(Contact) Force Control

ME 193B / 292B

(Contact) Force Control

- Humanoid Balancing

Posture and Balance Control for Biped Robots based on Contact Force Optimization

Christian Ott, Maximo A. Roa, and Gerd Hirzinger

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I. INTRODUCTION

- Quadrupedal Bounding

Quadruped Bounding Control with Variable Duty Cycle via Vertical Impulse Scaling

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Abstract—**This paper introduces a bounding gait control algorithm that allows a successful implementation of duty cycle modulation in the MIT Cheetah 2. Instead of controlling leg stiffness to emulate a 'springy leg' inspired from the Spring-Loaded-Inverted-Pendulum (SLIP) model, the algorithm prescribes vertical impulse by generating scaled ground reaction forces at each step to achieve the desired stance and total stride duration. Therefore, we can control the duty cycle: the percentage of the stance phase over the entire cycle. By prescribing the required vertical impulse of the ground reaction force at each step, the algorithm can adapt to variable duty cycles attributed to variations in running speed. Following linear momentum conservation law, in order to achieve a limit-cycle gait, the sum of all vertical ground reaction forces must match vertical momentum created by gravity during a cycle. In addition, we added a virtual compliance control in the**

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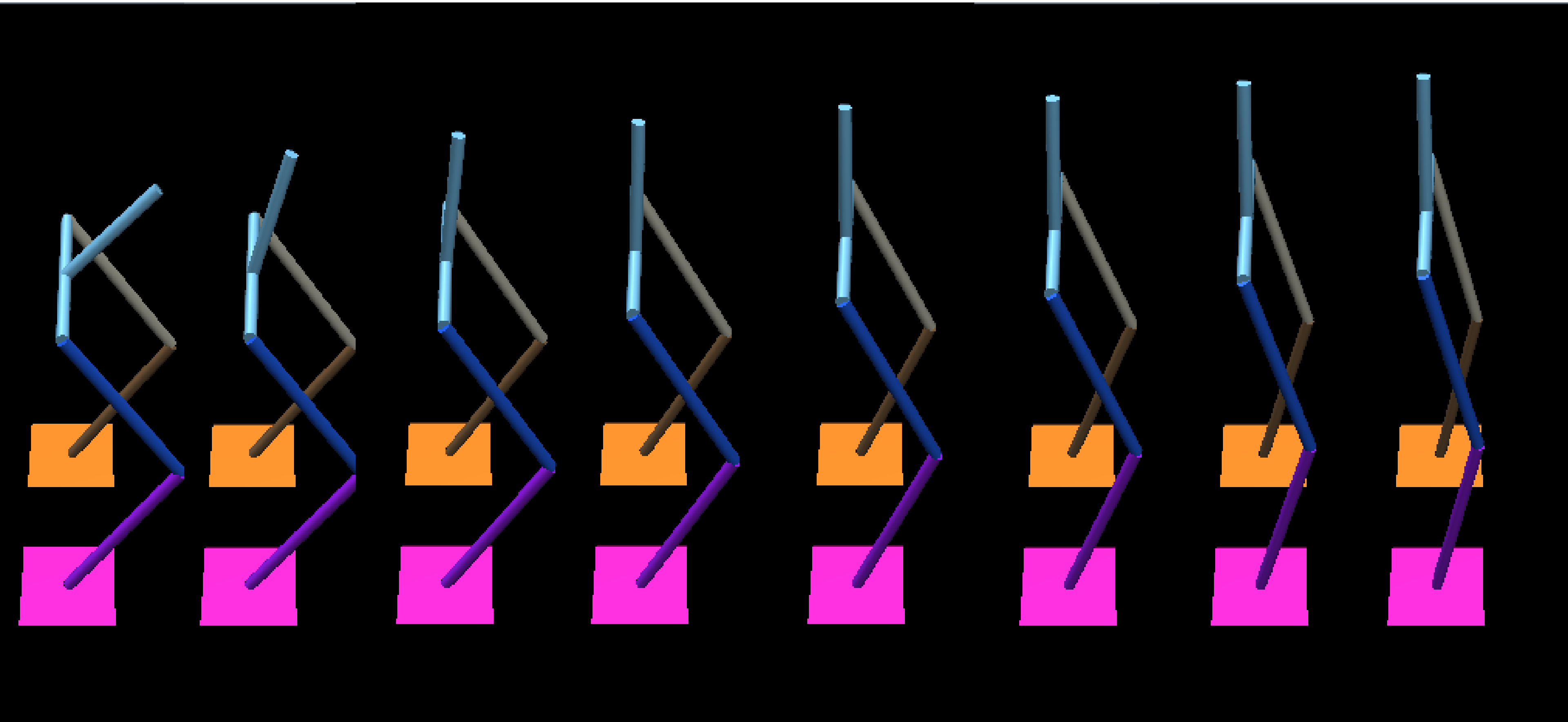
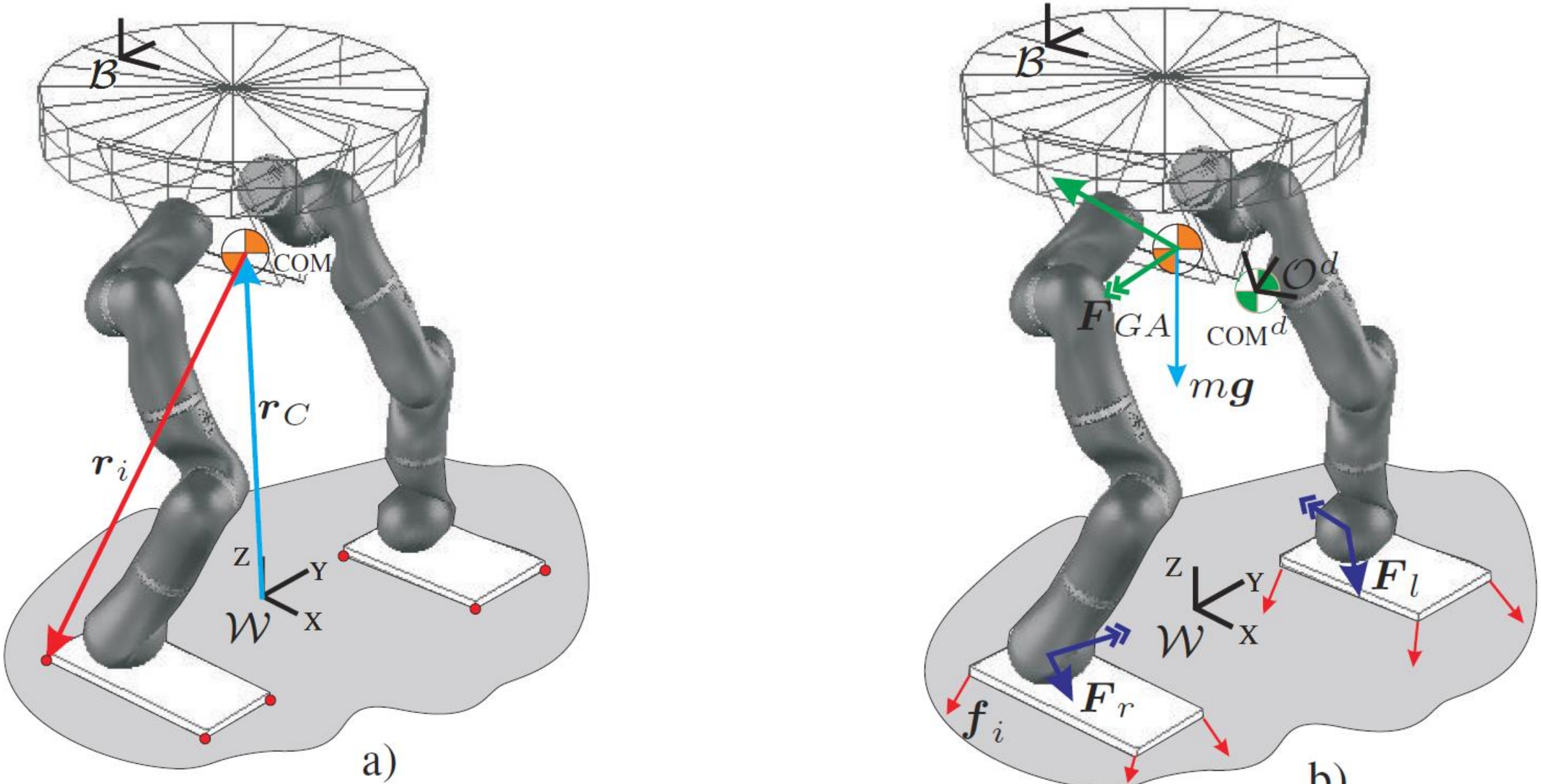
I. INTRODUCTION

