GRIEEL: The Gripper-Wheel Transformable Module

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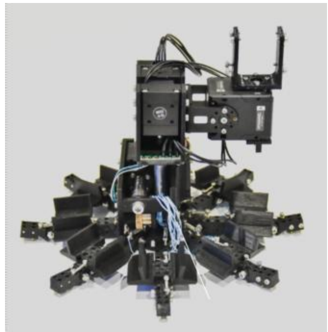
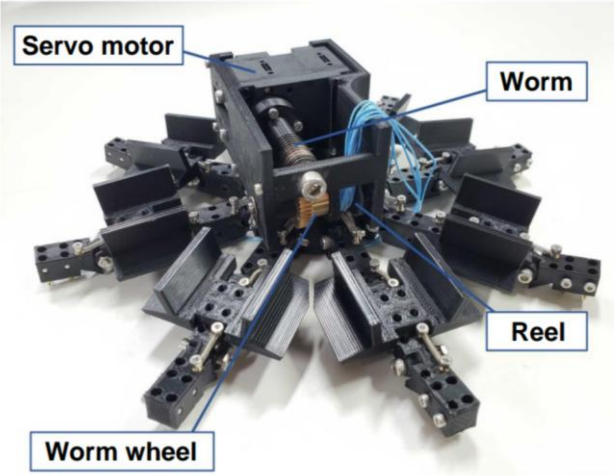
GRIEEL

GRIpper — **whEEL**







POLITECNICO MILANO 1863

TOHOKU UNIVERSITY

03/04/2025, Milano

Motion Control and Manipulability Analysis of LIMBERO-GRIEEL: a Multimodal Limbed Robot for Unstructured Environments

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Climbing Robotics Team

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MSc in Automation and Control Engineering

Academic year: 2024-2025

Advisor Prof. Luca Bascetta

Co-advisor Prof. Yoshida Kazuya

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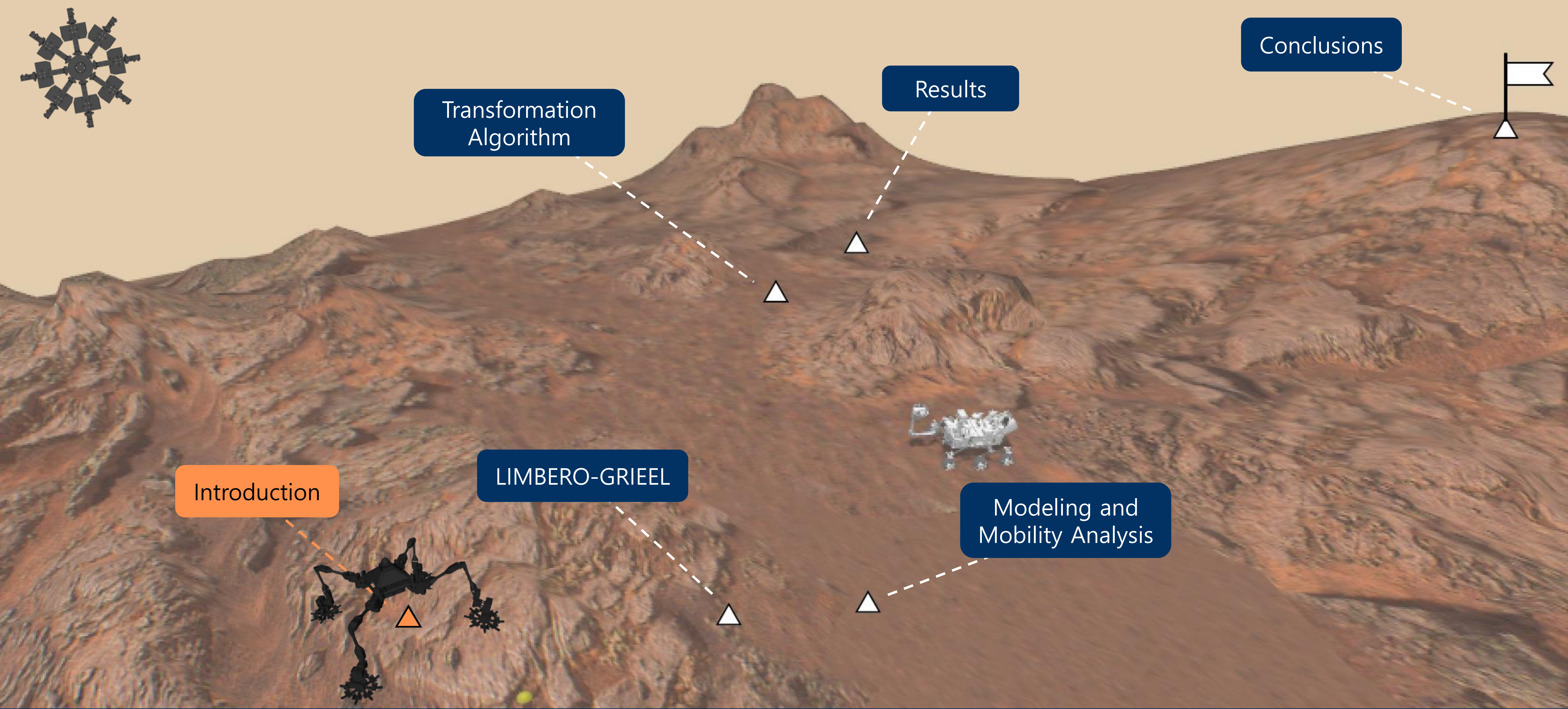

Background

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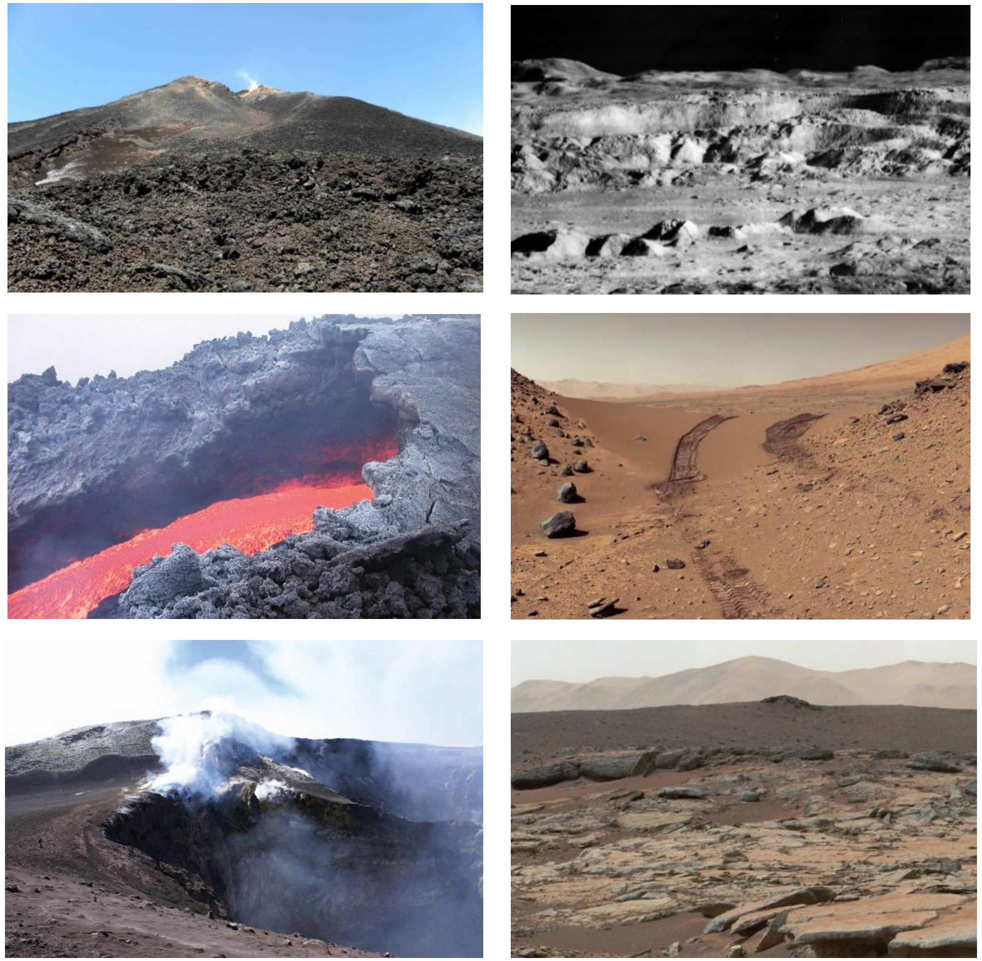
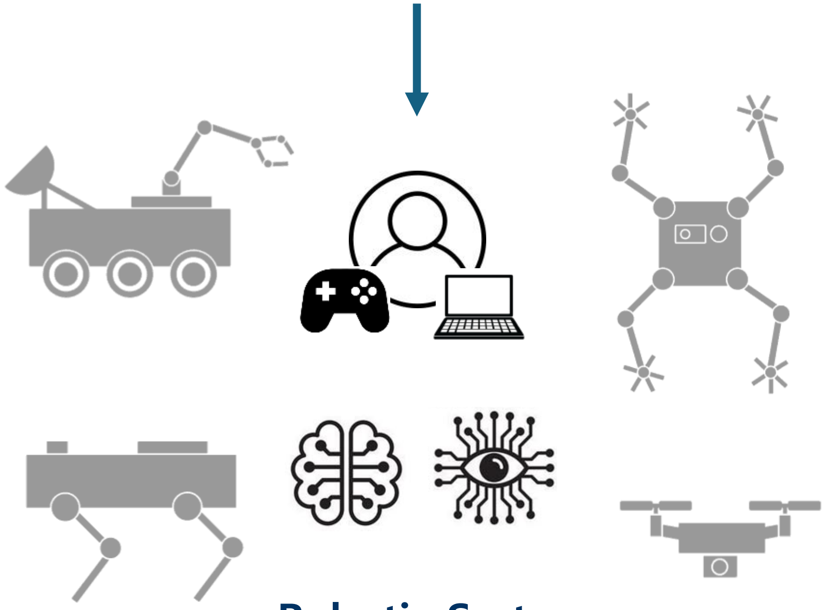
Monitoring and Exploration



Disaster response

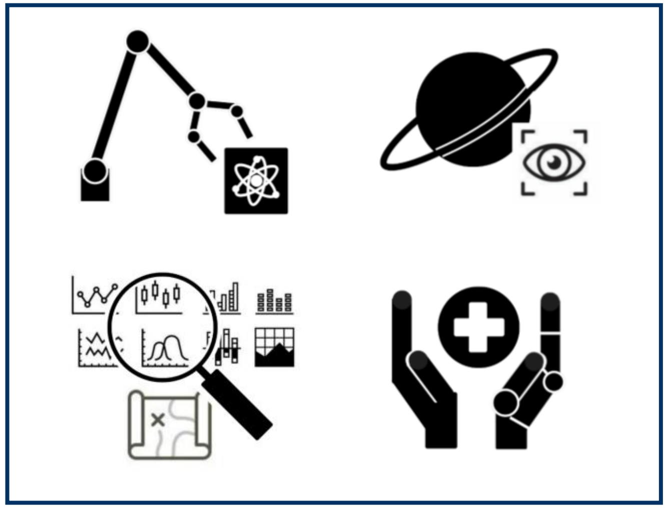
Challenges



Robotic Systems

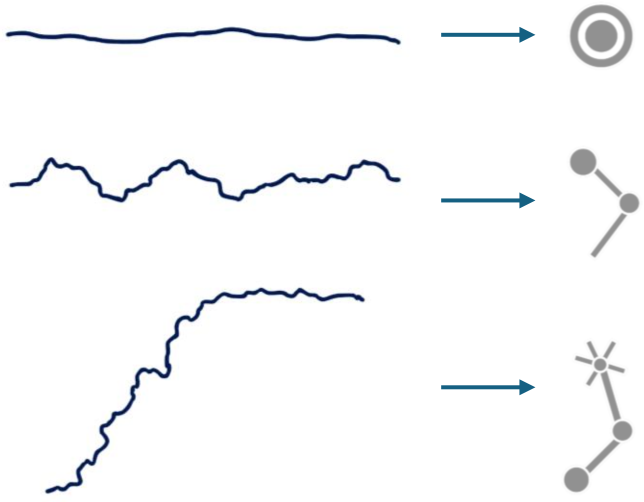
Motivation

Robot's tasks



- Collection of scientific samples
- Exploration of extreme environments
- Gathering of environmental data
- Safe and Rescue missions

Different terrains → Optimal locomotion



Classical Robotic systems

- Limited traversability
- Single purpose
- Multirobot coordination

Multimodal Robots

- Higher traversability
- Multipurpose machines

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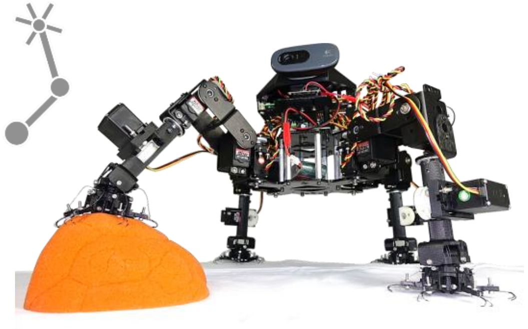
Objective

Climbing locomotion

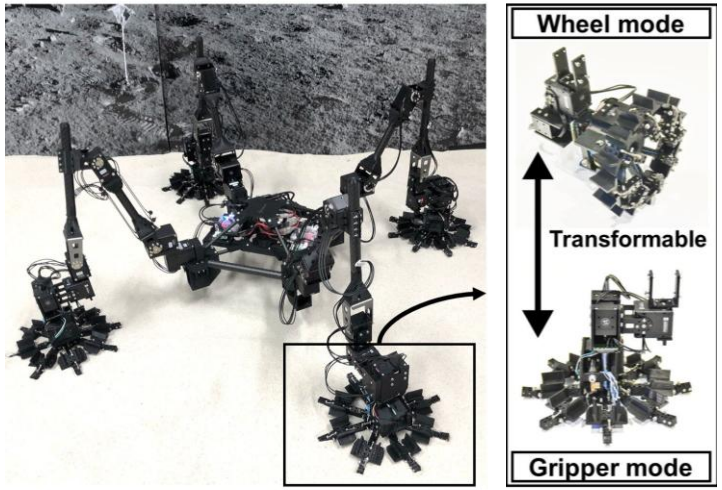


+

Wheeled locomotion

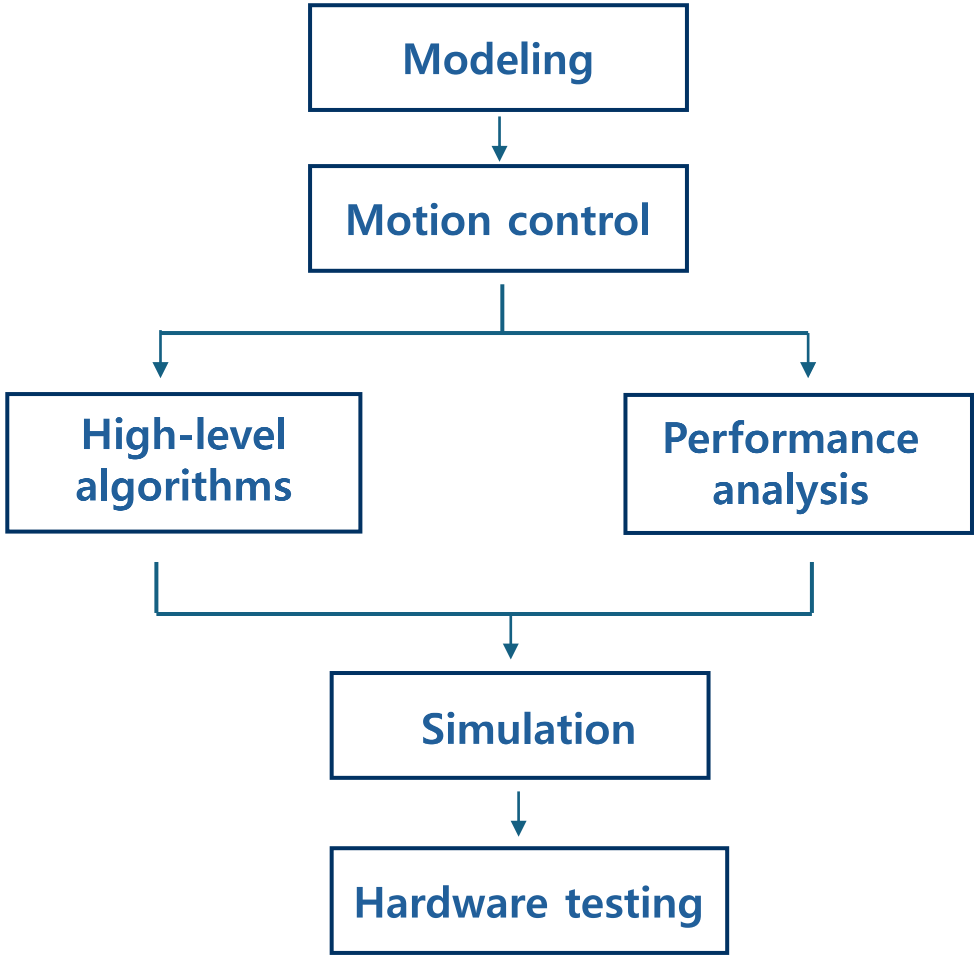
→

LIMBERO-GRIEEL



Multilimbed Multimodal gripper-wheel mobile robot

- **Wheeled locomotion**
- **Climbing locomotion**
- **Walking locomotion**
- **Manipulation**



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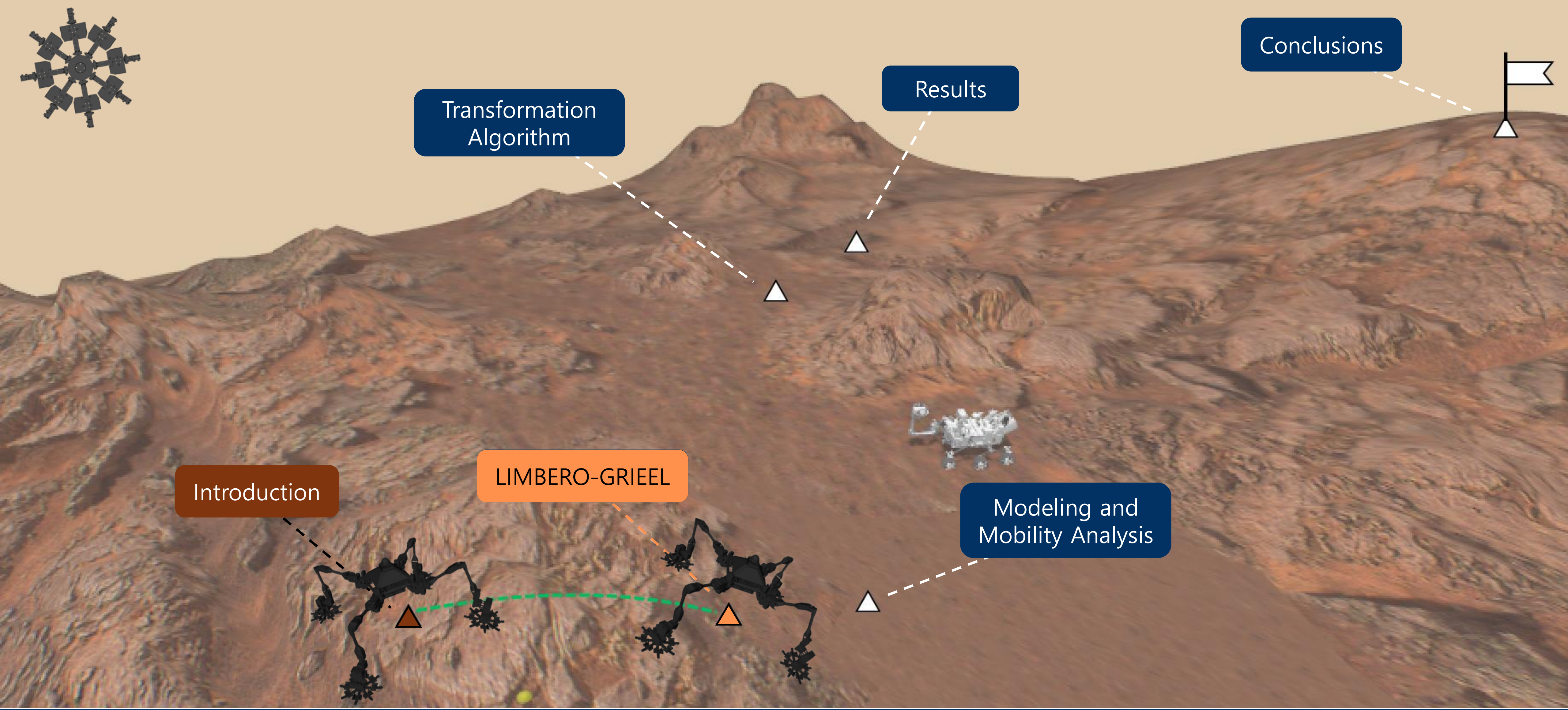
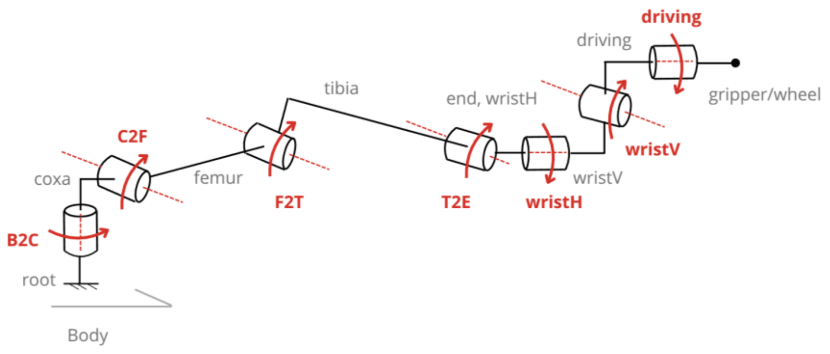
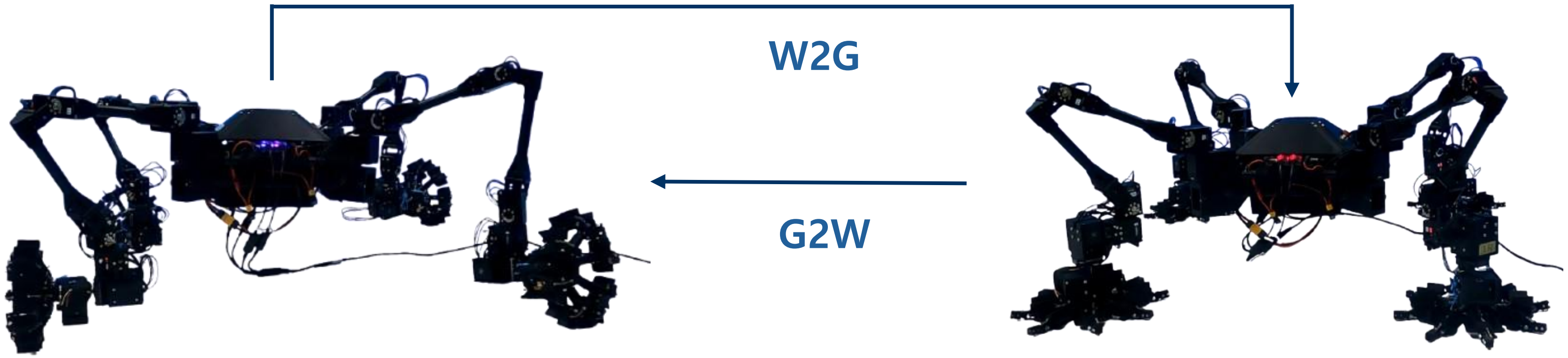

