[Humanoids 2022 Workshop] - Advancements in Trajectory Optimization and Model Predictive Control for Legged Systems

frontiers | Frontiers in Robotics and AI

Adaptive robot climbing with magnetic feet in unknown slippery structures

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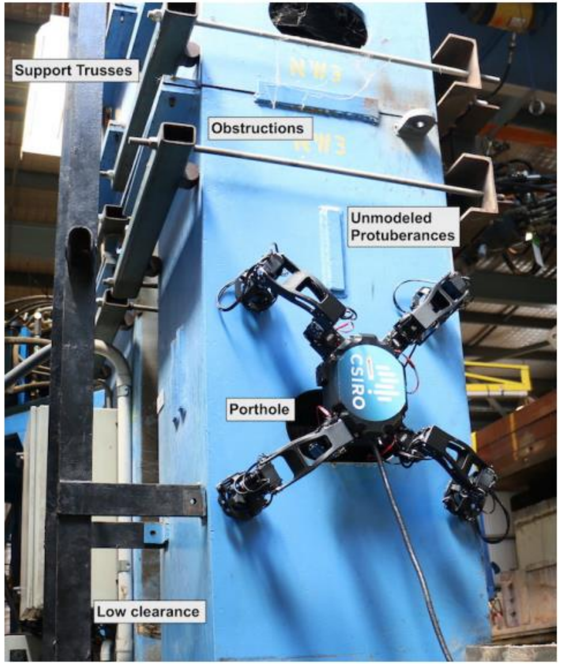
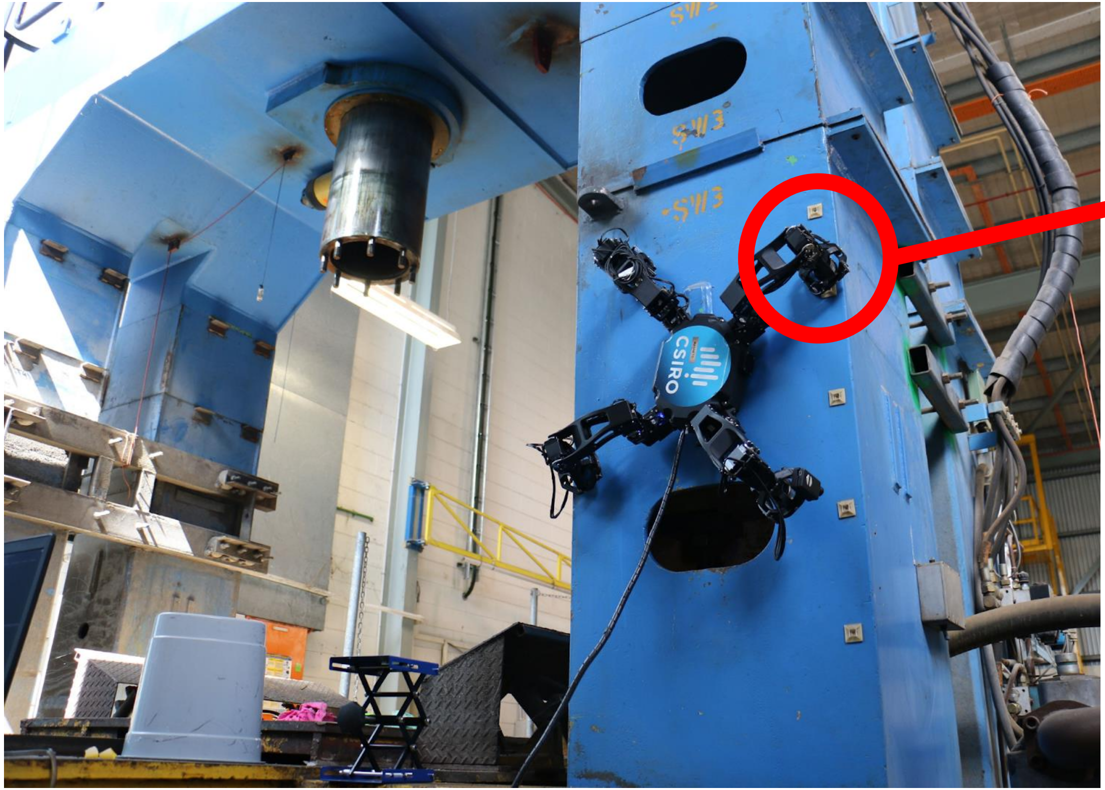
Climbing robots to reduce human risks at height*





* Bandyopadhyay, Tirthankar, et al. "Magneto: A versatile multi-limbed inspection robot." *2018 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*. IEEE, 2018.

However, unknown slippery conditions can cause problems

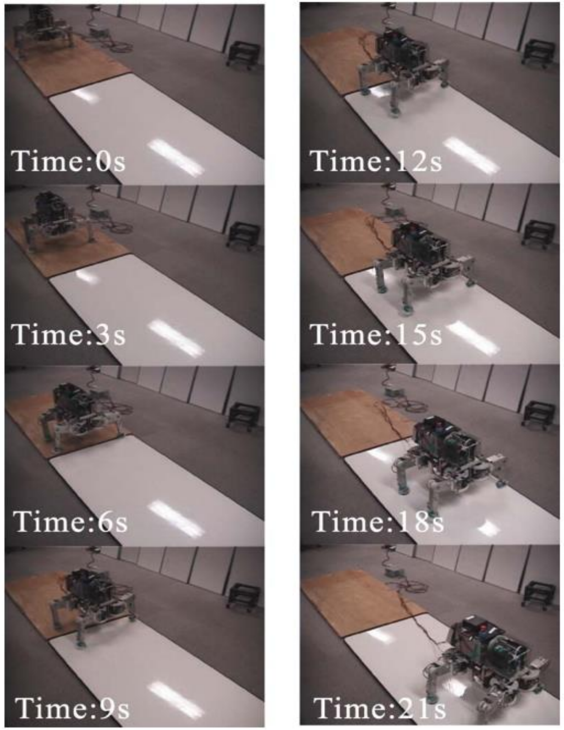


friction coefficient μ

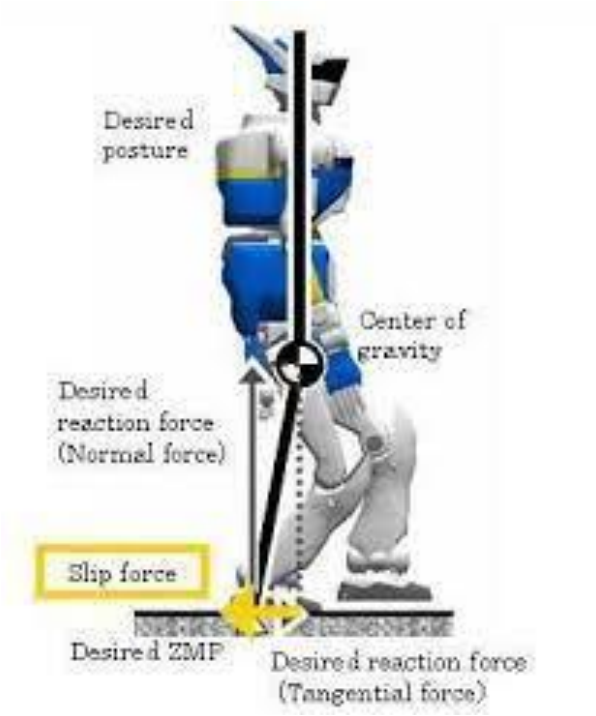
(magnetic) adhesive force F_m

…

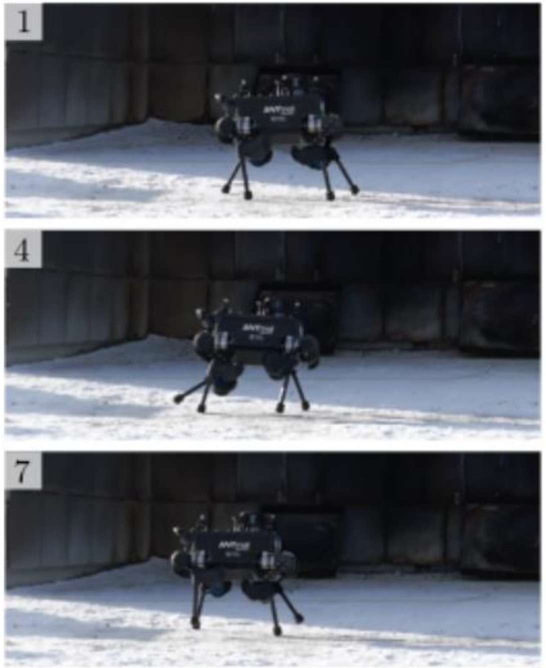
Related Works / Limitations



(Takemura et al. (2005))

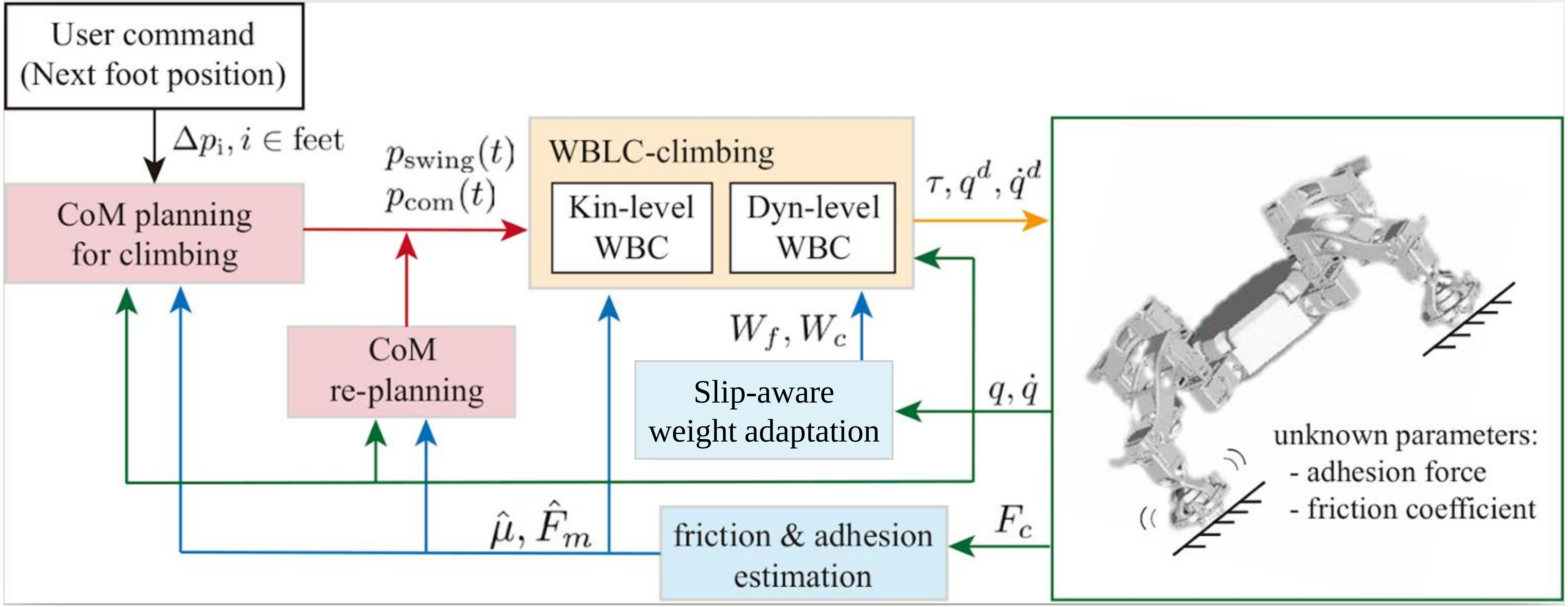


(Kaneko et al. (2005))