Paper [pdf]

Balancing Of A Biped Robot By Controlling Contact Forces

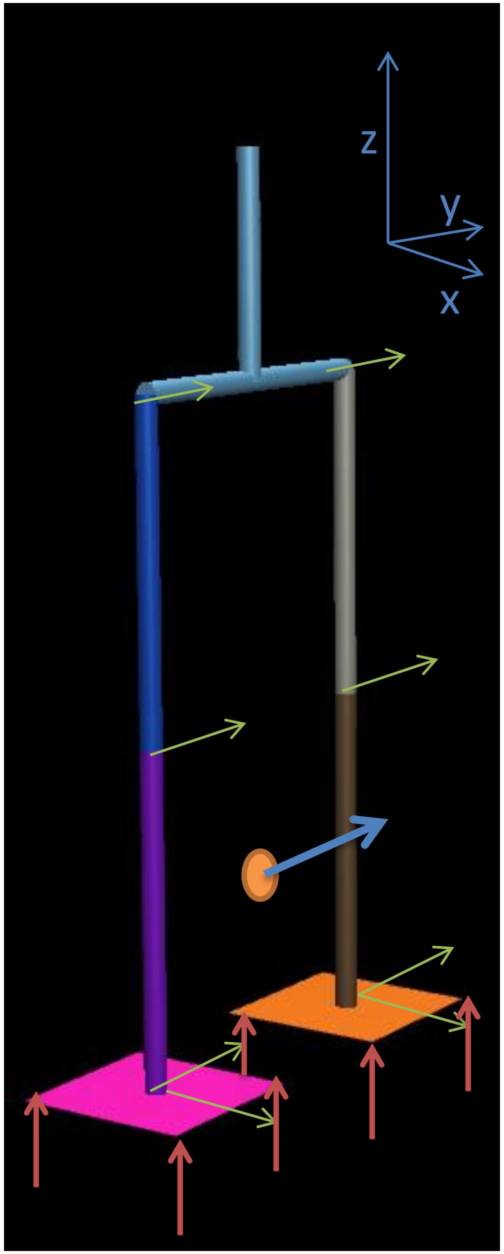




$\mathcal{B}$
COM
$\boldsymbol{r}_C$
$\boldsymbol{r}_i$
Z
Y
X
$\mathcal{W}$
a)
$\mathcal{B}$
$\boldsymbol{F}_{GA}$
$\mathcal{O}^d$
COM^d
$m\boldsymbol{g}$
$\boldsymbol{F}_l$
$\boldsymbol{F}_r$
Z
Y
X
$\mathcal{W}$
$\boldsymbol{f}_i$
b)

Methodology

- Controller -> find stabilizing wrench
  - » Desired COM position
  - » Desired torso orientation
- Grasp map -> find contact forces that produce the wrench
  - » Unilateral forces
  - » Inside the friction cone
- Torque map -> find motor torques that produce the action at the contacts



Posture Controller

- Calculates the desired wrench at the COM
- Desired Force

$$\boldsymbol{f}_{GA}^{d} = m\boldsymbol{g} + \boldsymbol{f}_{r}^{d}$$

$$\boldsymbol{f}_{r}^{d} = -K_p(\boldsymbol{r}_C - \boldsymbol{r}_C^d) - K_d(\dot{\boldsymbol{r}}_C - \dot{\boldsymbol{r}}_C^d)$$

