Ballistic Motion Planning

20184612 Ian Libao

Overview

- Motivation
- ***Paper 1: Ballistic Motion Planning***
- ***Paper 2: Single Leg Dynamic Motion Planning with Mixed-Integer Convex Optimization***
- Summary
- Quiz

Motivation

- Jumping motion introduces new shortcuts
  - Instead of going around an obstacle block, why not jump over it?
- Unreachable locations can become reachable
- This would increase complexity for the path planning algorithm

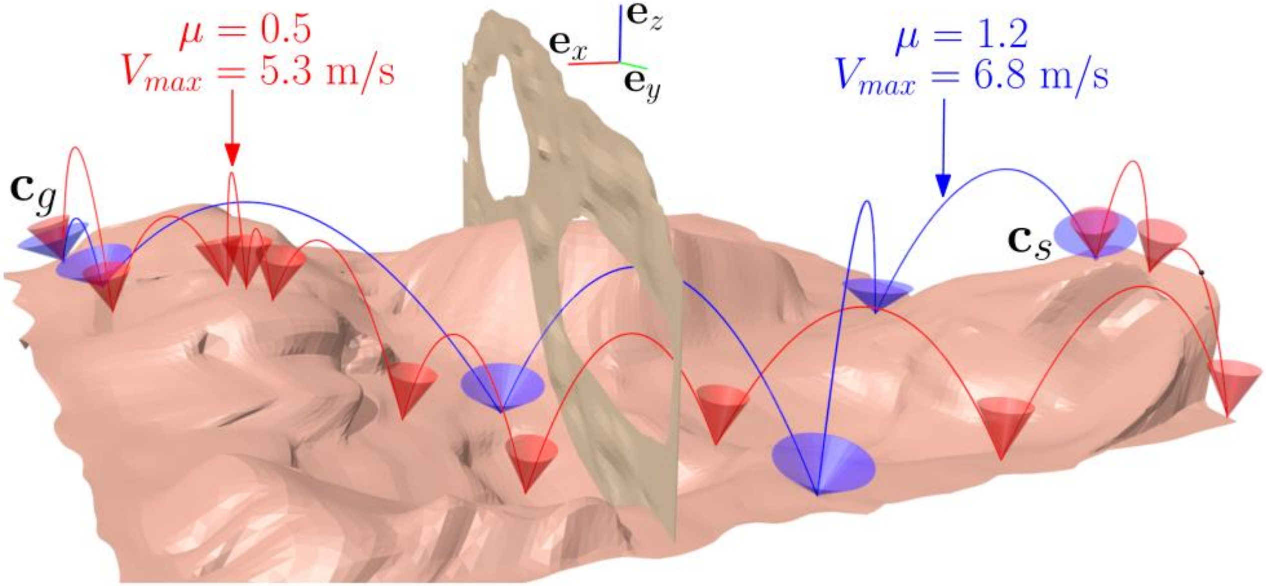
Paper 1: Ballistic Motion Planning

Mylene Campana | Jean-Paul Laumond

IROS 2016

Key Features

- Developed a motion planning algorithm for **jumping point robot** in arbitrary environment considering **slipping and velocity** constraints