Transformation Algorithm
Results
Conclusions
Introduction
LIMBERO-GRIEEL
Modeling and Mobility Analysis

Hardware Description

Limb DOFs

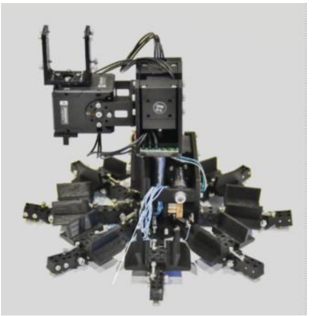


7 Degrees of freedom (DOFs)
+ Locking motor



Wheel Mode

wristH = π
wristV = π/2



Gripper Mode

wristH = 0
wristV = 0

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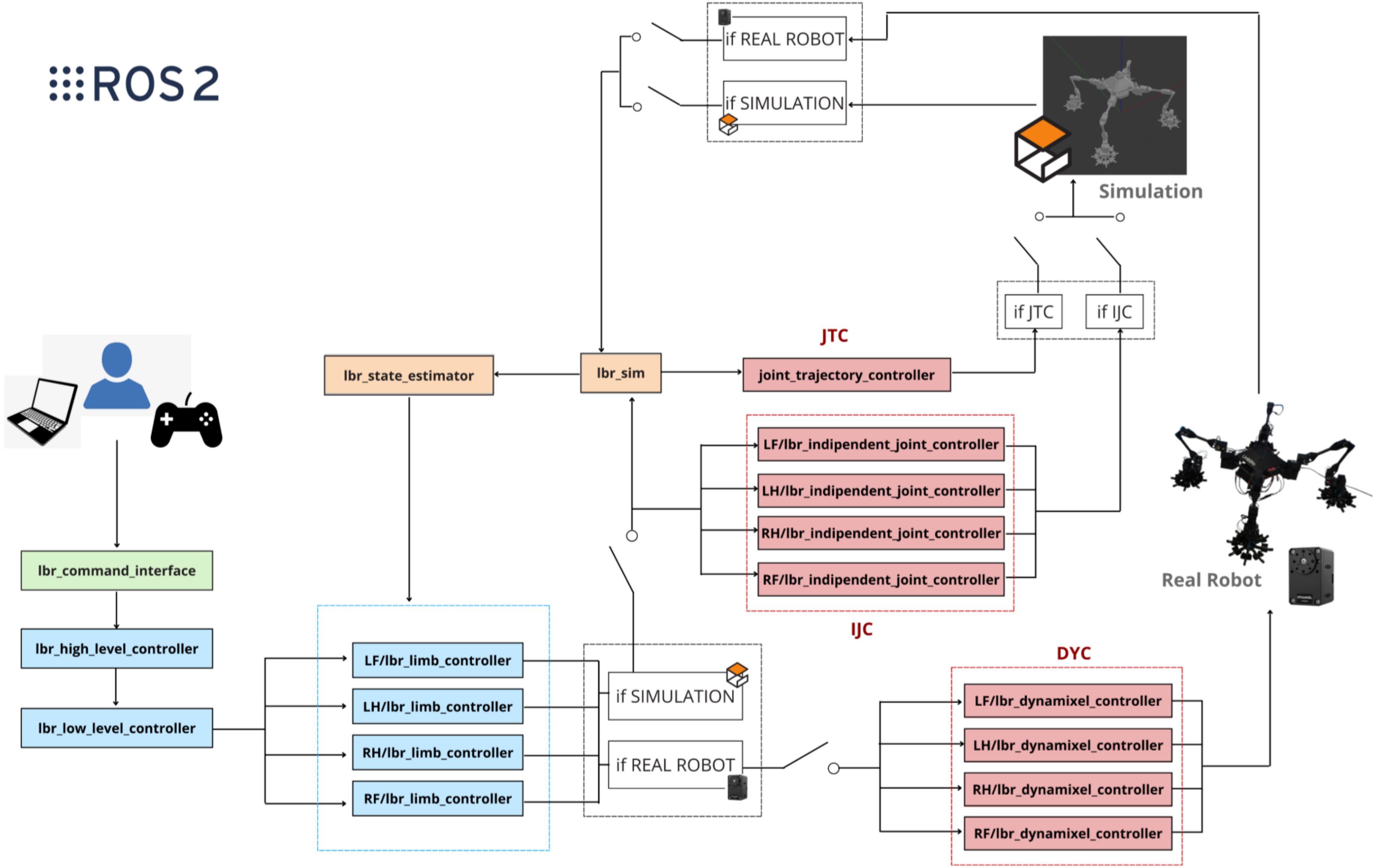
Software Description



ROS 2 communication and control infrastructure

- Multilayered architecture
- Modular
- Reusable
- Computationally efficient (C++ based)
- Debugging/Visualization tools (Rviz2, Plotjuggler)

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Simulation: ROS 2 - Gazebo Classic

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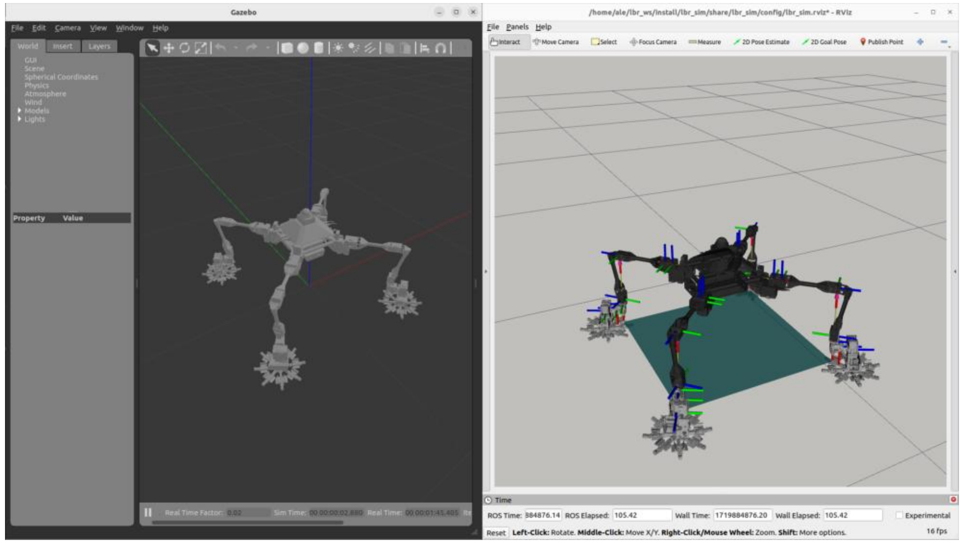
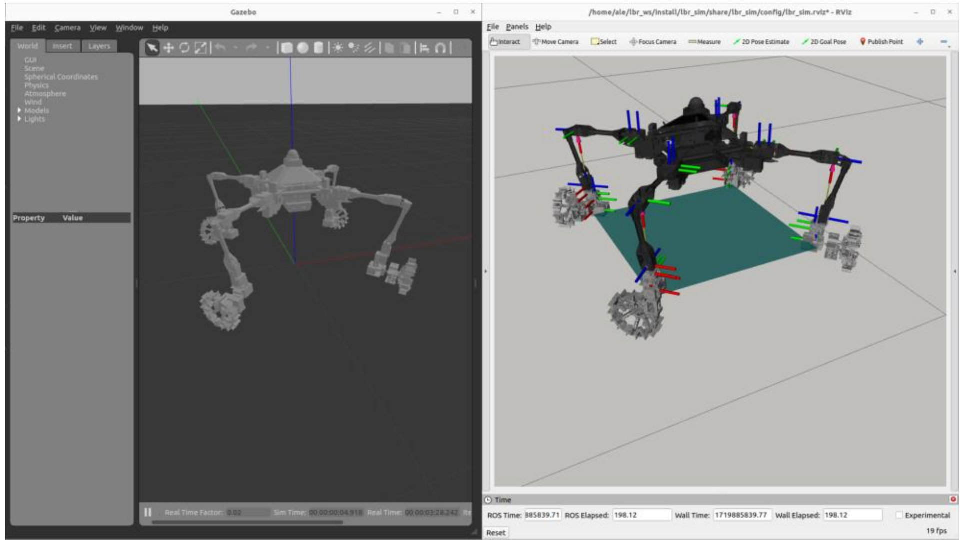
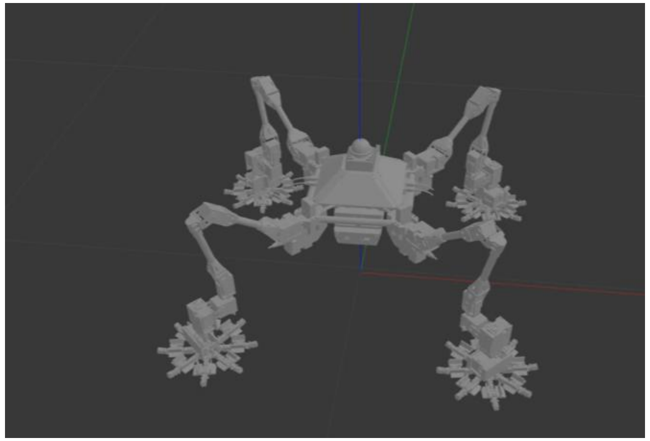
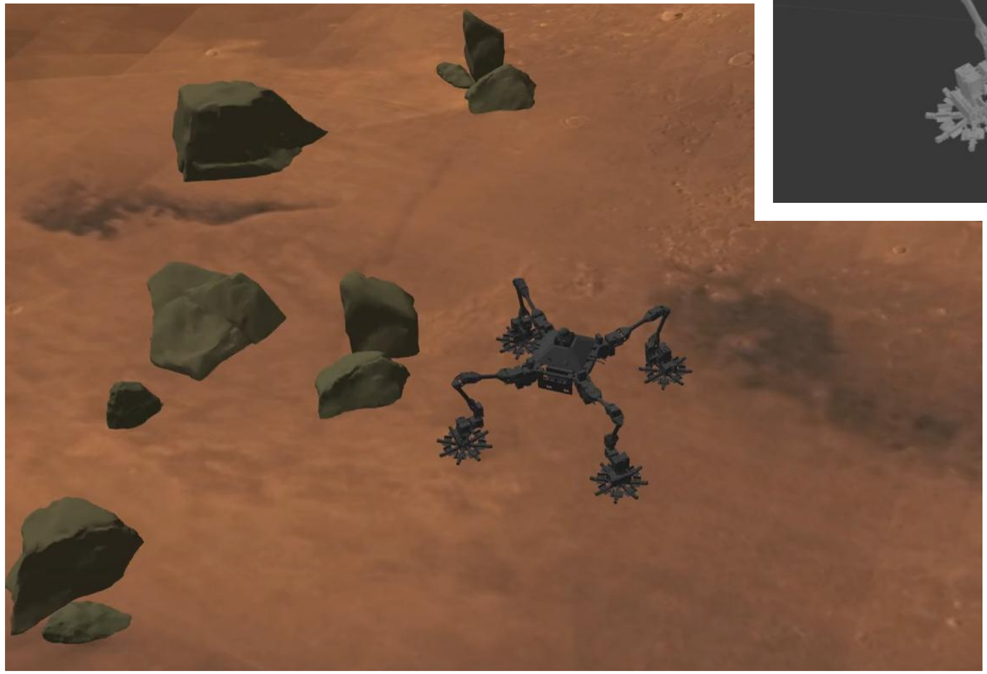




- ROS 2 components implementation
- Preliminary communication testing
- High-Level algorithms testing





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Simulation: ROS 2 - Gazebo Harmonic

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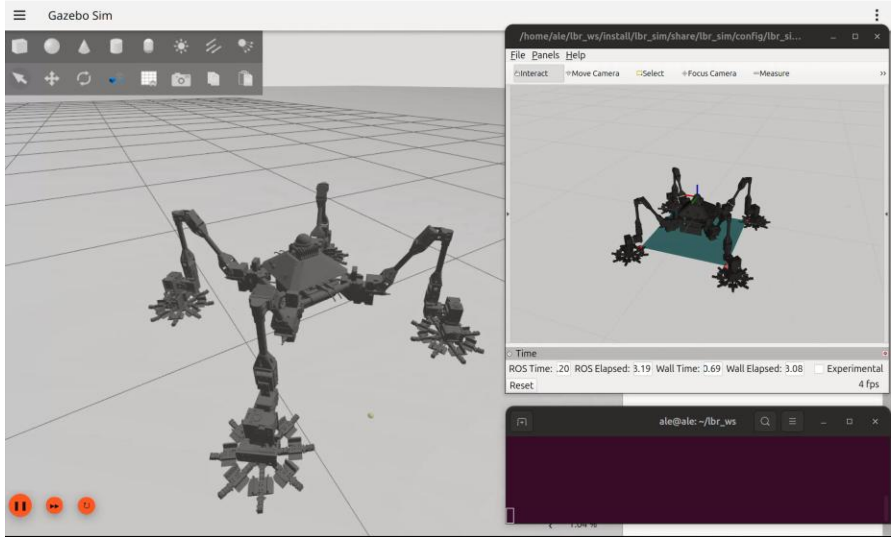
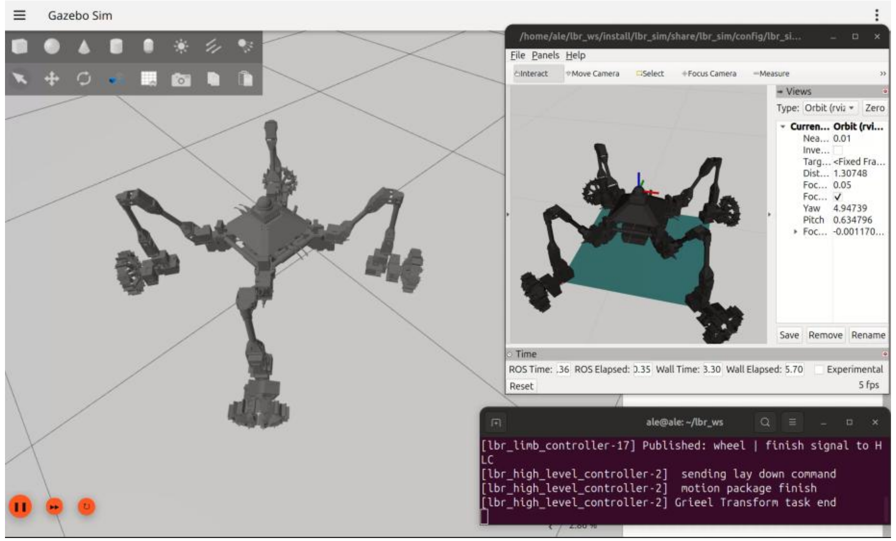
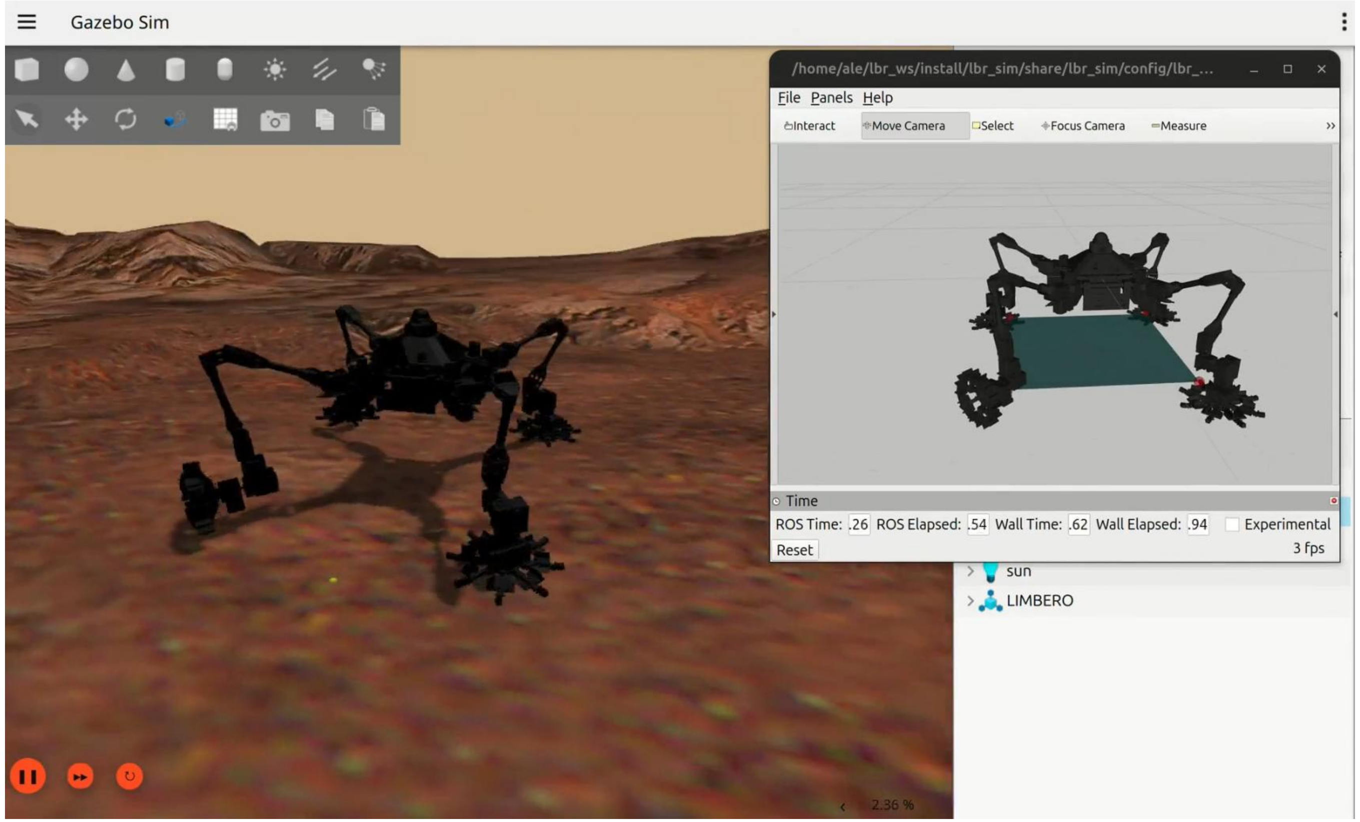
- Advanced motion testing
- Improve sim-to-real reliability
- New joint-controllers implementation







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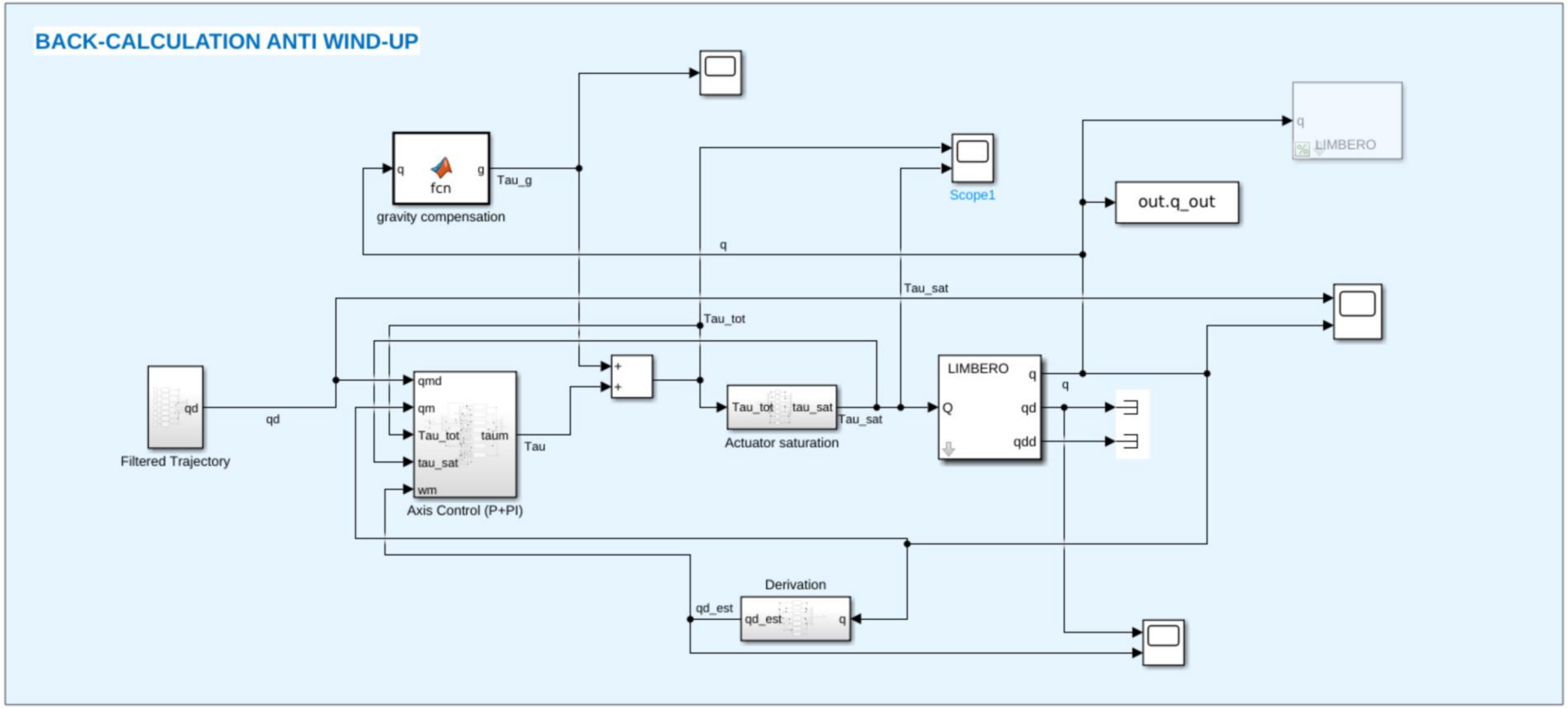
Simulation: MATLAB-Simulink



