Feasibility Retargeting for Multi-contact Teleoperation and Physical Interaction

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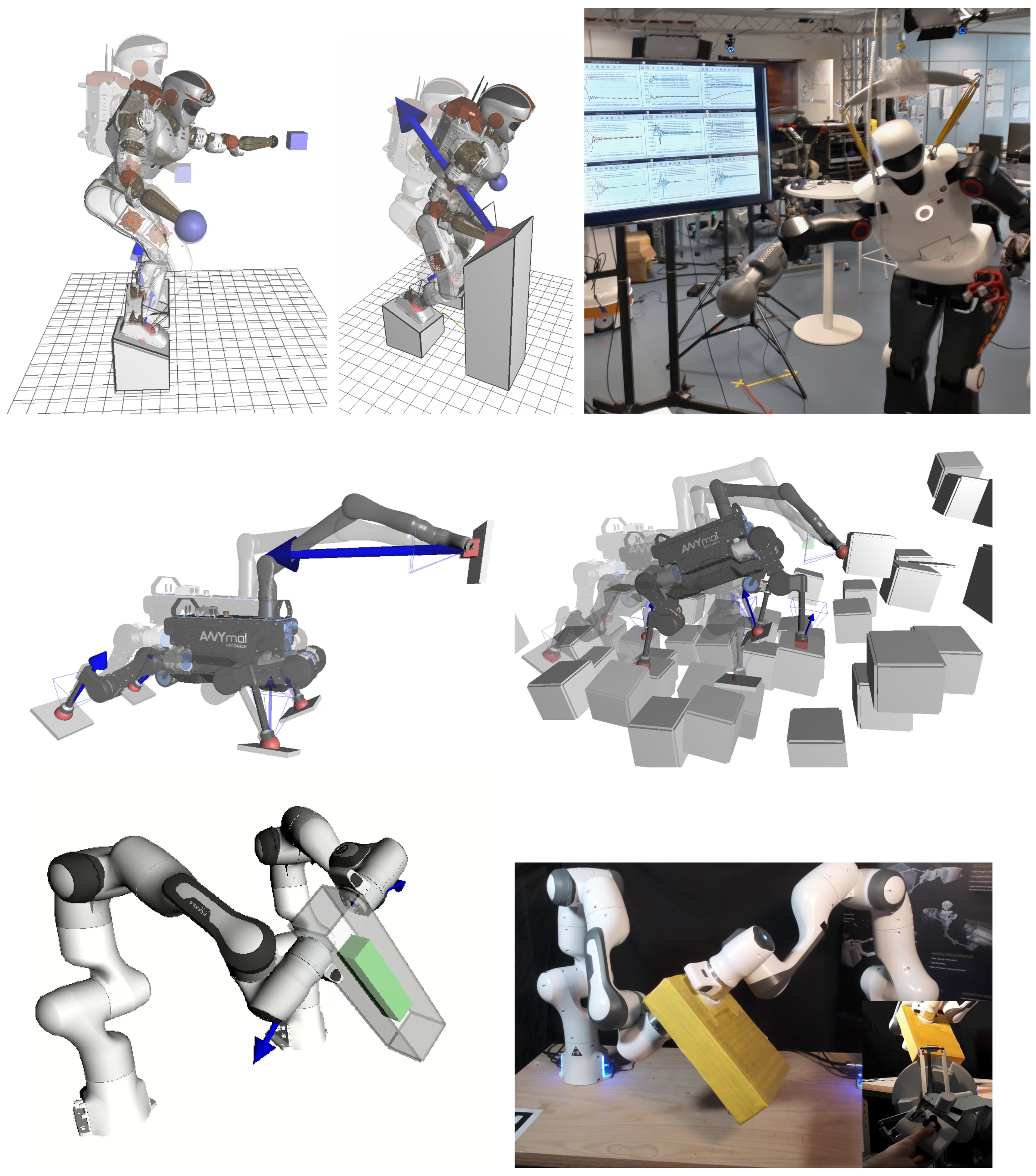
Main Idea

