A GEOMETRIC APPROACH TO ROBOTIC MANIPULATION IN PHYSICAL HUMAN-ROBOT INTERACTION

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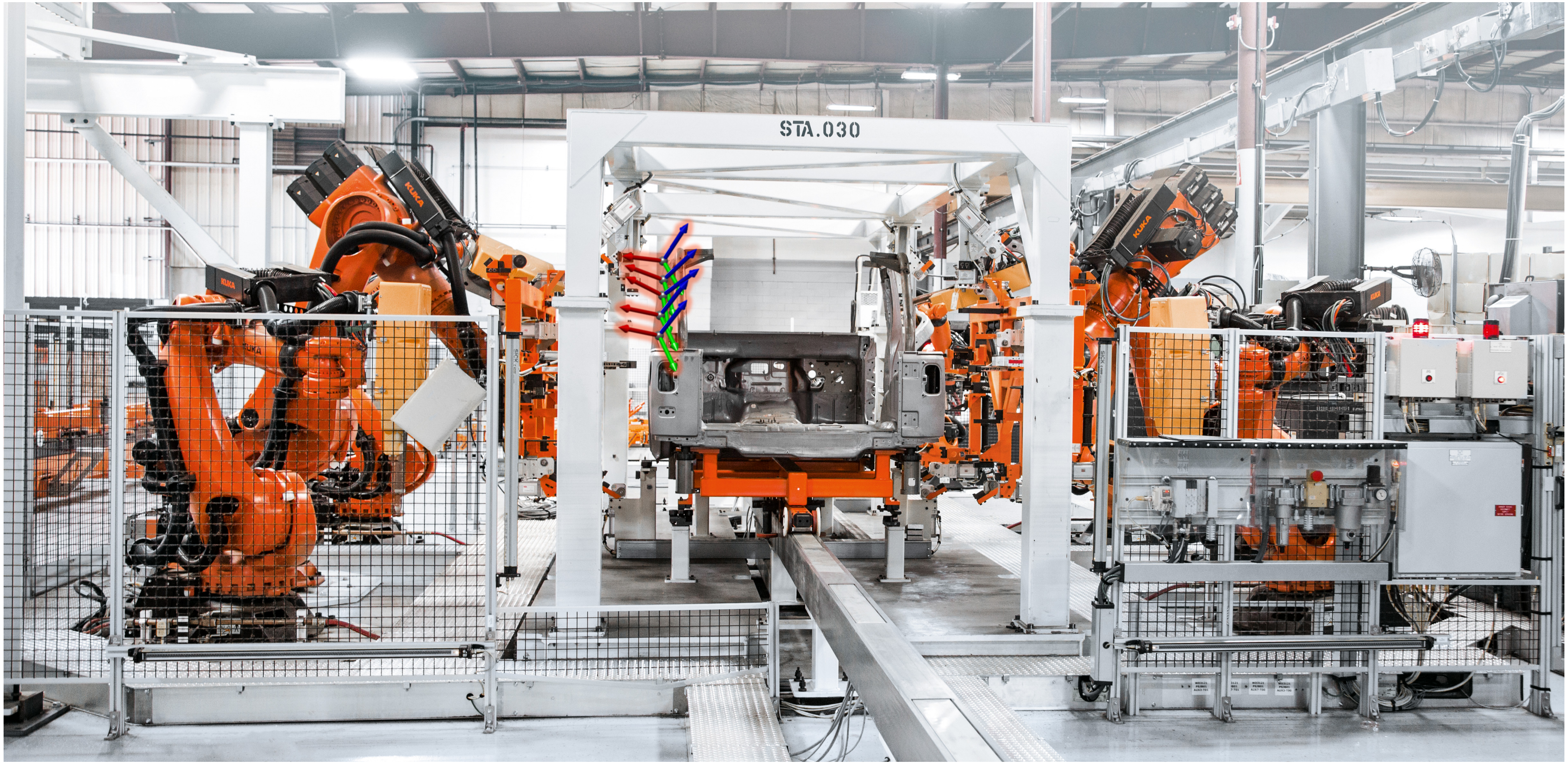
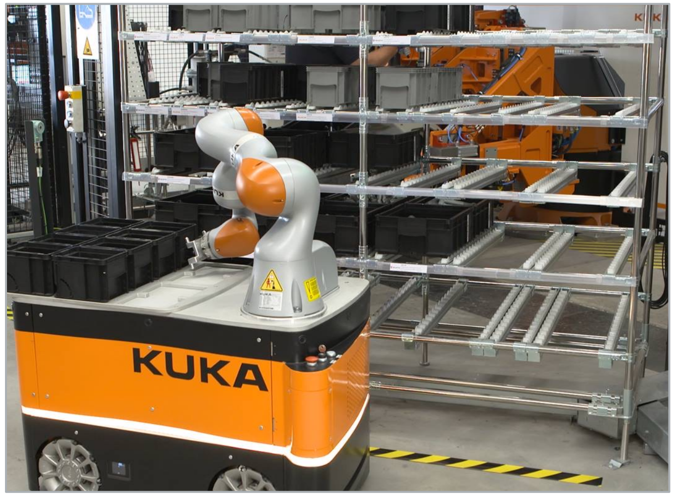
My world of robotics 2013

Source: https://www.kuka.com/



My world of robotics 2014 - 2017



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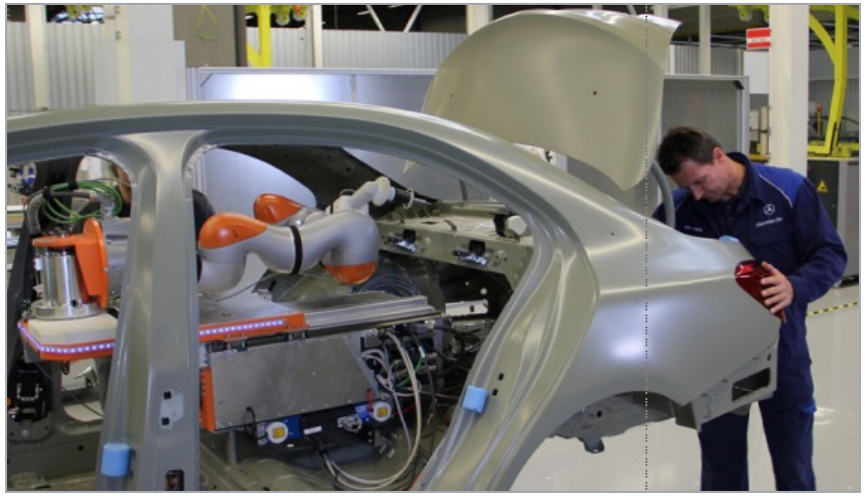
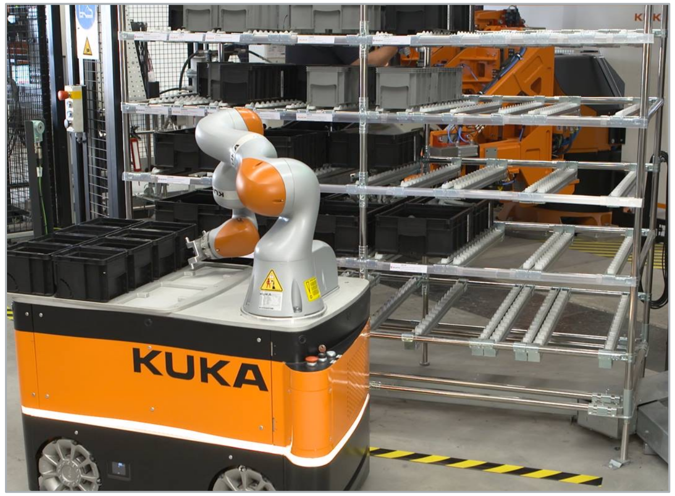


<u>Three main challenges</u>:

- 6D-frames impede programming
- Kinematic redundancy not easy to use
- Coordinate choices for safety implementation are crucial

