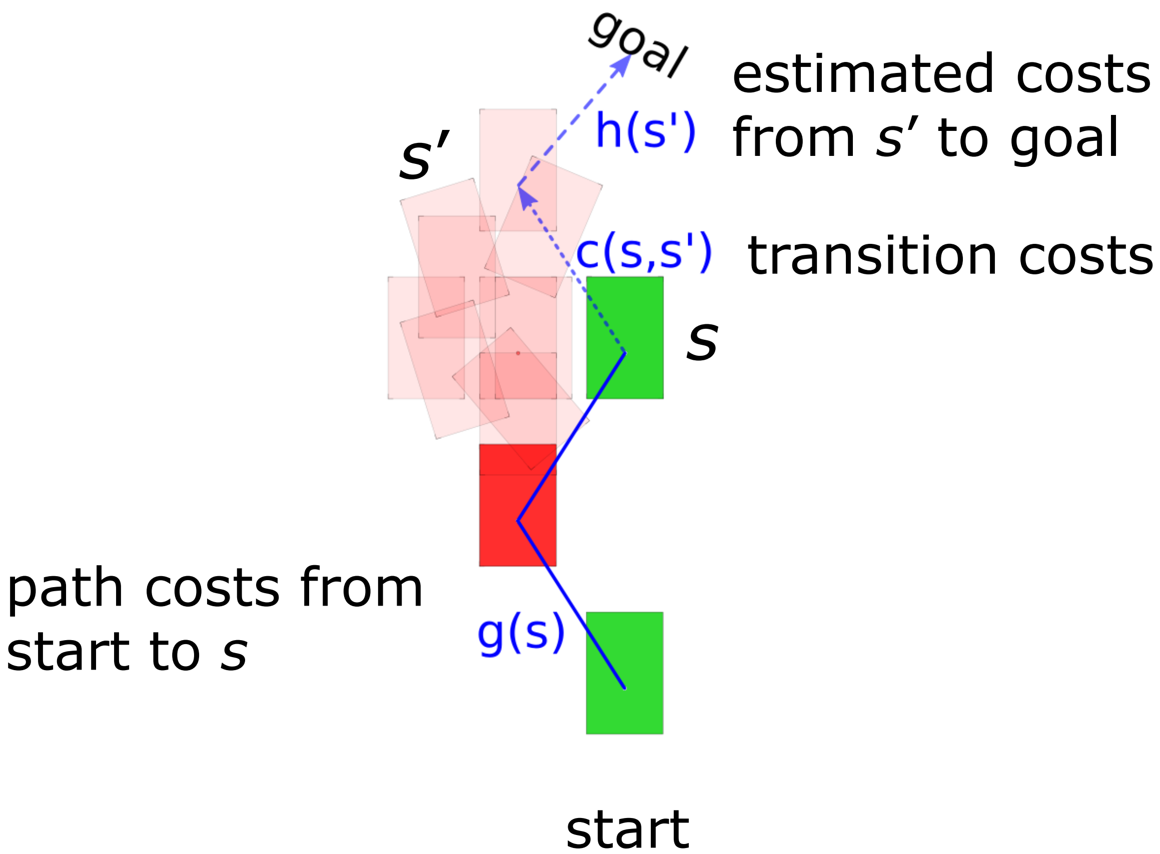
Footstep Planning



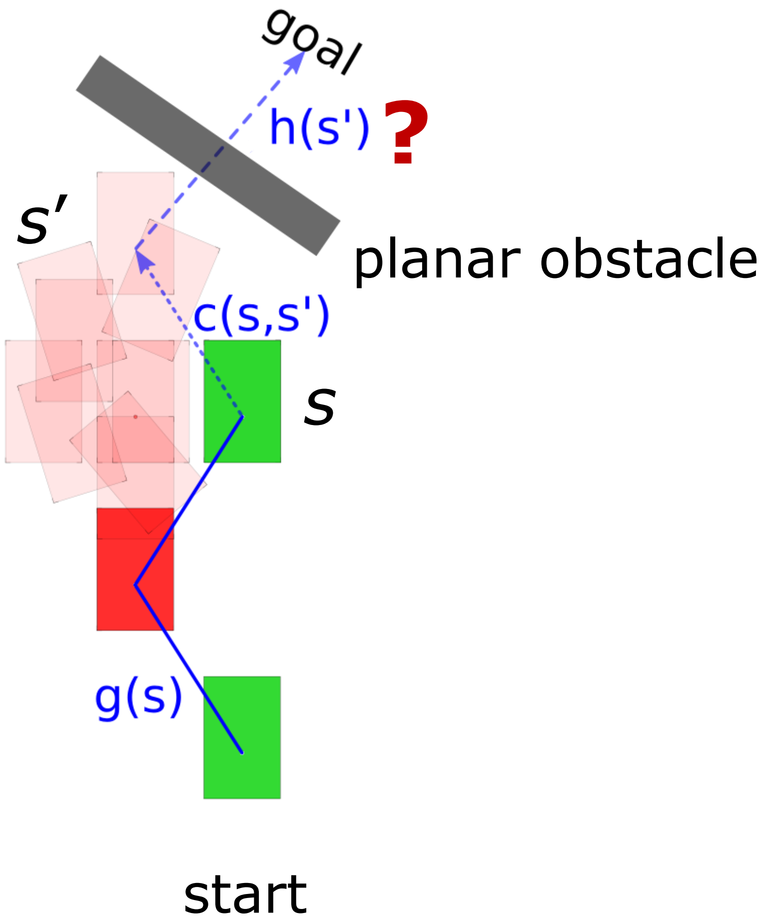
Footstep Planning



Footstep Planning

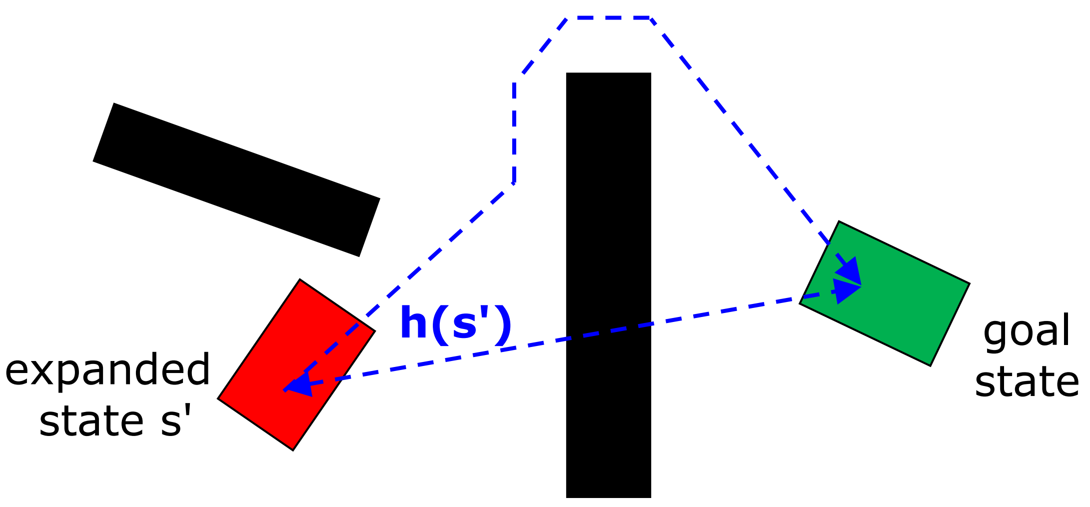


Footstep Planning



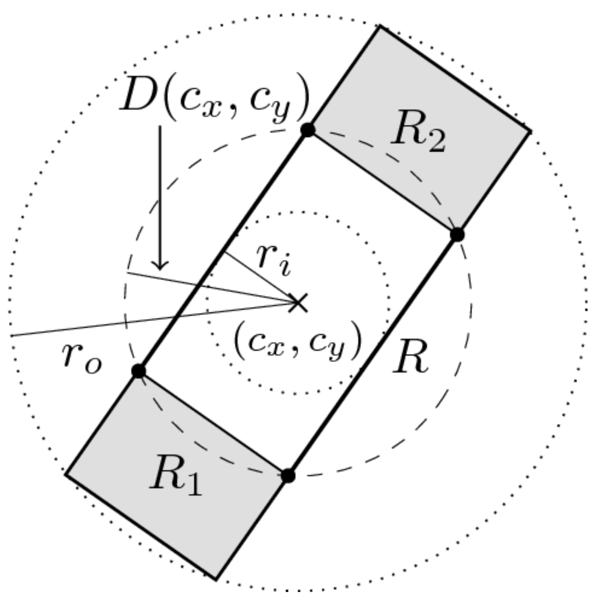
Heuristic

- Estimates the costs to the goal
- Critical for planner performance
- Usual choices:
  - Euclidean distance
  - 2D Dijkstra path



