Contact-aware Control of Dynamic Manipulation

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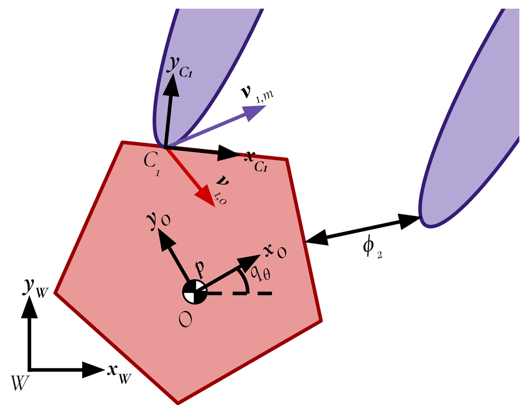
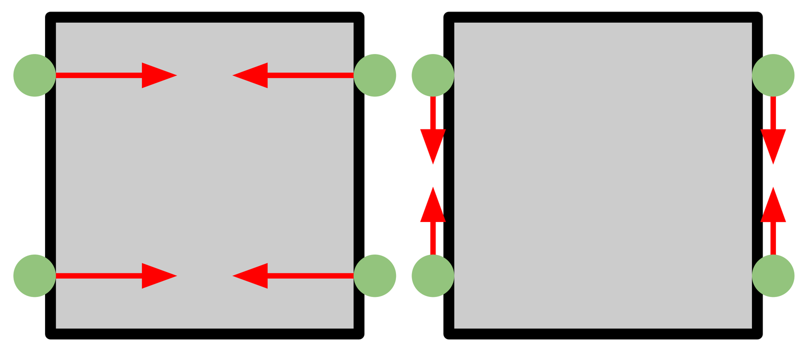
INTRODUCTION

- 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.
- **This project aims to to enable robots to intelligently make and break contact while manipulating complex and uncertain objects.**



QUASISTATIC MODELING [1]

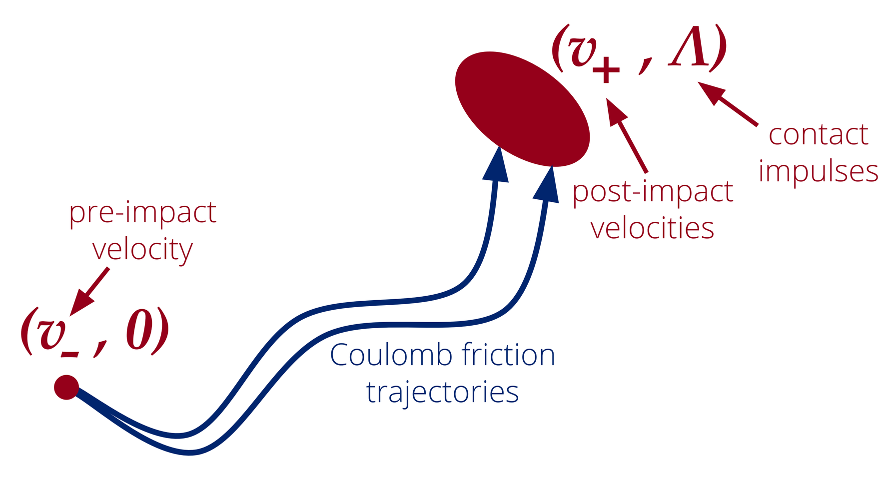
Prior, quasistatic approaches are fundamentally unable to capture grasping and jamming. We have developed a **comprehensive model for quasistatic manipulation**. By replacing pure velocity control with a more realistic force law, we derive a computationally efficient model for unification of pushing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



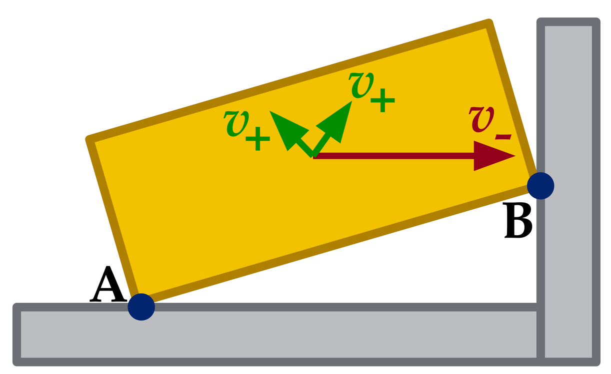
A square object contacted by four fingers, with commanded velocities shown. With traditional methods, (left) has no possible solutions and (right) yields ambiguous sticking or sliding behavior.

SIMULTANEOUS CONTACT [2]

- Simultaneous frictional impacts between rigid bodies are **pervasive, extremely sensitive, and poorly understood.**
- **We developed a continuous-time rigid body dynamics model that enables set-valued simulation and reasoning over impact ambiguity.**
- The product is a **single differential inclusion**, with guarantees on existence of solutions, that unifies continuous-time simulation and impact resolution.

