CLAWAR
02 Oct - 04 Oct 2023 FLORIANÓPOLIS, BRAZIL

Mobility Strategy of Multi-Limbed Climbing Robots for Asteroid Exploration

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[1]Tohoku University, Department of Aerospace Engineering

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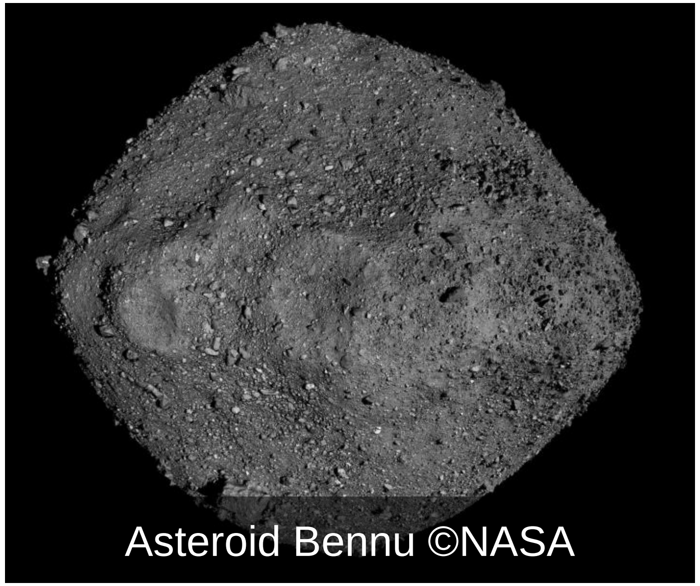
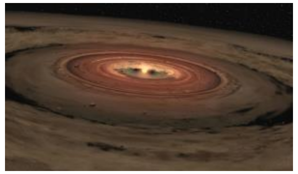
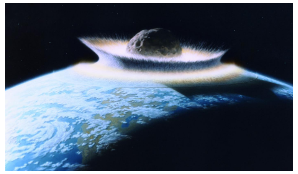
Introduction – Background

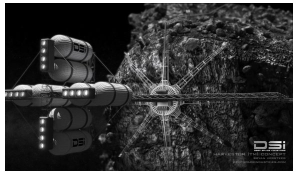
Importance of asteroids exploration[1]

- **Scientific**: asteroids could hold key information about the Solar System
- **Safety**: preventing potential hazardous impacts with Earth
- **Mining**: mine valuable materials for continuous space exploration


Asteroid Bennu ©NASA








Asteroid mining concept ©DSI/Bryan Versteeg

Robotic exploration of asteroids could be more efficient and safer

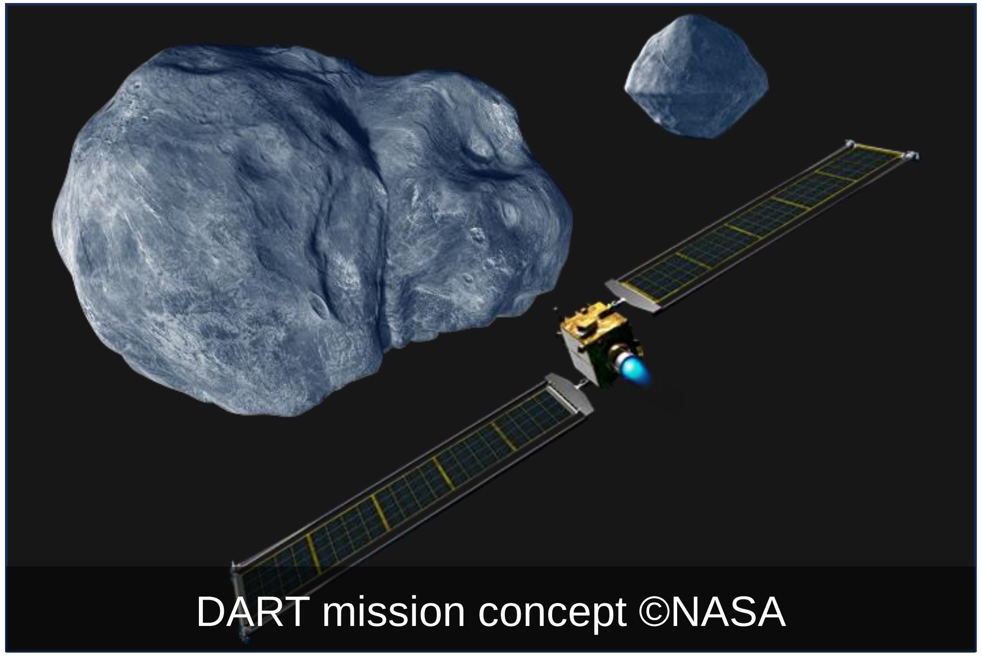
[1] V. Badescu, *Asteroids: Prospective energy and material resources*. (2013)

Introduction – Background

Robotic Exploration of Asteroids

- **Hayabusa2**: Collect samples to study asteroid composition[2]
- **DART**: Test asteroid trajectory deflection[3]


Hayabusa2 mission concept ©JAXA

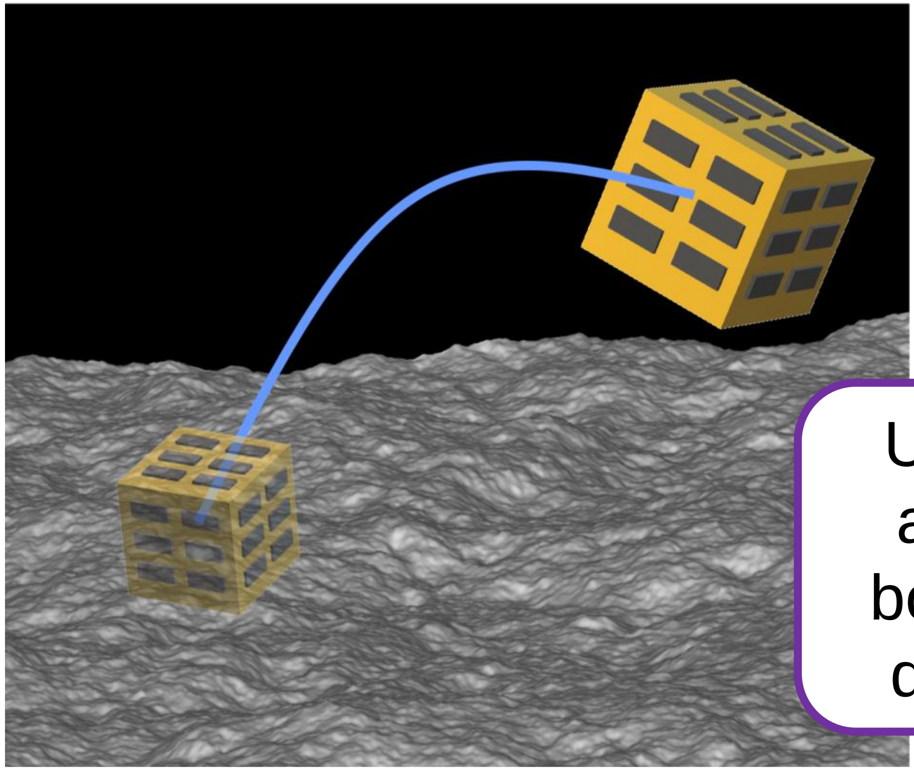

DART mission concept ©NASA

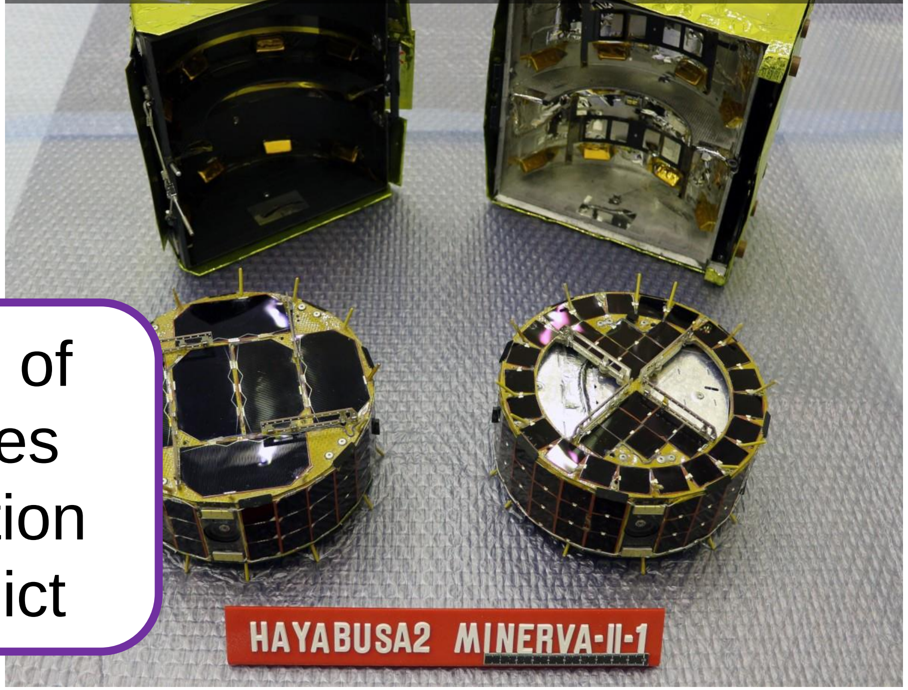
[2] Watanabe, S. *et al*.: Hayabusa2 mission overview. *Space Science Reviews*. **208**(1), 3–16 (2017)
[3] Reichert, S.: DART hits the bullseye. *Nature Physics*. **19**(4), 471 (2023)

Introduction – Related Works

In-situ Exploration of Asteroids using **Mobile Robots**

- Hopping Robots[4]





MINERVA-II-1 Rovers ©JAXA

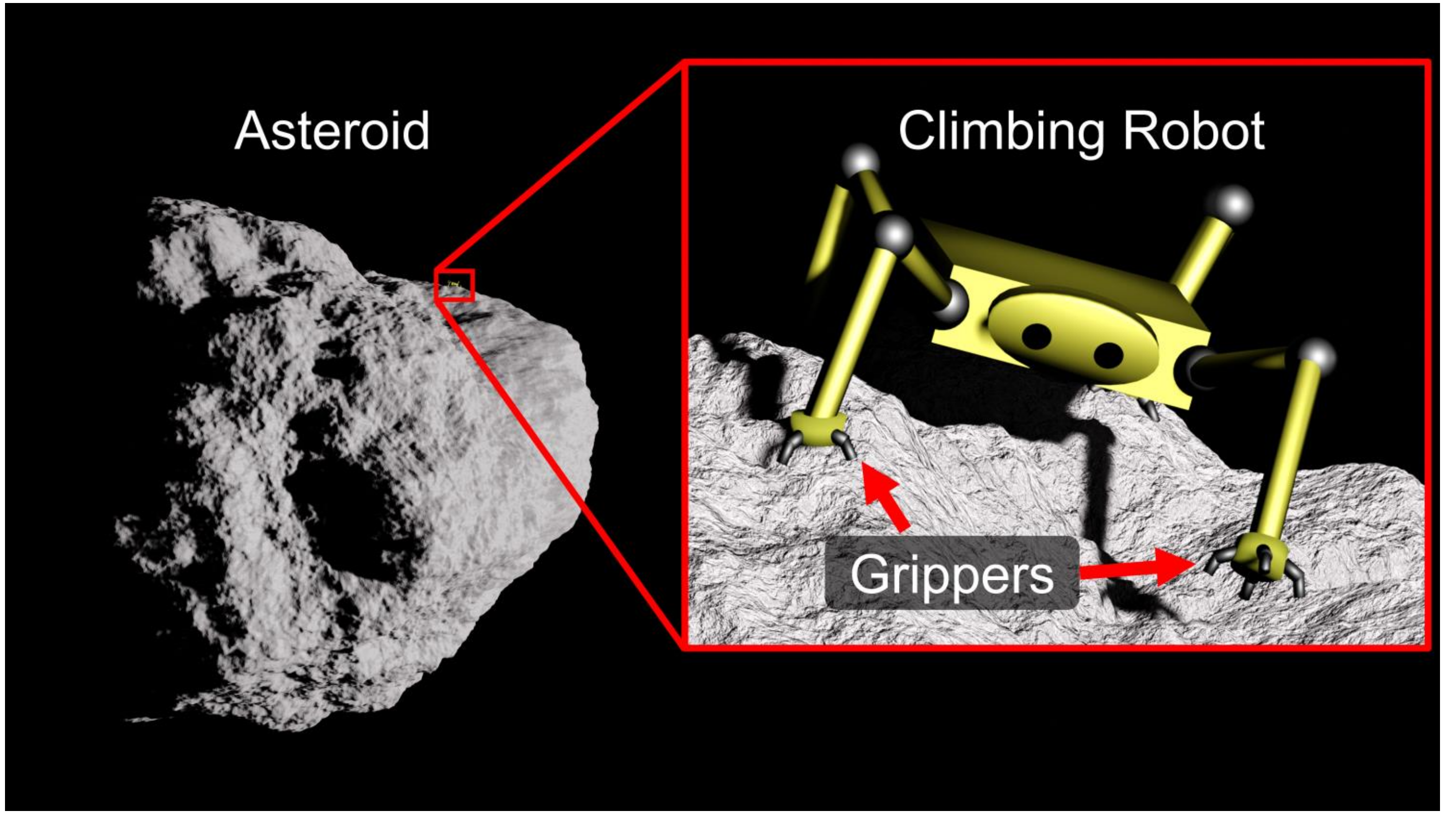
Uneven terrain of asteroids makes bouncing direction difficult to predict

