Contact-aware Control of Dynamic Manipulation

PI: Michael Posa (University of Pennsylvania)

Penn Engineering | GRASP Laboratory
General Robotics, Automation, Sensing & Perception Lab

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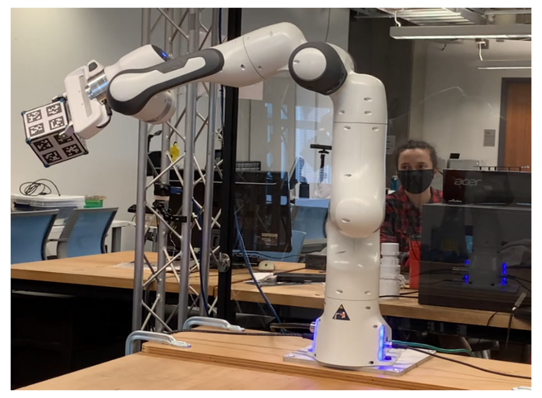
Dynamic Autonomy & Intelligent Robotics

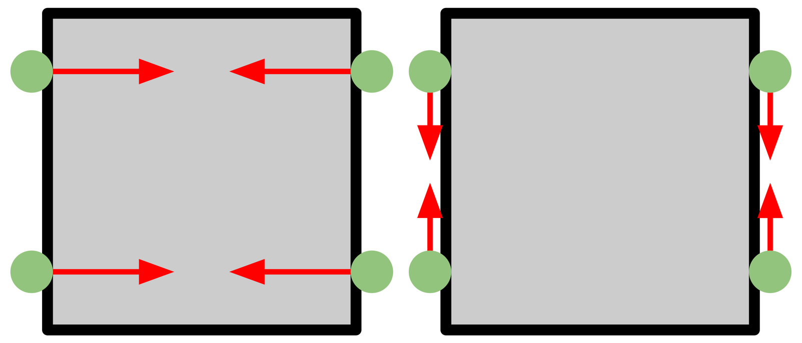
INTRODUCTION



- Frictional contact is **the fundamental behavior** of robot locomotion and manipulation.
- However, in uncertain environments, robots move slowly and cautiously, often avoiding, rather than embracing, contact.
- To enable complex, dynamic manipulation, this project made fundamental advances in **physics-based modeling and model learning**, with a focus on capturing the hybrid discontinuities that challenge standard methods.
- This project developed model-based control algorithms, leveraging tactile sensing for reactive feedback and 30 Hz, real-time planning that intelligently makes and breaks contact.

QUASISTATIC MODELING [1]

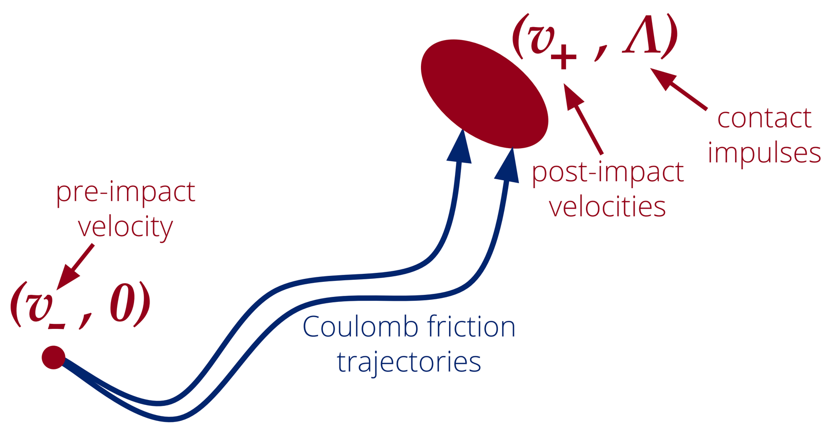
Prior, quasistatic approaches are fundamentally unable to capture grasping and jamming. We have developed a **comprehensive model for quasistatic manipulation**. By replacing pure velocity control with a more realistic force law, we derive a computationally efficient model for unification of pushing and grasping.



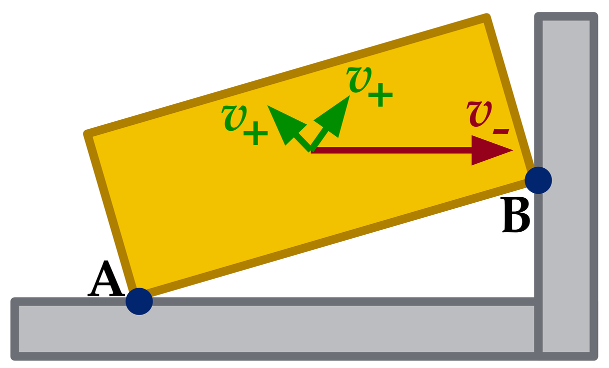
A square object contacted by four fingers, with commanded velocities shown. With traditional methods, (left) has no possible solutions and (right) yields ambiguous sticking or sliding behavior.

