NRI: FND: Contact-aware Control of Dynamic Manipulation

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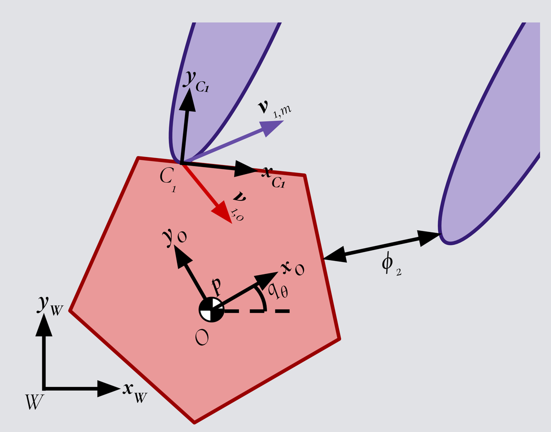
Introduction

Despite recent advances in picking and grasping, high-speed dexterous manipulation is yet unachieved. **In uncertain environments, robots move slowly and cautiously, often avoiding, rather than embracing, contact.**

The fundamental goal is to enable robots to intelligently make and break contact while manipulating complex and uncertain objects.



For this, we propose two hypotheses:

1. Formal, computational algorithms can **find** and **verify** simple, non-combinatoric, approaches to robotic grasping and manipulation.
2. Explicit consideration of the dynamics of manipulation can lead to more robust and more capable approaches.

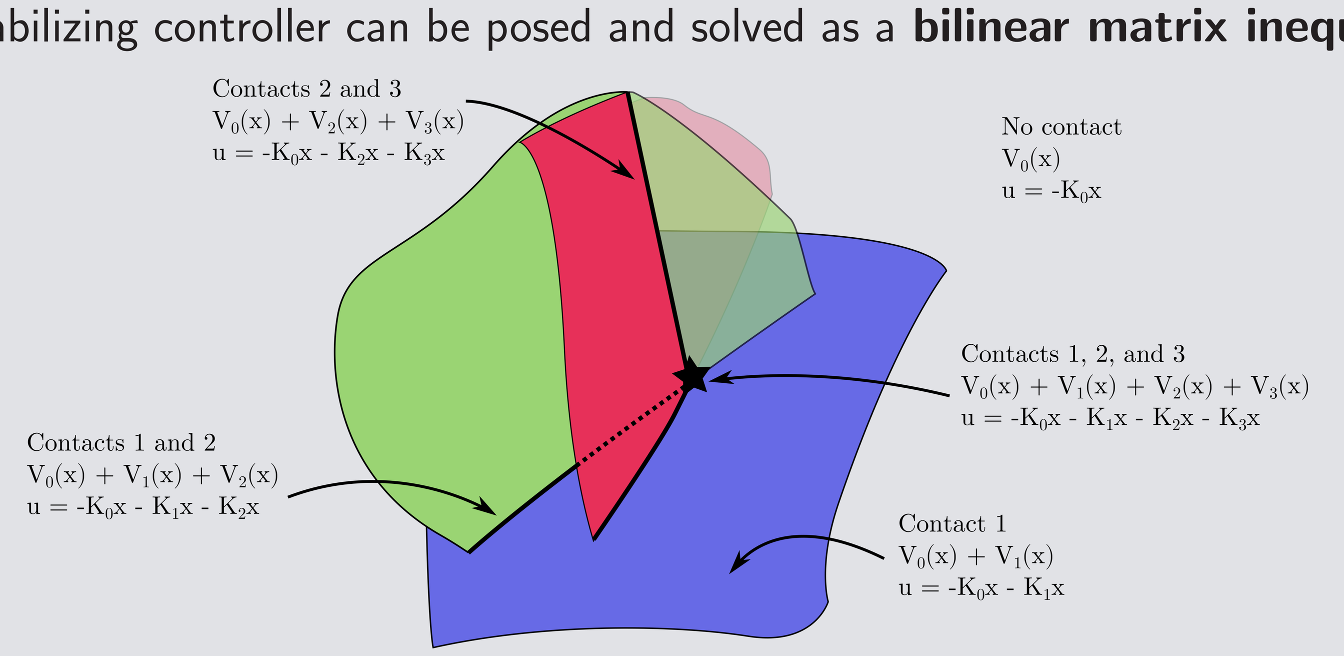
This project, new in 2018, will develop algorithms utilizing tactile sensing for dynamic and capable manipulation. Target tasks include: prehensile and nonprehensile pushing, two and three finger grasping, and in-hand dexterous manipulation.

