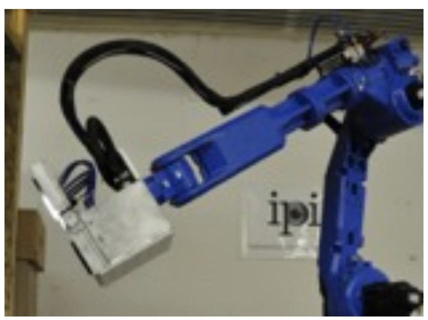
Finding Locally-Optimal, Collision-Free Trajectories with Sequential Convex Optimization

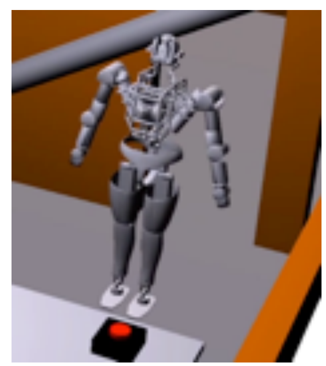
John Schulman, Jonathan Ho, Alex Lee,
Ibrahim Awwal, Henry Bradlow, Pieter Abbeel

Motion Planning



Industrial robot arm (6 DOF)

Mobile manipulator (18 DOF)



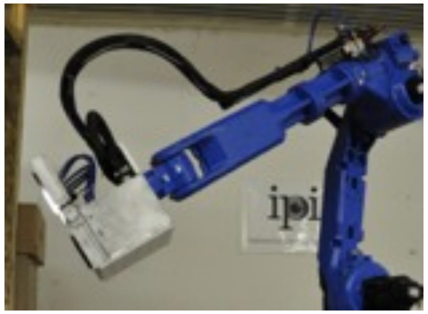
Humanoid (34 DOF)

Motion Planning

- Sampling-based methods like RRT
- Graph search methods like A*

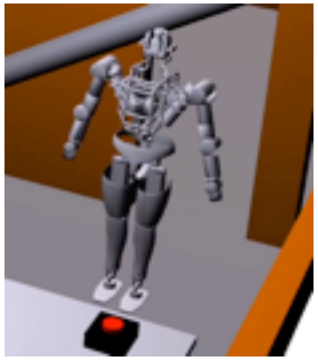
} slow down as dimensionality increases

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



Industrial robot arm (6 DOF)

Mobile manipulator (18 DOF)



Humanoid (34 DOF)

Trajectory Optimization

$$\min_{\boldsymbol{\theta}_{1:T}} \sum_t \|\boldsymbol{\theta}_{t+1} - \boldsymbol{\theta}_t\|^2 + \text{ other costs}$$

subject to

no collisions ⟵ non-convex

joint limits

other constraints

Trajectory Optimization

$$\min_{\boldsymbol{\theta}_{1:T}} \sum_t \|\boldsymbol{\theta}_{t+1} - \boldsymbol{\theta}_t\|^2 + \text{ other costs}$$