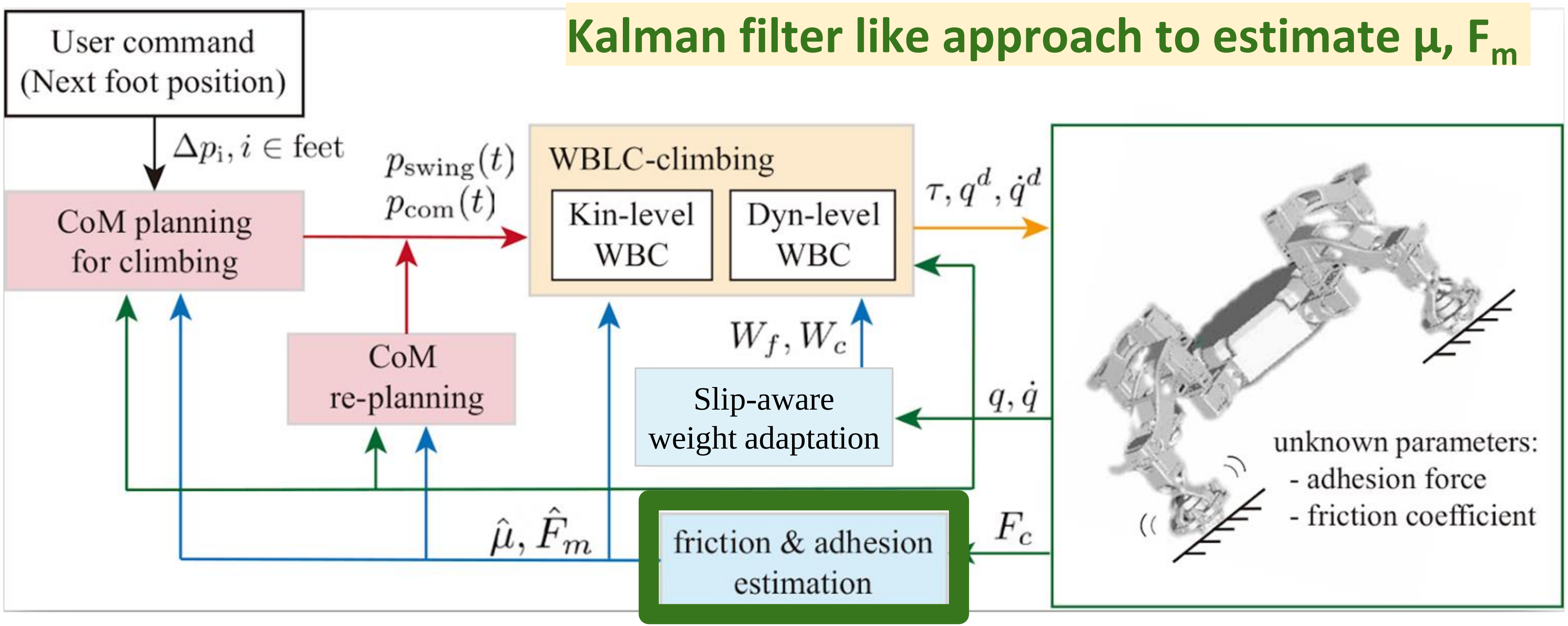


(Jenelten et al. (2019))