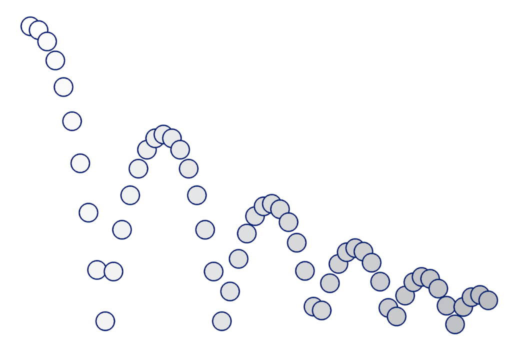


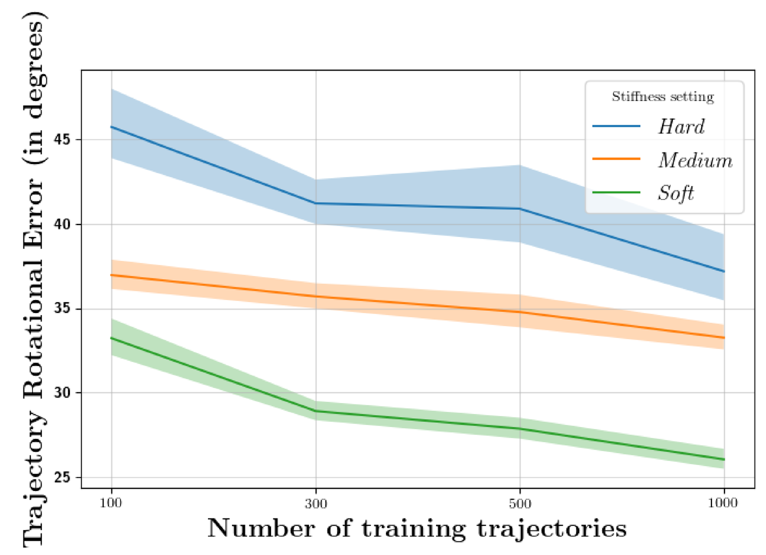
As an example, **subtle** non-uniqueness emerges even without simultaneous impact. A block sliding into a wall (right) will have sensitive behaviors due to propagation of impact events.



LEARNING DISCONTINUITY [3]

- Standard ML approaches to model learning, which bias toward continuity and simplicity, are fundamentally at odds with contact dynamics.
- Even for simple examples, like a bouncing ball, while our **intuitive understanding of the motion** is simple, the mapping $x_k \to x_{k+1}$ 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.