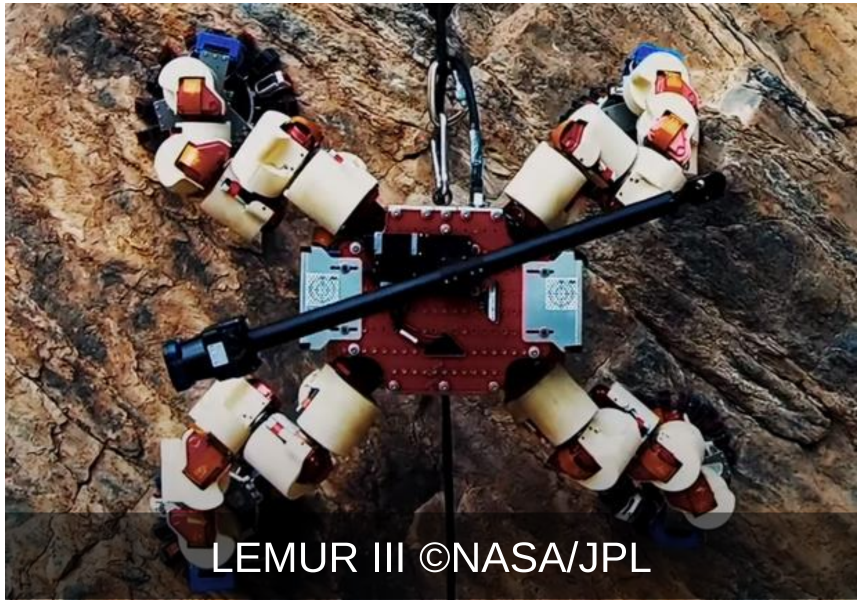
[4] Yoshimitsu, T., Kubota, T.: Asteroid surface exploration by Minerva-II small rovers. *18th Annual Meeting of the Asia Oceania Geosciences Society*. (2022)

Introduction – Related Works

In-situ Exploration of Asteroids using **Mobile Robots**

- Multi-Legged Climbing Robots[5]

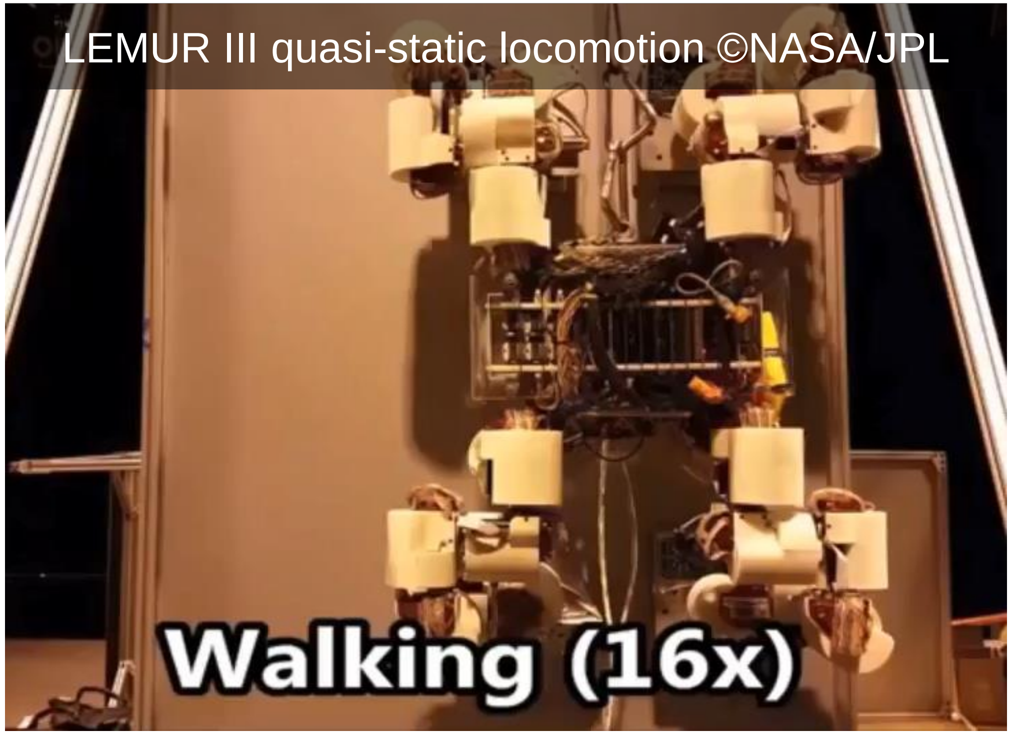


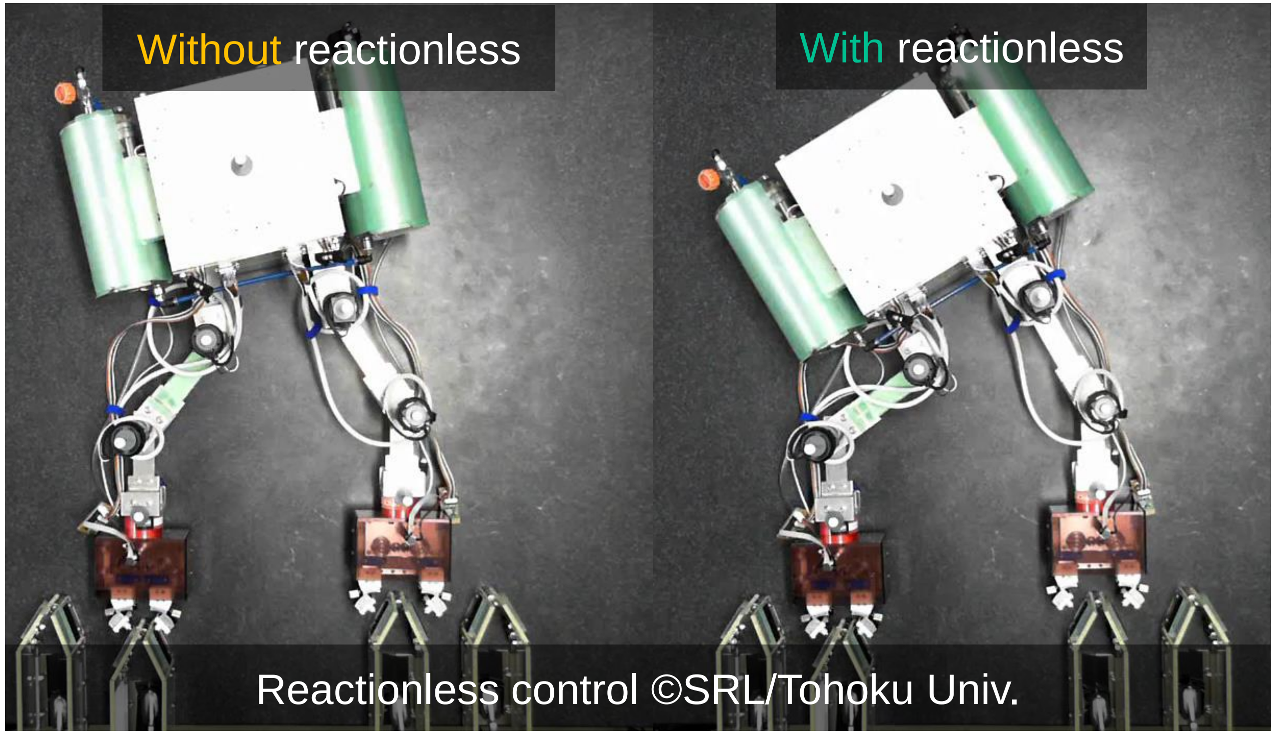


[5] Parness, A. *et al*.: Lemur 3: A limbed climbing robot for extreme terrain mobility in space. *IEEE ICRA*. (2017)

Introduction – Related Works

- **Mobility of Legged Robots** on Asteroids
  - Quasi-static locomotion[5]
  - Reactionless control[6]





[5] Parness, A. *et al*.: Lemur 3: A limbed climbing robot for extreme terrain mobility in space. *IEEE ICRA*. (2017)
[6] Yuguchi, Y. *et al*.: Analysis on motion control based on reaction null space for ground grip robot on an asteroid. *Trans. of JSASS*. (2016)

Introduction – Objective

Objective and Contributions

Propose a locomotion method for limbed robots on asteroids

Contributions:

- **Mobility strategy**:
  - Feasible gait planning with base adjustment to avoid collisions
  - Low-reaction motion planning to prevent gripper slippage
- **Validation**:
  - Multi-limbed robot simulation on rough surface
  - Bipedal robot experiment on emulated microgravity

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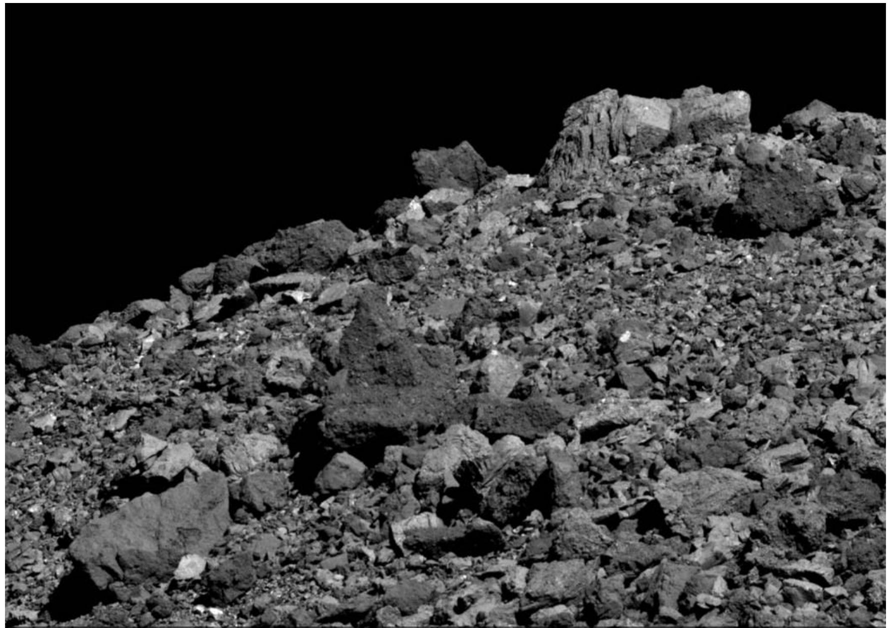
Mobility Strategy

Issues for mobility on asteroids

- **Rough terrain**: easy to collide with the surface
- **Microgravity**: easy to float away from the surface