The Proposed Control Architecture

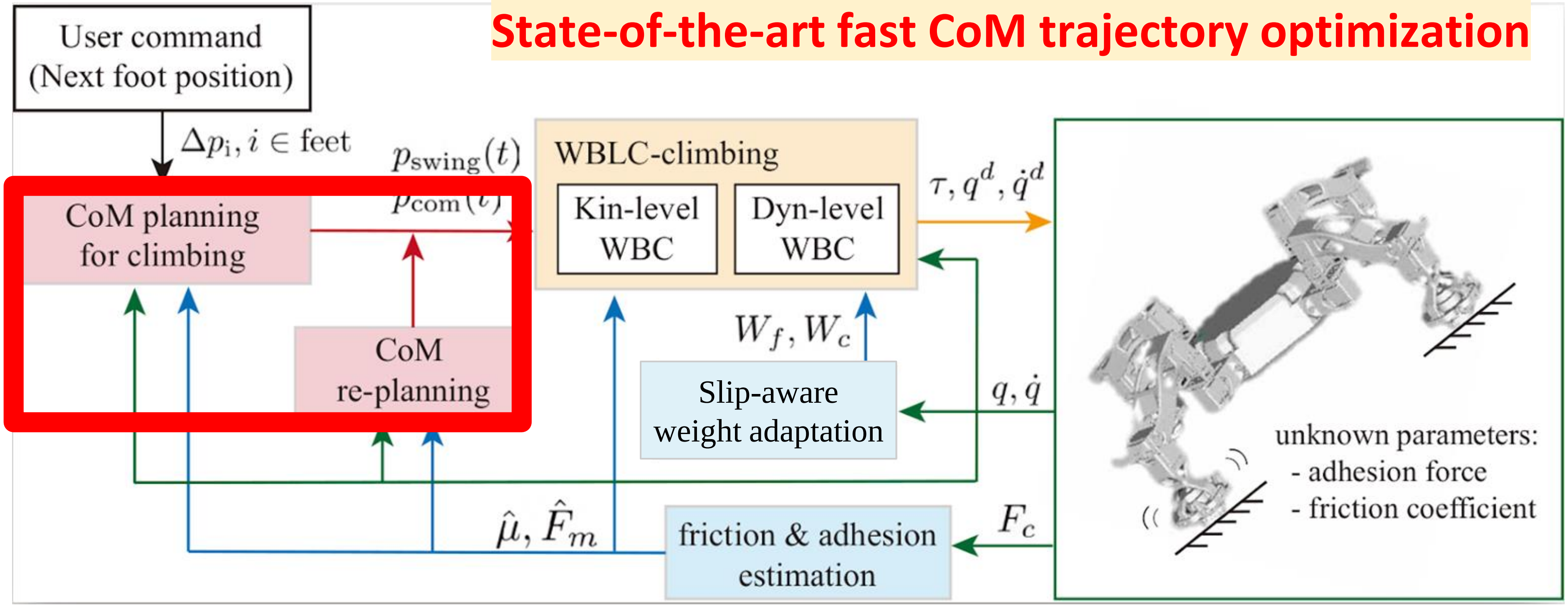


The Proposed Control Architecture

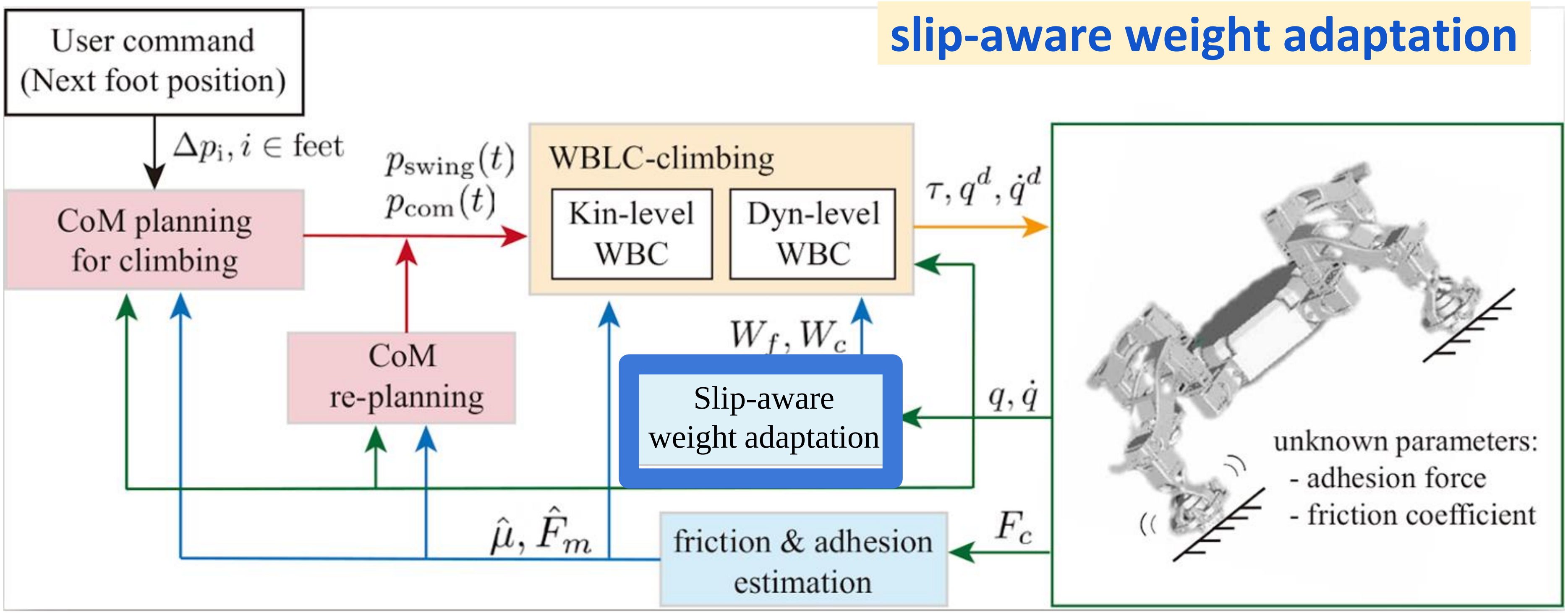


The Proposed Control Architecture

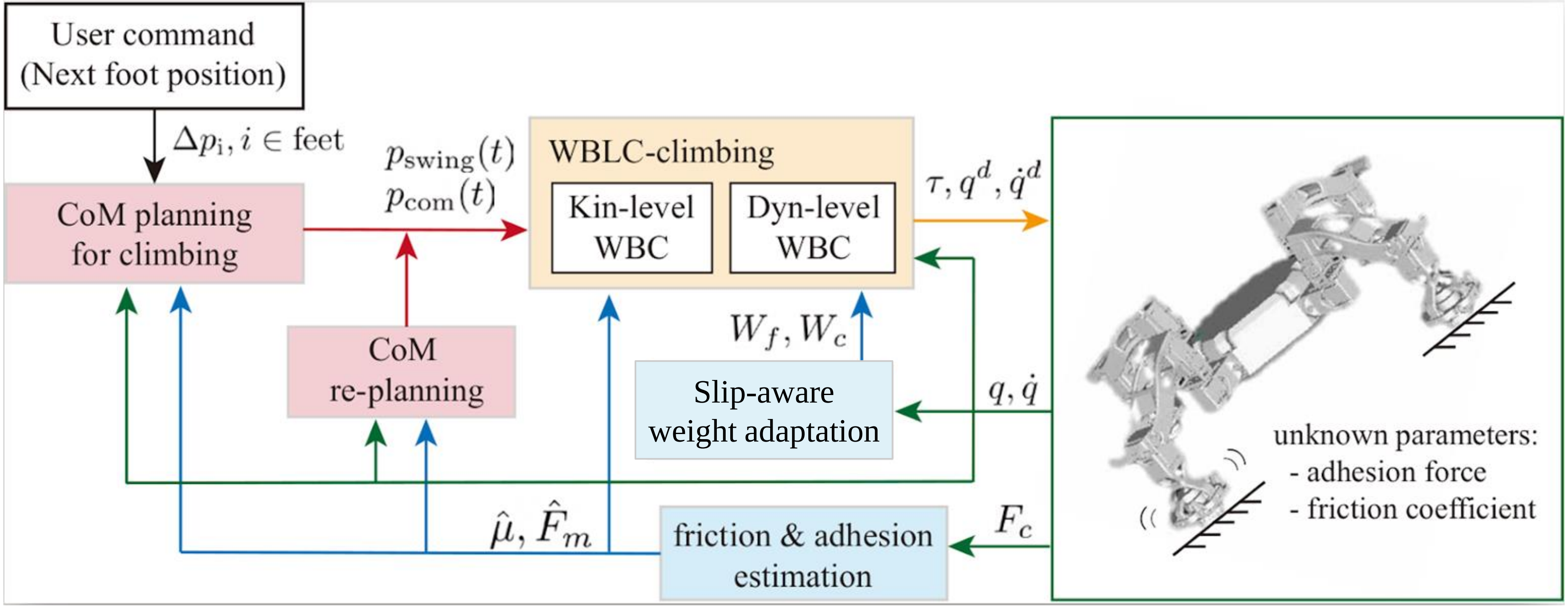
State-of-the-art fast CoM trajectory optimization



The Proposed Control Architecture



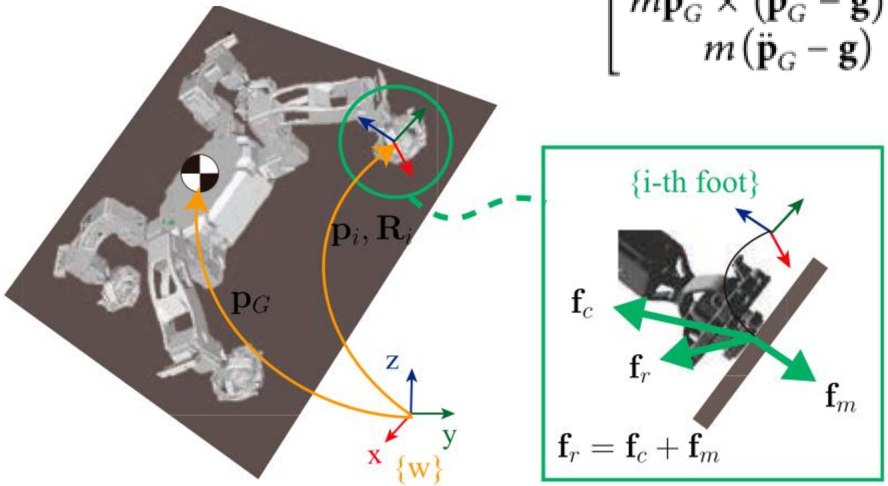
The Proposed Control Architecture



(i) Multi-contact CoM trajectory generation for climbing

Multi-contact CoM trajectory generation for climbing

- Centroidal dynamics with magnetic force



$$\begin{bmatrix} m\mathbf{p}_G \times (\ddot{\mathbf{p}}_G - \mathbf{g}) + \dot{\mathbf{L}} \\ m(\ddot{\mathbf{p}}_G - \mathbf{g}) \end{bmatrix} = \sum_{i\in \mathrm{Contact}} \begin{bmatrix} \mathbf{p}_i \times \mathbf{R}_i \mathbf{f}_{c,i} \\ \mathbf{R}_i\mathbf{f}_{c,i}\end{bmatrix} + \sum_{i\in\mathrm{Magnet}} \begin{bmatrix}\mathbf{p}_i \times \mathbf{R}_i\mathbf{f}_{m,i} \\ \mathbf{R}_i \mathbf{f}^i_m\end{bmatrix},$$

$$= \underbrace{\overbrace{\begin{bmatrix} \mathbf{p}_{c_1} \times \mathbf{R}_{c_1} & \cdots \\ \mathbf{R}_{c_1} & \cdots \end{bmatrix}}^{\mathcal{P}_c}}_{\mathcal{R}_c} \underbrace{\begin{bmatrix} \mathbf{f}_{c,c_1} \\ \vdots \end{bmatrix}}_{\mathbf{f}_c} + \underbrace{\overbrace{\begin{bmatrix} \mathbf{p}_{m_1} \times \mathbf{R}_{m_1} & \cdots \\ \mathbf{R}_{m_1} & \cdots \end{bmatrix}}^{\mathcal{P}_m}}_{\mathcal{R}_m} \underbrace{\begin{bmatrix} \mathbf{f}_{m,m_1} \\ \vdots \end{bmatrix}}_{\mathbf{f}_m}$$

$$= \begin{bmatrix} \mathcal{P}_c \\ \mathcal{R}_c \end{bmatrix} \mathbf{f}_c + \begin{bmatrix} \mathcal{P}_m \\ \mathcal{R}_m \end{bmatrix} \mathbf{f}_m, \qquad (5)$$

- Friction cone constraints $\mathbf{D}\mathbf{f}_c \geq 0,$

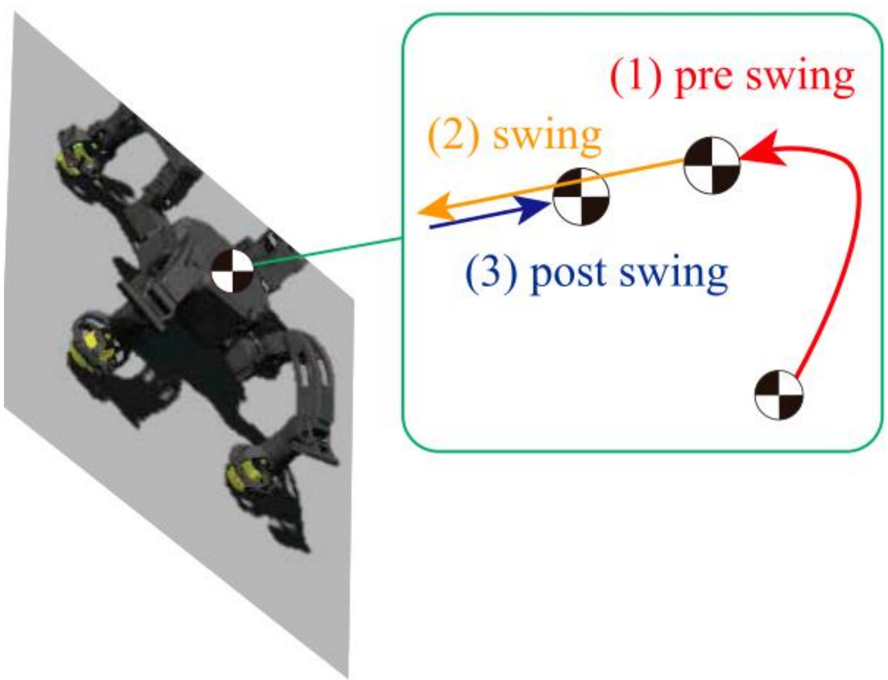
Multi-contact CoM trajectory generation for climbing

- Phase based CoM trajectory parameterization

$$\begin{bmatrix} m\mathbf{p}_G \times (\ddot{\mathbf{p}}_G - \mathbf{g}) + \dot{\mathbf{L}} \\ m(\ddot{\mathbf{p}}_G - \mathbf{g}) \end{bmatrix} = \begin{bmatrix} \mathcal{P}_c \\ \mathcal{R}_c \end{bmatrix} \mathbf{f}_c + \begin{bmatrix} \mathcal{P}_m \\ \mathcal{R}_m \end{bmatrix} \mathbf{f}_m$$

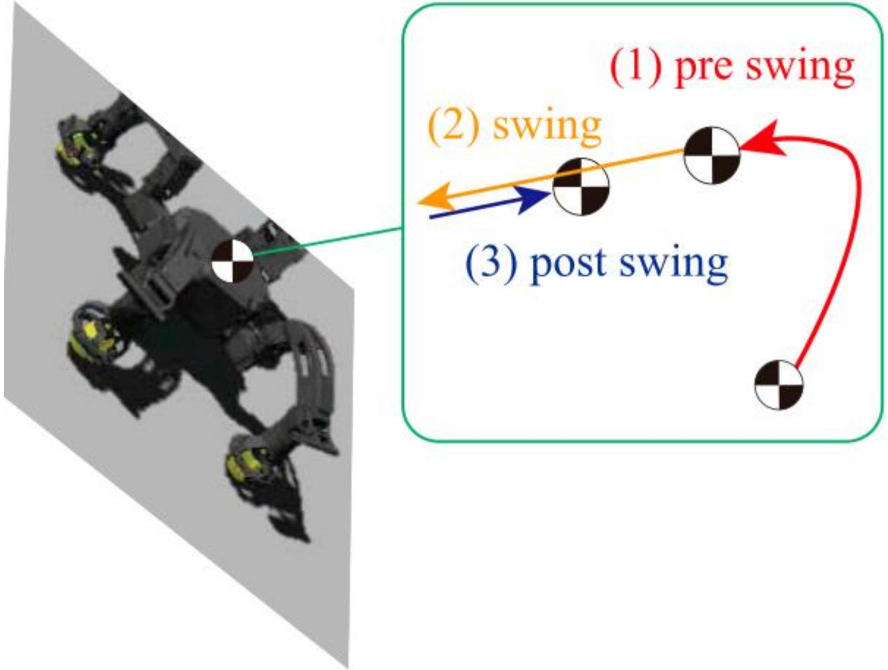
$$\mathbf{D}\mathbf{f}_c \geq 0,$$

Find $\mathbf{p_G(t)}$, $\mathbf{f_c(t)}$
satisfying equations
and inequality constraints!