Robust control synthesis

- The challenge in contact-rich manipulation lies in the discontinuous dynamics, due to frictional forces and impacts.
- We will design provably stable control policies, expanding on [2], that leverage tactile feedback, and model contact dynamics as a linear complementarity system

$$\dot{x} = Ax + Bu + C\lambda,$$
$$0 \le \lambda \perp Dx \ge 0.$$

- By leveraging this structure, controllers and certificates can be **non-combinatoric**.
- With this approach, even under the presence of uncertainty, the search for a stabilizing controller can be posed and solved as a **bilinear matrix inequality**.



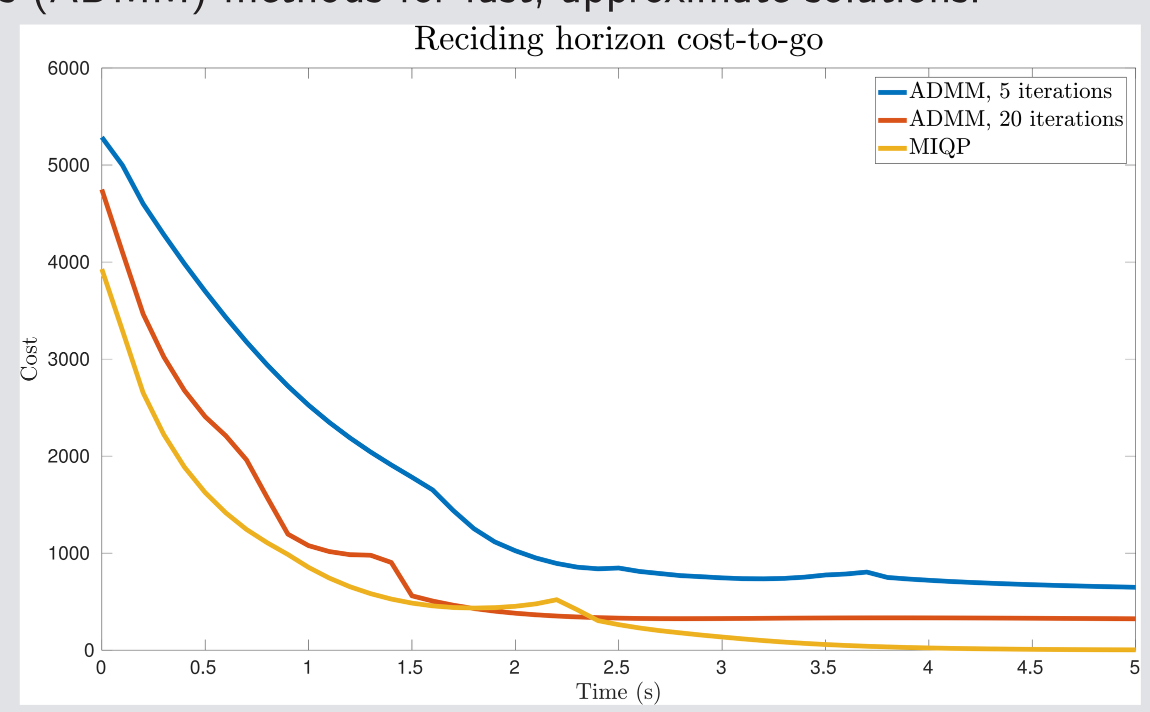
For three potential contacts, there are $2^3 = 8$ possible modes. Rather than define a separate policy per mode, we design and verify a policy where multiple contacts have an additive effect.

