Trajectory Optimization for Motion Planning

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Motion Planning

- Sampling-based methods (e.g., RRTs)
- Graph search methods (e.g., A*)

- Optimization-based methods
  - Reactive control
    - Potential-based methods (Khatib '86)
  - Optimize over entire trajectory
    - Elastic bands (Quinlan and Khatib '93)
    - CHOMP (Ratliff et al. '09) and variants (STOMP, ITOMP)

Trajectory Optimization

$$\min_{\theta_{1:T}} \quad \sum_t \|\theta_{t+1} - \theta_t\|^2 + \text{other costs}$$

$$\text{subject to} \quad \theta_0 = \text{start state}, \quad \theta_T \text{ in goal set}$$

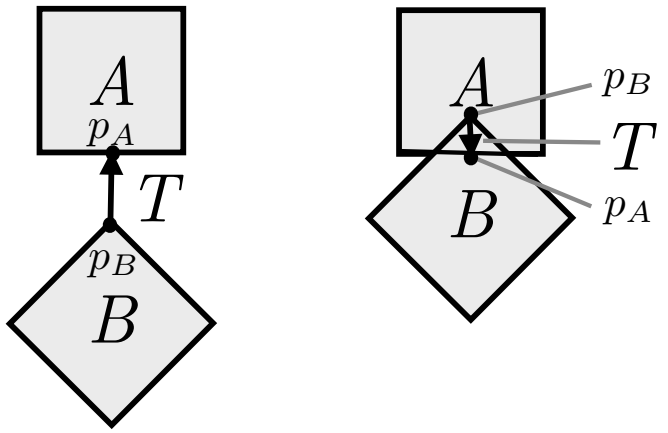
joint limits

for all robot parts, for all obstacles:

no collision $\longrightarrow$ ***non-convex***

Solution method: sequential convex optimization

Collision Constraints

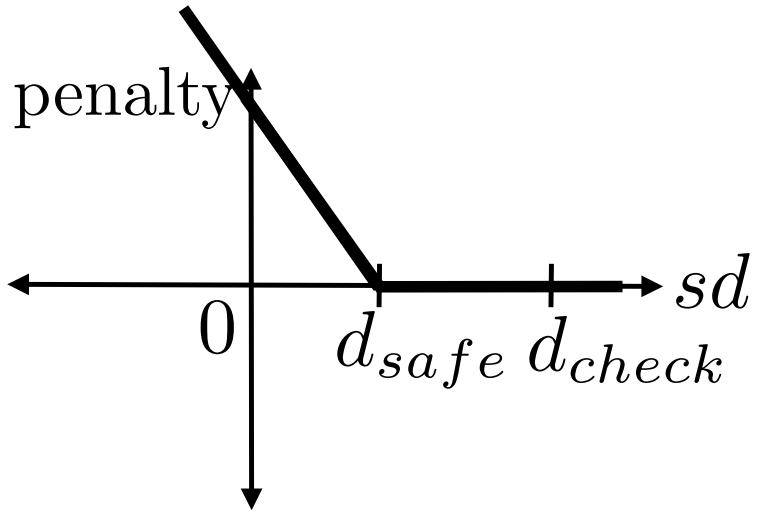


$sd > 0$ $sd < 0$

$$sd_{AB}(\theta) \approx \hat{n} \cdot (p_B - p_A(\theta))$$
$$\approx sd_{AB}(\theta_0) - \hat{n}^\top J_{P_A}(\theta_0)(\theta - \theta_0)$$

[SD from: Gilbert-Johnson-Keerthi (GJK) algorithm and Expanding Polytope Algorithm (EPA)]

