Safe and Efficient High Dimensional Motion Planning in Space-Time with Time Parameterized Prediction

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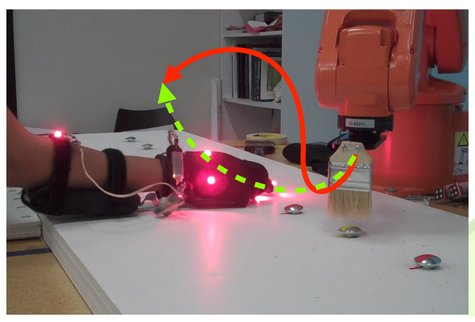
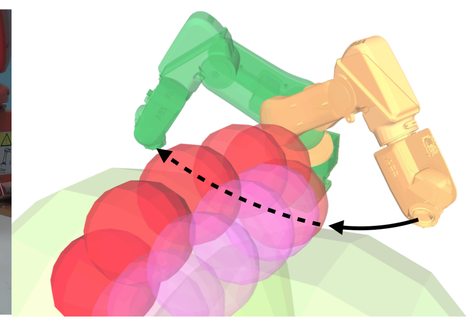
Motivation

- Human-robot physical collaboration in close proximity can improve working productivity and efficiency [1].





Challenges

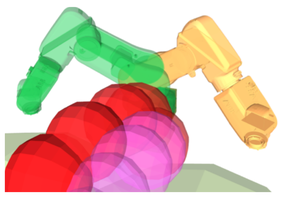
- Planning in space
  - Avoiding all obstacles' swept volumes in the near future.
  - ✓ **Safe**
  - ❑ Low flexibility for planning
  - ❑ Overly conservative solutions
- Planning in space and time
  - ✓ **Efficient** obstacle avoidance
  - ✓ High flexibility for planning
  - ❑ Computational complexity
    - High-dimensional C-space
    - Time domain

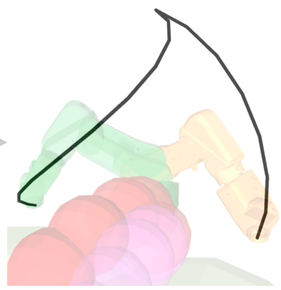
Contributions

- Combine the advantages from both:
  - ✓ **Safe + efficient solutions**
  - ✓ **Computational efficiency**
- Key insights
  1. First find a conservative path in C-space (configuration space).
  2. Further optimize the path for time parameterization in both C-space and the time domain.

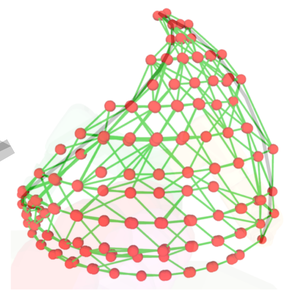
Lazy Safe-Interval Shortcut Probabilistic Roadmap Planner (Lazy SISPRM)

Configuration space





Path Sample
- Avoiding all obstacles' swept volumes
- Disregarding timestamps



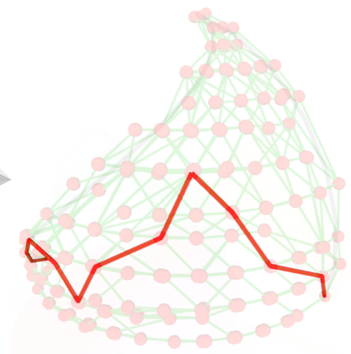
Shortcut Probabilistic Roadmap (SPRM)
- A graph composed of a set of shortcuts sampled along the path sample.