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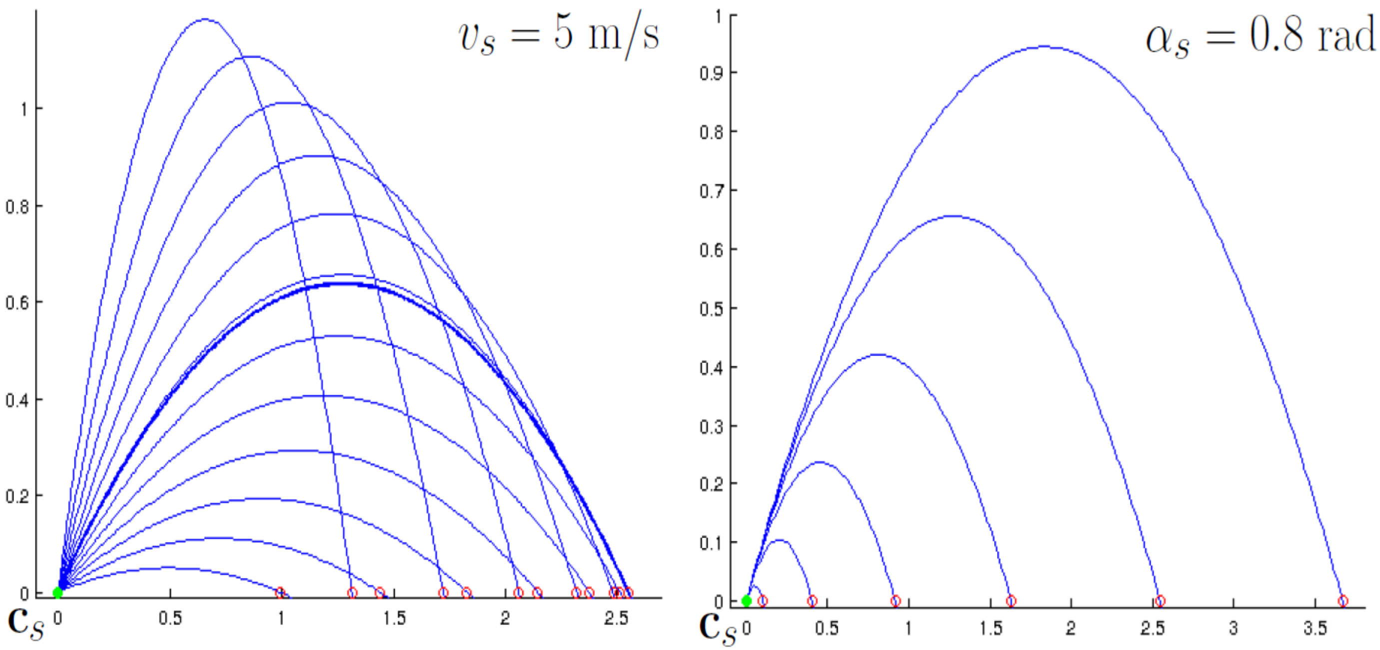
Accessible Space

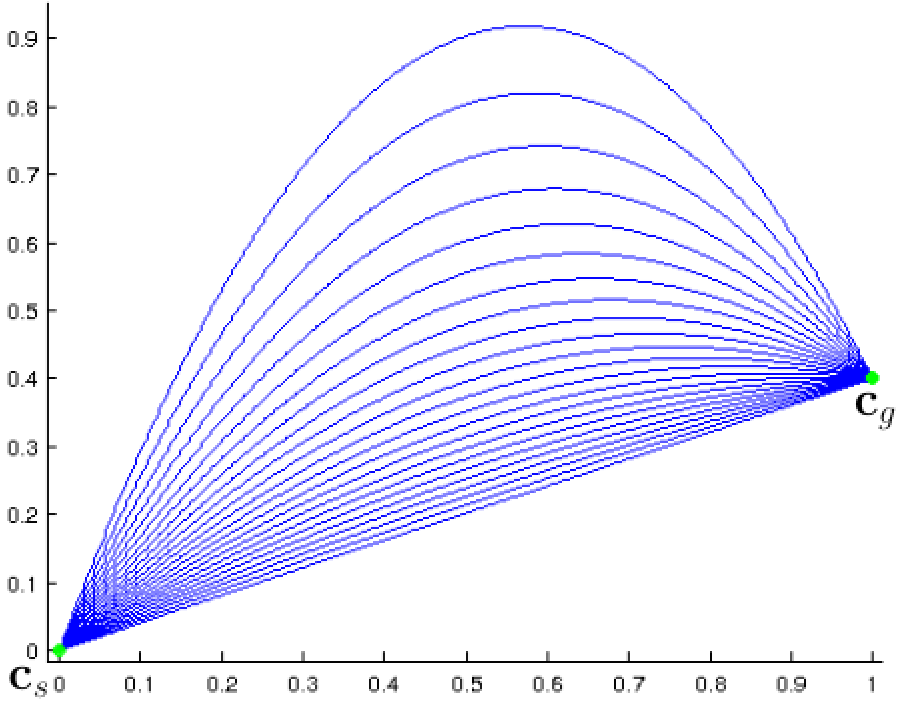
- Parabola trajectory is determined by **takeoff angle** and **initial velocity**

$$\mathbf{c}(t) = -\frac{g}{2}\,t^2\,\mathbf{e}_z + \dot{\mathbf{c}}_s\,t + \mathbf{c}_s$$