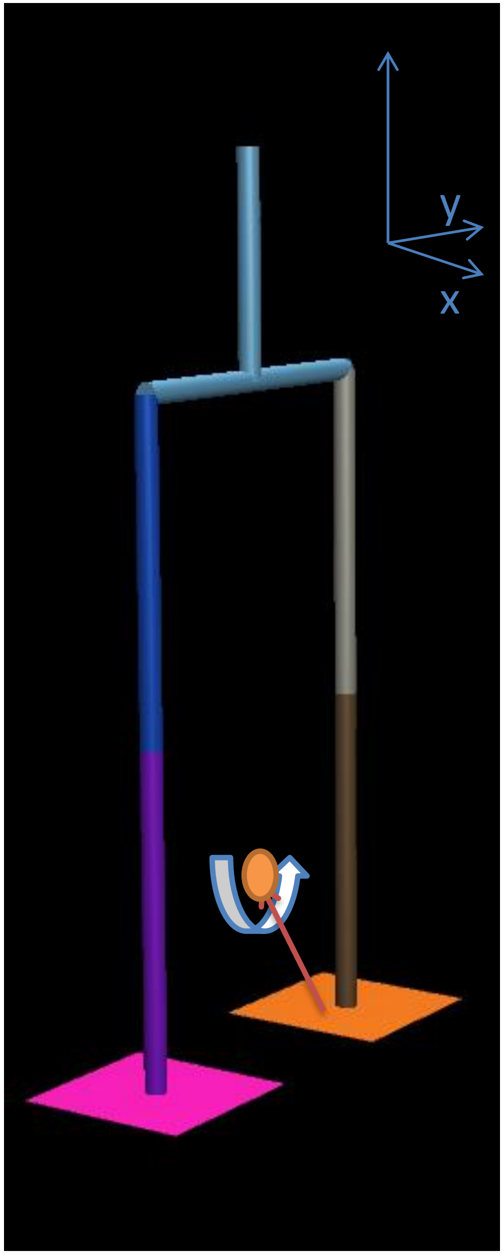
- Desired Moment
  - If δ and $\boldsymbol{\varepsilon}$ are the scalar and vector part of the quaternion giving the error in orientation,

$$\boldsymbol{\tau}_{GA}^{d} = {}^{W}\boldsymbol{R}_B(\boldsymbol{\tau}_r - \boldsymbol{D}_r(\boldsymbol{\omega} - \boldsymbol{\omega}^d))$$

$$\boldsymbol{\tau}_r = -2(\delta \boldsymbol{I} + \hat{\boldsymbol{\varepsilon}})\boldsymbol{K}_r\boldsymbol{\varepsilon}$$

- Desired Wrench

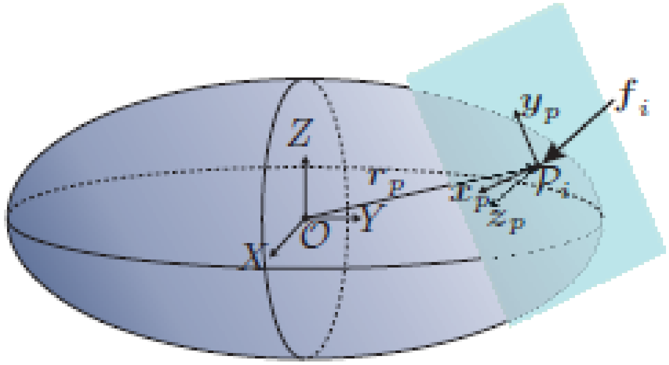
$$\boldsymbol{F}_{GA} = \begin{bmatrix} \boldsymbol{f}_{r}^{d} \\ \boldsymbol{\tau}_{GA}^{d} \end{bmatrix}$$



Frictional Grasping

- Wrench transformation Matrix

$$W_p = Ad_{op}^T = \begin{pmatrix} {}^O R_p & 0 \\ \hat{r}_p {}^O R_p & {}^O R_p \end{pmatrix}$$



- Wrench at the contact point

$$F_i = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} f_{ix} \\ f_{iy} \\ f_{iz} \end{bmatrix} = B_i f_i$$

- Grasp map G

$$F_O = [G_1 \dots G_\eta] \begin{bmatrix} f_1 \\ \vdots \\ f_\eta \end{bmatrix}$$

$$F_{Oi} = W_{pi} B_i f_i = G_i f_i$$

$$F_O = G f_C$$

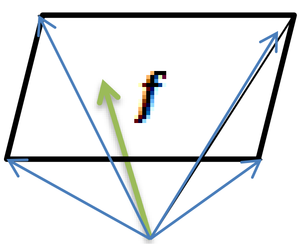
$$\boxed{G = \begin{pmatrix} {}^O R_{p1} & \cdots & {}^O R_{p\eta} \\ \hat{r}_{p1} {}^O R_{p1} & \cdots & \hat{r}_{p\eta} {}^O R_{p\eta} \end{pmatrix}}$$

Contact Forces reqd.