SIMULTANEOUS CONTACT [2, 3]

- Simultaneous frictional impacts between rigid bodies are **pervasive, extremely sensitive, and poorly understood.**
- **We developed a continuous-time rigid body model that for set-valued simulation and reasoning over contact ambiguity.**
- The result is a **single differential inclusion**, with solution guarantees, that unifies continuous-time simulation and impact events.

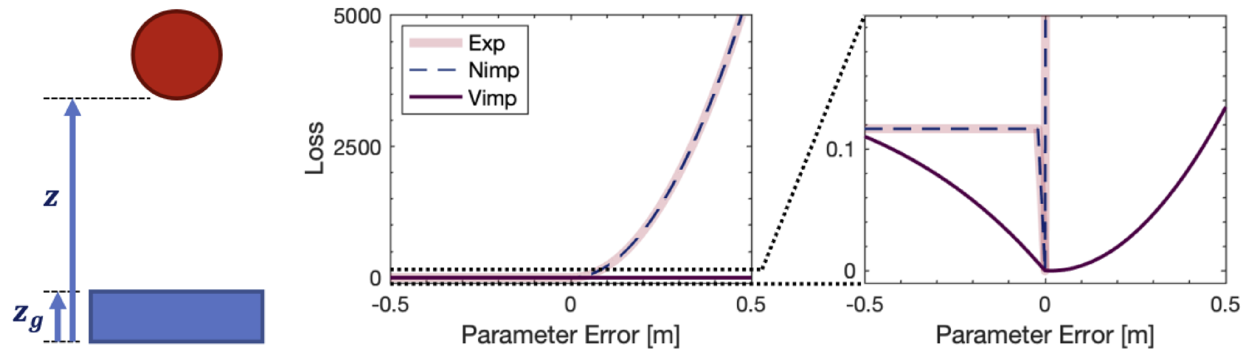


Non-uniqueness emerges even without simultaneous impact. A block sliding into a wall will have sensitive behaviors due to propagation of impact events.

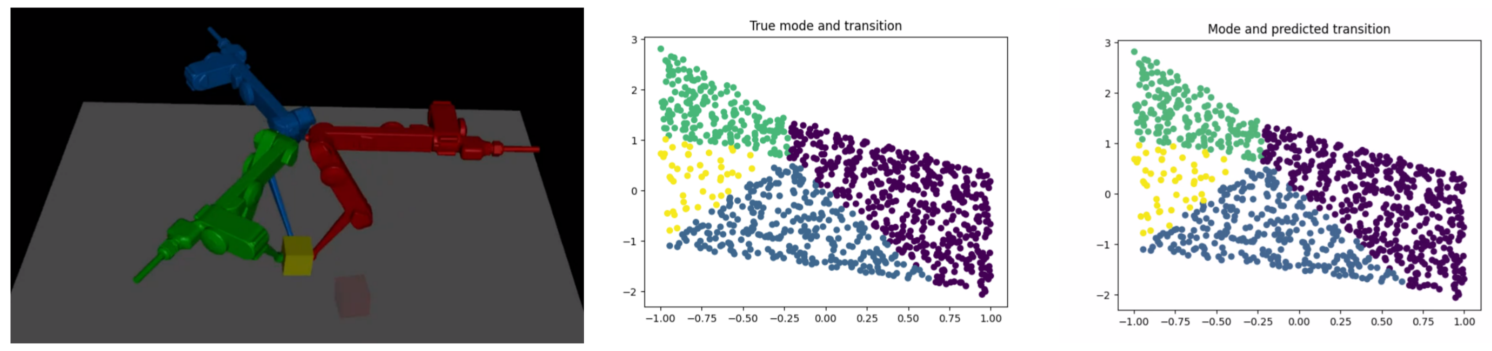


LEARNING DISCONTINUITY [4, 5, 6]

- Standard ML biases toward continuity and simplicity, are fundamentally at odds with multi-contact robotics.
- Even for simple examples, like a bouncing ball, while our **intuitive understanding of the motion** is simple, the mapping $x_k \rightarrow x_{k+1}$ is discontinuous at impact events.
- **Smoothing** used in physics simulators artificially simplifies the problem, where empirical results show a direct correlation between stiffness (hard being more realistic) and learning error [6].
- **Implicit learning**, leveraging complementarity structure, can dramatically reshape stiff optimization landscapes enabling learning to **provably generalize better** to unseen data [4].