Asteroid Bennu surface ©NASA

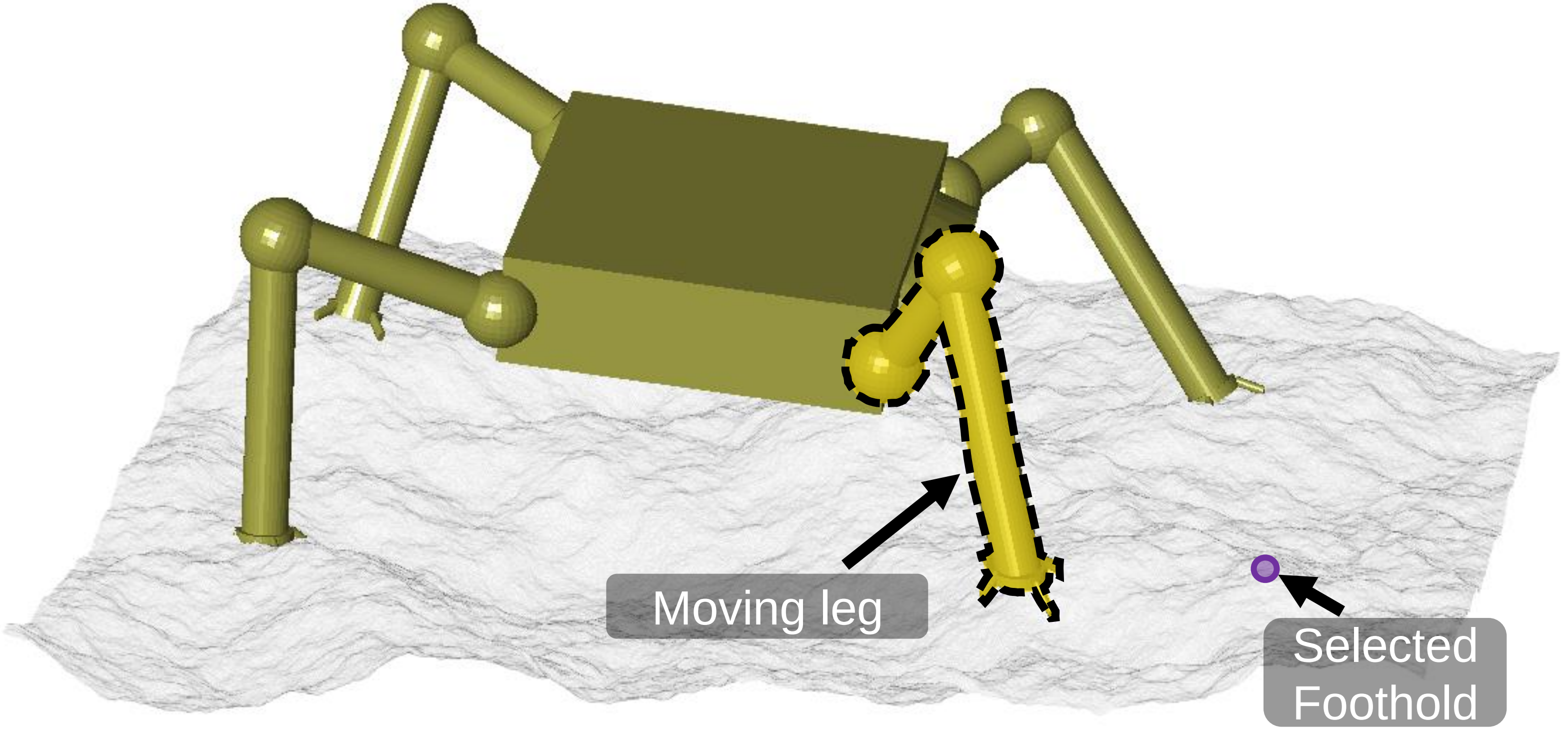
Floating food in the ISS ©Chris Hadfield/CSA/NASA

Gait Planning

Foothold selection:

- Assumptions (for simplification):
  - Periodic gait
  - Robot can grasp anywhere

Any **feasible** foothold selection or leg sequence applies

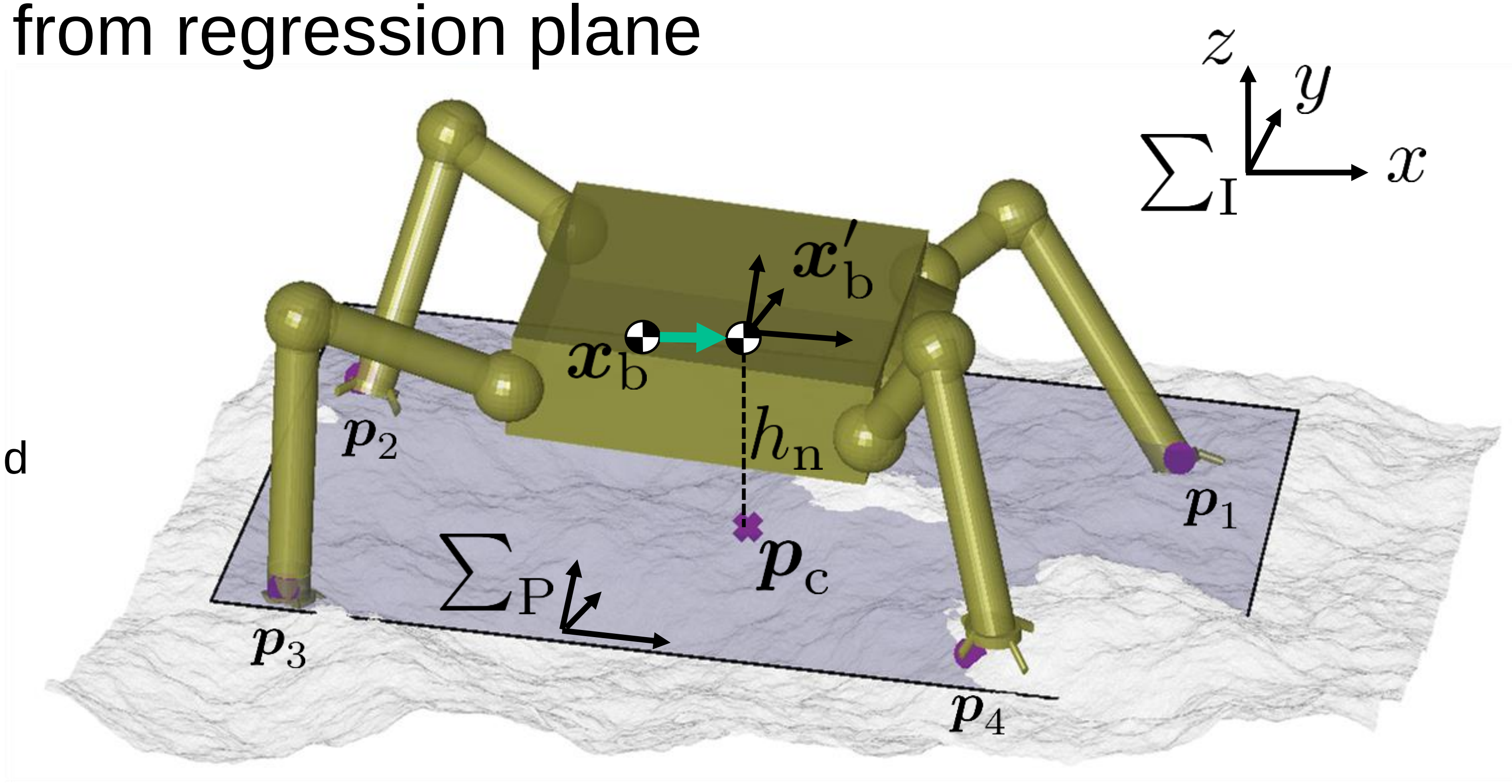


Gait Planning

Base movement:

- Separation from limb's motion
  - Base motion can be used during swinging phase
- New position/orientation from regression plane

$\boldsymbol{x}_b$: Initial Base Pose
Σ_I : Inertial Frame
$\boldsymbol{p}_1, \cdots, \boldsymbol{p}_n$: Contact positions
$\boldsymbol{p}_c$: Regression Plane Centroid
h_n : Nominal Height
Σ_P: Regression Plane Frame
$\boldsymbol{x}'_b$: New Base Pose



Gait Planning

Base movement:

- Collision avoidance (assuming map information is available)
  - Vertical base position to avoid collision:

$$x'_{b_z} = p_{c_z} + h_{\mathrm{n}} + \max(|d_{\mathrm{coll}}|) + h_{\mathrm{add}}$$

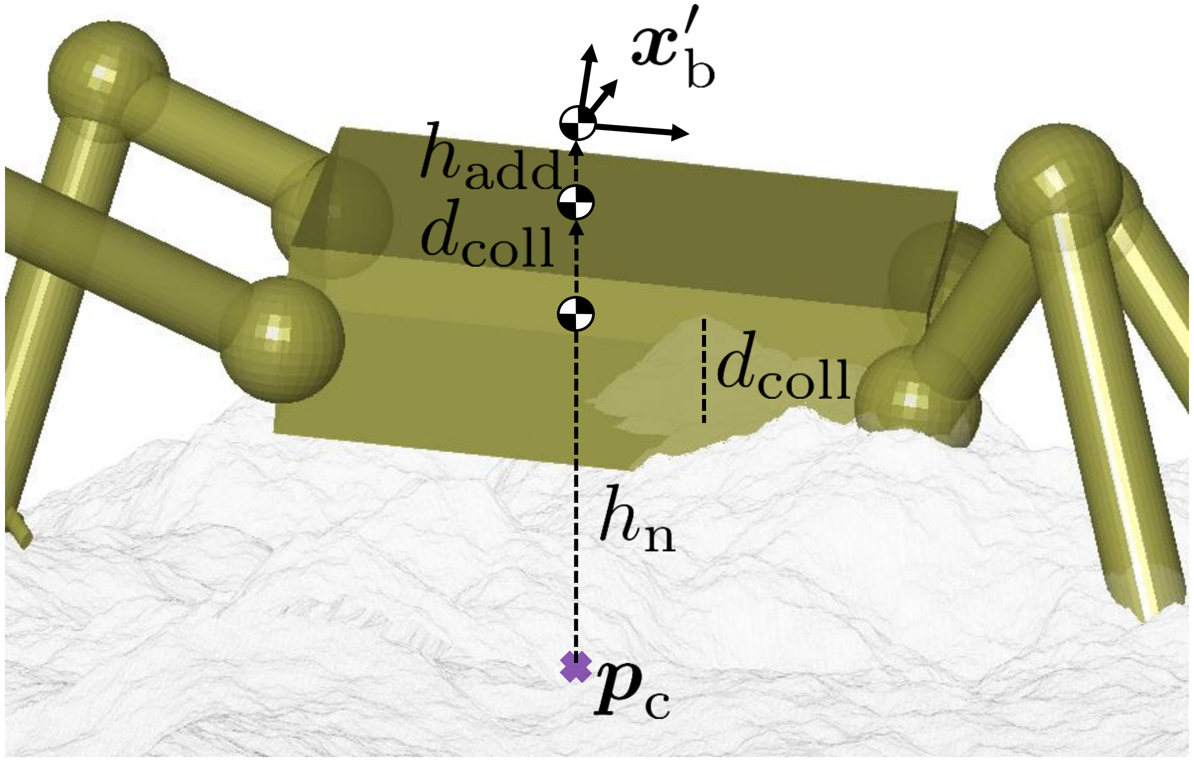
$\boldsymbol{p}_c$: Regression Plane Centroid