subject to

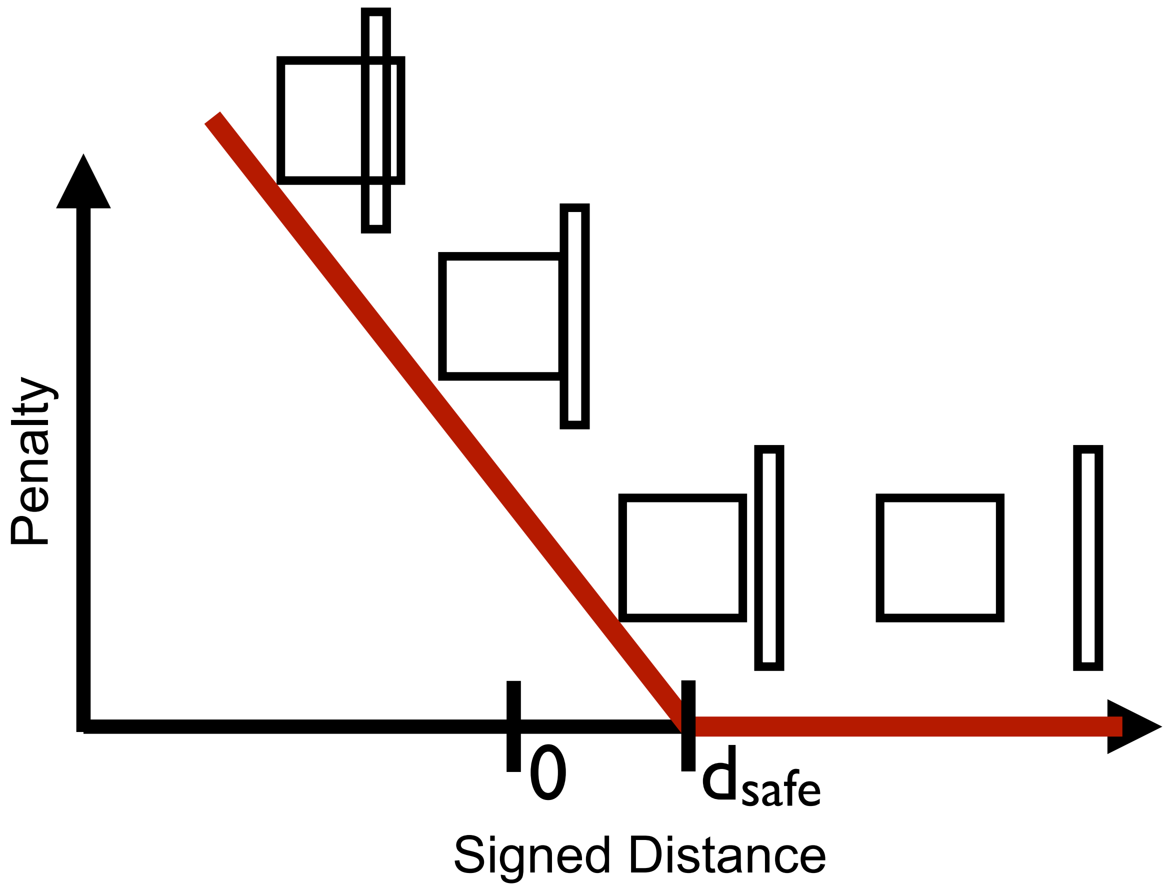
no collisions ← non-convex

joint limits

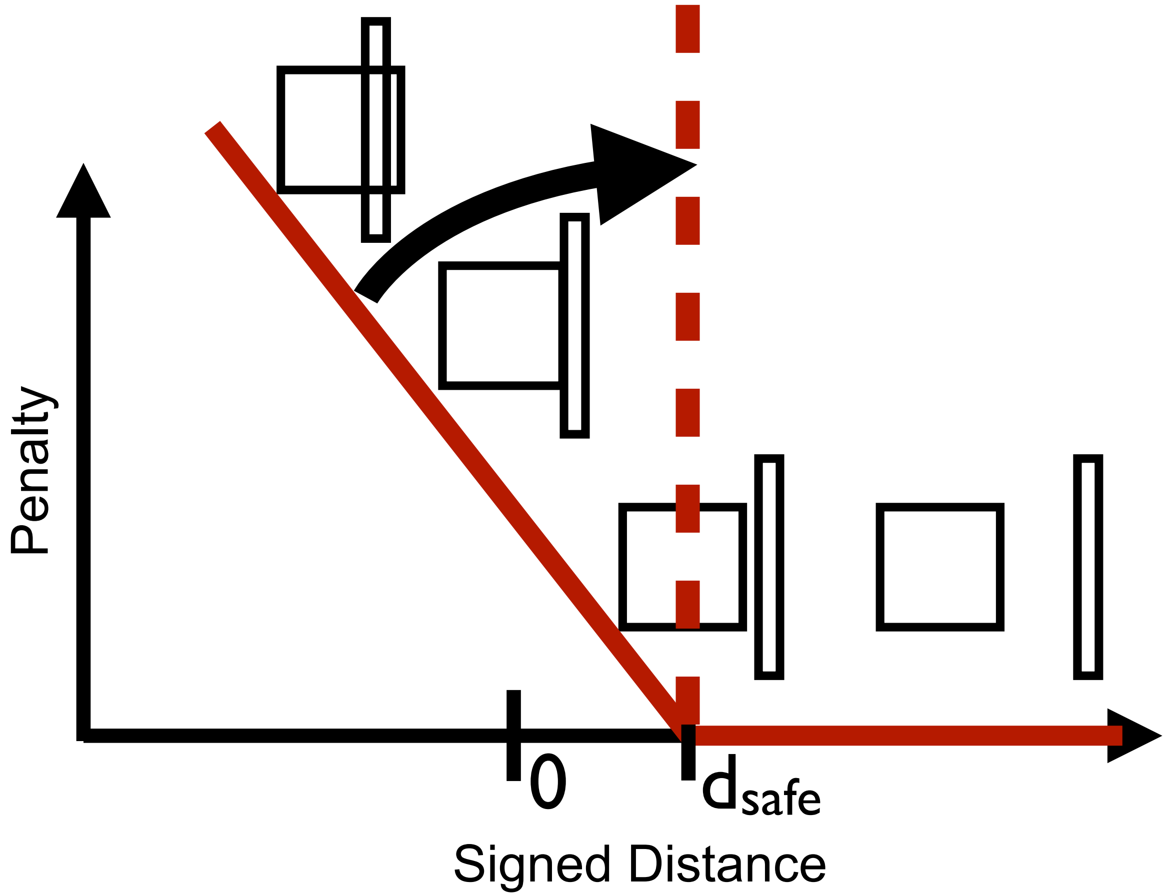
other constraints

- Sequential convex optimization
  - Repeatedly solve local convex approximation
- Challenge
  - Approximating collision constraint

Collision Constraint as L1 Penalty



