ETH zürich

Robotic Systems Lab

Contact-Implicit Planning for Athletic, Contact-Rich Tasks

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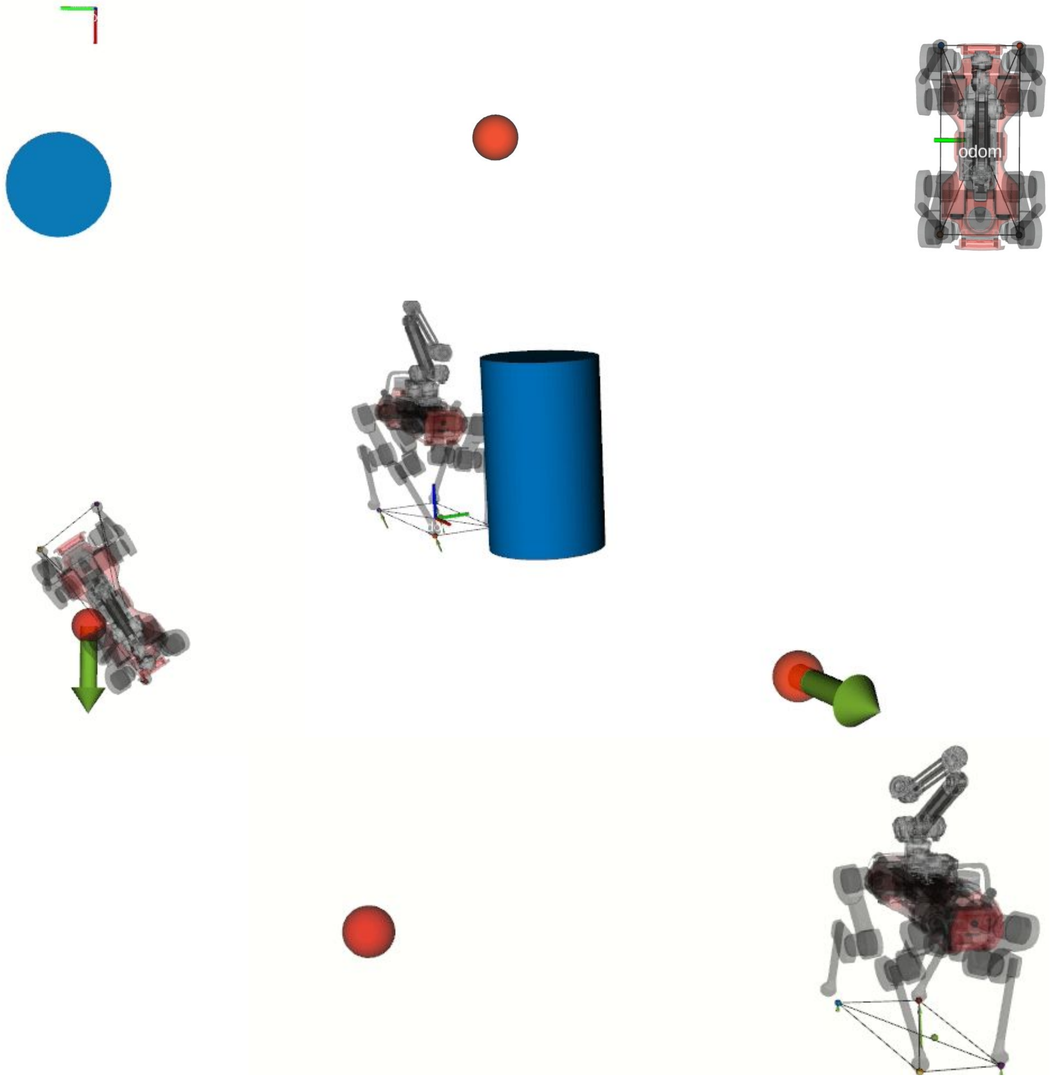
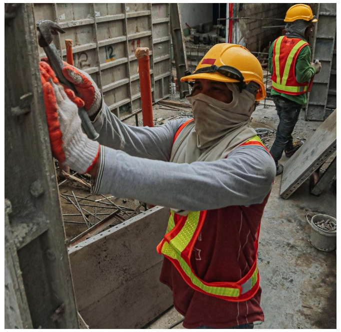
Semester Project Final Presentation
Supervisors: Jean-Pierre Sleiman, Jia-Ruei Chiu
Committee: Mayank Mittal
24 April 2023, Zurich



Motivation

➢ Physically intensive tasks require human level athleticism



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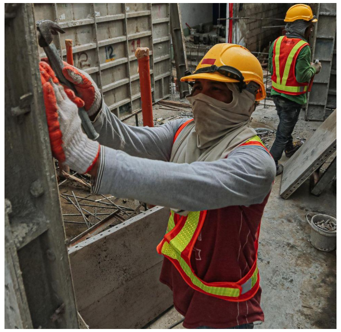


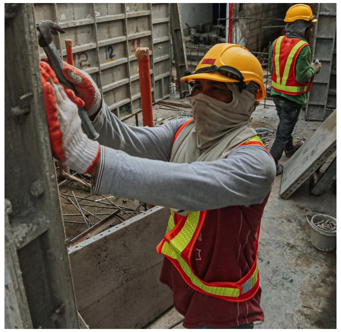
- ➢ Physically intensive tasks require human level athleticism
- ➢ From short reactive thinking to long horizon contact-exploiting planning

Motivation

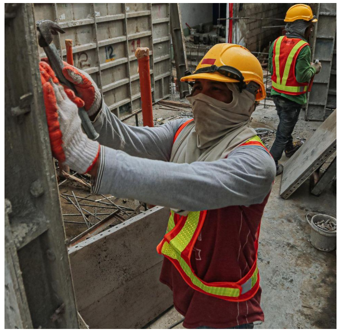
➢ Physically intensive tasks require human level athleticism