Efficient Collision Checking

- Footprint is rectangular with arbitrary orientation
- Evaluating the distance between foot center and the closest obstacle may not yield correct or optimal results
- Recursively subdivide footstep shape

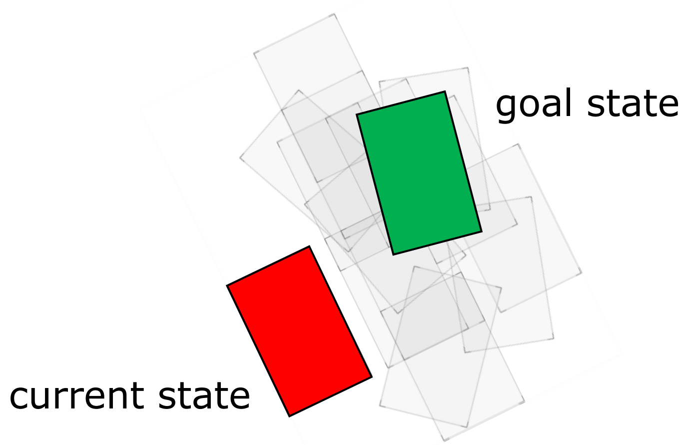


$D(c_x, c_y)$ = distance to the closest obstacle (precomputed map)

[Sprunk et al. (ICRA '11)]

Search-Based Footstep Planning

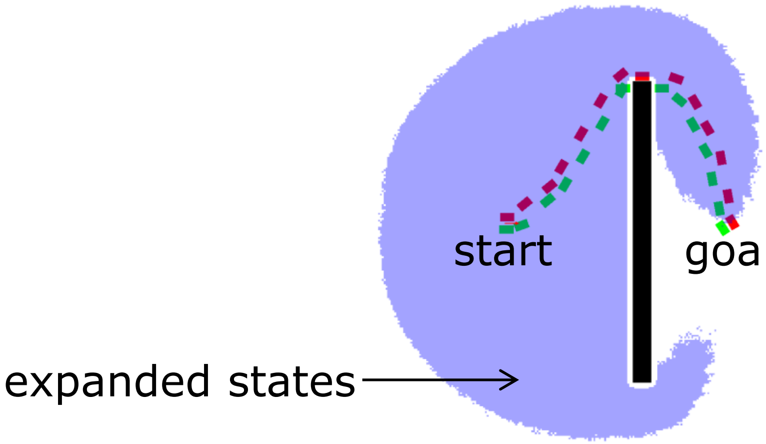
- Concatenation of footstep actions builds a lattice in the global search space
- Only valid states after a collision check are added
- Goal state may not be exactly reached, but it is sufficient to reach a state close by (within the motion range)



Search-Based Footstep Planning

- We can now apply heuristic search methods on the state lattice
- Search-based planning library: www.ros.org/wiki/sbpl
- Footstep planning implementation based on SBPL: www.ros.org/wiki/footstep_planner

Local Minima in the Search Space



- A* will search for the optimal result
- Initially sub-optimal results are often sufficient for navigation
- Provable sub-optimality instead of randomness yields more efficient paths

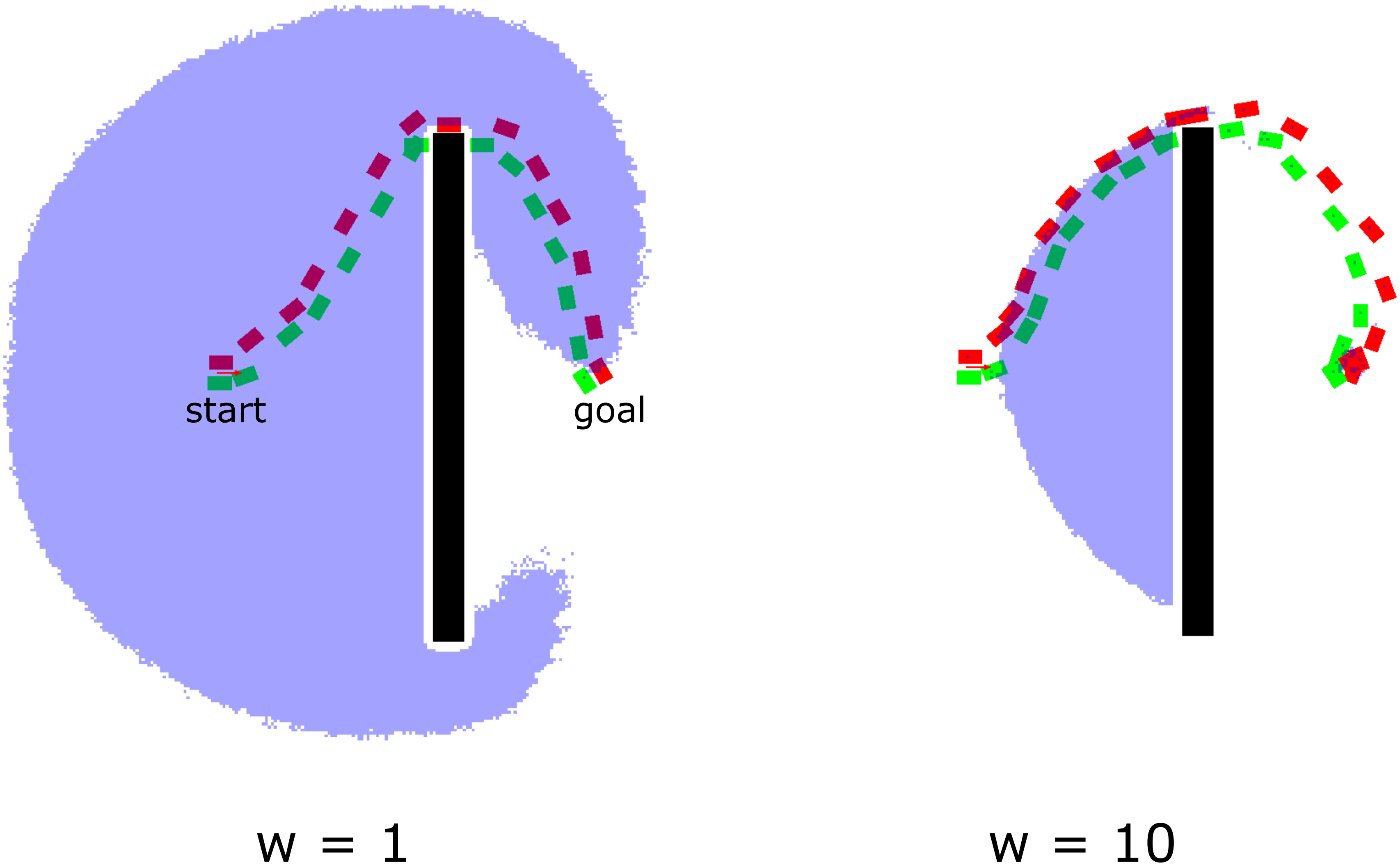
Anytime Repairing A* (ARA*)