- Flat ground assumption, $\boldsymbol{R}_{pi} = \boldsymbol{I}$

$$G_C = \begin{pmatrix} I_{3\times3} & \cdots & I_{3\times3} \\ \hat{r}_{P1} & \cdots & \hat{r}_{P\eta} \end{pmatrix}$$

- Solve the equation $\boldsymbol{F}_{GA} = \boldsymbol{G}_C \boldsymbol{f}_C$
- The solution is optimized to constrain the forces to
  - Always act outward from the ground
  - Lie within the friction cone
- Friction cone is approximated by a k-sided polyhedral convex cone, $\mu = 0.5$
  - The direction of the force vector can be expressed as a positive combination of the normal to the planes

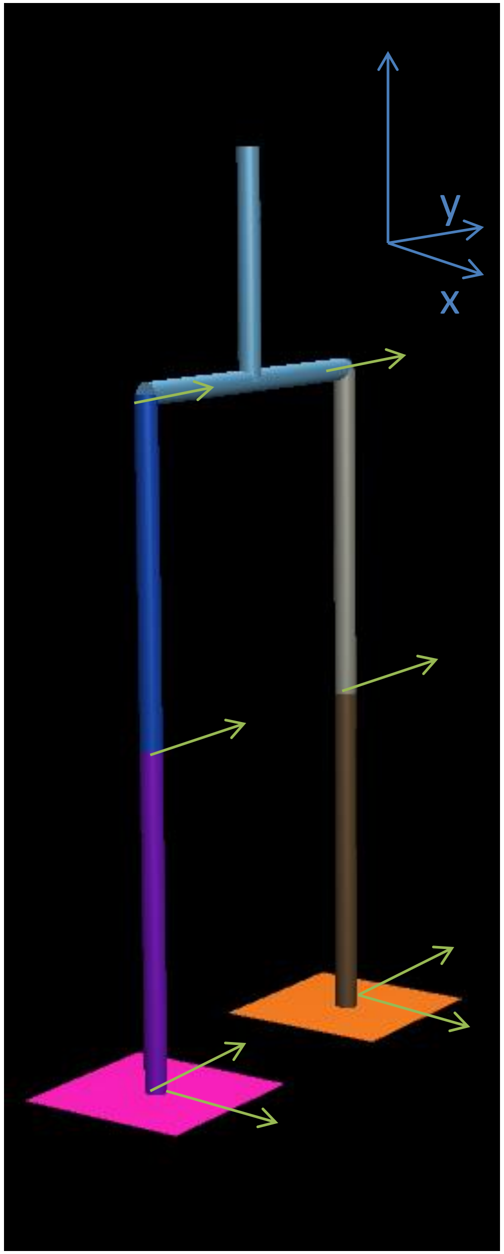


$$\boldsymbol{f} = \sum_{j=1}^{k} \boldsymbol{\sigma}_j \, \boldsymbol{n}_j \qquad \boldsymbol{\sigma}_j \geq 0$$

Dynamic Model

- 7-link, 8-joint, 14-DOF, 14 kg, 90 cm high in zero config.
- Compliant Ground
- Generalized coordinates:
  - (x,y,z) of torso's origin,
  - (r,p,y) torso orientation
  - joint angles
- Dynamics:

$$\begin{bmatrix} mI & \mathbf{0} \\ \mathbf{0} & M(q) \end{bmatrix} \dot{v}_C + \begin{pmatrix} \mathbf{0} \\ C(q, v_C) v_C \end{pmatrix} + \begin{pmatrix} mg \\ \mathbf{0} \end{pmatrix} = \begin{pmatrix} \mathbf{0} \\ \mathbf{0} \\ \tau \end{pmatrix} + \sum_{k=\{r,l\}} J_k(q)^T F_k$$



Contact forces -> Motor torques

- Use a wrench transformation matrix -> find the wrench at the COM of either feet
- In the quasi-static case, $\boldsymbol{v}_c = 0$, $(\dot{\boldsymbol{v}}_c) = 0$

  dynamics equation =>

$$\boxed{\boldsymbol{\tau} = -\sum_{k=\{r,l\}} \boldsymbol{J}_{ci}(\boldsymbol{q})^T \boldsymbol{F}_k}$$

- This expression maps the wrenches at the feet to the motor torques (under the assumption of quasi-static motion).

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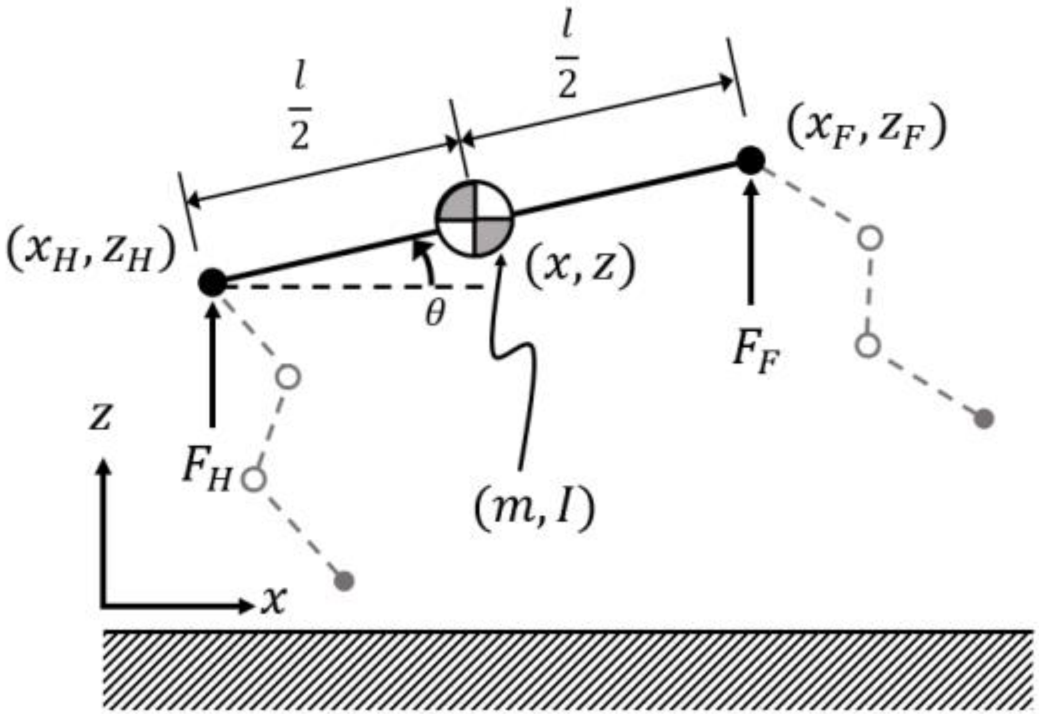
Paper [pdf]

