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CBF-Guided RRT with SDF Constraints with Spherical Robot Approximation under Noisy Map Estimations

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Description

1. Goal
    a. Enable safer and more reliable motion planning for manipulators under map uncertainty, without relying solely on binary collision checking.
2. Motivation
    i. • RRT struggles in narrow passages.
    ii. • Binary collision checks only detect failures after an unsafe extension.
    iii. • CBFs allow continuous safety constraints during steering.

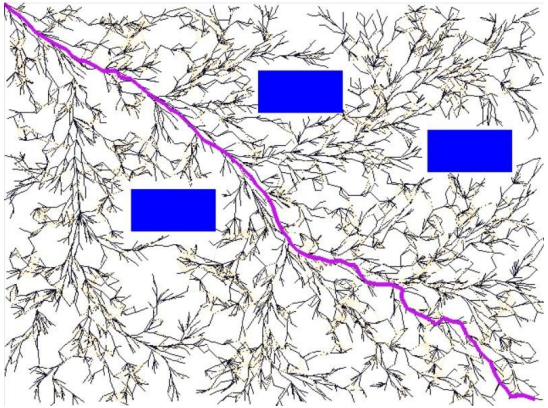
Baseline

RRT Characteristics

- Builds a tree via repeated sampling
- Steering uses straight-line interpolation in joint space
- Collision checking is binary after extension

Limitations Observed

- Frequently collides in tight or cluttered scenes
- Inefficient exploration due to failed extensions



Alternative

1. Key Idea

   Use CBFs to enforce safety during each small steering step, not after.

2. CBF Construction

   For each robot sphere k:

$$h_k(q) = \phi_{\text{safe}}(c_k(q)) - r_k$$

   with gradient:

$$\nabla h_k(q) = J_{c_k}(q)^\top \nabla \phi(c_k(q))$$

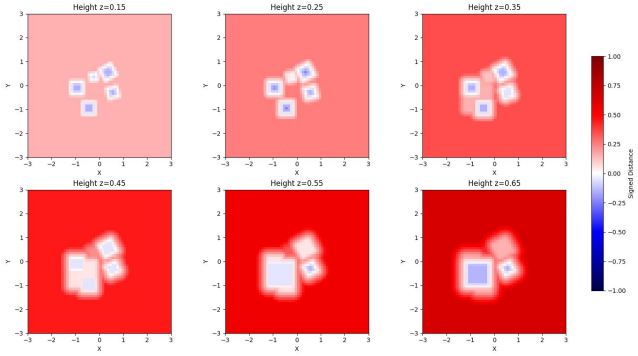
3. CBF-QP Steering

   Solve:

$$\min_u \|u - u_{\text{nom}}\|^2$$

   subject to:

$$\nabla h_k(q)^\top u + \alpha h_k(q) \geq 0 \quad \forall k$$



Results

- Single arm robot
  - Simple environment

σ	Succ. RRT-CBF	Succ. RRT	Nodes RRTCBF	Nodes RRT
0.000	1.00	1.00	**72.7** ±13.7	86.0 ± 30.8
0.005	1.00	1.00	**72.6** ±12.3	86.0 ± 30.8
0.010	1.00	1.00	**72.6** ±12.3	86.0 ± 30.8
0.020	1.00	1.00	**73.9** ±11.4	86.0 ± 30.8

  - Complex environment

σ	Succ. RRT-CBF	Succ. RRT	Nodes RRT-CBF	Nodes RRT
0.000	1.00	1.00	**80.4** ±13.8	81.2 ± 19.1
0.005	1.00	1.00	**73.4** ±15.2	81.2 ± 19.1
0.010	**1.00**	0.80	**73.4** ±15.2	81.2 ± 19.1
0.020	**1.00**	0.60	**74.4** ±14.0	81.2 ± 19.1

- Dual arm robot

σ	Succ. RRT-CBF	Succ. RRT	Nodes RRTCBF	Nodes RRT
0.000	1.00	1.00	**159.2** ±34.16	1288.8 ± 2101.59
0.005	**1.00**	0.80	**157.8** ±25.46	1288.8 ± 2101.5
0.010	**1.00**	0.60	**166.6** ±26.82	1288.8 ± 2101.5
0.020	**0.80**	0.60	**180** ±22.91	1288.8 ± 2101.5

Conclusion

- CBF guidance dramatically improves RRT robustness
- Minimal computational overhead for QP solves
- Works well under SDF noise and in complex multi-arm setups
- A principled safety-aware planner for real-world manipulation

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Thank you!