- Heuristic inflation by a factor w allows to efficiently deal with local minima: weighted A* (wA*)
- ARA* runs a series of wA* searches, iteratively lowering w as time allows
- Re-uses information from previous iterations

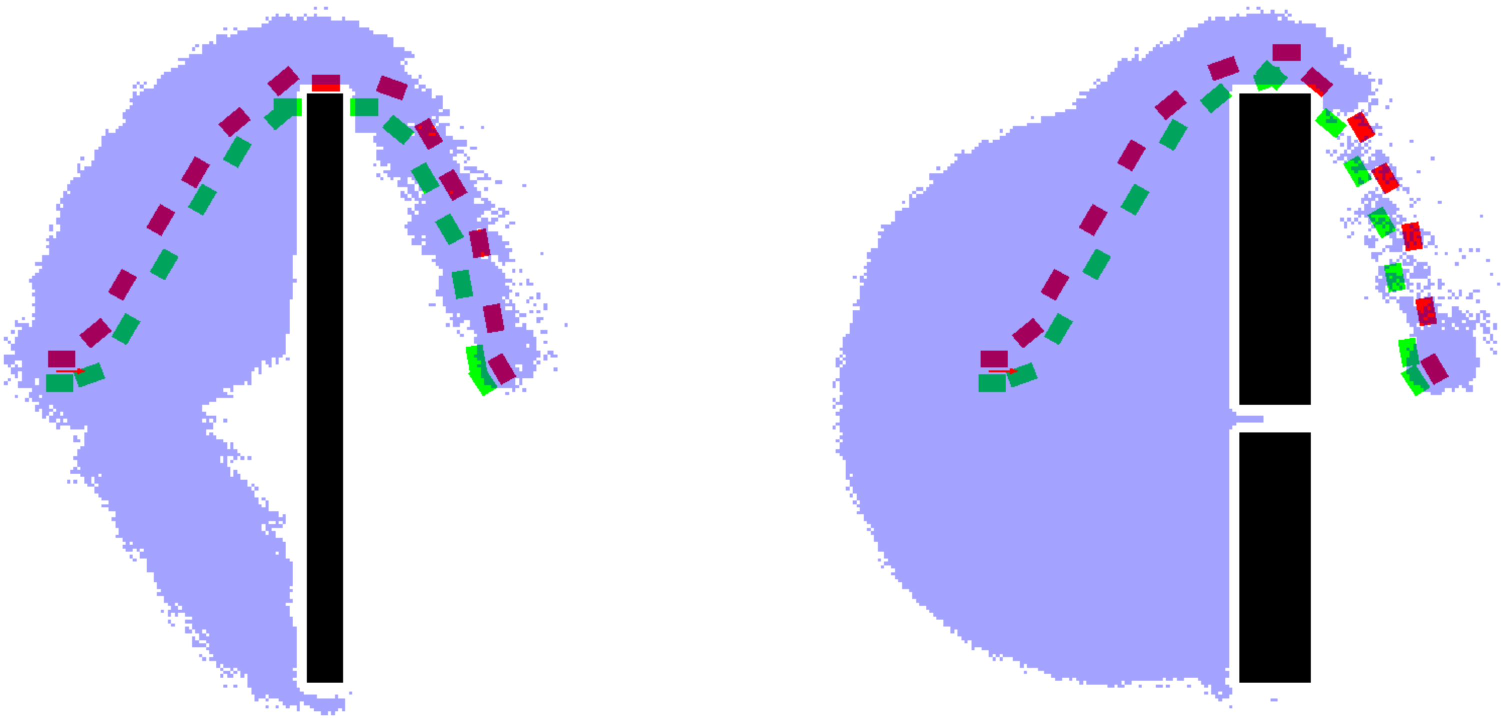
[Likhachev et al. (NIPS 2004), Hornung et al. (Humanoids 2012)]

Interactive Session III (Sa., 15:00)

ARA* with Euclidean Heuristic



ARA* with Dijkstra Heuristic

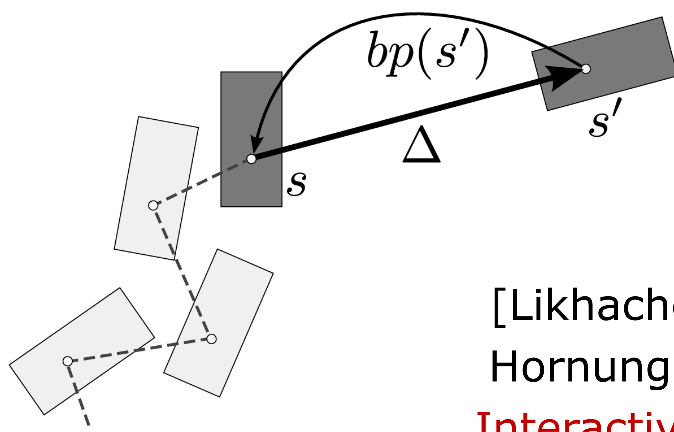


w = 1

Performance depends on well-designed heuristic

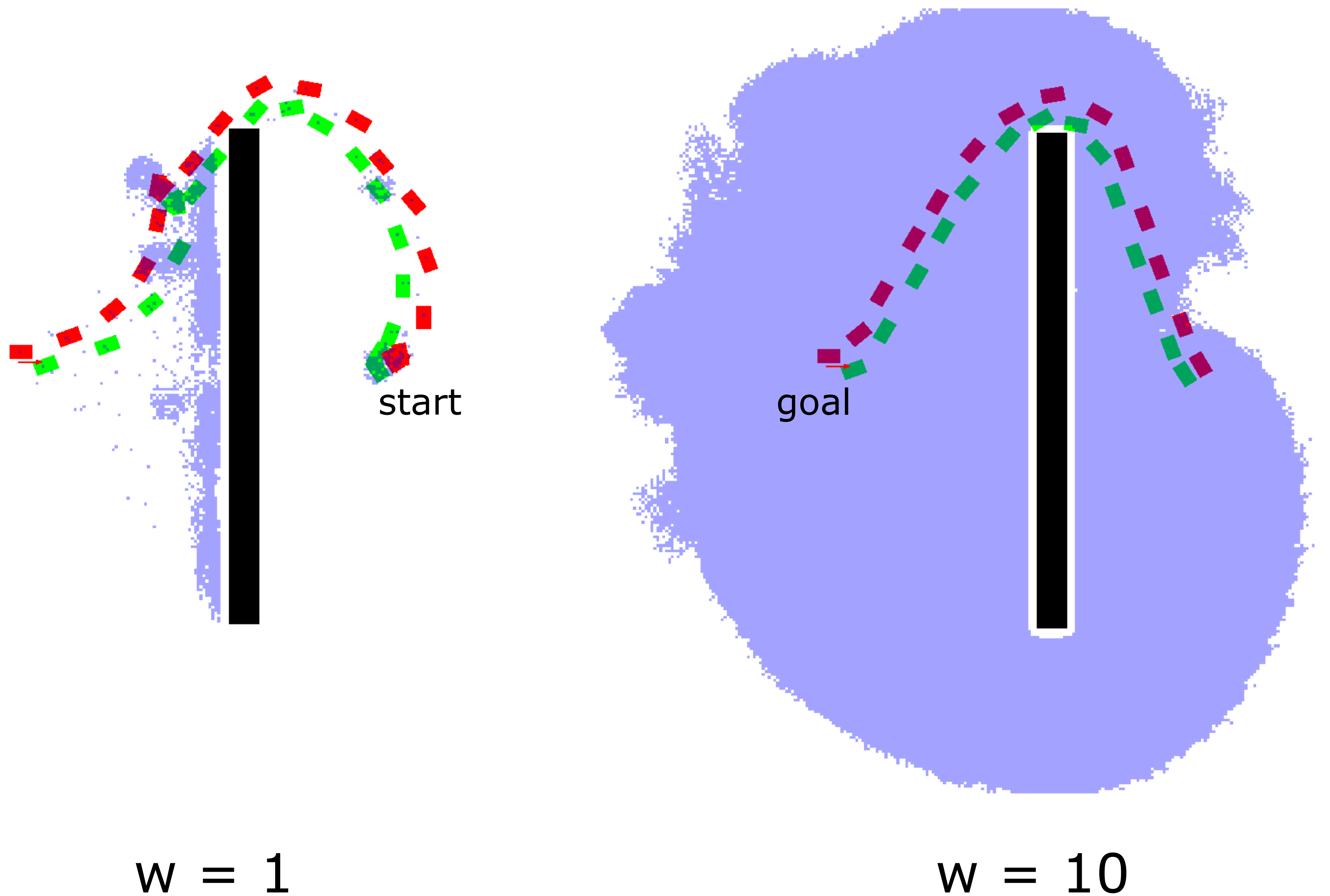
Randomized A* (R*)

