Sampling-Based MPC for Contact-Rich Manipulation

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PROBLEM FORMULATION

We wish to solve a contact-implicit, receding horizon control problem:

$$\min_{x_k, u_k, \lambda_k} \sum_{k=0}^{N-1} (x_k^T Q_k x_k + u_k^T R_k u_k) + x_N^T Q_N x_N$$

$$\begin{aligned} \text{s.t.} \quad & x_{k+1} = f(x_k, u_k, \lambda_k), \\ & 0 \leq \lambda_k \perp h(x_k, u_k, \lambda_k) \geq 0, \\ & x_0 = x(0), \\ & \text{for } k \in \{0, \dots, N-1\} \end{aligned}$$

However the nonlinear dynamics and complementarity constraints complicate the optimization and make real-time evaluation intractable.

We leverage recent progress in real-time, contact-implicit control [1] which uses linear complementarity system (LCS) approximations instead to describe the dynamics and complementarity constraints:

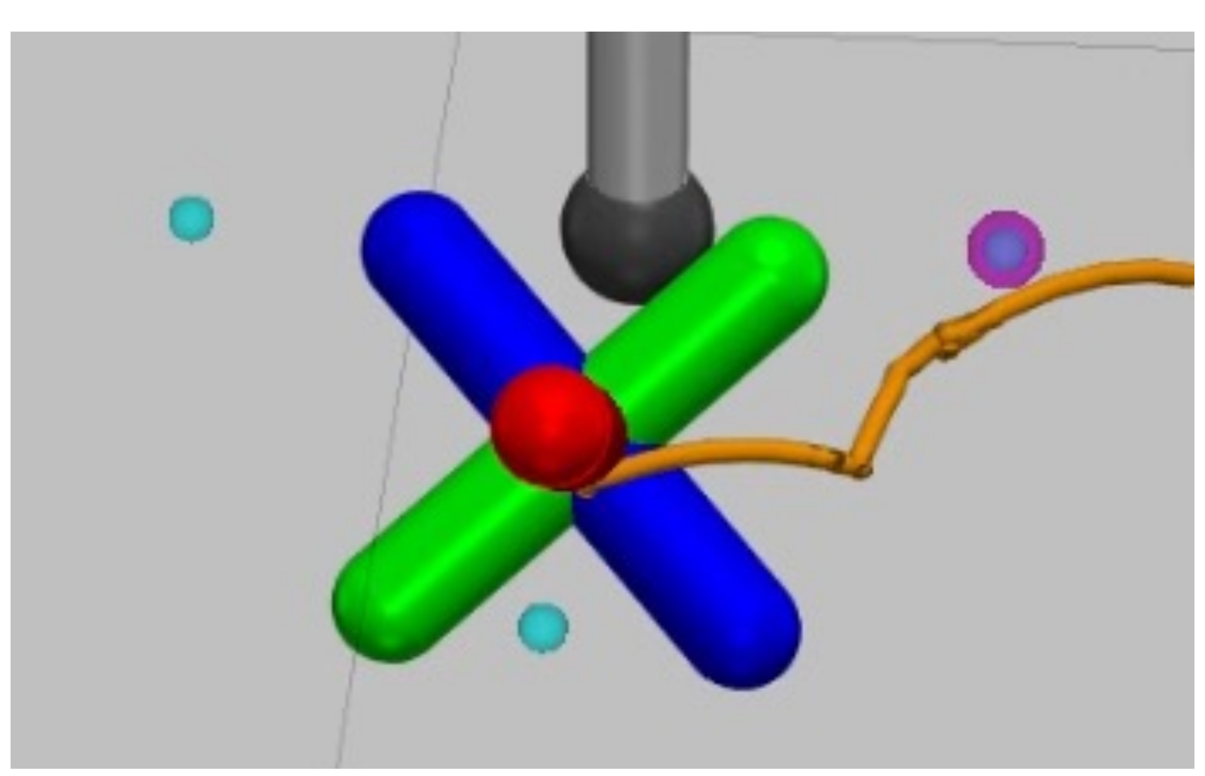
$$\begin{aligned} & x_{k+1} = Ax_k + Bu_k + D\lambda_k + d, \\ & 0 \leq \lambda_k \perp Ex_k + F\lambda_k + Hu_k + c \geq 0 \end{aligned}$$

The LCS approximations can be limiting and prohibit making goal progress. We counteract this limitation by sampling end effector locations in parallel and deciding when a different LCS view of the system is more amenable to making progress towards the goal. We directly compare costs of the above optimization problem from true and hypothetical configurations.

