Tuning-Free Contact-Implicit Trajectory Optimization

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Overview

Contact-implicit trajectory optimization (CITO) is a promising approach for automatic discovery of contact-interaction trajectories. However, CITO methods typically require tedious tuning or a tailored initial guess. To address this issue, we use a relaxed contact model along with an automatic penalty adjustment loop for suppressing the relaxation. Moreover, we propose a computationally-cheap post-process procedure to improve solutions using the contact information implied by the usage of relaxation in the previous iteration.

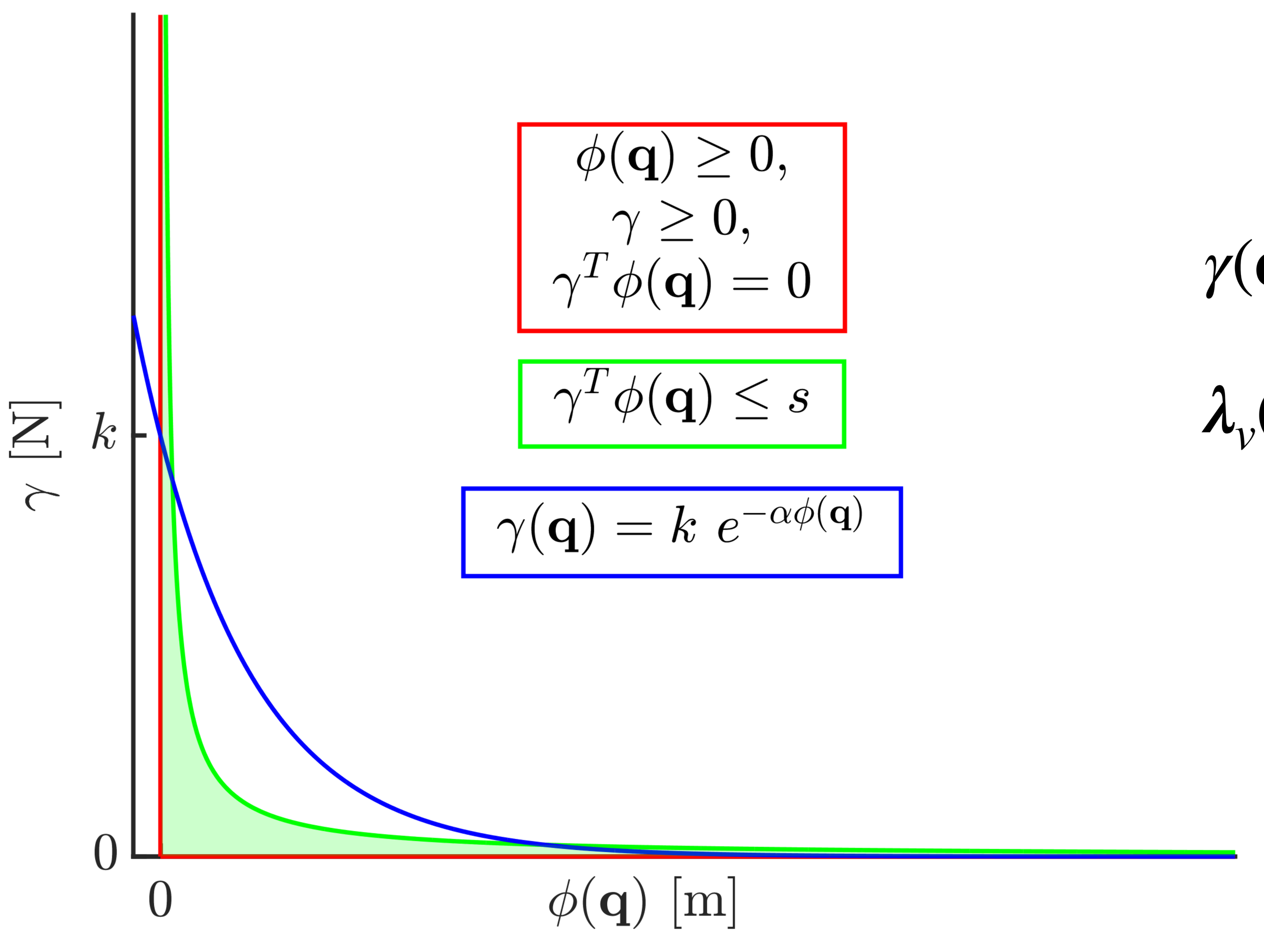
Dynamic Model

Underactuated dynamics with frictional rigid-body contacts, $\boldsymbol{\lambda}_c$, and smooth virtual forces, $\boldsymbol{\lambda}_v$:

$$\mathbf{M}(\mathbf{q})\ddot{\mathbf{q}} + \mathbf{c}(\mathbf{q}, \dot{\mathbf{q}}) = \mathbf{S}_a^T\boldsymbol{\tau} + \mathbf{J}_c^T(\mathbf{q})\boldsymbol{\lambda}_c + \mathbf{S}_u^T\boldsymbol{\lambda}_v$$