- Iteratively constructs a graph of sparsely placed randomized sub-goals (exploration)
- Plans between sub-goals with wA*, preferring easy-to-plan sequences
- Iteratively lowers w as time allows



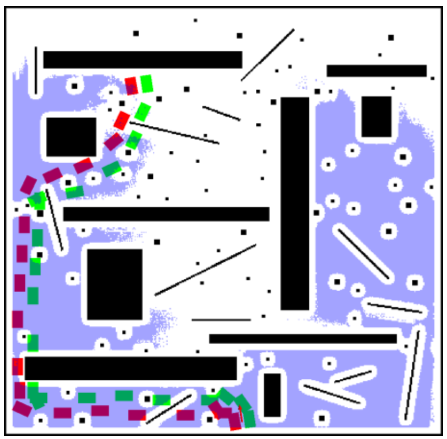
[Likhachev & Stentz (AAAI 2008), Hornung et al. (Humanoids 2012)]
Interactive Session III (Sa., 15:00)

R* with Euclidean Heuristic



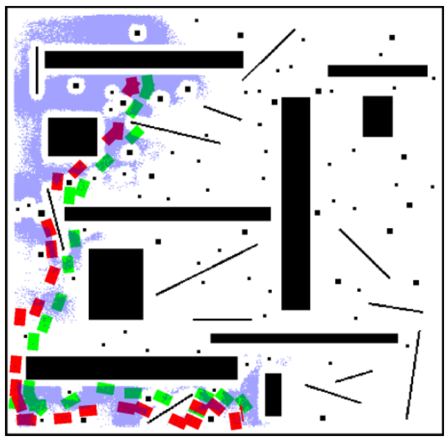
Planning in Dense Clutter Until First Solution

A*
Euclidean heur.



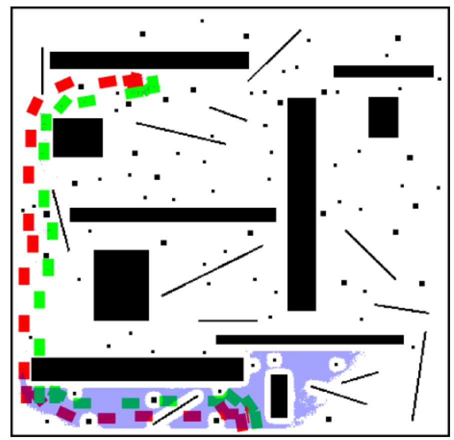
11.9 sec.

R*
Euclidean heur.



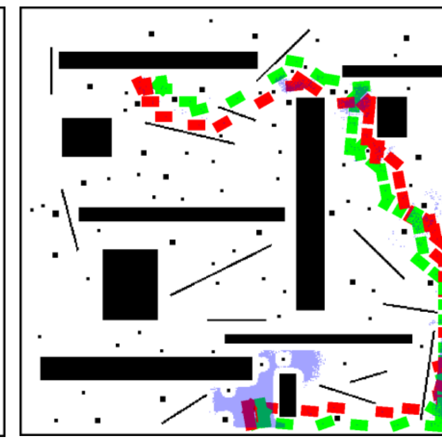
0.4 sec.

ARA*
Euclidean heur.



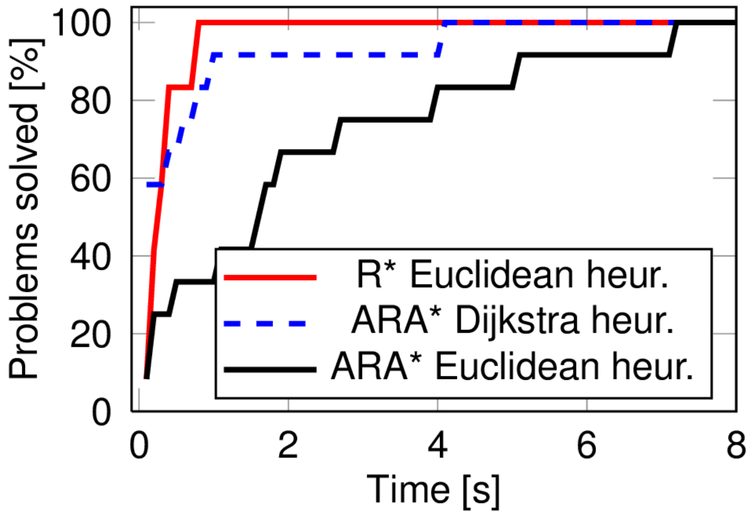
2.7 sec.

ARA*
Dijkstra heur.



0.7 sec.