My world of robotics 2018 - now



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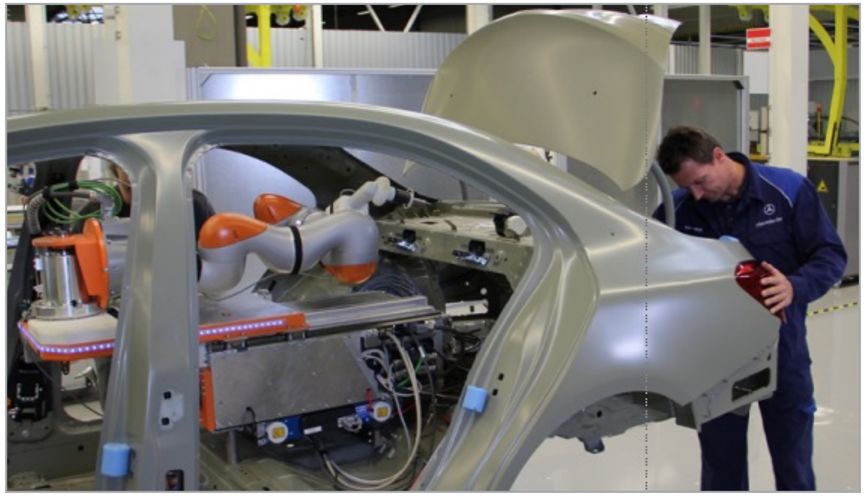


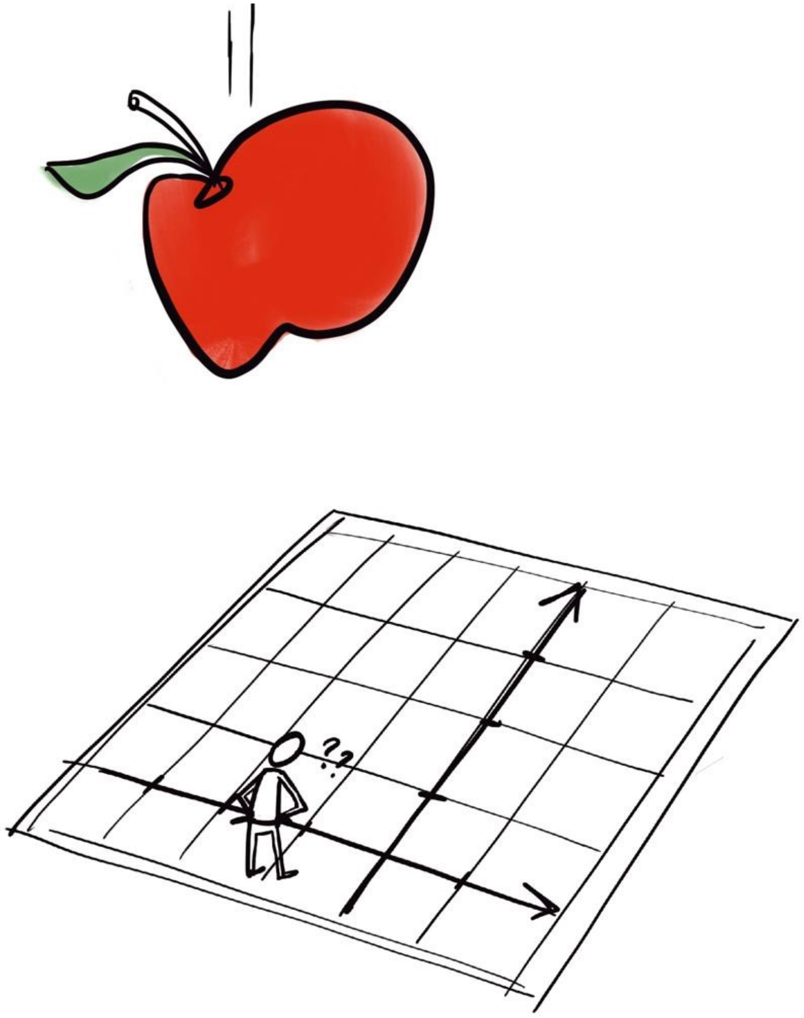
<u>Three main challenges</u>:

- 6D-frames impede programming
- Kinematic redundancy not easy to use
- Coordinate choices for safety implementation are crucial

<u>Research questions of my thesis</u>:

- Can a robot fulfil one or even multiple tasks?
- How can we realize an efficient and stable robot (multi-task) control?
- How can we facilitate the safety programming for physical Human-Robot Interaction?

I. Dexterity: single task

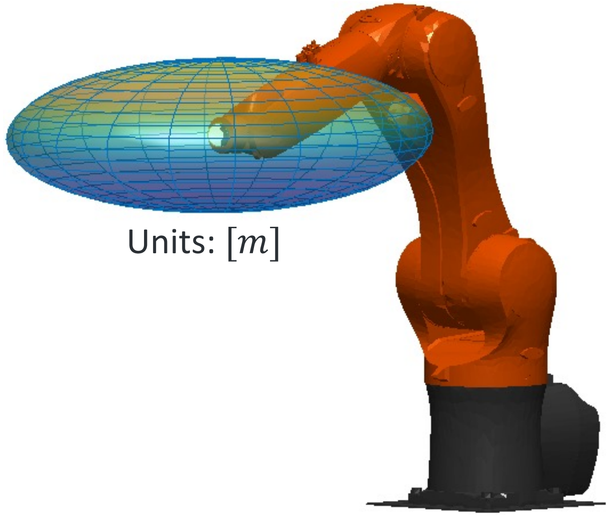


Problem statement: Coordinate dependency of dexterity measures

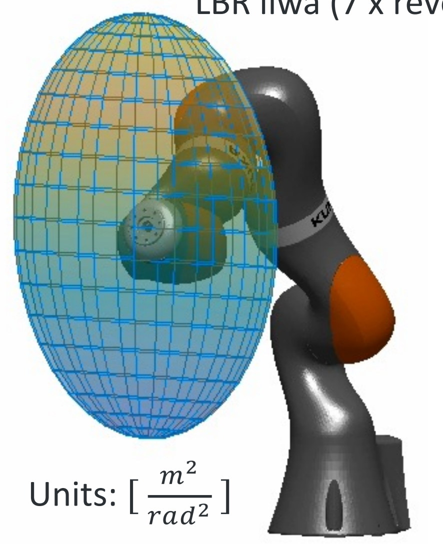
- Dexterity is strongly related to the Jacobian matrix $\boldsymbol{J}(\boldsymbol{q}) = \begin{pmatrix} \boldsymbol{J}(\boldsymbol{q})_p \\ \boldsymbol{J}(\boldsymbol{q})_w \end{pmatrix}$
- Workspace ellipsoid: $\dot{\boldsymbol{p}}^T \left(\boldsymbol{J}(\boldsymbol{q})\boldsymbol{J}(\boldsymbol{q})^T \right)^{-1} \dot{\boldsymbol{p}} = 1$ (Yoshikawa, 1985)
- Shape and orientation of ellipsoid: Eigenvectors and Eigenvalues of $\boldsymbol{J}(\boldsymbol{q})\boldsymbol{J}(\boldsymbol{q})^T$

- Involves choice for a Generalized Inverse of $\boldsymbol{J}(\boldsymbol{q})$: $\boldsymbol{J}(\boldsymbol{q})^{\#} = \boldsymbol{W}^{-1}\boldsymbol{J}(\boldsymbol{q})^{\boldsymbol{T}}\left(\boldsymbol{J}(\boldsymbol{q})\boldsymbol{W}^{-1}\boldsymbol{J}(\boldsymbol{q})^{\boldsymbol{T}}\right)^{-\boldsymbol{1}}$
- A common choice is: $\boldsymbol{W}^{-1} = \boldsymbol{I}$ (Identity) → Moore-Penrose Inverse
- Problem 1: different choices for $\boldsymbol{W}^{-1}$ lead to different manipulability results (Lachner et al., 2020)

Agilus (6 x revolute joints)



LBR iiwa (7 x revolute joints)