➢ From short reactive thinking to long horizon contact-exploiting planning

➢ Spectrum of possibilities is endless

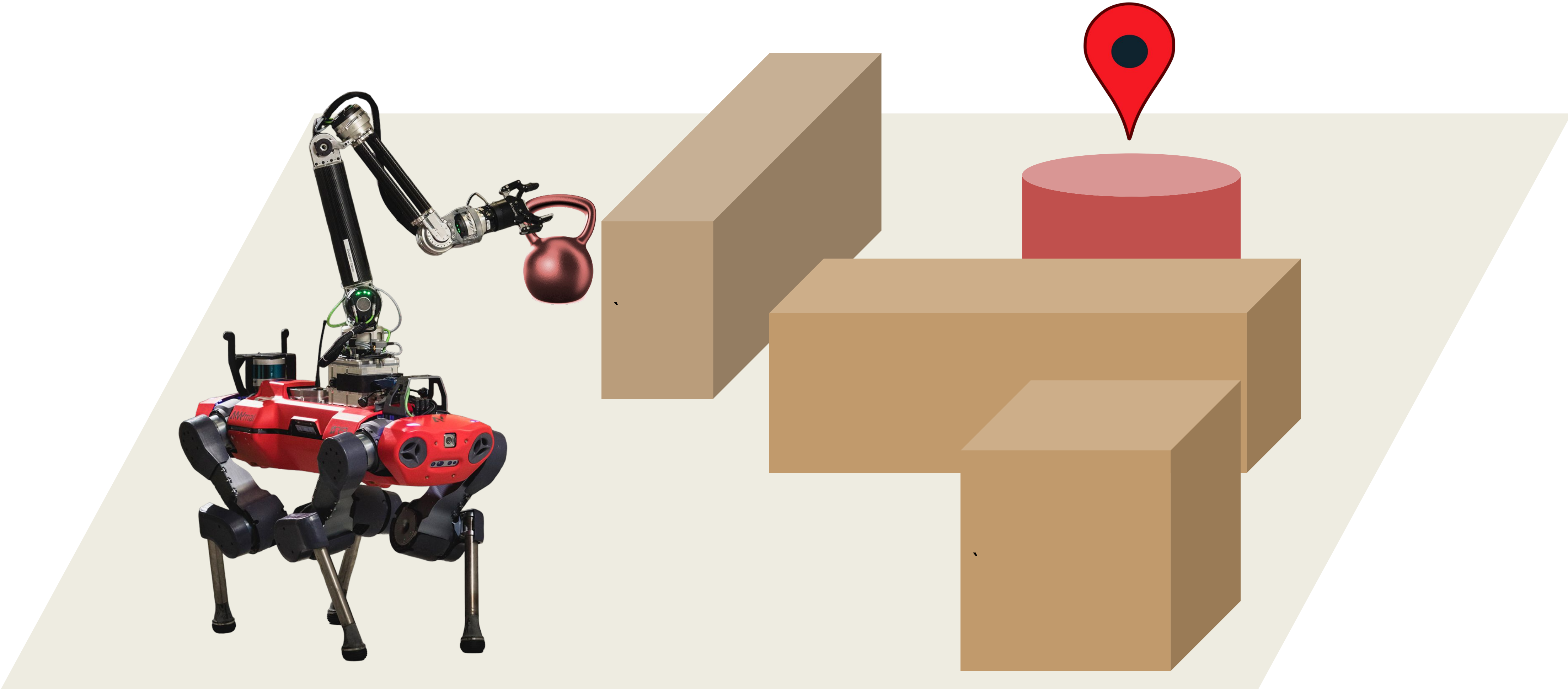


Motivation

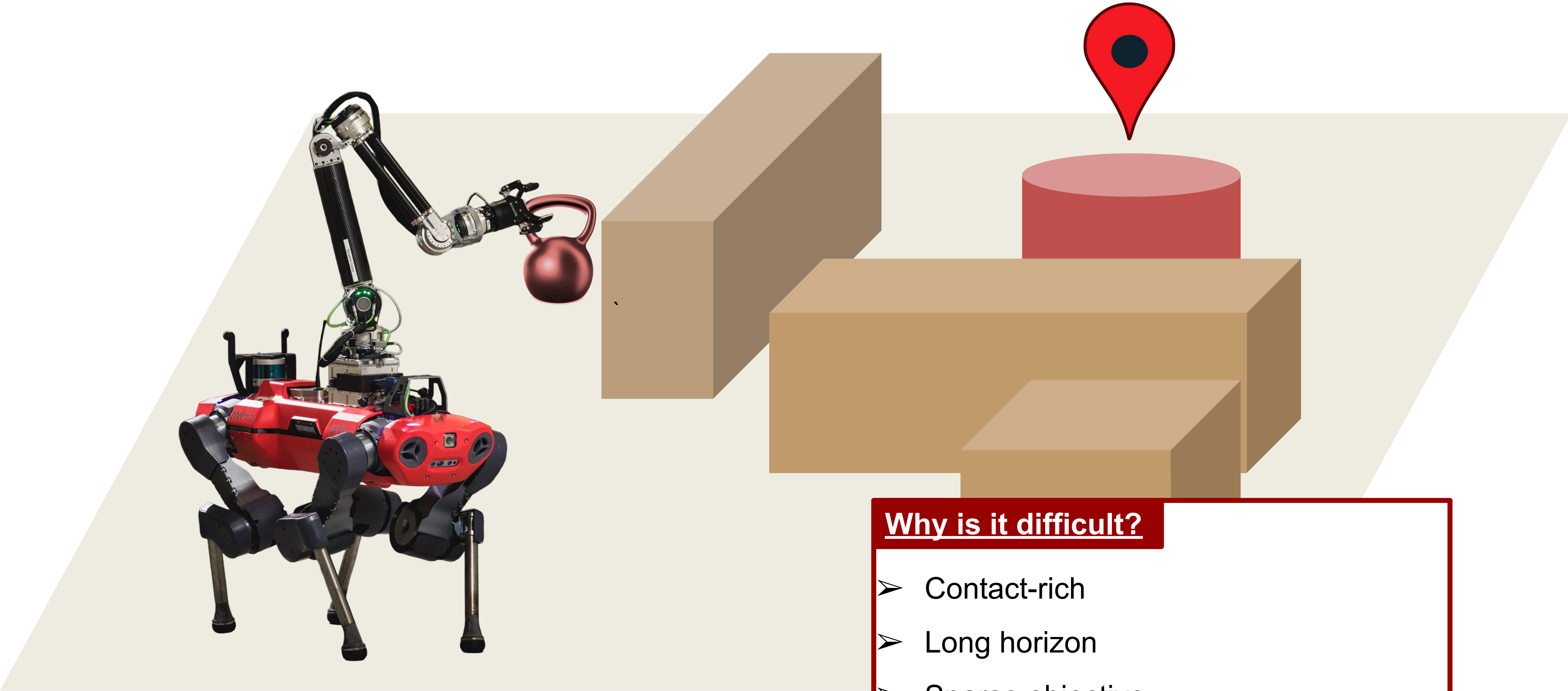


- ➢ Physically intensive tasks require human level athleticism
- ➢ From short reactive thinking to long horizon contact-exploiting planning
- ➢ Spectrum of possibilities is endless
- ➢ Task-agnostic approach for a platform like ANYmal or ALMA

An example



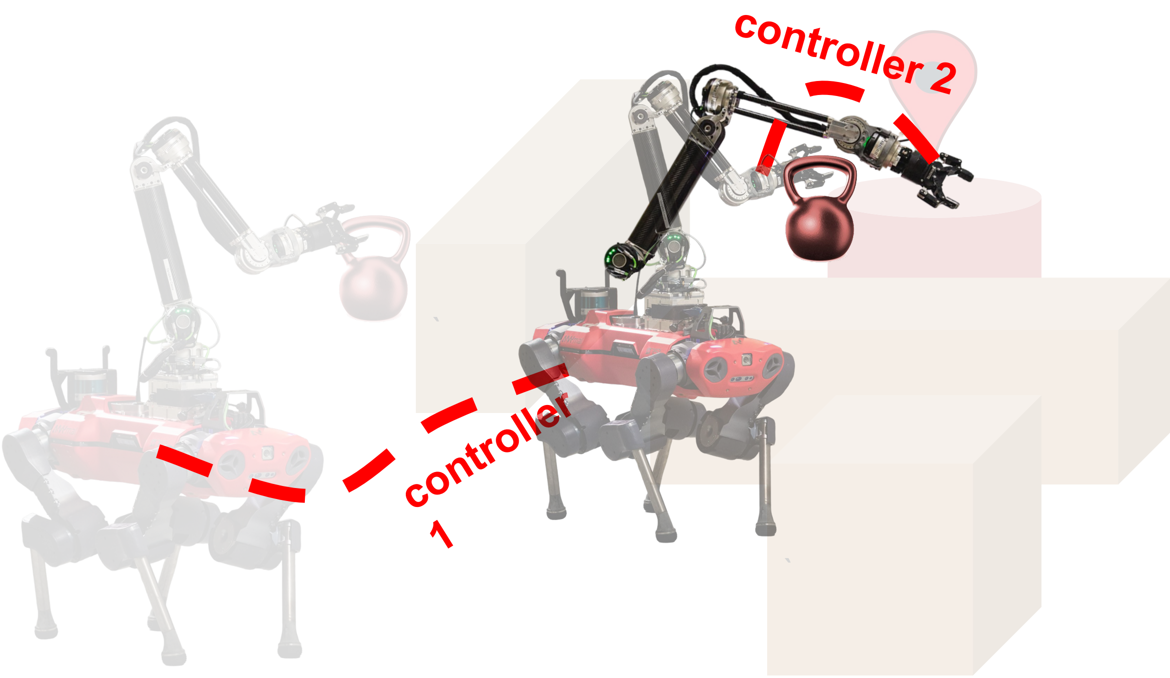
An example

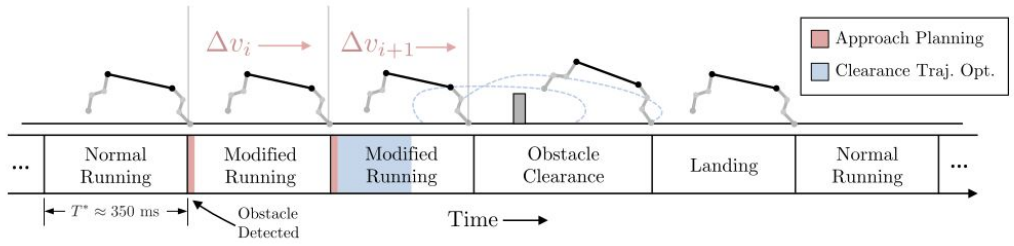


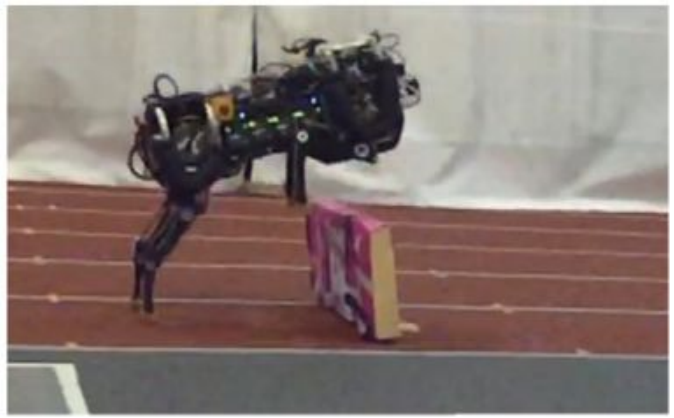
Why is it difficult?