Multi-contact CoM trajectory generation for climbing

- Phase based CoM trajectory parameterization



https://www.youtube.com/watch?v=6Ov8QqA7TNU

Multi-contact CoM trajectory generation for climbing

- Phase based CoM trajectory parameterization

$$\begin{bmatrix} m\mathbf{p}_G \times (\ddot{\mathbf{p}}_G - \mathbf{g}) + \dot{\mathbf{L}} \\ m(\ddot{\mathbf{p}}_G - \mathbf{g}) \end{bmatrix} = \begin{bmatrix} \mathcal{P}_c \\ \mathcal{R}_c \end{bmatrix} \mathbf{f}_c + \begin{bmatrix} \mathcal{P}_m \\ \mathcal{R}_m \end{bmatrix} \mathbf{f}_m$$

$$\mathbf{D}\mathbf{f}_c \geq 0,$$

Assumption 1

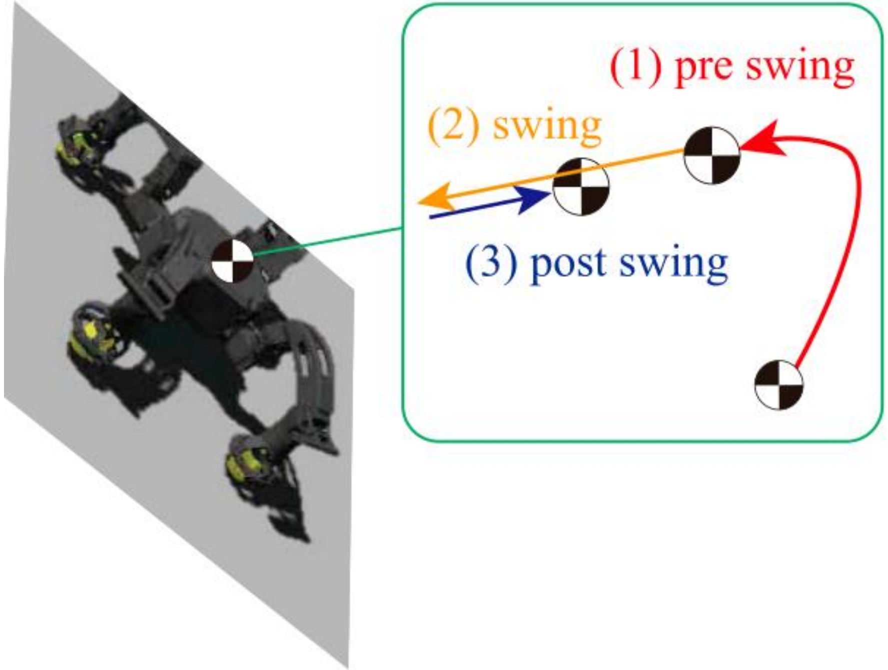
$\mathbf{p}_G$ ~ Hermite Cubic Spline

Assumption 2

Pre-swing motion is safe

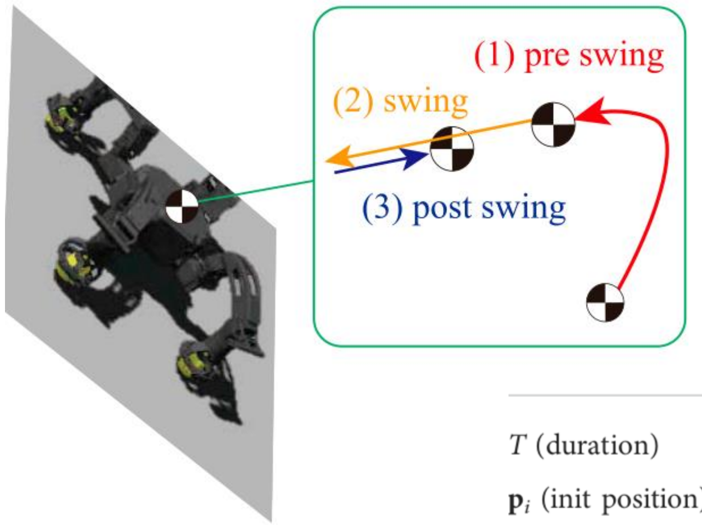
Assumption 3 $\mathbf{p}_G \times \ddot{\mathbf{p}}_G$ → non-linear

$$\dot{\mathbf{p}}_G^{\text{swing}} // \dot{\mathbf{p}}_G^{\text{post swing}}$$



Multi-contact CoM trajectory generation for climbing

- Phase based CoM trajectory parameterization



- Cubic Hermite Spline

$$p_{HS}(t; T, \mathbf{p}_i, \mathbf{p}_g, \mathbf{v}_i, \mathbf{v}_g)$$

$$\Rightarrow \ddot{\mathbf{p}}_G^{\text{swing}}(t) = \alpha \mathbf{d}, \ddot{\mathbf{p}}_G^{\text{post swing}}(t) = \beta \mathbf{d},$$

	(1) Pre swing	(2) Swing	(3) Post swing
T (duration)	T_1	T_2	T_3
$\mathbf{p}_i$ (init position)	$\mathbf{p}_a$	$\mathbf{p}_1 = \mathbf{p}_b + (\frac{1}{2}\beta T_3^2 + \beta T_3 T_2 + \frac{1}{2}\alpha T_2^2)\mathbf{d}$	$\mathbf{p}_2$
$\mathbf{p}_g$ (goal position)	$\mathbf{p}_1$	$\mathbf{p}_2 = \mathbf{p}_b + \frac{1}{2}\beta T_3^2 \mathbf{d}$	$\mathbf{p}_b$
$\mathbf{v}_i$ (init velocity)	$\mathbf{0}$	$\mathbf{v}_1 = (-\beta T_3 - \alpha T_2)\mathbf{d}$	$\mathbf{v}_2$
$\mathbf{v}_g$ (goal velocity)	$\mathbf{v}_1$	$\mathbf{v}_2 = (-\beta T_3)\mathbf{d}$	$\mathbf{0}$

Multi-contact CoM trajectory generation for climbing

- Phase based CoM trajectory parameterization

Assumption 2 | pre-swing motion is safe

2) Swing

$$\begin{bmatrix} \mathcal{P}_s - [\mathbf{p}_b]_\times \mathcal{R}_s \\ \mathcal{R}_s \end{bmatrix} \mathbf{f}_c = \begin{bmatrix} \frac{1}{2} m [\mathbf{g}]_\times (T_2 - t)^2 \\ m\mathbf{I}_3 \end{bmatrix} \alpha \mathbf{d} + \begin{bmatrix} \frac{1}{2} m [\mathbf{g}]_\times T_3 (T_3 + 2T_2 - t) \\ 0 \end{bmatrix} \beta \mathbf{d} + \begin{bmatrix} \dot{\mathbf{L}} - (\mathcal{P}_s - [\mathbf{p}_b]_\times \mathcal{R}_s) \mathbf{f}_m \\ -m\mathbf{g} - \mathcal{R}_s \mathbf{f}_m \end{bmatrix}$$

$$\Leftrightarrow \quad \mathbf{A}_s \mathbf{f}_c = \mathbf{B}_{sa}(t) \alpha \mathbf{d} + \mathbf{B}_{sb}(t) \beta \mathbf{d} + \mathbf{c}_s, \quad \forall t \in (0, T_2)$$

$$\mathbf{D}_s \mathbf{f}_c \geq 0$$

3) Post Swing

$$\begin{bmatrix} \mathcal{P}_f - [\mathbf{p}_b]_\times \mathcal{R}_f \\ \mathcal{R}_f \end{bmatrix} \mathbf{f}_c = \begin{bmatrix} \frac{1}{2} m [\mathbf{g}]_\times (T_3 - t)^2 \\ m\mathbf{I}_3 \end{bmatrix} \beta \mathbf{d} + \begin{bmatrix} \dot{\mathbf{L}} - (\mathcal{P}_f - [\mathbf{p}_b]_\times \mathcal{R}_f) \mathbf{f}_m \\ -m\mathbf{g} - \mathcal{R}_f \mathbf{f}_m \end{bmatrix}$$

$$\Leftrightarrow \quad \mathbf{A}_f \mathbf{f}_c = \mathbf{B}_f(t) \beta \mathbf{d} + \mathbf{c}_f, \quad \forall t \in (0, T_3),$$

$$\mathbf{D}_f \mathbf{f}_c \geq 0$$

Multi-contact CoM trajectory generation for climbing

- Problem solution for parameterized CoM trajectory generation

find $\alpha, \beta, \mathbf{d}$ subject to

2) Swing

$$\mathbf{A}_s \mathbf{f}_c = \mathbf{B}_{sa}(t)\alpha\mathbf{d} + \mathbf{B}_{sb}(t)\beta\mathbf{d} + \mathbf{c}_s, \quad \forall t \in (0, T_2)$$

$$\mathbf{D}_s \mathbf{f}_c \geq 0$$

3) Post Swing

$$\mathbf{A}_f \mathbf{f}_c = \mathbf{B}_f(t)\beta\mathbf{d} + \mathbf{c}_f, \quad \forall t \in (0, T_3)$$

$$\mathbf{D}_f \mathbf{f}_c \geq 0$$

➡ Still nonlinear terms: multiplication of variables, $\alpha\mathbf{d}$, $\beta\mathbf{d}$

Multi-contact CoM trajectory generation for climbing

- Problem solution for parameterized CoM trajectory generation

Strategy 1	Choose $\gamma = \frac{\alpha}{\beta}$ that minimizes the max dist b/w CoM goal position & swing phase trajectory

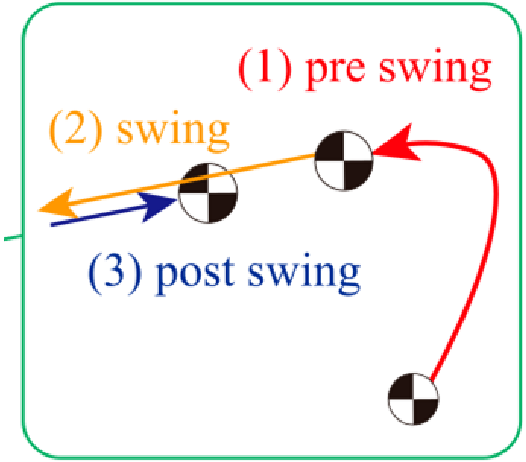
$$\gamma^* = \arg\min_{\gamma} \left(\max_{t} |g_\gamma(t)|, \quad t \in (0, T_2) \right),$$

$$\text{where} \quad \mathbf{p}_s(t) - \mathbf{p}_b = g_\gamma(t) \cdot \beta \mathbf{d}, \quad t \in (0, T_2),$$

$$g_\gamma(t) = \frac{1}{2}\gamma(T_2 - t)^2 + T_3(T_2 - t) + \frac{1}{2}T_3^2,$$