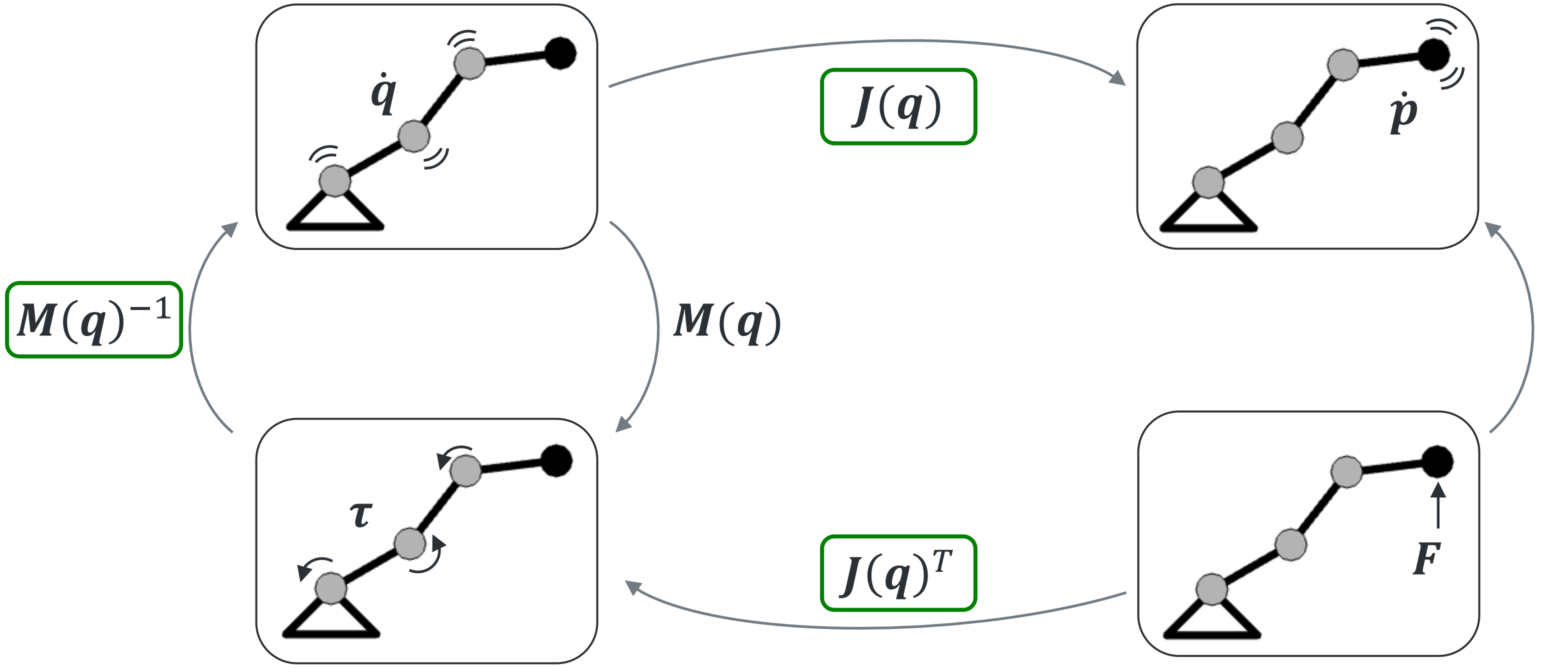


YouBot (3 x prismatic joints, 5 x revolute joints)

Problem 2: Mismatch of units arises! (Lachner et al., 2020)

Units: $[\frac{m^2}{rad^2}] + [\ ]$

Finding: Consistent mapping between robotic spaces

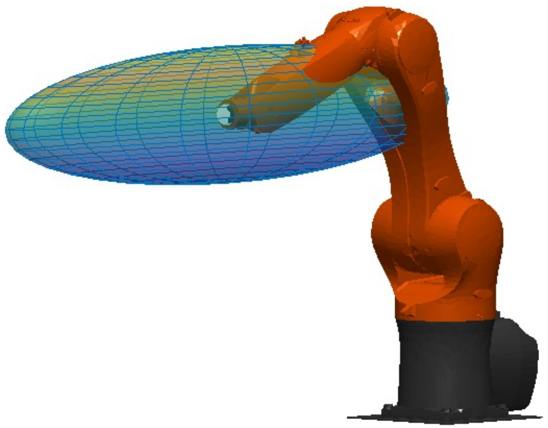


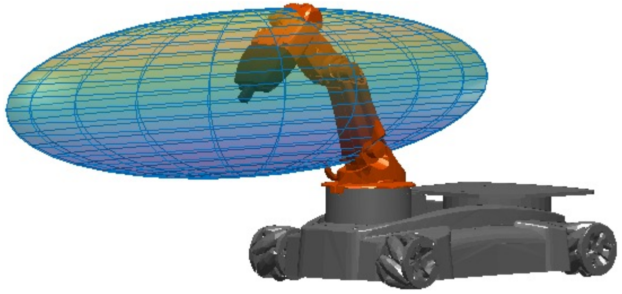
Additional contributions:

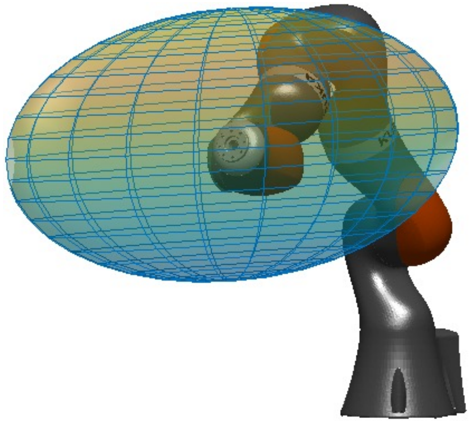
- Generalization for se(3) (twists and wrenches)

$$\Lambda(q)^{-1} = J(q)\, \overbrace{M(q)^{-1}}^{W^{-1}}\, J(q)^T$$

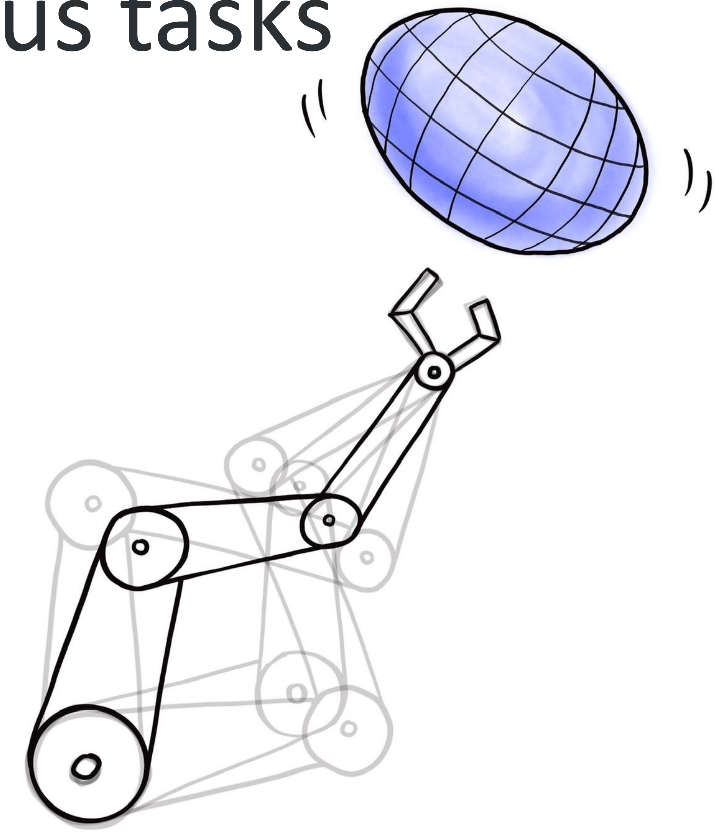
- Induced metric $\Lambda(q)^{-1}$ (Lachner et al., 2020)
- Meaningful choice for W^{-1}
- Equal units: $^{1}/_{[\,kg\,]}$
- Works for all robots!







II. Dexterity: multiple simultaneous tasks



Problem statement: Task conflicts and their detection

- Impedance Control: Multiple impedances can be superimposed (Hogan, 1985)
- Impedance superposition might yield task conflicts (Hermus, Lachner et al., 2022)
- Nullspace projection can resolve the task conflict (Khatib, 1987)

Task 1 ↓ Task 2 ↓

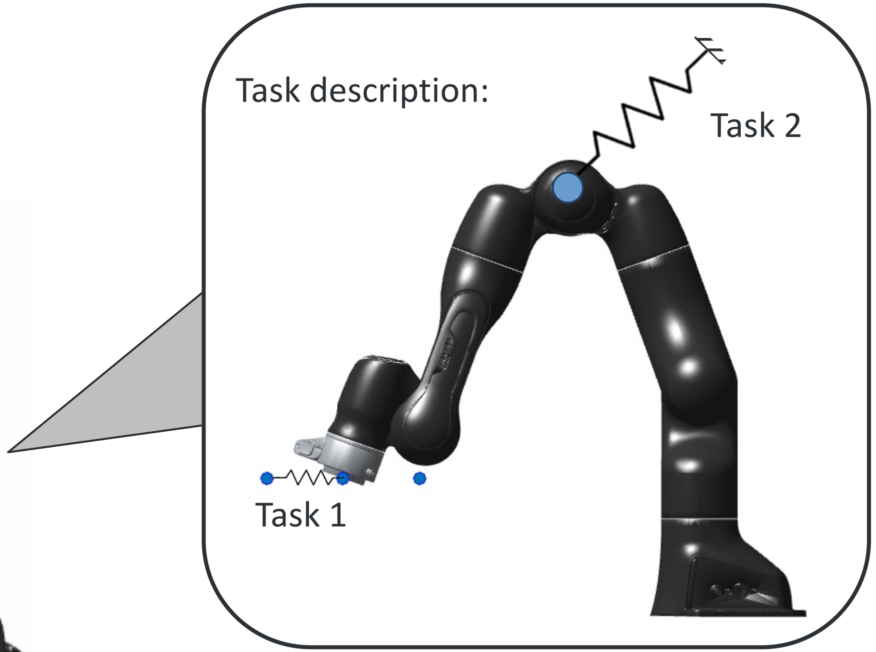
$$\boldsymbol{\tau}_{net} = \boldsymbol{\tau}_1 + \boldsymbol{\tau}_2$$

$$\boldsymbol{\tau}_{net} = \boldsymbol{\tau}_1 + \boldsymbol{N}_1 \boldsymbol{\tau}_2$$