h_n : Nominal Height

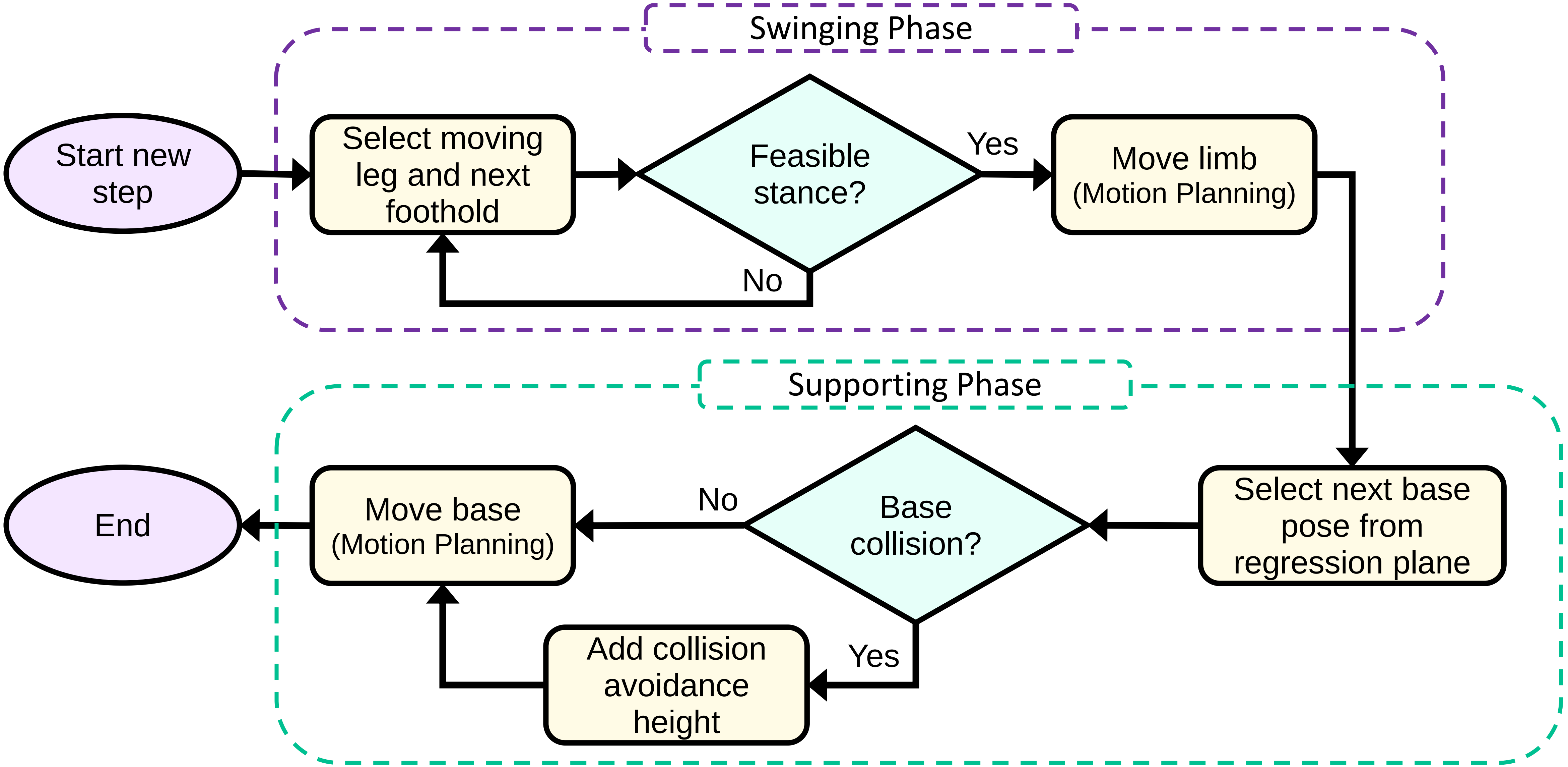
d_{coll} : Collision Depth

h_{add} : Additional Safety Height

$\boldsymbol{x}'_b$: New Base Pose



Gait Planning – Flowchart

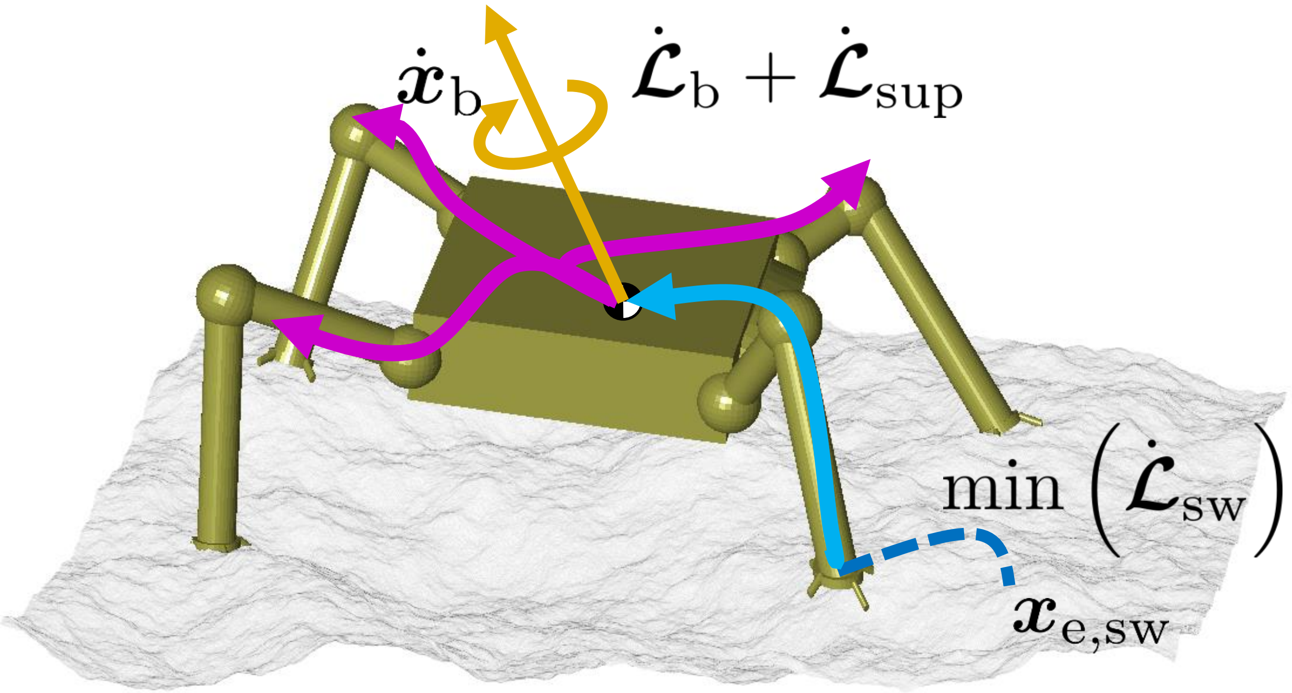


Motion Planning

Reaction-Aware Motion Planning (**RAMP**) overview[7]

- Combines 2 strategies:
  - Low-Reaction Swing Trajectory
  - Distribution of momentum

Reduce change in momentum to avoid gripper slippage due to excessive reactions



[7] Ribeiro, W.F.R. *et al.*: RAMP: Reaction-aware motion planning of multi-legged robots for locomotion in microgravity. *IEEE ICRA*. (2023)

Motion Planning – LRST

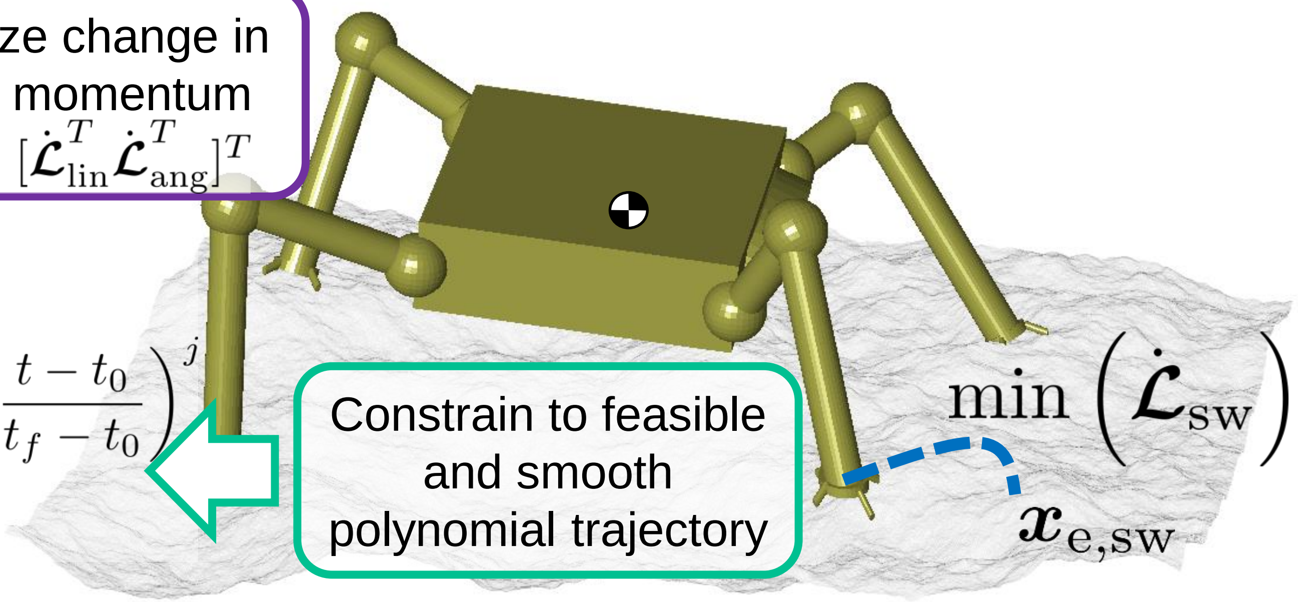
Low-Reaction Swing Trajectory:[8]

- Plan swinging trajectory with minimum swing momentum change
  - Optimization Problem:

$$
\begin{aligned}
\min_{\boldsymbol{A}_{B3},\boldsymbol{A}_{B4}} \quad & C_1 \max\left(\left|\dot{\boldsymbol{\mathcal{L}}}_{\text{lin}}(t)\right|\right) \\
& + C_2 \max\left(\left|\dot{\boldsymbol{\mathcal{L}}}_{\text{ang}}(t)\right|\right) \\
& + C_3 \left|h_{\text{sw}} - \max\left(x_{\text{e,sw}_z}(t)\right)\right| \\
\text{s. t.} \quad & \boldsymbol{x}_{e,\text{sw}}(t) = \sum_{j=0}^{7} \boldsymbol{A}_{Bj} \binom{7}{j} \left(\frac{t_f - t}{t_f - t_0}\right)^{7-j} \left(\frac{t - t_0}{t_f - t_0}\right)^{j} \\
& \phi_{\text{sw,min}} \leq \phi_{\text{sw}}(t) \leq \phi_{\text{sw,max}}
\end{aligned}
$$

Minimize change in swing momentum $\dot{\boldsymbol{\mathcal{L}}}_{\text{sw}} = [\dot{\boldsymbol{\mathcal{L}}}_{\text{lin}}^T \dot{\boldsymbol{\mathcal{L}}}_{\text{ang}}^T]^T$

Constrain to feasible and smooth polynomial trajectory



[8] Ribeiro, W.F.R. *et al.*: Low-reaction trajectory generation for a legged robot in microgravity. *IEEE/SICE SII*. (2022)

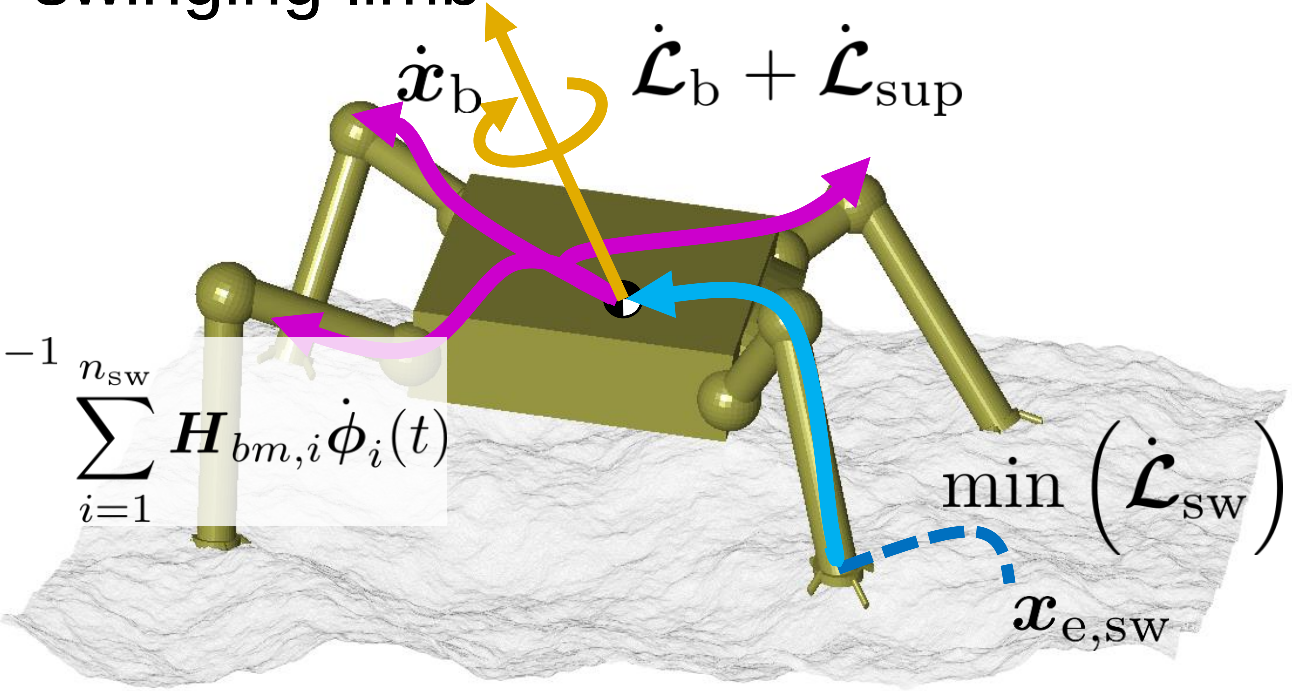
Motion Planning – MD

Momentum Distribution:[7]

