Understanding Impact Uncertainty in Legged Robots

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MOTIVATION

We want to improve the robustness of legged robots to making (and breaking) contact, which we can address through:

- **Robust trajectory optimization** which requires:
  - Understanding what types of uncertainty matter (ground height/stiffness, impact velocity)
  - Understanding how uncertainty is mapped through an impact event
- **Robust controller design** which requires:
  - Understanding of what makes a particular controller brittle to impact uncertainty

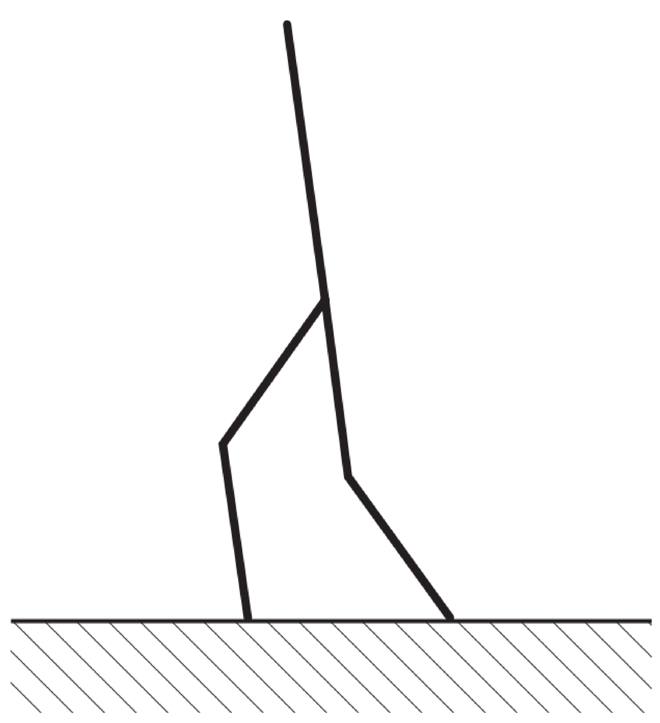
We need to better understand what is happening during an impact event.

Essential Questions

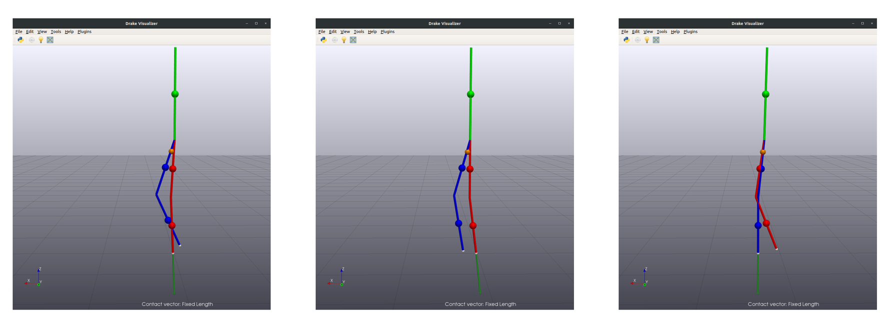
1. What happens when impacts do not resolve instantaneously?
   - What control strategy should we use during the impact event?
   - What are the contributions of the non-impulsive terms?
2. How is uncertainty mapped through impact events?
3. Why are certain control strategies robust to impacts?

CASE STUDY

Simple Model: Rabbit Walking



- 14 states
- Hybrid LQR controller
- Single point-foot contact



METHODS

1. Generate a hybrid trajectory using trajectory optimization assuming rigid impacts:
$$M(q)(\dot{q}^+ - \dot{q}^-) = J(q)^T \Lambda$$
2. Track the trajectory using Hybrid LQR in a simulator with "soft" ground.
3. Run a parameter sweep across:
   - perturbations in initial state
   - controller switching times
   - ground stiffness
4. Quantify the contribution of the full dynamics over the impact event:

2
$$M(\dot{q}^+ - \dot{q}^-) = \int_{t^-}^{t^+} Bu(t) + C(\dot{q}, q) + g(q) + J(q)^T \lambda \, dt$$

[1] Nima Fazeli, Samuel Zapolsky, Evan Drumwright, and Alberto Rodriguez. Learning Data-Efficient Rigid-Body Contact Models: Case Study of Planar Impact. oct 2017.