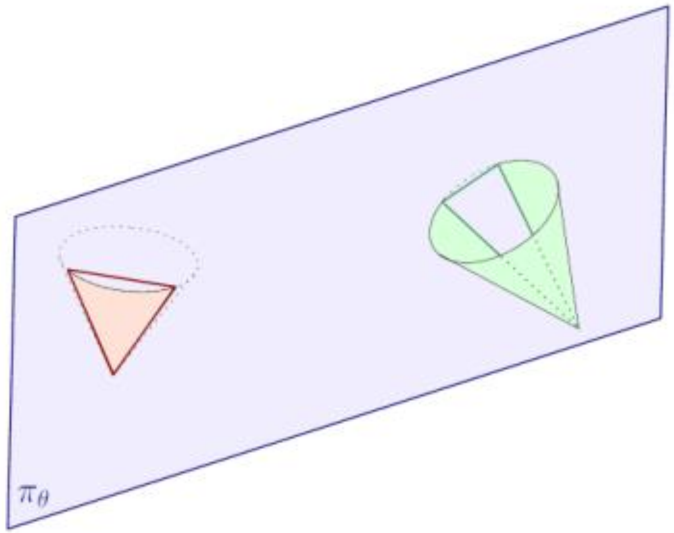
Goal Oriented Ballistic Motion

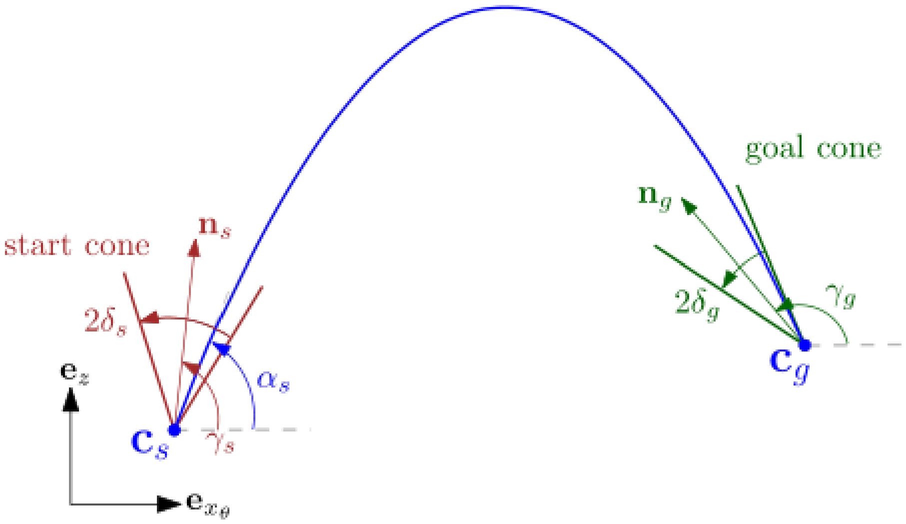
- **Physically-feasible parabolas** linking cs and cg with varying takeoff angles



Non-sliding Constraints

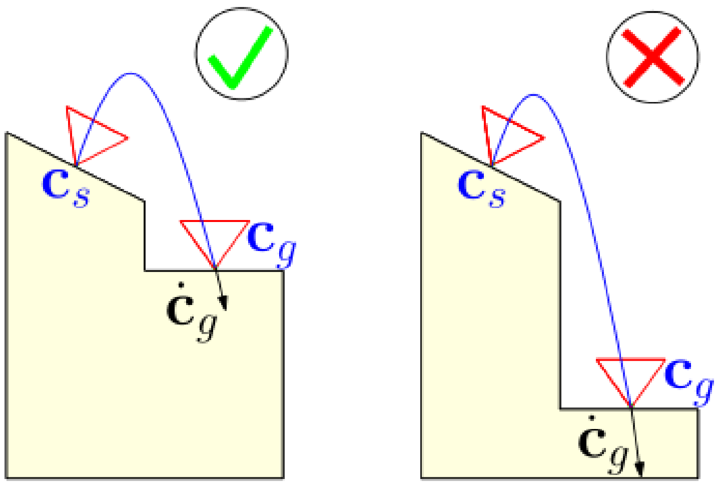
- Intersection between parabola plane and friction cones