Penalty for Collision Constraints



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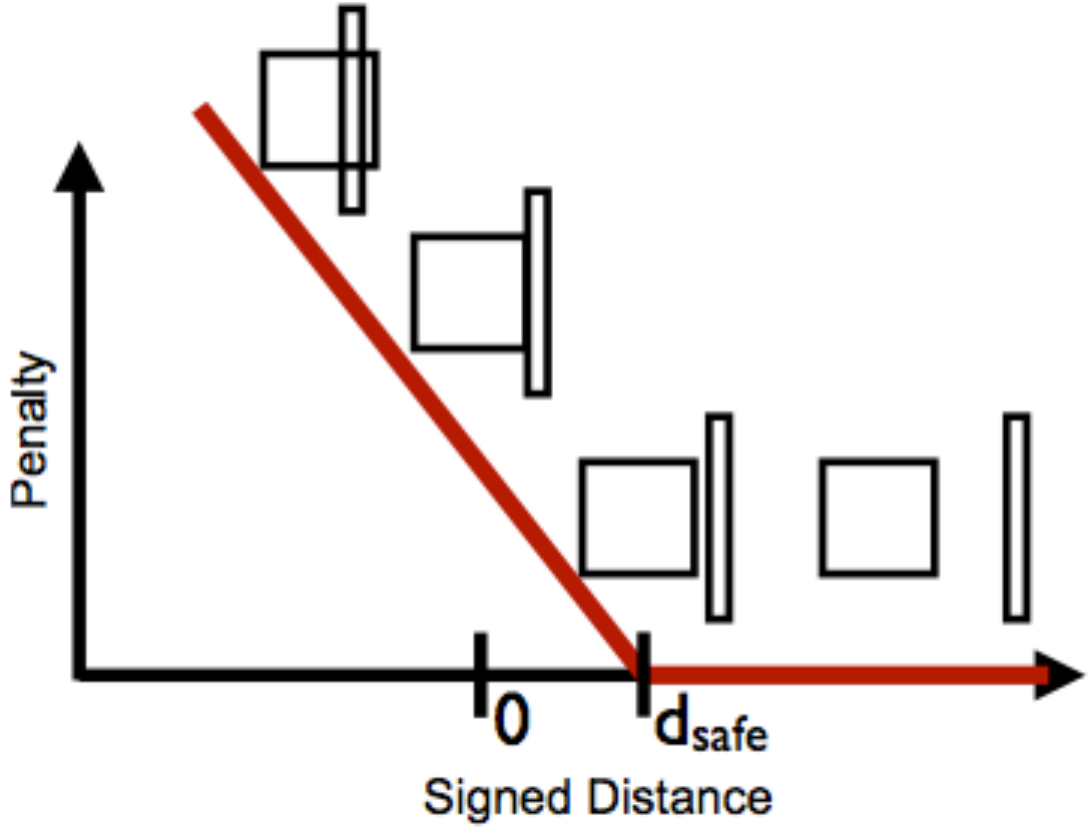