- Contact-rich
- Long horizon
- Sparse objective

Current approaches: ***Human guidance** in defining behaviors*

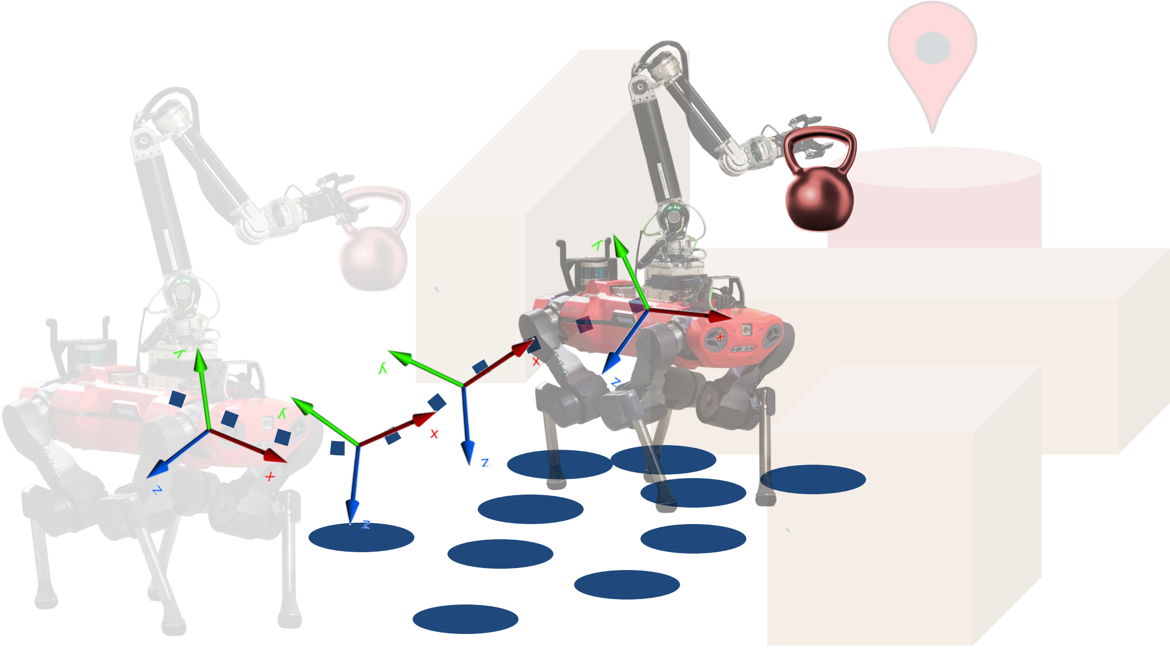


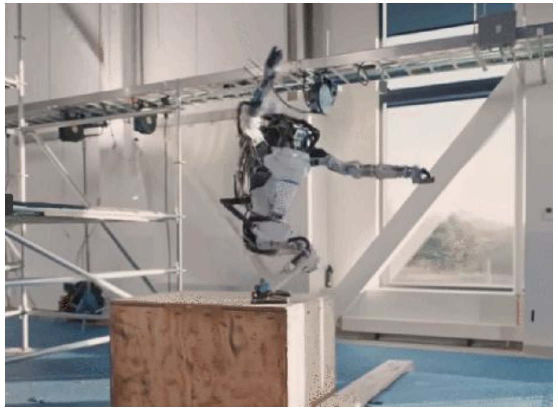




Source: Jumping over obstacles with MIT Cheetah 2

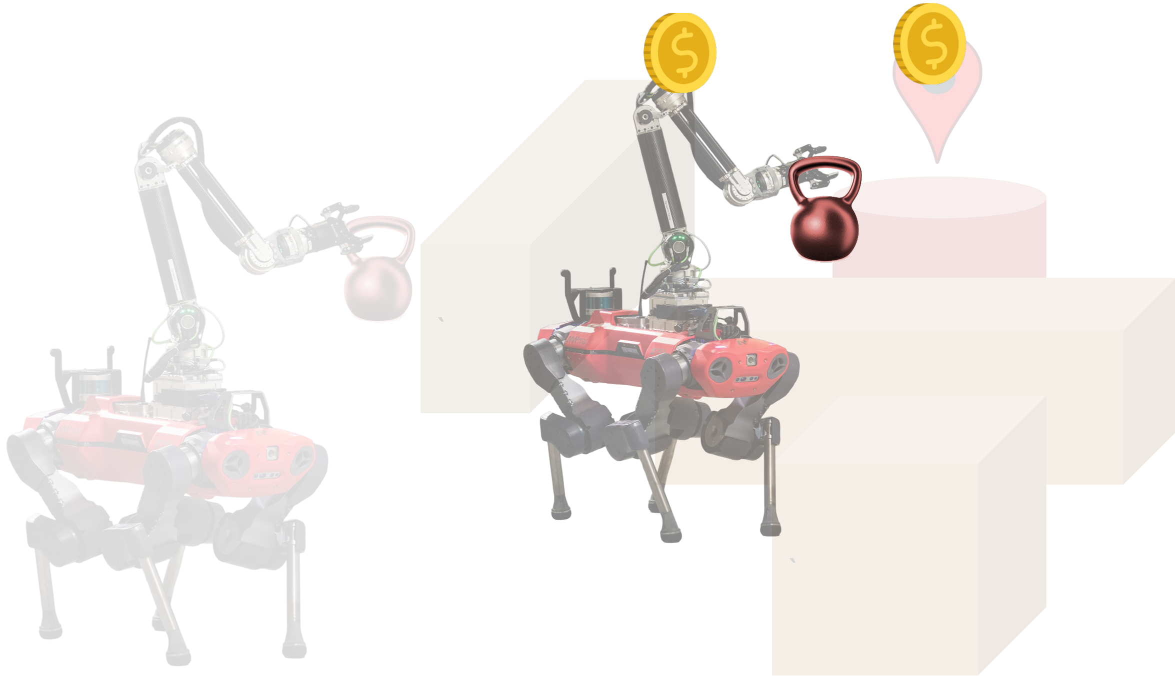
Current approaches: ***Human guidance*** *in defining behaviors*





Source: Atlas Gets a Grip | Boston Dynamics.

Current approaches: ***Human guidance*** *in generation of behaviors*

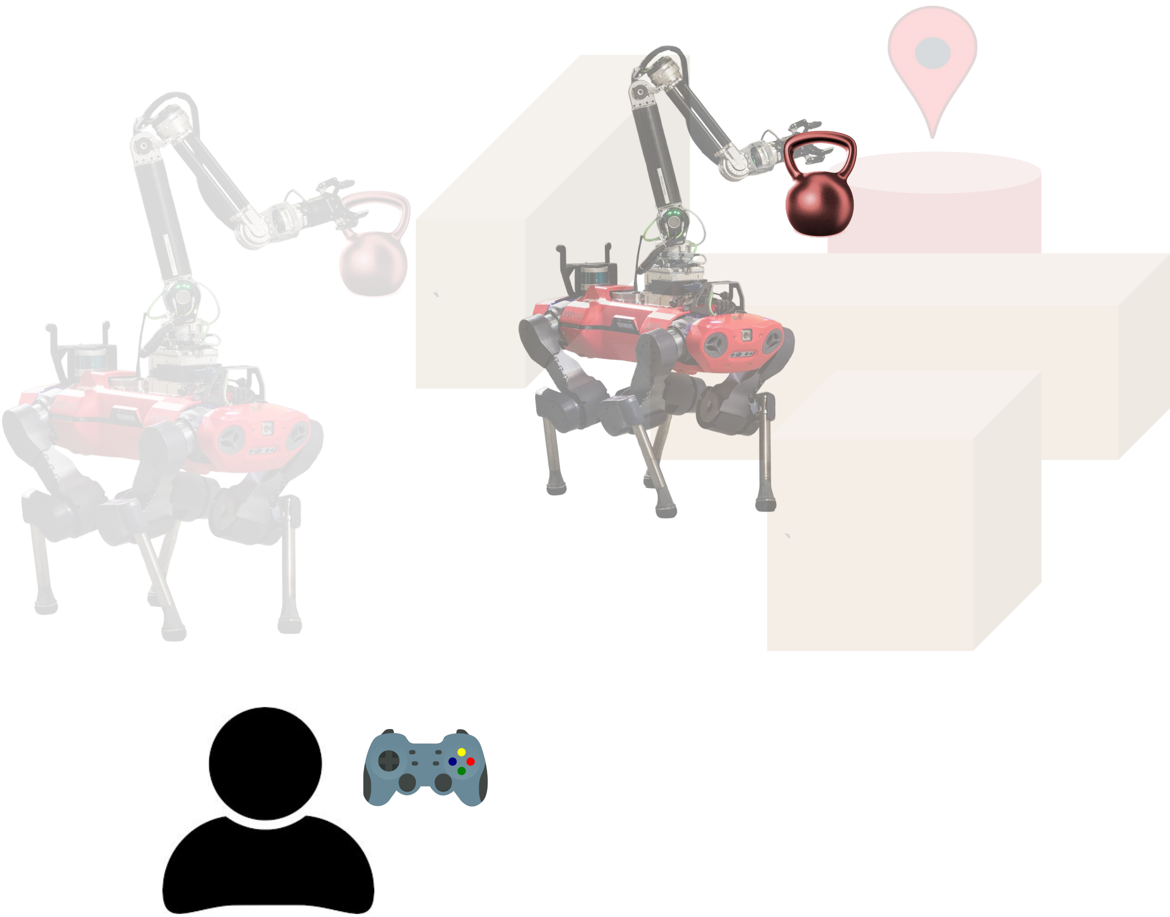


Term	Expression
Projected Ball Velocity	$\exp\{-\delta_v \|\mathbf{v}_b - \mathbf{v}_{\mathrm{cmd}}\|^2\}$
Robot Ball Distance	$\exp\{-\delta_p \|\mathbf{p}_{\mathrm{b}} - \mathbf{p}_{\mathrm{FRHip}}\|^2\}$
Yaw Alignment	$\exp\{-\delta_\psi (e^2_{\mathrm{rbcmd}} + e^2_{\mathrm{rbbase}})\}$
Ball Velocity Norm	$\exp\{-\delta_n (\|v_{\mathrm{cmd}}\| - \|v_b\|)^2\}$
Ball Velocity Angle	$1 - (\psi_b - \psi_{\mathrm{cmd}})^2 / \pi^2$
Swing Phase Schedule	$[1 - \mathbf{C}^{\mathrm{cmd}}_{\mathrm{foot}}(\boldsymbol{\theta}^{\mathrm{cmd}}, t)]\exp\{-\delta_{\mathrm{cf}} \|\mathbf{f}^{\mathrm{foot}}\|^2\}$
Stance Phase Schedule	$[\mathbf{C}^{\mathrm{cmd}}_{\mathrm{foot}}(\boldsymbol{\theta}^{\mathrm{cmd}}, t)]\exp\{-\delta_{\mathrm{cv}} \|\mathbf{v}^{\mathrm{foot}}_{\mathrm{xy}}\|^2\}$

"Reward terms for the soccer dribbling task."

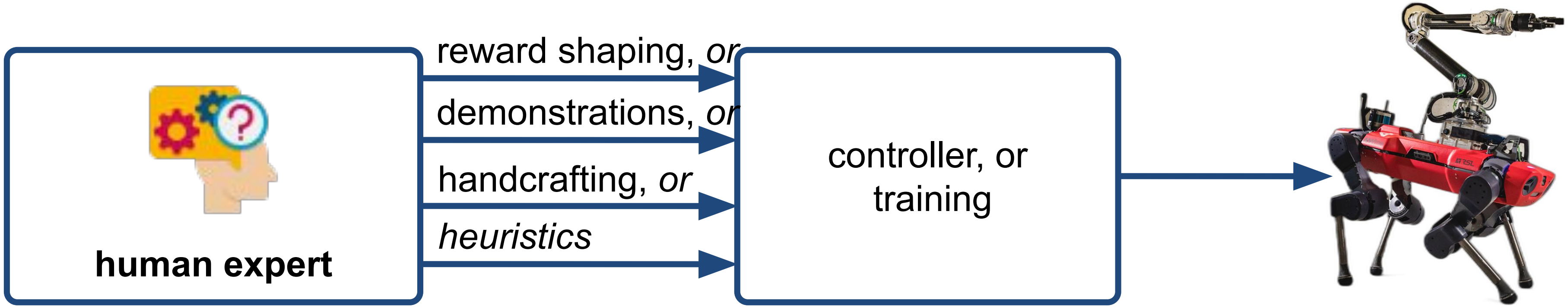
Source: Reinforcement Learning for Quadrupedal Dribbling in the Wild

Current approaches: ***Human guidance*** *in generation of behaviors*



Source: Learning Model Predictive Controllers with Real-Time Attention for Real-World Navigation

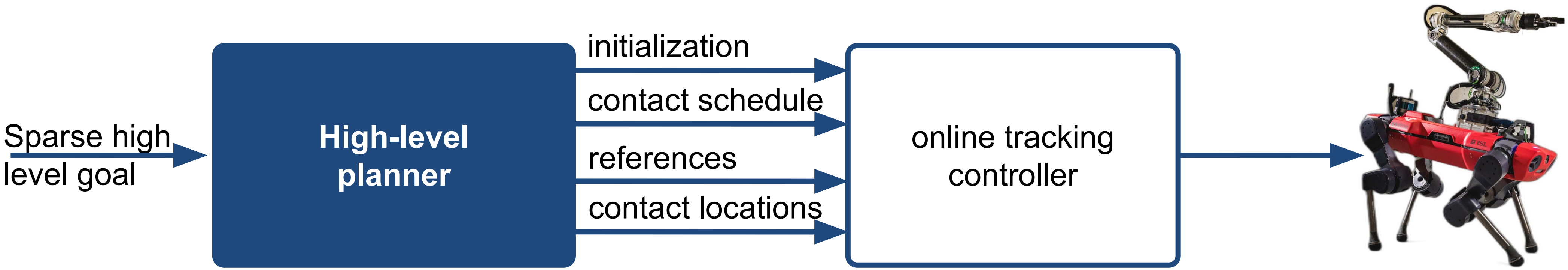
What’s currently done



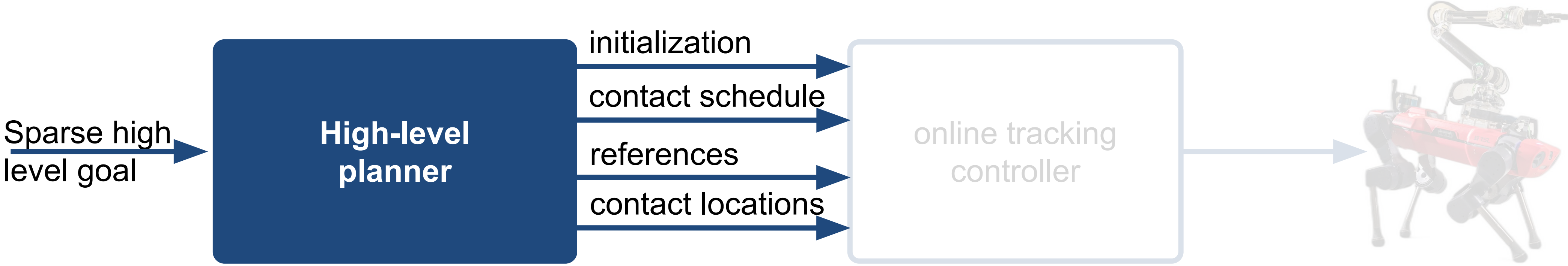
What’s currently done

task-specific, costly and compromises performance.