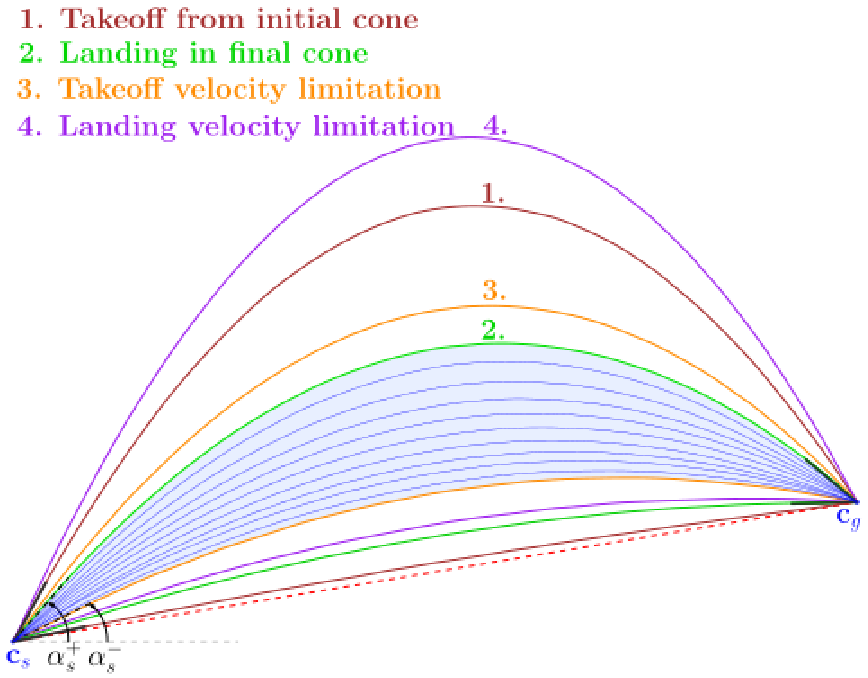




Velocity Constraints

- $v_s \leq V_{max}$
- $\begin{cases} \alpha_3^- = (V_{max}^2 - \sqrt{\Delta})/gX_\theta \\ \alpha_3^+ = (V_{max}^2 + \sqrt{\Delta})/gX_\theta \end{cases}$





Motion Planning

- Probabilistic Roadmap Planner
  - Build Roadmap
  - Link nodes with Steer algorithm
  - Over when start and goal position are connected
- Steer Algorithm
  - Selection of takeoff angle
- Beam Algorithm
  - Computes all possible parabola paths
  - Outputs range of permissible angles

Results

- **https://www.youtube.com/watch?v=vv_K7HqANmk&feature=youtu.be**

Strengths and Limitations

- Small computational cost
- Arbitrary environment

- Point robot representation limitation
  - No stance dynamics
- Frictionless Jumps

Paper 2: Single Leg Dynamic Motion Planning with Mixed-Integer Convex Optimization

Yanran Ding | Chuanzheng Li | Hae-Won Park

IROS 2018

Key Features

- Used **mixed-integer convex programming** formulation for dynamic motion planning
- Capable of planning consecutive jumps through challenging terrains

Phases of Jumping Robot

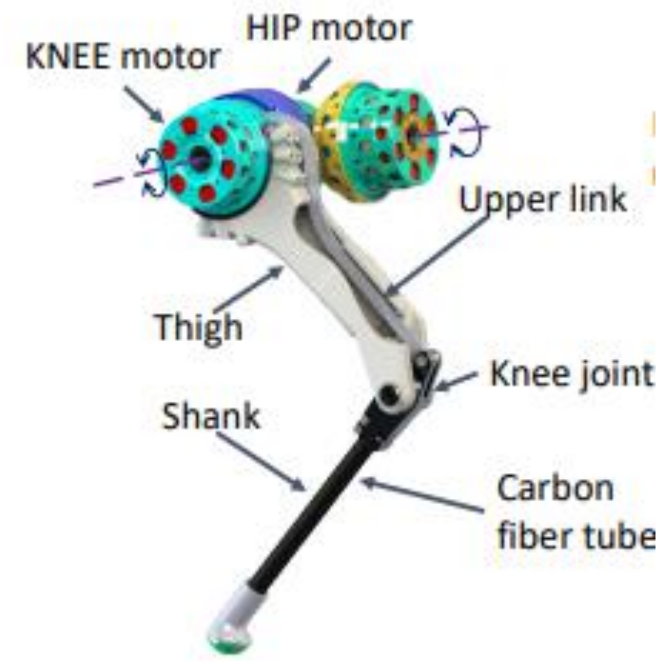
- Stance Phase
  - Leg is in contact with the ground
  - Actuators to apply force
- Flight Phase
  - Follows ballistic motion
  - Choosing foot holds

Constraints

- Joint Torques do not exceed actuator limits
- Goal region should be reached at the end of the motion
- Ground reaction force (GRF) must be within friction cone