Planning in Dense Clutter Until First Solution

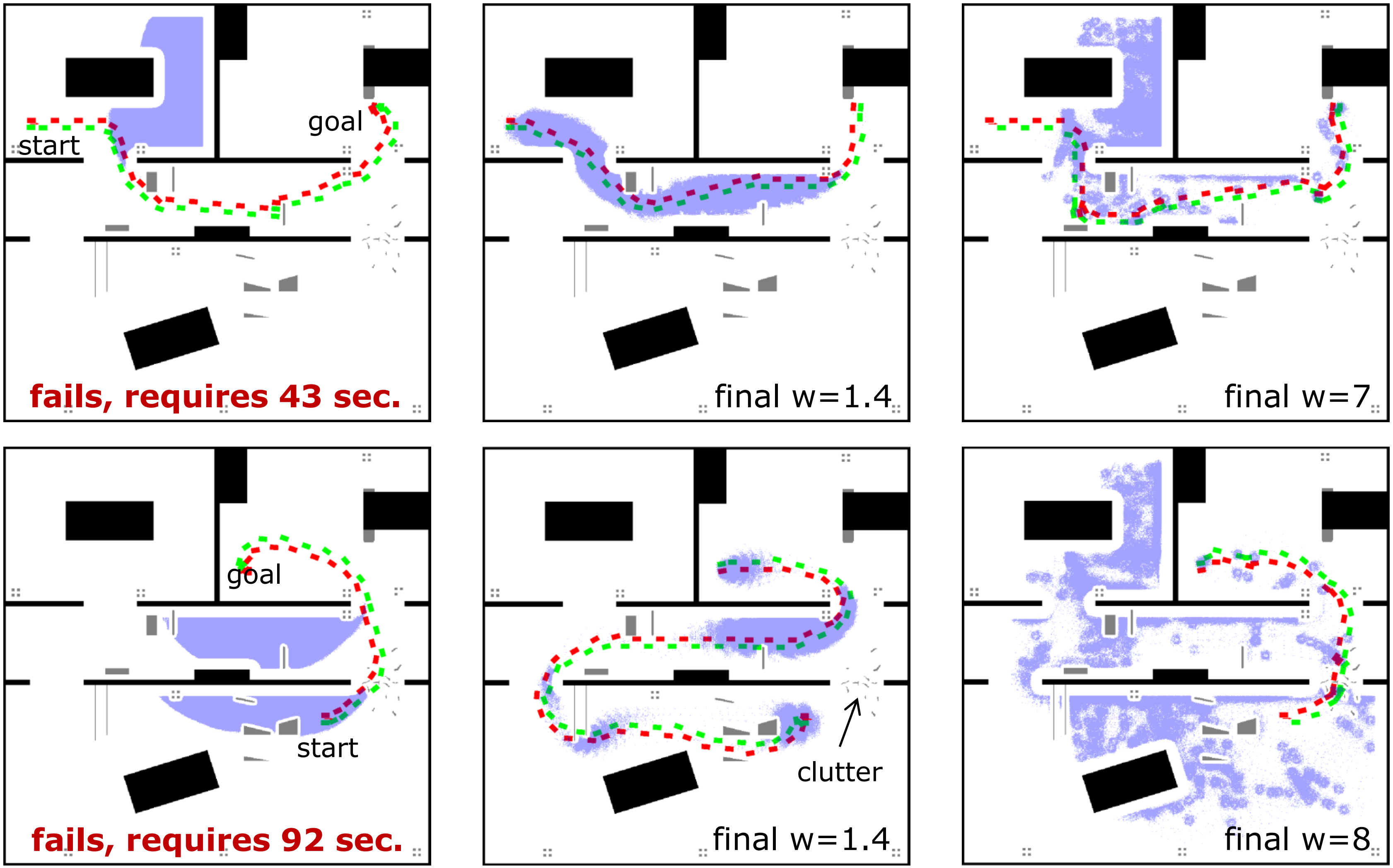


Planner	Heuristic	Planning time [s]	Path costs
R* (w=5)	Euclidean	0.32 ± 0.23	16.45 ± 3.16
ARA* (w=5)	Euclidean	2.15 ± 2.21	13.57 ± 1.15
ARA* (w=5)	2D Dijkstra	0.56 ± 1.13	20.41 ± 5.08
A* (w=1)	Euclidean	33.31 ± 15.00	11.06 ± 1.20

- 12 random start and goal locations
- ARA* finds fast results only with the 2D Dijkstra heuristic, leading to longer paths due to its inadmissibility
- **R* finds fast results even with the Euclidean heuristic**

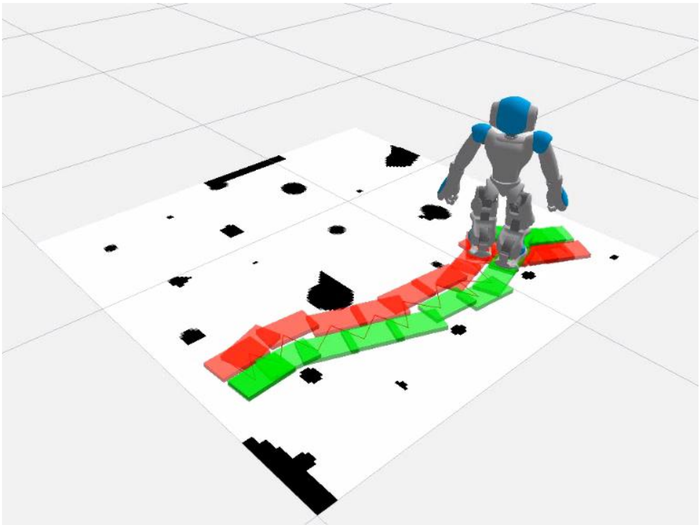
Planning with a Time Limit (5s)

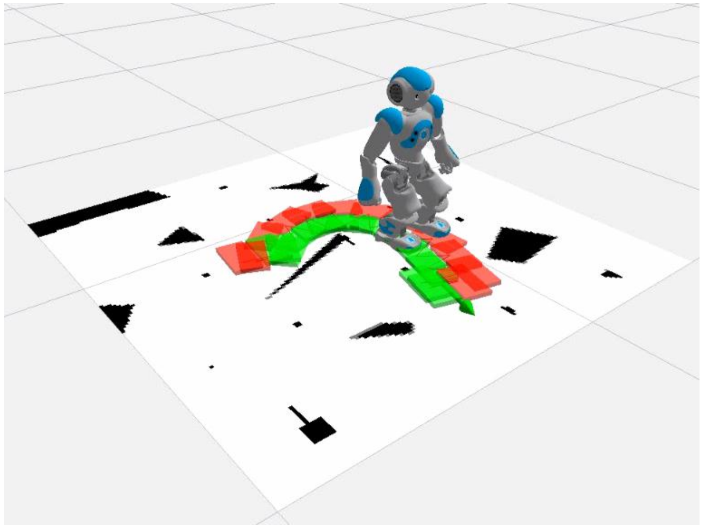
ARA* Euclidean heuristic | **ARA*** Dijkstra heuristic | **R*** Euclidean heuristic



Anytime Planning Results

- Performance of ARA* depends on well-designed heuristic
- Dijkstra heuristic may be inadmissible and can lead to wrong results
- R* with the Euclidean heuristic finds efficient plans in short time