Quadrupedal Bounding

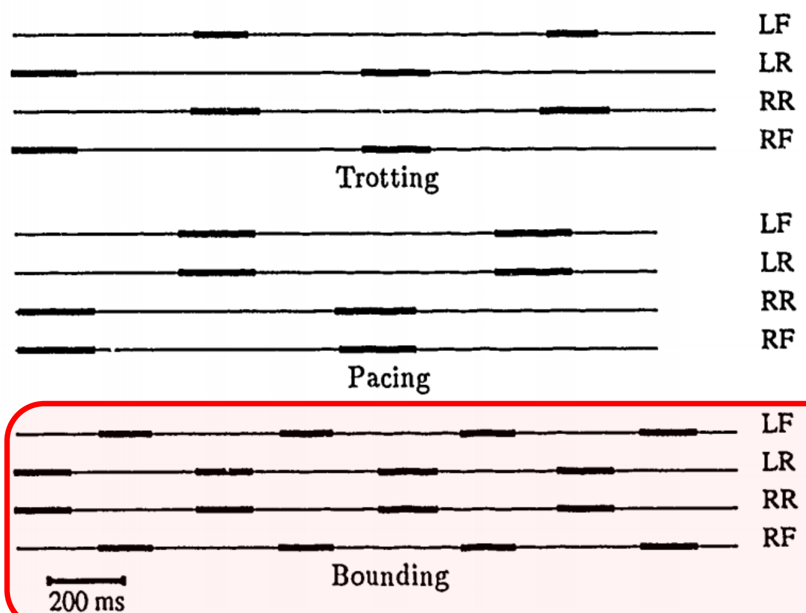
https://youtu.be/5XiNiaCuABo

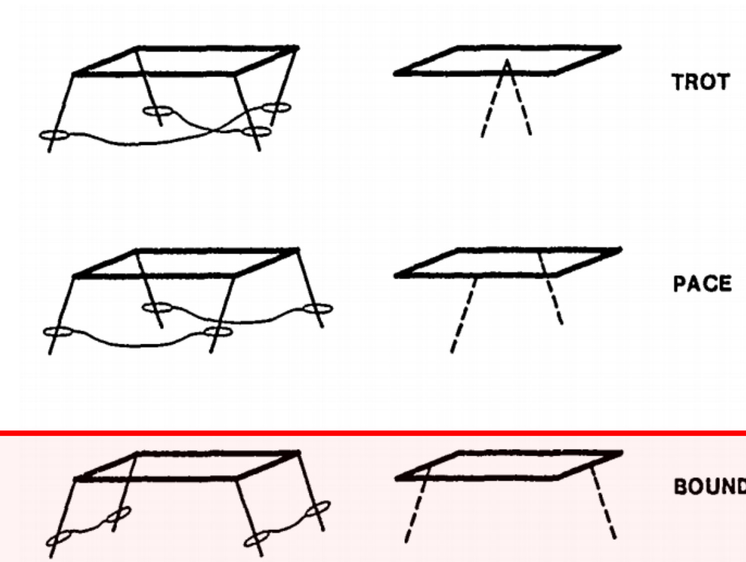
Simple Planar Model for Bounding



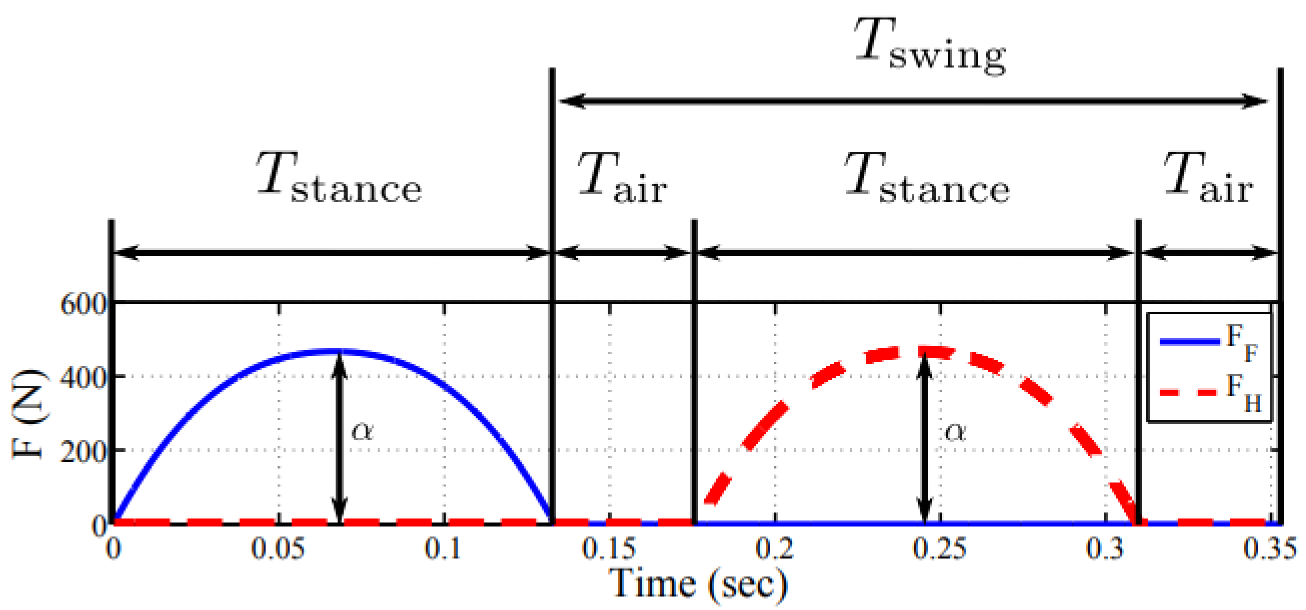