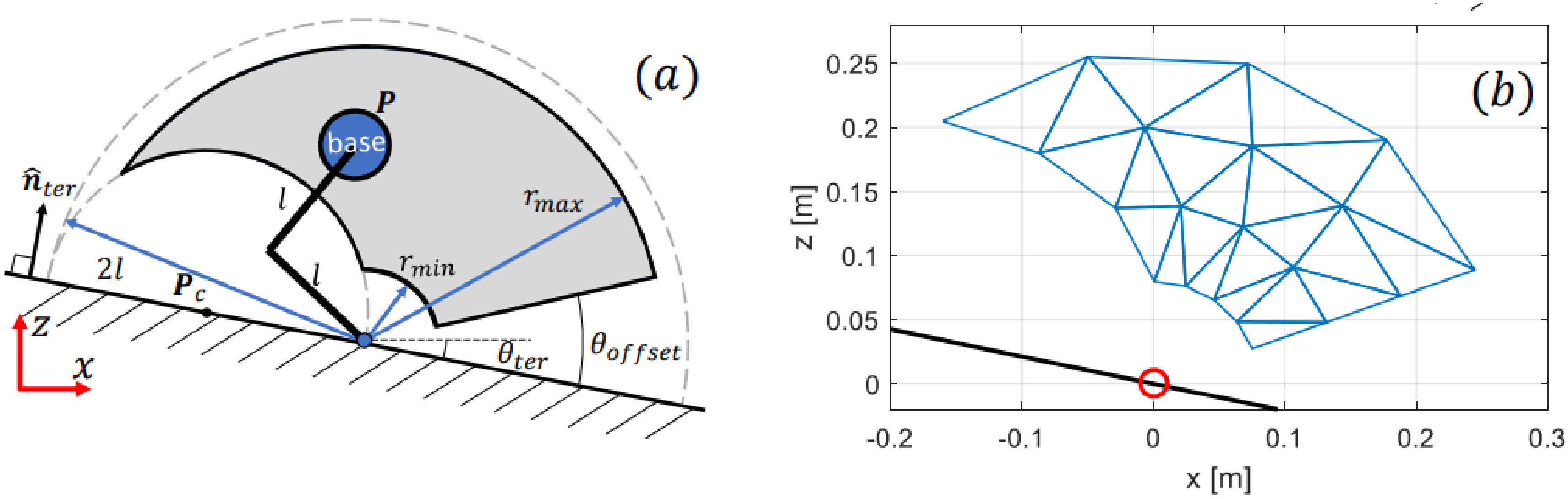
Point Mass Dynamic Model

- To simplify dynamics
- Center of Mass assumed to be in the Base Center



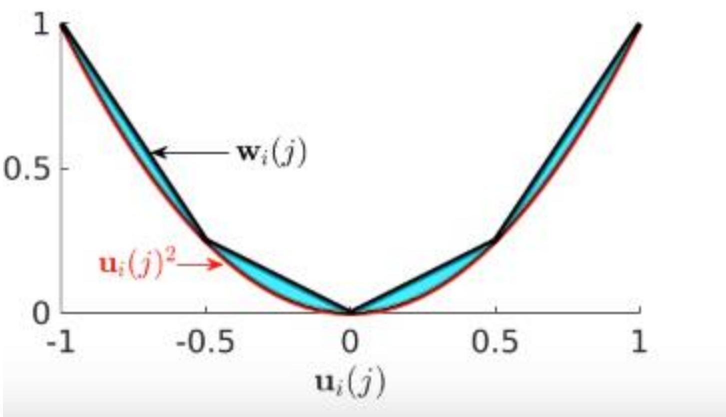
Mixed-integer Convex Torque Constraint

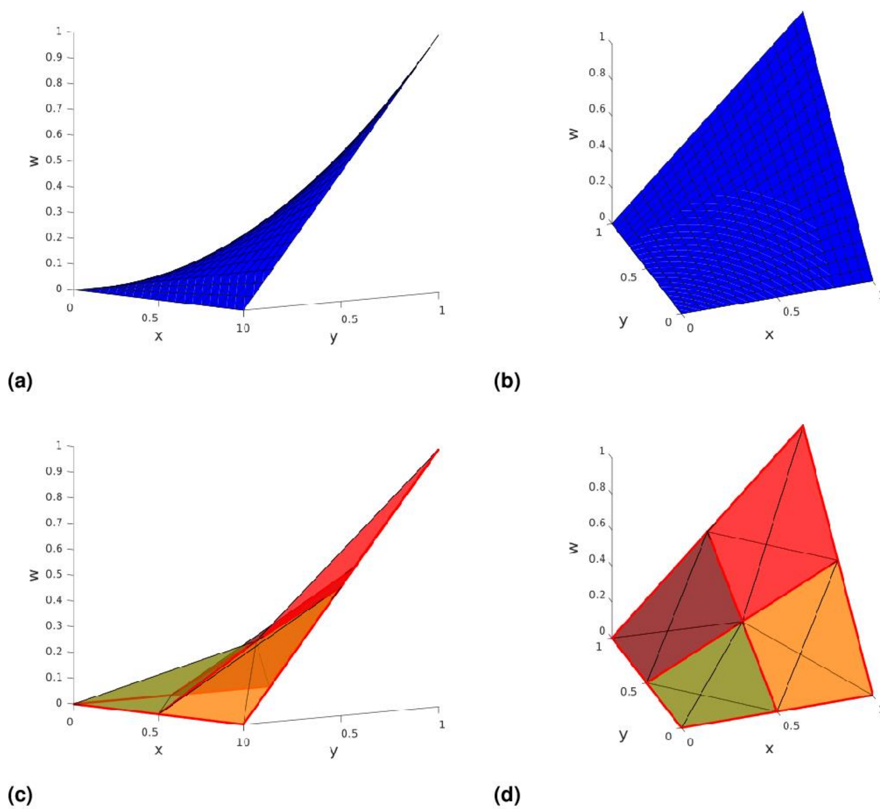
- Workspace Discretization