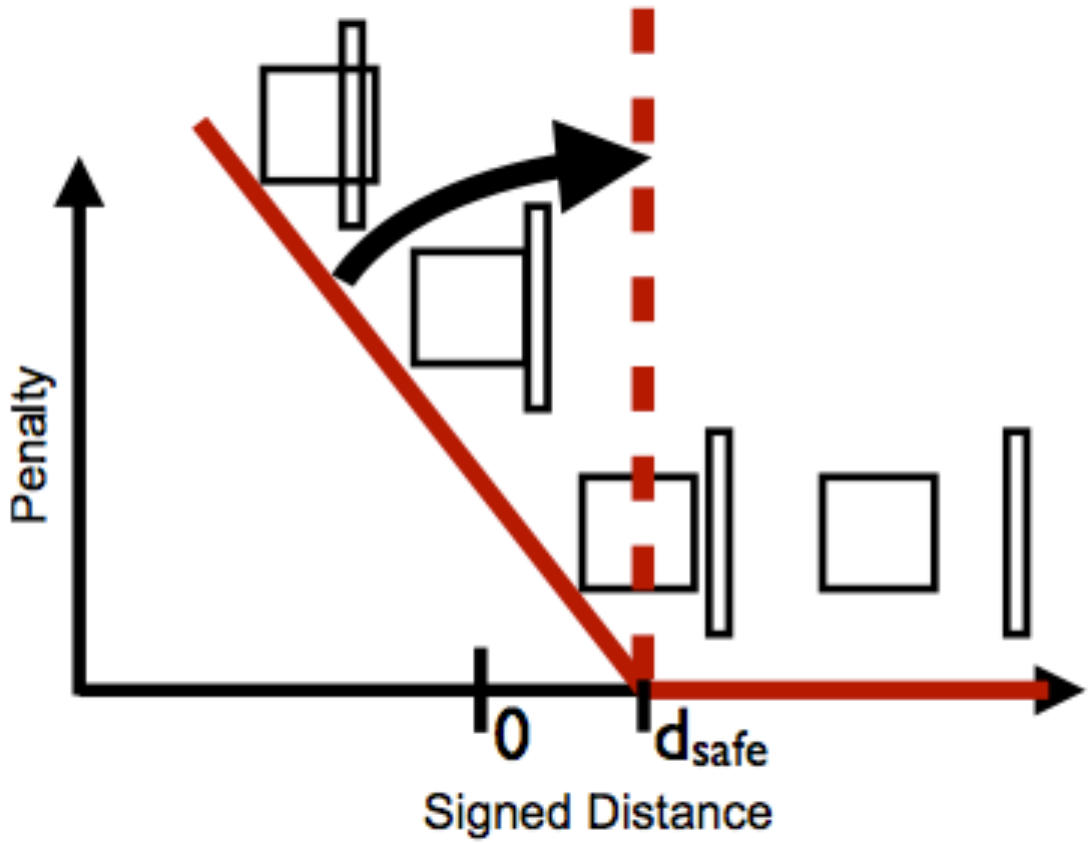
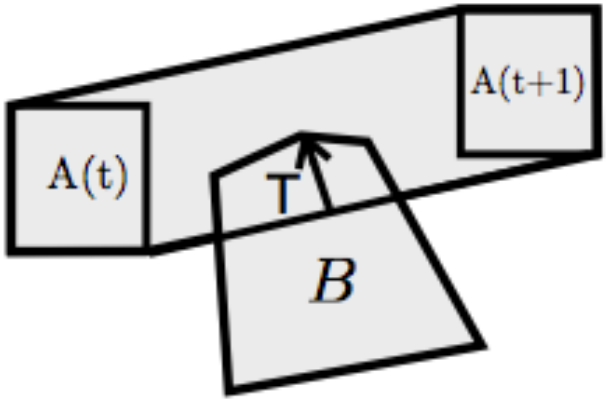
Collision Constraint as L1 Penalty