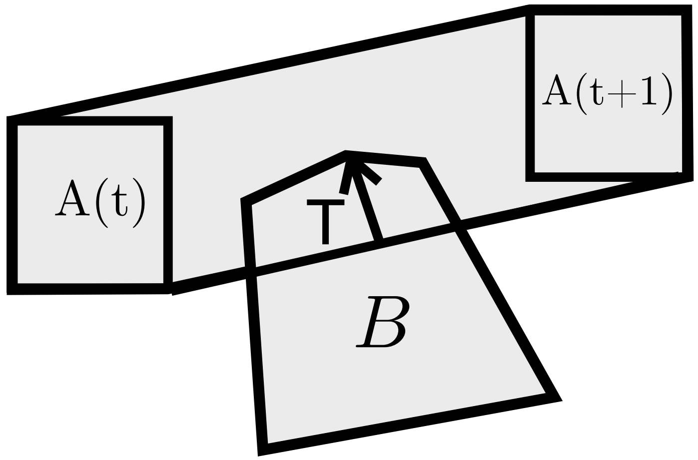
Collision Constraint as L1 Penalty



Linearize w.r.t. degrees of freedom

$$\mathrm{sd}_{AB}(\boldsymbol{\theta}) \approx \mathrm{sd}_{AB}(\boldsymbol{\theta}_0) + \hat{\mathbf{n}}^T J_{\mathbf{p}_A}(\boldsymbol{\theta}_0)(\boldsymbol{\theta} - \boldsymbol{\theta}_0)$$