Real-time approximately-optimal feedback

- Given the richness of the world and of potential tasks, it is also necessary to develop real-time, but-high performance, policies.
- A robot might encounter a novel tool, and need grasp, perform in-hand reorientation, and execute a task with that tool.
- We pose the problem using model predictive control (MPC), where complementarity dynamics represent the manipulator making and breaking contact.

$$\underset{x_k, u_k, \lambda_k \text{ for } k=1,\dots,n}{\text{minimize}} \quad x_n^T Q_f x_n + \sum_k x_k^T Q x_k + u_k^T R u_k$$
$$\text{subj. to} \quad x_{k+1} = Ax_k + Bu_k + C\lambda_k$$
$$0 \le \lambda_k \perp Dx_{k+1} \ge 0$$

- This is a **non-convex** problem, and can be equivalently expressed as a mixed integer quadratic program (MIQP). As MIQPs are NP-hard and too slow to solve, our preliminary work has explored alternating direction method of multipliers (ADMM) methods for fast, approximate solutions.



For a simple, multi-contact system, we compare the performance of the optimal cost, given by solving the MIQP, with the performance of an ADMM approach, limited to a fixed iteration count.

Experimental setup

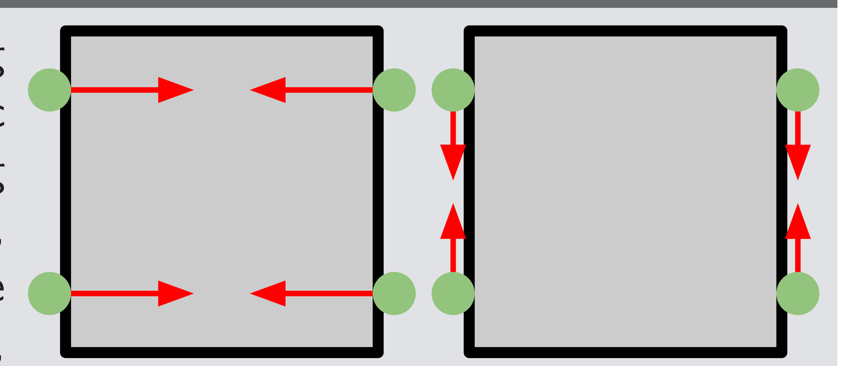
Experiments will be carried out using a manipulation system within the GRASP Lab at the University of Pennsylvania. Hardware specifics include:

- a KUKA LBR iiwa manipulator for high-accuracy force control and positioning,
- Robotiq two- and three-finger grippers for grasping,
- and a GelSight tactile sensor for high-resolution force measurement.

We will also make heavy use of high-fidelity simulations, using the Drake software library, which enable rapid development and testing. We understand the limitations of our existing hardware, particularly the speed and dexterity of the grippers. Simulation will permit evaluation of methods which require capabilities that exceed, within reasonable limits, the available hardware.

Quasistatic modeling

Quasistatic approaches, assuming direct control of the robotic manipulator's velocity, have a long history in manipulation. However, prior quasistatic approaches are unable to capture grasping and jamming, as these motions are incompatible with pure velocity control. To resolve these issues, we have developed a novel, model for planar, quasistatic manipulation [1].



A square object contacted by four fingers, with commanded velocities shown. Under traditional quasistatic models, the example on the left has no possible solutions. On the right, the configuration yields ambiguous behavior. Depending on the forces, the object may remain stationary or slide.