[1] Aydinoglu, Wei, and Posa, *Consensus complementarity control for multi-contact MPC*, 2023.

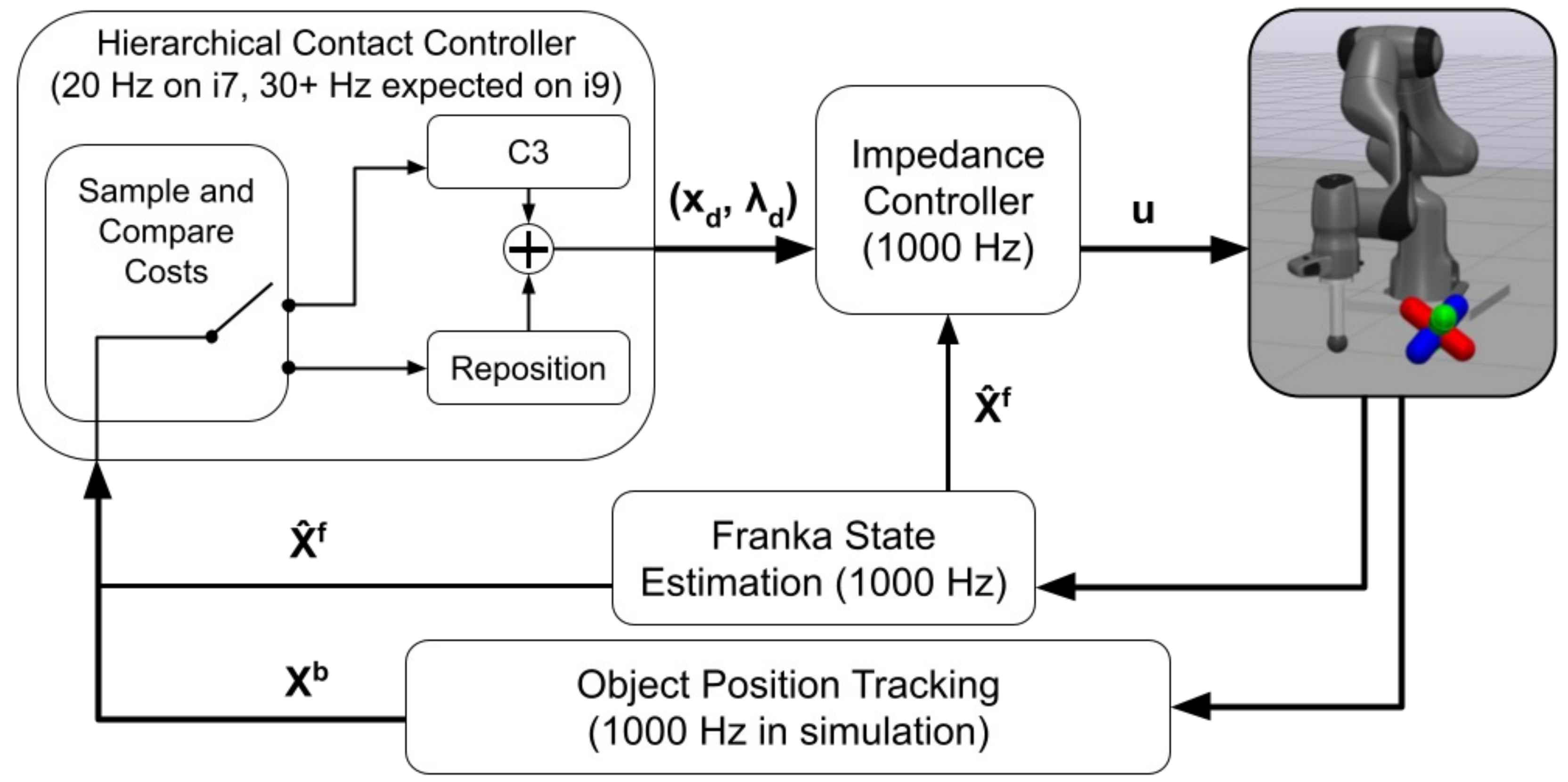
SIMULATION RESULTS: JACK TOPPLING

Our controller can be used with more complicated geometry and scales based on the number of contact pairs. For this jack example, the number of contact pairs is 4 (three capsules each with the ground, one between the end effector and the jack).