Background: Mixed Integer Convex Optimization

- Non-convex optimization to convex optimization

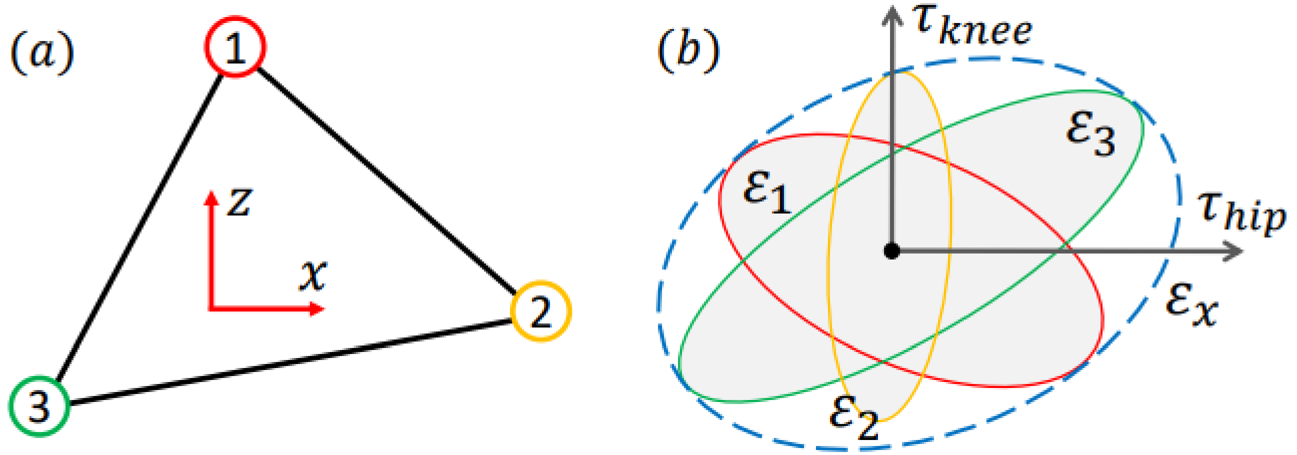




Mixed-integer Convex Torque Constraint

- Convex Outer-Approximation of Torque Ellipsoid

$$||\boldsymbol{J}^T(\boldsymbol{p}) \cdot \boldsymbol{F}||_\infty \leq \tau_{max}$$

