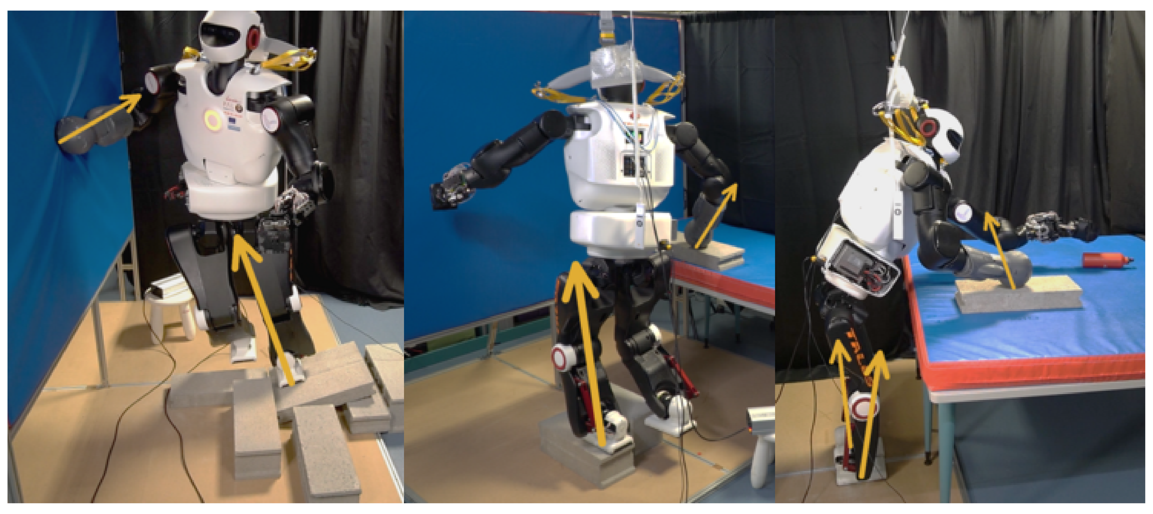
Multi-Contact Whole-Body Force Control for Position-Controlled Robots

Quentin Rouxel, Serena Ivaldi, Jean-Baptiste Mouret

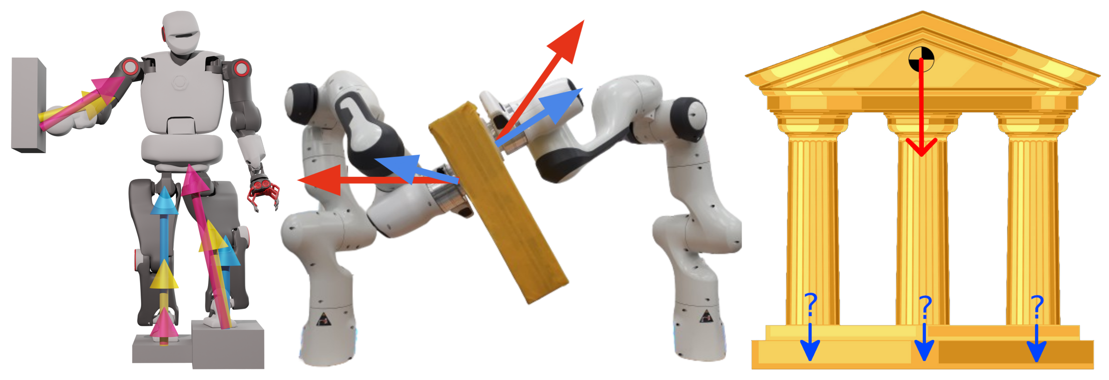
Inria, Université de Lorraine, CNRS, Loria, F-54000.

Project Website

https://hucebot.github.io/seiko_controller_website/



Multi-Contact on Position-Controlled Robots



- Multi-contact tasks require realizing **specific contact force distribution**
- **Redundancy in force distribution**: one posture, multiple force distributions