Collision Constraint as L1 Penalty



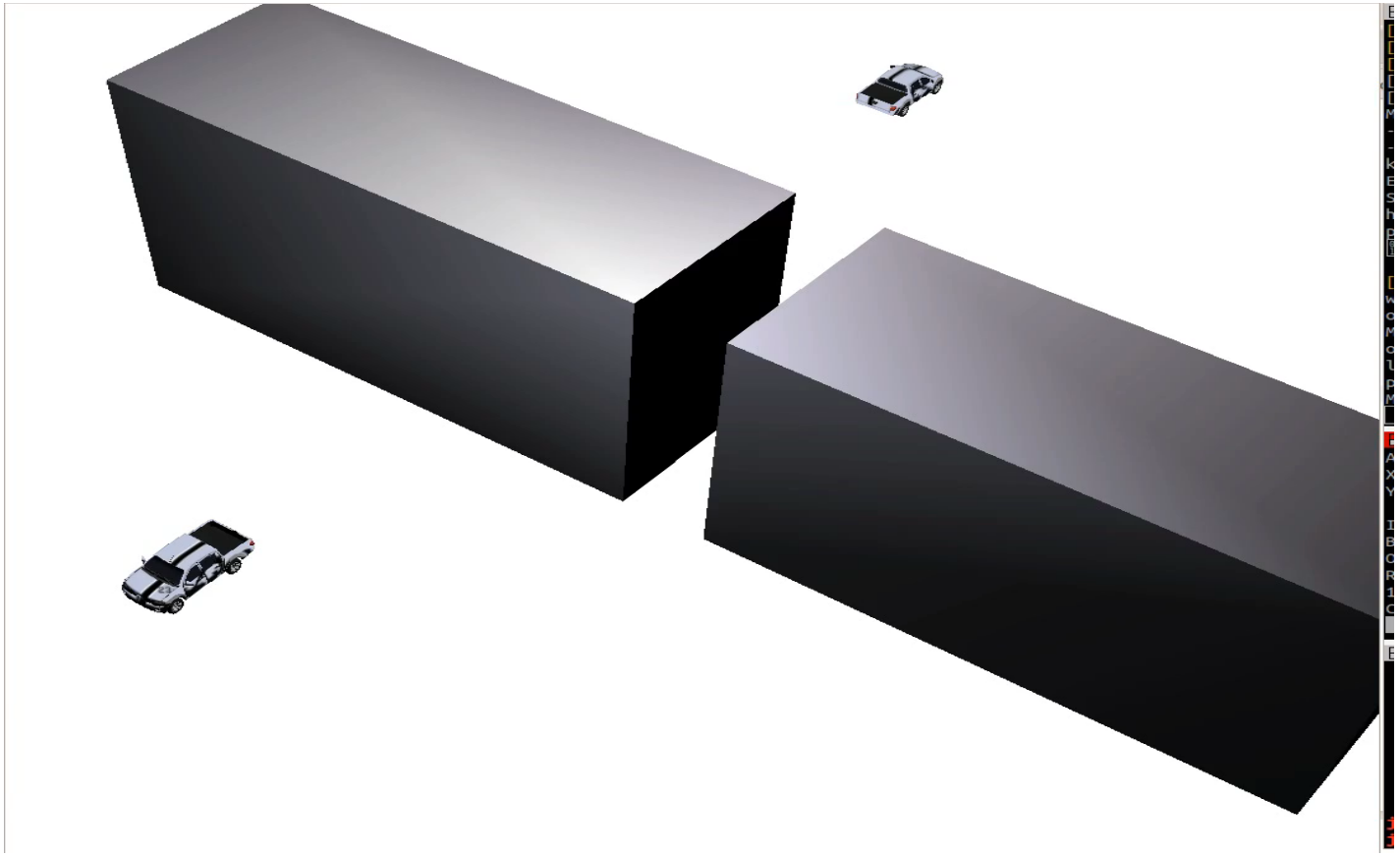
Continuous-Time Safety



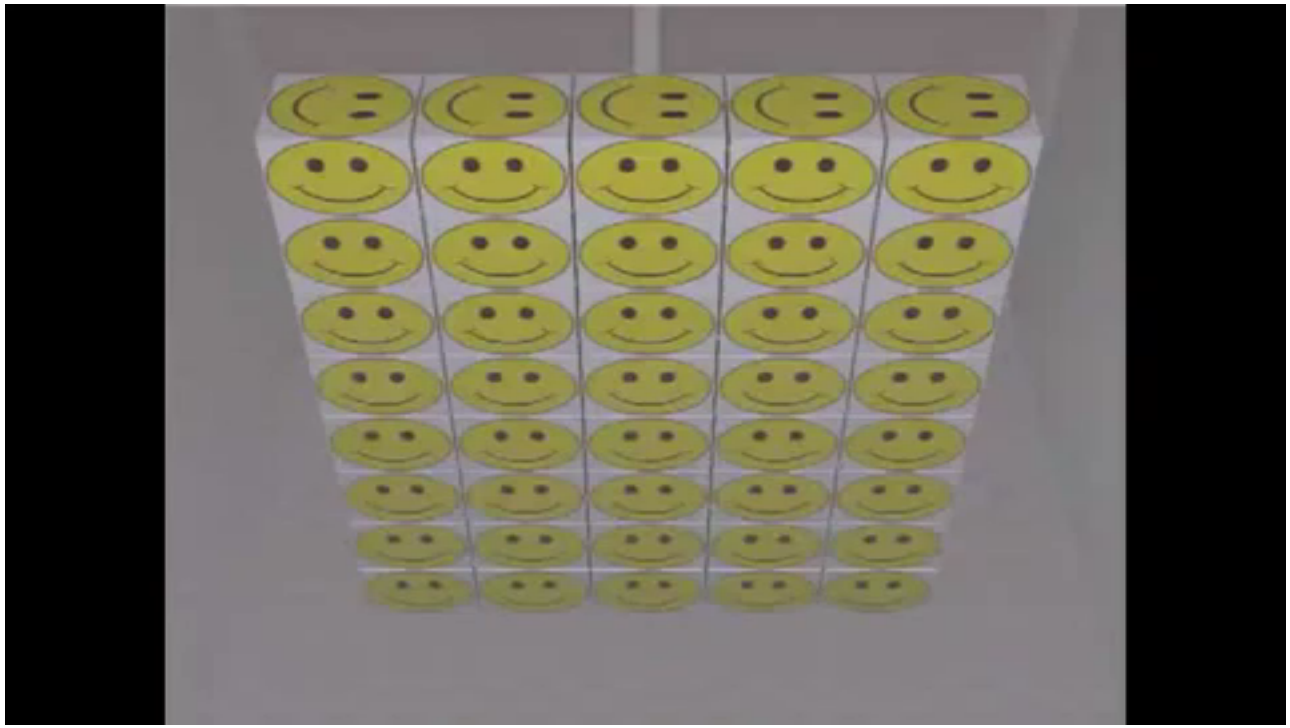
Collision check against swept-out volume

- Allows coarsely sampling trajectory
  - Overall faster
- Finds better local optima