Bounding Gait

- Trot vs Pace vs Bound



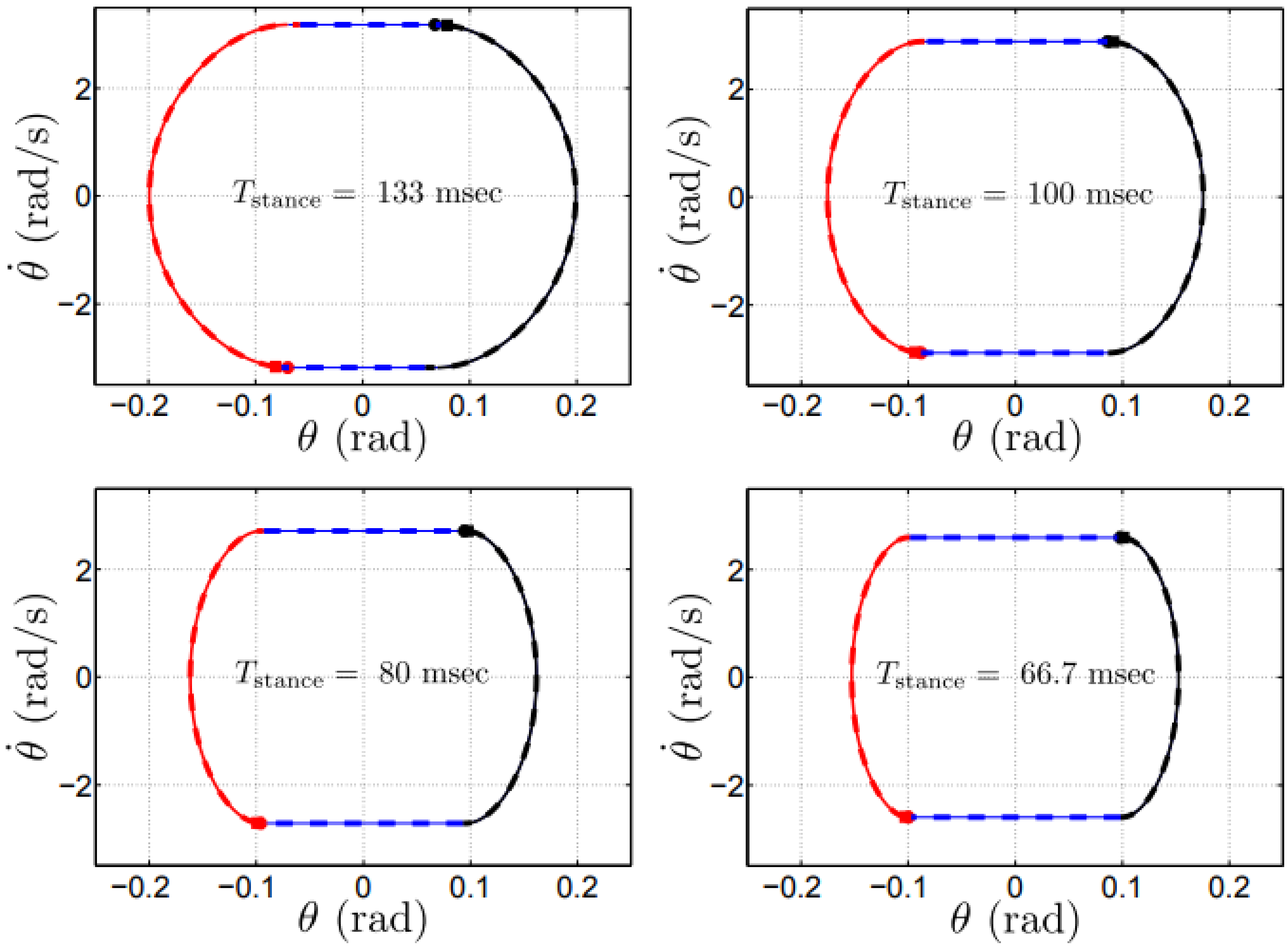


Force Profile

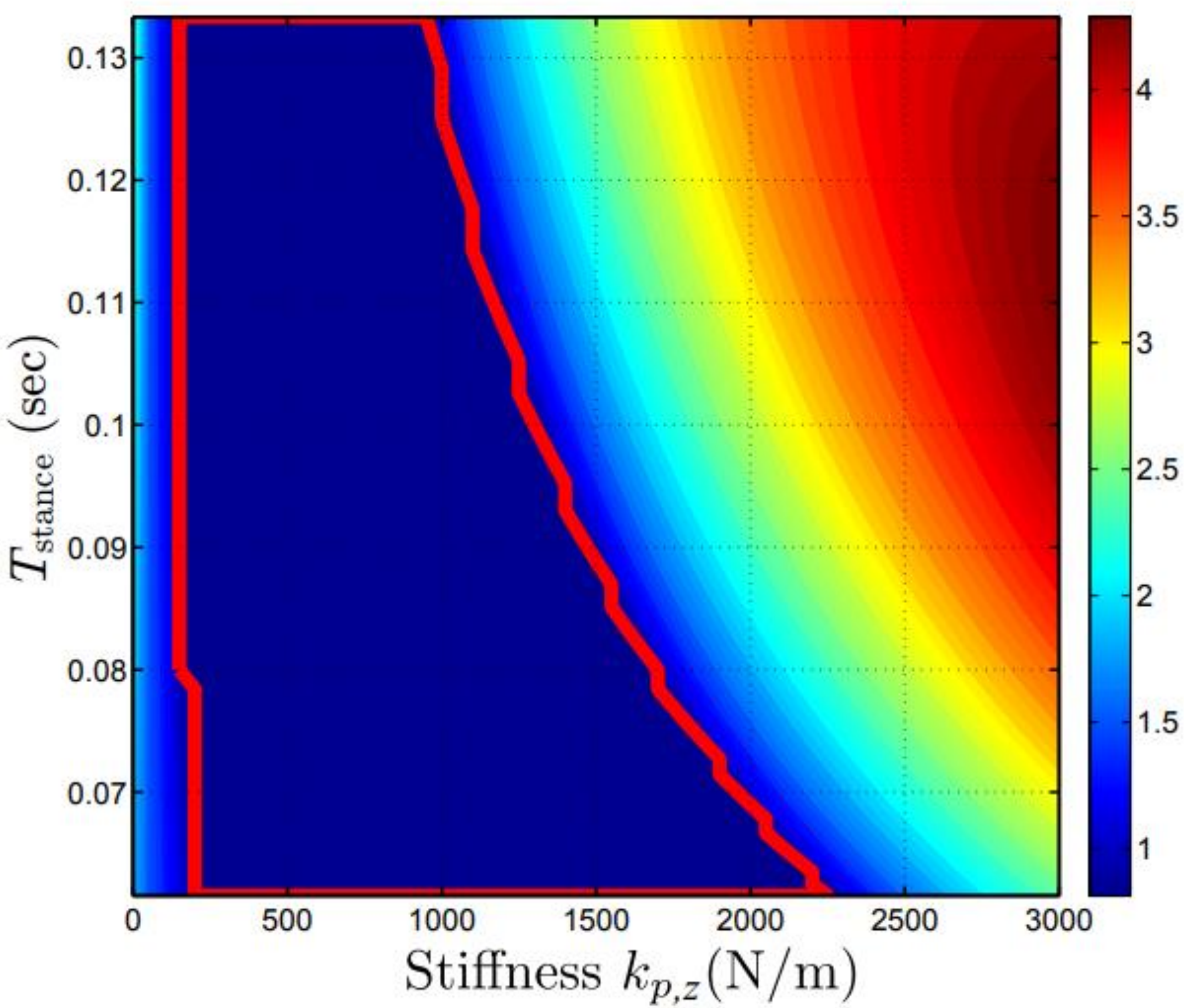


$$T_{air} = \frac{T_{\text{swing}} - T_{\text{stance}}}{2}$$