The controller goal is to track a specified trajectory with the jack. Samples are drawn in blue with the optimal sample in pink. The orange path denotes the jack's travel.

HIERARCHICAL CONTROLLER ARCHITECTURE



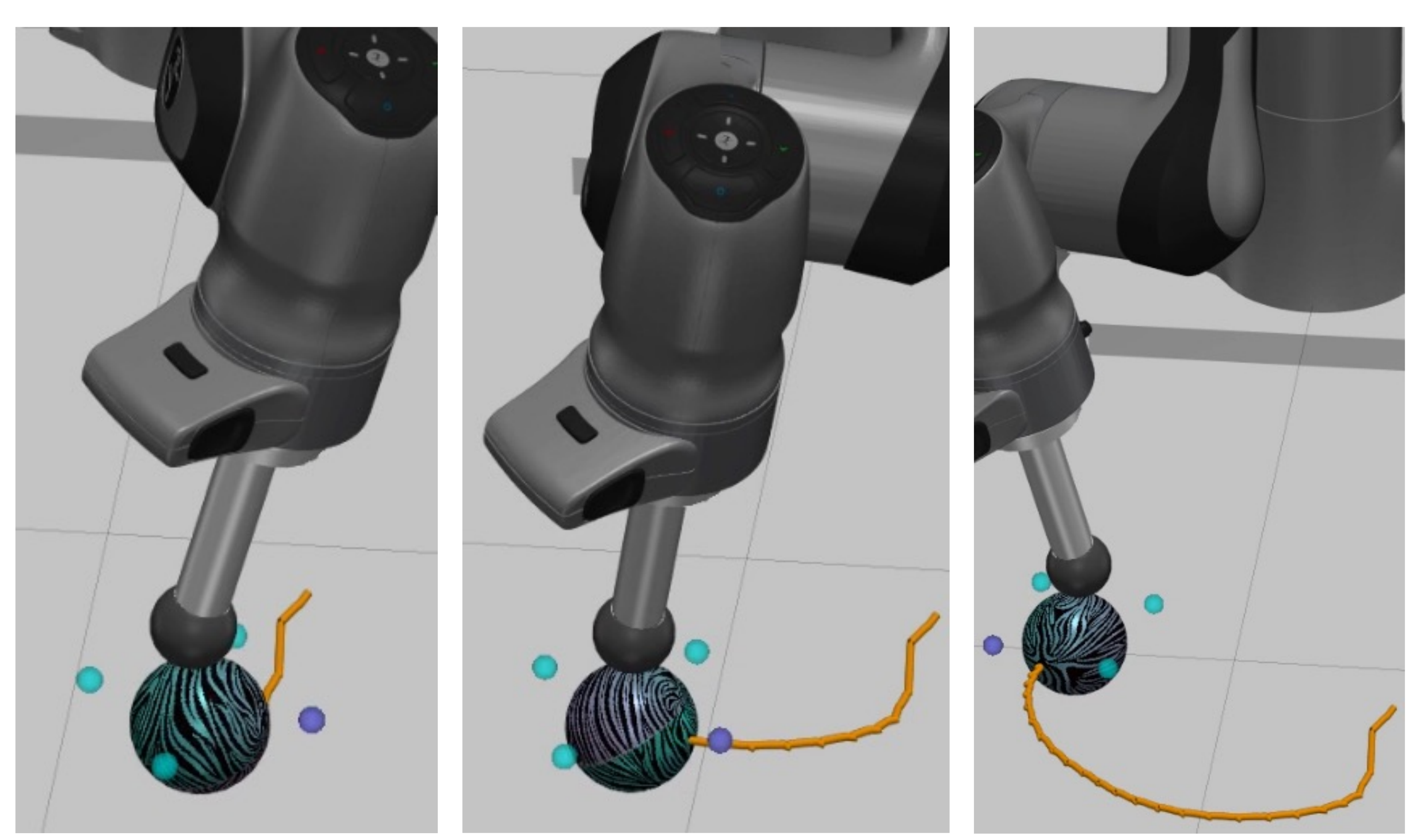
Our hierarchical controller performs real-time, contact-implicit control for contact-rich manipulation. It makes hybrid decisions at two levels:

1. Computing contact-implicit control trajectories (using C3) to achieve a goal.
2. Determining whether to perform control from the current end effector location or to reposition to a more advantageous configuration.

SIMULATION RESULTS: SPHERE ROLLING

We simulate and control a Franka Panda robotic arm using Drake.

The controller goal is to use a spherical end effector to manipulate a spherical object to track a circular trajectory.

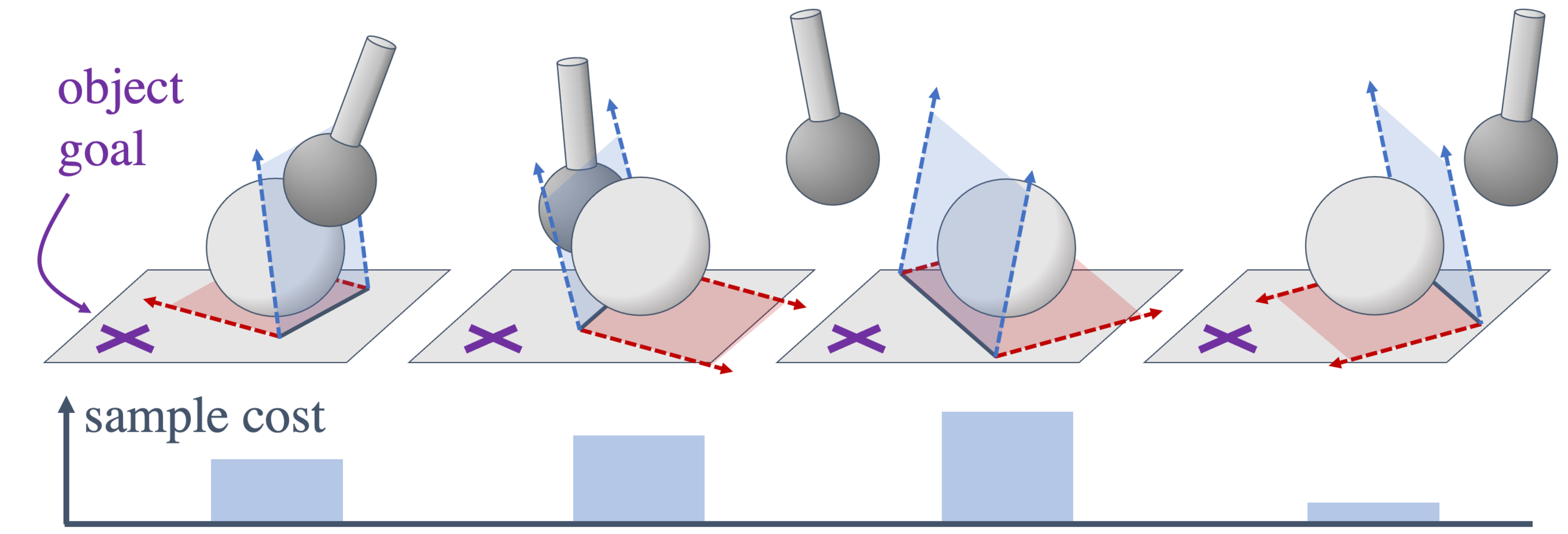


Sample locations are drawn in blue, with the optimal sample in purple. The orange path denotes the sphere's travel.