Continuous-Time Safety

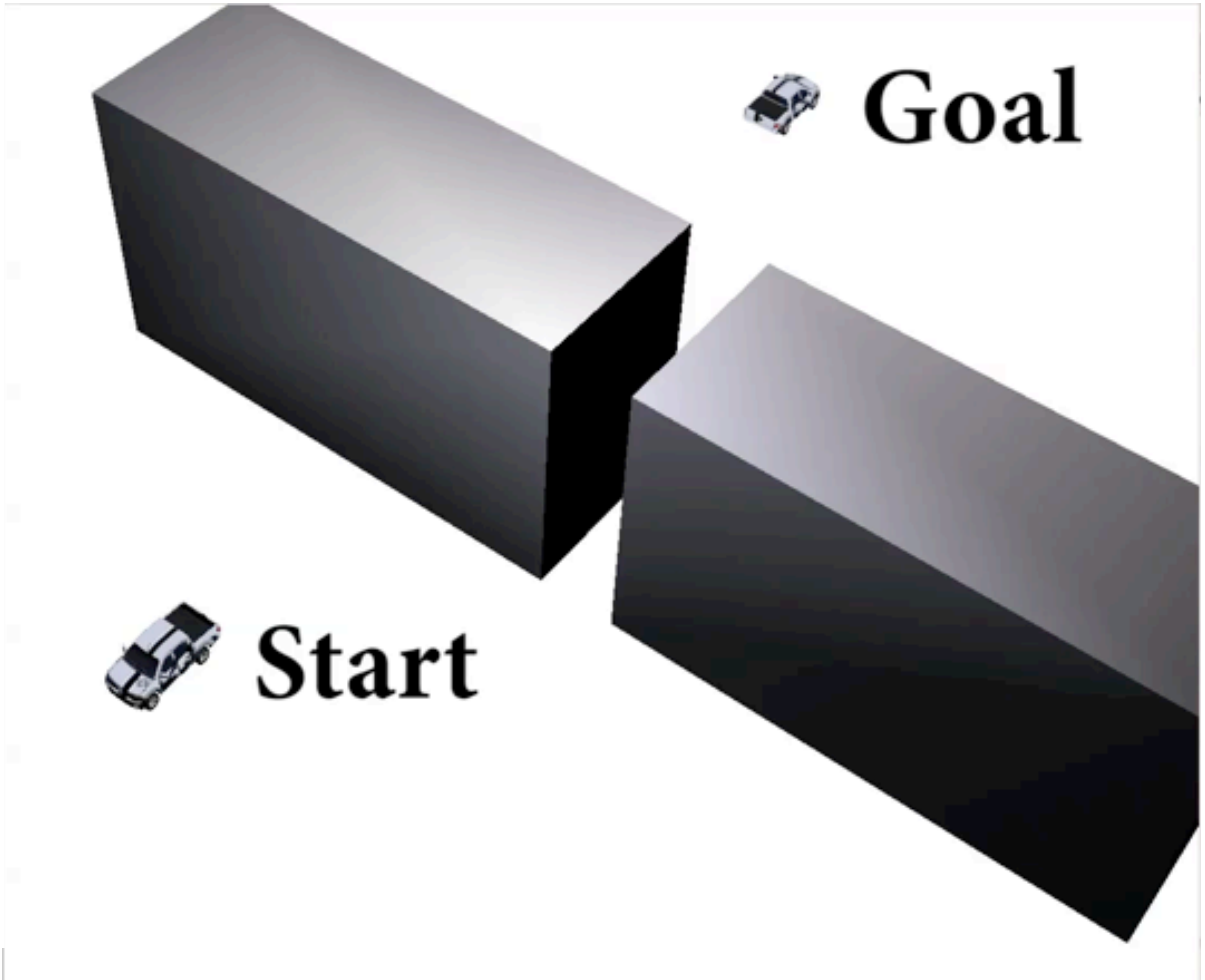


Collision check against swept-out volume

- Continuous-time collision avoidance
- Allows coarsely sampling trajectory
  - overall faster
- Finds better local optima