Assuming $\gamma* \neq 0$ and solving for $\gamma < 0$, we get the following:

$$\gamma^* = -\frac{T_3(T_2 + T_3) + T_3\sqrt{(T_2 + T_3)^2 + T_2^2}}{T_2^2}. \qquad (11)$$



Multi-contact CoM trajectory generation for climbing

- Problem solution for parameterized CoM trajectory generation

Strategy 1	Choose $\gamma = \frac{\alpha}{\beta}$ that minimizes the max dist b/w CoM goal position & swing phase trajectory.

find ~~$\alpha, \beta, \mathbf{d}$~~ $\beta\mathbf{d}$ subject to

2) Swing

$$\mathbf{A}_s\mathbf{f}_c = (\mathbf{B}_{sa}(t)\gamma^* + \mathbf{B}_{sb}(t))\beta\mathbf{d} + \mathbf{c}_s, \quad \forall t \in (0, T_2)$$

$$\mathbf{D}_s\mathbf{f}_c \geq 0$$

3) Post Swing

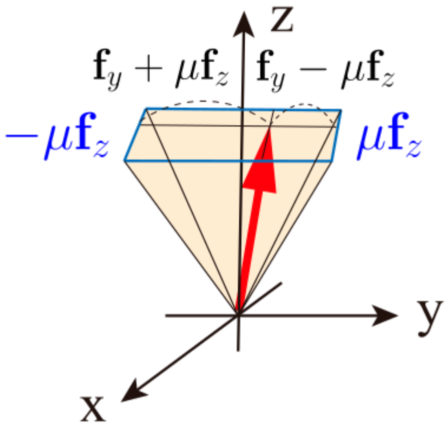
$$\mathbf{A}_f\mathbf{f}_c = \mathbf{B}_f(t)\beta\mathbf{d} + \mathbf{c}_f, \quad \forall t \in (0, T_3)$$

$$\mathbf{D}_f\mathbf{f}_c \geq 0$$

Multi-contact CoM trajectory generation for climbing

- Problem solution for parameterized CoM trajectory generation

Strategy 2	Take $\mathbf{f}_c$ that is located as close to the center of the cone as possible.



$$\min \quad \mathbf{f}_c^\top \mathbf{W} \mathbf{f}_c = \sum_{c \in C} \left(\frac{(f_x^c)^2 + (f_y^c)^2 + 2(\tilde{\mu}^c f_z^c)^2}{(\mu^c)^2} \right)$$

$$\text{s.t.} \quad \mathbf{A}\mathbf{f}_c = \mathbf{b}$$

➡ $\mathbf{f}_c = \mathbf{W}^{-1}\mathbf{A}^\top(\mathbf{A}\mathbf{W}^{-1}\mathbf{A}^\top)^{-1}\mathbf{b}$

➡ Find $\mathbf{x} = \beta \mathbf{d}$

$$\text{s.t.} \ \mathbf{D}_s\mathbf{A}_s^{-1}(\mathbf{B}_{sa}(t)\gamma^* + \mathbf{B}_{sb}(t))\mathbf{x} + \mathbf{D}_s\mathbf{A}_s^{-1}\mathbf{c}_s \geq 0, \quad \forall t \in (0, T_2)$$

$$\mathbf{D}_f\mathbf{A}_f^{-1}\mathbf{B}_f(t)\mathbf{x} + \mathbf{D}_f\mathbf{A}_f^{-1}\mathbf{c}_f \geq 0, \quad \forall t \in (0, T_3).$$

Multi-contact CoM trajectory generation for climbing

- Problem solution for parameterized CoM trajectory generation

Strategy 3	Necessary and sufficient condition to satisfy inequality over the given time horizon.

Find $\mathbf{x} = \beta\mathbf{d}$ s.t.

$$(\frac{1}{2}mf_s(t)\mathbf{D}_s\mathbf{A}_s^{-1}{}_{1;3}[\mathbf{g}]_\times + m\gamma^*\mathbf{D}_s\mathbf{A}_s^{-1}{}_{4;6})\mathbf{x} + \mathbf{D}_s\mathbf{A}_s^{-1}\mathbf{c}_s \geq 0 \quad t \in (0, T_2)$$

$$(\frac{1}{2}mf_f(t)\mathbf{D}_f\mathbf{A}_f^{-1}{}_{1;3}[\mathbf{g}]_\times + m\gamma^*\mathbf{D}_f\mathbf{A}_f^{-1}{}_{4;6})\mathbf{x} + \mathbf{D}_f\mathbf{A}_f^{-1}\mathbf{c}_f \geq 0 \quad t \in (0, T_3)$$

Proposition 1. Given an inequality $(f(t)\mathbf{B}_1 + \mathbf{B}_2)\mathbf{x} + \mathbf{c} \geq 0$ defined over a bounded function, $f_{\min} \leq f(t) \leq f_{\max}, \forall t \in (0, T)$, if an inequality holds at the boundary values $(f_{\min}\mathbf{B}_1 + \mathbf{B}_2)\mathbf{x} + \mathbf{c} \geq 0, (f_{\max}\mathbf{B}_1 + \mathbf{B}_2)\mathbf{x} + \mathbf{c} \geq 0$ for **x**,

Then $(f(t)\mathbf{B}_1 + \mathbf{B}_2)\mathbf{x} + \mathbf{c} \geq 0, \forall t \in (0, T)$

Multi-contact CoM trajectory generation for climbing

- Problem solution for parameterized CoM trajectory generation

Strategy 3	Necessary and sufficient condition to satisfy inequality over the given time horizon.

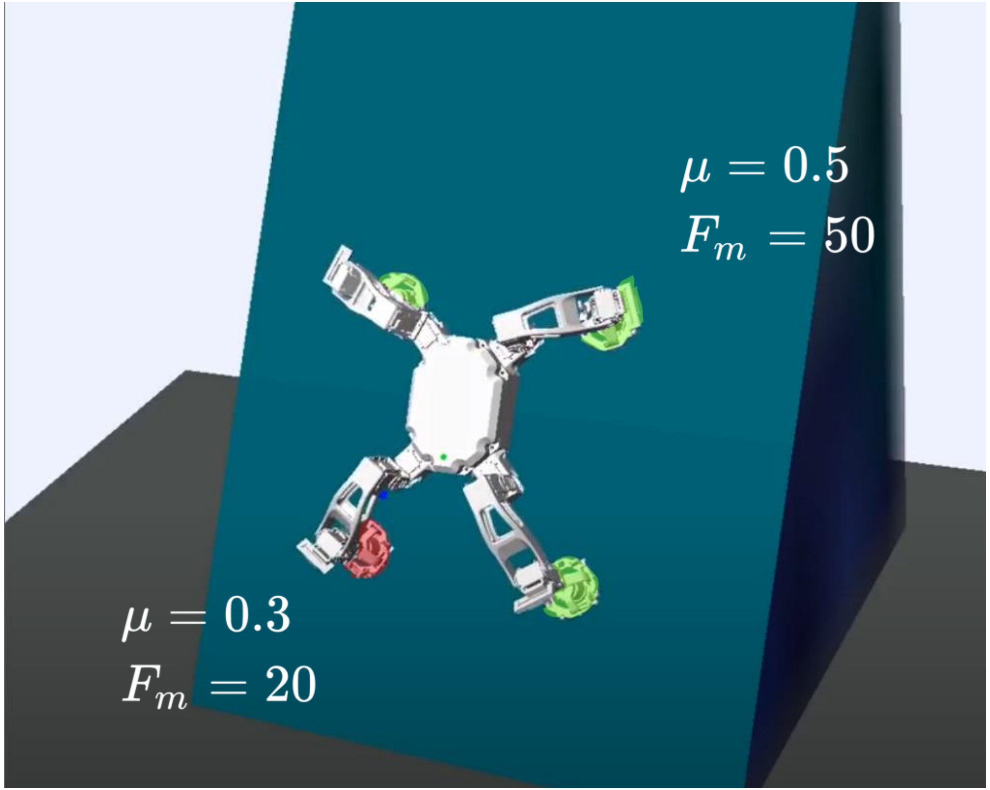
$$\min \quad \|\mathbf{x}\|^2,$$

subject to

$$\underbrace{\begin{bmatrix} \frac{1}{2} m f_{s,\min} \mathbf{D}_s \mathbf{A}_s^{-1} 1;3 [\mathbf{g}]_\times + m\gamma^* \mathbf{D}_s \mathbf{A}_s^{-1} 4;6 \\ \frac{1}{2} m f_{s,\max} \mathbf{D}_s \mathbf{A}_s^{-1} 1;3 [\mathbf{g}]_\times + m\gamma^* \mathbf{D}_s \mathbf{A}_s^{-1} 4;6 \\ \frac{1}{2} m f_{f,\min} \mathbf{D}_f \mathbf{A}_f^{-1} 1;3 [\mathbf{g}]_\times + m \mathbf{D}_f \mathbf{A}_f^{-1} 4;6 \\ \frac{1}{2} m f_{f,\max} \mathbf{D}_f \mathbf{A}_f^{-1} 1;3 [\mathbf{g}]_\times + m \mathbf{D}_f \mathbf{A}_f^{-1} 4;6 \end{bmatrix}}_{\mathbf{D}_x} \mathbf{x} + \underbrace{\begin{bmatrix} \mathbf{D}_s \mathbf{A}_s^{-1} \mathbf{c}_s \\ \mathbf{D}_s \mathbf{A}_s^{-1} \mathbf{c}_s \\ \mathbf{D}_f \mathbf{A}_f^{-1} \mathbf{c}_f \\ \mathbf{D}_f \mathbf{A}_f^{-1} \mathbf{c}_f \end{bmatrix}}_{\mathbf{d}_x} \geq 0$$

where $\mathbf{x} = \beta \mathbf{d} \in \mathbb{R}^3$, $\mathbf{D}_x \in \mathbb{R}^{70\times3}$, and $\mathbf{d}_x \in \mathbb{R}^{70}$