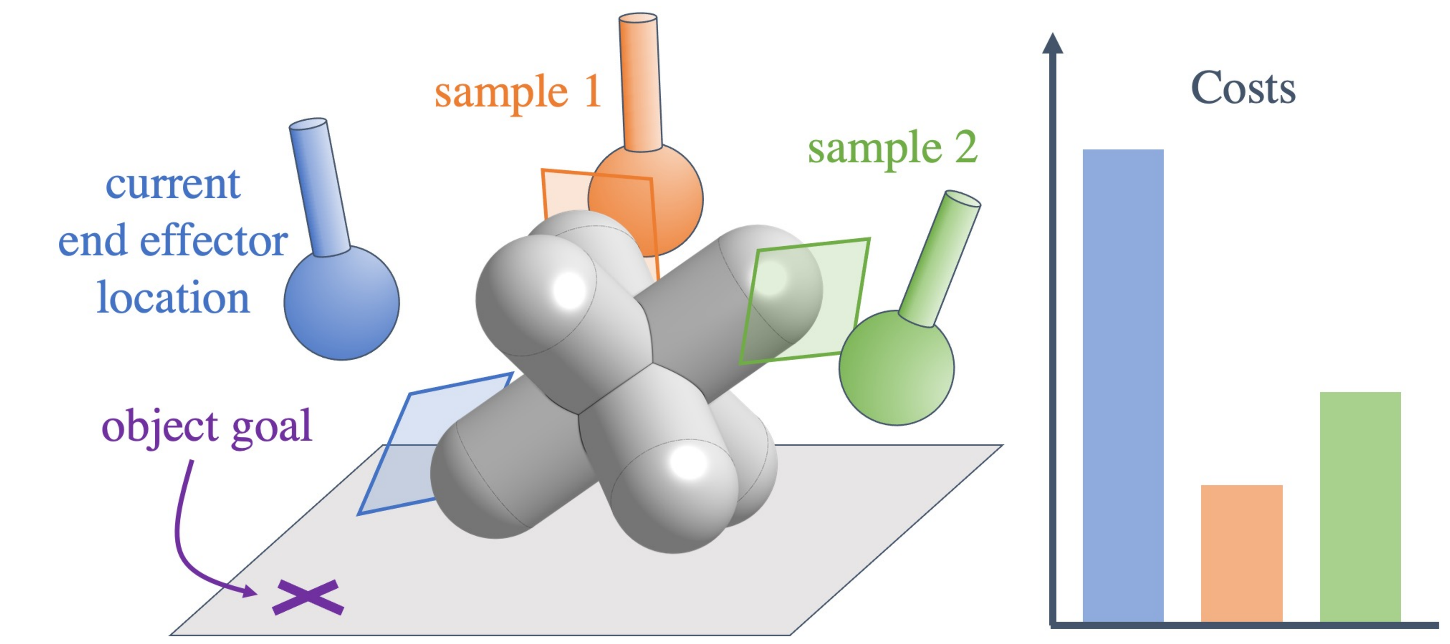
The robot successfully manipulates the sphere in a circular trajectory.

SAMPLING LINEAR COMPLEMENTARITY SYSTEM (LCS) APPROXIMATIONS

The linear complementarity system (LCS) approximation of an object-other geometry collision pair treats the object as a hyperplane tangent to the object contact surface at the point of smallest signed distance.



These samples represent current or potential configurations from which to perform control via C3. We rank these samples using C3's cost plus repositioning-related costs.



Our controller pursues the sample with least total cost; repositioning to the sample if necessary, running C3 otherwise.

FUTURE WORK

Future work will:

- Explore other sampling strategies.
- Improve performance on simulated examples via tuning.
- Demonstrate utility on hardware.

CONNECT WITH BIBIT

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