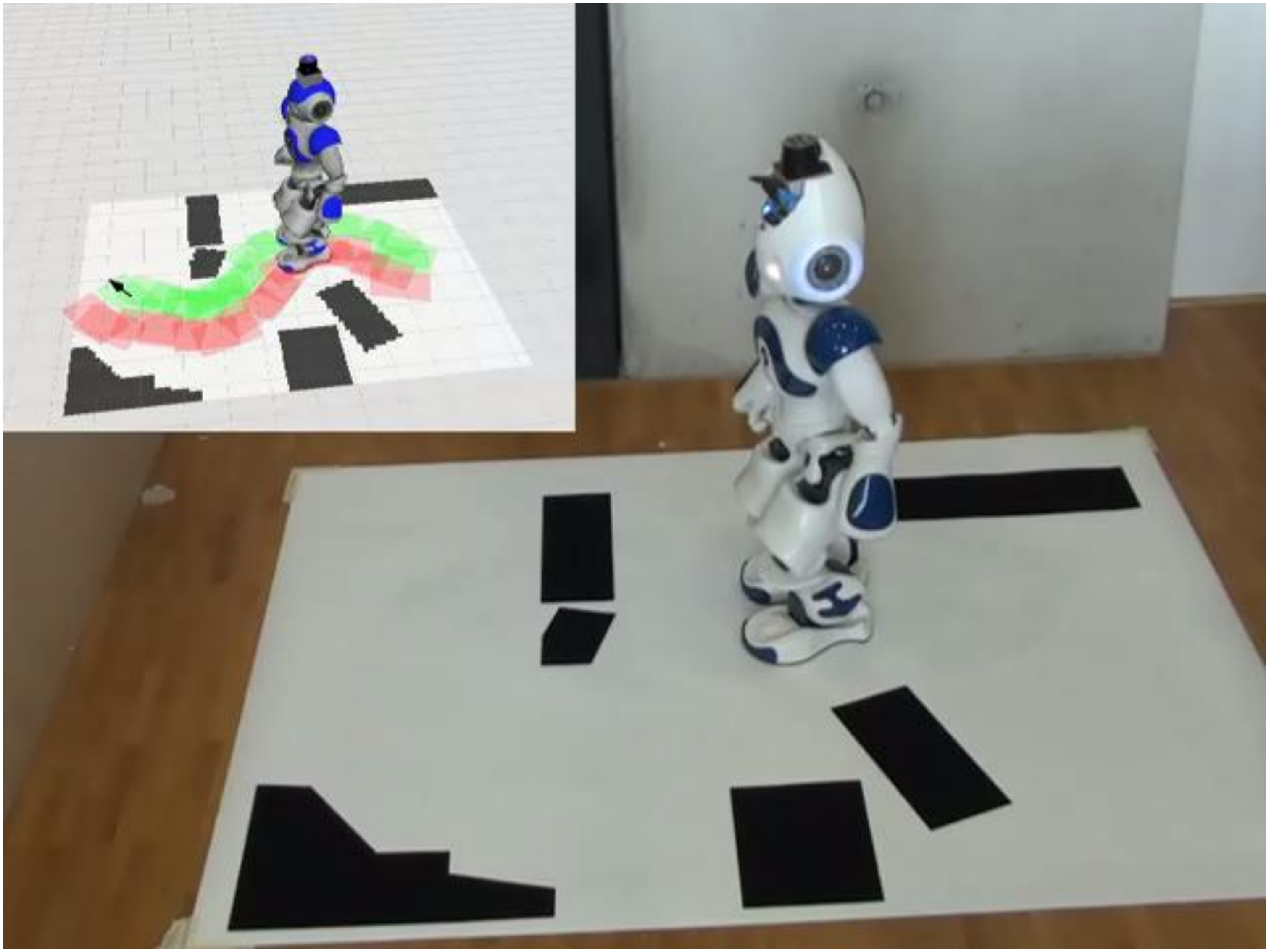


Dynamic A* (D*)

- Allows for efficient re-planning in case of
  - Changes in the environment
  - Deviations from the initial path
- Re-uses state information from previous searches
- Planning backwards increases the efficiency in case of updated localization estimates
- Anytime version: AD*

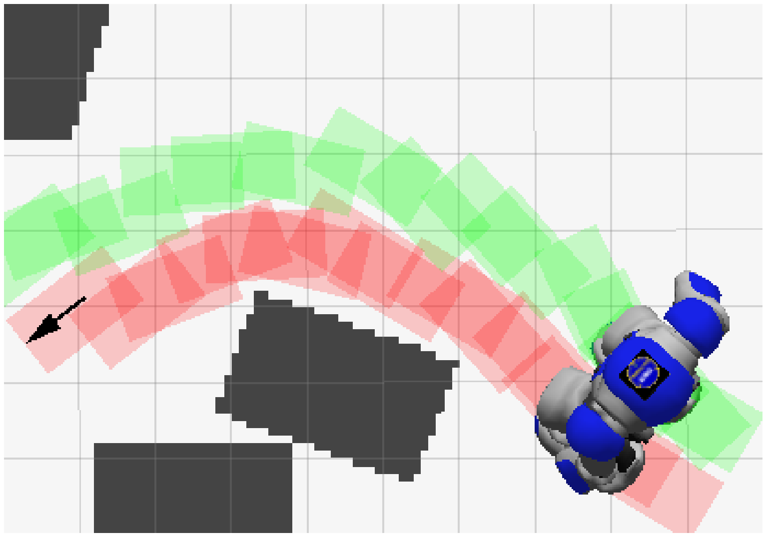
[Koenig & Likhachev (AAAI ‘00), Garimort (ICRA ’11)]

D* Plan Execution with a Nao

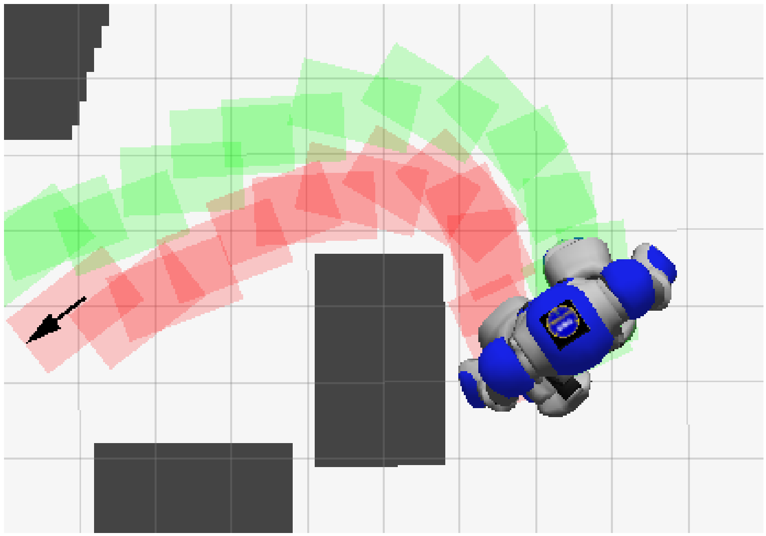


Efficient Replanning

- Plans may become invalid due to changes in the environment
- D* allows for efficient plan re-usage