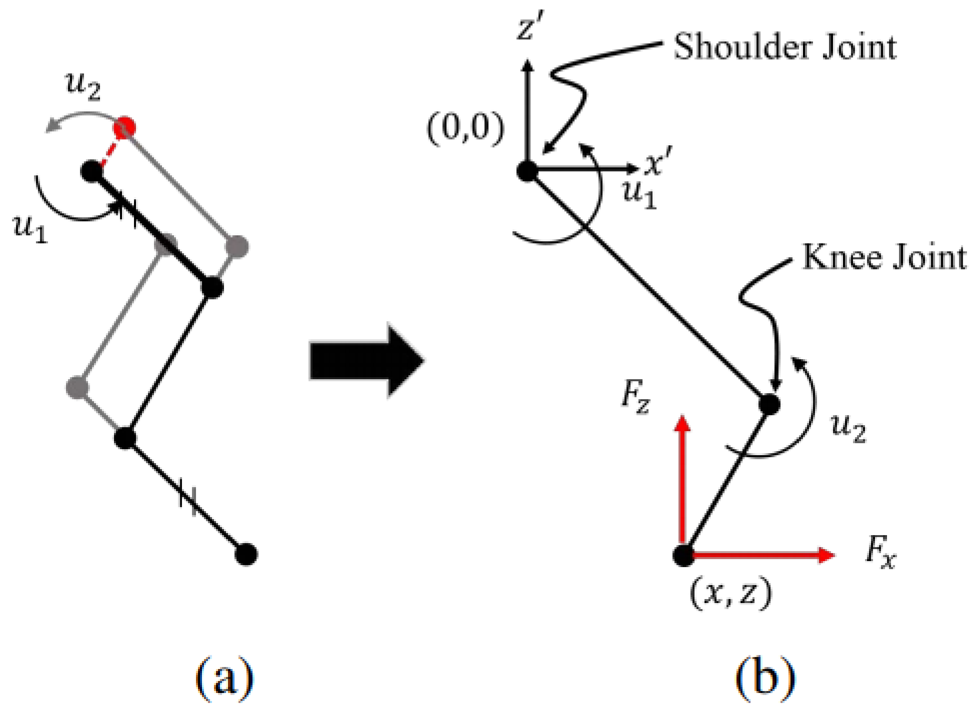
Periodic Oribits



Periodic Oribits



Mapping Force to Robot

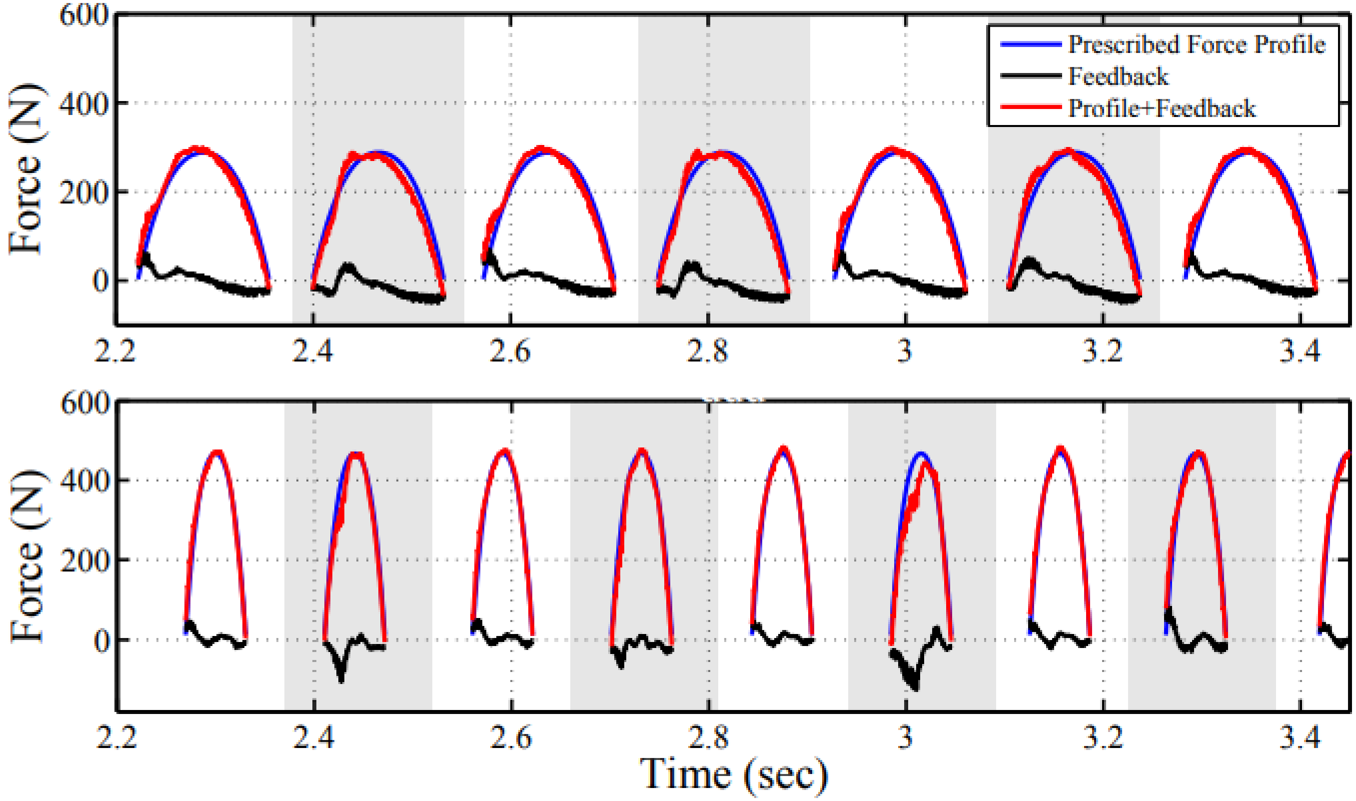


$$u = J_{xz}^T \begin{bmatrix} F_x \\ F_z \end{bmatrix}$$

Experiments