- Plan the remaining body part's motion to compensate at least part of momentum change caused by swinging limb

$$\boldsymbol{\mathcal{L}} = \boldsymbol{\mathcal{L}}_{\mathrm{b}} + \boldsymbol{\mathcal{L}}_{\mathrm{sup}} + \boldsymbol{\mathcal{L}}_{\mathrm{sw}} = 0$$

$$\boldsymbol{\mathcal{L}}_{\mathrm{b}} + \boldsymbol{\mathcal{L}}_{\mathrm{sup}} = -\alpha \boldsymbol{\mathcal{L}}_{\mathrm{sw}}$$



- Base velocity

$$\dot{\boldsymbol{x}}_b(t) = -\alpha \left(\boldsymbol{H}_b - \sum_{i=1}^{n_{\mathrm{sup}}} \boldsymbol{H}_{bm,i} \boldsymbol{J}_{m,i}^{+} \boldsymbol{J}_{b,i} \right)^{-1} \sum_{i=1}^{n_{\mathrm{sw}}} \boldsymbol{H}_{bm,i} \dot{\boldsymbol{\phi}}_i(t)$$

Momentum Distribution Factor α dictates how much momentum is distributed

[7] Ribeiro, W.F.R. *et al.*: RAMP: Reaction-aware motion planning of multi-legged robots for locomotion in microgravity. *IEEE ICRA*. (2023)

Motion Planning – MD

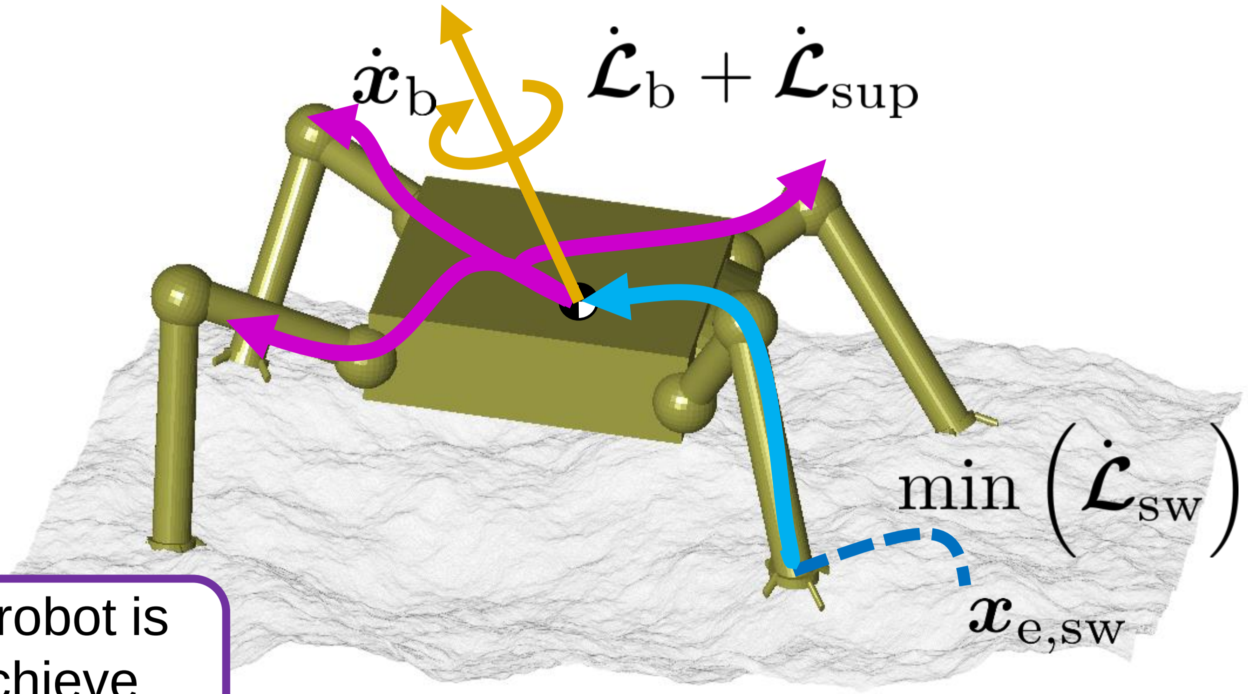
Momentum Distribution:[7]

- Definition of momentum distribution factor from manipulability

Momentum Distribution can cause the robot to reach unfeasible configurations due to extra motion

$$\alpha(t) = \frac{\min\left(w_i(t)\right) - w_{\min}}{w_{\max} - w_{\min}}$$

$$w_i(t) = \sqrt{\det\left(\boldsymbol{J}_{m,i}(t)\boldsymbol{J}_{m,i}(t)^T\right)}$$



By distributing less momentum when the robot is close to unfeasible configurations, we achieve feasible motions with low reactions

[7] Ribeiro, W.F.R. *et al.*: RAMP: Reaction-aware motion planning of multi-legged robots for locomotion in microgravity. *IEEE ICRA*. (2023)

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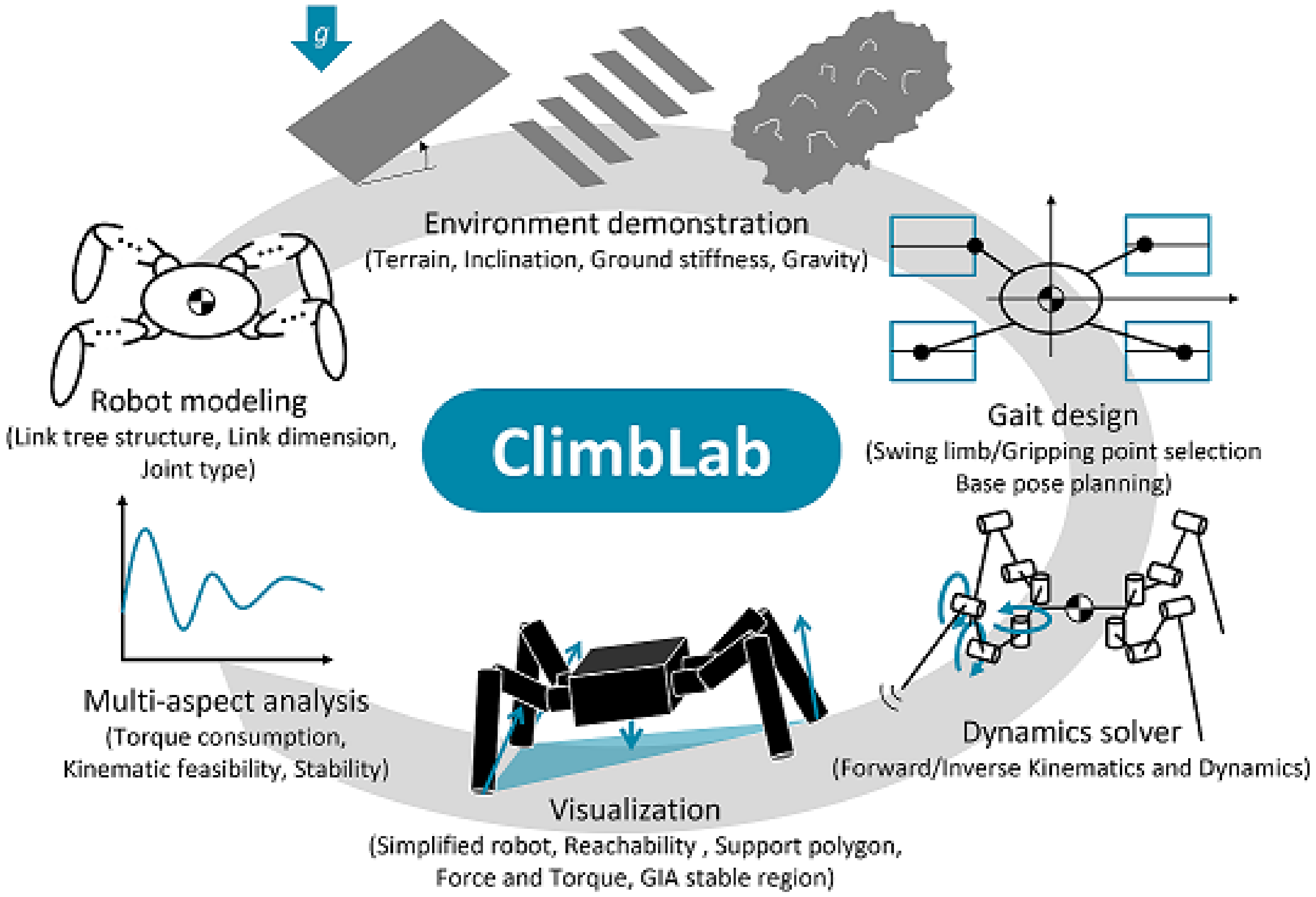
Simulations

ClimbLab:[9]

- Dynamic simulator in MATLAB focused on climbing robots
- Possible to model different robots and environments, and test different locomotion patterns



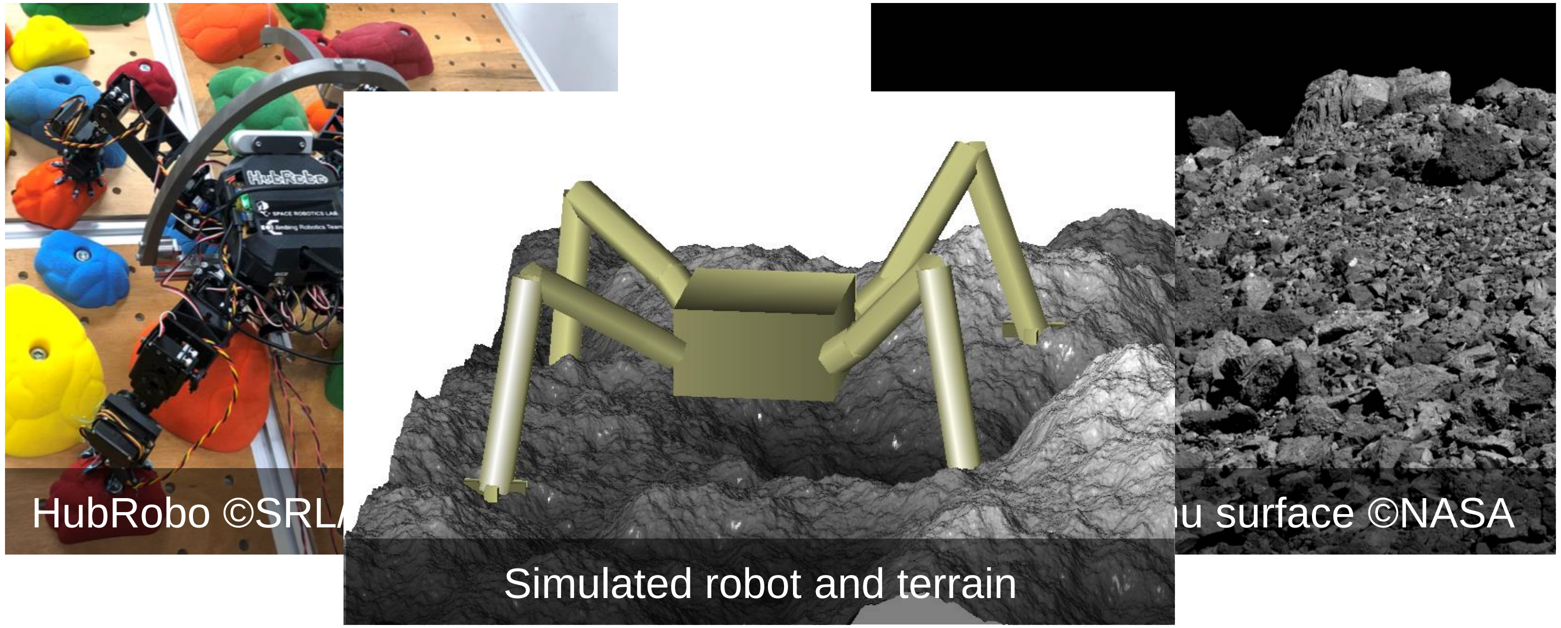
[9] Uno, K. *et al.*: ClimbLab: MATLAB simulation platform for legged climbing robotics. *CLAWAR*. (2022)