What we need


Sparse high level goal
High-level planner
initialization
contact schedule
references
contact locations
online tracking controller

What we need



Goal: **Automate** the generation of the motion through **contact-implicit** trajectory optimization (CITO) with **minimal**, **high-level guidance**

Method selection

Framework requirements

- ❏ Minimal guidance/ task-agnostic
- ❏ Contact-implicit
- ❏ Physical feasibility
- ❏ Realizable on hardware
- ❏ Numerically stable
- ❏ Scales to multi-contact, long horizon tasks

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Existing contact-implicit methods

- Combinatorial approaches [1]
- Hybrid dynamics methods
- Smooth contact
- Hard contact (constrained optimization)

1. For example, mixed-integer formulations [5] presented promising results but require symmetry and periodicity restrictions and only tractable in 2D

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combinatorial mode explosion

physically incorrect

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Existing contact-implicit methods

- ~~Combinatorial approaches~~
- ~~Hybrid dynamics methods~~
- ~~Smooth contact~~
- **Hard contact (constrained optimization)**

Background: *Complementarity Constraints*

- Contact physics as constraints on the decision variables

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- Contact physics as constraints on the decision variables

- Separation

$$0 \leq f_i^N(\boldsymbol{u}(k)) \perp \phi_i(\boldsymbol{x}(k+1)) \geq 0$$

Background: *Complementarity Constraints*

- Contact physics as constraints on the decision variables

- **Separation**

$$0 \le \overbrace{f_i^N(\boldsymbol{u}(k))}^{\text{Unilateral force constraint}} \perp \overbrace{\phi_i(\boldsymbol{x}(k+1))}^{\text{Non-penetration constraint}} \ge 0$$

$$\underbrace{f_i^N(\boldsymbol{u}(k)) \perp \phi_i(\boldsymbol{x}(k+1))}_{\text{No force at a distance}}$$

Background: *Complementarity Constraints*

- Contact physics as constraints on the decision variables

- Separation

$$0 \leq f_i^N(\boldsymbol{u}(k)) \perp \phi_i(\boldsymbol{x}(k+1)) \geq 0$$

- **Sliding**

$$0 \leq f_i^N(\boldsymbol{u}(k)) \perp \boldsymbol{v}_i^T(\boldsymbol{x}(k+1))$$

Background: *Complementarity Constraints*

- Contact physics as constraints on the decision variables

- Separation

$$0 \leq f_i^N(\boldsymbol{u}(k)) \perp \phi_i(\boldsymbol{x}(k+1)) \geq 0$$

- **Sliding**

$$0 \leq f_i^N \underbrace{(\boldsymbol{u}(k)) \perp \boldsymbol{v}_i^T(\boldsymbol{x}(k+1))}_{\text{No force when non-zero tangential velocity}}$$

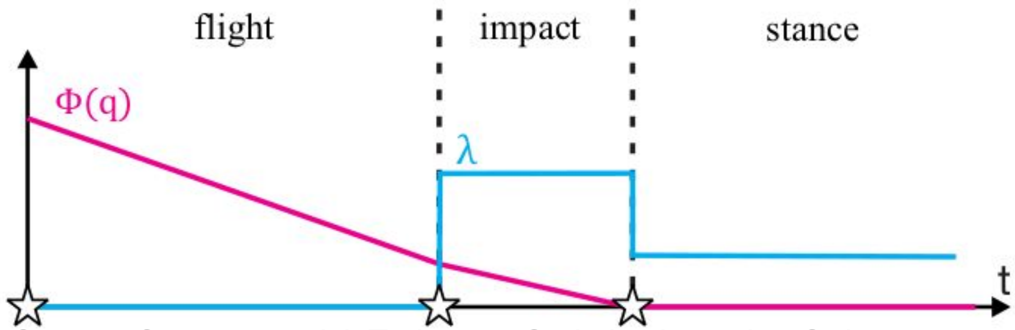
Background: *Time-stepping integration scheme* [1]

- Note the indexing:

$$0 \leq f_i^N(\boldsymbol{u}(k)) \perp \phi_i(\boldsymbol{x}(k+1)) \geq 0$$

$$0 \leq f_i^N(\boldsymbol{u}(k)) \perp \boldsymbol{v}_i^T(\boldsymbol{x}(k+1))$$

- Contact impulse can be non-zero if and only if there is contact at the end of the interval [2]
- Contact impulses appear as average contact forces over time interval



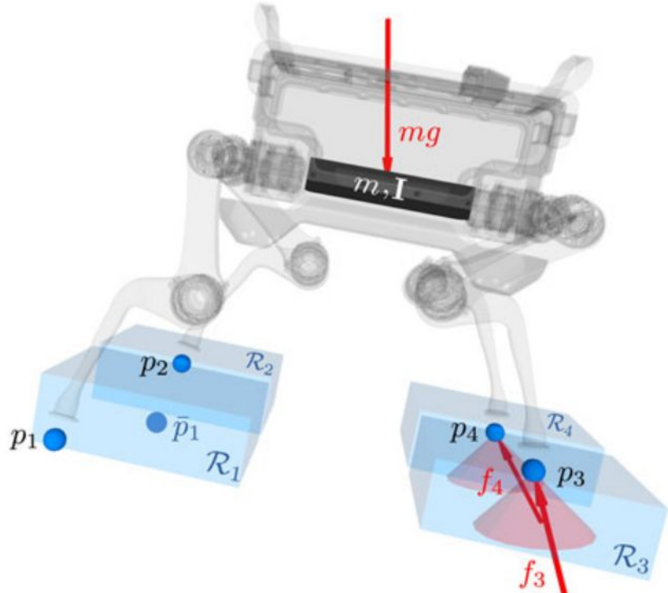
Source: Contact-Implicit Trajectory Optimization using Orthogonal Collocation

1. D. Stewart, J. C. Trinkle. "An implicit time-stepping scheme for rigid body dynamics with coulomb friction."
2. Posa, Michael Michael Antonio. Optimization for control and planning of multi-contact dynamic motion. Diss. Massachusetts Institute of Technology, 2017.

Single Rigid Body (SRB) model

$$
\boldsymbol{x} = \begin{bmatrix} \boldsymbol{c} \\ \theta_{yaw} \\ \theta_{pitch} \\ \theta_{roll} \\ \dot{\boldsymbol{c}} \\ \boldsymbol{\omega} \\ \boldsymbol{r}_1 \\ \vdots \\ \boldsymbol{r}_{n_c} \\ \dot{\boldsymbol{r}}_1 \\ \vdots \\ \dot{\boldsymbol{r}}_{n_c} \end{bmatrix} \qquad \boldsymbol{u} = \begin{bmatrix} \boldsymbol{f}_1 \\ \vdots \\ \boldsymbol{f}_{n_c} \\ \ddot{\boldsymbol{r}}_1 \\ \vdots \\ \ddot{\boldsymbol{r}}_{n_c} \end{bmatrix}
$$

$$i = 1 \dots n_c \qquad k = 0 \dots N$$



Source: Gait and Trajectory Optimization for Legged Systems Through Phase-Based End-Effector Parameterization [8]

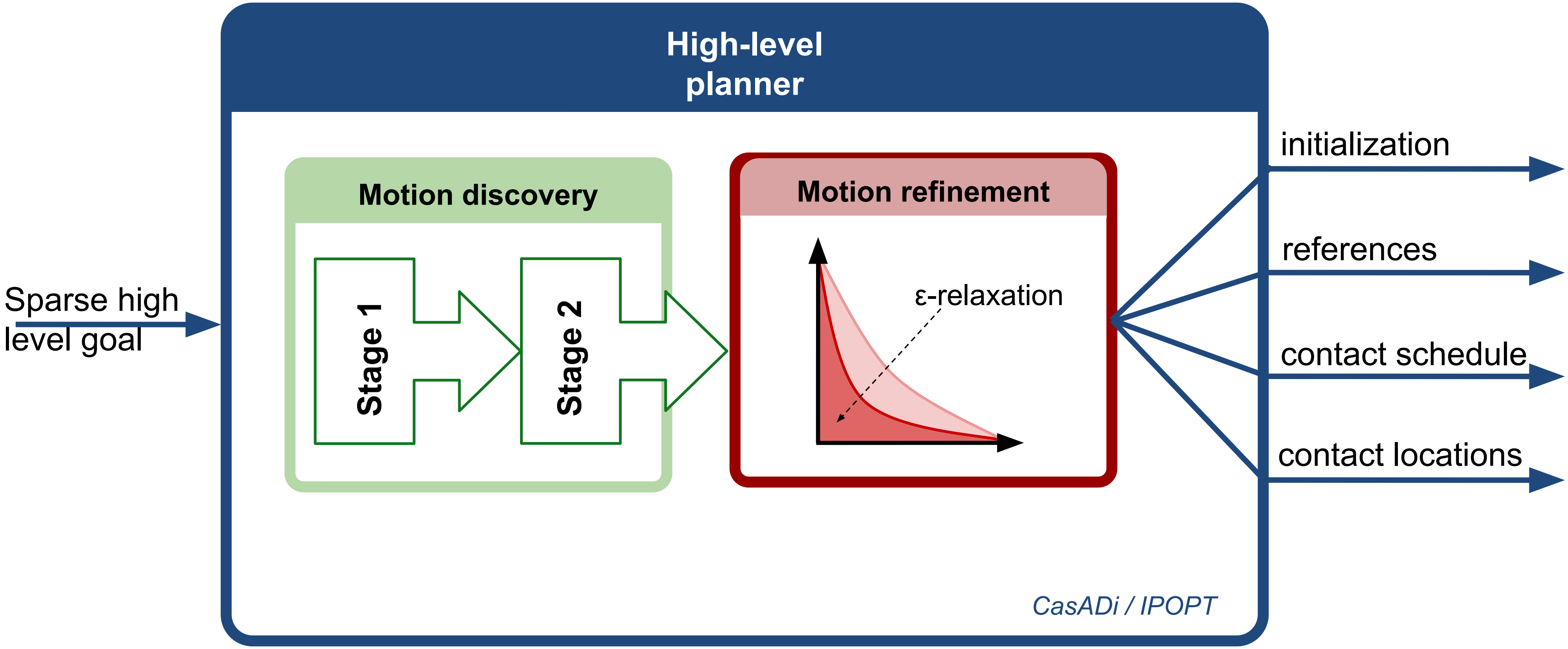
$$\dot{\boldsymbol{\theta}} = \boldsymbol{T}(\boldsymbol{\theta})\, \boldsymbol{\omega}$$

$$\dot{\boldsymbol{\omega}} = \boldsymbol{I}_{\mathcal{W}}^{-1}(\boldsymbol{\theta})\, \left(\sum_{i=1}^{n_c} \boldsymbol{f}_i \times (\boldsymbol{r}_i - \boldsymbol{c}) - \boldsymbol{\omega} \times \boldsymbol{I}_{\mathcal{W}}(\boldsymbol{\theta})\, \boldsymbol{\omega}\right)$$

$$\ddot{\mathbf{c}} = \sum_{i=1}^{n_c} \frac{\boldsymbol{f}_i}{m} + \boldsymbol{g}$$

where $\boldsymbol{I}_{\mathcal{W}}(\boldsymbol{\theta}) = {}_{\mathcal{W}}\boldsymbol{R}_{\mathcal{B}}(\boldsymbol{\theta})\, \boldsymbol{I}_{\mathcal{B}}\, {}_{\mathcal{W}}\boldsymbol{R}_{\mathcal{B}}(\boldsymbol{\theta})^T$