- Joint-controllers design and tuning
- Approximated Single limb simulation

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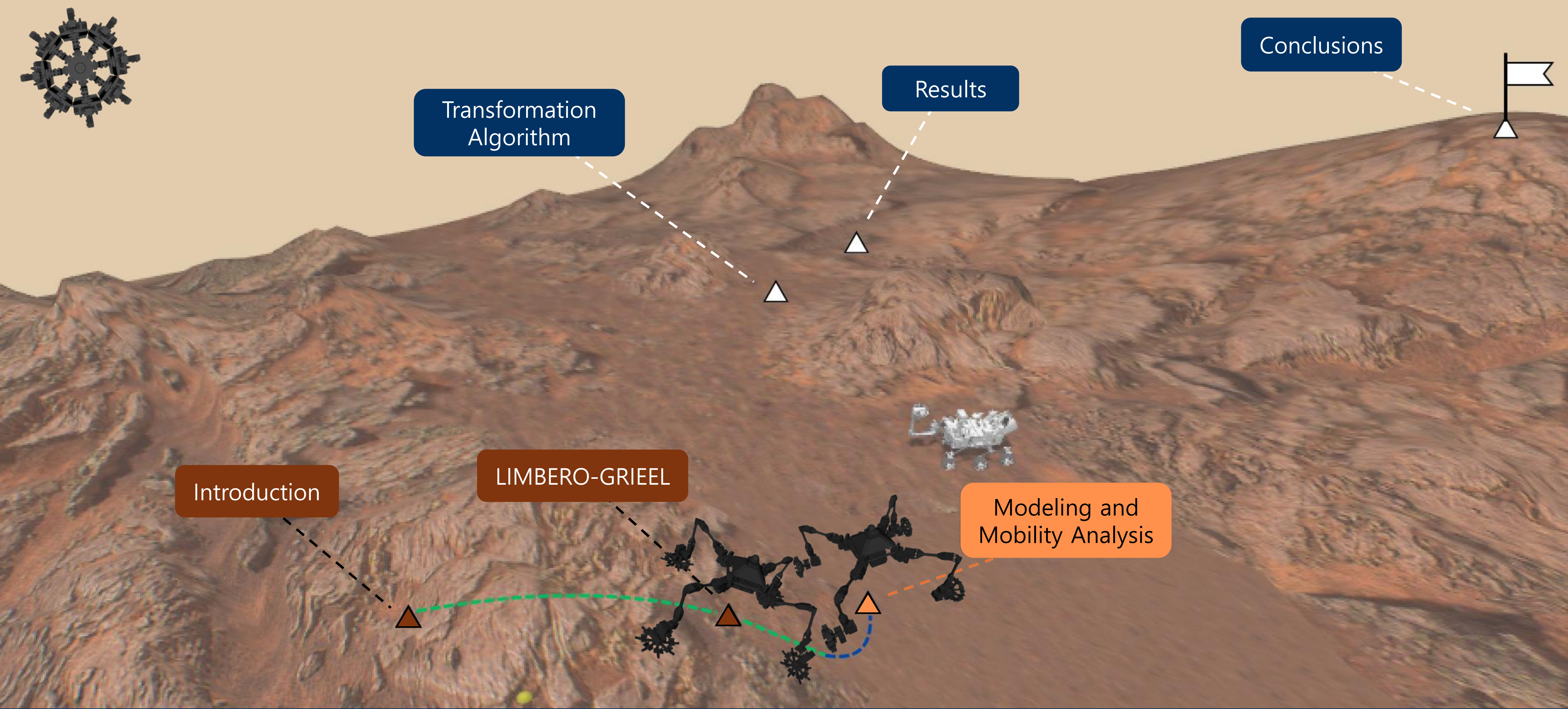
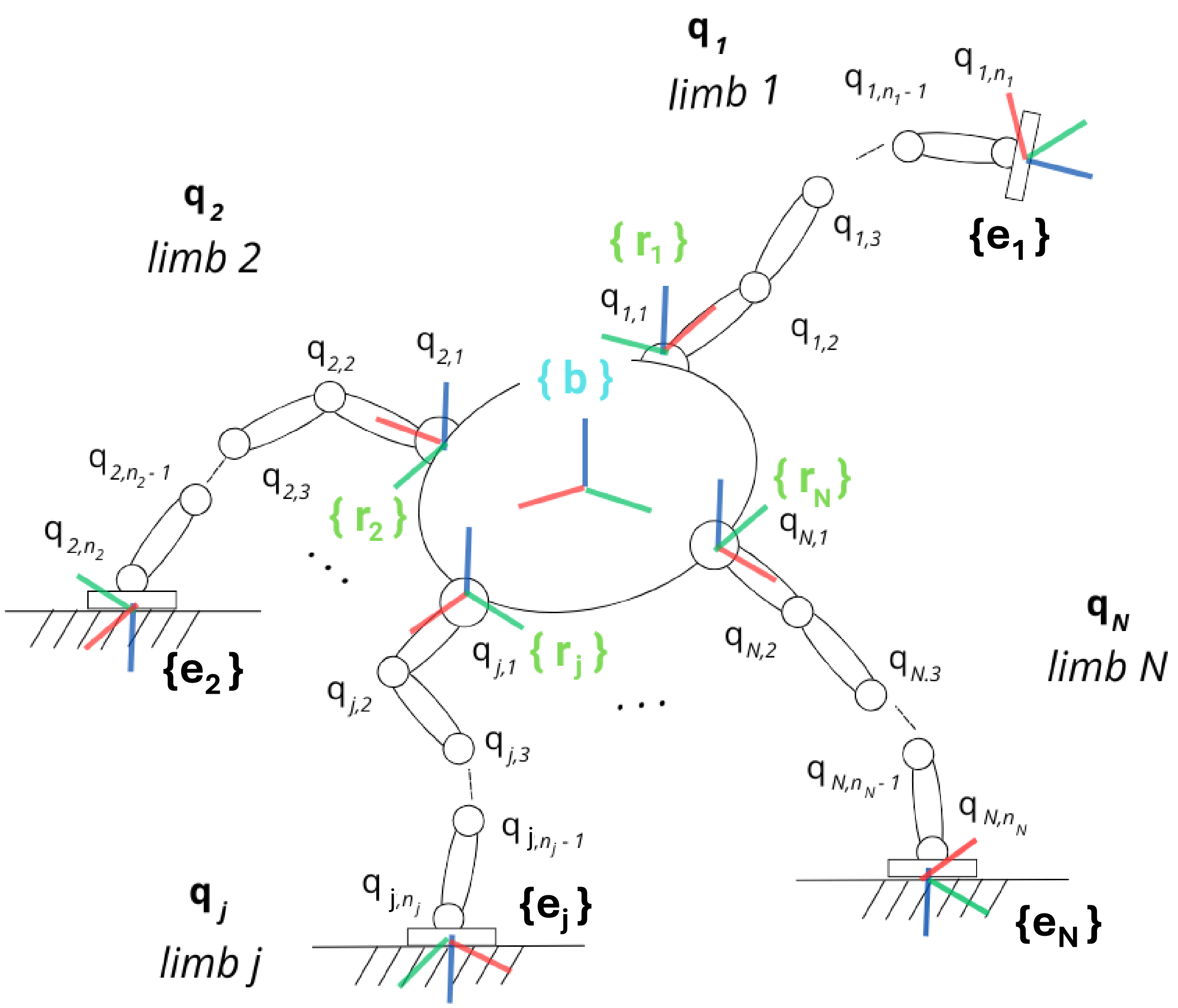


Kinematic Model: Forward and Inverse Kinematic



Symbols

$$j \in J = \{1, \dots, N\}, \quad J_c \subseteq J, \quad N_c = |J_c|, \quad \mathbf{b}, \quad \mathbf{e}_j, \quad \mathbf{r}_j$$

$$\mathbf{q}_j \in \mathbb{R}^{n_j} \qquad \mathbf{q} = \begin{bmatrix} \mathbf{q}_1 & \cdots & \mathbf{q}_N \end{bmatrix}^T \in \mathbb{R}^n, \quad n = \sum_j n_j$$

$$\mathbf{T}^0_\mathrm{f}(\mathbf{q}) = \begin{bmatrix} \mathbf{R}^0_\mathrm{f}(\mathbf{q}) & {}^0\mathbf{p}_\mathrm{f}(\mathbf{q}) \\ \mathbf{0}^\top & 1 \end{bmatrix}$$

Forward Kinematics

$$\mathbf{x} = k(\mathbf{q}) \in \mathbb{R}^m$$

$$\mathbf{T}^{\mathrm{b}}_{\mathrm{e_j}}(\mathbf{q_j}) = \mathbf{T}^{\mathrm{b}}_{\mathrm{r_j}} \cdot \mathbf{T}^{\mathrm{r}}_{\mathrm{j_0}} \cdot \mathbf{T}^{\mathrm{j_0}}_{\mathrm{j_1}}(\mathbf{q_{j,1}}) \cdot \cdots \cdot \mathbf{T}^{\mathrm{j_{i-1}}}_{\mathrm{j_i}}(\mathbf{q_{j,i}}) \cdot \cdots \cdot \mathbf{T}^{\mathrm{j_{n_j-1}}}_{\mathrm{j_{n_j}}}(\mathbf{q_{j,n_j}}) \cdot \mathbf{T}^{\mathrm{j_{n_j}}}_{\mathrm{e_j}}, \forall j = 1, \dots, N$$

Inverse Kinematics

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Kinematic Model: Multiarm parallelism

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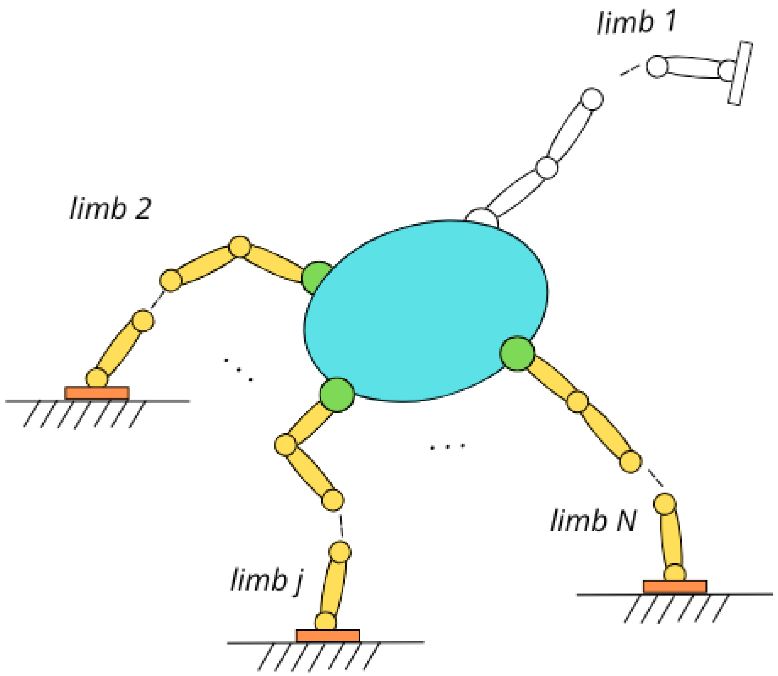
Limbed Robot



N_C contact limbs

Limb

Limb root

Limb end

Base

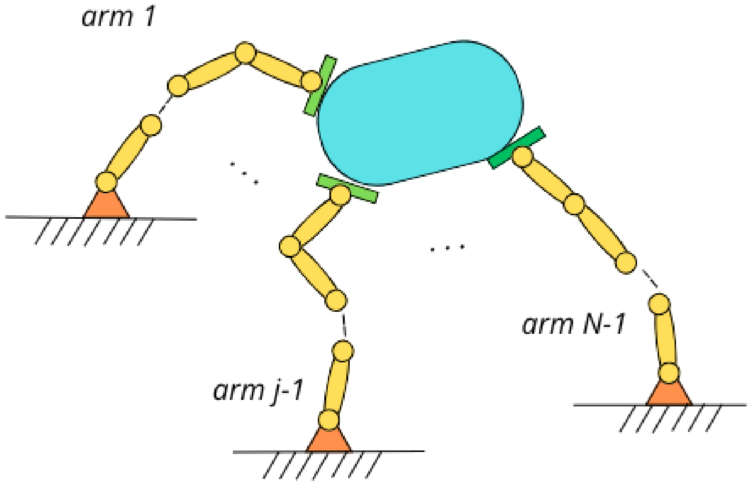
Assumptions

- Rigid gripper-ground contact
- Tight grasp

Multilimb-Multiarm duality

⟺

Cooperative Manipulators



N_C cooperating arms

Arm

Arm EE

Arm base

Object

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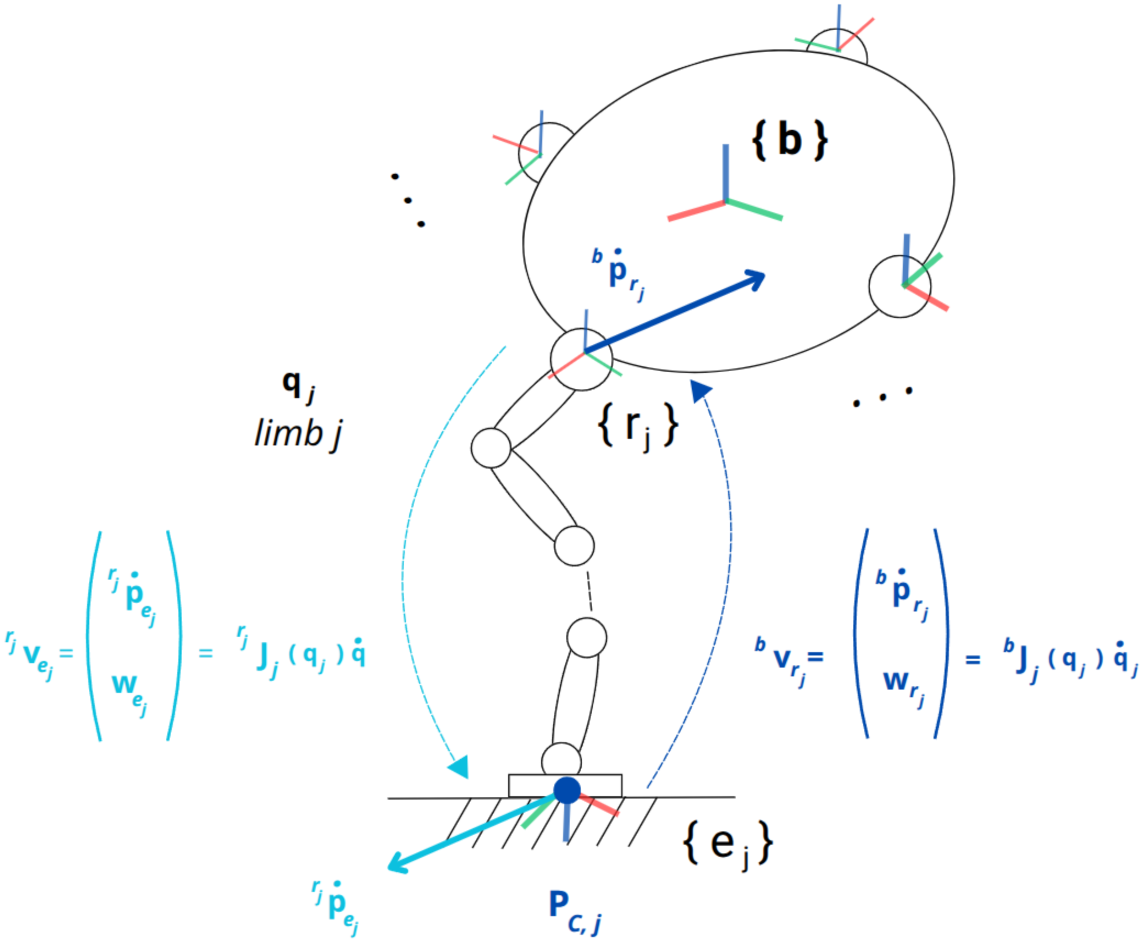
Kinematic Model: Differential Kinematics



Symbols

$\dot{\mathbf{q}}_j \in \mathbb{R}^{n_j}$ $\quad \dot{\mathbf{q}} \in \mathbb{R}^{n}$

${}^{\mathbf{h}}\mathbf{v_k} \in \mathbb{R}^{6}$ $\quad {}^{\mathbf{h}}\mathbf{J_k} \in \mathbb{R}^{6\times 6}$ $\quad \mathbf{J_k^h} \in \mathbb{R}^{6\times 6}$

Velocity relation (assumptions)

$$ {}^{\mathbf{e_j}}\mathbf{v_{r_j}} = -{}^{\mathbf{r_j}}\mathbf{v_{e_j}} $$

$$ {}^{\mathbf{b}}\mathbf{v_{r_j}} = -\mathbf{J^{b}_{r_j}}\,{}^{\mathbf{r_j}}\mathbf{J_j}(\mathbf{q_j})\cdot\dot{\mathbf{q}}_\mathbf{j} = {}^{\mathbf{b}}\mathbf{J_j}(\mathbf{q_j})\cdot\dot{\mathbf{q}}_\mathbf{j} $$

$$ \mathbf{J_0^k} = \begin{bmatrix} \mathbf{R_0^k} & \mathbf{0_{3\times3}} \\ \mathbf{0_{3\times3}} & \mathbf{R_0^k} \end{bmatrix} $$

Differential Kinematics model

$$ {}^{\mathbf{b}}\mathbf{J_j}(\mathbf{q_j}) = -\mathbf{J^{b}_{r_j}}\,{}^{\mathbf{r_j}}\mathbf{J_j}(\mathbf{q_j}) $$

$$ \mathbf{J}(\mathbf{q}) = diag({}^{\mathbf{b}}\mathbf{J_1}(\mathbf{q_1})\dots{}^{\mathbf{b}}\mathbf{J_j}(\mathbf{q_j})\dots{}^{\mathbf{b}}\mathbf{J_N}(\mathbf{q}_N)), \quad \mathbf{J_j}(\mathbf{q}_j) = \mathbf{0} \in \mathbb{R}^{m\times n_j} \quad \text{if } j \notin J_c $$

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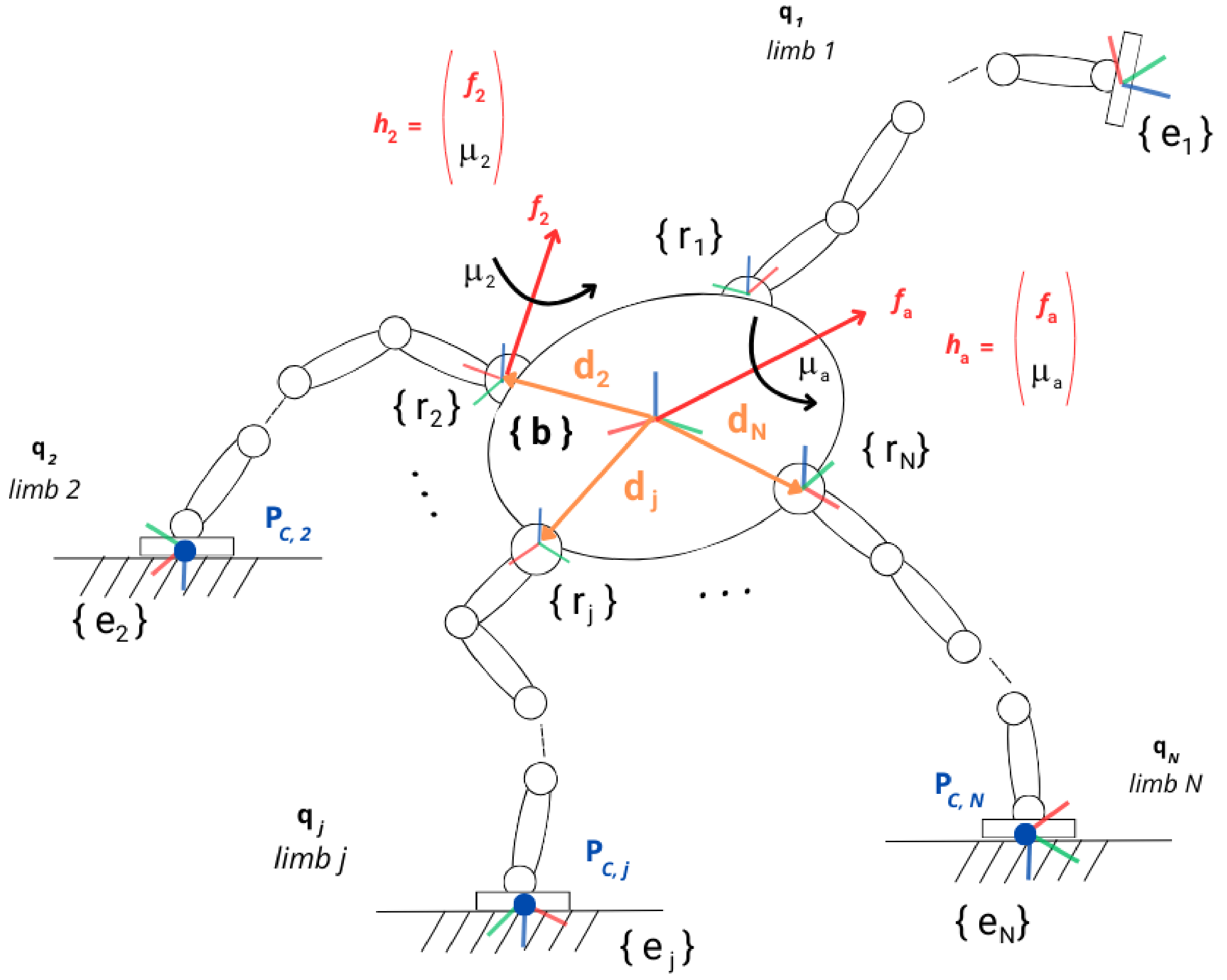
Kinematic Model: Differential Kinematics



Symbols

$\mathbf{W} \in \mathbb{R}^{m\times M}$ $\quad \mathbf{h}_a \in \mathbb{R}^m$ $\quad \mathbf{v}_a \in \mathbb{R}^m$ $\quad \mathbf{h} \in \mathbb{R}^M, M = m \cdot N_c$

$\tau \in \mathbb{R}^n$

Quantities definition

$$\mathbf{W} = [\mathbf{W}_1 \dots \mathbf{W}_j \dots \mathbf{W}_N],$$

$$\mathbf{h}_a = \mathbf{W}\mathbf{h}$$

$$\mathbf{h} = \mathbf{W}^{\dagger}\mathbf{h}_a$$

$$\begin{cases} \mathbf{W}_j = \mathbf{0} \in \mathbb{R}^{m\times m} & \text{if } j \notin J_c \\ \mathbf{W}_j = \begin{bmatrix} \mathbf{I}_3 & \mathbf{0}_3 \\ \mathbf{R}_j & \mathbf{I}_3 \end{bmatrix}, & \text{if } j \in J_c \end{cases}$$

$$\mathbf{d}_j \times \mathbf{f}_j = \mathbf{R}_j \mathbf{f}_j$$

Equations

$$\mathbf{J}_a^T(\mathbf{q}) = \mathbf{J}^T(\mathbf{q})\mathbf{W}^{\dagger} \in \mathbb{R}^{n\times m}$$

$$\tau = \mathbf{J}_a^T(\mathbf{q})\mathbf{h}_a$$

$$\mathbf{v}_a = \mathbf{J}_a(\mathbf{q})\dot{\mathbf{q}}$$

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Manipulability Analysis

Absolute Base Manipulability Ellipsoid equations

$$\mathbf{h}_a^T\overbrace{[\mathbf{J}_a(\mathbf{q})\mathbf{J}_a^T(\mathbf{q})]}^{\mathbf{E}_a \,\in\, \mathbb{R}^{m\times m}}\mathbf{h}_a = 1$$

$$\mathbf{v}_a^T[\mathbf{J}_a(\mathbf{q})\mathbf{J}_a^T(\mathbf{q})]^{-1}\mathbf{v}_a = 1$$

$$\mathbf{J}_a = \begin{bmatrix} \mathbf{J}_{\mathbf{P}a} \\ \mathbf{J}_{\mathbf{O}a} \end{bmatrix} \qquad \mathbf{E}_a = \begin{bmatrix} \mathbf{E}_{\mathbf{T}a} & \mathbf{E}_{\mathbf{TR}a} \\ \mathbf{E}_{\mathbf{TR}a}^{\mathbf{T}} & \mathbf{E}_{\mathbf{R}a} \end{bmatrix}$$

$$\dot{\mathbf{p}}_a^T[\mathbf{E}_{\mathbf{T}a}]^{-1}\dot{\mathbf{p}}_a = 1$$ Absolute Translational Base Velocity Manipulability Ellipsoid (ATBVME)

$$\omega_a^T[\mathbf{E}_{\mathbf{R}a}]^{-1}\omega_a = 1$$ Absolute Rotational Base Velocity Manipulability Ellipsoid (ARBVME)