$T_{stance} = 133ms$

$T_{stance} = 61.5ms$



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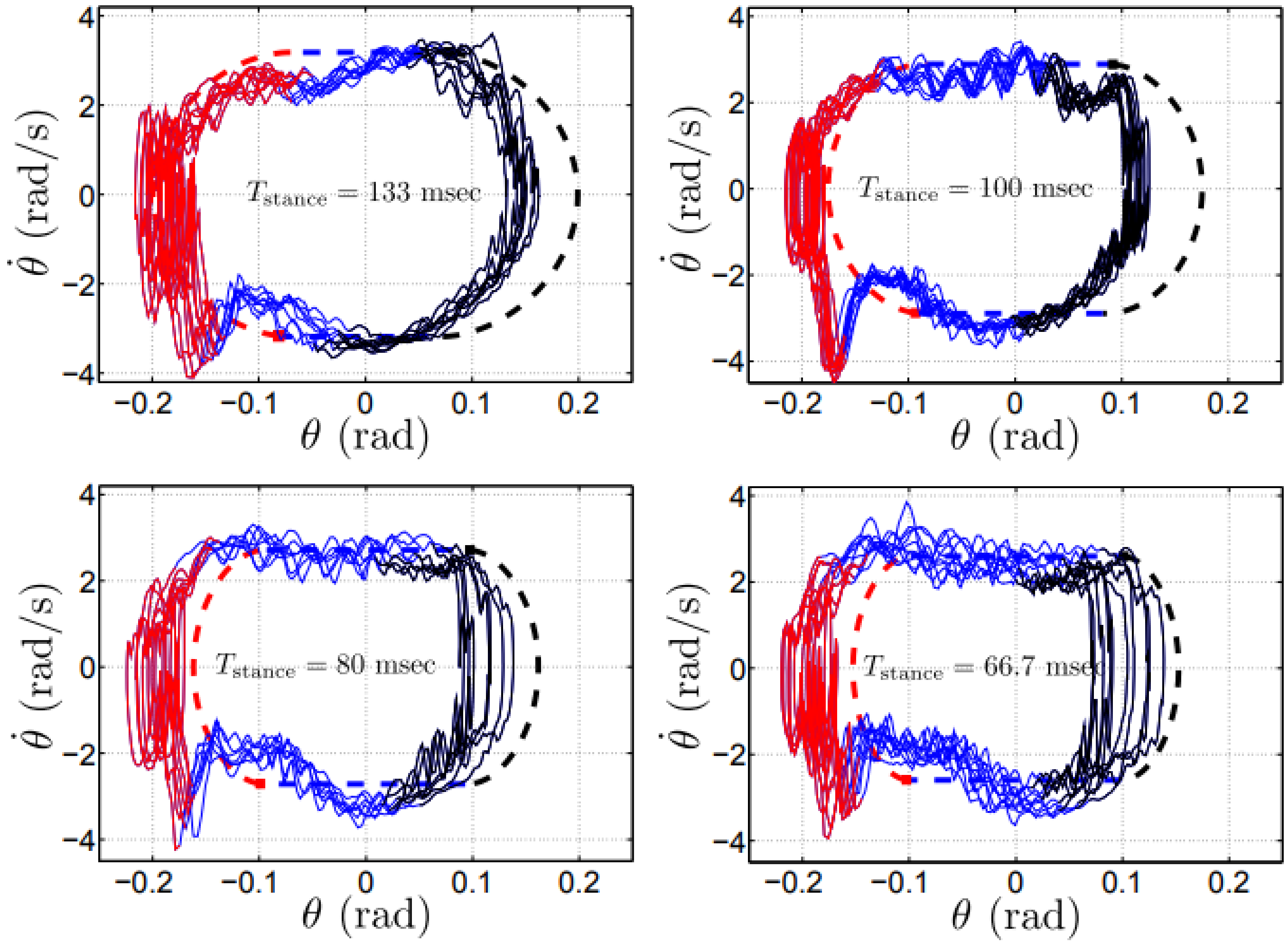

MIT Cheetah 3
(Force Control + MPC)

https://youtu.be/QZ1DaQgg3lE