Simulations

- **Objective:**
  - Test proposed mobility strategy for multi-limbed climbing robot on rough terrain
  - Compare with baseline traditional strategy (no base collision avoidance, no RAMP)

Conditions:

- Robot model: HubRobo[10]
- Terrain model: Fractal, 30 mm std. dev.
- Gravity: 10^{-6} G
- Max. holding force: 0.9 N
- Swinging period: 1.75 s
- Supporting period: 1.75 s
- Step stride: 8 cm
- Step height: 4 cm
- LRST coeff.: C_1 = 7, C_2 = 1.75, C_3 = 30



HubRobo ©SRL/

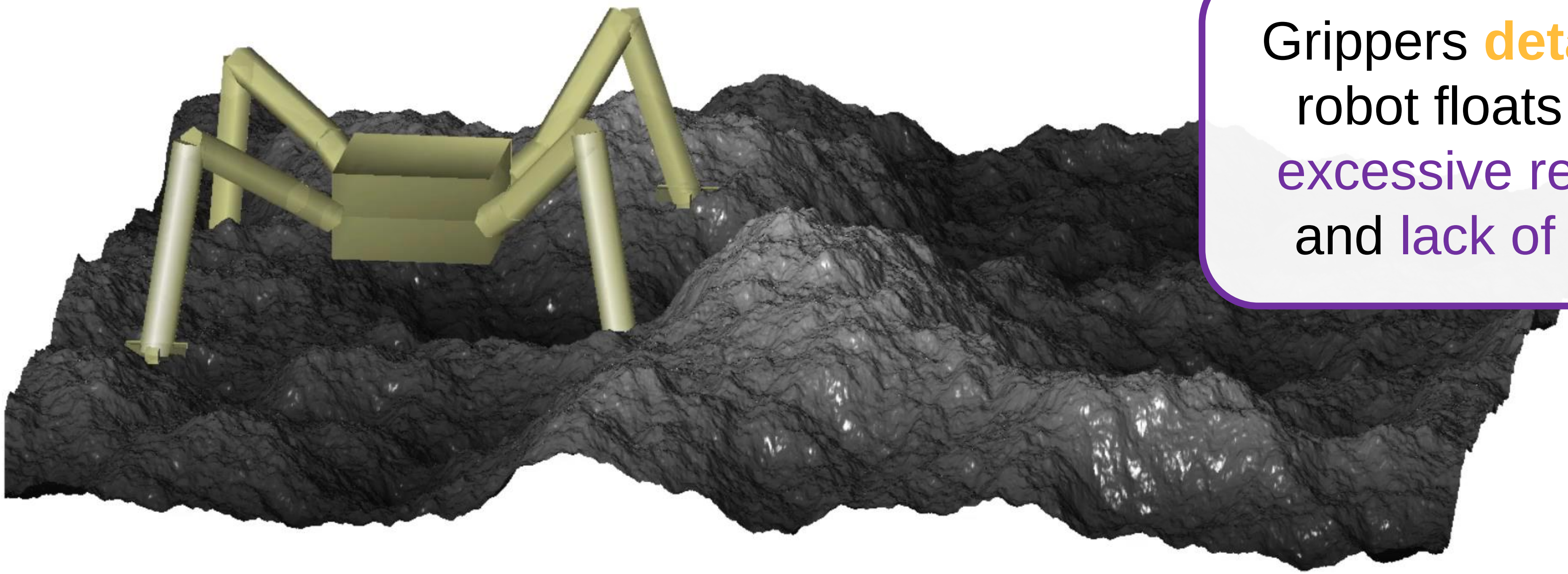
…u surface ©NASA

Simulated robot and terrain

[10] Uno, K. *et al*.: Hubrobo: a lightweight multi-limbed climbing robot for exploration in challenging terrain. *IEEE Humanoids*. (2021)

Simulations

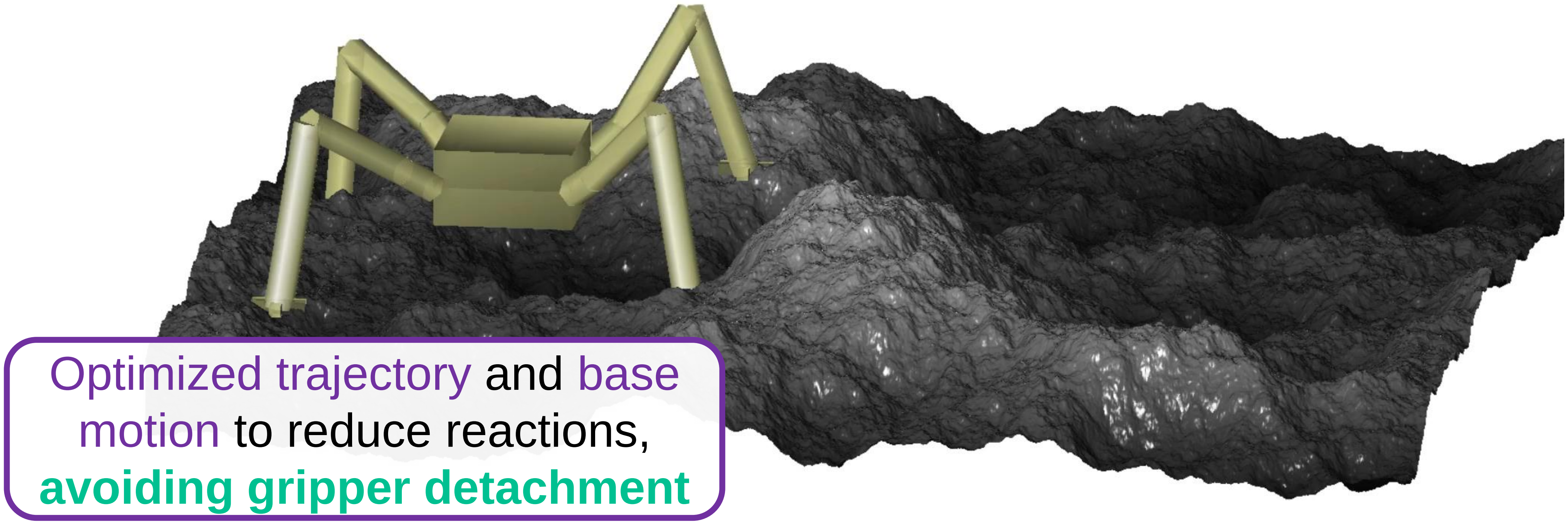
Simulation **without** proposed strategy



Grippers **detach** and robot floats due to excessive reactions and lack of gravity

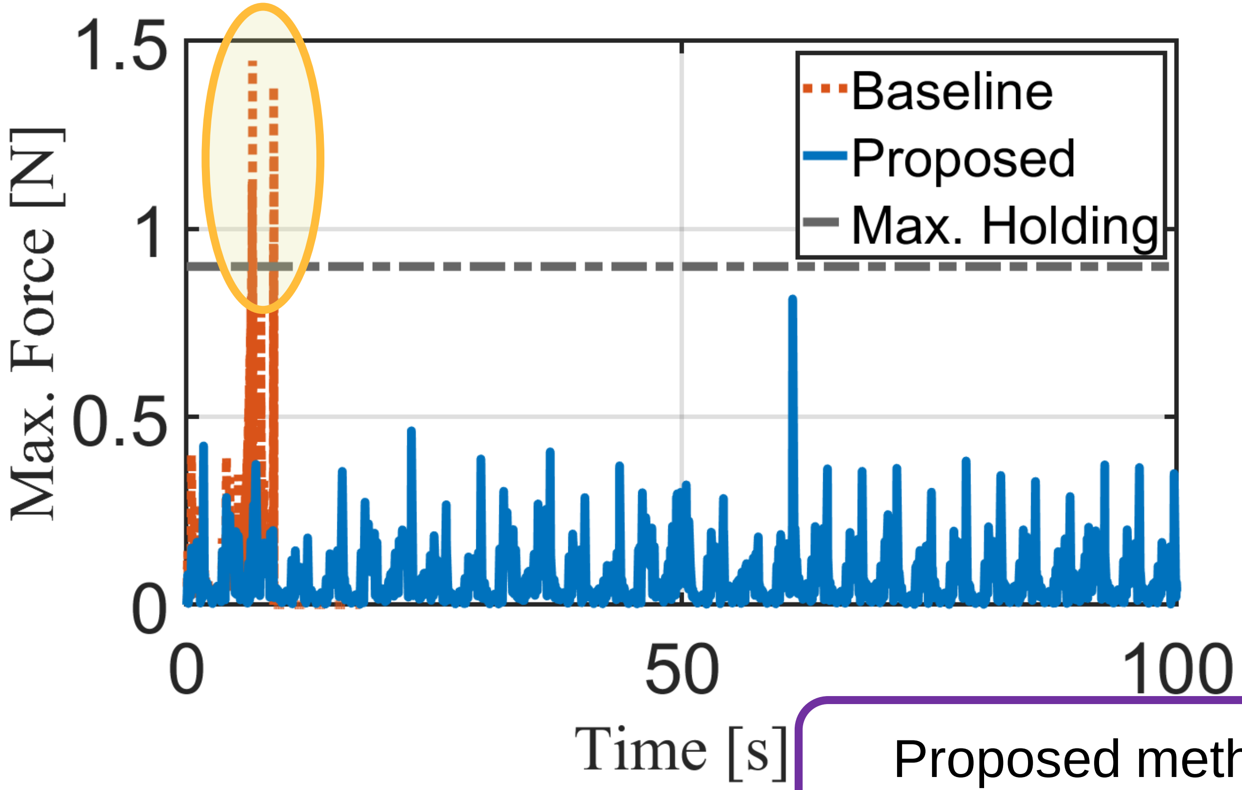
Simulations

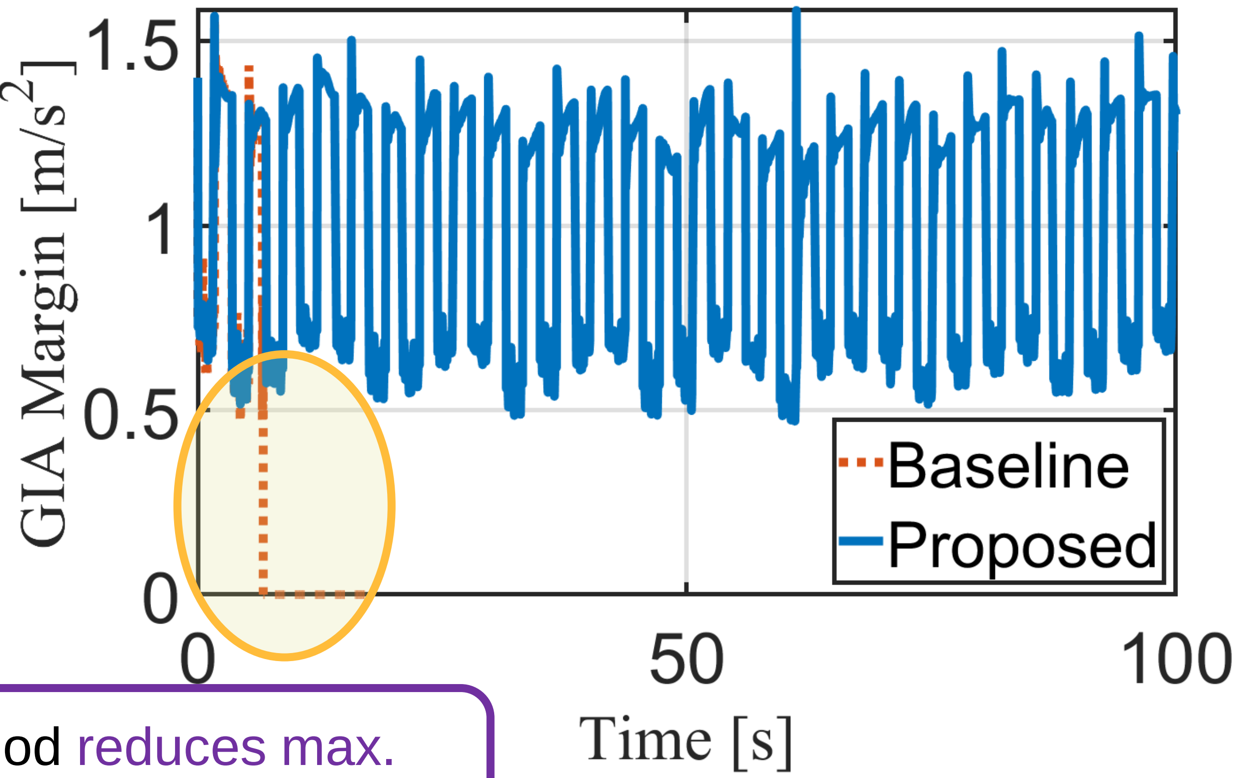
Simulation **with** proposed strategy



Simulations – Comparison

- Maximum contact force and stability measure[11]