Optimization: Toy Example

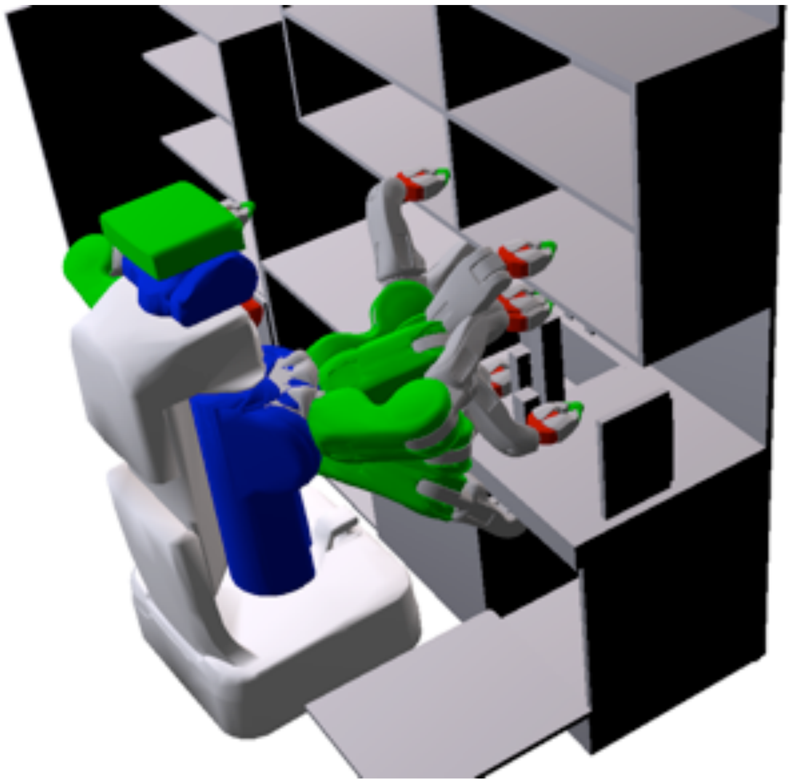
Optimization: Toy Example



Benchmark: Example Scenes

7 DOF (one arm)

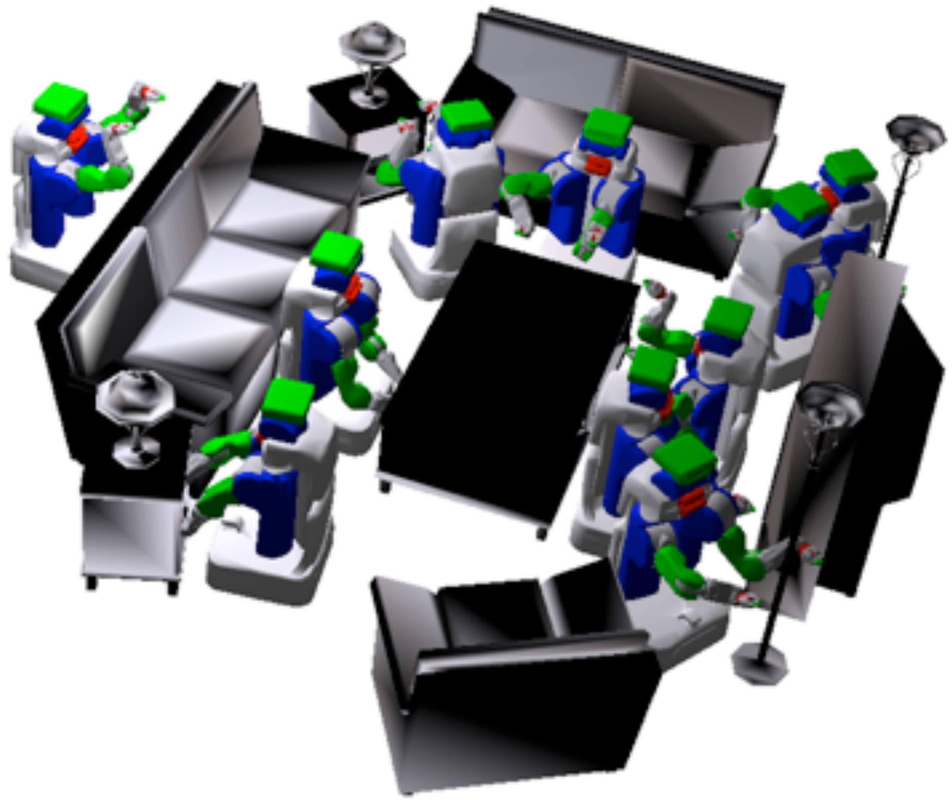
198 problems



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

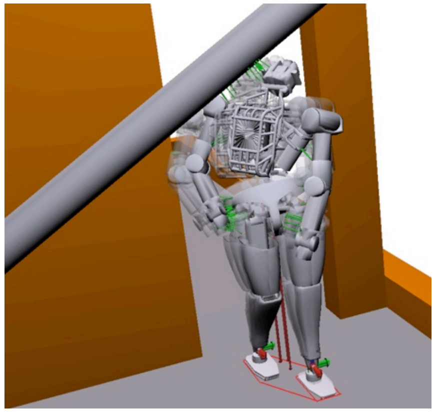
Arm planning (7 DOF) 10s limit			
	Trajopt	**BiRRT (*)**	**CHOMP**
success	99%	97%	85%
time (s)	0.32	1.2	6.0
path length	1.2	1.6	2.6