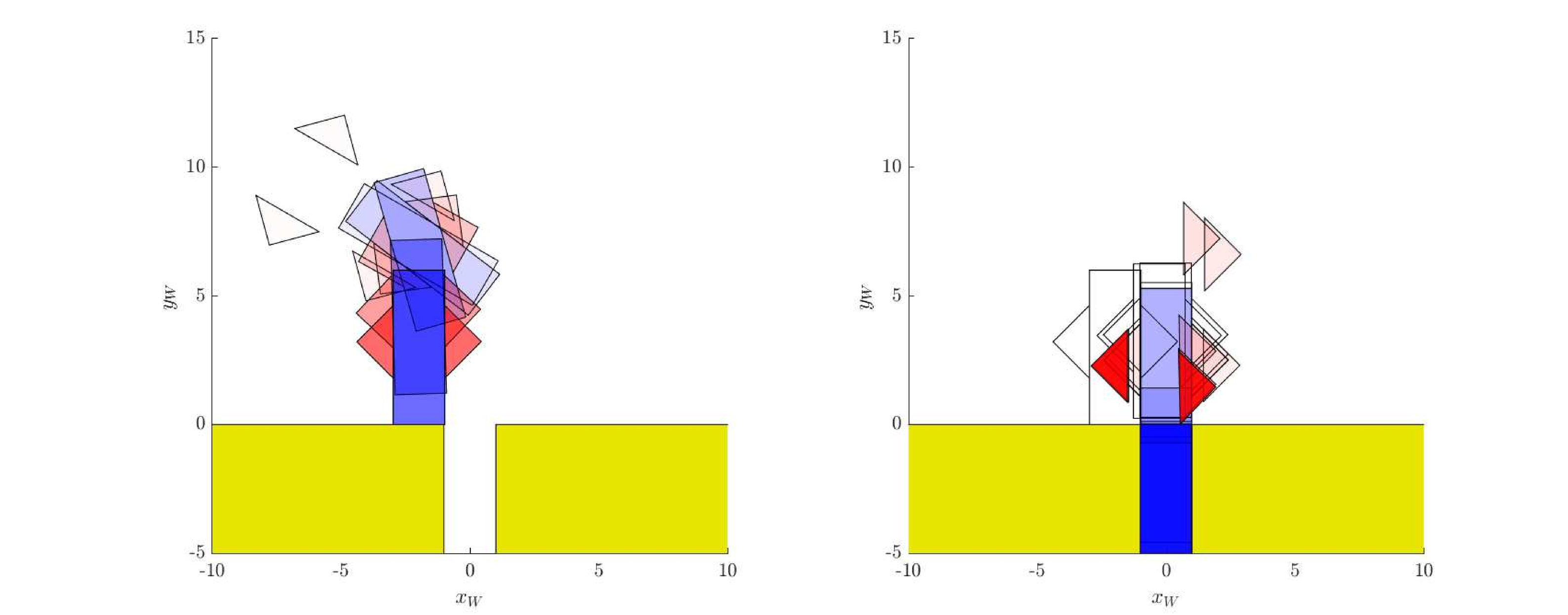
By incorporating a linear relationship between contact forces F, commanded manipulator velocity u, and resultant velocity v,

$$u - v = KF,$$

and considering large gains K, we derive a rich model of quasistatic manipulation.

- **Computationally efficient:** written as a linear complementarity problem (LCP).
- **Provable existence:** the LCP is guaranteed to have solutions for all commands, including pushing, grasping, and jamming.
- **Limiting behavior:** captures the reality of feedback-based velocity control, approximating pure velocity commands when dynamically feasible.

This modeling approach will enable high-speed control and planning, with ongoing to explicitly address uncertain and stochastic systems.



A peg-in-hole trajectory. (Left) grasping and orientation against the wall. Right: sliding and insertion.

References

[1] Mathew Halm and Michael Posa. A Quasi-static Model and Simulation Approach for Pushing, Grasping, and Jamming. In *To appear in the Workshop on the Algorithmic Foundations of Robotics (WAFR)*, 2018.

[2] Michael Posa, Mark Tobenkin, and Russ Tedrake. Stability analysis and control of rigid-body systems with impacts and friction. *IEEE Transactions on Automatic Control (TAC)*, 61(6):1423–1437, jun 2016.

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