- Important for industry: know that a task will be sacrificed before it happens

Nullspace Projection:

Impedance Superposition:



Finding: Prediction of conflicts between simultaneous tasks

- Nullspace projection: $\boldsymbol{\tau}_{net} = \boldsymbol{\tau}_1 + \boldsymbol{N}_1 \boldsymbol{\tau}_2$

$$= \boldsymbol{\tau}_1 + \underbrace{\boldsymbol{N}_1 \boldsymbol{J}_2(\boldsymbol{q})^T}\, \boldsymbol{F}_2$$

Task-consistent Jacobian: $\boldsymbol{J}_2^{TC}(\boldsymbol{q}) = \boldsymbol{J}_2(\boldsymbol{q})\boldsymbol{N}_1^T$ (Khatib and Sentis, 2004)

- Task-consistent Jacobian drops rank during task conflict with task 1

- But: Dependent on joint types (units)
- From first result:

$$\boldsymbol{\Lambda}_2(\boldsymbol{q})^{-1} = \boldsymbol{J}_2(\boldsymbol{q})\, \boldsymbol{M}(\boldsymbol{q})^{-1}\, \boldsymbol{J}_2(\boldsymbol{q})^T$$

$$\boldsymbol{\Lambda}_2^{TC}(\boldsymbol{q})^{-1} = \boldsymbol{J}_2^{TC}(\boldsymbol{q})\, \boldsymbol{M}(\boldsymbol{q})^{-1}\, \boldsymbol{J}_2^{TC}(\boldsymbol{q})^T$$

→ Independent on joint types (Schettino, Lachner et al., 2020)

→ Physical quantity: $[\frac{1}{kg}]$

- For a given direction $\boldsymbol{u}$:

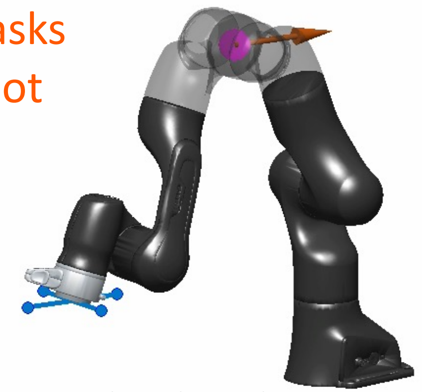
$$m_{TC} = (\, \boldsymbol{u}^T\, \boldsymbol{\Lambda}_2^{TC}(\boldsymbol{q})^{-1}\, \boldsymbol{u}\,)^{-1}$$

- **Intuition: virtual mass counteracting task 1** (Lachner et al., 2022)
- Task conflict can be related to the robot weight (or payload)
- In this example, conflict if: $m_{TC} > \frac{1}{2}\, m_{payload}$

Additional contributions :

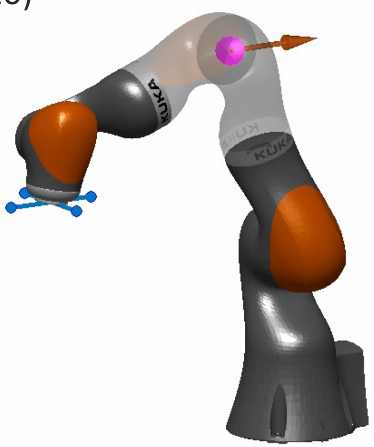
- Extension for rotational tasks
- Experiments on a real robot

m_{tc} = 1.0998 (kg)



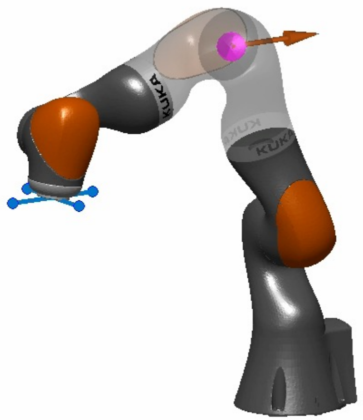
Franka, 3 kg payload

m_{tc} = 5.3148 (kg)



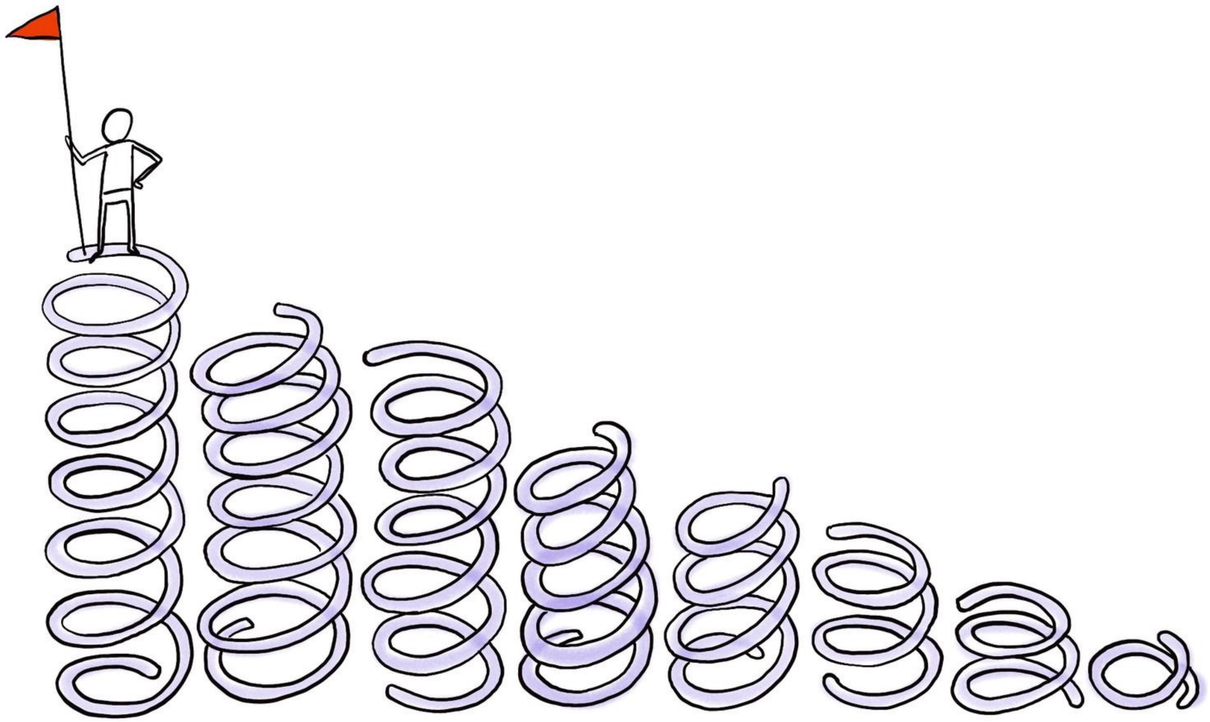
LBR iiwa, 14 kg payload

m_{tc} = 3.4755 (kg)