Framework


Sparse high
level goal
High-level
planner
Motion discovery
Stage 1
Stage 2
Motion refinement
ε-relaxation
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initialization
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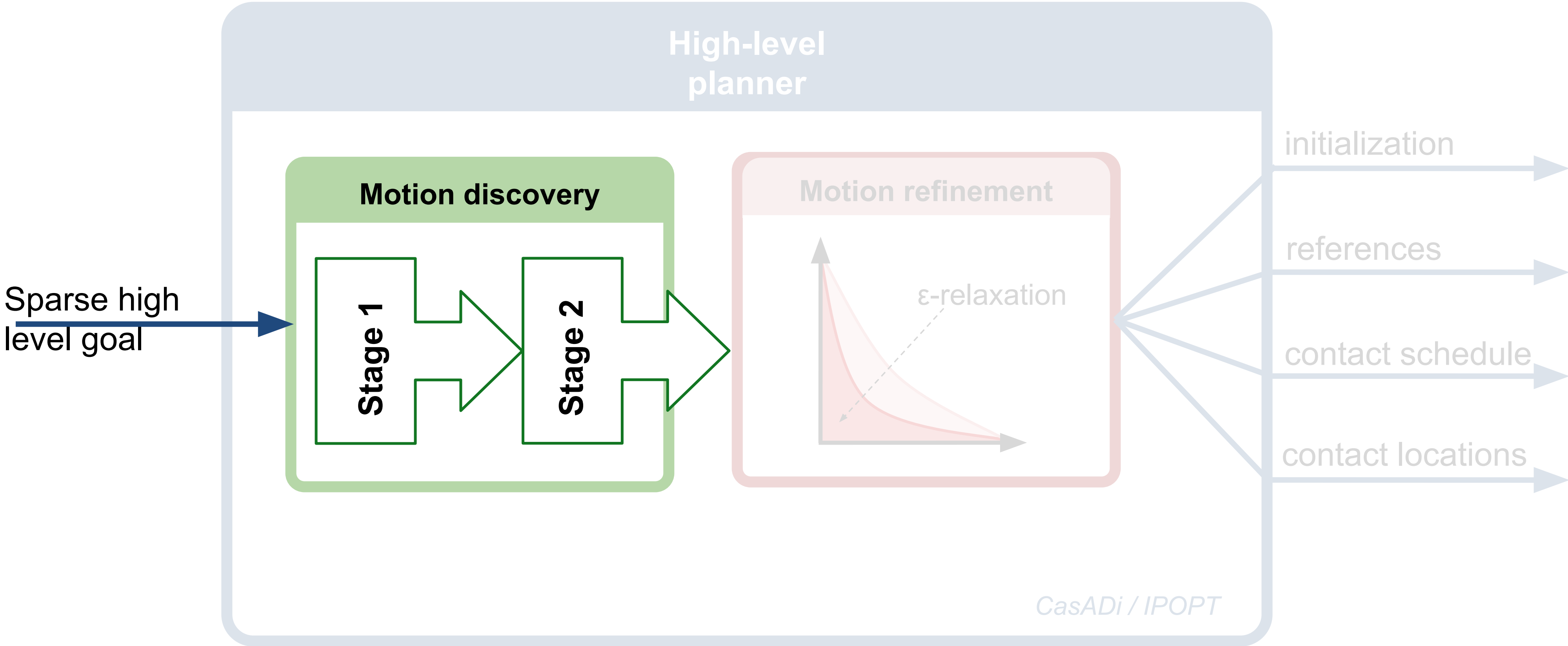
contact locations

Framework



High-level planner
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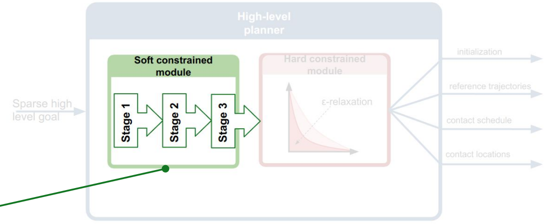
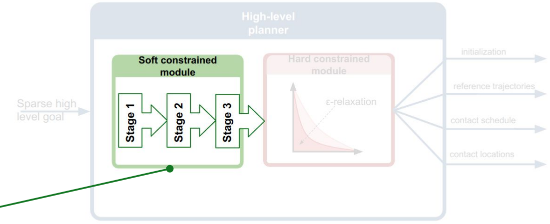


$$
\begin{aligned}
\min_{X,U} \quad & ||\boldsymbol{x}(N) - \boldsymbol{x}_{ref}(N)||^2_{Q_f} + \sum_{k=0}^{N-1} ||\boldsymbol{x}(k) - \boldsymbol{x}_{ref}(k)||^2_Q + ||\boldsymbol{u}(k)||^2_R \\
& + w_{CIO} \sum_{i=1}^{n_c} g(f_i^N(\boldsymbol{u}(k))) \left(\phi_i(\boldsymbol{x}(k+1))^2 + ||\boldsymbol{v}_i^T(\boldsymbol{x}(k+1))||_2^2\right) \\
\text{s.t.} \quad & \boldsymbol{x}(k+1) = f(\boldsymbol{x}(k), \boldsymbol{u}(k)) \\
& x(0) = x_0 \\
& \boldsymbol{x}(k) \in \Psi(\boldsymbol{x}(k)) \\
& ||\boldsymbol{f}_i^T(\boldsymbol{u}(k))||_\infty \leq \mu\, f_i^N(\boldsymbol{u}(k)) \\
& 0 \leq f_i^N(\boldsymbol{u}(k)) \leq f_{N,limit} \\
& 0 \leq \phi_i(\boldsymbol{x}(k)) \\
& \boldsymbol{A}_{x_N} \boldsymbol{x}(N) = \boldsymbol{b}_{x_N}
\end{aligned}
$$

Analogous to work by I. Mordatch et al [3]

Motion discovery



$$\min_{X,U} \quad ||\boldsymbol{x}(N) - \boldsymbol{x}_{ref}(N)||^2_{Q_f} + \sum_{k=0}^{N-1} ||\boldsymbol{x}(k) - \boldsymbol{x}_{ref}(k)||^2_Q + ||\boldsymbol{u}(k)||^2_R$$

$$+ w_{CIO} \sum_{i=1}^{n_c} g(f_i^N(\boldsymbol{u}(k))) \left(\phi_i(\boldsymbol{x}(k+1))^2 + ||\boldsymbol{v}_i^T(\boldsymbol{x}(k+1))||_2^2\right)$$

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& A_{x_N} x(N) = b_{x_N}
\end{aligned}$$

Quadratic state input cost

Dynamics
Kinematic (box) constraints
Friction pyramid
Initial condition
Non-penetration

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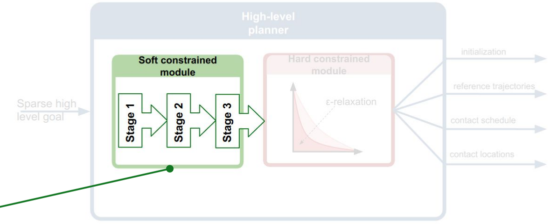
Motion discovery



$$
\begin{aligned}
\min_{X,U} \quad & ||\boldsymbol{x}(N) - \boldsymbol{x}_{ref}(N)||^2_{Q_f} + \sum_{k=0}^{N-1} ||\boldsymbol{x}(k) - \boldsymbol{x}_{ref}(k)||^2_Q + ||\boldsymbol{u}(k)||^2_R \\
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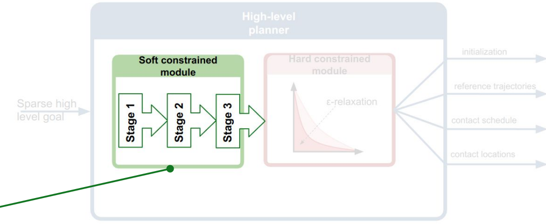
\end{aligned}
$$

Contact physics as a cost

Analogous to work by I. Mordatch et al [3]