Velocity scaling

$$\dot{\mathbf{q}}_{lim,j} = \begin{bmatrix} \dot{q}_{lim,1} & \dot{q}_{lim,2} & \dots & \dot{q}_{lim,n_j} \end{bmatrix}^T$$

$$\mathbf{Q}_{lim} = diag\left(\begin{bmatrix} \dot{\mathbf{q}}_{lim,1} & \dot{\mathbf{q}}_{lim,2} & \dots & \dot{\mathbf{q}}_{lim,N} \end{bmatrix}\right)$$

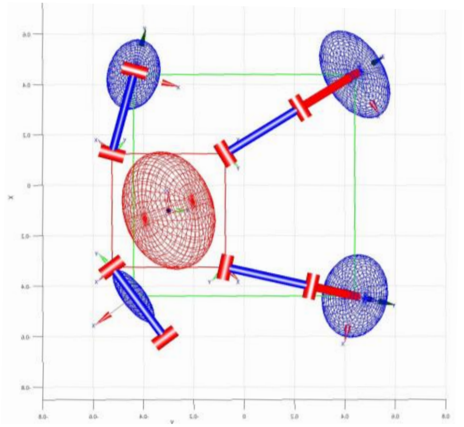
$$\tilde{\dot{\mathbf{q}}} = \mathbf{Q}_{lim}^{-1}\dot{\mathbf{q}}$$

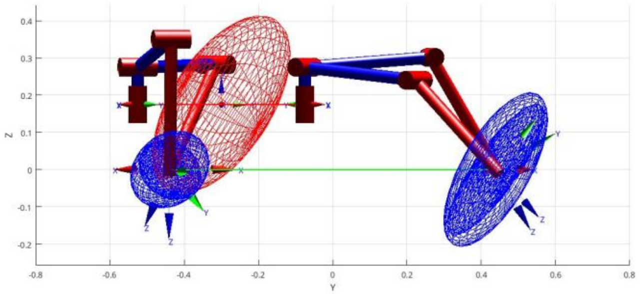
$$\tilde{\dot{\mathbf{q}}}^T\tilde{\dot{\mathbf{q}}} = 1$$

$$\tilde{\mathbf{J}}(q) = \mathbf{J}(q)\cdot\mathbf{Q}_{lim}$$

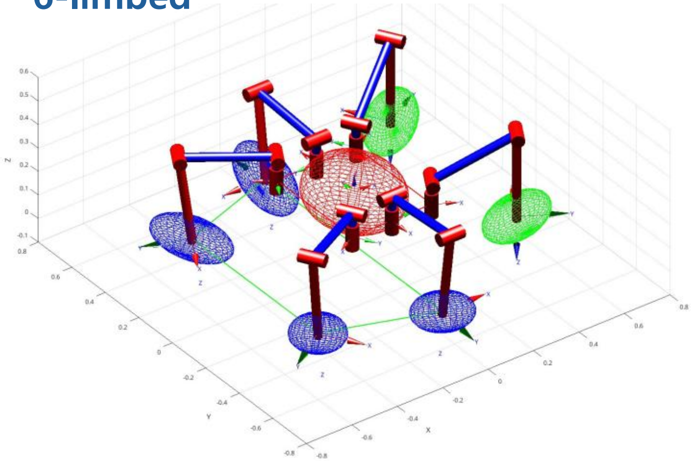
$$\tilde{\mathbf{J}}_a^T(\mathbf{q}) = \tilde{\mathbf{J}}^T(\mathbf{q})\mathbf{W}^{\dagger} \in \mathbb{R}^{n\times m}$$

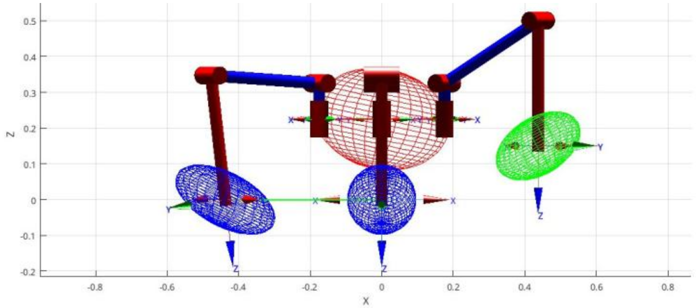
4-limbed





6-limbed





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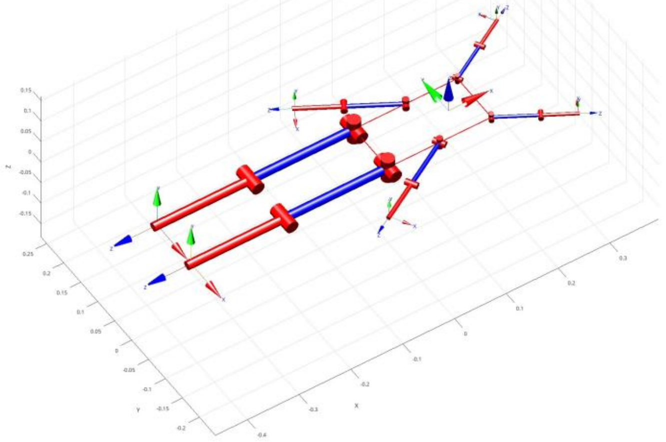
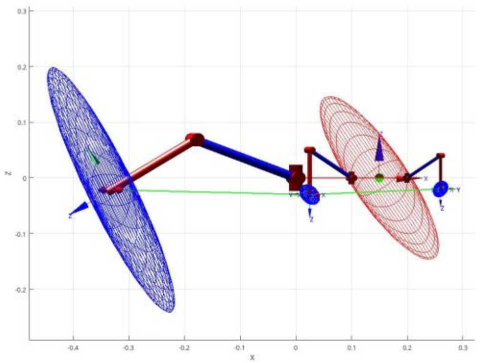
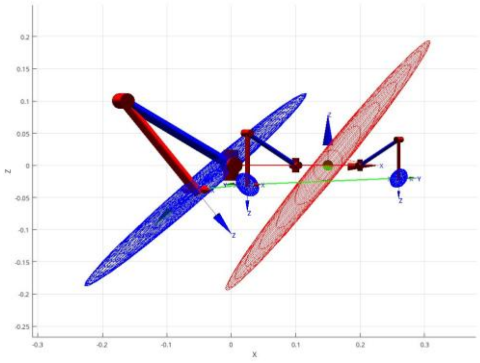
Manipulability Analysis: Bioinspired Example



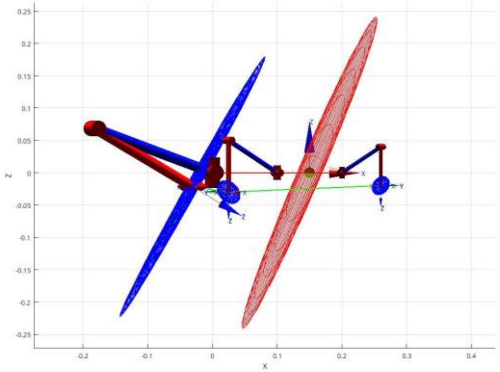
Jumping: sensitivity to rear legs configuration $|q_{LB/RB,1}| = 15^\circ$

$q_{LB/RB,2} = -20^\circ,\ q_{LB/RB,3} = 50^\circ$

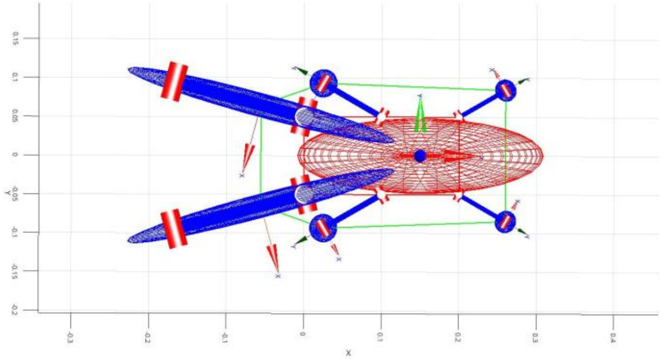


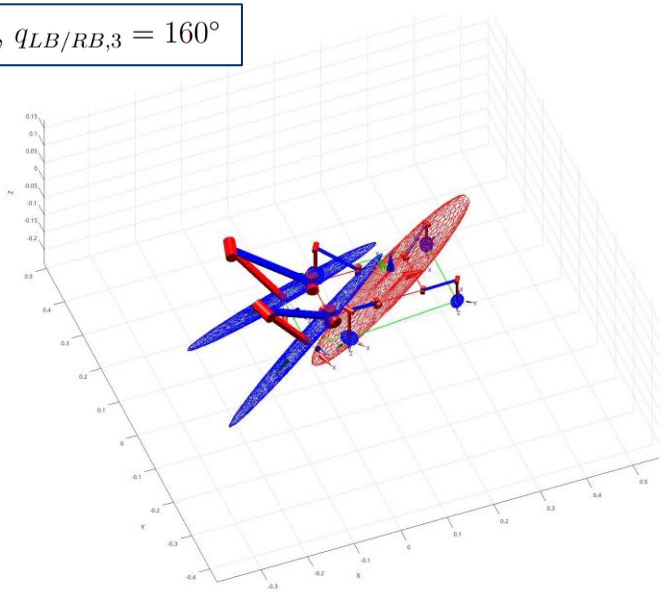


$q_{LB/RB,2} = -30^\circ,\ q_{LB/RB,3} = 170^\circ$



$q_{LB/RB,2} = -30^\circ,\ q_{LB/RB,3} = 160^\circ$





Configuration and Limits

$$\mathbf{q} = \begin{bmatrix} \mathbf{q}_{LF} & \mathbf{q}_{LM} & \mathbf{q}_{LB} & \mathbf{q}_{RF} & \mathbf{q}_{RM} & \mathbf{q}_{RB} \end{bmatrix}^T \in \mathbb{R}^{18}$$

$$\dot{\mathbf{q}}_{lim,LF/RF} = \begin{bmatrix} 0.8 & 0.8 & 0.8 \end{bmatrix}$$

$$\dot{\mathbf{q}}_{lim,LM/RM} = \begin{bmatrix} 0.8 & 0.8 & 0.8 \end{bmatrix}$$

$$\dot{\mathbf{q}}_{lim,LB/RB} = \begin{bmatrix} 1.0 & 1.0 & 4.0 \end{bmatrix}$$

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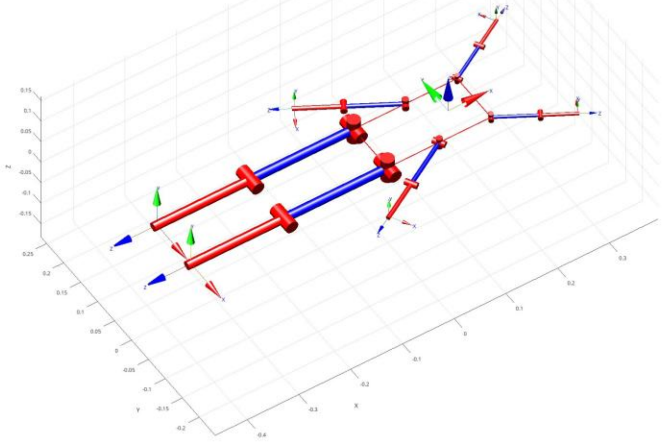
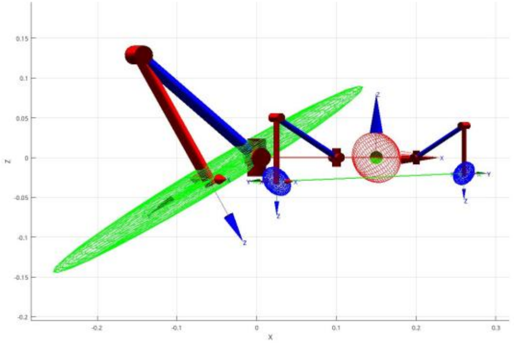
Manipulability Analysis: Bioinspired Example

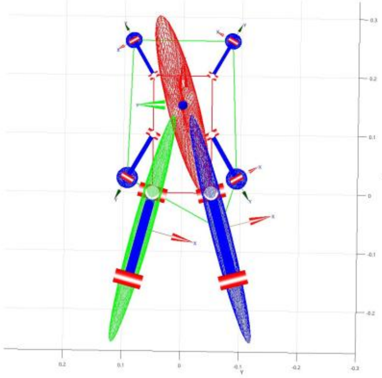


Jumping: sensitivity to rear legs availability and orientation

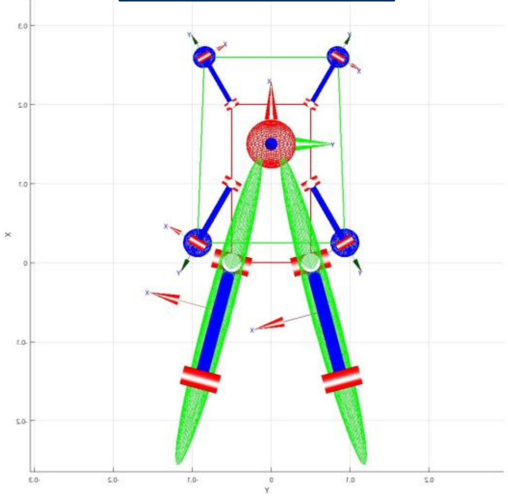
$|q_{LB/RB,1}| = 15°$ $q_{LB/RB,2} = -30°$, $q_{LB/RB,3} = 160°$



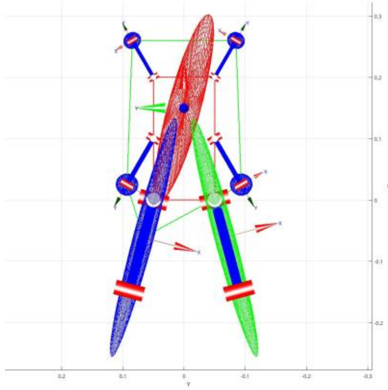
NOT LB



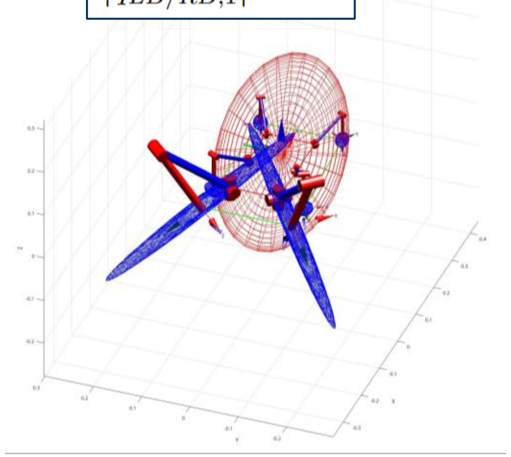
NOT LB and RB



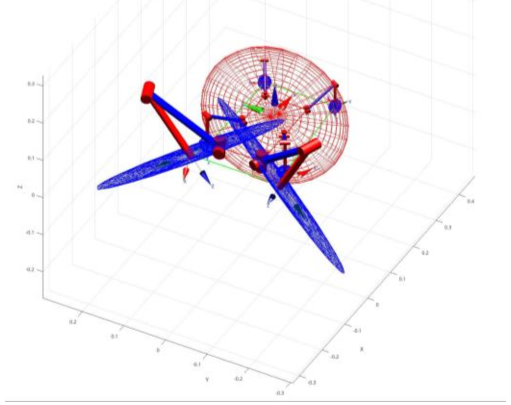
NOT RB



$|q_{LB/RB,1}| = 45°$



$|q_{LB/RB,1}| = 70°$



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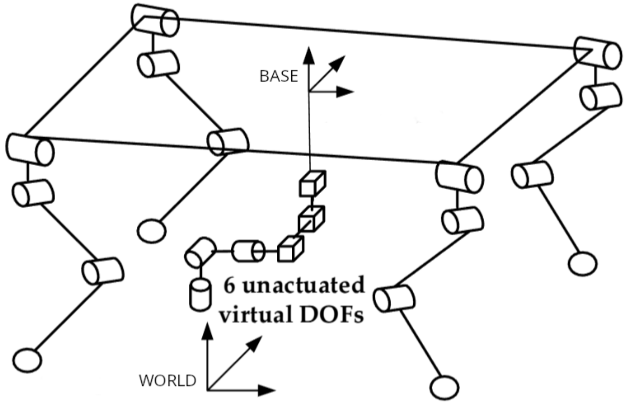
Dynamic Model

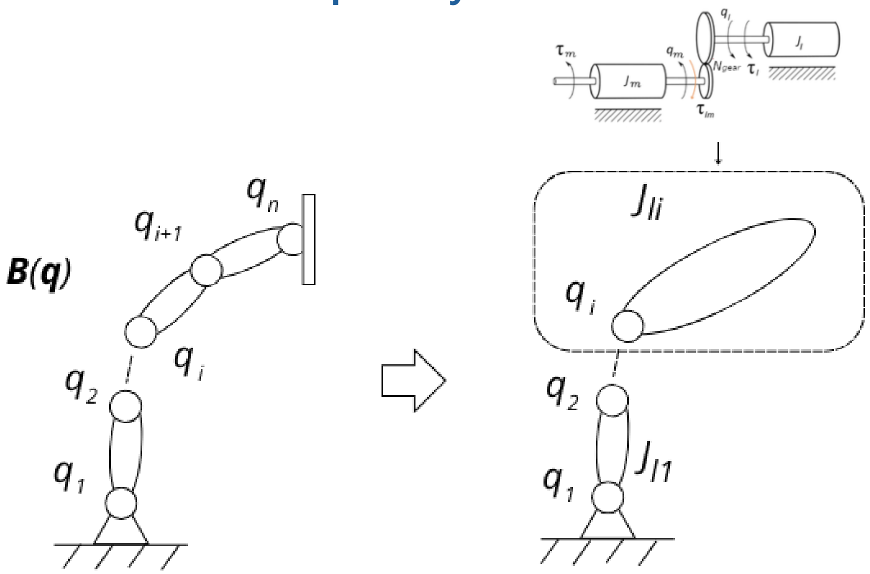
Floating Base Dynamics



$$\mathbf{q} = \begin{bmatrix} \mathbf{q_b} & \mathbf{q_1} & \mathbf{q_2} & \dots & \mathbf{q_N} \end{bmatrix}^T \qquad \mathbf{q} \in \mathbb{R}^{n+6}, (n = \textstyle\sum_j n_j)$$

$$\begin{cases} \mathbf{B}(\mathbf{q})\ddot{\mathbf{q}} + \mathbf{C}(\mathbf{q},\dot{\mathbf{q}})\dot{\mathbf{q}} + \mathbf{g}(\mathbf{q}) = \mathbf{J_M}^T(\mathbf{q})\tau - \mathbf{J_C}^T(\mathbf{q})\mathbf{h_c} \\ \mathbf{J_c}\ddot{\mathbf{q}} + \dot{\mathbf{J}}_\mathbf{c}\dot{\mathbf{q}} = 0 \end{cases}$$

Decoupled Dynamics



$$\left(J_{mi} + \frac{J_{li}}{N^2_{gear,i}}\right)\ddot{q}_{mi} = \tau_{mi} - \frac{\tau_{di}}{N_{gear,i}} \qquad i = 1, \dots, n$$

$$\tau_{di} = \sum_{j \neq i} C_{ij}(\mathbf{q}) \cdot \dot{q}_j^2 + \sum_{j \neq i} B_{ij}(\mathbf{q}) \cdot \ddot{q}_j + g_i(\mathbf{q})$$

LIMBERO-GRIEEL Model

$$j \in J = \{1, 2, 3, 4\}, \quad J_c \subseteq J$$

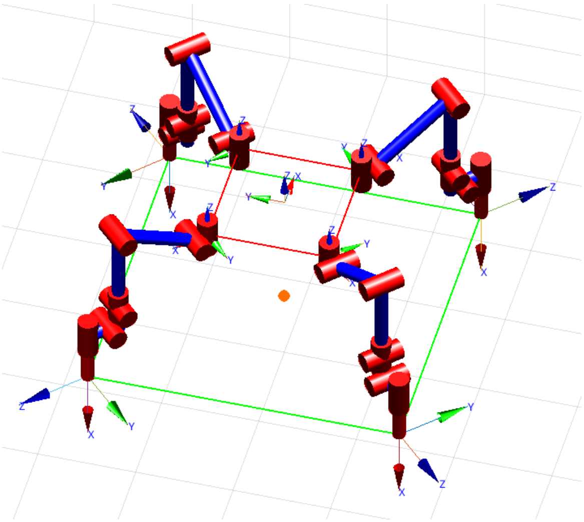
$$N = |J| = 4, \quad N_c = |J_c|$$

$$n_j = 7, \quad n = n_j \cdot N = 28$$

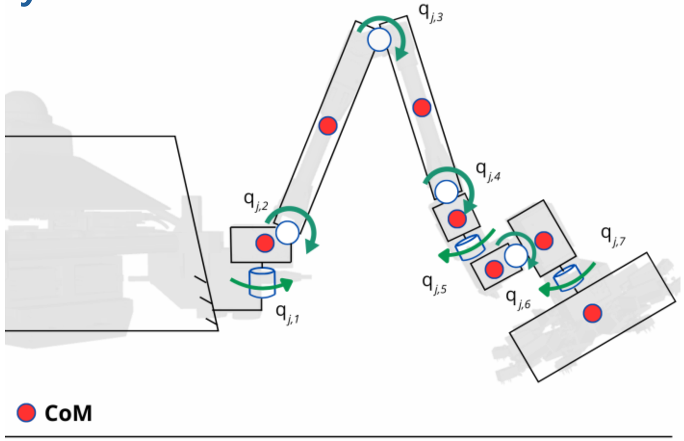
$$\mathbf{q}_j = \begin{bmatrix} q_{j,1} & q_{j,2} & q_{j,3} & q_{j,4} & q_{j,5} & q_{j,6} & q_{j,7} \end{bmatrix}^T \in \mathbb{R}^7$$

