Torque-Limited Manipulation Planning with Contact

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***Abstract*—By making contact with the environment and leveraging the contact dynamics, robot manipulators can reach configurations well outside their static reachability and carry payload outside their capability (Fig 1). We adapt our previously developed INSAT algorithm [1] to tackle the problem of torque-limited manipulation planning through contact. INSAT requires NO prior over contact mode sequence and NO initial template or seed for trajectory optimization. INSAT achieves this by interleaving graph search to explore the joint configuration space (which determines the contact mode) with several incremental trajectory optimizations seeded by neighborhood solutions to find dynamically feasible trajectories. We demonstrate our results with the pick and place of an overweight payload by leveraging robot-environment contact on a Kinova Gen3 robot in MuJoCo.**

I. Approach Overview

Our method consists of two interleaved components running concurrently, a low-dimensional discrete graph-search in the manipulator configuration space and the high-dimensional trajectory optimization in the joint velocity and contact model parameter space. We first explain the trajectory optimization setup used to generate the full dimensional edge in the graph whose cost is used to drive the low-dimensional search. We then describe the adaptation of INSAT for our application.

A. Trajectory Optimization for Planning through Contact

The trajectory optimizer is set up to solve a boundary value problem by finding a joint torque input trajectory that connects two manipulator configurations. We solve the trajectory optimization problem using Successive Convexification (SCvx) [2]. SCvx solves a sequence of smooth quadratic approximations of the original nonlinear problem subjected to linearized dynamics. But, as the hybrid system dynamics with contact is discontinuous, the linearization of dynamics is poor. To alleviate this, we use the tunable soft contact model in MuJoCo [3] to iteratively solve the trajectory optimization problem (Eq. 1). We begin with the relaxed setting for the contact model (non-zero virtual contact forces even when not in contact) in which the hybrid system dyanamics (manipulator dynamics + contact dynamics with the environment) is smooth and solve the Eq. 1 using SCvx. We then iteratively tighten the contact model softness and re-solve Eq. 1 by warm-starting with the solution from the previous relaxed iteration.

$$\min_{\boldsymbol{\tau}[.]} \quad \|\mathbf{x}[N] - \mathbf{x}_{goal}\|_2 + \sum_{i=0}^{N-1} \|\boldsymbol{\tau}[i]\|_2 \tag{1a}$$

$$\text{s.t.} \quad \mathbf{x}[i+1] = \mathbf{f}(\mathbf{x}_i, \mathbf{u}_i), \tag{1b}$$

$$\mathbf{x}(0) = \mathbf{x}_0, \mathbf{x}(N) \in \mathbf{X}_{goal} \tag{1c}$$

$$|\dot{\mathbf{x}}(t)| \leq \dot{\mathbf{x}}_{\lim} \tag{1d}$$

$$|\boldsymbol{\tau}(t)| \leq \boldsymbol{\tau}_{\lim}, \boldsymbol{\tau} \in \mathbf{U} \tag{1e}$$

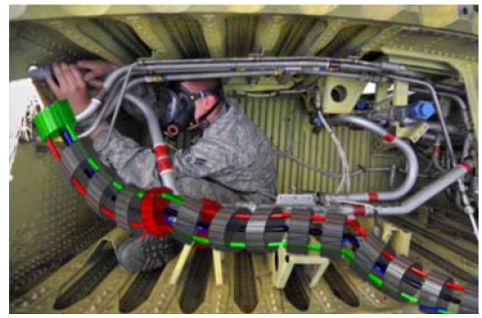

Fig. 1: An example of a hyperredundant robot manipulator lifting a heavy tool in a confined space by leveraging contact with the environment to assist a human worker.

where the state $\mathbf{x}$ contains joint angles and joint velocity, $\boldsymbol{\tau}$ is the joint torque vector and $\mathbf{f}$ is the hybrid system dynamics.