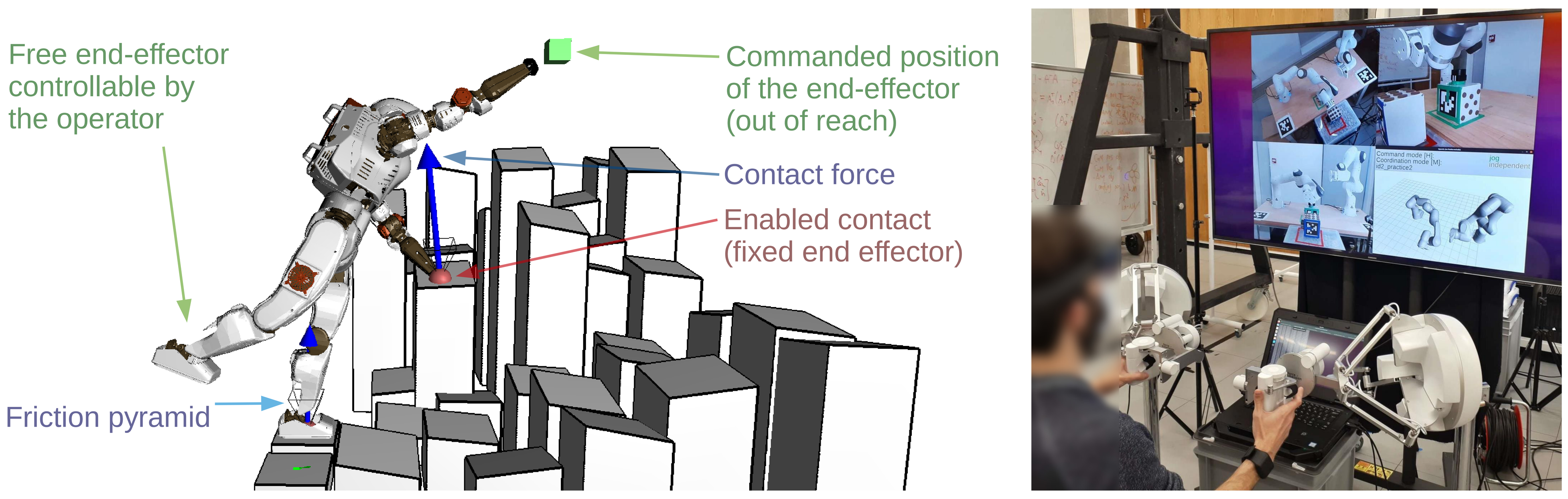
How do contact forces in multi-contact change with the posture? We differentiate the equation of motion in static case to formulate a SQP with balance constraints

Addressed Problem and Contributions

Multi-contact	Feasibility Constraint
Contact switch for loco-manipulation	Errors/mistakes in human commands
Non-coplanar surfaces	Not to fall ⇒ static equilibrium
Distribution of contact forces	Kinematic, actuator, contact constraints
Teleoperation	**Physical Interaction**
Retargeting Cartesian commands	Remote and local operators collaboration
Unknown operator intention	Compliance behavior for physical guidance
Efficient for real time (under 1ms)	Explicitly resist against infeasible pushes



Teleoperated configurations on Valkyrie and Talos humanoid robots, on ANYmal quadruped robot and on dual arms bimanual Franka robot. Multi-contact configuration with static equilibrium, pushing tasks, locomotion on uneven terrain and manipulation of large objects.



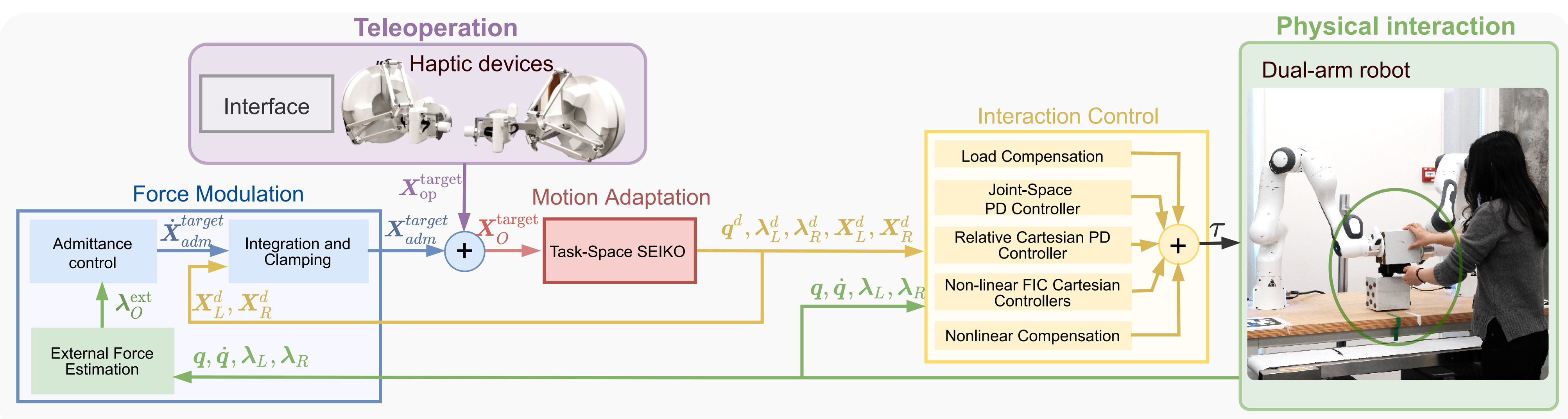
User interfaces for multi-contact teleoperation. *Left*: Operator commands free end-effectors' pose and triggers contact switch. *Right*: Remote bimanual docking and assembly task.