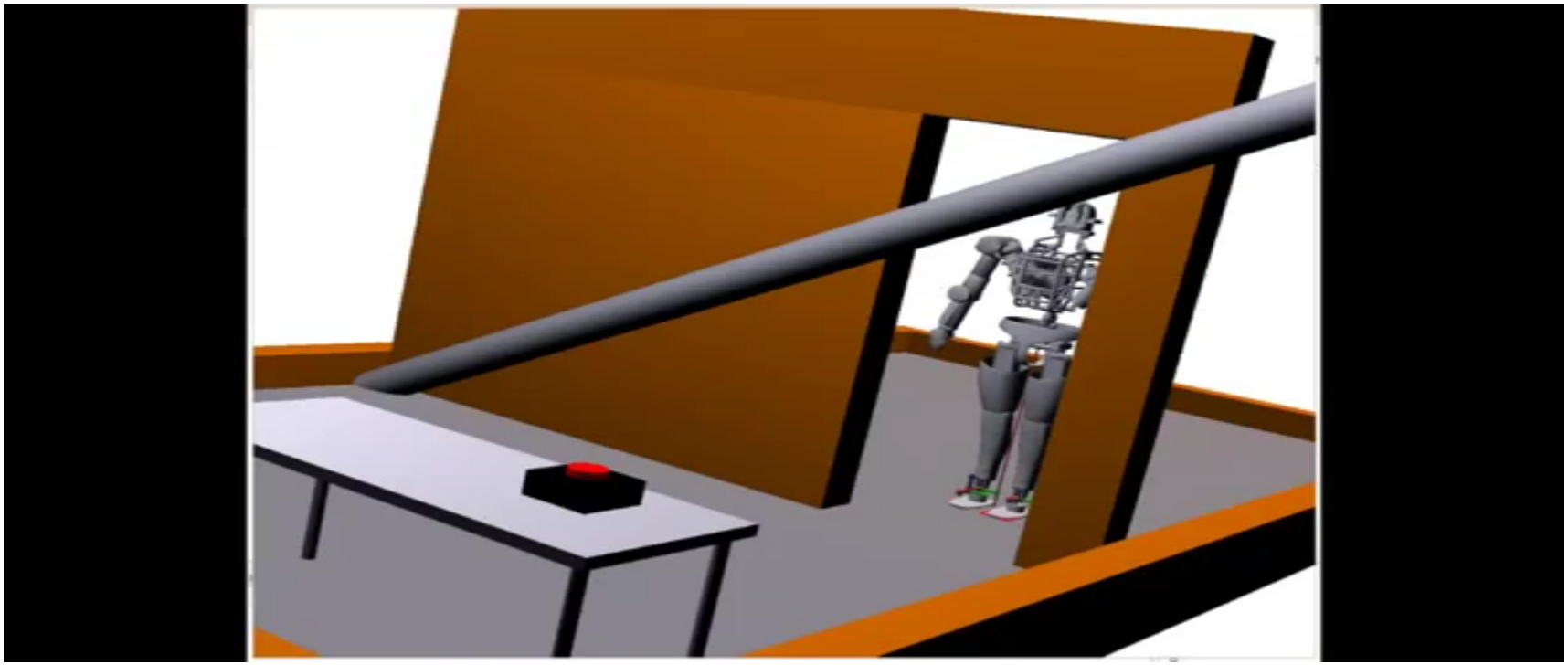
Collision-free Path for Dubin's Car



Experiments: Industrial Box Picking



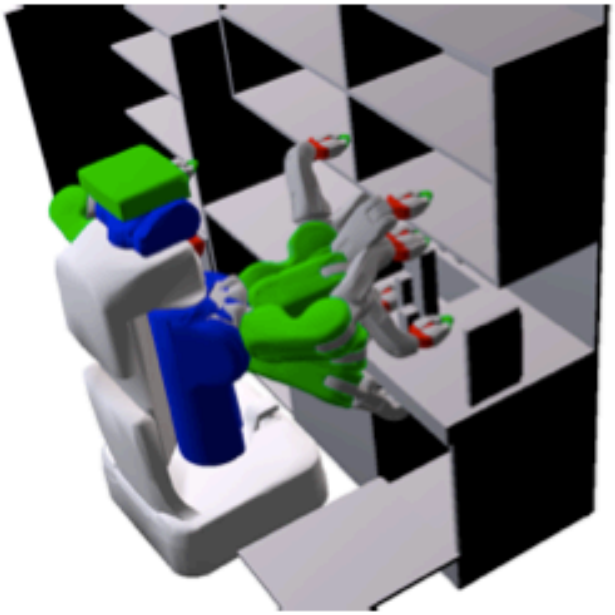
Experiments: DRC Robot



Benchmark

7 DOF (one arm)

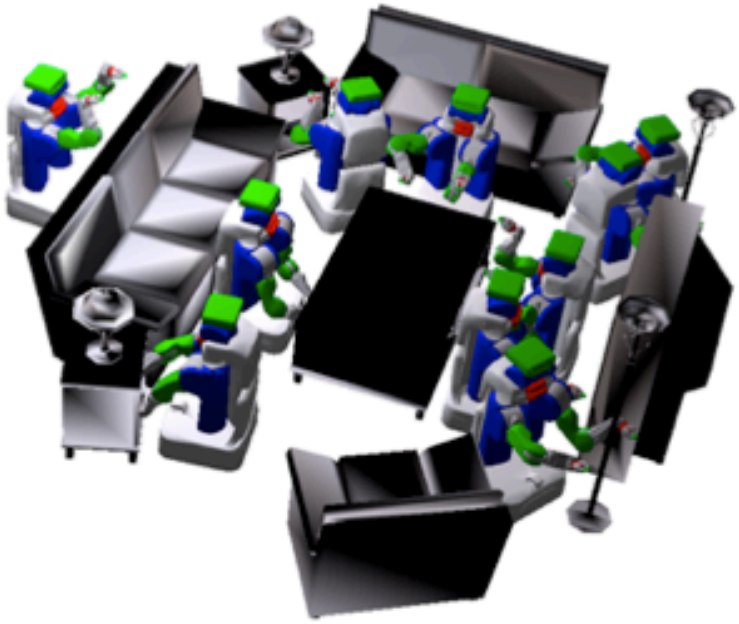
198 problems



example scene (taken from MoveIt collection)

18 DOF (two arms + base + torso)

96 problems