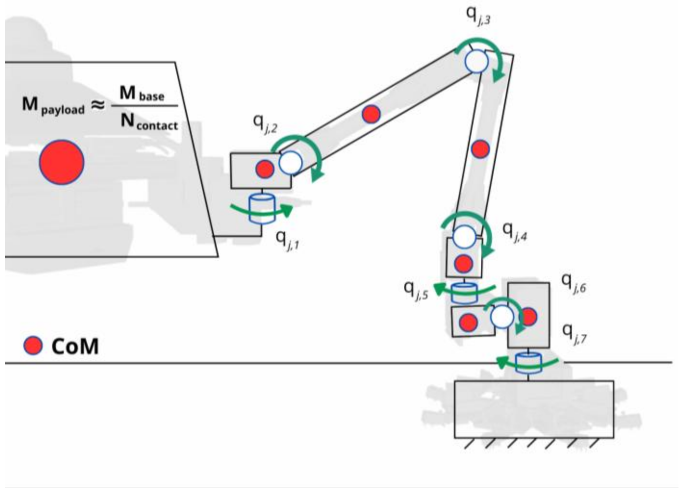
$$\mathbf{q} = \begin{bmatrix} \mathbf{q}_1 & \mathbf{q}_2 & \mathbf{q}_3 & \mathbf{q}_4 \end{bmatrix}^T \in \mathbb{R}^{28}$$

Kinematics

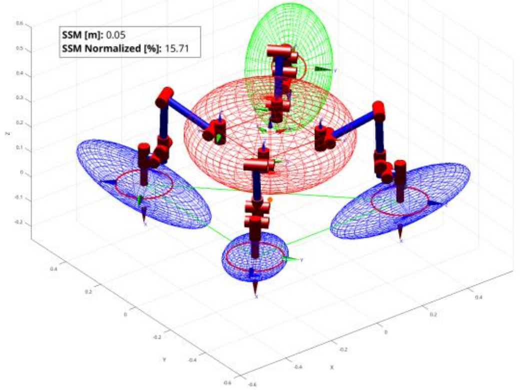


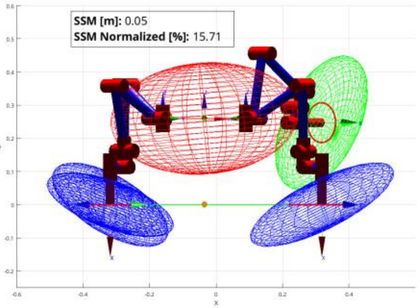
Dynamics

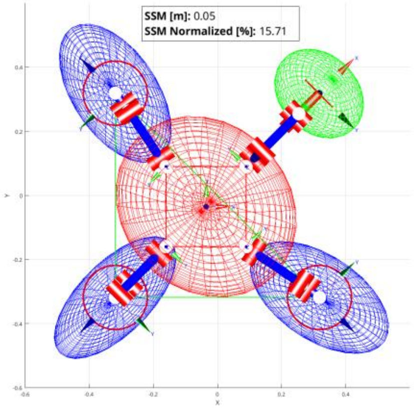




Manipulability







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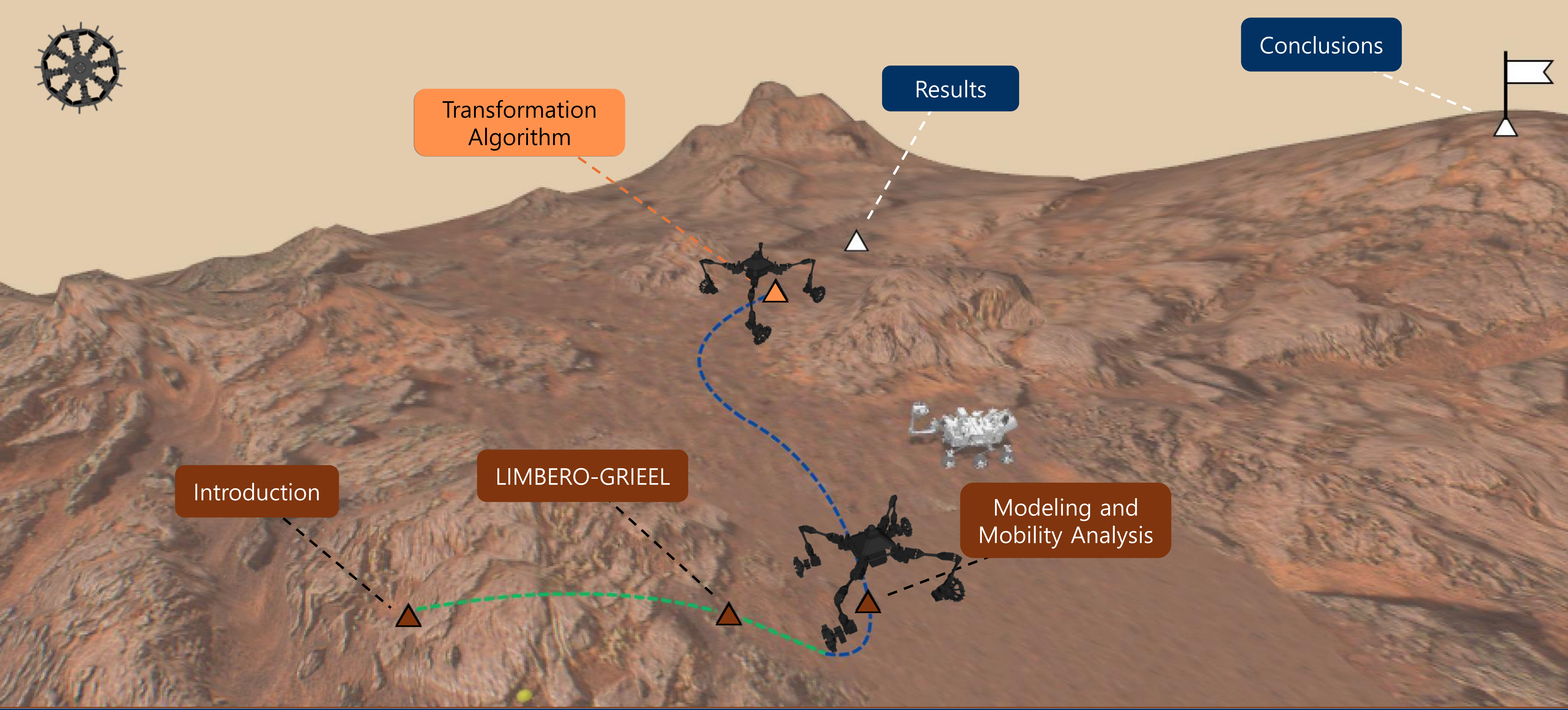

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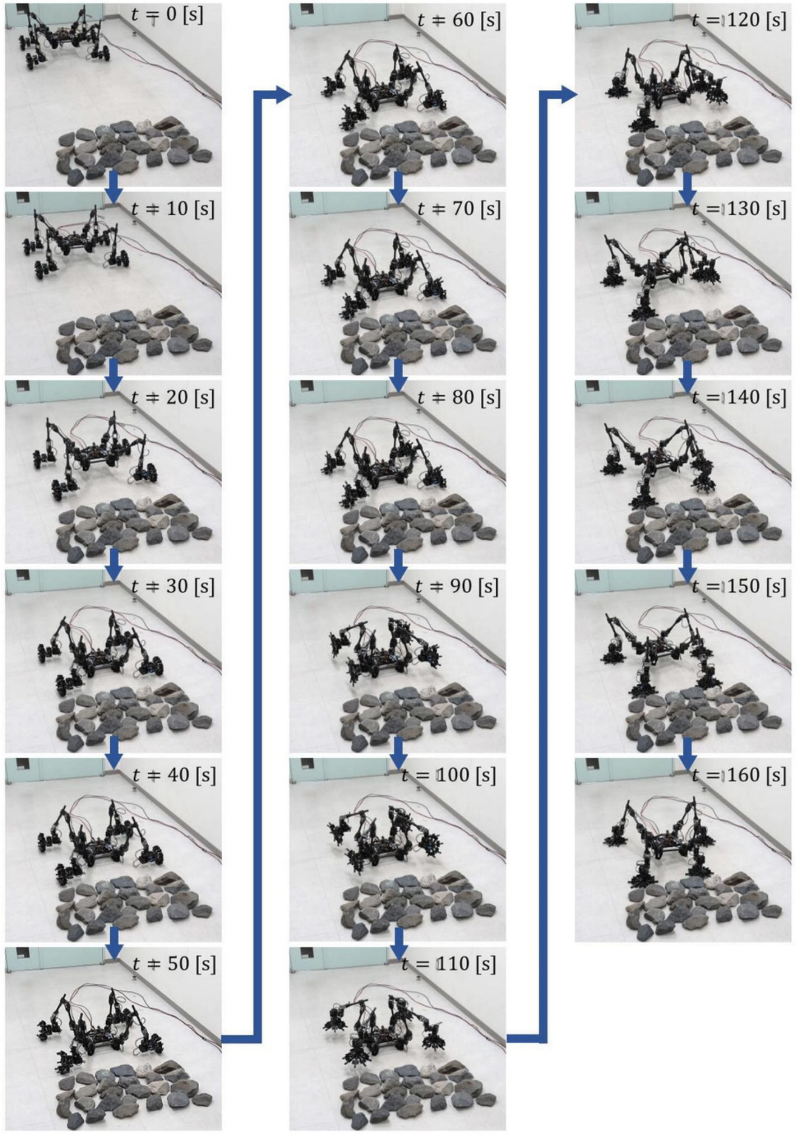
Previous Sequence



- Quick and simple
- Always stable **in flat terrains**

- Not flexible
- Base wear in rough terrains
- Not stable in **generic terrains**

Improvement ideas

- Hold the base above the ground
- Transform limb-ends singularly

Multilimbed Robots Stability

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Support polygon

$$SP = \mathrm{Conv}(J_c) = \left\{ \sum_{j \in J_c} \lambda_j \mathbf{P}_{c.j} \;\middle|\; \sum_{j \in J_c} \lambda_j = 1,\ \lambda_j \geq 0,\ \forall j \in J_c \right\}$$

$$\sigma_{SS}(\overline{\mathbf{P}}_{CoM}) = \begin{cases} +1 & \text{if } \exists \lambda_j \geq 0\ ,\ j \in J_c \mid \sum_{j \in J_c} \lambda_j = 1\ , \overline{\mathbf{P}}_{CoM} = \sum_{j \in J_c} \lambda_j \mathbf{P}_{c.j} \\ -1 & \text{otherwise} \end{cases}$$

Static stability (SS) criterion

A legged locomotion machine supported by a stationary horizontal plane surface is statically stable at time t if and only if the vertical projection of the center of gravity of the machine onto the supporting surface lies within its support pattern at the given time

↕

SSM ≥ 0

Static Stability Margin

$$SSM = \sigma_{SS}(\overline{\mathbf{P}}_{CoM}) \cdot \min_j \frac{\left|(\mathbf{P}_{c,j+1} - \mathbf{P}_{c,j}) \times (\mathbf{P}_{c,j} - \overline{\mathbf{P}}_{CoM})\right|}{||\mathbf{P}_{c,j+1} - \mathbf{P}_{c,j}||}$$

$$SSM_{\%} = \frac{SSM}{SSM_{max}} \cdot 100$$

Limitations and alternatives

- sloped terrains and relevant dynamics
- Zero Moment Point (ZMP),
  Tumble Stability (TS),
  Gravito Inertia Acceleration (GIA)

↓

Assumption

The locomotion mode transition occurs in approximately flat terrains, with quasi static motion

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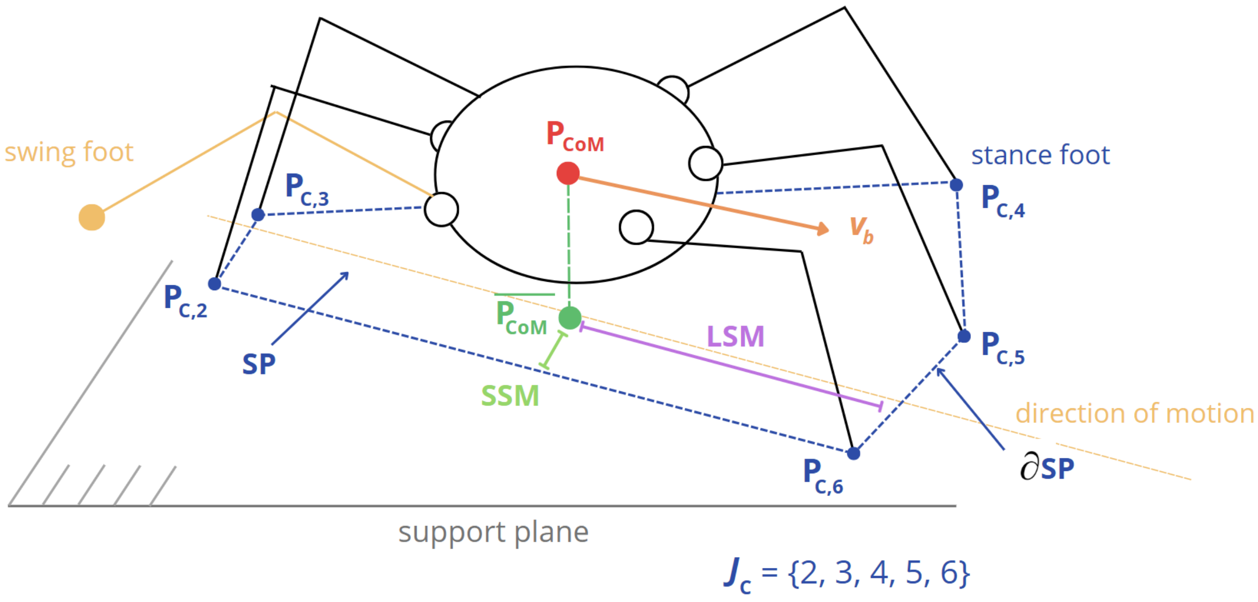
Multilimbed Robots Stability

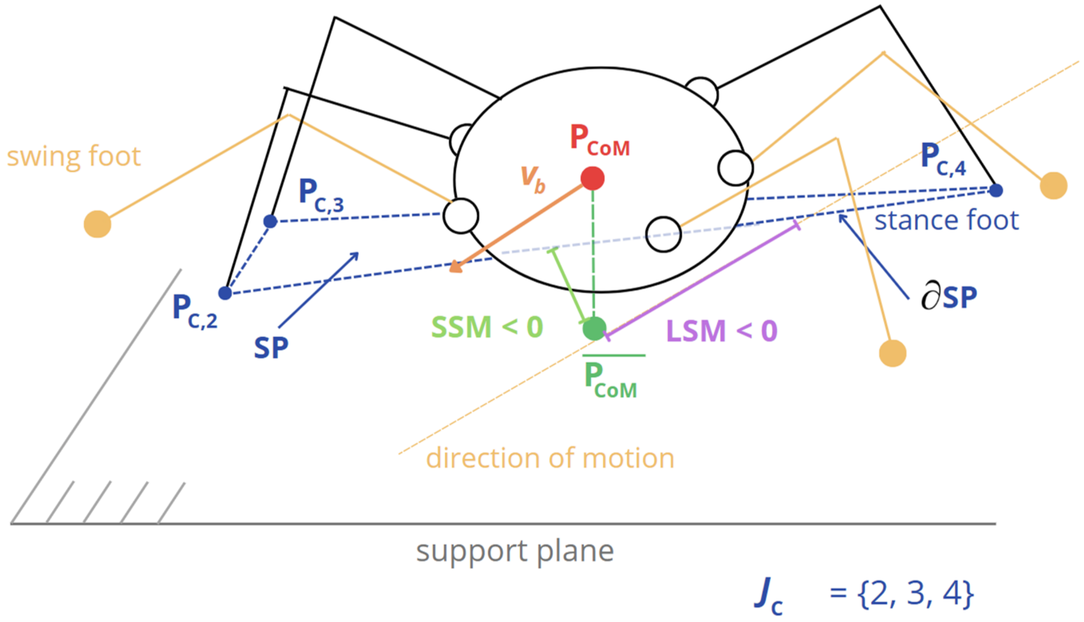
Stable

SSM ≥ 0

Unstable

SSM < 0





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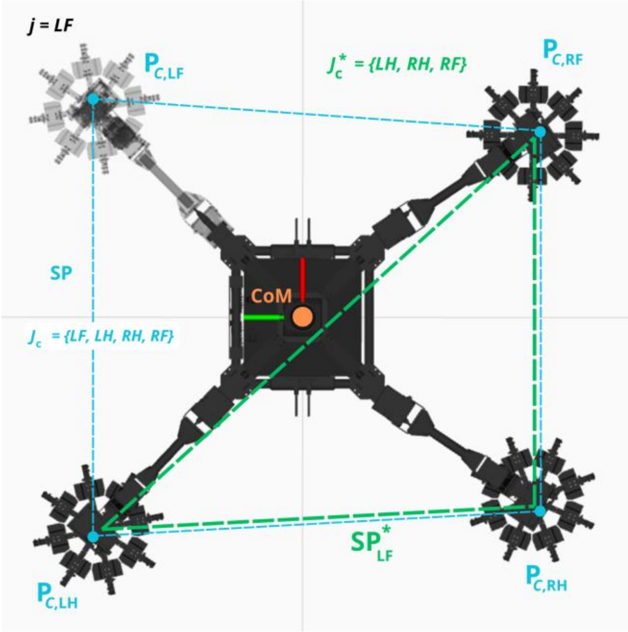
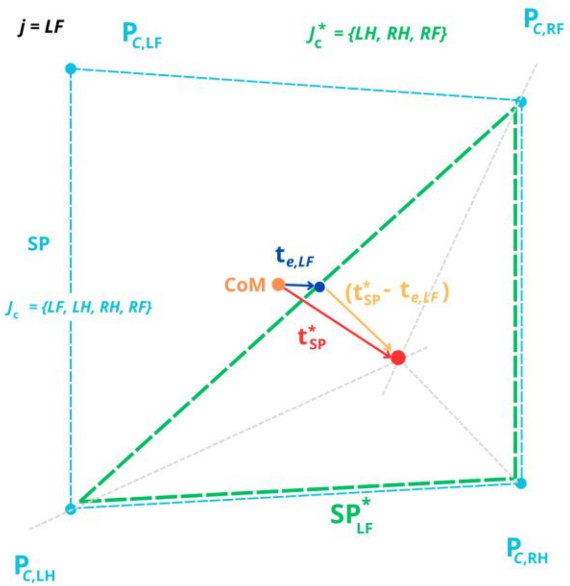
Proposed Sequence: Single Transformation

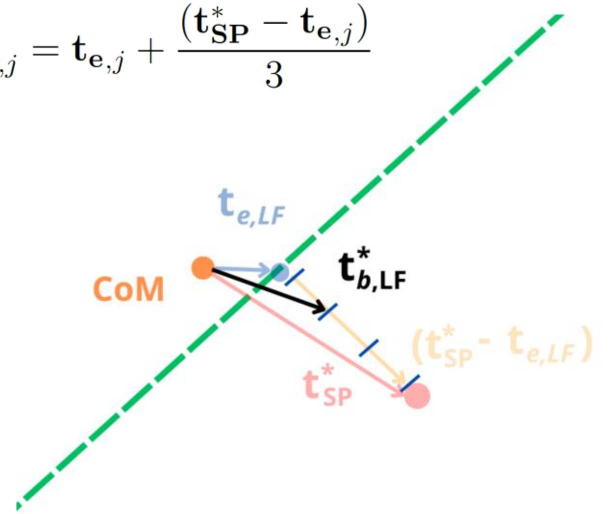
Transformation idea: Anticipative base translation

1. Consider the next limb to transform (raised)
2. Move the base to keep Static Stability during the upcoming motion tasks
3. Perform transformation motion tasks





$$\mathbf{t}^*_{\mathbf{b},j} = \mathbf{t}_{\mathbf{e},j} + \frac{(\mathbf{t}^*_{\mathbf{SP}} - \mathbf{t}_{\mathbf{e},j})}{3}$$



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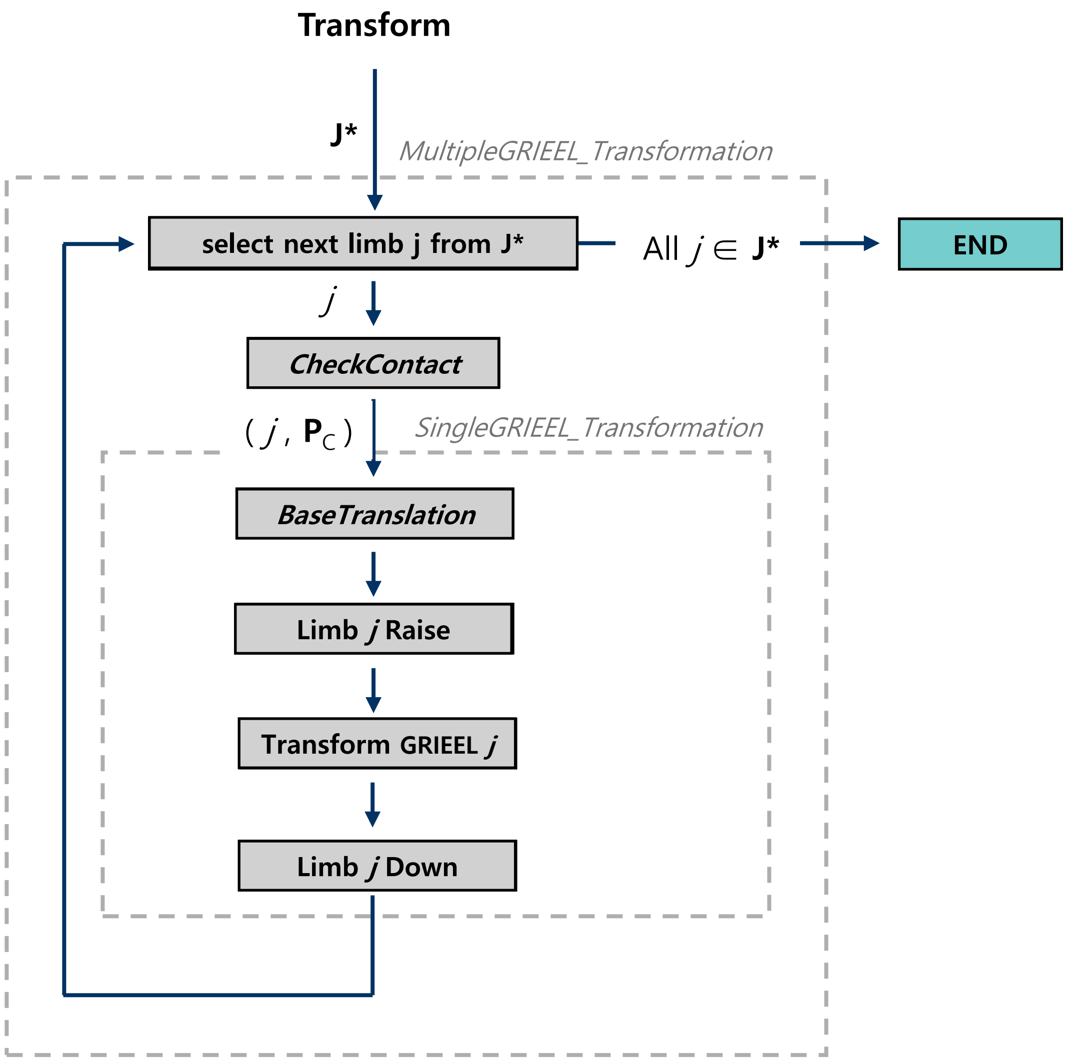
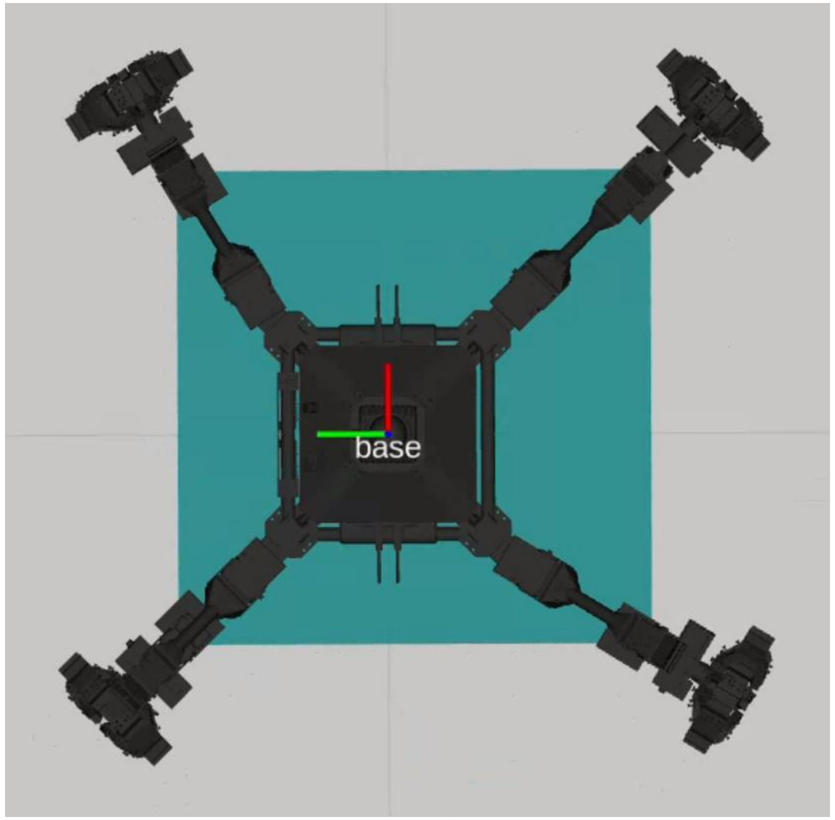
Proposed Sequence: Algorithm