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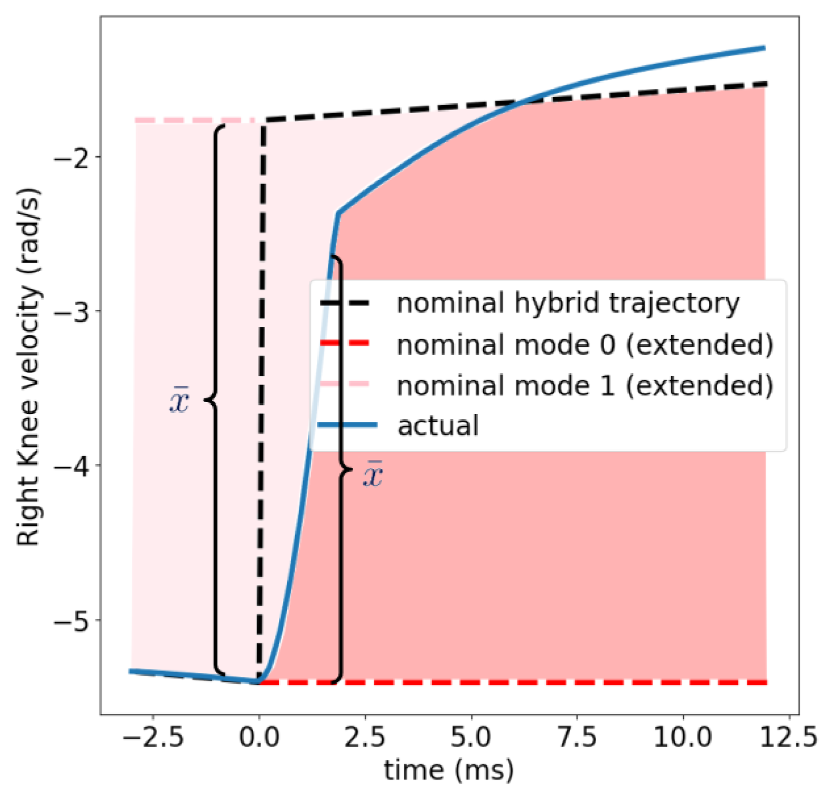
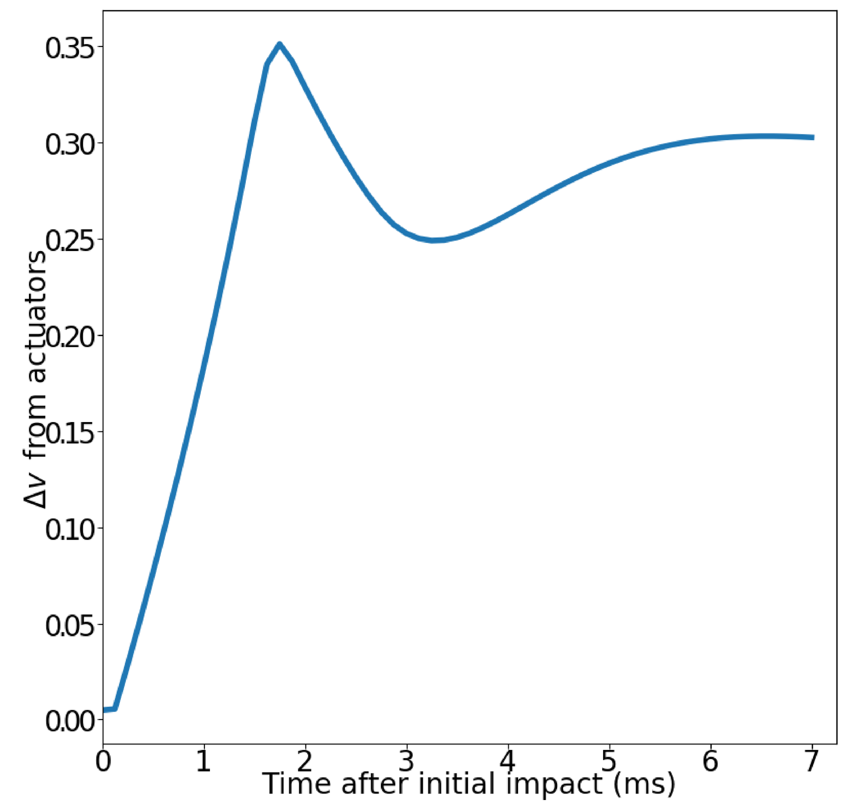
RELAXATION OF INSTANTANEOUS IMPACTS