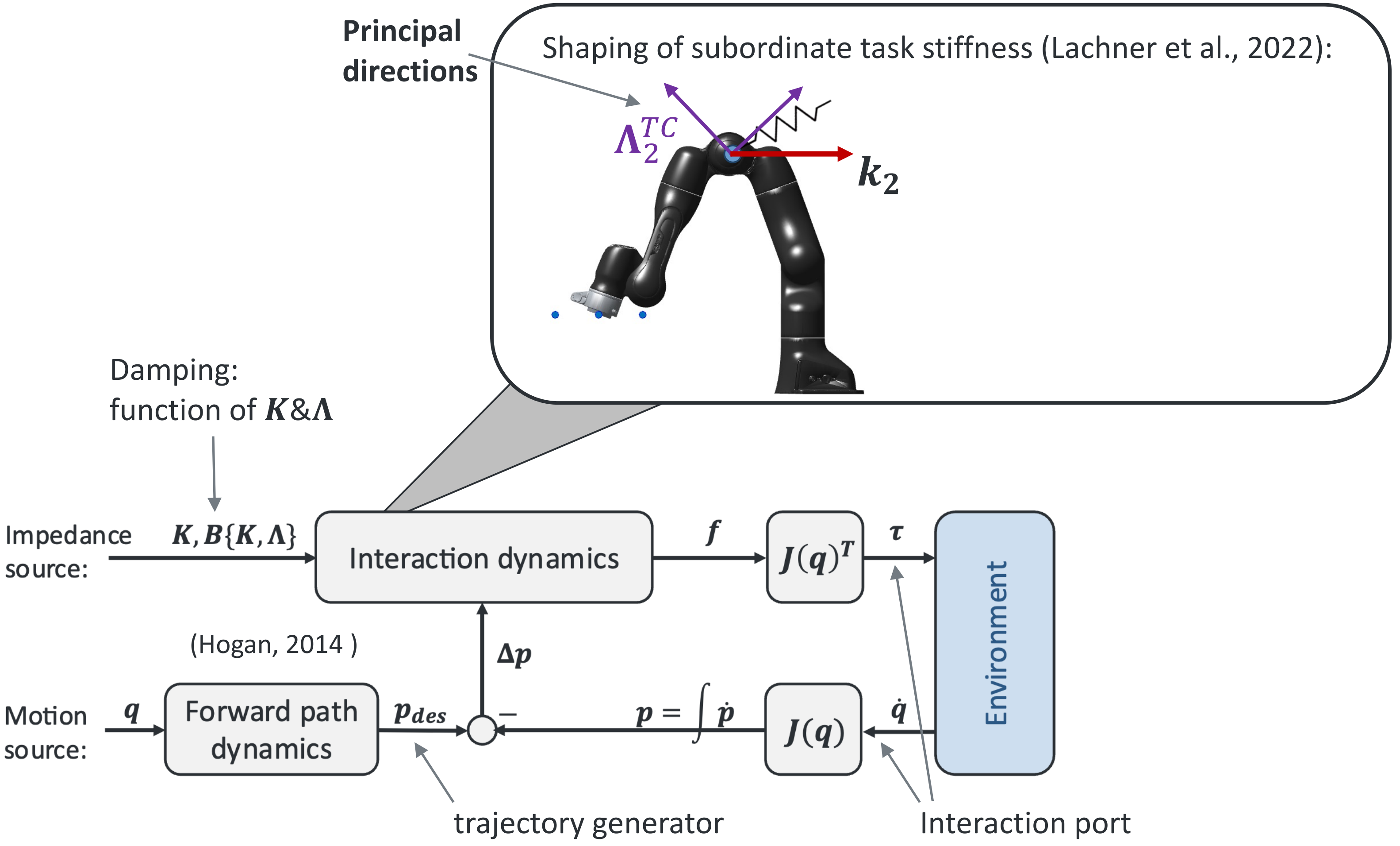
LBR iiwa, 7 kg payload

III. Multi-task impedance control



Finding: Impedance shaping for multi-task control

- Equivalent network structure of impedance control



Finding: Impedance shaping for multi-task control

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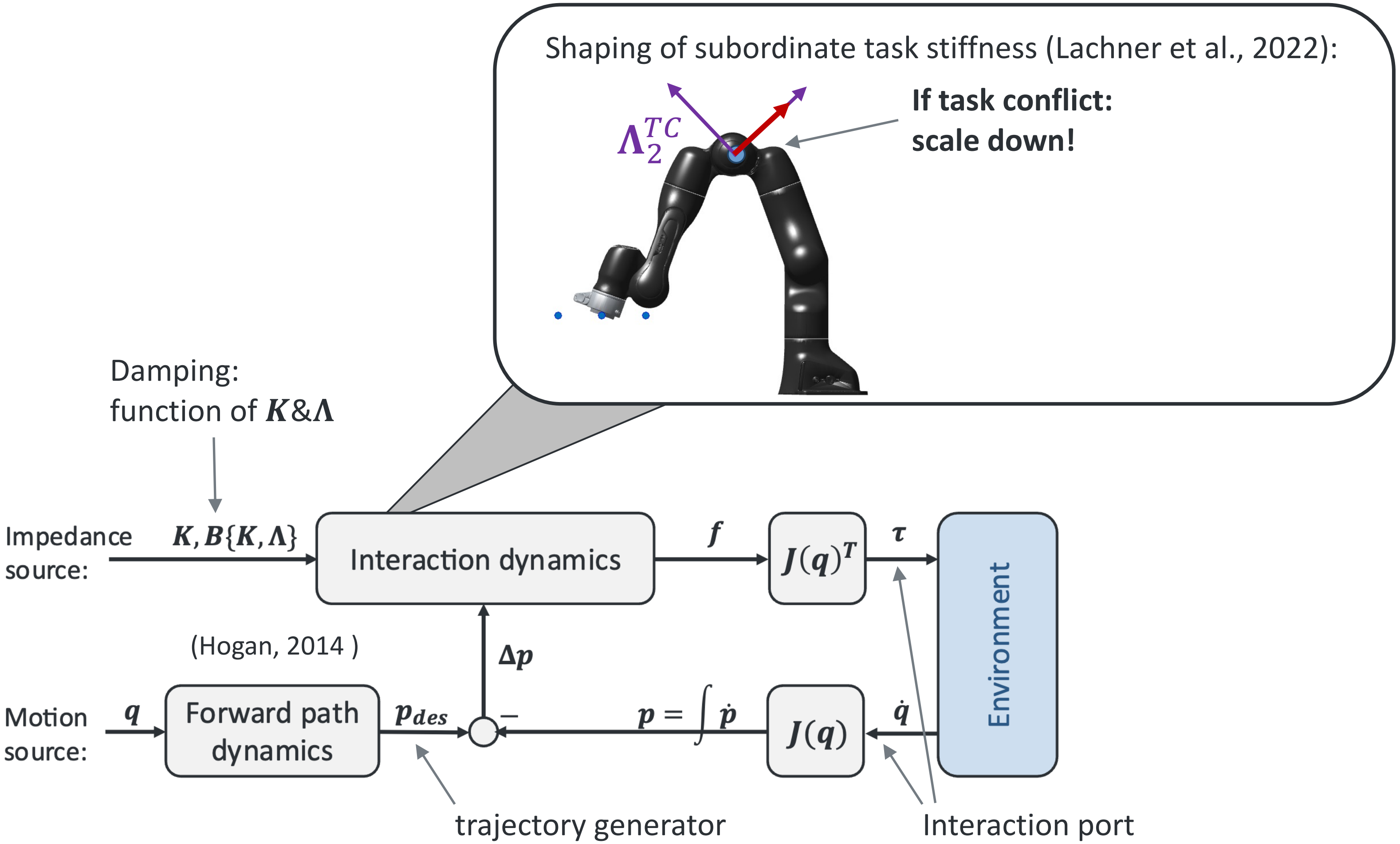