SEIKO: Multi-contact Optimization Retargeting

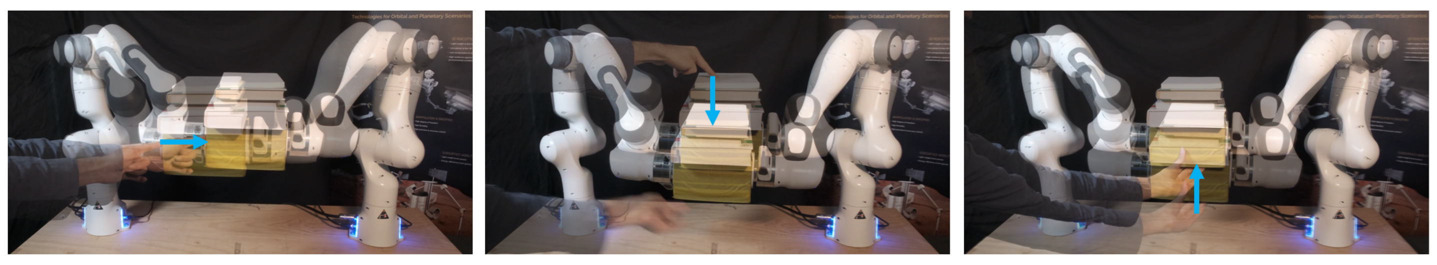
- Inputs: free end-effector pose commands, contact state (enabled or disabled)
- Output: quasi-static feasible configuration (joint position, joint torque, contact wrenches, effector poses)
- Nonlinear problem: solve with Sequential Quadratic Programming (SQP)
- Only one iteration (QP resolution) per time step

SEIKO (Sequential Equilibrium Inverse Kinematic Optimization):

- QP optimizes for posture and contact wrenches changes
- Minimize effectors distance to human commands and minimize joint torques and contact wrenches
- QP equality constraints: differentiated equation of motion in static case
- QP inequality constraints: joint limits and contact conditions for feasibility



Overall architecture for bimanual manipulation of heavy object.
Admittance controller generates velocity commands from external guidance forces on object.
Velocity commands from interaction and absolute pose commands from remote operator are combined.
SEIKO adapts combined commands to produce feasible desired posture and contact wrenches.
Interaction controller realizes the desired configuration using passive impedance and load compensation.



Collaboration between a local operator and a dual-arm robot to move heavy objects through physical interaction.

$$\min_{\dot{\boldsymbol{x}}} \ \|\boldsymbol{C}_{\text{cost}}(\boldsymbol{x}_t)\dot{\boldsymbol{x}} - \boldsymbol{c}_{\text{cost}}(\boldsymbol{x}_t)\|_w^2 \ \text{ s.t.}$$
$$\boldsymbol{C}_{\text{eq}}(\boldsymbol{x}_t)\dot{\boldsymbol{x}} + \boldsymbol{c}_{\text{eq}}(\boldsymbol{x}_t) = 0, \quad \boldsymbol{C}_{\text{ineq}}(\boldsymbol{x}_t)\dot{\boldsymbol{x}} + \boldsymbol{c}_{\text{ineq}}(\boldsymbol{x}_t) \geqslant 0$$
$$\text{where } \boldsymbol{x}_t = \begin{bmatrix}\boldsymbol{q}^d \\ \boldsymbol{\lambda}^d\end{bmatrix}, \dot{\boldsymbol{x}} = \begin{bmatrix}\dot{\boldsymbol{q}} \\ \dot{\boldsymbol{\lambda}}\end{bmatrix},$$
$$\boldsymbol{x}_{t+1} = \boldsymbol{x}_t + \dot{\boldsymbol{x}}\Delta t$$

Pinocchio library computes the analytical partial derivatives of the static equation of motion to formulate $\boldsymbol{C}_{\text{eq}}, \boldsymbol{c}_{\text{eq}}$:
$\boldsymbol{G}(\boldsymbol{q}+\Delta\boldsymbol{q}) = \boldsymbol{S}(\boldsymbol{\tau}+\Delta\boldsymbol{\tau}) + \boldsymbol{J}(\boldsymbol{q}+\Delta\boldsymbol{q})^{\mathsf{T}}(\boldsymbol{\lambda}+\Delta\boldsymbol{\lambda})$

Results

- Humanoid and quadruped in simulation (Gazebo and PyBullet); Balance of the system
- Dual-arm manipulation on real hardware; Balance of the manipulated object
- Fast real time computation (SEIKO QP under 1ms)
- Quasi-static assumption valid for many loco manipulation tasks. With conservative tuning ⇒ hand motion of 30cm/s possible

[1] Q. Rouxel, K. Yuan, R. Wen, and Z. Li, "Multicontact motion retargeting using whole-body optimization of full kinematics and sequential force equilibrium," *IEEE/ASME Transactions on Mechatronics, pp. 1–11, 2022.*

[2] R. Wen, Q. Rouxel, M. Mistry, Z. Li, and C. Tiseo, "Collaborative Bimanual Manipulation Using Optimal Motion Adaptation and Interaction Control," *IEEE Robotics & Automation Magazine, pp. 2-14, 2023.*