example scene (imported from Trimble 3d Warehouse / Google Sketchup)

Benchmark Results

Arm planning (7 DOF) 10s limit			
	Trajopt	BiRRT (*)	CHOMP
success	99%	97%	85%
time (s)	0.32	1.2	6.0
path length	1.2	1.6	2.6

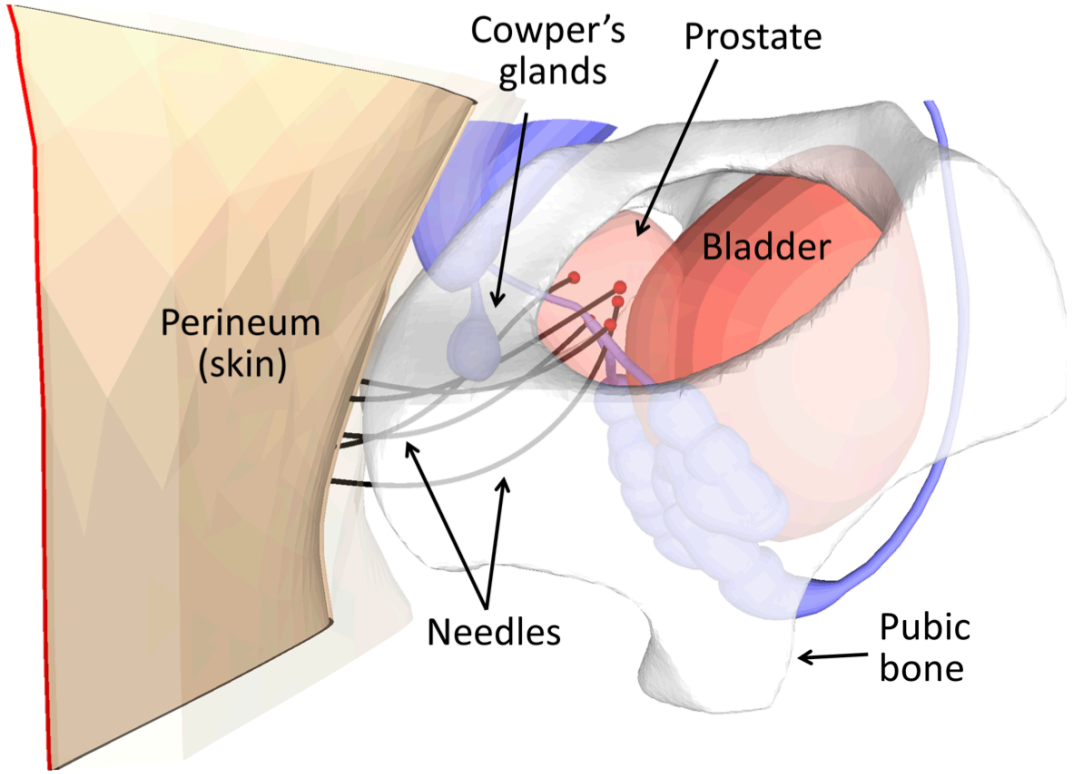
Full body (18 DOF) 30s limit			
	Trajopt	BiRRT (*)	CHOMP (**)
success	84%	53%	N/A
time (s)	7.6	18	N/A
path length	1.1	1.6	N/A