Finding: Impedance shaping for multi-task control

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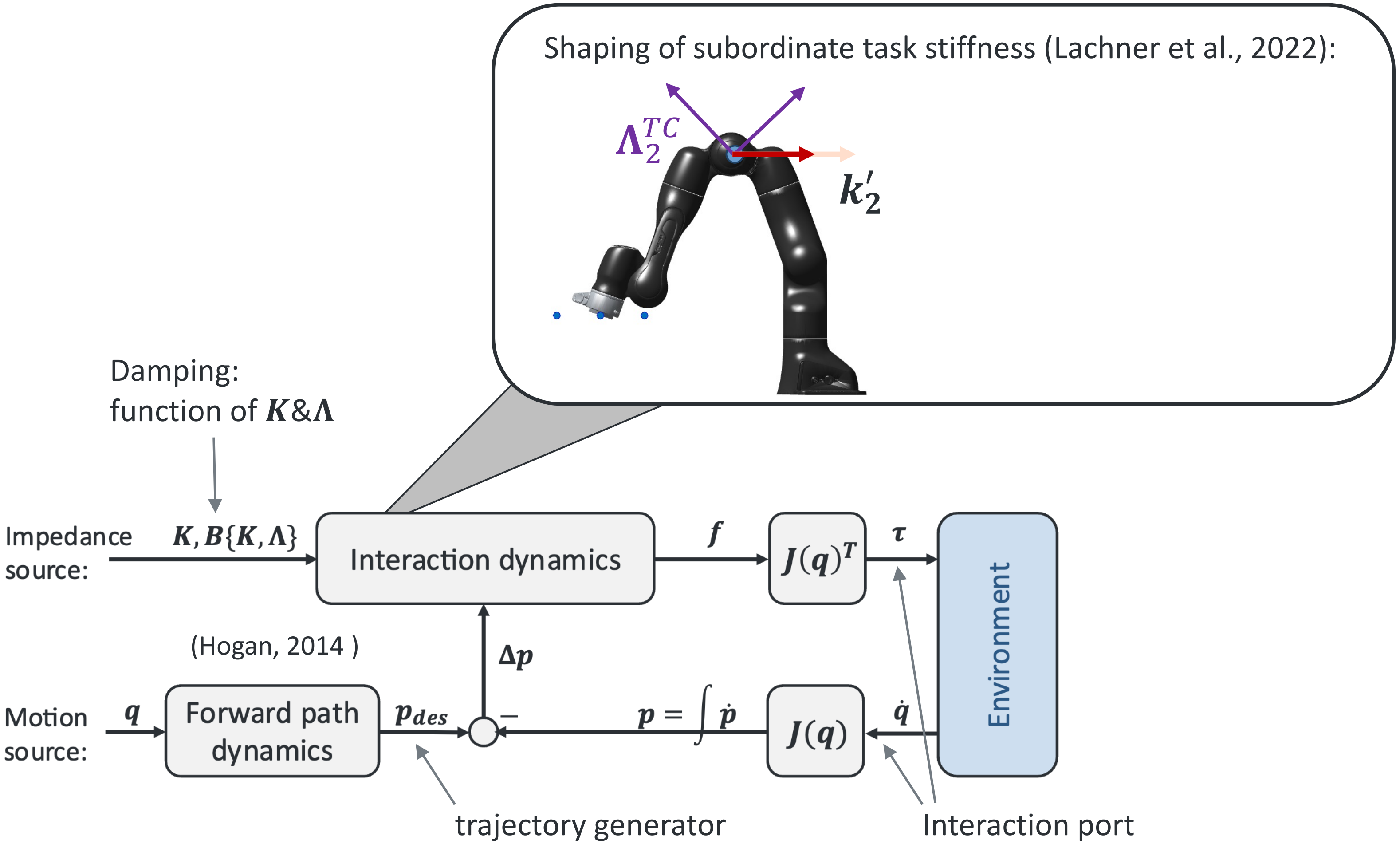
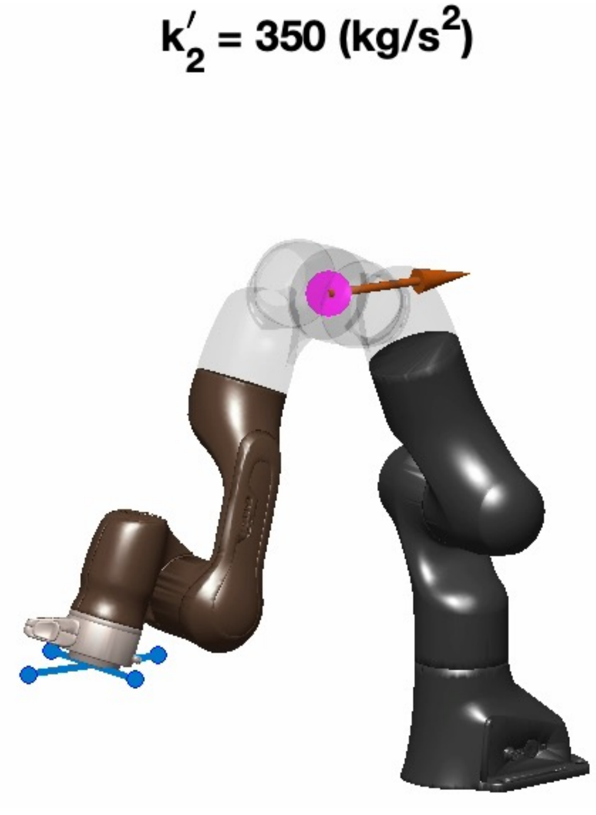


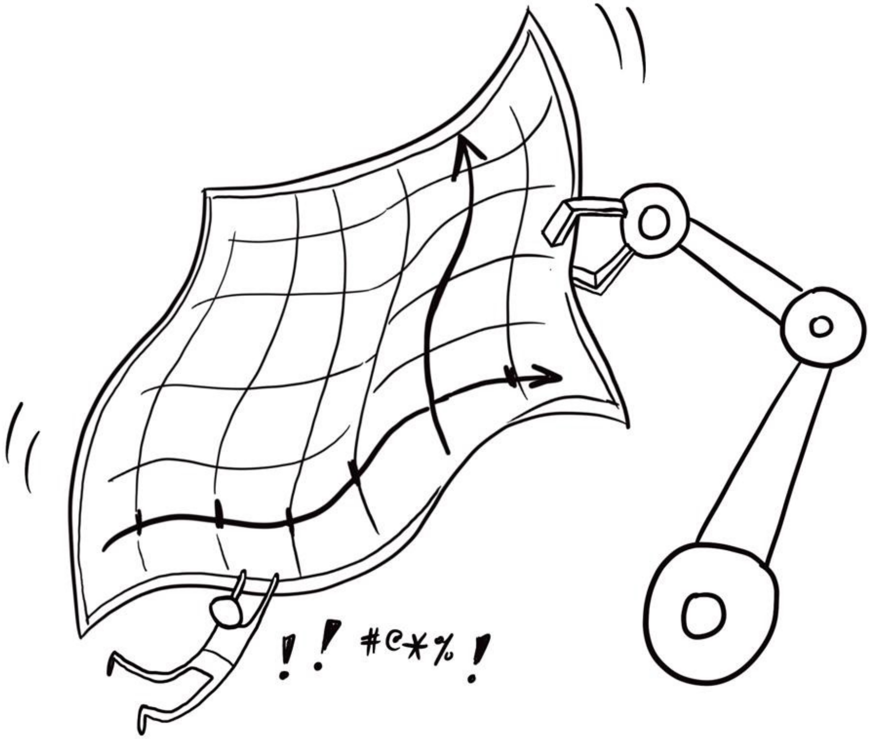
Additional contributions:

- Extension for rotational tasks
- Extension to multiple tasks
- Passivity layer
- Experiments on a real robot