Relaxed Contact Model

Exert smooth virtual forces on the unactuated DOF to provide the optimization with a smooth relationship between the configuration of the system and task completion



$$\gamma(\mathbf{q}) = ke^{-\alpha\phi(\mathbf{q})}$$

$$\boldsymbol{\lambda}_v(\mathbf{q}) = \gamma(\mathbf{q})[\mathbb{1}_3 \ \ -\hat{\mathbf{d}}]^T\mathbf{n}(\mathbf{q})$$

Trajectory Optimization

The following non-convex constrained problem is solved using successive convexification (SCVX) algorithm:

$$\underset{\mathbf{U}}{\text{minimize}}\ C(\mathbf{X}, \mathbf{U}) \triangleq C_F(\mathbf{X}, \mathbf{U}) + \sum_{i=1}^{N} C_I(\mathbf{x}_i, \mathbf{u}_i)$$

subject to:

$\mathbf{x}_{i+1} = f(\mathbf{x}_i, \mathbf{u}_i)$ for $i = 1, \ldots, N$,

$\mathbf{u}_L \leq \mathbf{u}_{1,\ldots,N} \leq \mathbf{u}_U$,

$\mathbf{x}_L \leq \mathbf{x}_{1,\ldots,N+1} \leq \mathbf{x}_U$.