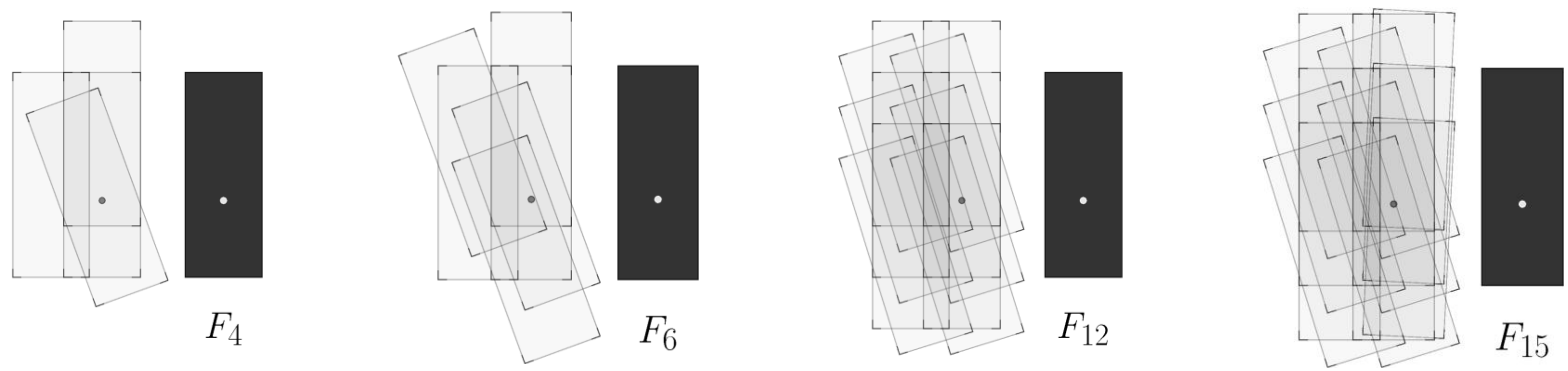


2966 states, 1.05s

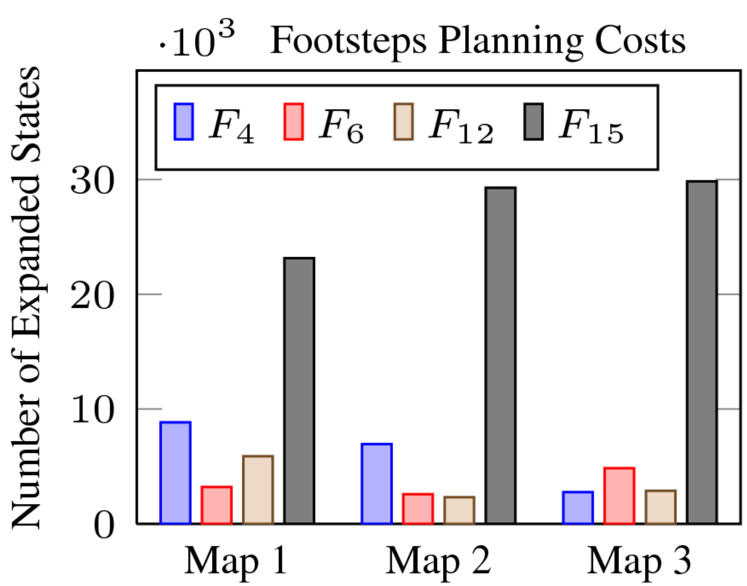


956 states, 0.53s

Different Footstep Sets for Nao

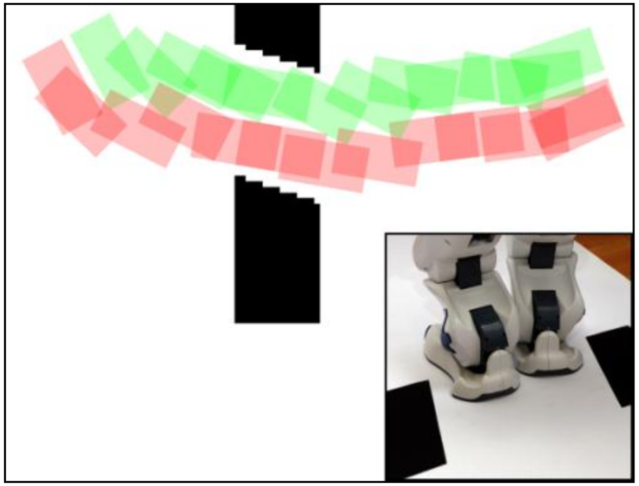


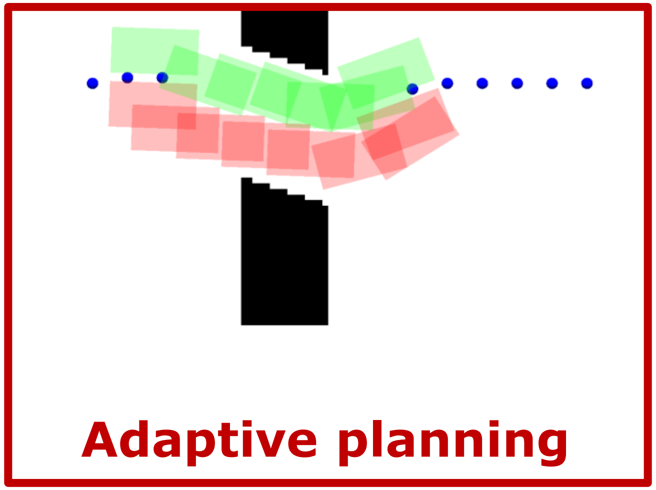
- F_{12} and F_{15} lead to significantly shorter paths
- F_{15} has a significantly higher planning time
- Result: F_{12} yields shortest paths with efficient planning times



Adaptive Level-of-Detail Planning

- Planning the whole path with footsteps may not always be desired in large open spaces
- Adaptive level-of-detail planning: Combine fast grid-based 2D planning in open spaces with footstep planning near obstacles

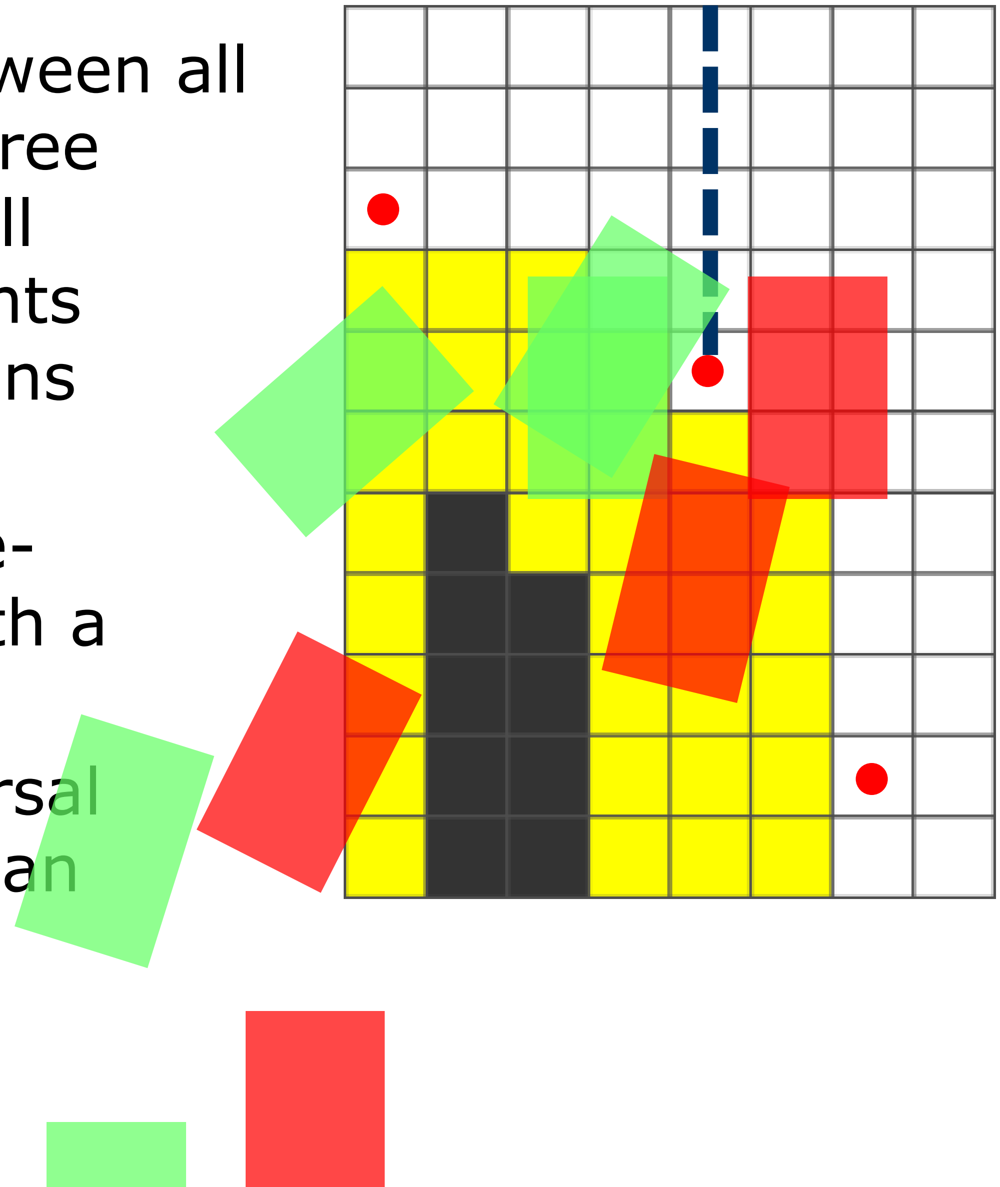




[Hornung & Bennewitz (ICRA ‘11)]