Impedance Shaping: solid
Impedance Superposition: transparent

IV. Safe physical Human-Robot Interaction



Problem statement: Coordinate dependency in industrial safety certification

Programming

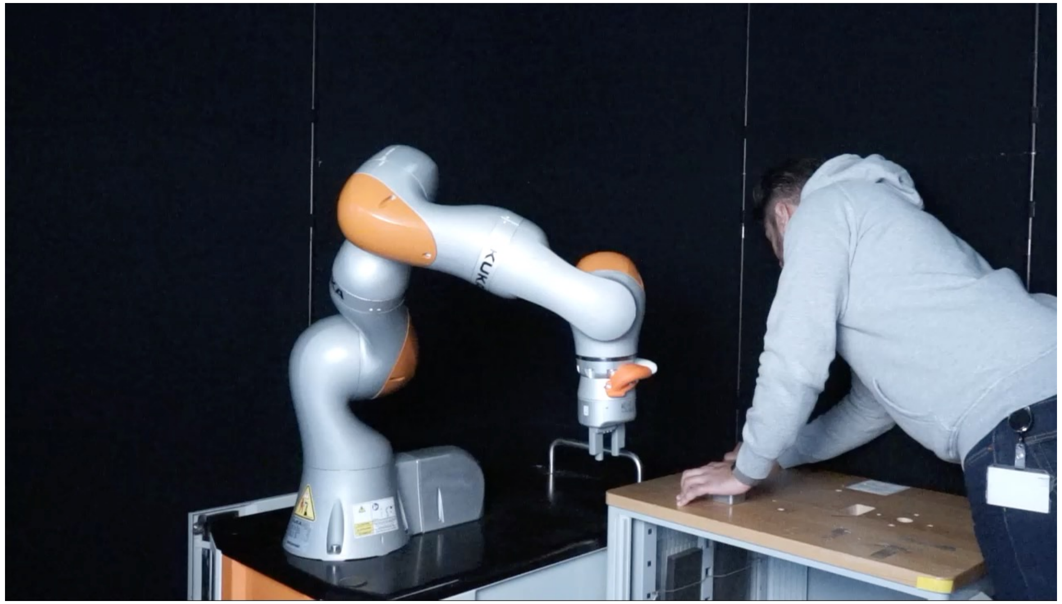
Application with random velocity

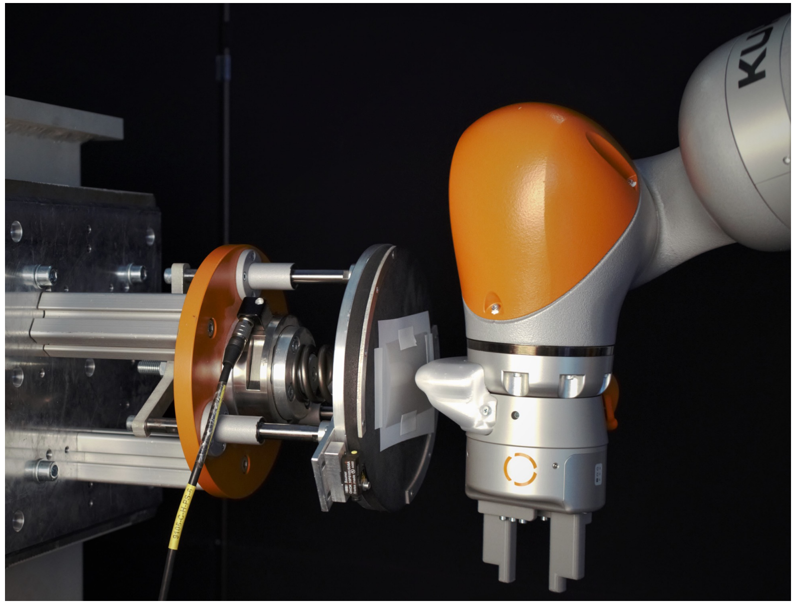
Safety verification

Collision test and adaptation of velocity

Safety setting : Stop, Collision detection, Velocity monitoring

CE-sign





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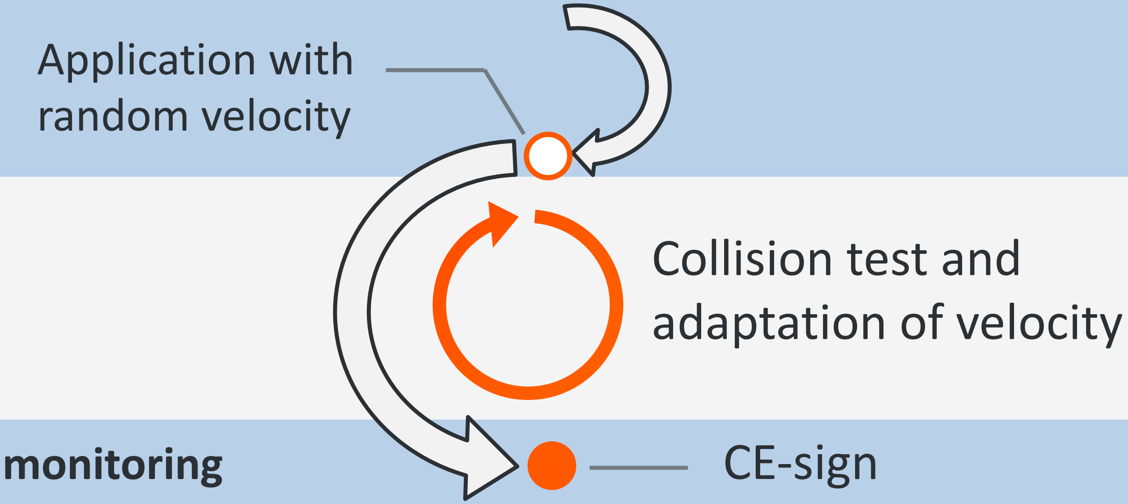
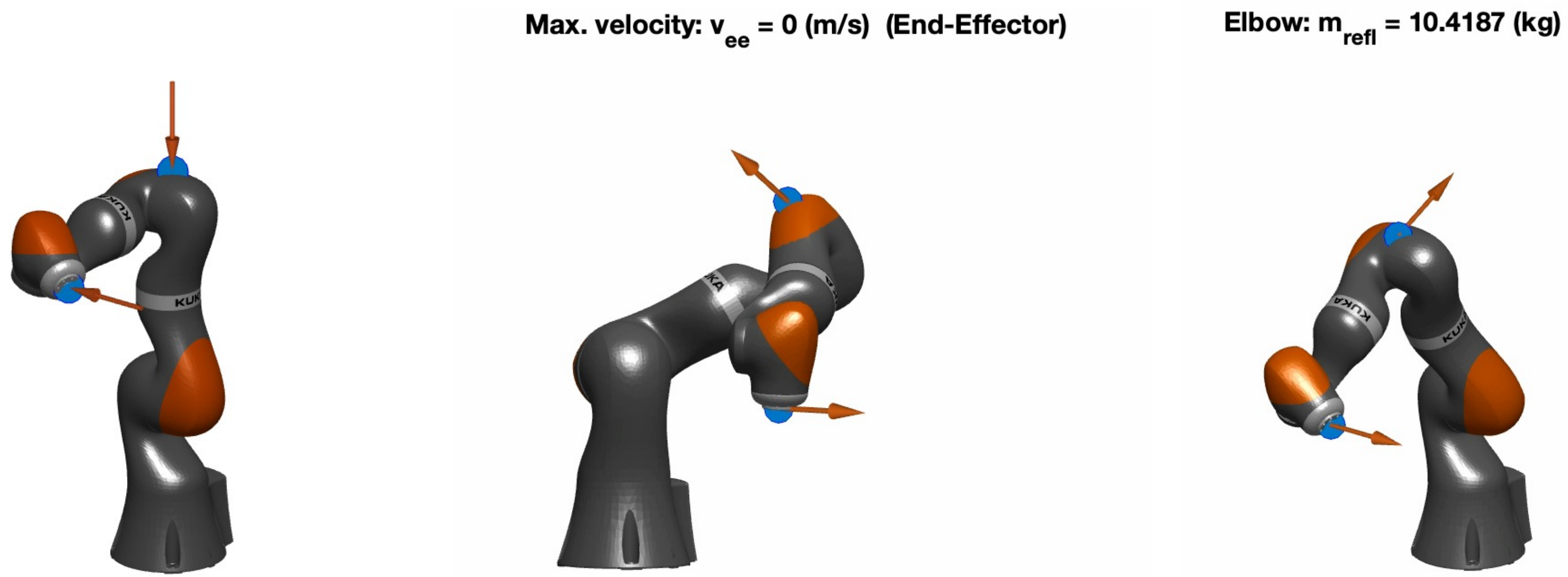
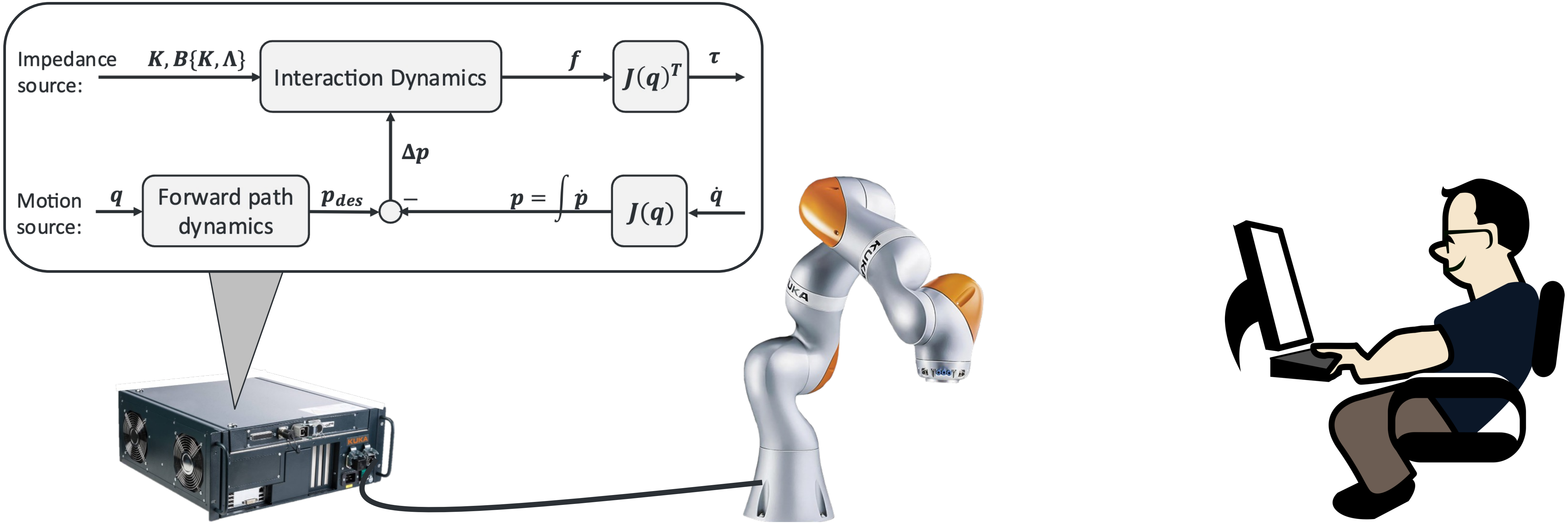