B. INSAT: INterleaved Search And Trajectory Optimization

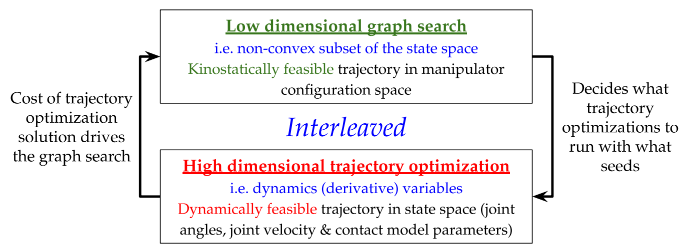

Fig. 2: A schematic of working principle of INSAT

We refer the reader to [1] for the detailed working principle of INSAT. Fig 2 and 3 provide visual support for the application of INSAT algorithm to torque-limited manipulation planning through contact and its working on a planar example. INSAT performs interleaved search on discrete low-dimensional manipulator configuration space and continuous high-dimensional joint velocity and contact model parameter space. The low dimensional search gets the manipulator around obstacles and evaluates various contact mode sequences. The high-dimensional trajectory optimization validates or invalidates the dynamic feasibility of paths discovered by the low-dimensional search. Consequently, INSAT generates dynamically feasible trajectory for the manipulator to brace with the environment, offset/stay within its torque limits, and reach the desired goal.

II. Simulation Results

Our algorithm is tested in simulation on Kinova Gen3 manipulator. The planner discovers the right contact behavior to carry the payload and swings to pump energy into the system and drive to the goal (see Fig. 4 caption).