WHEEL MODE



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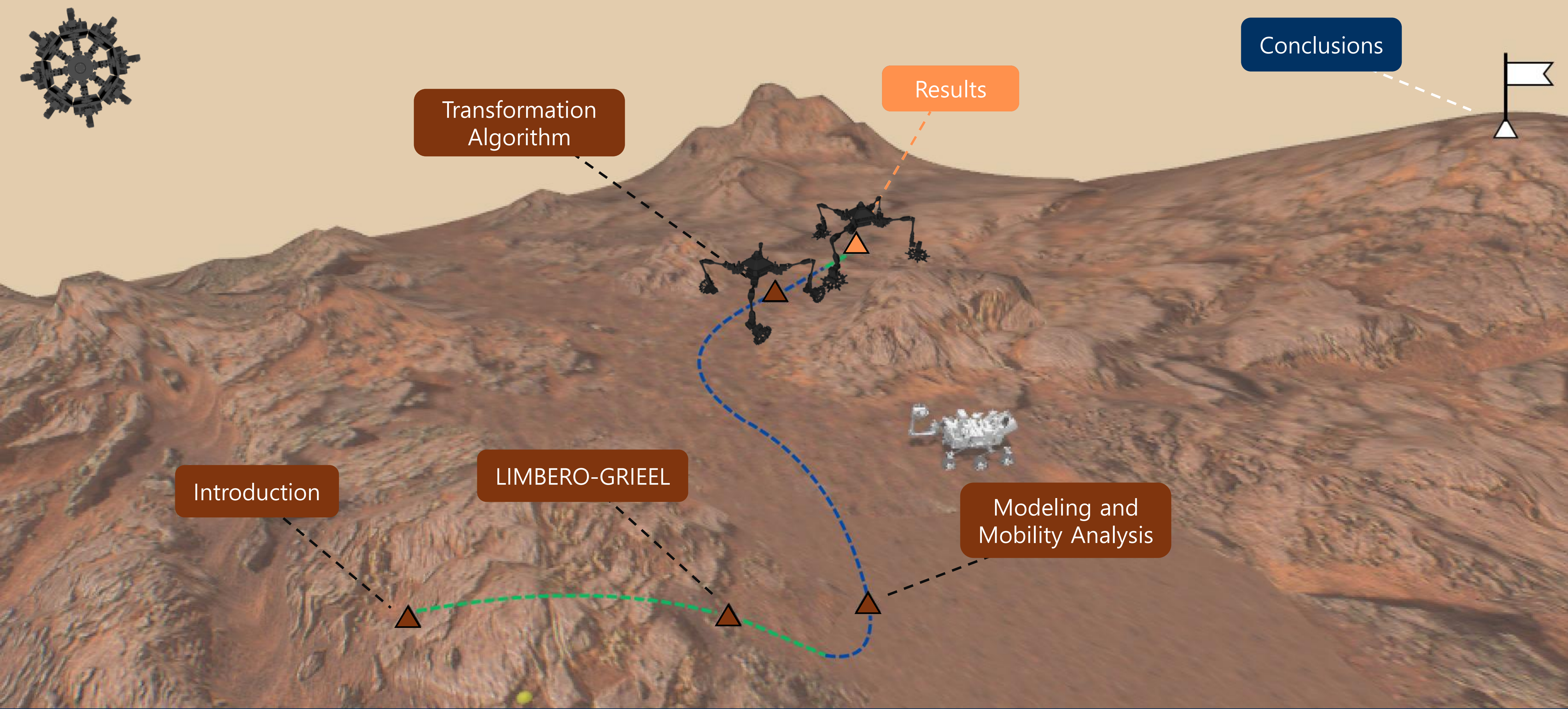

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Experiments: Preliminary Tests and Setup

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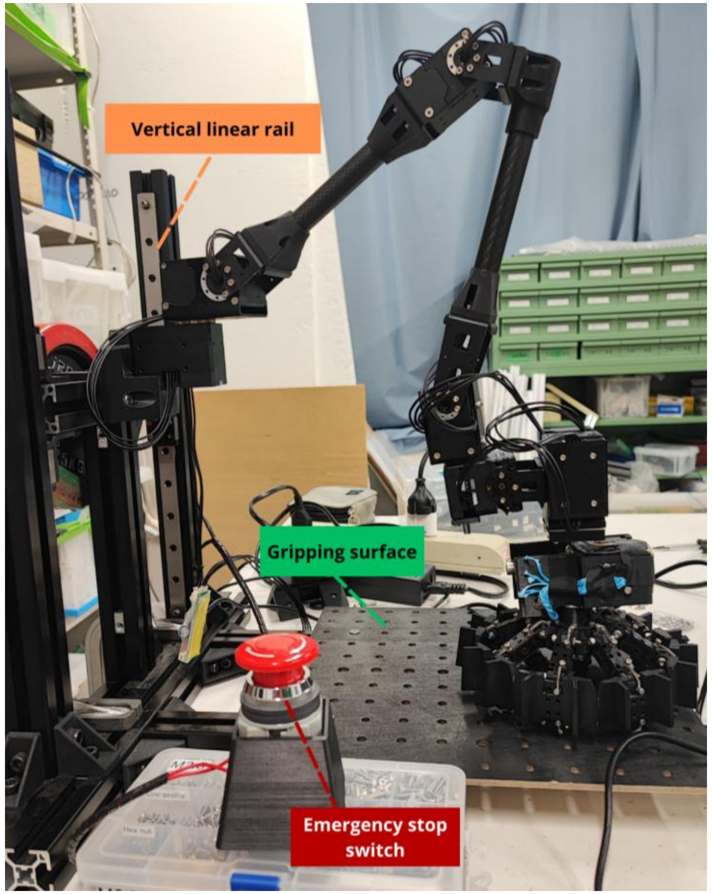
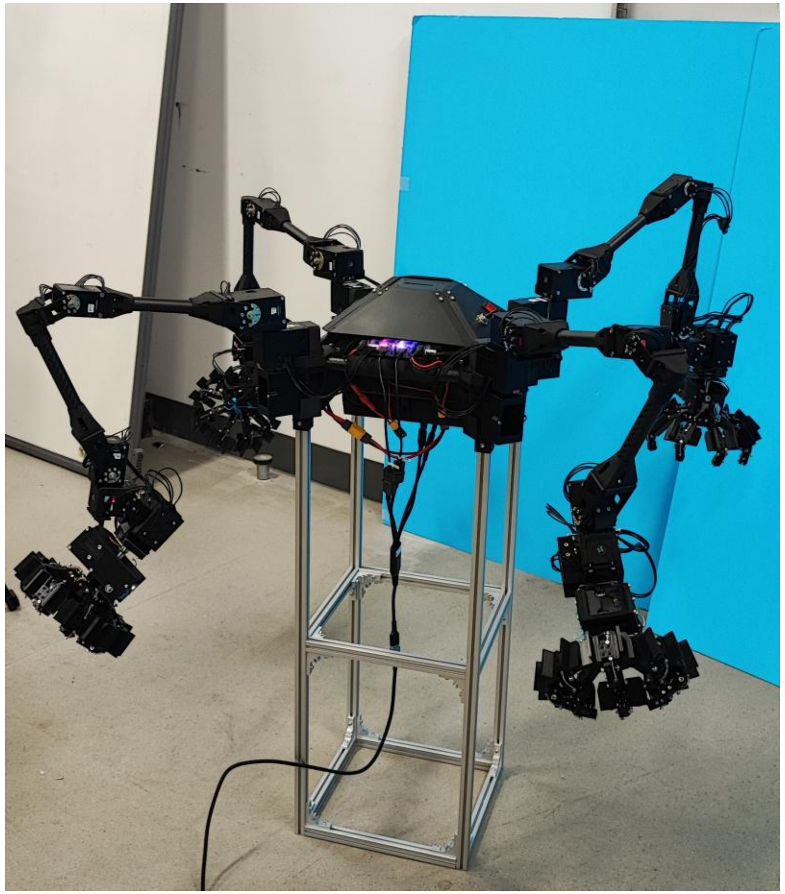
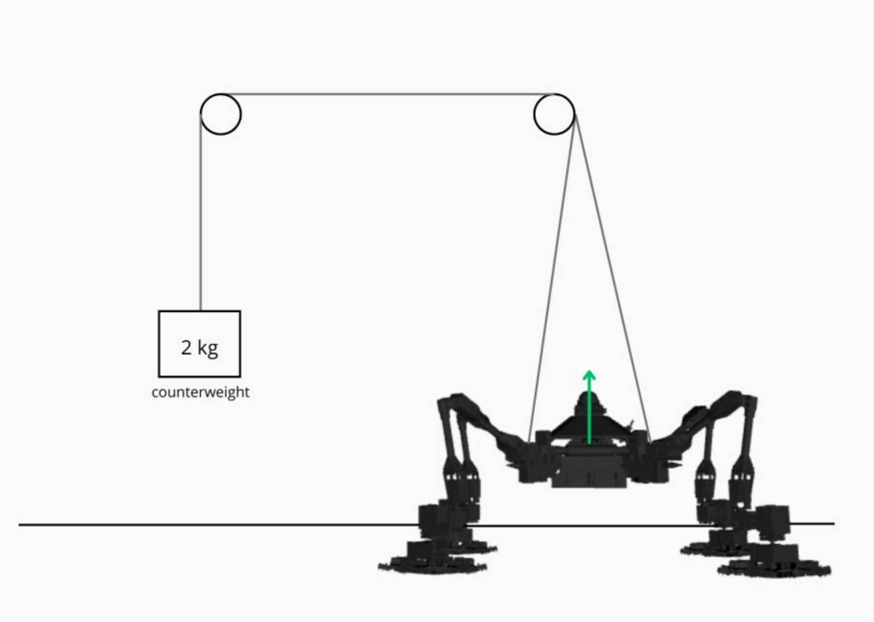
Single Limb Test



Robot Test



Counterweight



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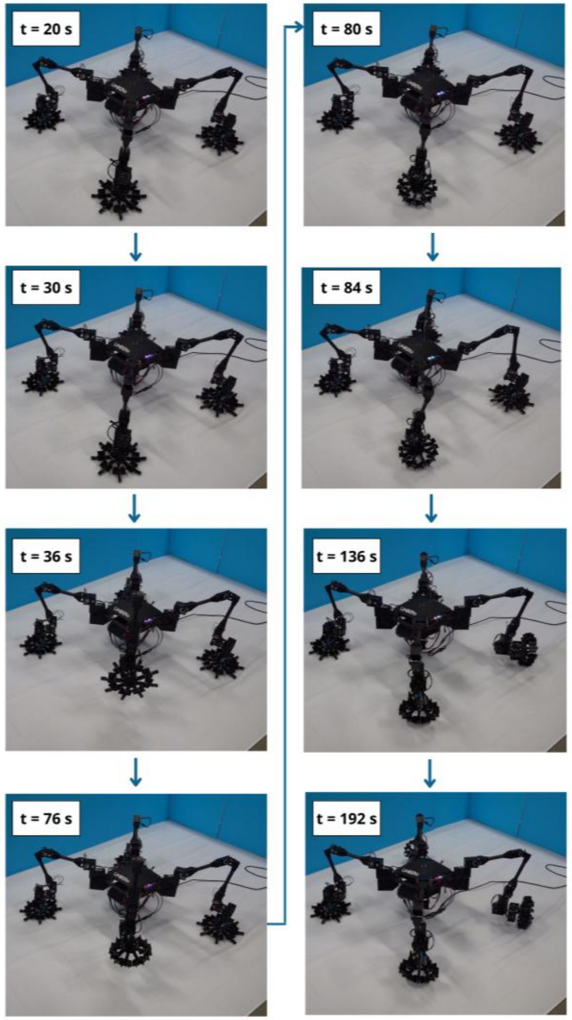
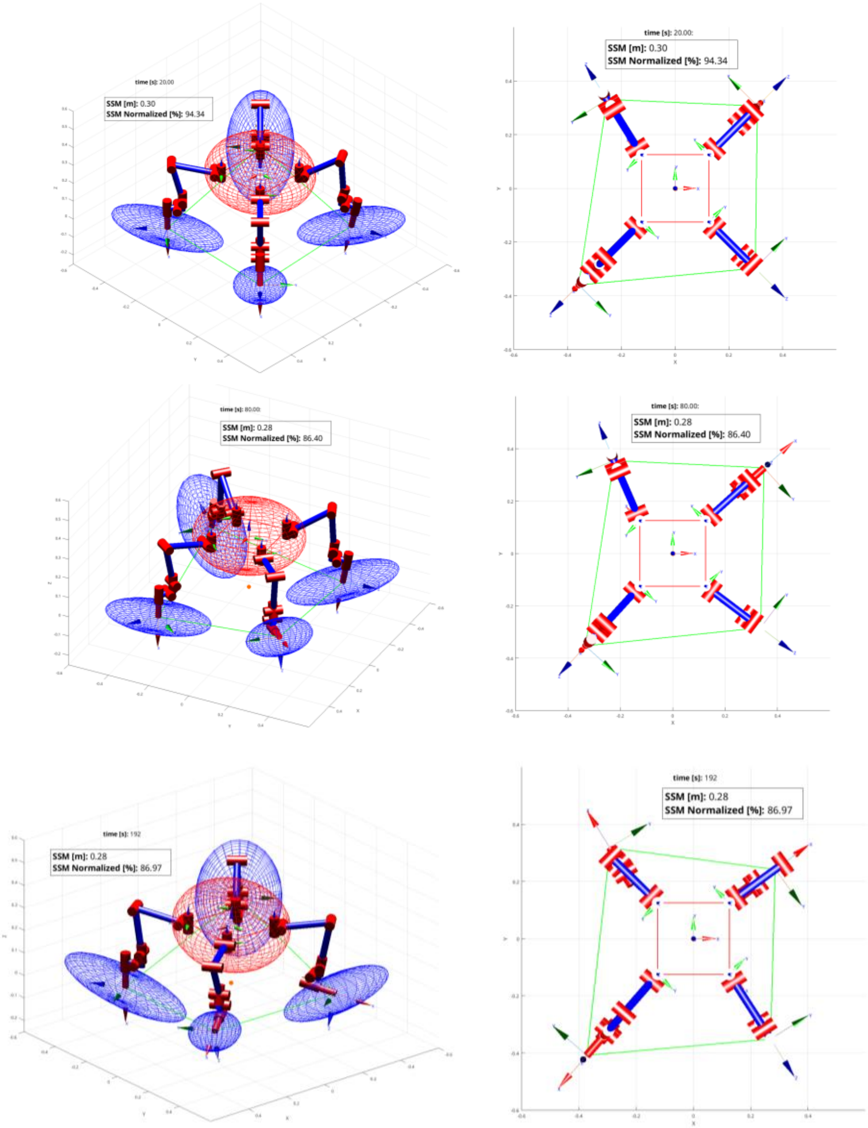
Experiments





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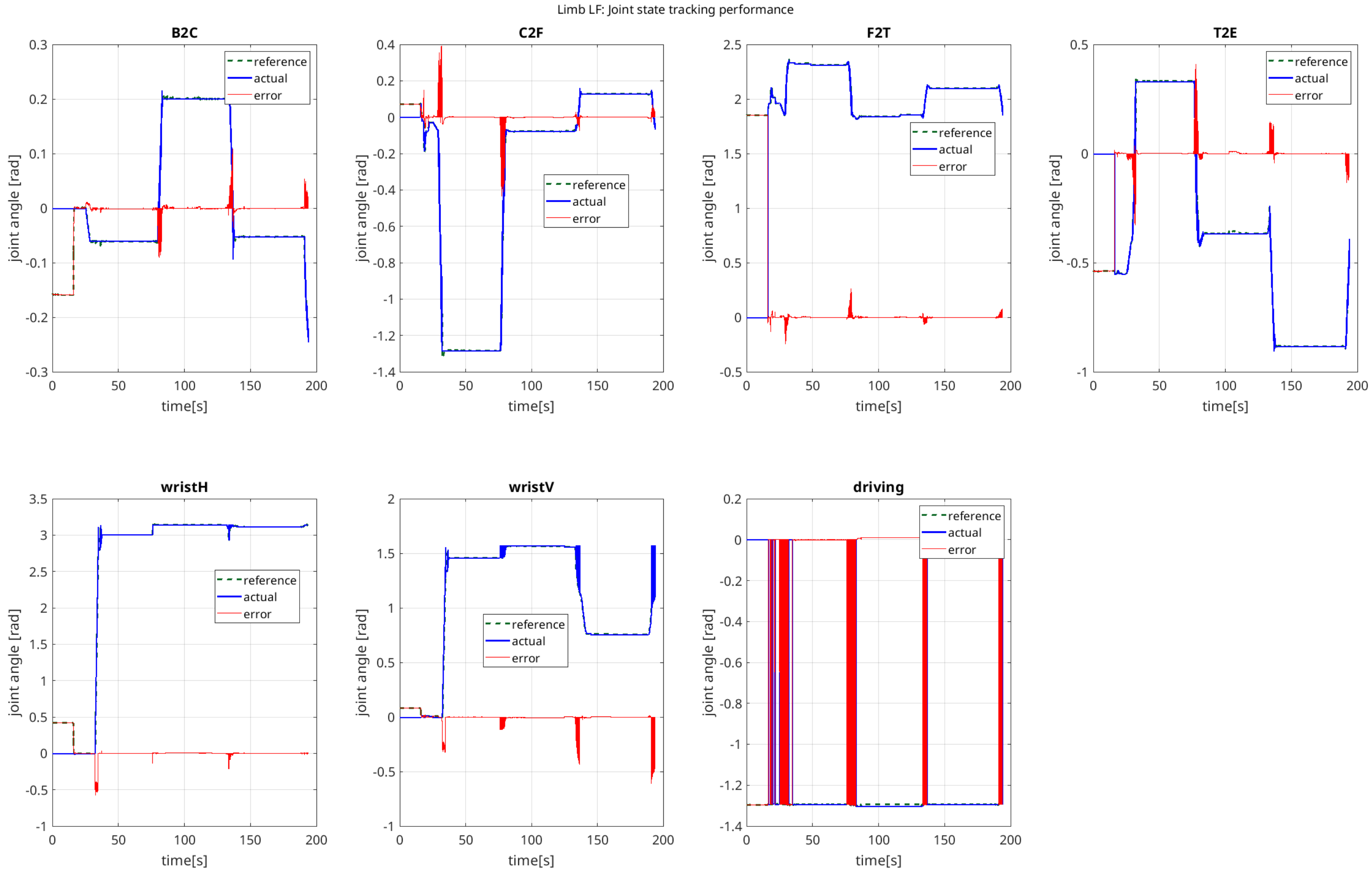
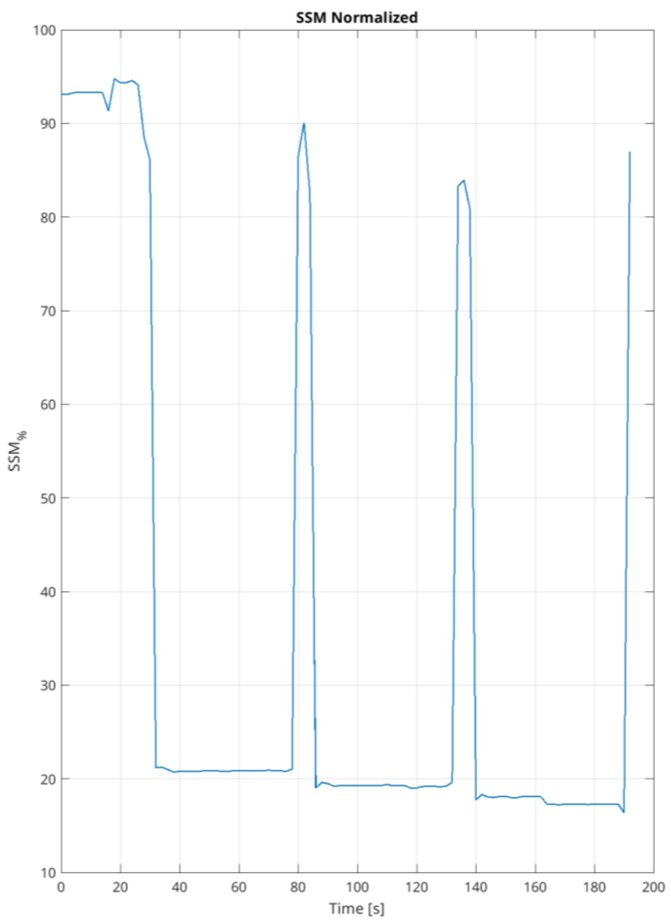
Experiments