Finding: Coordinate invariant robot control for safe physical interaction

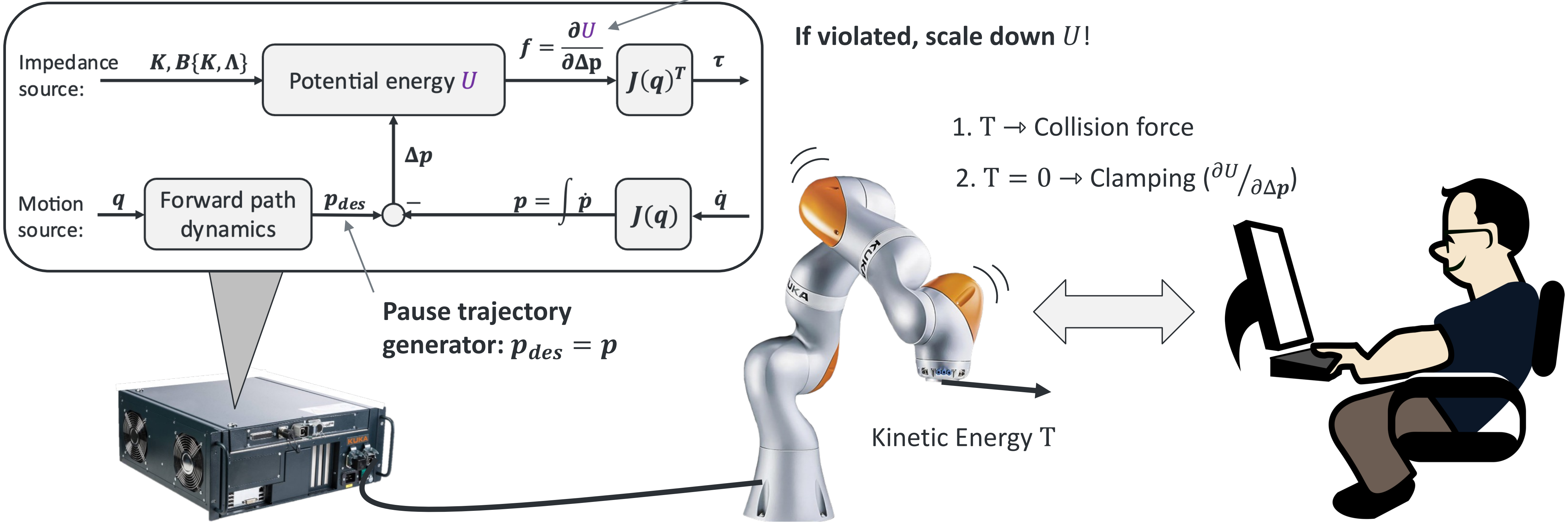
- Controlled robotic system: Controller, Robot, Environment
- An Impedance Controller shapes the energy flow at the interaction port



Finding: Coordinate invariant robot control for safe physical interaction

- Controlled robotic system: Controller, Robot, Environment
- An Impedance Controller shapes the energy flow at the interaction port
- Causality of energy flow:

We set an energy budget for $L = U + T$ (Lachner et al., 2021)
(defined by standards and regulations)



Finding: Coordinate invariant robot control for safe physical interaction

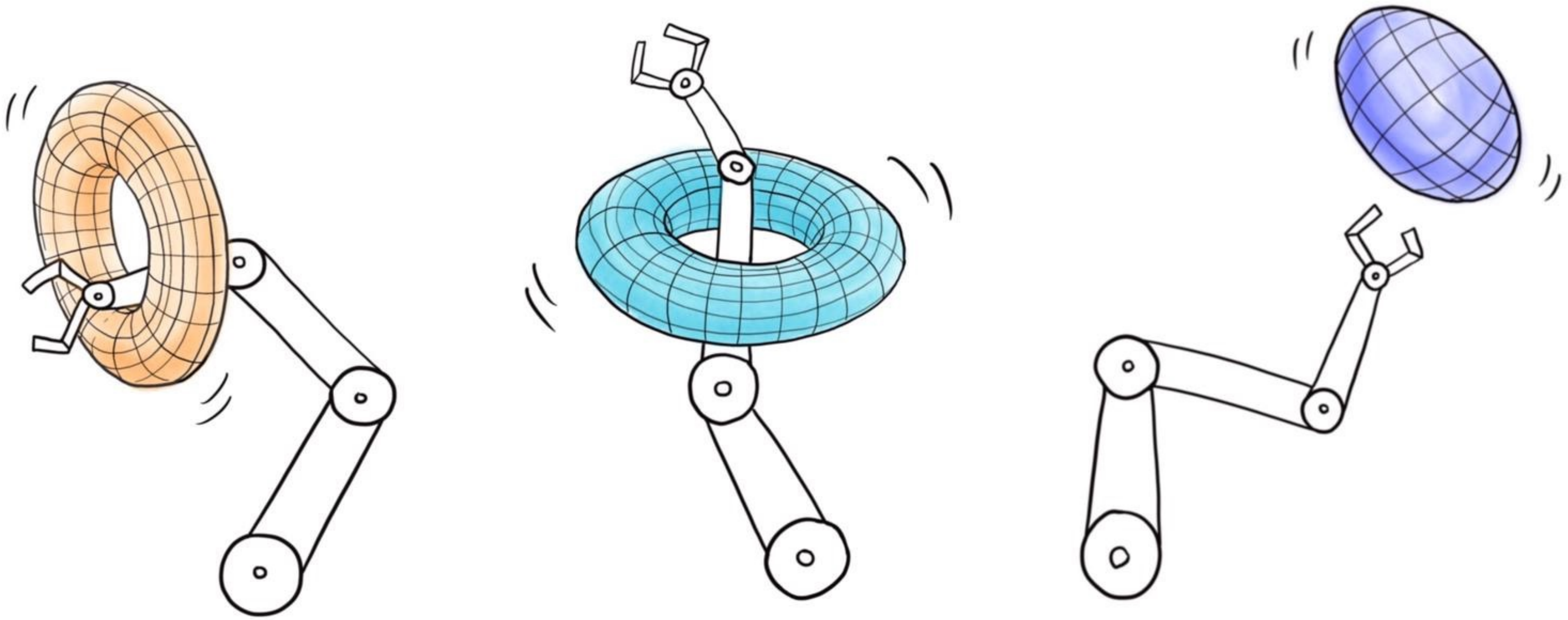
Interactive robot behavior

Resolving clamping dangers

<u>Additional contributions:</u>

- Safety verification with certified equipment
- Comparison with state-of-the-art methods

V. Summary of contributions



Contributions of the thesis

- Journal papers: Mechanism and Machine Theory, IEEE Transactions on Robotics (2x), International Journal of Robotics Research
- Conference papers: IEEE IROS (2x)
- Published patents (KUKA and UTwente)
    - https://patents.google.com/patent/DE102019205651B3/
    - https://patents.google.com/patent/DE102020209866B3/
    - https://patents.google.com/patent/WO2017144682A1/
- Transfer within KUKA
    - One algorithm part of an existing product
    - Used own algorithms to support two customer projects
    - Patented safety concept transferred to series development
- Software `[EXP]licit`©: Robot kinematics and dynamics based on Exponential Maps
    - Licensed and filed by MIT
    - The simulations (including code) of this presentation are available on GIT!
      Link: https://github.com/explicit-robotics/Explicit-MATLAB

Thanks for your attention!