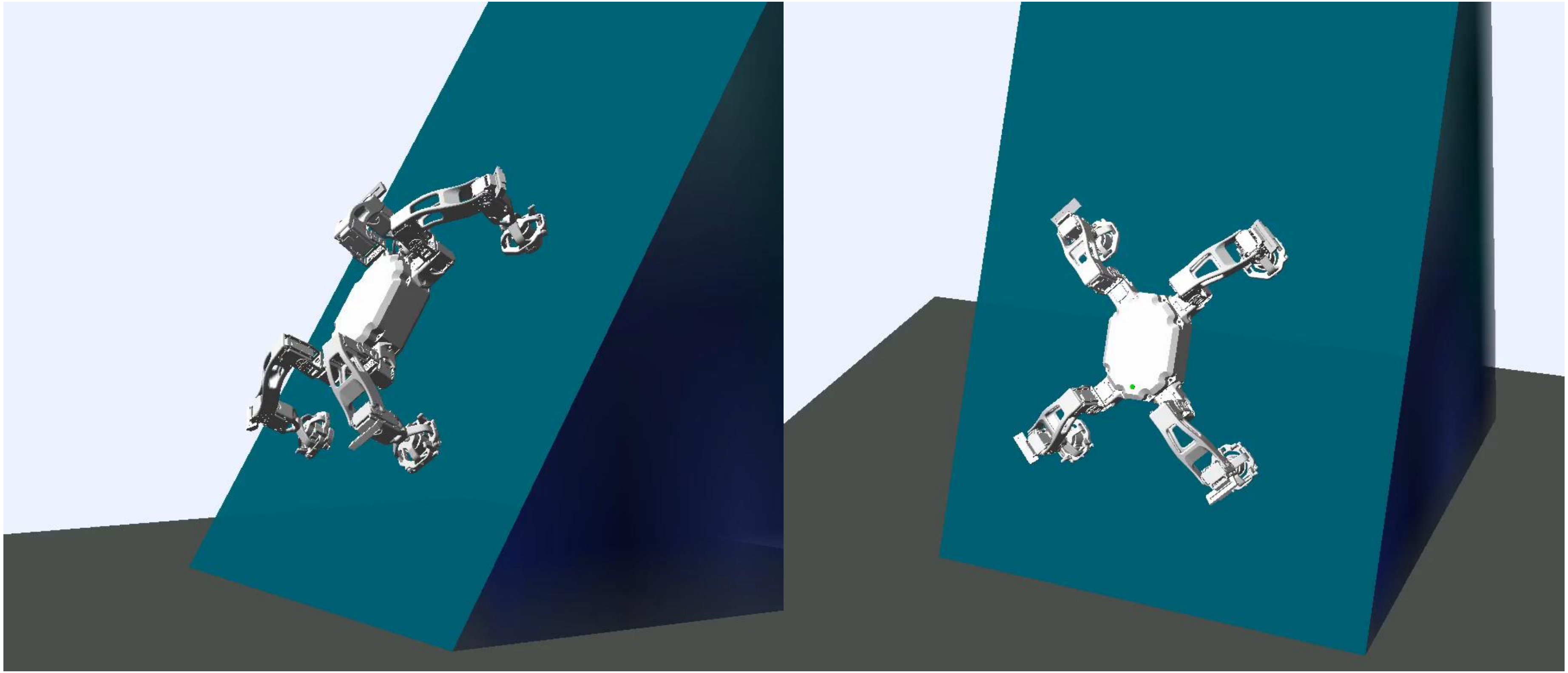
Multi-contact CoM trajectory generation for climbing



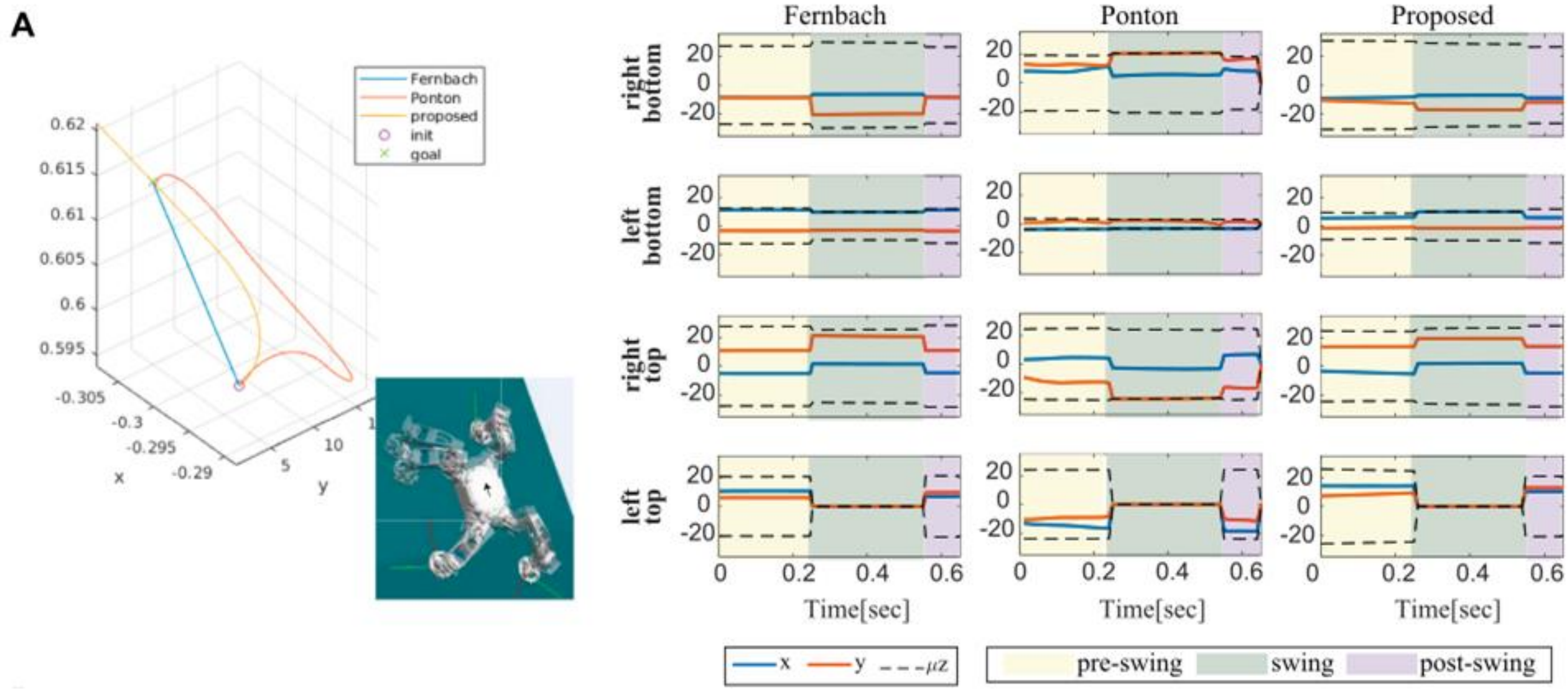
Scenario:

climbing on a flat slope
with weak adhesion
& slippery contact
at the left bottom foot

Multi-contact CoM trajectory generation for climbing

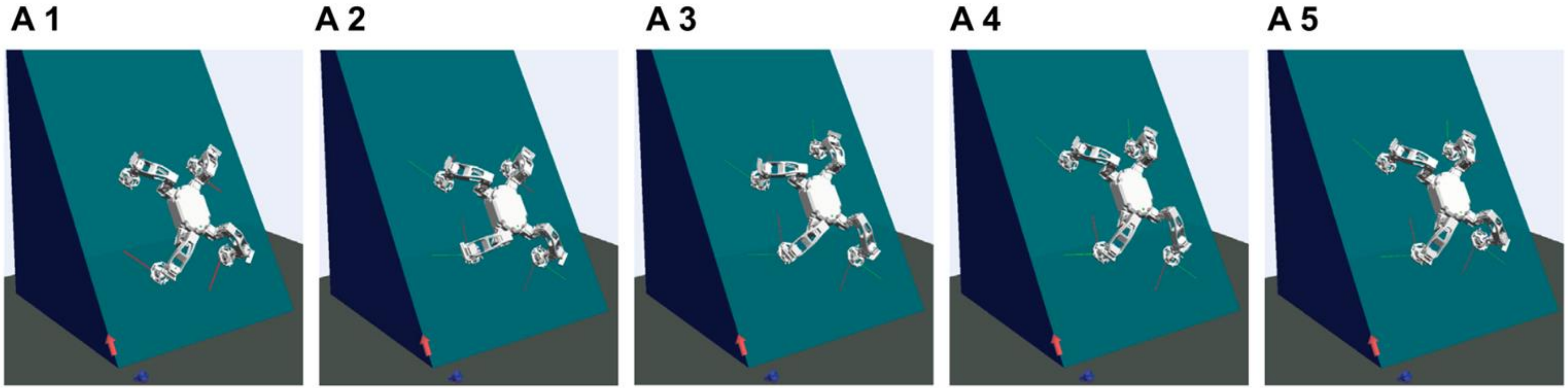


Comparison benchmark of CoM Trajectory Optimization



* Fernbach et al. “C-croc: Continuous and convex resolution of centroidal dynamic trajectories for legged robots in multicontact scenarios.” TRO 2022
* Ponton et al. “On time optimization of centroidal momentum dynamics.” ICRA 2018

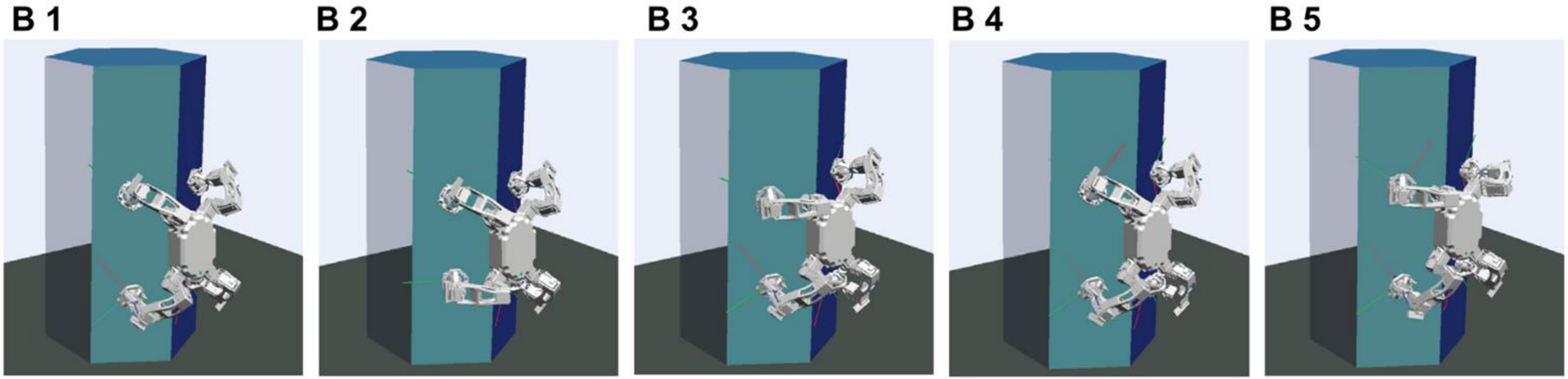
Comparison benchmark of CoM Trajectory Optimization



Computation time [ms] for flat slope climbing scenario(motion horizon = 0.65 s)

	Swing foot	Left bottom	Right top	Left top	Right bottom
	Proposed method	5.22e-02	5.23e-02	5.45e-02	5.67e-02
Method	Ponton et al. (2018) (ΔT = 10ms)	2,400	2,230	2,280	2,330
	Ponton et al. (2018) (ΔT = 50ms)	313	295	303	314
	Fernbach et al. (2020)	7.51	7.32	7.81	7.35