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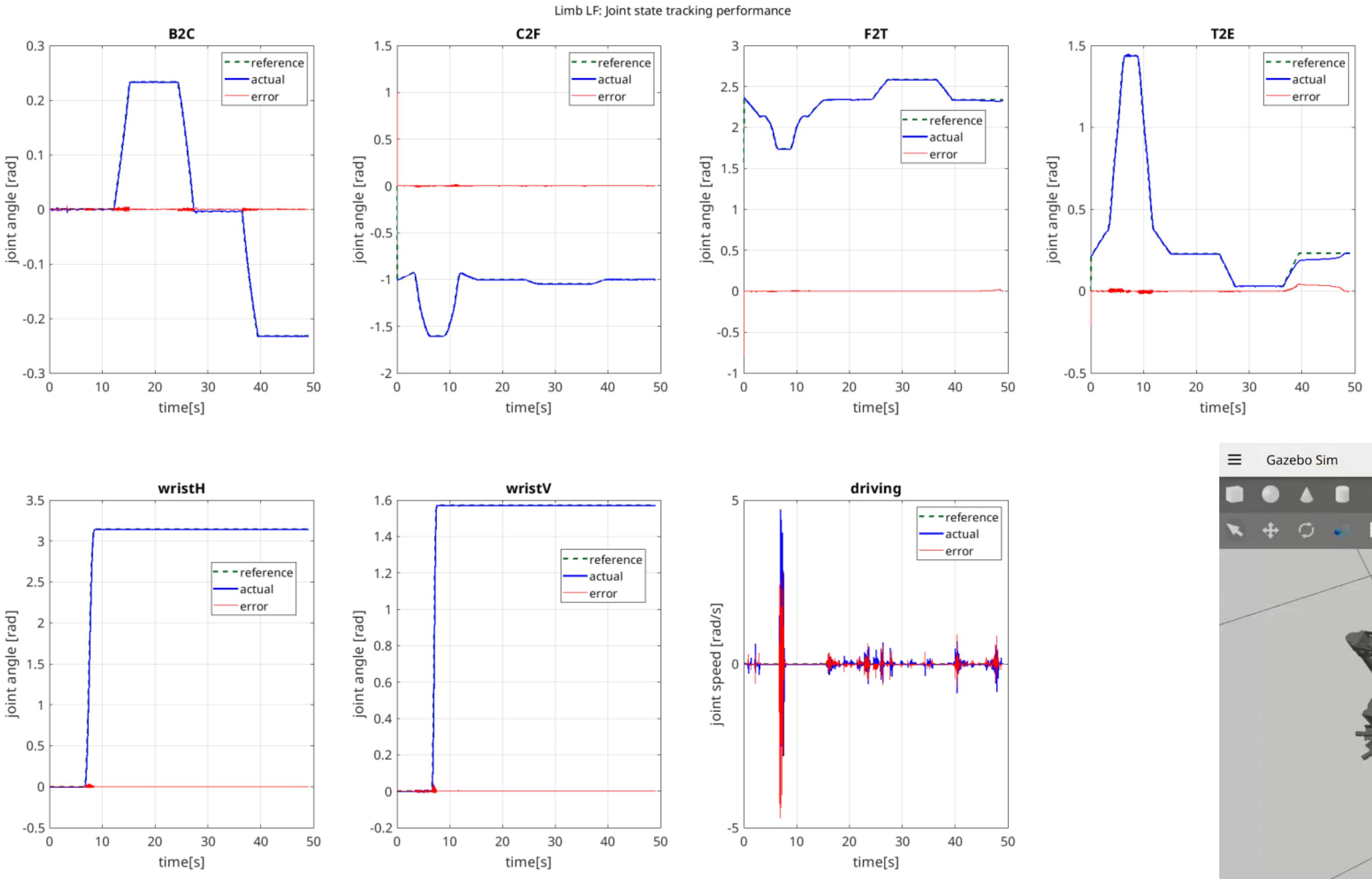
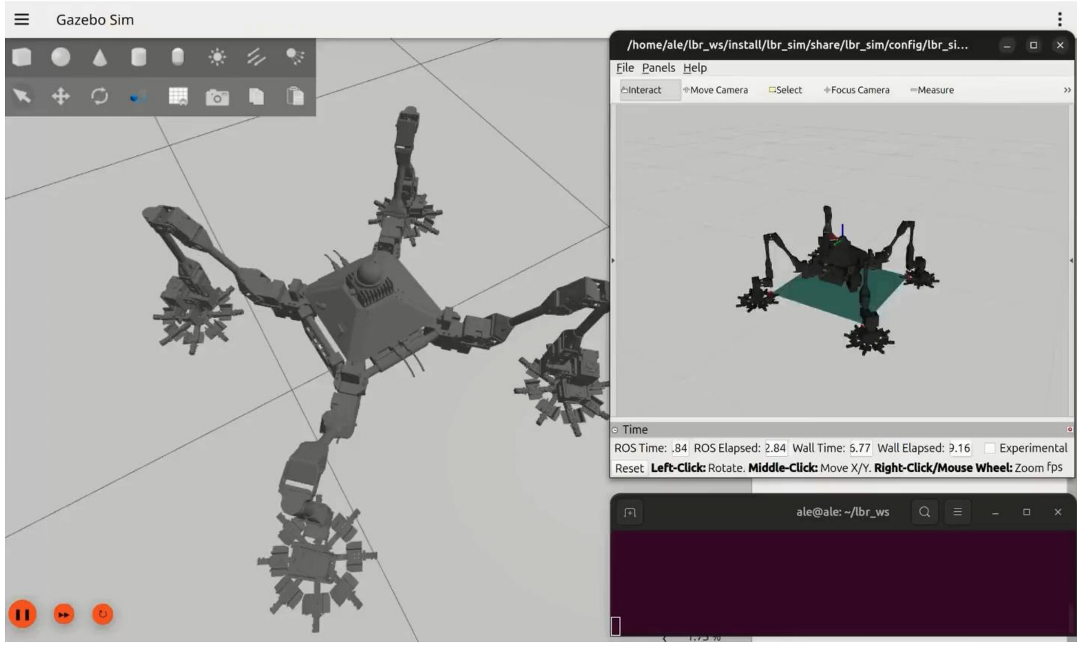
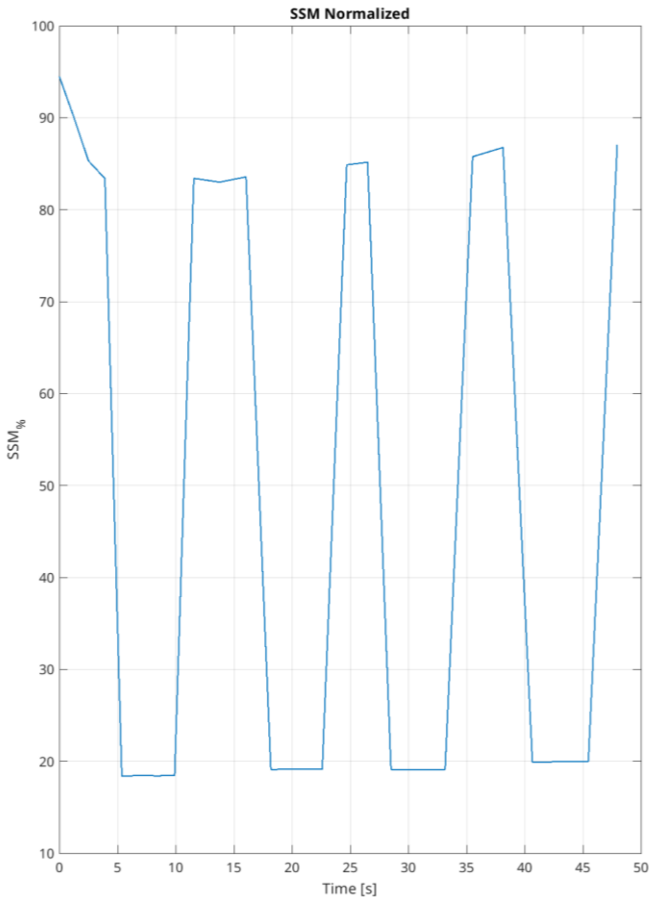
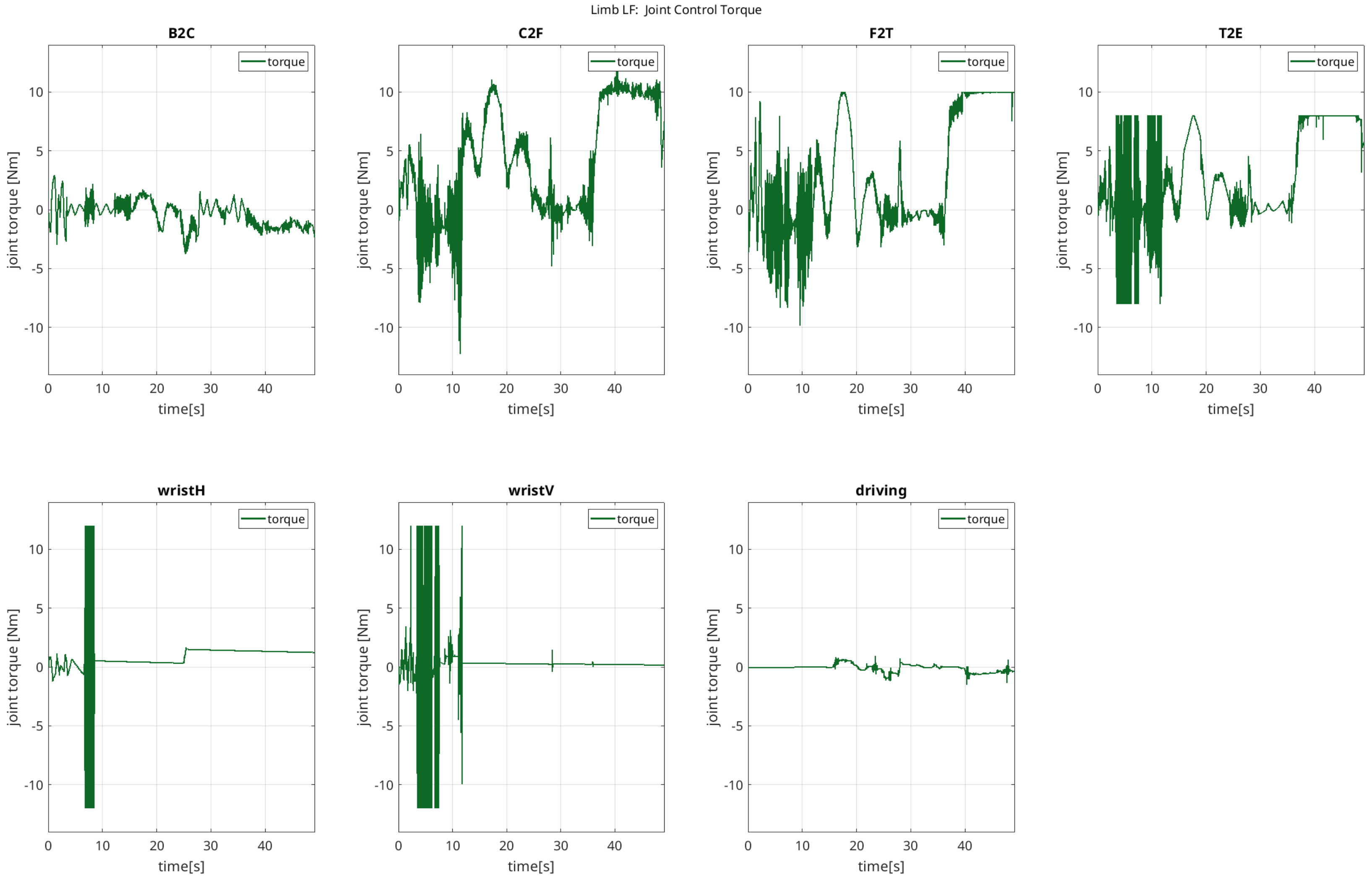
Simulations: G2W





Simulations: G2W





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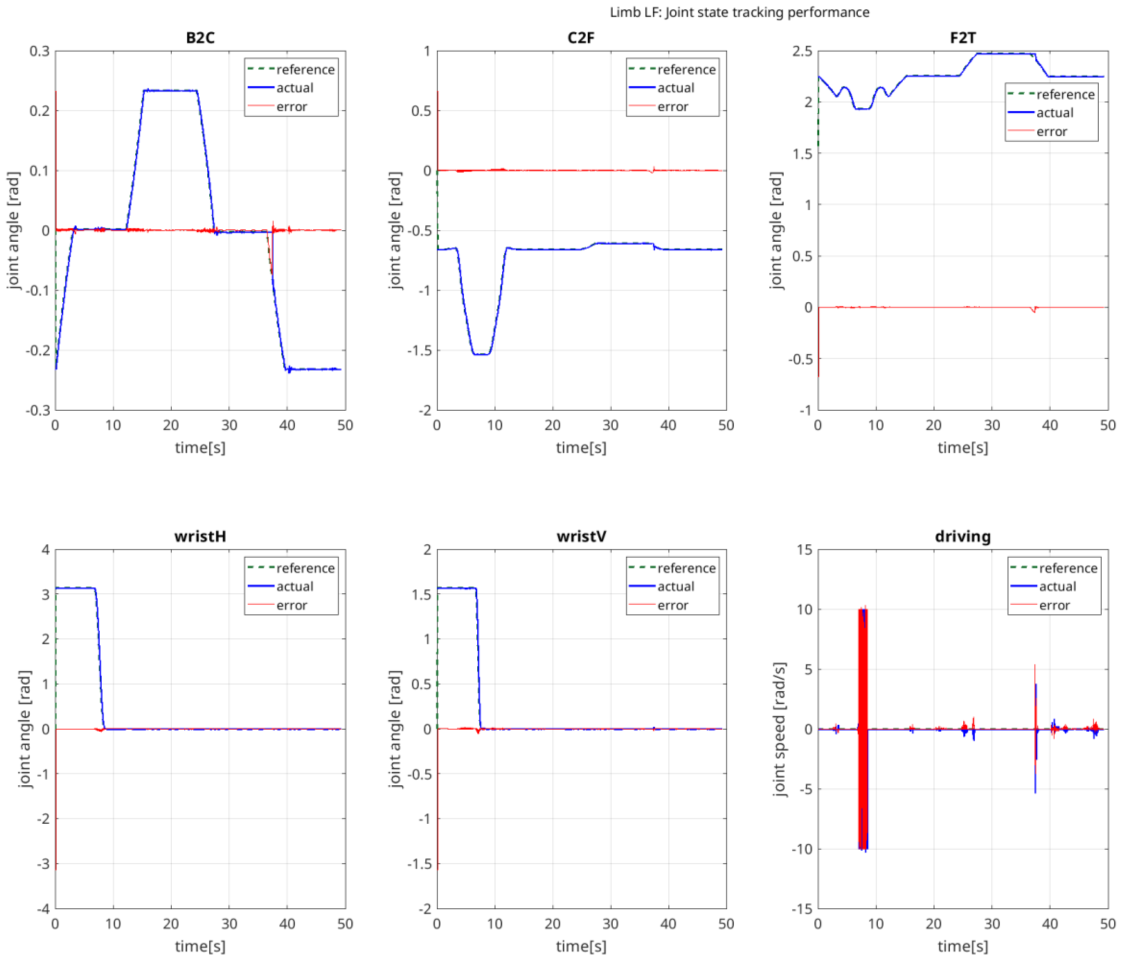
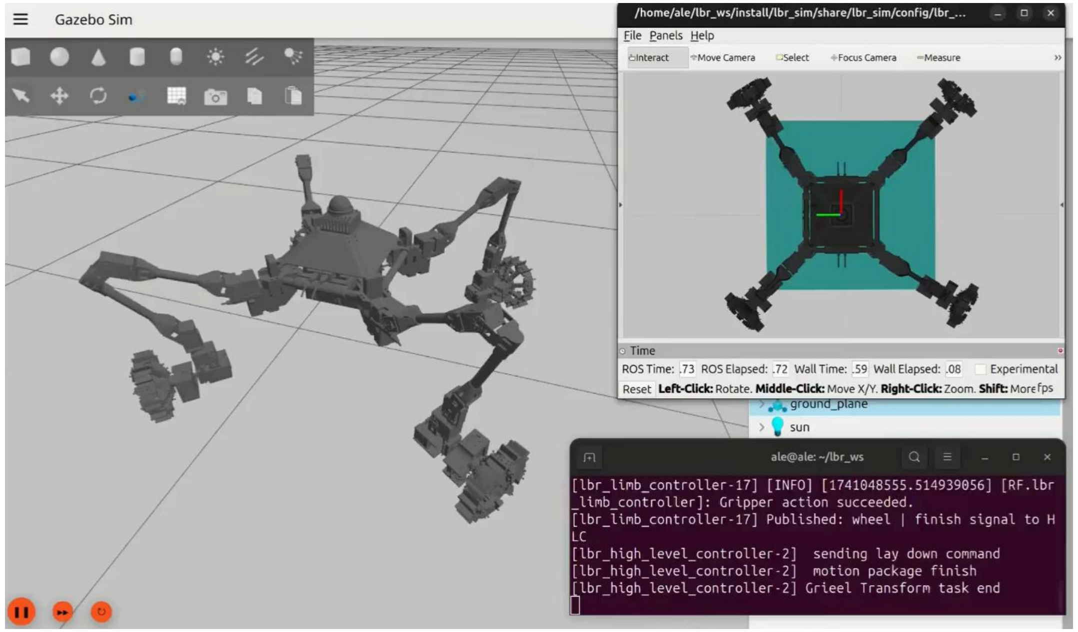
Simulations: W2G





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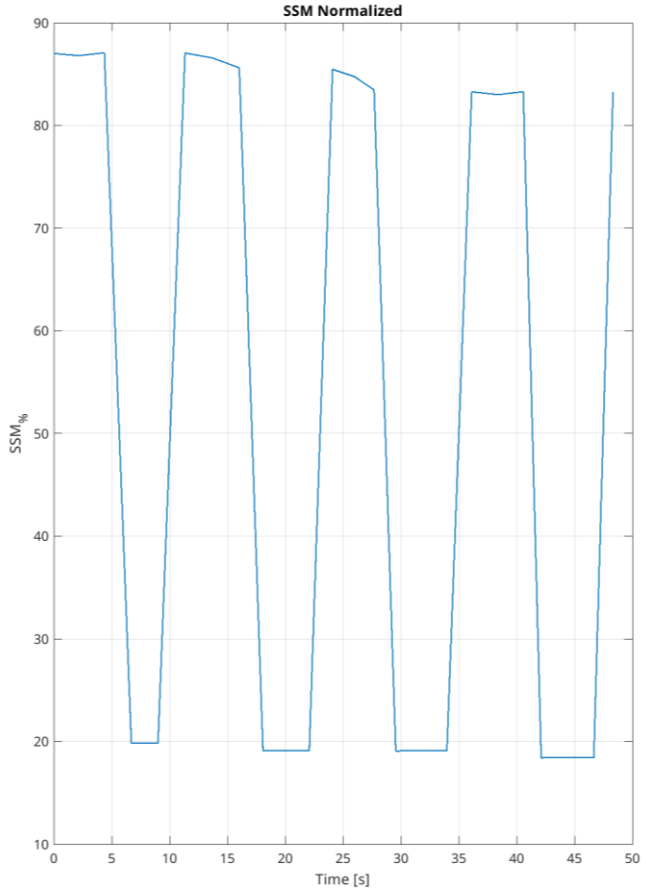
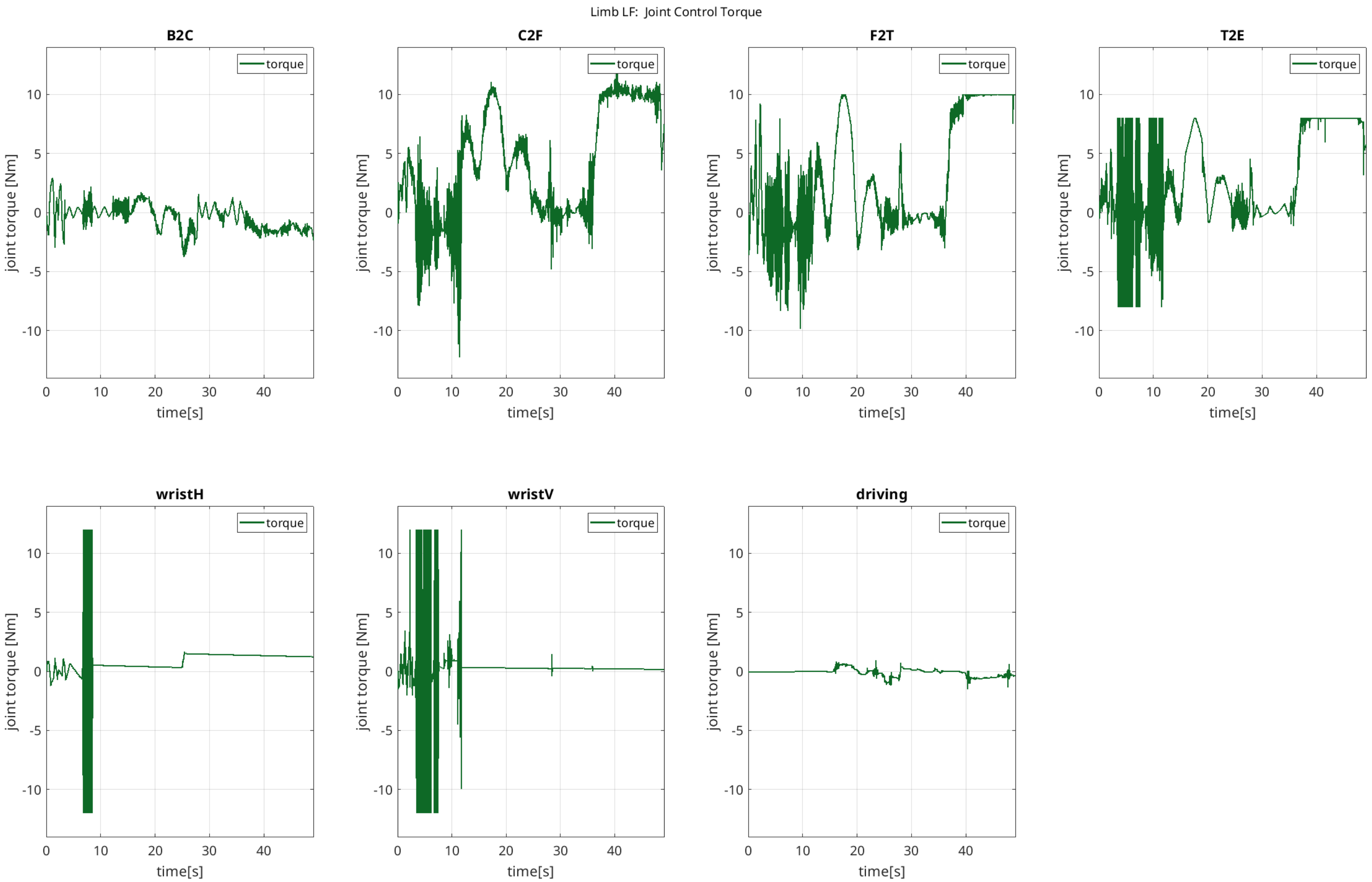
Simulations: W2G