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

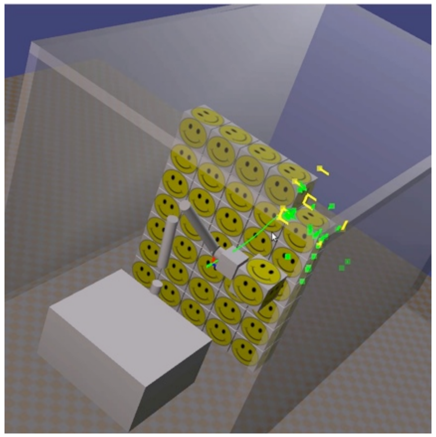
(*) Top-performing algorithm from MoveIt/OMPL
(**) Not supported in available implementation

Other Experiments -- Videos at Interactive Session

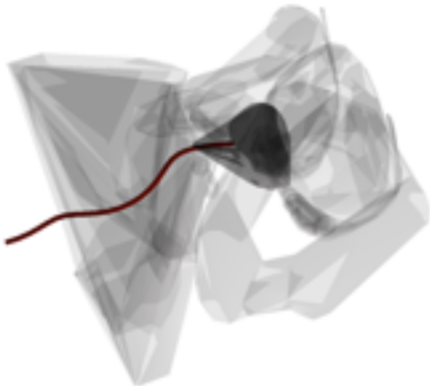
- Planning for 34-DOF humanoid (stability constraints)



- Box picking with industrial robot (orientation constraints)

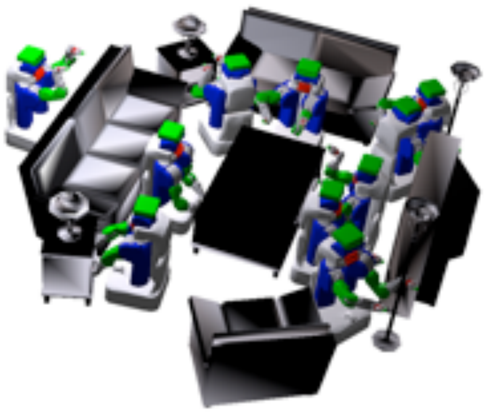
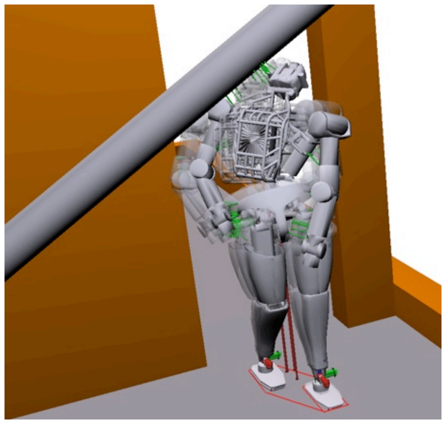
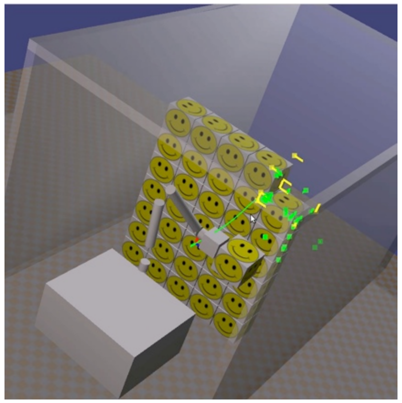
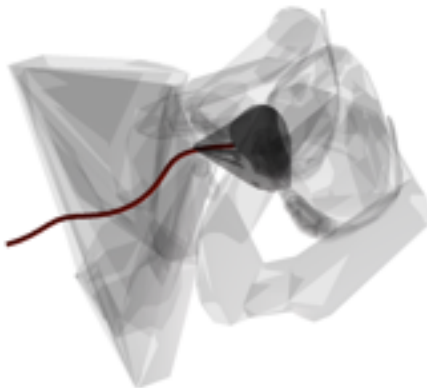


- Constant-curvature 3D needle steering (non-holonomic constraint)



Try it out yourself!

- Code and docs: rll.berkeley.edu/trajopt
- Run our benchmark: github.com/joschu/planning_benchmark

Thanks!

- Code and docs: rll.berkeley.edu/trajopt
- Run our benchmark: github.com/joschu/planning_benchmark