Motion discovery



$$
\begin{aligned}
\min_{X,U} \quad & ||x(N) - x_{ref}(N)||^2_{Q_f} + \sum_{k=0}^{N-1} ||x(k) - x_{ref}(k)||^2_Q + ||u(k)||^2_R \\
& + w_{CIO} \sum_{i=1}^{n_c} g(f_i^N(u(k))) \left(\phi_i(x(k+1))^2 + ||v_i^T(x(k+1))||_2^2\right) \\
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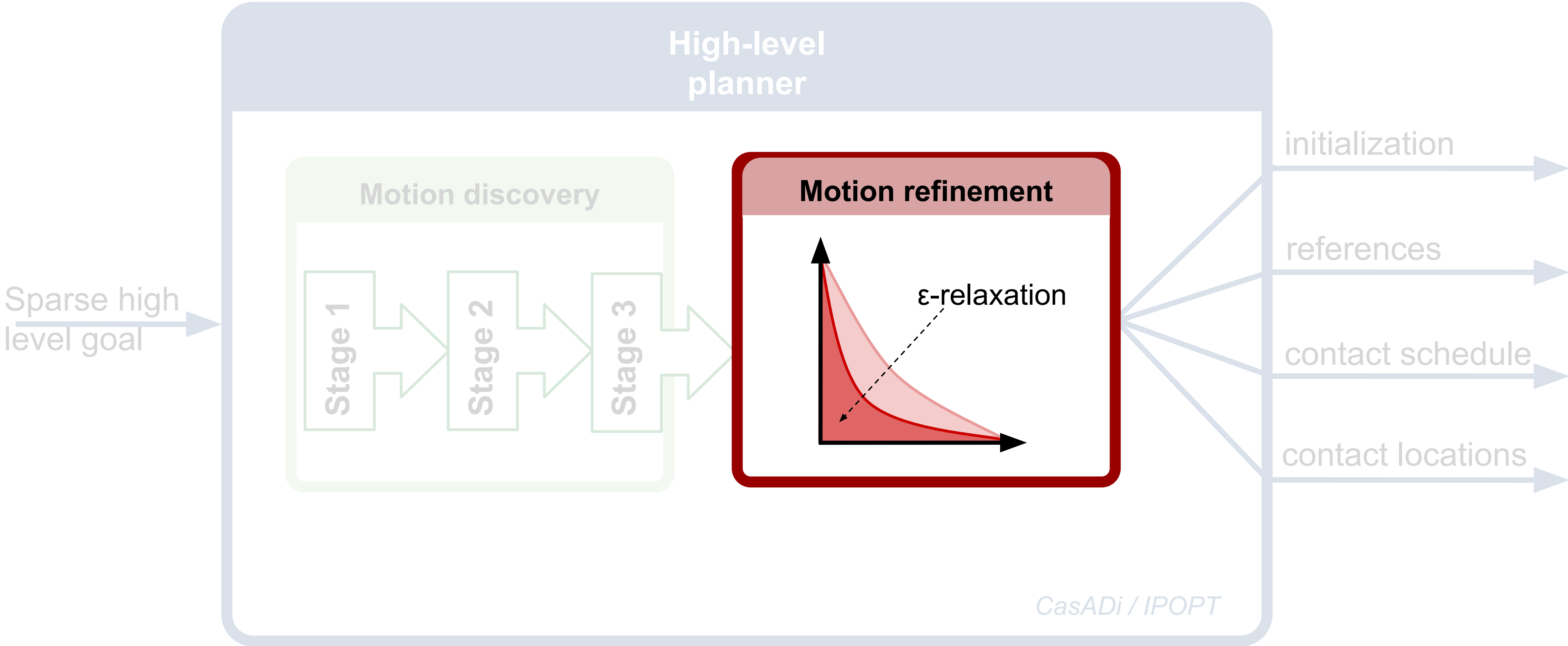
\end{aligned}
$$

Terminal constraint to encode task

Analogous to work by I. Mordatch et al [3]

Framework


High-level
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Motion refinement

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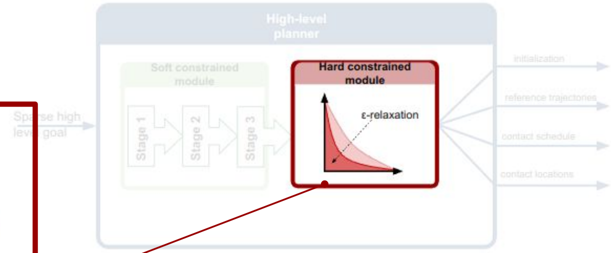
& 0 \leq \phi_i(\boldsymbol{x}(k+1)) \leq M_\phi \, (1 - \boldsymbol{z}_i(k)) \\
& ||\boldsymbol{v}_i^T(\boldsymbol{x}(k+1))||_\infty \leq M_v \, (1 - \boldsymbol{z}_i(k)) \\
& \boldsymbol{z}_i(k)^T \cdot \boldsymbol{z}_i(k) \leq \varepsilon \\
& \boldsymbol{z}(k) \in [0, 1] \\
& \boldsymbol{A}_{x_N} \boldsymbol{x}(N) = \boldsymbol{b}_{x_N}
\end{aligned}
$$



Analogous to work by M. Posa et al [1], [2]

Motion refinement

$$
\begin{aligned}
\min_{X,U,Z} \quad & \|\boldsymbol{x}(N) - \boldsymbol{x}_{ref}(N)\|^2_{Q_f} + \sum_{k=0}^{N-1} \|\boldsymbol{x}(k) - \boldsymbol{x}_{ref}(k)\|^2_Q + \|\boldsymbol{u}(k)\|^2_R \\
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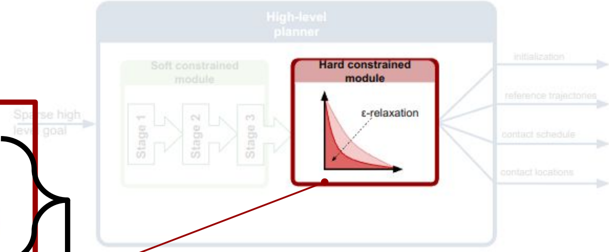
$$



Quadratic state input cost

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Initial condition
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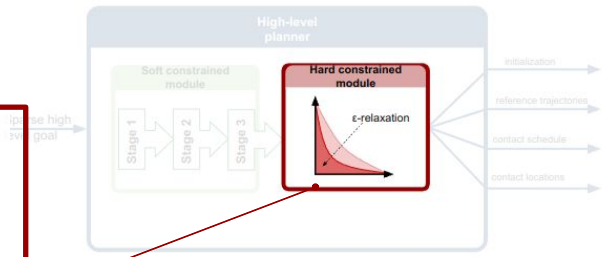
Motion refinement



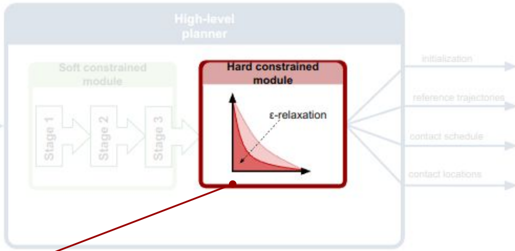
$$\min_{X,U,Z} \quad ||\boldsymbol{x}(N) - \boldsymbol{x}_{ref}(N)||^2_{Q_f} + \sum_{k=0}^{N-1} ||\boldsymbol{x}(k) - \boldsymbol{x}_{ref}(k)||^2_Q + ||\boldsymbol{u}(k)||^2_R$$

$$\begin{aligned}
\text{s.t.} \quad & \boldsymbol{x}(k+1) = f(\boldsymbol{x}(k), \boldsymbol{u}(k)) \\
& x(0) = x_0 \\
& \boldsymbol{x}(k) \in \Psi(\boldsymbol{x}(k)) \\
& ||\boldsymbol{f}_i^T(\boldsymbol{u}(k))||_\infty \leq \mu \, f_i^N(\boldsymbol{u}(k)) \\
& \left.\begin{aligned}
& 0 \leq f_i^N(\boldsymbol{u}(k)) \leq M_f \, \boldsymbol{z}_i(k) \\
& 0 \leq \phi_i(\boldsymbol{x}(k+1)) \leq M_\phi \, (1 - \boldsymbol{z}_i(k)) \\
& ||\boldsymbol{v}_i^T(\boldsymbol{x}(k+1))||_\infty \leq M_v \, (1 - \boldsymbol{z}_i(k))
\end{aligned}\right\} \\
& \boldsymbol{z}_i(k)^T \cdot \boldsymbol{z}_i(k) \leq \varepsilon \\
& \boldsymbol{z}(k) \in [0, 1] \\
& \boldsymbol{A}_{x_N} \boldsymbol{x}(N) = \boldsymbol{b}_{x_N}
\end{aligned}$$

Big-M formulation for complementarity constraints

Motion refinement

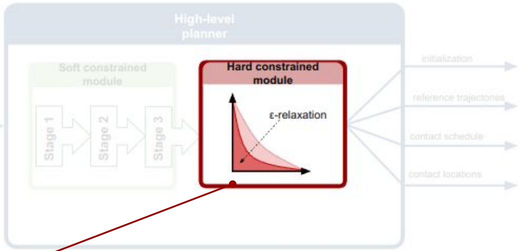
$$
\begin{aligned}
\min_{X,U,Z} \quad & ||\boldsymbol{x}(N) - \boldsymbol{x}_{ref}(N)||^2_{Q_f} + \sum_{k=0}^{N-1} ||\boldsymbol{x}(k) - \boldsymbol{x}_{ref}(k)||^2_{Q} + ||\boldsymbol{u}(k)||^2_{R} \\
\text{s.t.} \quad & \boldsymbol{x}(k+1) = f(\boldsymbol{x}(k), \boldsymbol{u}(k)) \\
& x(0) = x_0 \\
& \boldsymbol{x}(k) \in \Psi(\boldsymbol{x}(k)) \\
& ||\boldsymbol{f}_i^T(\boldsymbol{u}(k))||_\infty \leq \mu \, f_i^N(\boldsymbol{u}(k)) \\
& 0 \leq f_i^N(\boldsymbol{u}(k)) \leq M_f \, \boldsymbol{z}_i(k) \\
& 0 \leq \phi_i(\boldsymbol{x}(k+1)) \leq M_\phi \, (1 - \boldsymbol{z}_i(k)) \\
& ||\boldsymbol{v}_i^T(\boldsymbol{x}(k+1))||_\infty \leq M_v \, (1 - \boldsymbol{z}_i(k)) \\
& \left.\begin{aligned} & \boldsymbol{z}_i(k)^T \cdot \boldsymbol{z}_i(k) \leq \varepsilon \\ & \boldsymbol{z}(k) \in [0, 1] \end{aligned}\right\} \\
& \boldsymbol{A}_{x_N} \boldsymbol{x}(N) = \boldsymbol{b}_{x_N}
\end{aligned}
$$



Relaxed orthogonality constraint on relaxed integer variables

Analogous to work by M. Posa et al [1], [2]