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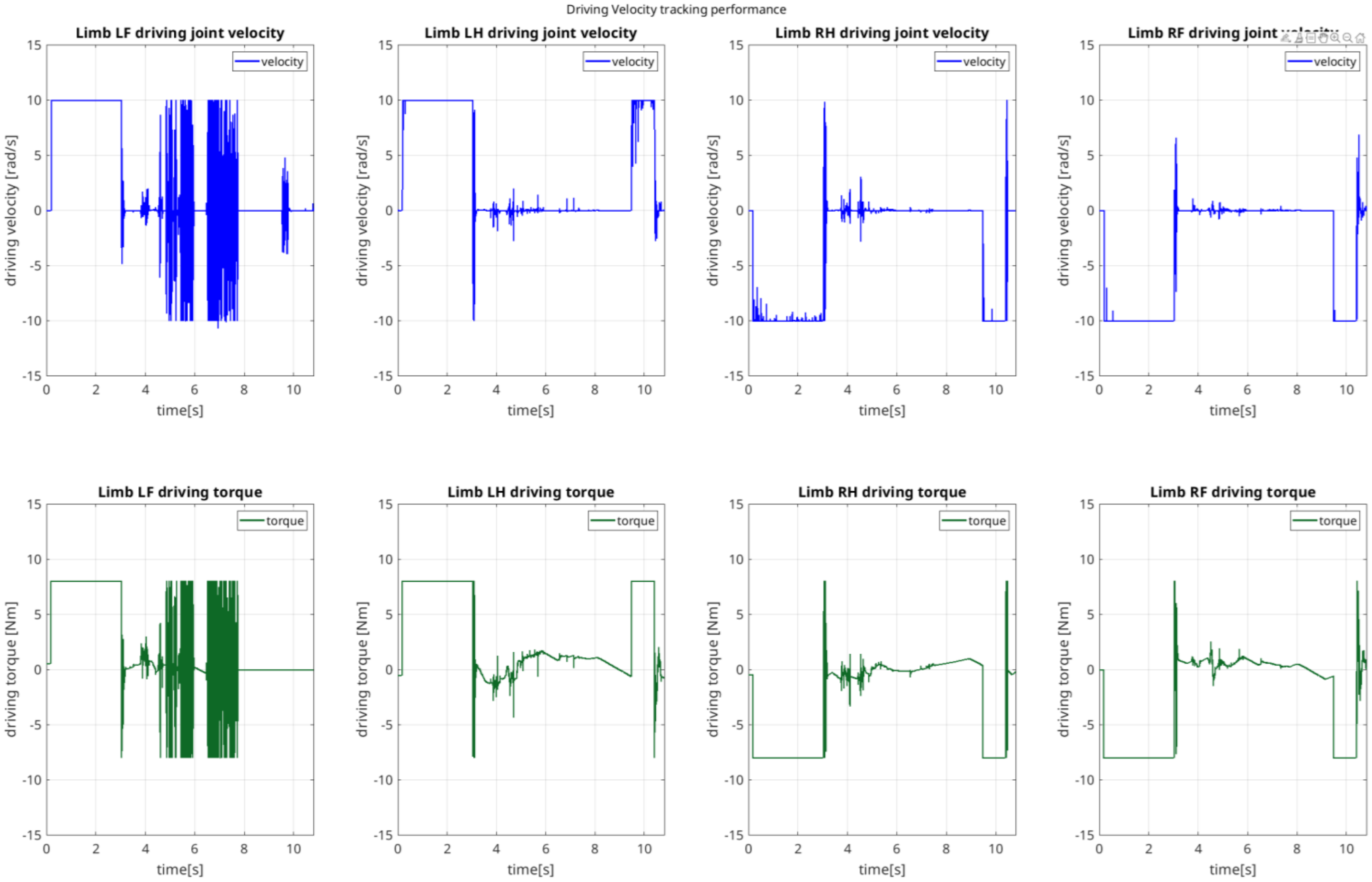
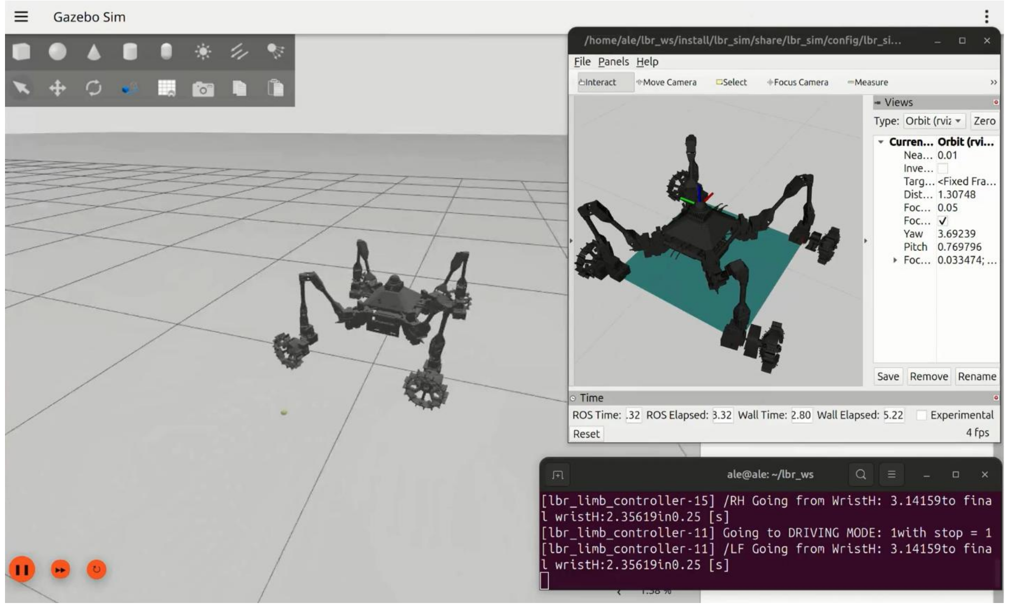
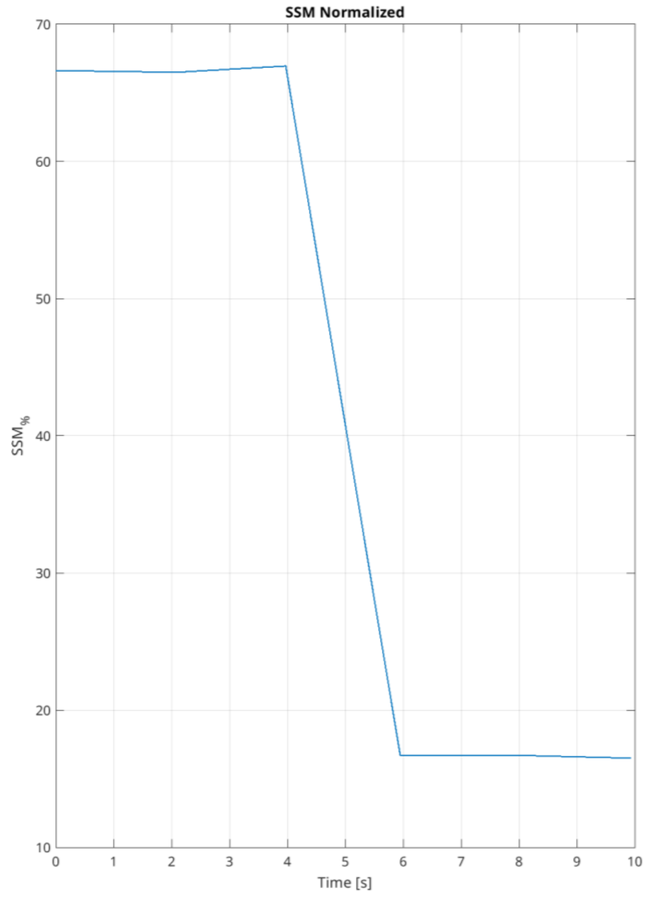
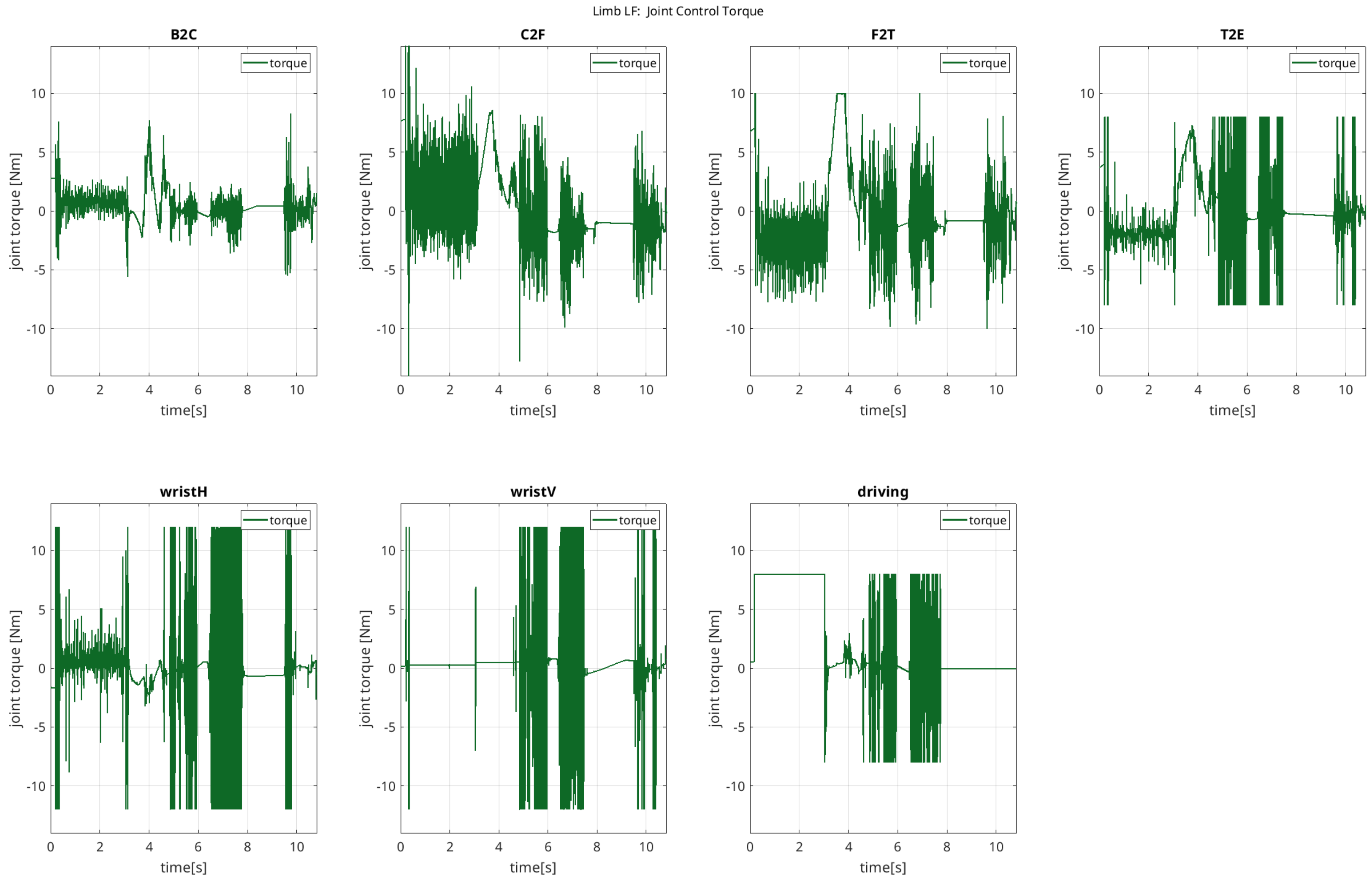
Simulations: Driving





Simulations: Driving





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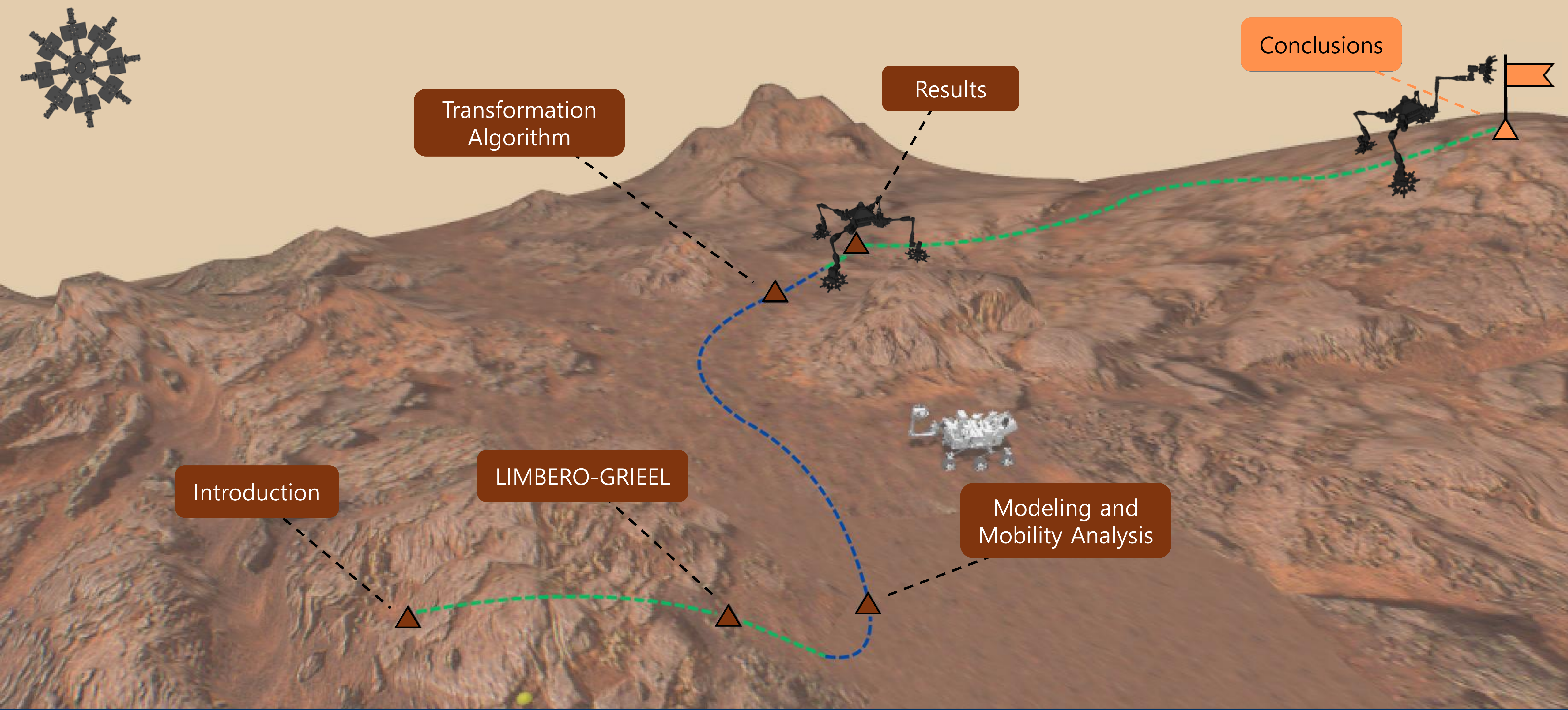

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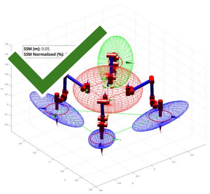
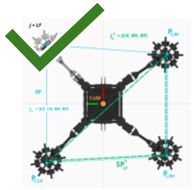
Achievements

The SPACE ROBOTICS LAB

- Multilayered motion controller architecture
- Simulation environment



- Dexterity analysis (BME)



- Reliable transformation algorithm

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Limitations

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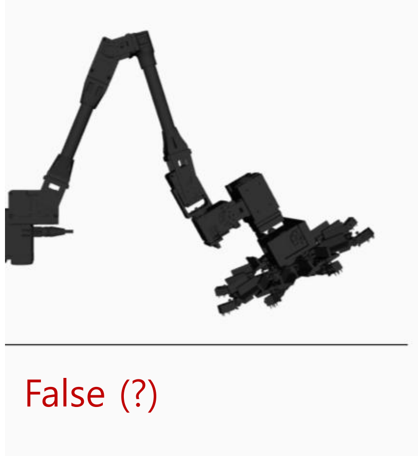
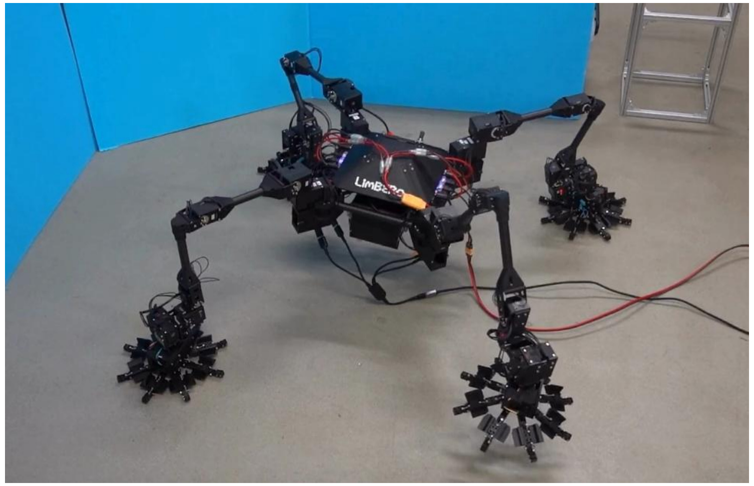
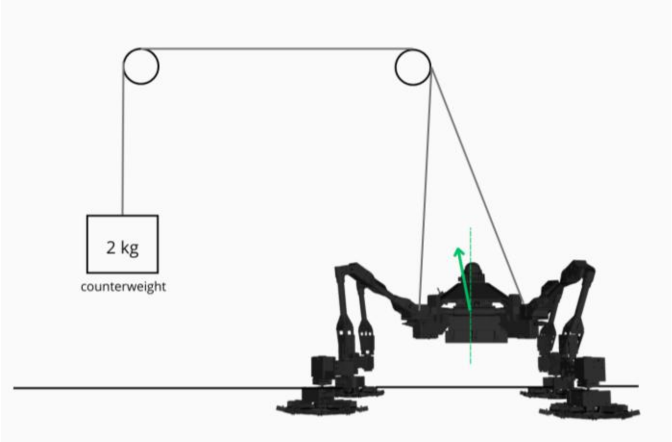
Contact estimation



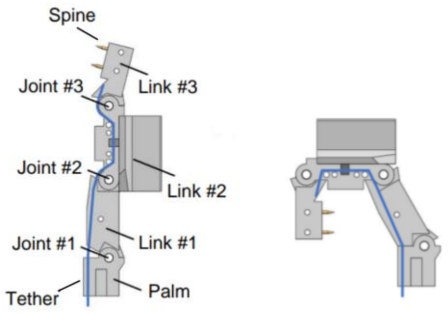
Joints motor dimensioning



Counterweight



Unknown GRIEEL module state



Gripper or Wheel Mode?

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Future Work

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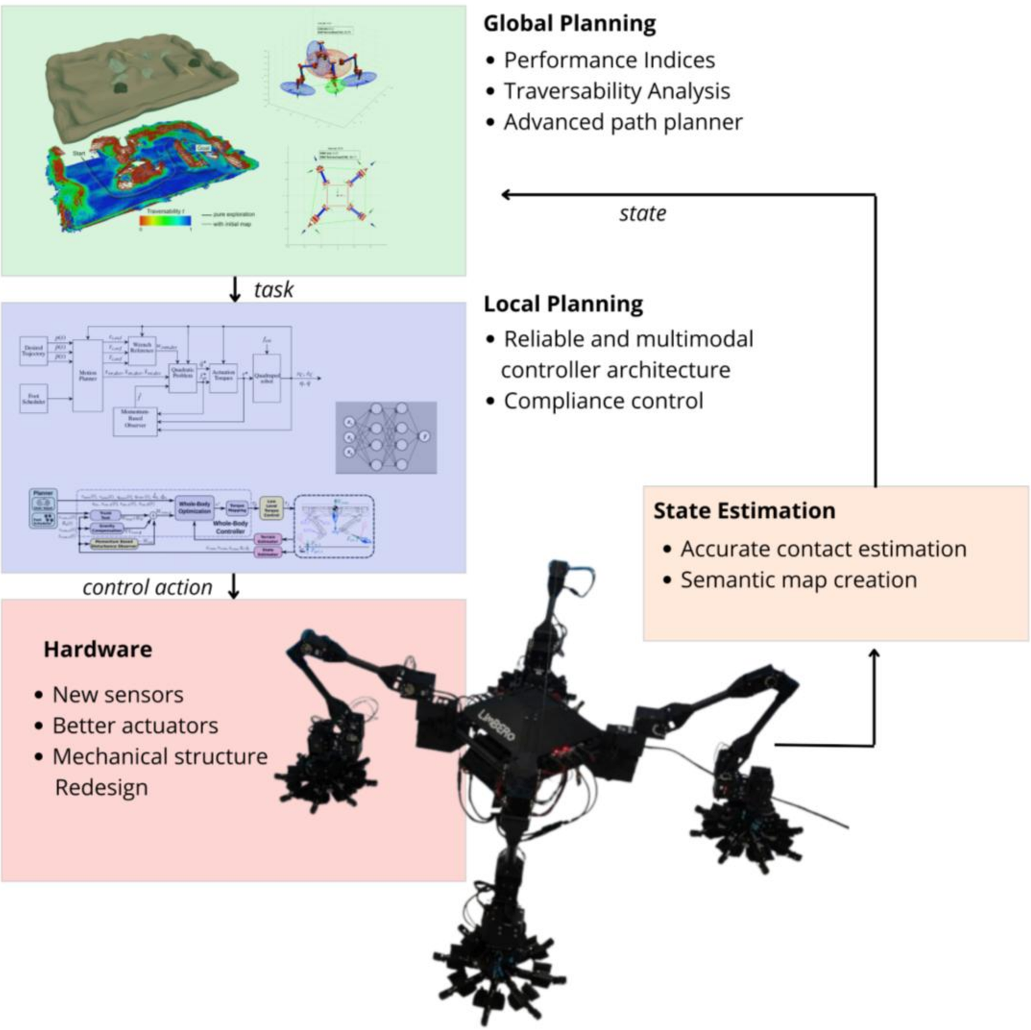
Roadmap



Local Planning (Controller)

- Low-level controllers such as Whole Body, Impedance or Data Driven

Global Planning

- High-level traversability analysis
- optimal path (foothold) generation
- Autonomous mission planning
- Performance indices

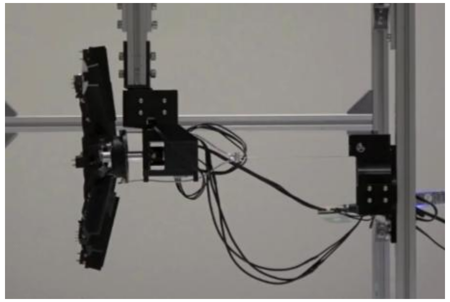
Hardware

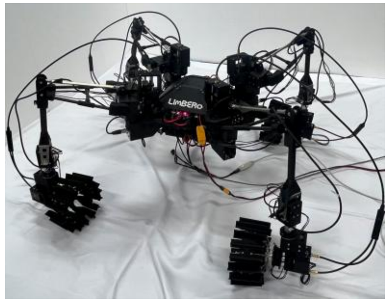
- New sensors
- Proper actuators
- Mechanical structure

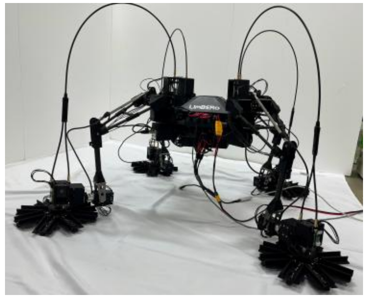
Software

- Independent GRIEEL architecture
- New simulator

LIMBERO-GRIEEL v2







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THANKS FOR LISTENING

QUESTIONS or CURIOSITIES ?

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