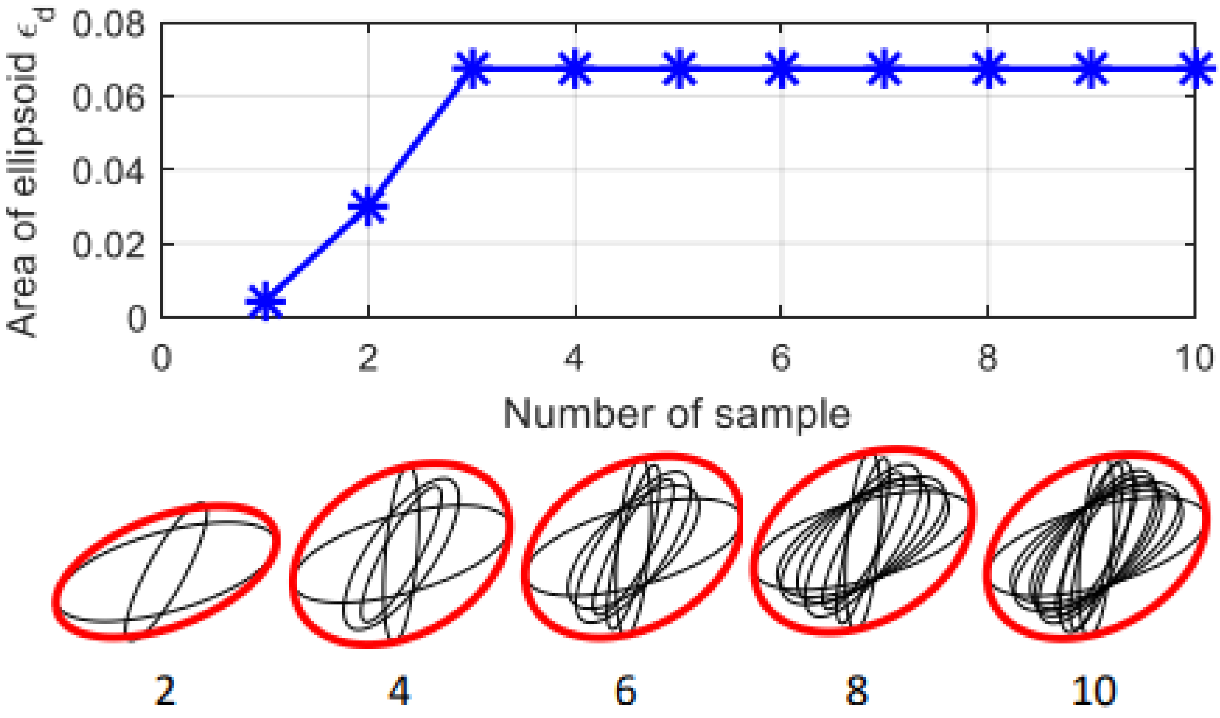


$$\boldsymbol{F}^T \boldsymbol{J}_n \cdot \boldsymbol{J}_n{}^T \boldsymbol{F} \leq \boldsymbol{F}^T \boldsymbol{X} \boldsymbol{F}, \qquad \forall n$$

$$\boldsymbol{F}^T \boldsymbol{X} \boldsymbol{F} \leq \tau_{max}^2$$

Mixed-integer Convex Torque Constraint

- Convex Outer-Approximation of Torque Ellipsoid



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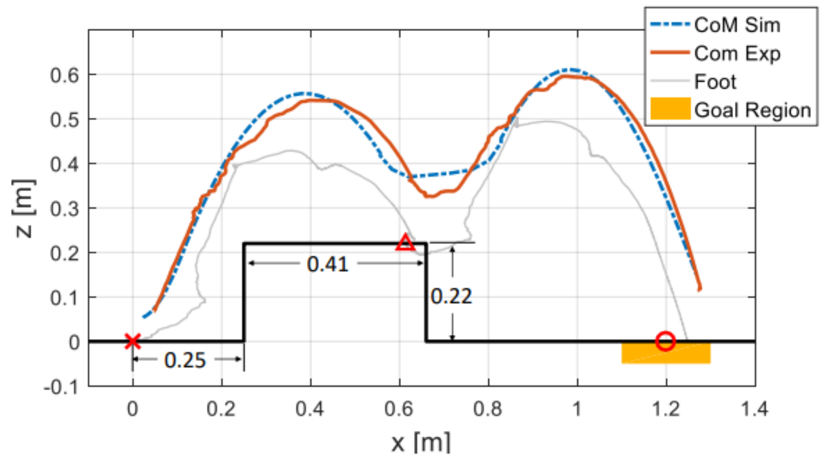
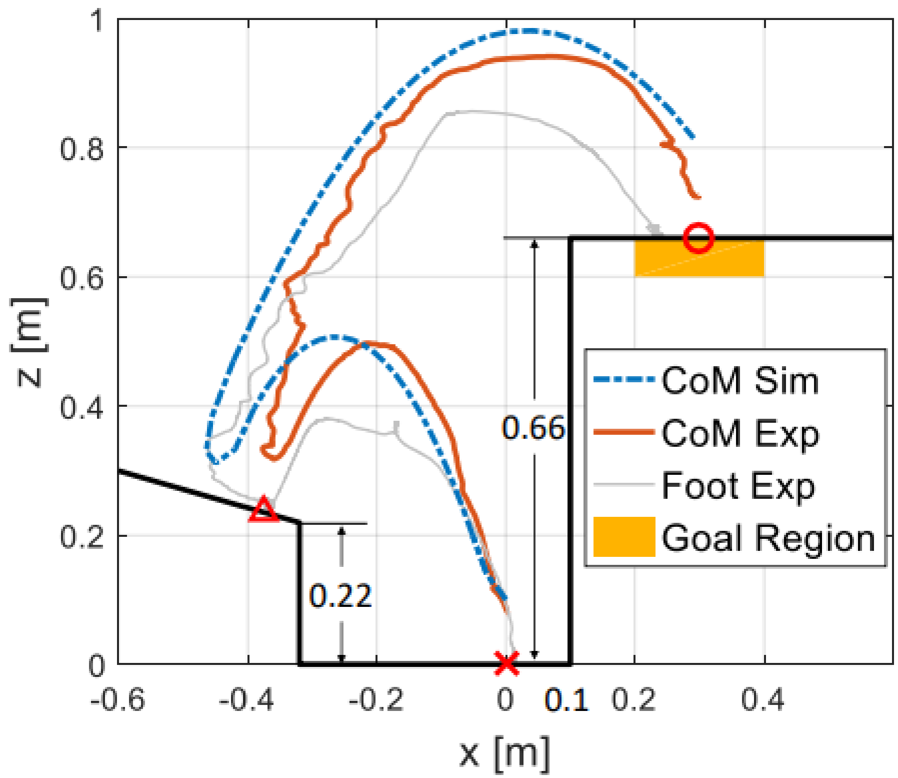
Other Implementation