A switching controller will apply incorrect efforts during impact

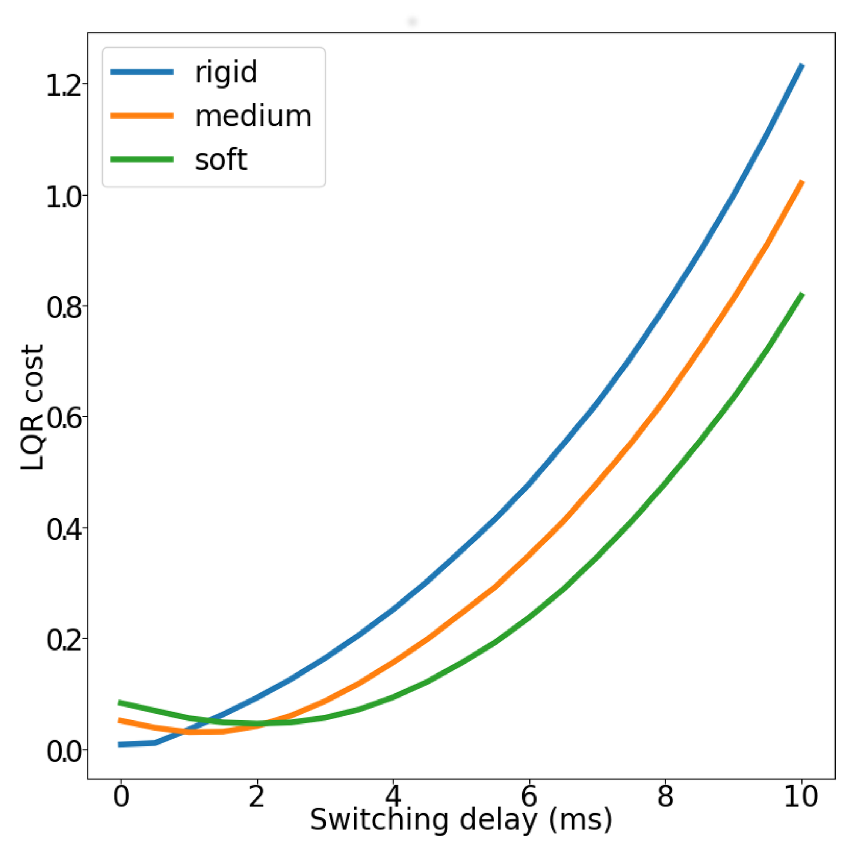


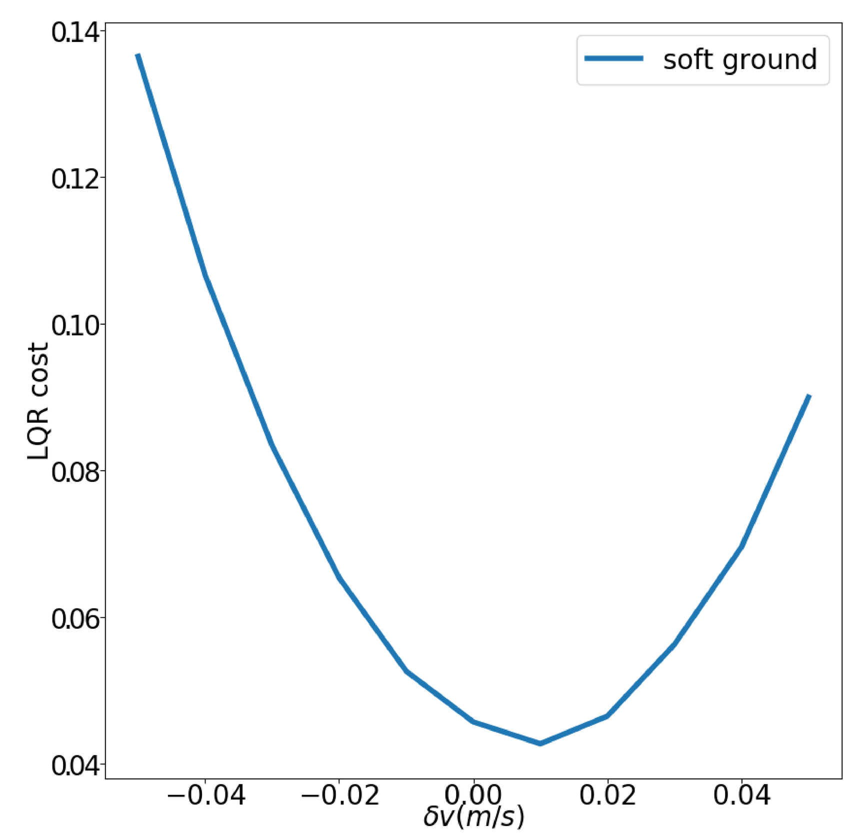
The controller efforts applied over impact are NOT negligible



- A purely impulse impact model will not fully capture how the state, and therefore uncertainty is mapped through an impact event.
- Hybrid reset maps currently look like:
$$x^+ = R(x^-)$$
- Instead, we should include dependencies on controller strategy, ground stiffness (and possibly others).

SENSITIVITY ANALYSIS





- Switching controllers are more brittle to rigid ground
- The optimal switching time depends on the ground stiffness
- To a much lesser degree, it is better to make contact with a lower impact velocity.
- For context, a LQR cost of 1.0 corresponds to .1 - .5 rad/s error in the joint velocity.

*Rigid, Medium, and Soft refer to ground stiffness, where the ground is modeled as a damped spring. Soft has an average ground penetration of 0.5mm.

SUMMARY

- Impacts are not well modeled by rigid impulsive models [1]. Even in simulation environments.
- Switching controllers, which include any controller that uses finite state machines, may not want to switch states as soon as contact is detected.
- The optimal switching is a function of impact duration, pre/post impact gains.
- Need data collected from real legged robots impacting the ground to develop a better impact model.

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