Motion refinement

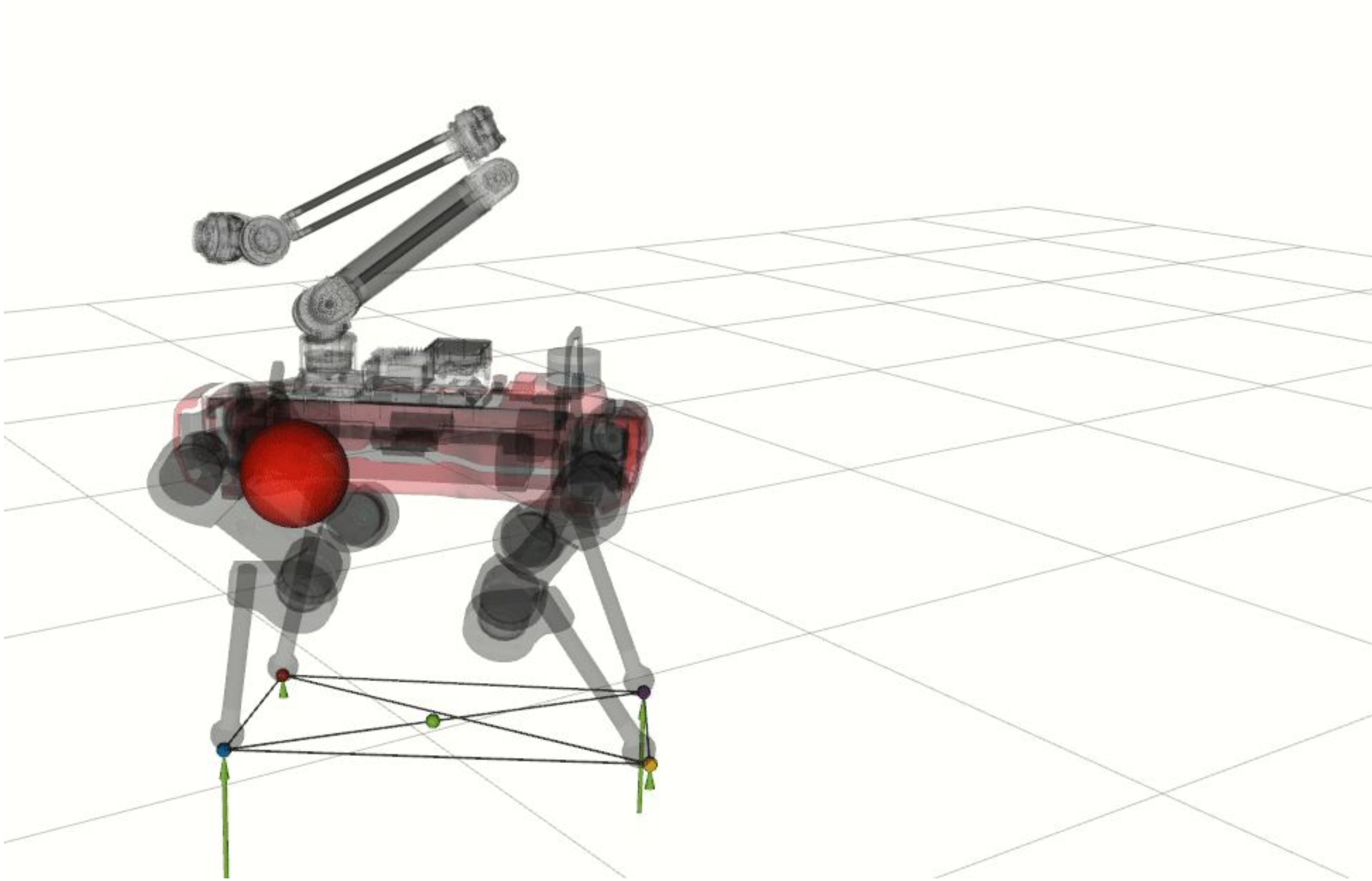


$$
\begin{aligned}
\min_{X,U,Z} \quad & ||\boldsymbol{x}(N) - \boldsymbol{x}_{ref}(N)||^2_{Q_f} + \sum_{k=0}^{N-1} ||\boldsymbol{x}(k) - \boldsymbol{x}_{ref}(k)||^2_Q + ||\boldsymbol{u}(k)||^2_R \\
\text{s.t.} \quad & \boldsymbol{x}(k+1) = f(\boldsymbol{x}(k), \boldsymbol{u}(k)) \\
& x(0) = x_0 \\
& \boldsymbol{x}(k) \in \Psi(\boldsymbol{x}(k)) \\
& ||\boldsymbol{f}_i^T(\boldsymbol{u}(k))||_\infty \leq \mu\, f_i^N(\boldsymbol{u}(k)) \\
& 0 \leq f_i^N(\boldsymbol{u}(k)) \leq M_f\, \boldsymbol{z}_i(k) \\
& 0 \leq \phi_i(\boldsymbol{x}(k+1)) \leq M_\phi\, (1 - \boldsymbol{z}_i(k)) \\
& ||\boldsymbol{v}_i^T(\boldsymbol{x}(k+1))||_\infty \leq M_v\, (1 - \boldsymbol{z}_i(k)) \\
& \boldsymbol{z}_i(k)^T \cdot \boldsymbol{z}_i(k) \leq \varepsilon \\
& \boldsymbol{z}(k) \in [0, 1] \\
& \boldsymbol{A}_{x_N} \boldsymbol{x}(N) = \boldsymbol{b}_{x_N}
\end{aligned}
$$

Terminal constraint (encodes task)

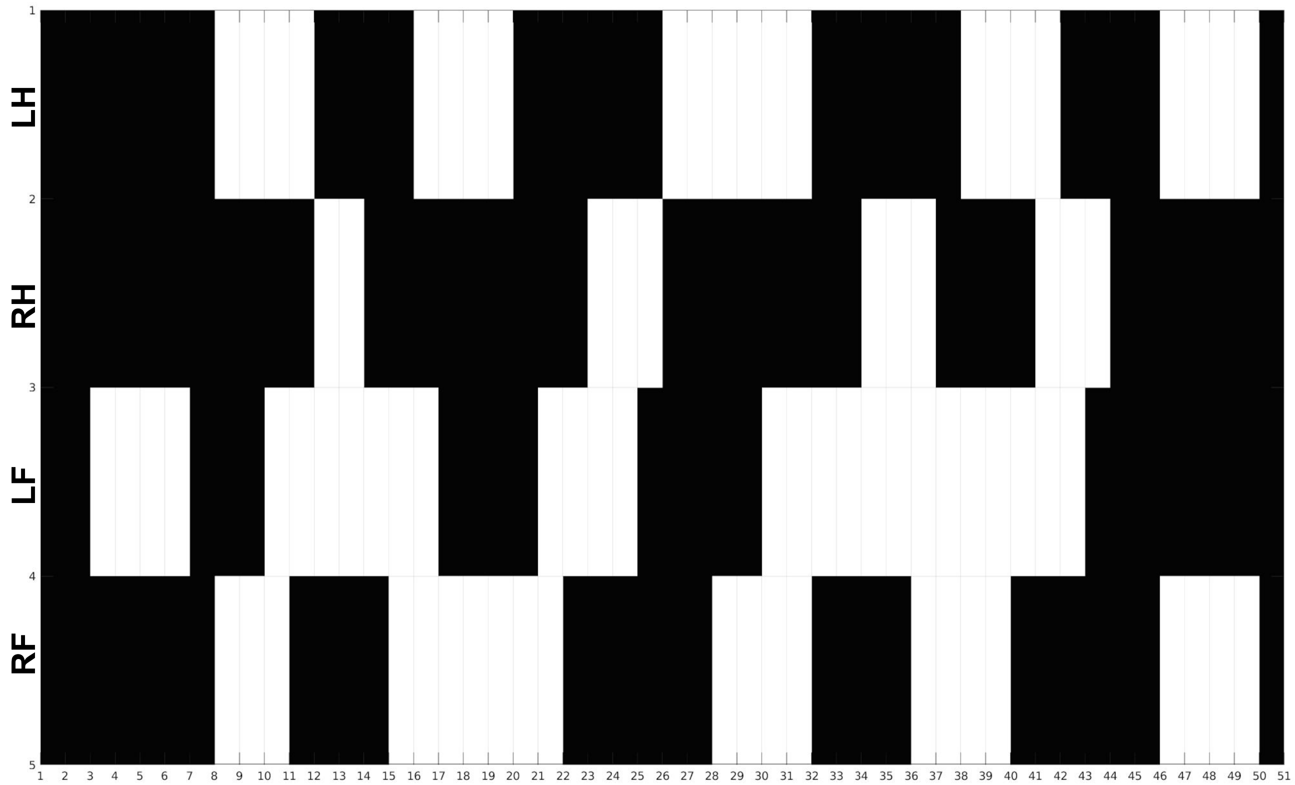
Analogous to work by M. Posa et al [1], [2]

Combined local navigation and locomotion



Motion refinement:

- **Direct handle on contact modes**
- For example:
  - ≥2 feet in contact
  - Penalize fast contact switches
  - Initial and final modes

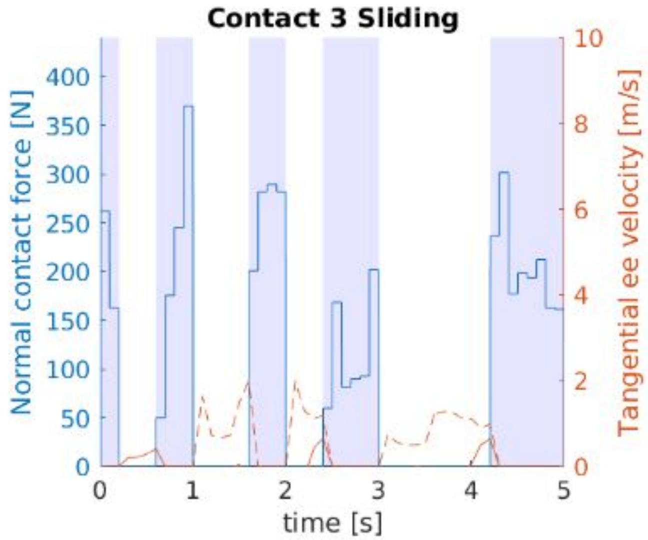


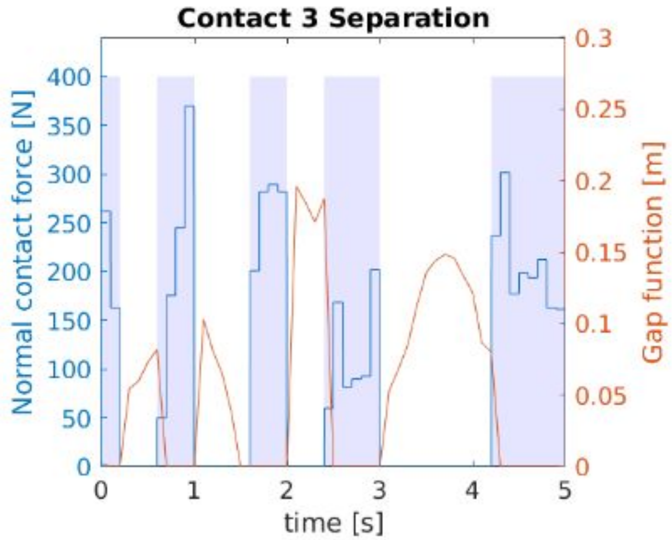
Modifications made to contact modes in motion refinement module*

* For visualization purposes. The contact modes are not explicitly encoded in the solution of the motion discovery module, but obtained through a projection operation.