As a contingency plan

Time domain

Safe-Interval Shortcut Probabilistic Roadmap (SISPRM)
- A graph where each node is a safe interval $\theta q = (q, [t, t'])$, wherein q is collision-free within [t, t'] but not before t or after t'. [2]

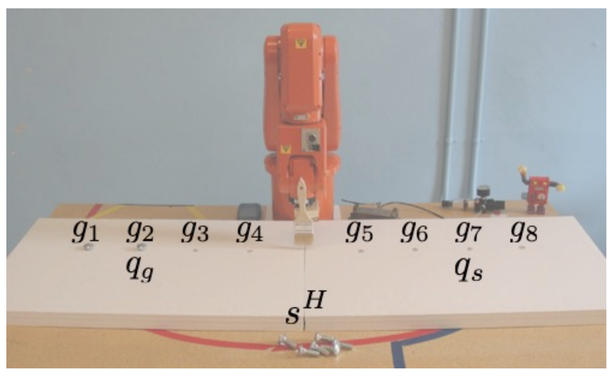
Optimal search
- Lazy collision checking



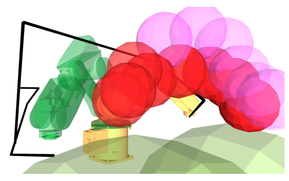
Experiment
- A human hand: sH => g_{3,4,5,6} => sH
  - 80 trajectories collected in a user study [3].
- Robot: g7 => g2

Metrics
- ❖ Average execution time
- Average planning time ~ 0.25 sec [4]
- Average path length = L2-Norm in C-space
- Success rate = collision free && goal reached

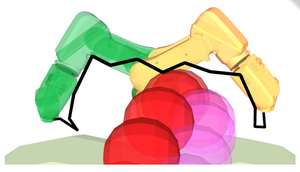
Experiments and Results



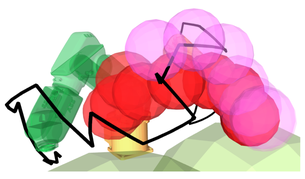
Lazy SISPRM



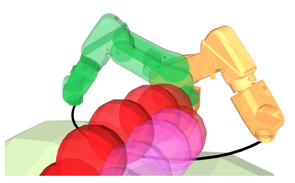
RRT∗-τ [7] (1st solution)



A-SIPP [5] (1st solution)



KD-RRT-τ [6]



ITOMP-τ [8]

Planner	Success Rate	Avg. Exec. Time (s)	Avg. Plan. Time (ms)	Avg. Path Length (rad)
Lazy SISPRM	**97.50%**	**1.59**	**171**	**3.0222**
RRT-star-t [7]	95.00%	10.47	114,008	12.8308
Anytime SIPP [5] (Safe Interval Path Planning)	57.50%	1.53	5,446	4.8408
SIPP MP [5] (Motion Primitives)	98.73%	1.70	60,281	2.8093
Anytime SIPP MP [5]	100%	1.71	173	3.0850
Kinodynamic RRT-t [6]	95.00%	6.49	142	10.5751
ITOMP-t [8] (Trajectory Optimization)	92.50%	2.65	320	2.2688

Blue - significance compared against Lazy SISPRM (ANOVA)

[1] P. A. Lasota and J. A. Shah, "Analyzing the effects of human-aware motion planning on close-proximity human–robot collaboration," Human factors, 2015.
[2] M. Phillips and M. Likhachev, "Sipp: Safe interval path planning for dynamic environments," in ICRA, 2011.
[3] P. A. Lasota, G. F. Rossano, and J. A. Shah, "Toward safe close- proximity human-robot interaction with standard industrial robots," in CASE, 2014.
[4] P. A. Lasota and J. A. Shah, "A multiple-predictor approach to human motion prediction," in ICRA, 2017.
[5] V. Narayanan, M. Phillips, and M. Likhachev, "Anytime safe interval path planning for dynamic environments," in IROS, 2012.
[6] S. M. LaValle and J. J. Kuffner Jr, "Randomized kinodynamic planning," IJRR, 2001.
[7] S. Karaman, M. R. Walter, A. Perez, E. Frazzoli, and S. Teller, "Anytime motion planning using the rrt*," in ICRA, 2011.
[8] C. Park, J. Pan, and D. Manocha, "Itomp: Incremental trajectory optimization for real-time replanning in dynamic environments." in ICAPS, 2012.