Final cost for the desired pose:
$C_F \triangleq w_1 p_e^2 + w_2\theta_e^2$

Integrated cost for virtual forces:
$C_I \triangleq \omega\,||\mathbf{k}_i||_1$

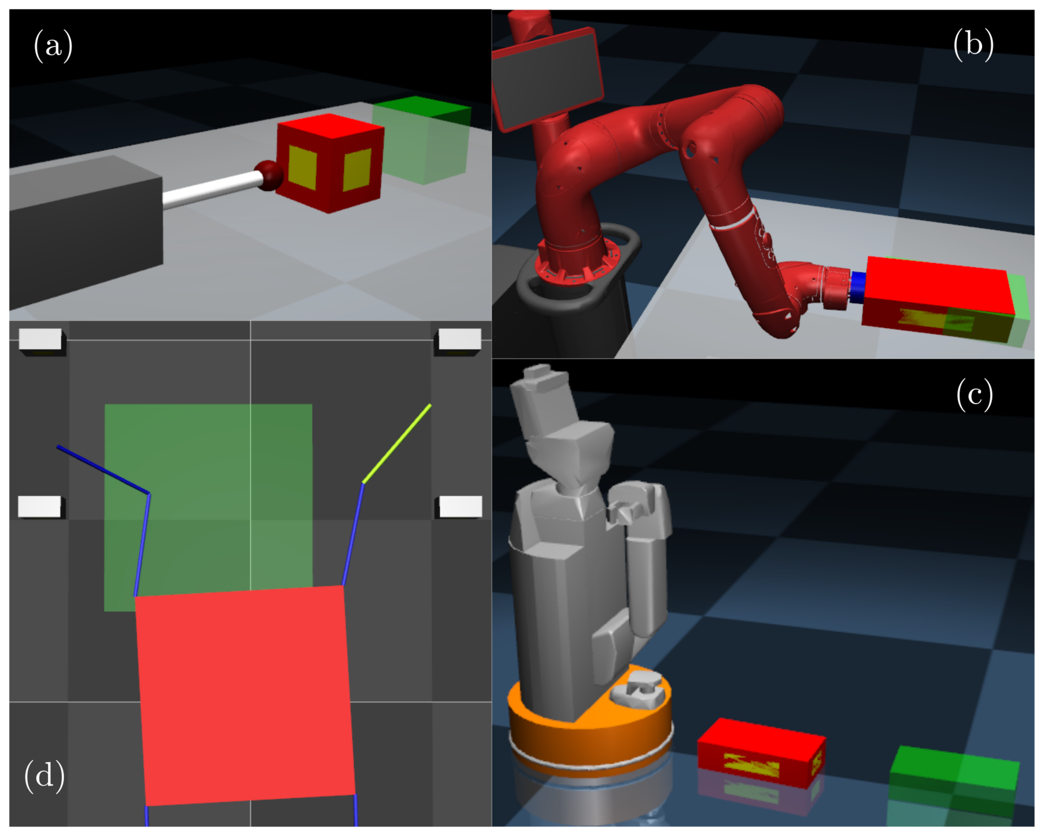
Penalty Loop Approach

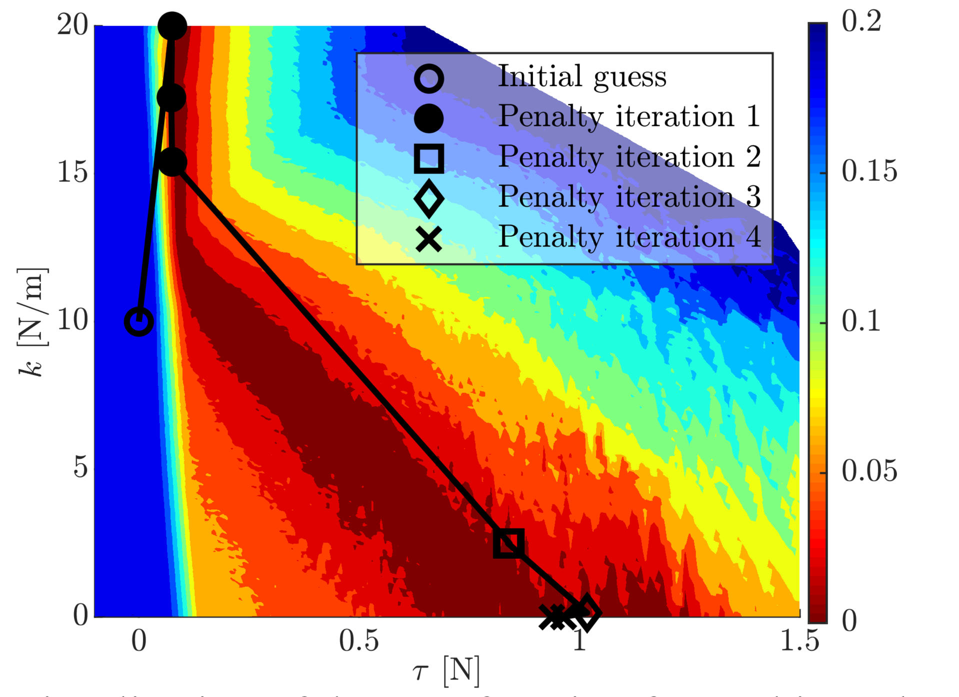
Start with a light penalty on the relaxation such that the task is completed using only virtual forces, then increase the penalty until a feasible motion is found by repeating the following steps:

1. Solve the trajectory optimization problem using SCVX
2. Adjust the penalty considering whether the task constraints are satisfied
3. If satisfied, apply the post process that:
   - pulls virtually-active contact candidates on the robot towards the corresponding contact surfaces in the environment and
   - reduces the excessive virtual stiffness values.