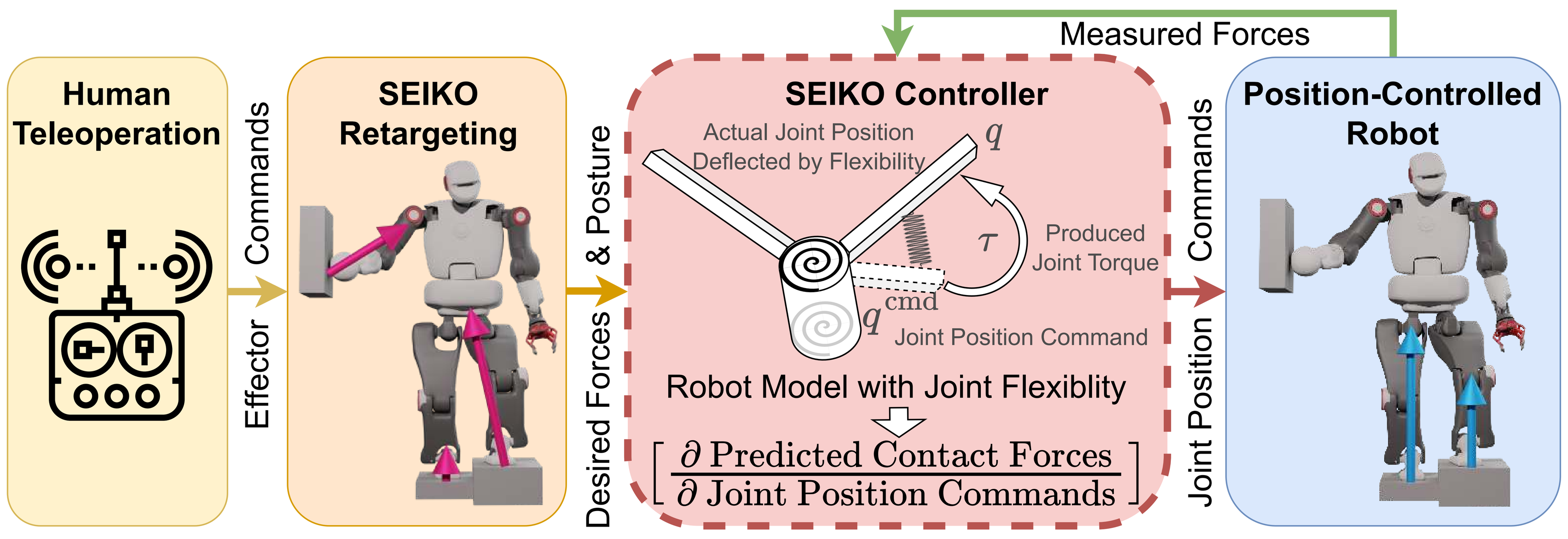
- Position-controlled robots are still widespread and are more robust to model errors than torque-controlled
- But position-controlled robots cannot directly control contact forces

Problem: How to control contact force on position controlled robot?

Main Ideas

- Real systems always have internal flexibilities/impedance
- With flexibilities, force distribution is uniquely defined
- Flexibilities are unobservable, but can be predicted with nonlinear whole-body optimization
- For a given joint position command, the whole-body configuration is unique and well defined
- **Joint position commands are optimized to get desired contact forces given flexibilities**

SEIKO: Sequential Equilibrium Inverse Kinematic Optimization



- Whole-Body admittance controller using two Sequential Quadratic Program optimizations
- **Input**: Cartesian command for each effector (position and/or velocity) + contact switch trigger
- **Output**: corrected joint position commands realizing desired posture and contact forces
- **SEIKO Retargeting**: computes feasible desired whole-body configurations from commands
- **SEIKO Controller**: updates joint position command to indirectly regulate forces exploiting flexibilities

QP Formulations

SEIKO Retargeting

- **Inputs**: target pose and contact state for each effector
- **Solve for**: desired joint position, contact force, joint torque
- **Objectives**: reach target effector pose and minimize joint torque
- **Constraints**: balance, contact stability, joint kinematic and torque limits

SEIKO Controller

- **Inputs**: measured contact forces, desired whole-body configuration
- **Solve for**: corrected joint position, predicted joint position, torque and contact forces under flexibility deflections
- **Objectives**: regulate contact forces
- **Constraints**: balance, joint kinematic and torque limits

Equilibrium Equation and Flexibility Model

Assumption: quasi-static equilibrium

Whole-body equilibrium equation:

$$g(q) = S\tau + J(q)^{\mathsf{T}}\lambda$$

Elastic joint flexibility model:

$$\tau^{\text{flex}} = K(\theta^{\text{cmd}} - \theta^{\text{flex}})$$

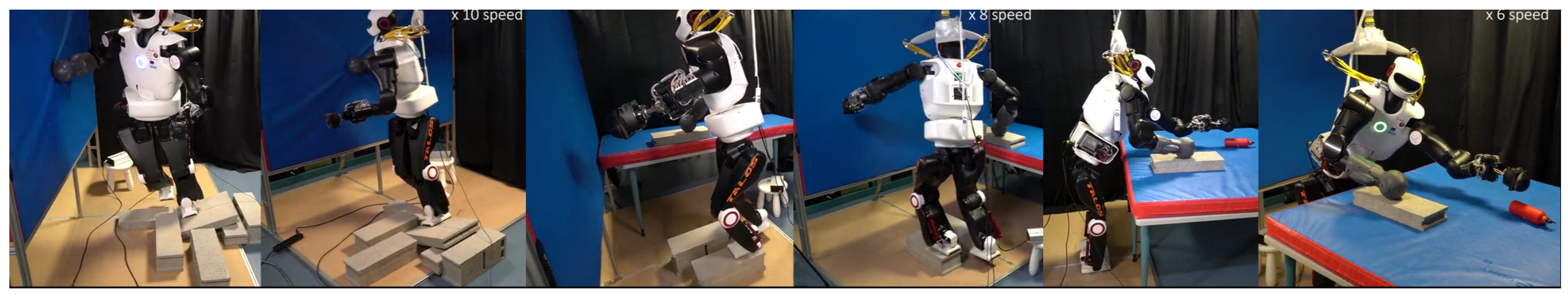
Linearization of the equilibrium equation:

$$g(q) + \frac{\partial g}{\partial q}\Delta q = S\tau + S\Delta\tau + J(q)^{\mathsf{T}}\lambda + J(q)^{\mathsf{T}}\Delta\lambda + \left(\frac{\partial J^{\mathsf{T}}}{\partial q}\lambda\right)\Delta q$$

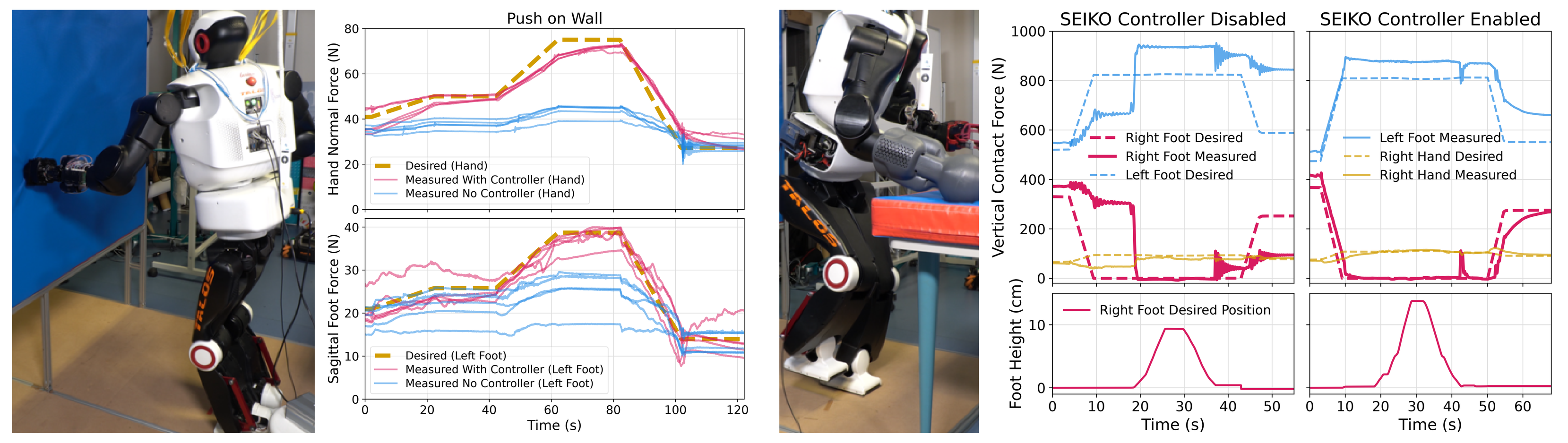
Feedback law over measured contact forces:

$$\Delta\lambda^{\text{effort}} = \Delta\lambda^{\text{d}} + K_p(\lambda^{\text{d}} - \tilde{\lambda}^{\text{read}}) - K_d\dot{\lambda}^{\text{read}}$$