(*) Top-performing algorithm from MoveIt/OMPL
(**) Not supported in available implementation

[RSS 2013]

Experiments: PR2

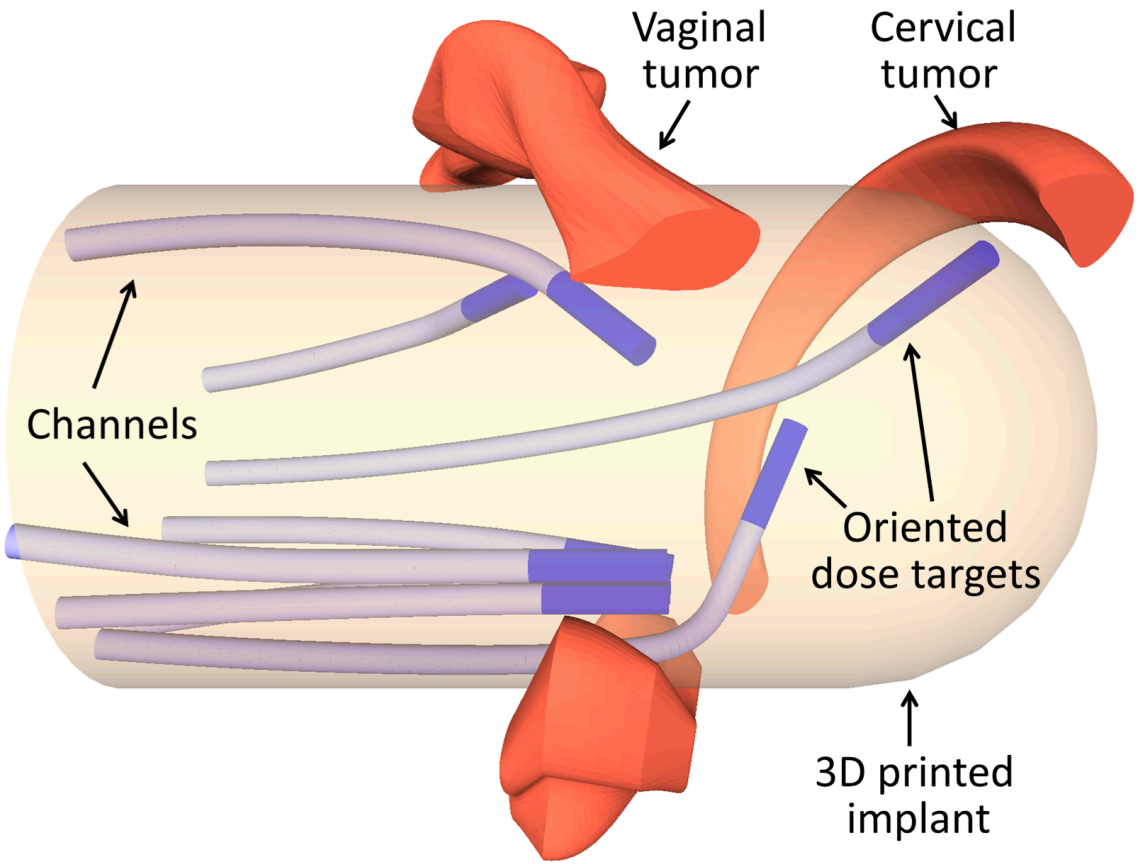
Medical Application 1: Needle Steering



Resulting paths: (i) shorter, (ii) less twist (i.e., less tissue carved up), (iii) found more quickly—replanning!

[ICRA 2014]

Medical Application 2: Channel Planning



[ICRA 2014]

Try It Yourself

- Code and docs: rll.berkeley.edu/trajopt

- Benchmark: github.com/joschu/planning_benchmark