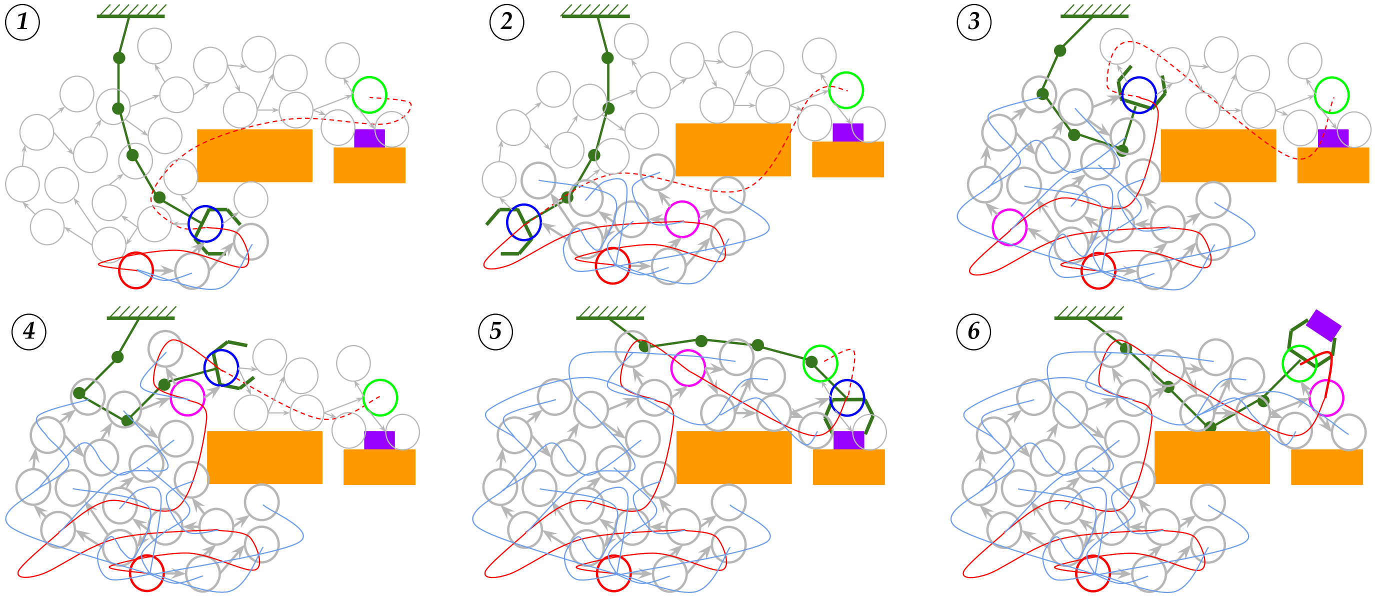

Fig. 3: Graphical illustration of INSAT using a 2D planar arm lifting a payload by making contact. The low-dimensional graph is shown with grey nodes and edges (thicker nodes correspond to expanded ones) and the high-dimensional trajectory optimization output is shown with splines connecting the nodes. For the sake of visual clarity, the nodes here denote the end effector configuration of the arm. In the low-dimensional graph, the start node is shown in red, goal in green, newly generated node from vertex expansion in blue, waypoint node for INSAT repair phase [1] in pink. In the high-dimensional graph, the trajectory optimization output to previously expanded nodes and currently generated node are shown with blue and red spline respectively. As the objective is to minimize total joint torque, we can see that INSAT finds a trajectory for the planar arm to swing over the obstacles to grab the payload and lift it by making contact.

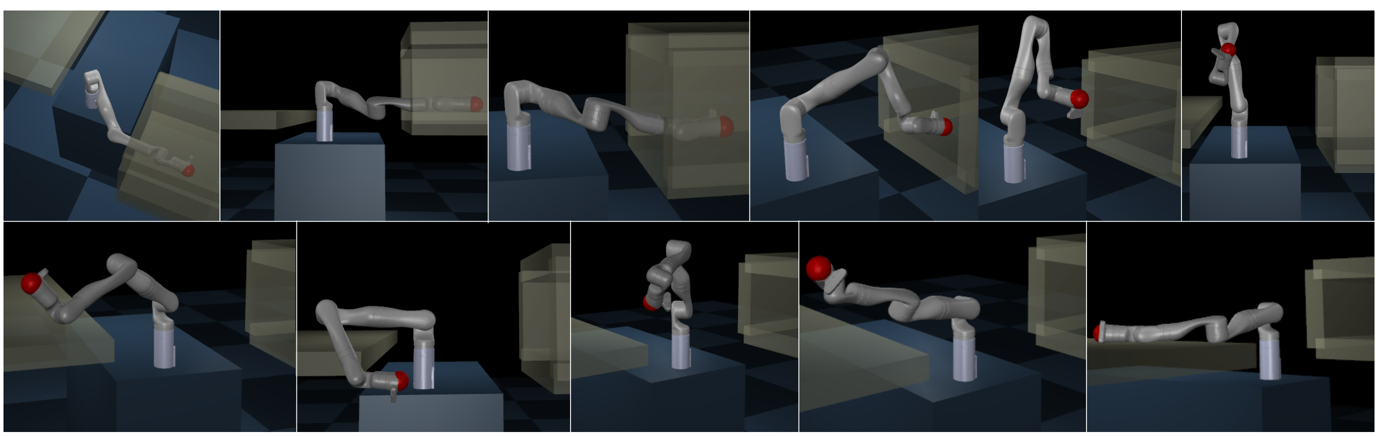

Fig. 4: (Row-major order from top-left) Snapshots of trajector generated by INSAT for a pick and place task of an object (shown as red sphere) using Kinova Gen3 robot from a confined shelf to a table. The mass of the object is set to violate the static torque limits of the manipulator (when no contact support from the environment) at the start configuration. The robot maintains the contact with the shelf as much as possible by dragging the object out and swinging across its base to pump energy to eventually carry the object on to the table. The task requires reasonably long horizon planning in which standalone trajectory optimization struggles. By guiding the trajectory optimization with graph search over manipulator configurations, INSAT is able to produce a dynamically feasible trajectory of interesting behavior.

References

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