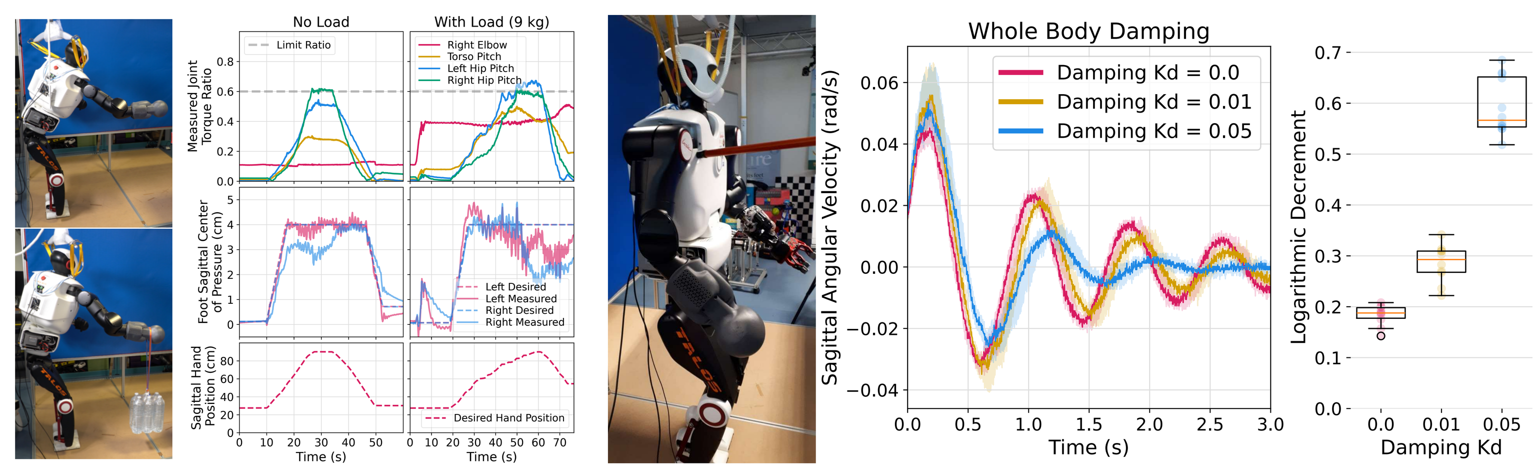
Experiments on Talos Humanoid Robot



Teleoperated multi-contact motions: traversal of sloped uneven ground with wall contact (left), stepping up 15 cm with enhanced stability (middle), and hand contact extending reaching distance (right)

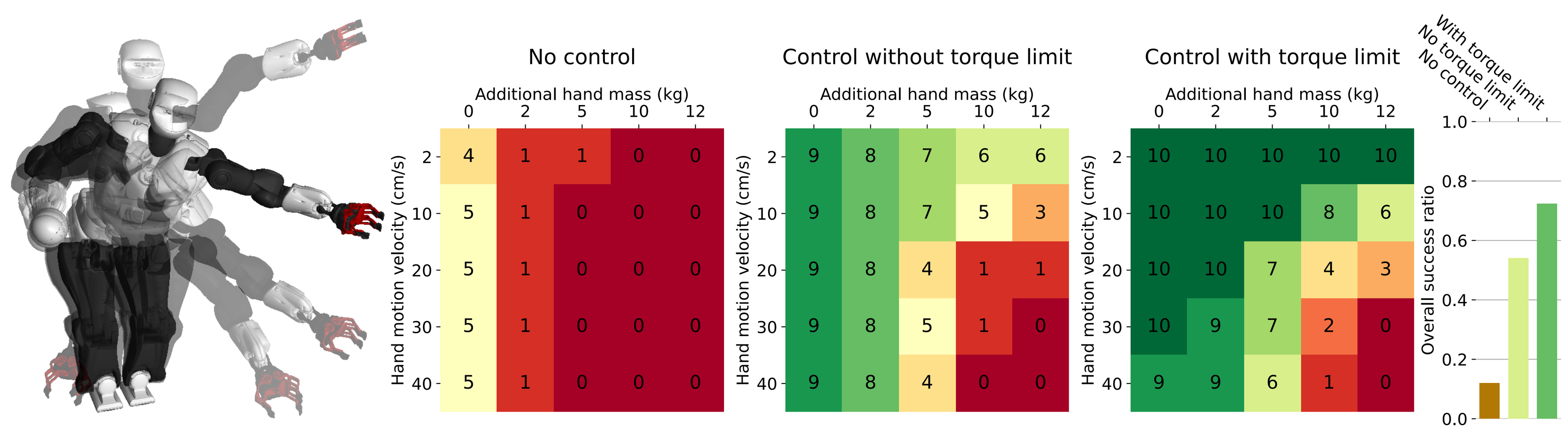


Tracking of hand contact force during pushing task (left), and smooth contact switching (right)



Far reach with and without unmodeled load (left), and damping effect over torso oscillations (right)

Robustness Against Motion Speed and Model Error



- Number of successful trials without fall (out of 10) of reaching motions near feasibility boundary
- Varying hand velocity (2 cm/s to 40 cm/s) and added hand mass (none to 12 kg)
- Compare without the SEIKO Controller (left), with the SEIKO Controller but without considering joint torque limits (middle), and using the full control method (right)

References

[1] Q. Rouxel et al. "Multicontact motion retargeting using whole-body optimization of full kinematics and sequential force equilibrium". In: *IEEE/ASME T-MECH* (2022).

[2] R. Wen et al. "Collaborative Bimanual Manipulation Using Optimal Motion Adaptation and Interaction Control Retargetting Human Commands to Feasible Robot Control References". In: *IEEE RAM* (2023).