Physical feasibility

- Strict feasibility of contact physics



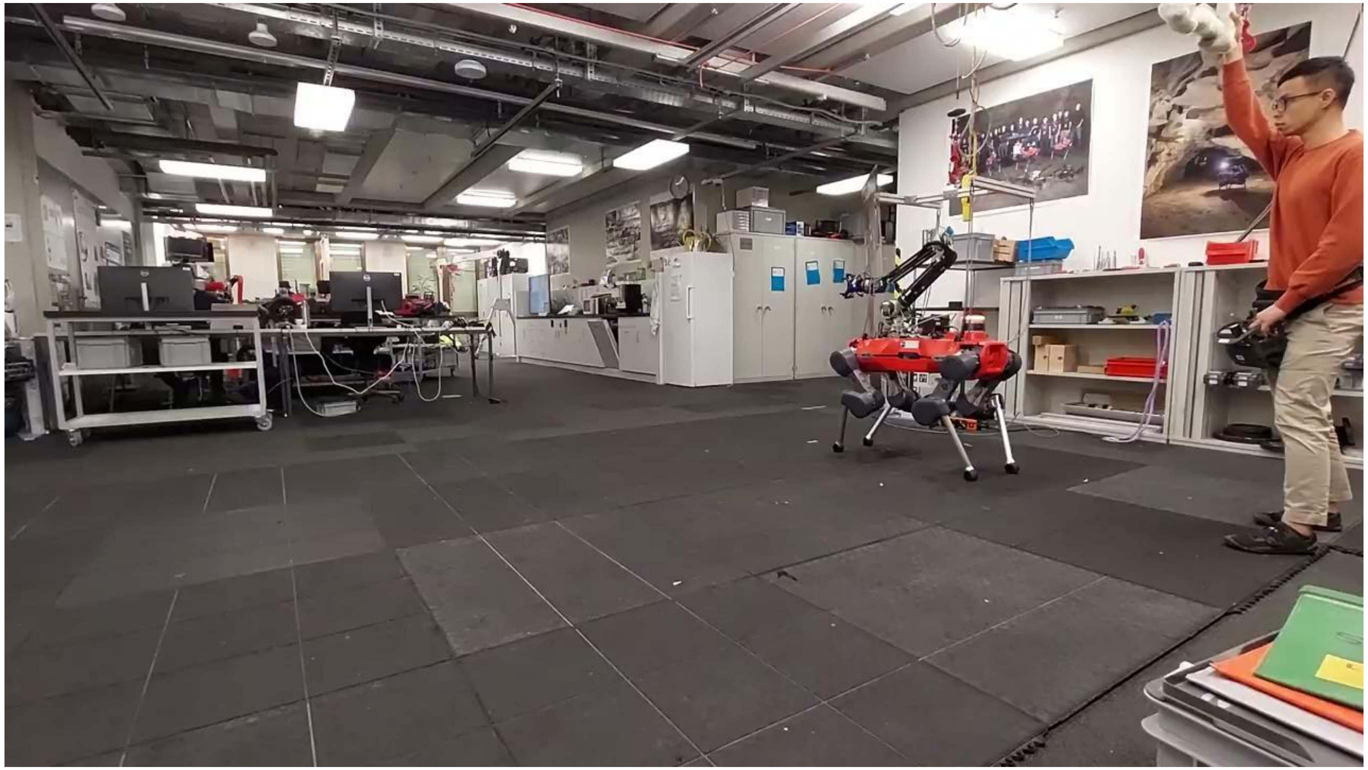


Legend
Stance Swing

- Validated results in Gazebo

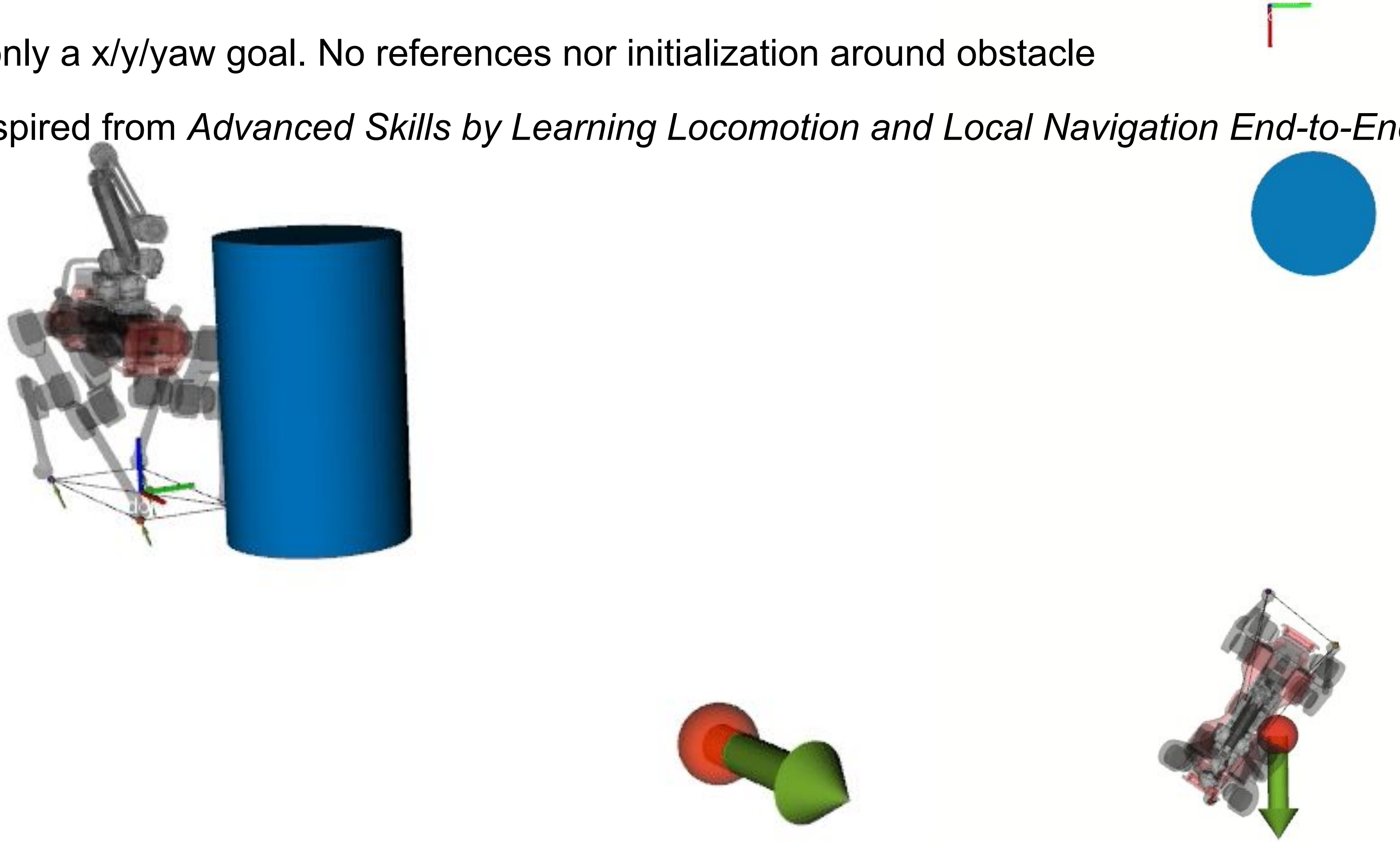
Physical feasibility

- Online tracking controller after polishing
- Validated results on hardware



Local navigation and locomotion

- Given only a x/y/yaw goal. No references nor initialization around obstacle
- Task inspired from *Advanced Skills by Learning Locomotion and Local Navigation End-to-End* [9]



Limitations

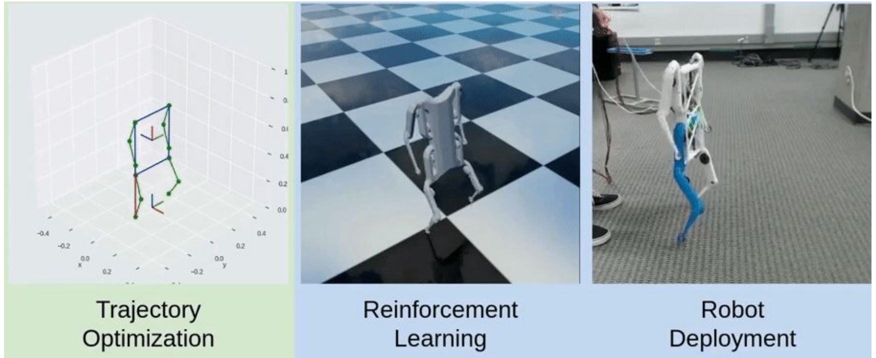
- Fast contact switches still possible to occur
- Computational time
- **Failure** in presence of **fast contact switches and dynamism** in generated references
    - Replace model-based tracking controller with **learning based controller**

Key takeaways

- **Smooth contact models work well for motion discovery**
  - Do not act directly based on that solution: continuation method/stagewise training/ or references
- **Splines** drastically reduce search space and improve computational efficiency
  - Do not use them directly for variables that exhibit discontinuity
- **Right level, right space**
  - High level contact-implicit planner: Cartesian space SRBD model
  - Low level: joint space

Future work

- **Imitation of generated references using RL**
- Extend to **loco-manipulation tasks**
  - Dynamic throw of heavy object
- Contact-implicit MPC
  - Learn mode scheduler offline (supervised learning)
- Reduce computational cost
  - C++ implementation or code generation



Source: OPT-Mimic: Imitation of Optimized Trajectories for Dynamic Quadruped Behaviors [10]

Questions?

References

[1] Posa, Michael, Cecilia Cantu, and Russ Tedrake. "A direct method for trajectory optimization of rigid bodies through contact."

[2] Stewart, David, and Jeffrey C. Trinkle. "An implicit time-stepping scheme for rigid body dynamics with coulomb friction."

[3] Mordatch, Igor, Emanuel Todorov, and Zoran Popović. "Discovery of complex behaviors through contact-invariant optimization."

[4] Aydinoglu, Alp, and Michael Posa. "Real-time multi-contact model predictive control via admm."

[5] Valenzuela, Andrés Klee. Mixed-integer convex optimization for planning aggressive motions of legged robots over rough terrain.

[6] Park, Hae-Won, Patrick M. Wensing, and Sangbae Kim. "Jumping over obstacles with MIT Cheetah 2."

[7] Atlas Gets a Grip | Boston Dynamics. (n.d.). Retrieved from https://www.youtube.com/watch?v=-e1_QhJ1EhQ.

[8] Winkler, Alexander W., et al. "Gait and trajectory optimization for legged systems through phase-based end-effector parameterization."

[9] Rudin, Nikita, et al. "Advanced Skills by Learning Locomotion and Local Navigation End-to-End."

[10] Fuchioka, Yuni, Zhaoming Xie, and Michiel van de Panne. "OPT-Mimic: Imitation of Optimized Trajectories for Dynamic Quadruped Behaviors."