Comparison benchmark of CoM Trajectory Optimization



Computation time [ms] for hexagonal structure climbing scenario(motion horizon = 0.8s)

	Swing foot	Left bottom	Right top	Left top	Right bottom
	Proposed method	5.29e-02	5.78e-02	5.33e-02	5.91e-02
Method	Ponton et al. (2018) (ΔT = 50ms)	365	332	326	379
	Fernbach et al. (2020)	1.40	1.58	1.40	1.59

(ii) Contact parameter estimation and CoM re-planning

Contact parameter estimation and CoM re-planning

- Friction and magnetic adhesion force estimation
  - Frictional force(tangential) equation: $f_t = \sqrt{f_x^2 + f_y^2},$

$$\hat{f}_t = \hat{\mu}\left(f_z + \hat{f}_m\right),$$

  - Unknown environment parameters: $\boldsymbol{\theta} = [\hat{\mu}, \hat{\mu}\hat{f}_m]^\top$

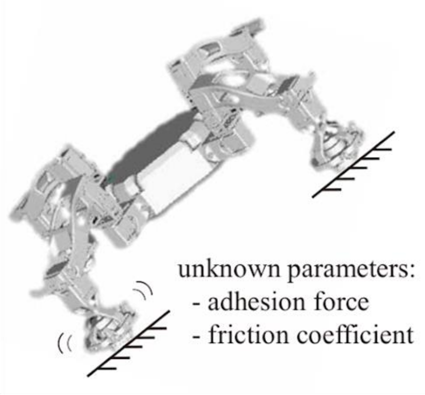
i) Least squares estimator

$$\begin{bmatrix} \sum f_z(t) & \sum 1 \\ \sum f_z(t)^2 & \sum f_z(t) \end{bmatrix} \begin{bmatrix} \hat{\mu} \\ \hat{\mu}\hat{f}_m \end{bmatrix} = \begin{bmatrix} \sum f_t(t) \\ \sum f_t(t) f_z(t) \end{bmatrix}$$

ii) Kalman filter like estimator

$$\boldsymbol{\theta}_{k+1} = \boldsymbol{\theta}_k + \mathbf{w}_k, \quad \mathbf{w}_k \sim \mathcal{N}(0, \mathbf{Q}_k),$$
$$\mathbf{z}_k = \mathbf{H}_k \boldsymbol{\theta}_k + \mathbf{v}_k, \quad \mathbf{v}_k \sim \mathcal{N}(0, \mathbf{R}_k),$$

$$\text{where} \quad \mathbf{z}_k = \begin{bmatrix} f_t(t_k - T + 1) \\ \vdots \\ f_t(t_k) \end{bmatrix}, \quad \mathbf{H}_k = \begin{bmatrix} f_z(t_k - T + 1) & 1 \\ \vdots & \vdots \\ f_z(t_k - T + 1) & 1 \end{bmatrix}$$



Kalman filter solution

$$\mathbf{K}_k = (\mathbf{P}_{k-1} + \mathbf{Q}_k)\mathbf{H}_k^\top \left(\mathbf{H}_k (\mathbf{P}_{k-1} + \mathbf{Q}_k)\mathbf{H}_k^\top + \mathbf{R}_k\right)^{-1}$$
$$\mathbf{P}_k = (\mathbf{I} - \mathbf{K}_k\mathbf{H}_k)(\mathbf{P}_{k-1} + \mathbf{Q}_k),$$
$$\hat{\boldsymbol{\theta}}_k = \hat{\boldsymbol{\theta}}_{k-1} + \mathbf{K}_k\left(\mathbf{z}_k - \mathbf{H}_k\hat{\boldsymbol{\theta}}_{k-1}\right).$$

Contact parameter estimation and CoM re-planning

- Friction and magnetic adhesion force estimation

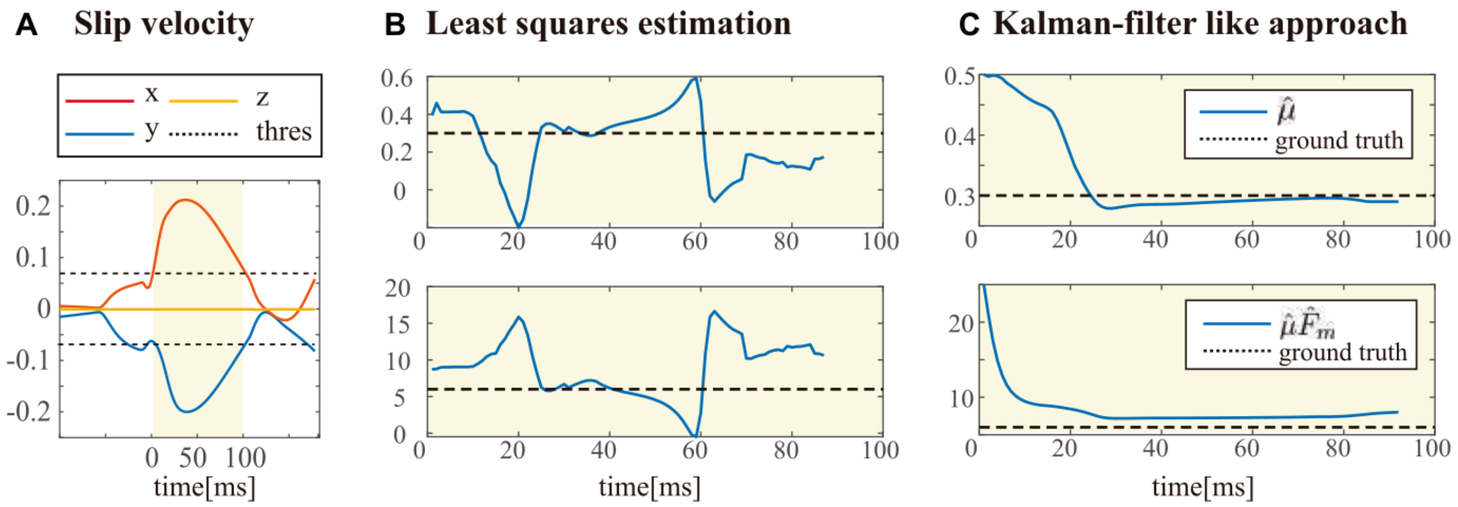


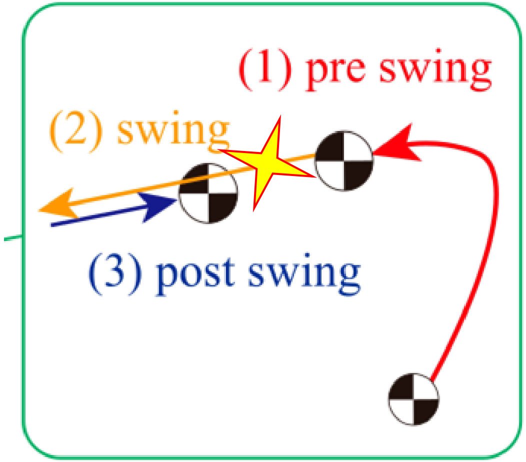
FIGURE 6

Estimation of unknown environment parameters = $[\mu, \mu F_m]^T$ during the slip condition. **(A)** shows the condition of the estimation activation. Once the contact velocity exceeds the threshold during the certain amount of time, we declare the slip detection so that the estimation can be executed. Yellow areas in the plots represent where the estimation is activated. **(B)** and **(C)** present the resulting estimation obtained by two different approaches, least-squares, and Kalman filter–like approach.

Contact parameter estimation and CoM re-planning

- CoM re-planning for slip reflex

CoM replanning required during the swing phase?



	(2) Swing	(3) Post swing
T (duration)	$T_2' = T_2 - t_{\text{now}}$	T_3
$\mathbf{p}_i$ (init position)	$\mathbf{p}_a$	$\mathbf{p}_1$
$\mathbf{p}_g$ (goal position)	$\mathbf{p}_1 = \mathbf{p}_a + \frac{1}{2}\alpha T_2'^2 \mathbf{d}$	$\mathbf{p}_b$
$\mathbf{v}_i$ (init velocity)	$\mathbf{0}$	$\mathbf{v}_1$
$\mathbf{v}_g$ (goal velocity)	$\mathbf{v}_1 = \alpha T_2' \mathbf{d}$	$\mathbf{0}$

➡ Similarly, we can formulate the reduced problem

$$\begin{aligned} \min \quad & \|\mathbf{x}\|^2, \\ \text{subject to} \quad & \mathbf{D}_x' \mathbf{x} + \mathbf{d}_x' \geq 0 \end{aligned}$$

(iii) Online weight adaptation to stabilize slippery motions

Online weight adaptation to stabilize slippery motions

$$\min_{\delta\ddot{\mathbf{q}},\mathbf{F}_r,\ddot{\mathbf{x}}_c}, \quad \delta\ddot{\mathbf{q}}^\top \mathbf{W}_{\ddot{\mathbf{q}}}\delta\ddot{\mathbf{q}} + \mathbf{F}_r^\top \mathbf{W}_f \mathbf{F}_r + \ddot{\mathbf{x}}_c^\top \mathbf{W}_c \ddot{\mathbf{x}}_c,$$

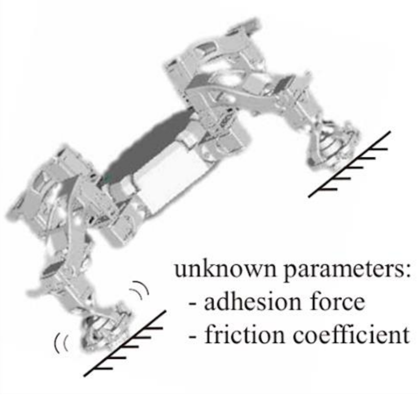
$$\begin{bmatrix} fx \\ fy \\ fz \\ \vdots \end{bmatrix}^\top \begin{bmatrix} \omega_{fx} & 0 & 0 & \cdots \\ 0 & \omega_{fy} & 0 & \cdots \\ 0 & 0 & \omega_{fz} & \cdots \\ \vdots & \vdots & \vdots & \ddots \end{bmatrix} \begin{bmatrix} fx \\ fy \\ fz \\ \vdots \end{bmatrix}$$

- Slippage rate: α_s (>1, bigger if more slip)