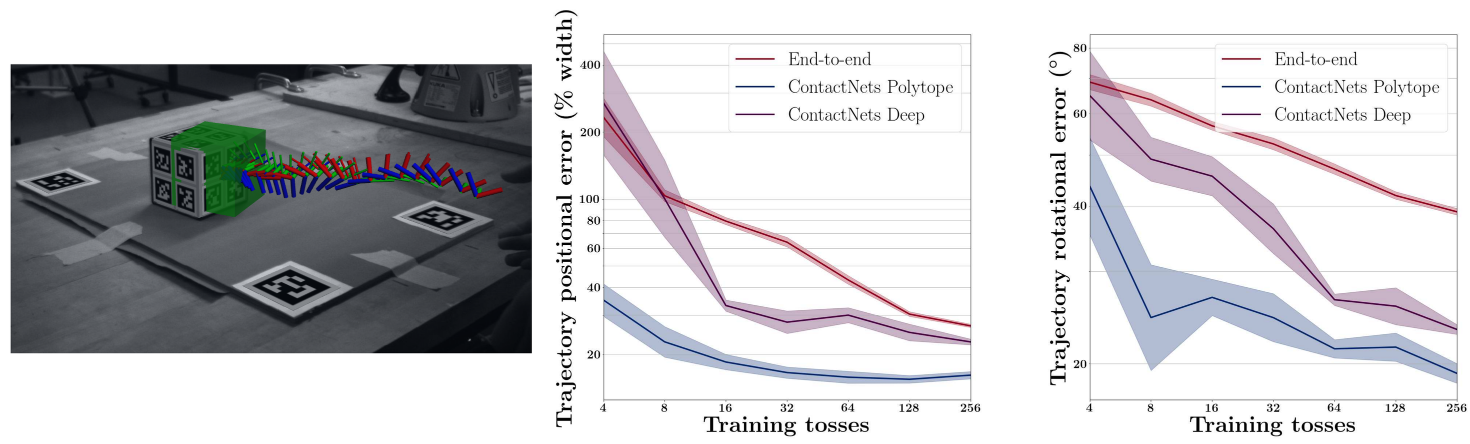
- Thees approaches scale to piecewise-affine systems with thousands of pieces and contact-rich manipulation [5].



CONTACTNETS [7]

ContactNets learns discontinuous physics without introducing artificial smoothing.

- A physics-inspired representation, generalizing geometry and friction with neural networks, is a **smooth** encoding of discontinuity.
- Direct simulation of candidate models leads to poorly conditioned training. Via **bilevel optimization**, we **hypothesize** potential forces that must simultaneously correspond to a candidate model and match observed data.



Using motion capture, we toss a cube against the ground and record its rolling, bouncing, and sliding trajectories. While standard DNNs struggle to learn from limited data, ContactNets variations are able to rapidly segment the discontinuous modes and achieve highly accurate trajectory rollouts with only seconds of data.

CONTACT-AWARE CONTROL SYNTHESIS [8, 9, 10, 11]

The challenge in contact-rich manipulation lies in the discontinuous dynamics, due to frictional forces and impacts. Model dynamics as a Linear Complementarity System (LCS)

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

Two algorithms:

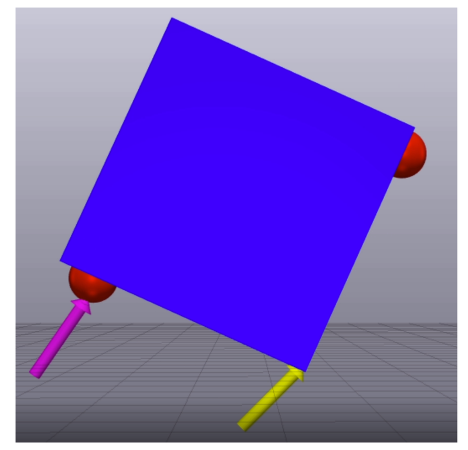
1. **Lyapunov stable** control policies $u = Kx + L\lambda$ that leverage tactile feedback. Synthesize by solving a a **bilinear matrix inequality**
2. **Consensus Complementarity Control (C3)**: real-time MPC that explores potential contact sequences. Consensus ADMM formulation that leverages complementarity structure.

EXAMPLE: CART-POLE WITH SOFT WALLS

- The pole impacts two foam walls, often at high speeds.
- Linearization cannot reason about the walls, but LCS controllers can.
- C3 and reactive tactile feedback stabilize the physical system.

EXAMPLE: TWO-FINGER MANIPULATION

Two fingers (red) move across and manipulate a planar object (blue), where the object can also touch the ground. Normal and frictional forces are shown as arrows. C3 generates manipulation plans, reasoning about stick-slip transitions at three contact points. With a planning horizon of 10 steps, the controller runs at over 30 Hz.



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https://dair.seas.upenn.edu, posa@seas.upenn.edu

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