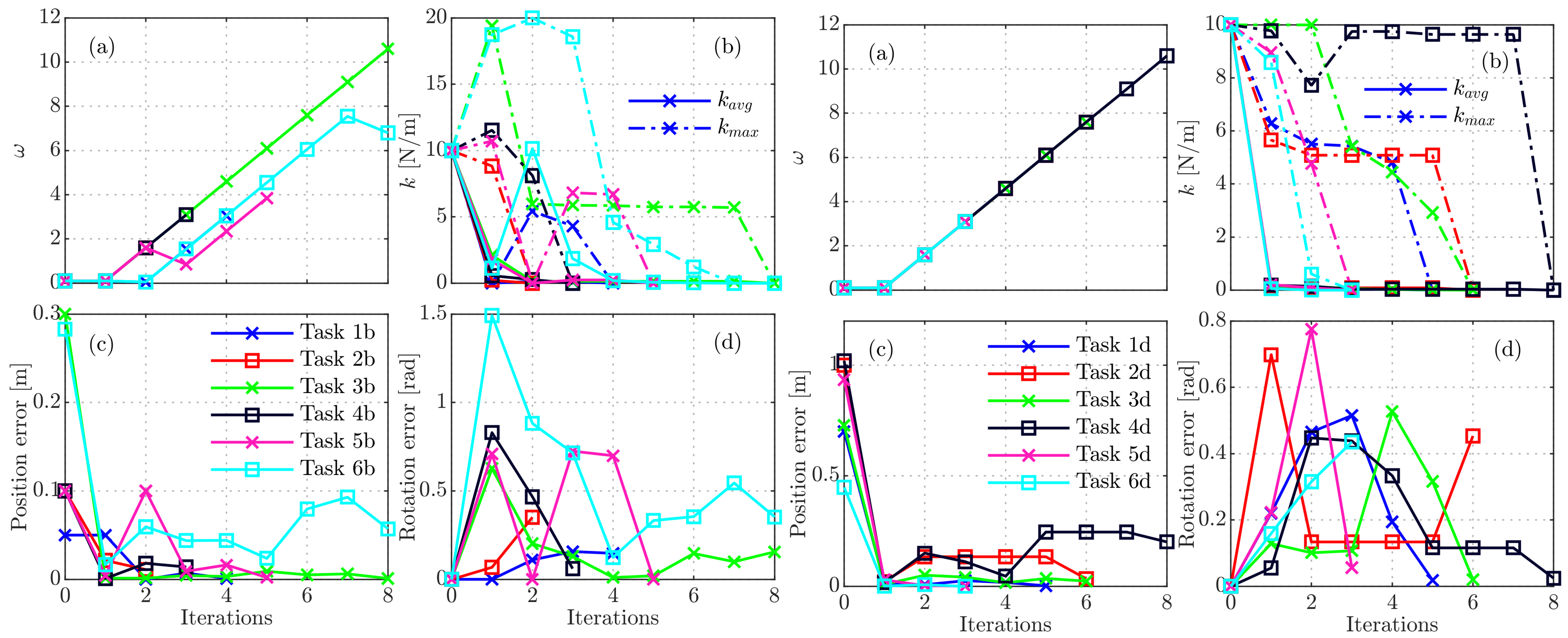
Results

The proposed framework is tested in simulation experiments for non-prehensile manipulation using a 1-DOF pusher, a 7-DOF arm, and a mobile robot as well as for planar locomotion in zero gravity. The results demonstrate that the method can find motions with maintained contacts for sensitive pushing tasks and highly-dynamic behaviors with impact-like contacts using identical initial conditions.





A visualization of the cost function for pushing a box with a 1-DOF pusher in a single time step of 1 s and the progress of the penalty loop



Changes of (a) the penalty, (b) the average and maximum stiffness, (c) position error, and (d) rotation error over penalty iterations for the 7-DOF robot arm and locomotion in zero gravity tasks

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