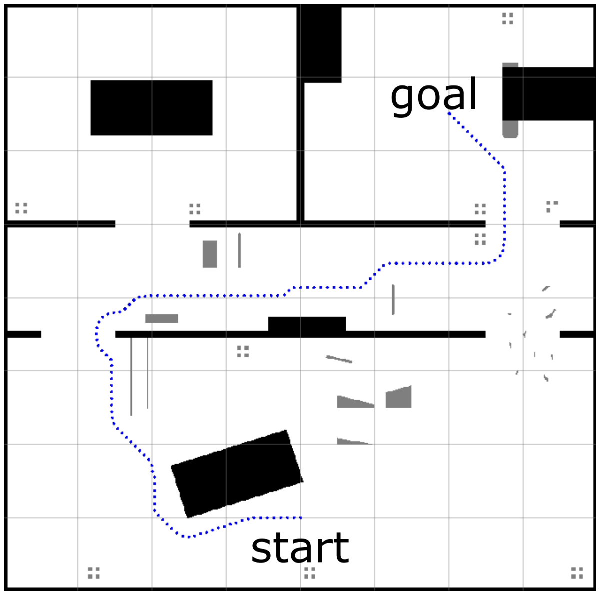
Adaptive Level-of-Detail Planning

- Allow transitions between all neighboring cells in free areas and between all sampled contour points across obstacle regions
- Traversal costs are estimated from a pre-planning stage or with a learned heuristic
- Every obstacle traversal triggers a footstep plan



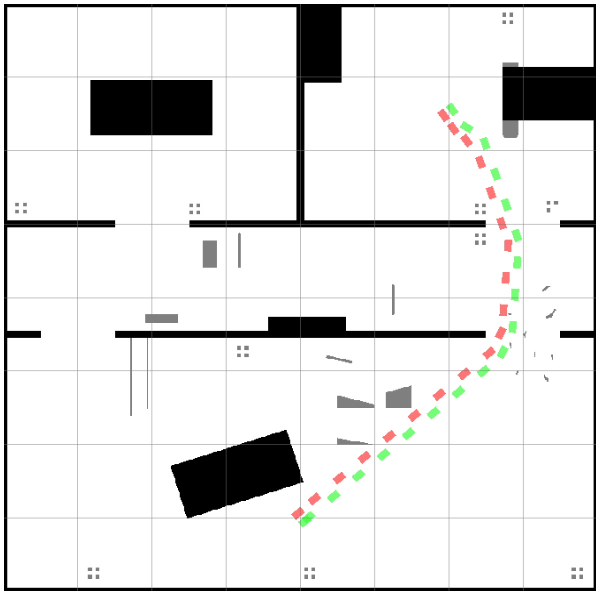
Adaptive Planning Results

2D Planning



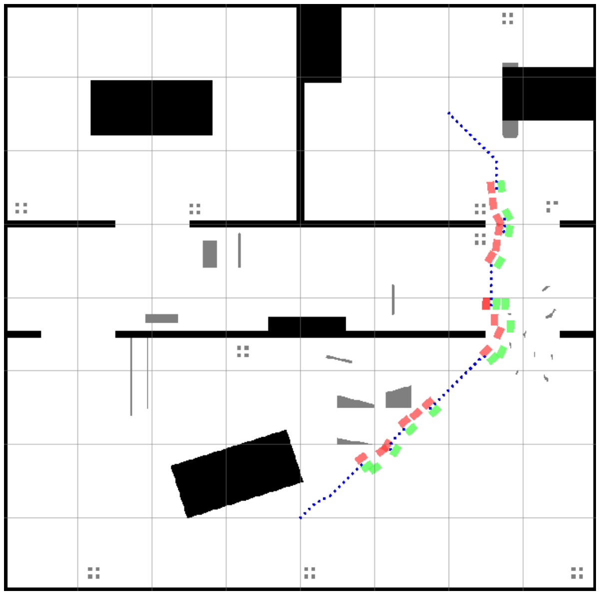
<1 s planning time
High path costs

Footstep Planning



29 s planning time

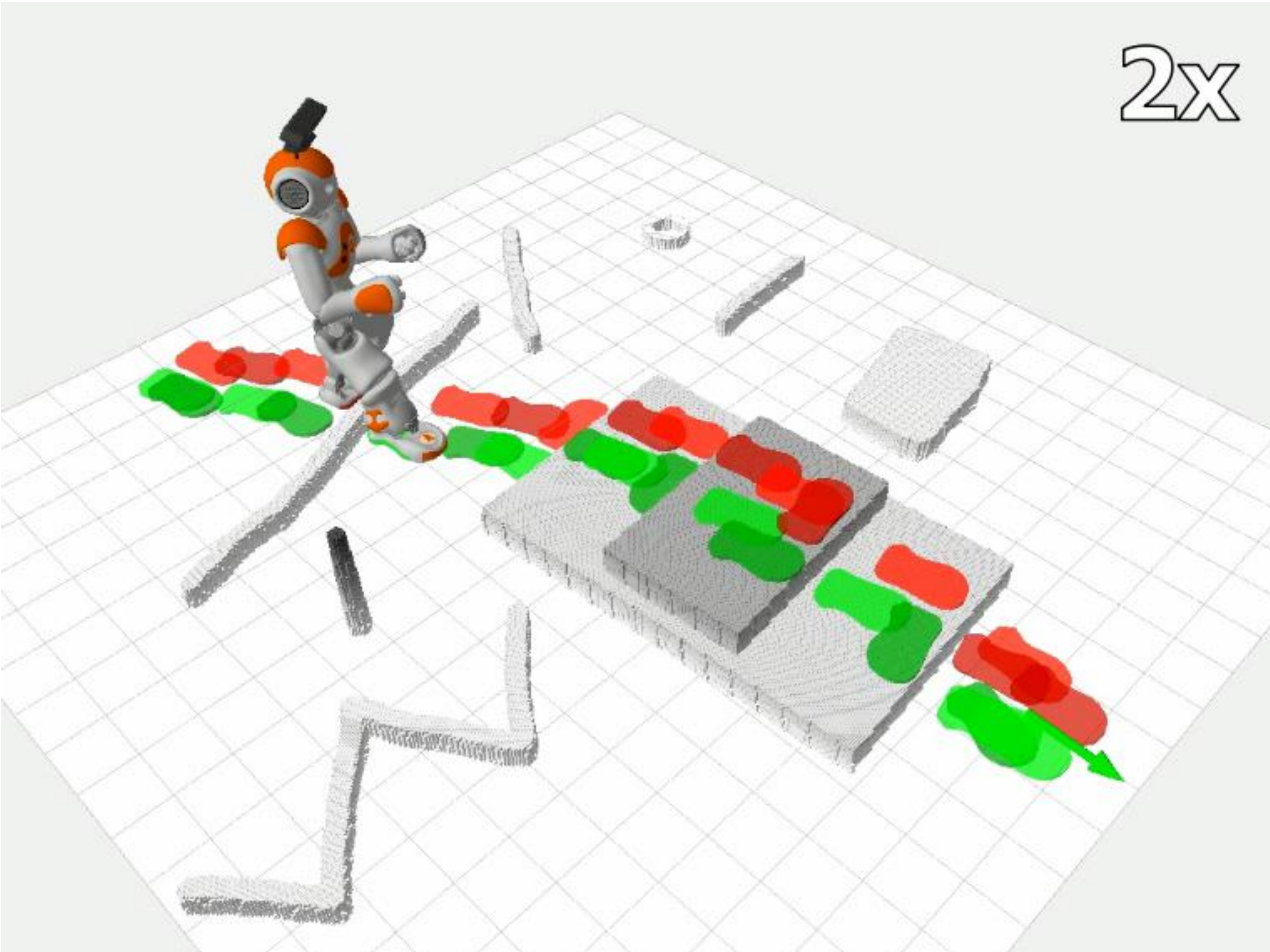
Adaptive Planning



<1s planning time, costs only 2% higher

Fast planning times and efficient solutions with adaptive level-of-detail planning

Current Work: Planning in 3D



Summary

- Anytime search-based footstep planning with suboptimality bounds: ARA* and R*
- Replanning during navigation with AD*
- Heuristic influences planner behavior
- Adaptive level-of-detail planning to combine 2D with footstep planning
- Available open source in ROS: www.ros.org/wiki/footstep_planner

➡ Interactive Session III (Saturday, 15:00)

Thank you!