- McCormick Envelope Approximation
- Foothold Position choice
- GRF Constraints

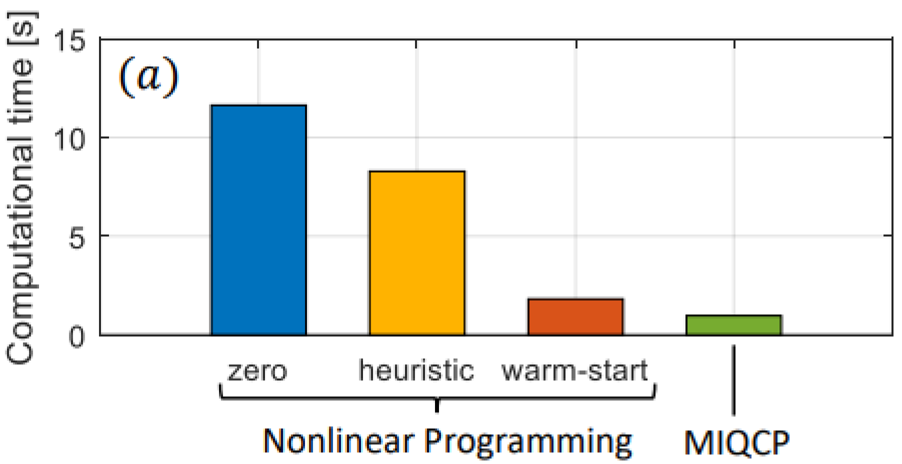
Results

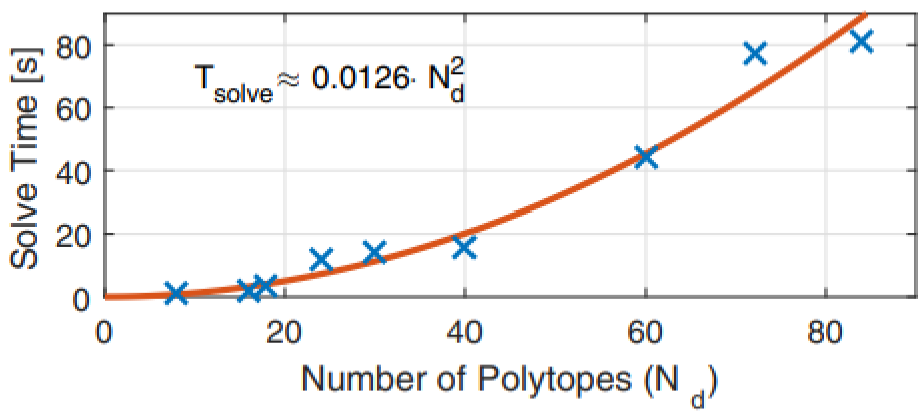
- https://www.youtube.com/watch?v=0pFYjoUKGu0





Performance





Summary

Summary

- Paper 1: Ballistic Motion Planning
  - Jumping point robot navigating in 3d environment
  - 2 constraints due to the friction cone
  - Constraint to limit takeoff velocity -> robot's speed capacity
  - Constraint to limit landing velocity -> impact force tolerance
- Paper 2: Single Leg Dynamic Motion Plannning with Mixed-Integer Convex Optimization
  - Implemented ballistic motion planning for a real robot and simplifies the non-convexity of actuator torque constraint through Mixed-Integer Convex Optimization

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