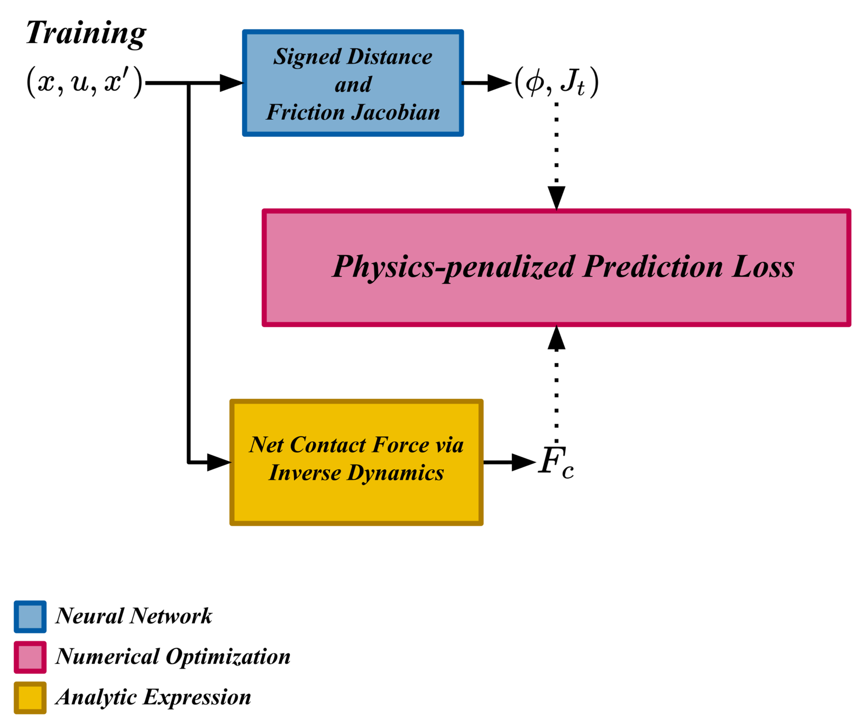




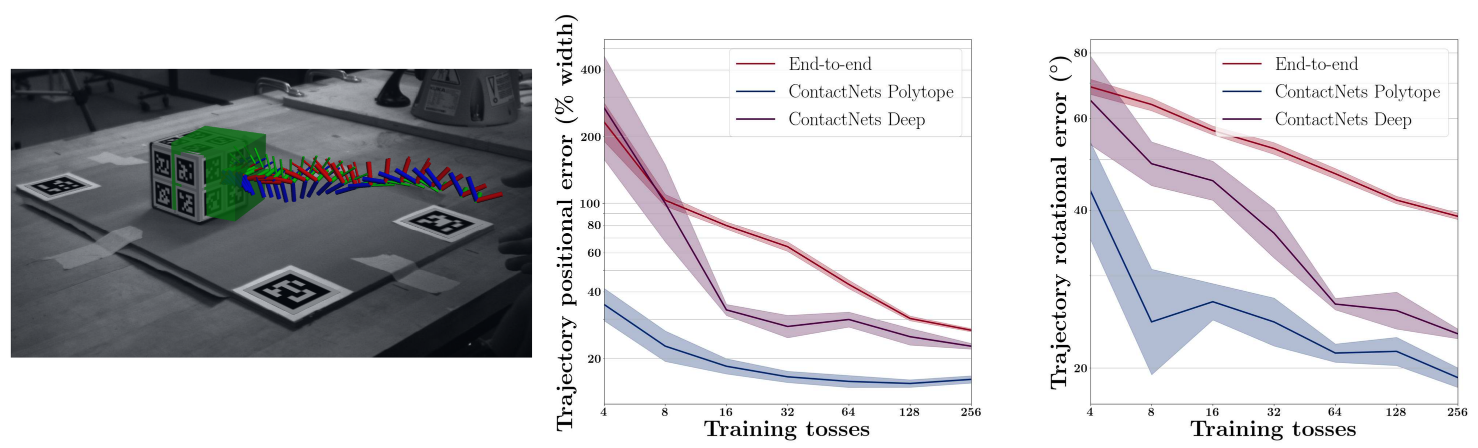
CONTACTNETS [4]

The **ContactNets** framework directly 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 [5, 6, 7]

- The challenge in contact-rich manipulation lies in the discontinuous dynamics, due to frictional forces and impacts.
- We design **provably stable control policies that leverage tactile feedback**.
- Modeling dynamics as a Linear Complementarity System (LCS)

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

- Mirror this structure in the controller and Lyapunov function

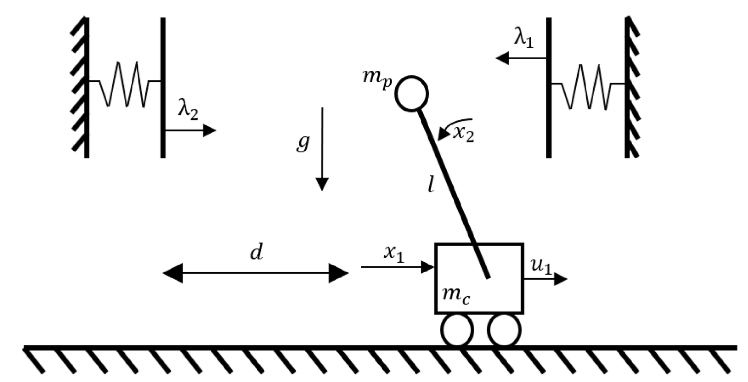
$$u = -Kx - L\lambda, \qquad V = \begin{bmatrix} x \\ \lambda \end{bmatrix}^T Q \begin{bmatrix} x \\ \lambda \end{bmatrix}.$$

Controllers and certificates utilize tactile feedback, are piecewise-differentiable, but are **non-combinatoric** and scalable.

- Synthesis of a stabilizing controller solved as a **bilinear matrix inequality**.

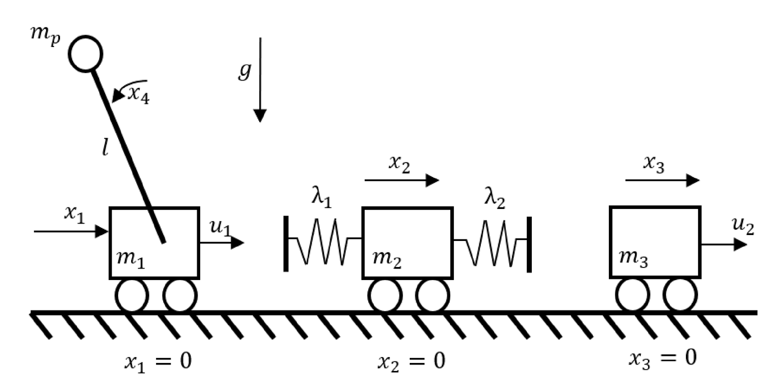
EXAMPLE: CART-POLE WITH SOFT WALLS

- Two stiff spring-based walls that interact with the pole
- Linearization-based methods cannot reason about the non-smooth dynamics, but linearizing the *smooth* aspects of the dynamics and kinematics gives a LCS and stabilizing controller.



EXAMPLE: PARTIAL STATE FEEDBACK

- Tactile feedback can be used when state is unknown.
- The middle underactuated cart is not sensed.
- Imposing sparsity constraints on control policy, we still synthesize a provably stabilizing strategy.



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