Proposed method reduces max. contact forces, increasing stability

[11] Ribeiro, W.F.R. *et al.*: Dynamic equilibrium of climbing robots based on stability polyhedron for gravito-inertial acceleration. *CLAWAR*. (2020)

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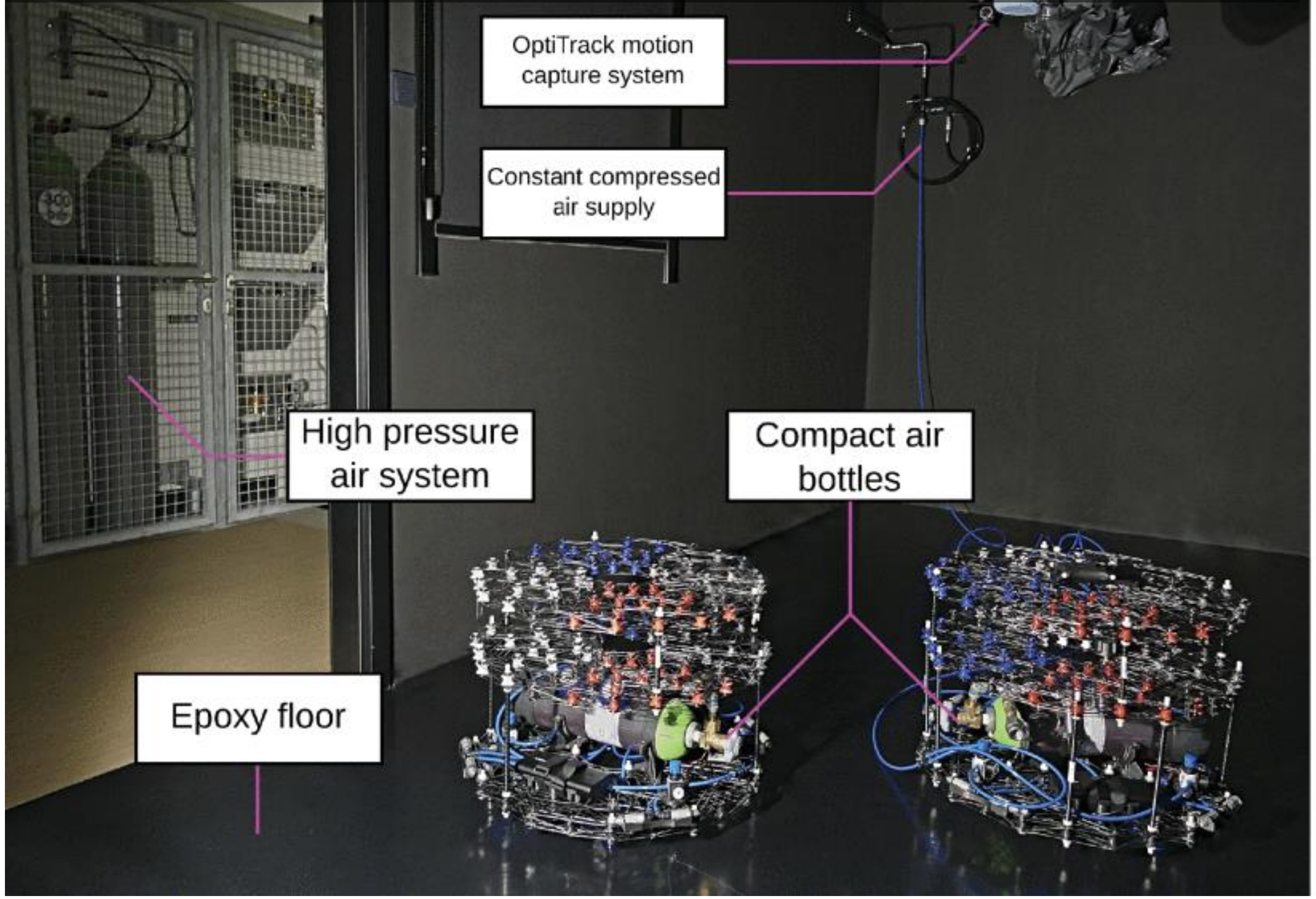
Experiments

Air-Floating Platform

- High-pressure air levitates the robot on a flat epoxy floor, eliminating friction
- No horizontal forces acting on the robot creates an emulated microgravity environment in 2D

Floating platforms in Zero-G Lab[12] ©SnT/Univ. of Luxembourg



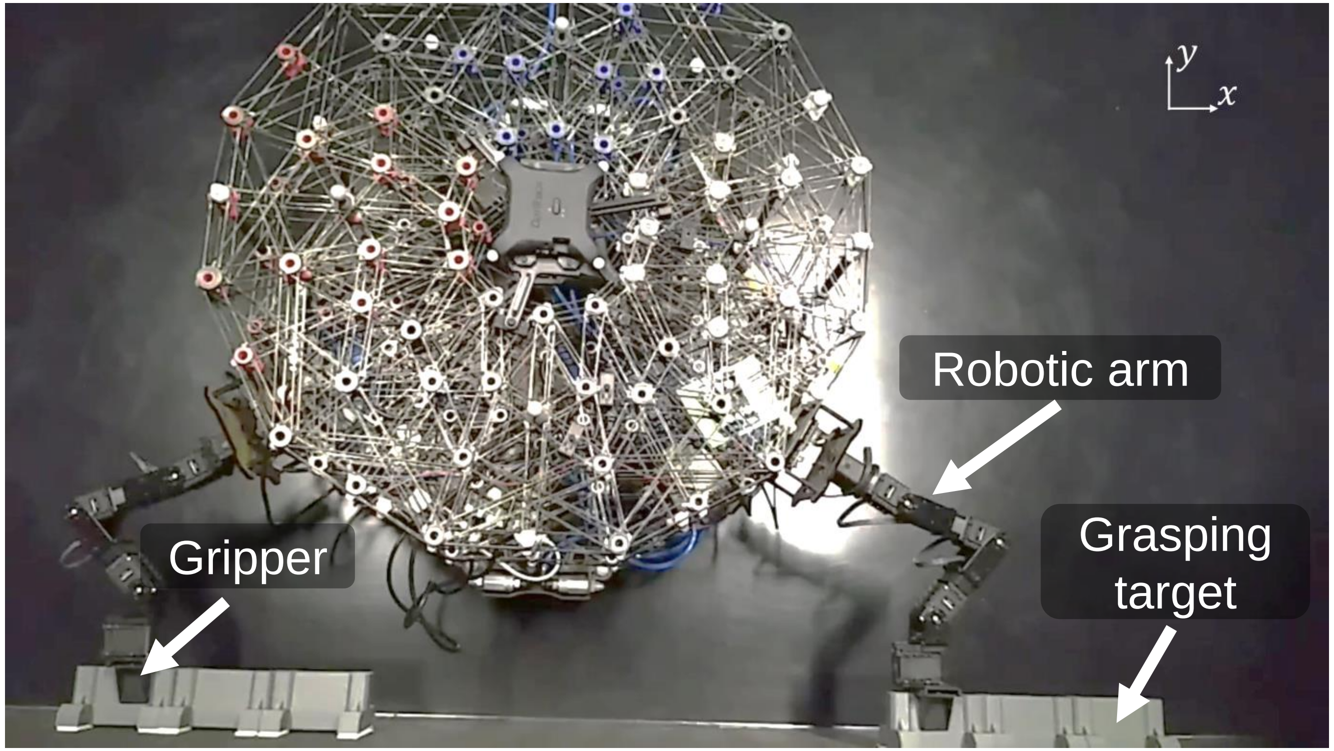
[12] Yalcın, B.C. et al.: Ultra light floating platform: An orbital emulator for space applications. *IEEE ICRA Late Breaking Results*. (2023)

Experiments

- **Objective:**
  - Test proposed mobility strategy for climbing robot on emulated microgravity
  - Compare with baseline traditional strategy (no base collision avoidance, no RAMP)

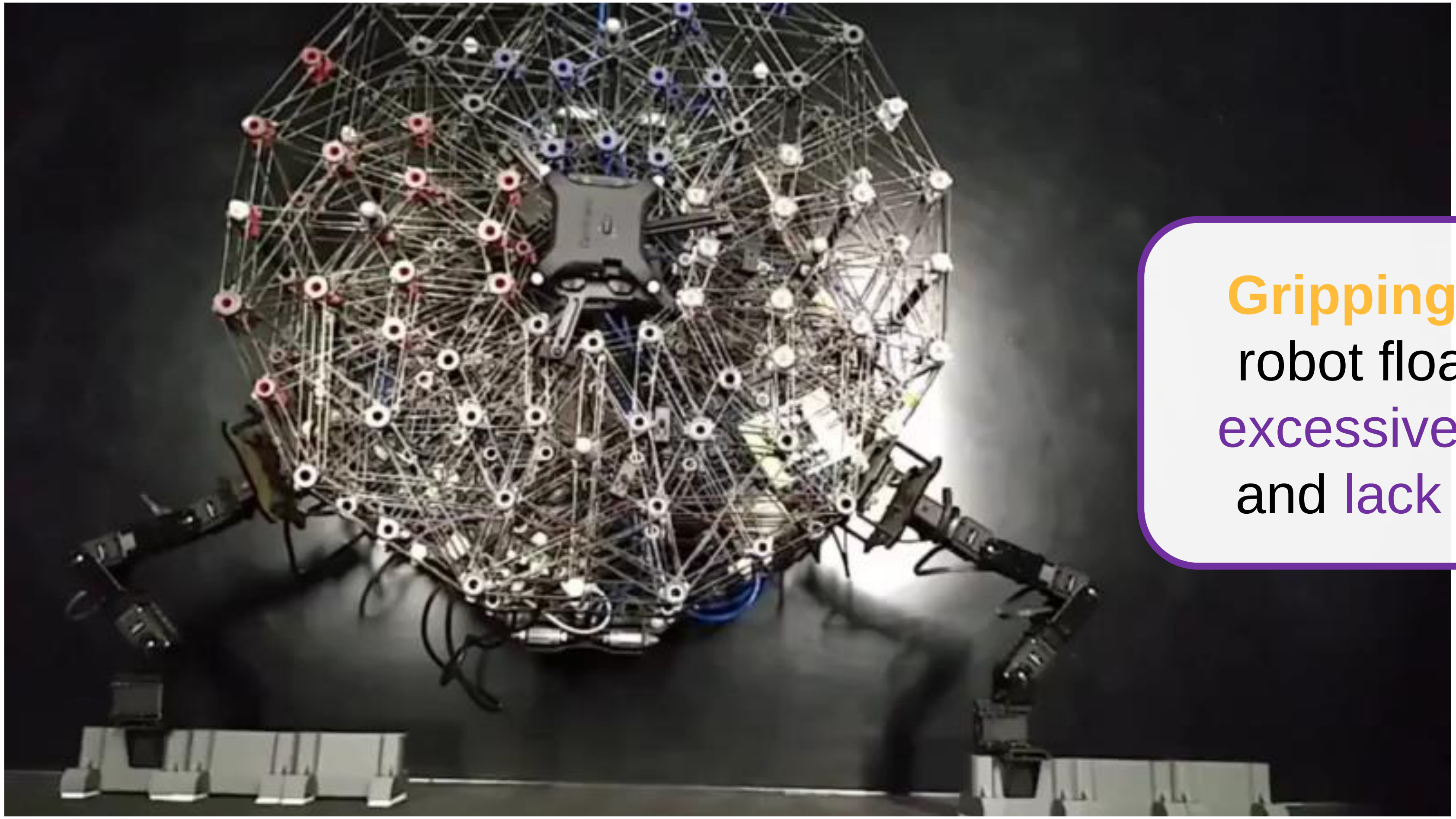
Conditions:

- Robot: Air-Floating Platform with 2 robotic arms and 2 pinching grippers
- Sensors: IMU
- Terrain model: 3D printed grasping targets
- Swinging period: 5 s
- Supporting period: 5 s
- Grasping/releasing period: 5 s
- Step stride: 10 cm
- Step height: 4 cm
- LRST coeff.: C_1 = 40, C_2 = 0, C_3 = 8
- Momentum distribution factor: 0.3



Experiments

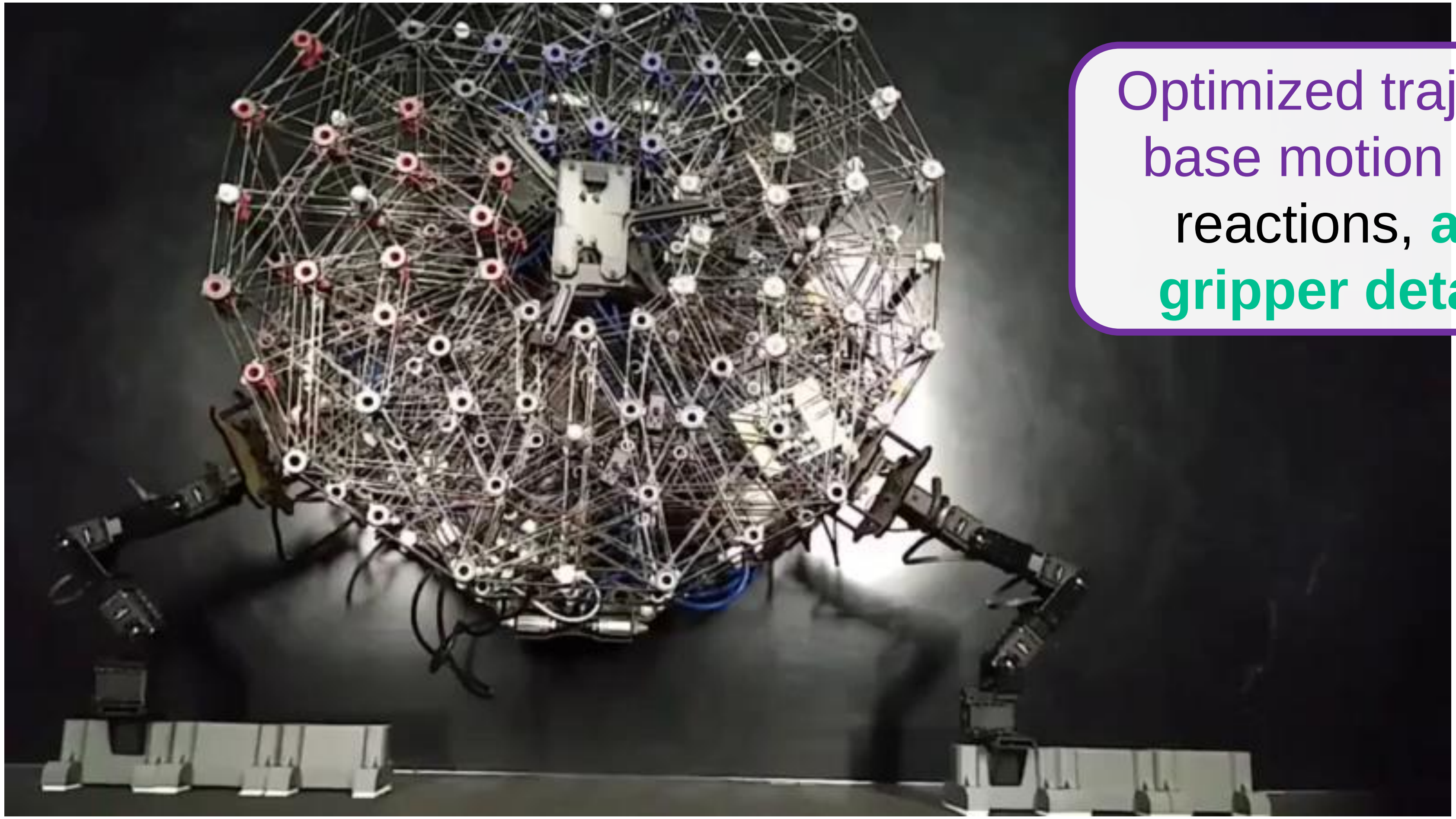
- Experiment **without** proposed strategy



Gripping fails and robot floats due to excessive reactions and lack of gravity

Experiments

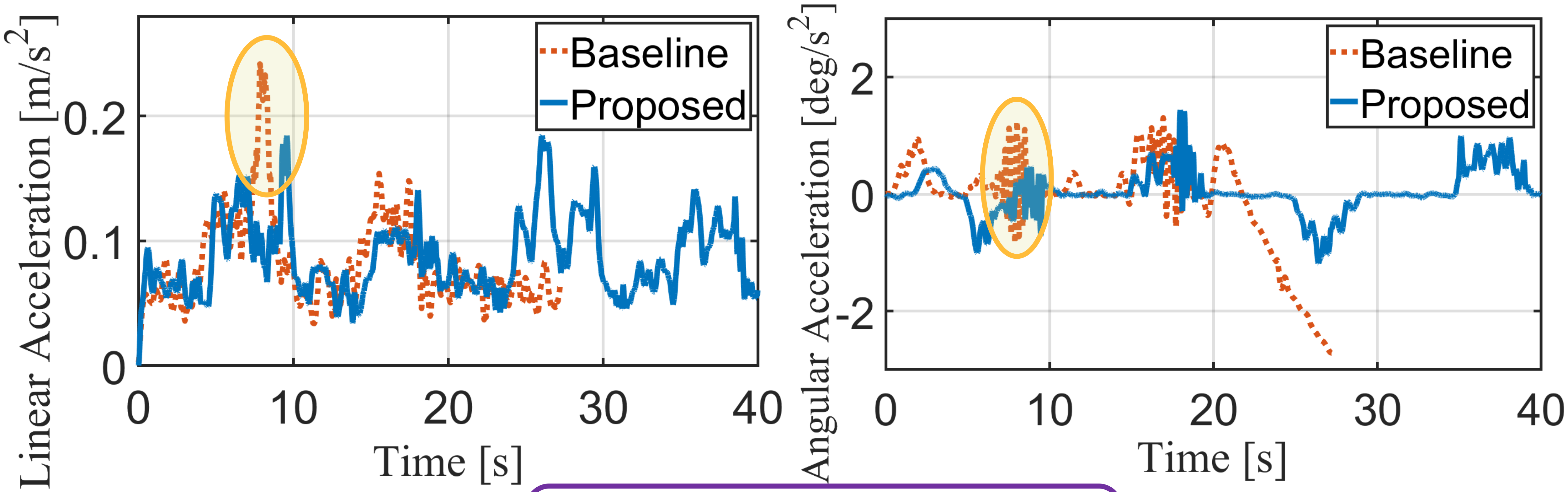
- Experiment **with** proposed strategy



Optimized trajectory and base motion to reduce reactions, **avoiding gripper detachment**

Experiments – Comparison

- Linear and angular measured accelerations



Proposed method reduces max. acceleration during swinging phase, increasing locomotion stability

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Conclusions

- Proposed a method for mobility of multi-limbed climbing robots on asteroids
  - Feasible gait planning avoiding collisions with the surface
  - Feasible motion planning reducing reactions to prevent gripper slippage
- Validation of the proposed method using simulations and experiments
  - Dynamic simulation of multi-limbed robot on rough surface
  - Experiment on emulated microgravity facility

Thank you for your attention!

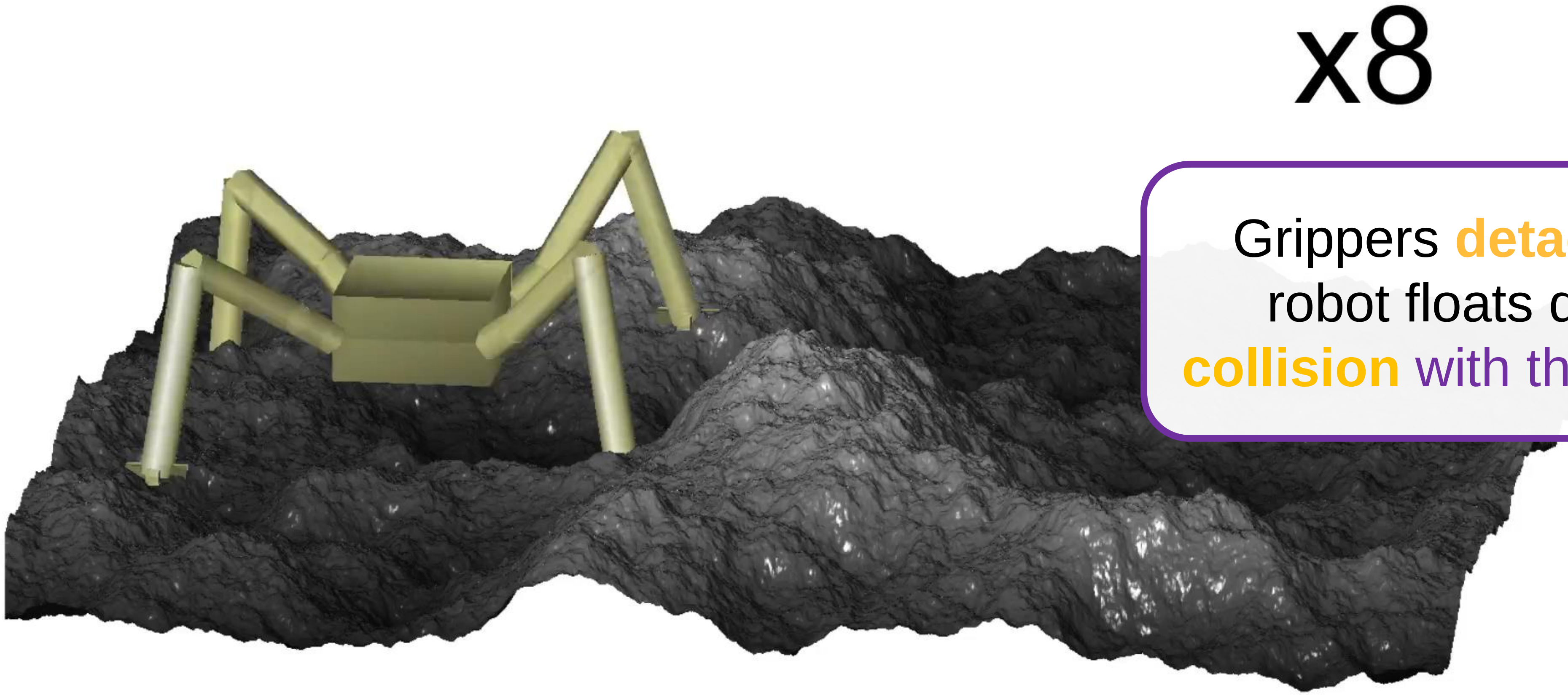
Q&A

Contact: warley@dc.tohoku.ac.jp

Additional slides

Simulations

Simulation **without** proposed strategy



Grippers **detach** and robot floats due to **collision** with the ground