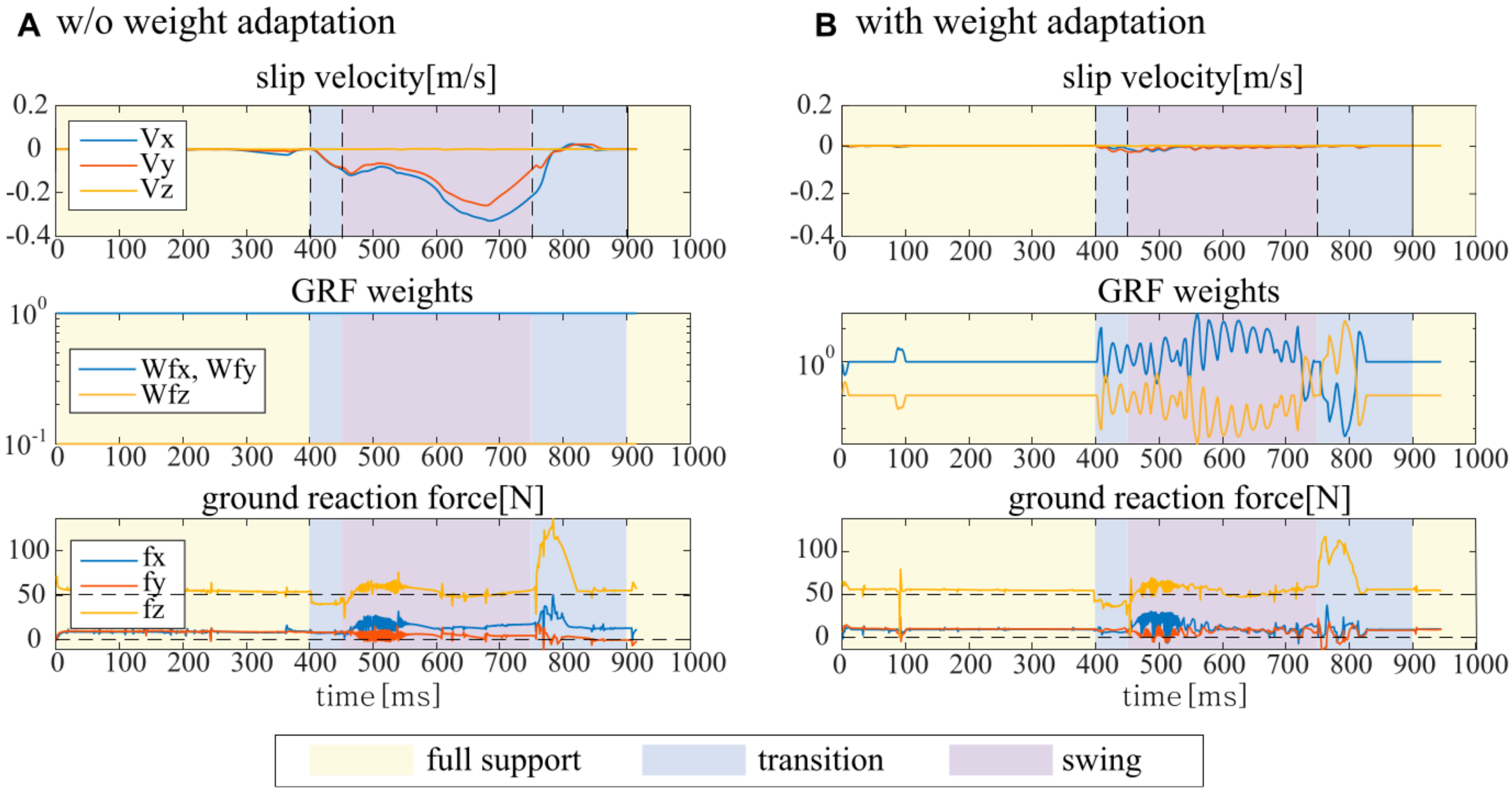
$$\alpha_s = \begin{cases} 1 & \text{if } \|\mathbf{v}_{\text{contact foot}}\| \le v_{\text{threshold}} \\ \dfrac{\|\mathbf{v}_{\text{contact foot}}\|}{v_{\text{threshold}}} & \text{otherwise} \end{cases}$$

- Weight adaptation to the slippage

$$\Rightarrow \quad w_{fx_i}, w_{fy_i} = \begin{cases} \alpha_{si} w_{xy}, \\ \dfrac{1}{\alpha_{si}} w_{xy}, \end{cases} \text{and}, w_{fz_i} = \begin{cases} \dfrac{1}{\alpha_{si}} w_z, & \text{if } \alpha_{si} > 1, \\ \alpha_{si} w_z, & \text{otherwise.} \end{cases}$$



Slippage reduction performance of weight adaptation



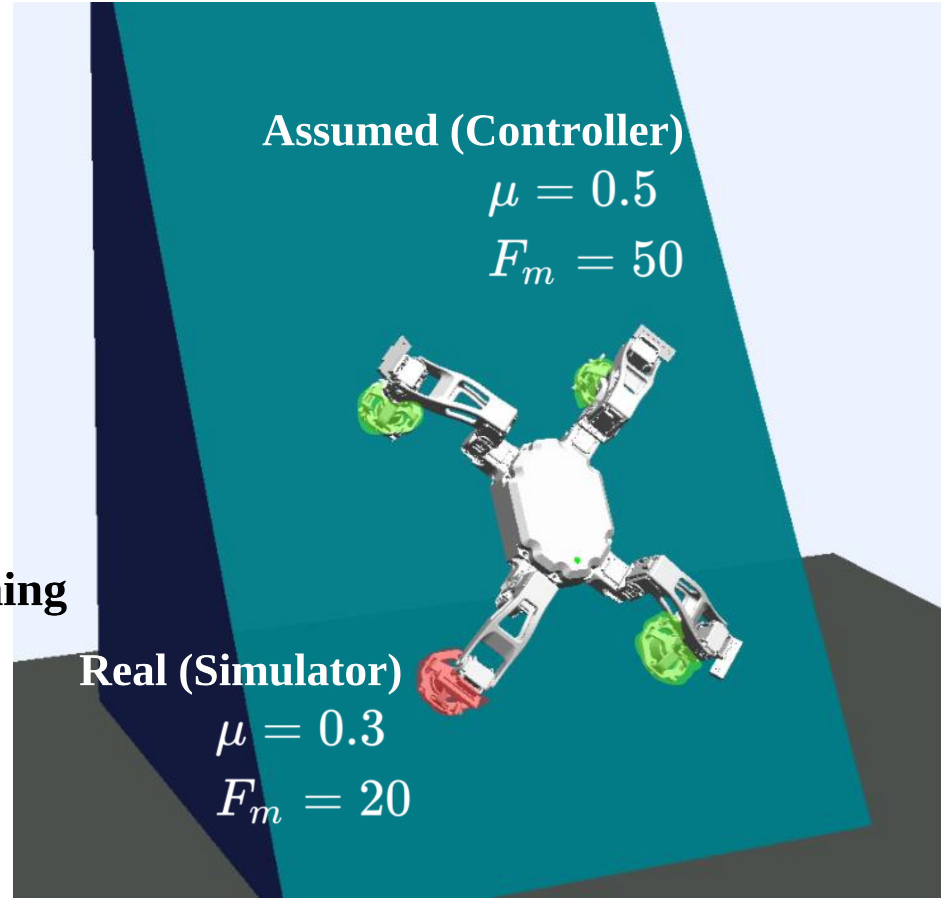
Simulation Results

Climbing in unknown slippery conditions

Scenario

Climbing on a flat slope with
one foot in unknown slippery condition

A. **Without Any Adaptation**
B. **Parameter Estimation + CoM Replanning**
C. **Online Weight Adaptation**
D. **Both Strategies(B & C)**



1. W/O any adaptation

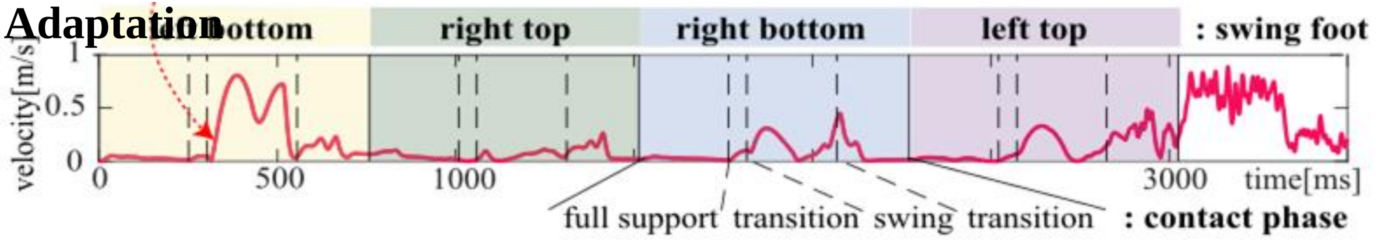
2. Param Estimation + CoM Replanning

3. Weight Adaptation for QP-based WBC

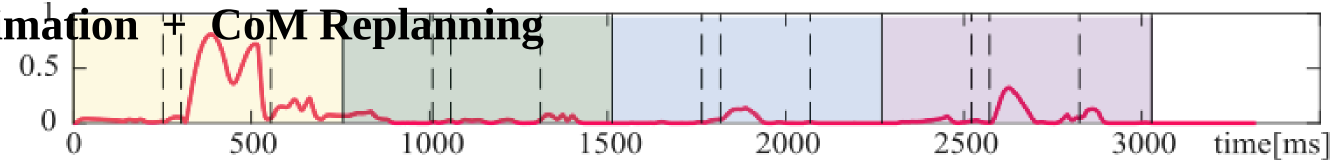
4. Both (replanning+weight adaptation)

Velocity of the left bottom foot (in unknown slippery condition)

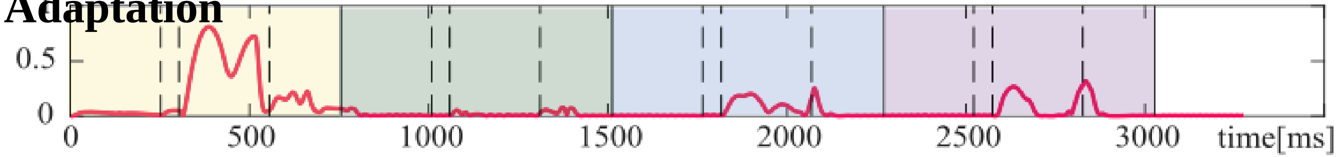
A. Without Any Adaptation



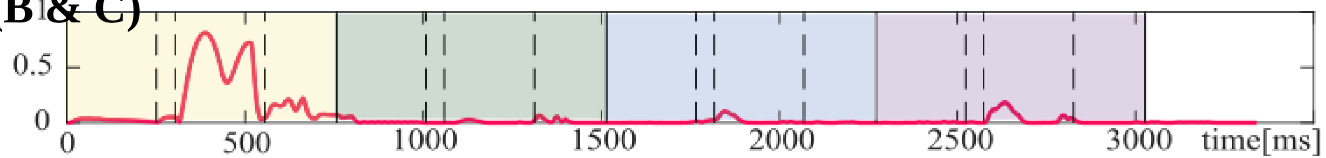
A. Parameter Estimation + CoM Replanning



A. Online Weight Adaptation



A. Both Strategies(B & C)



Thank you for listening!

Q&A