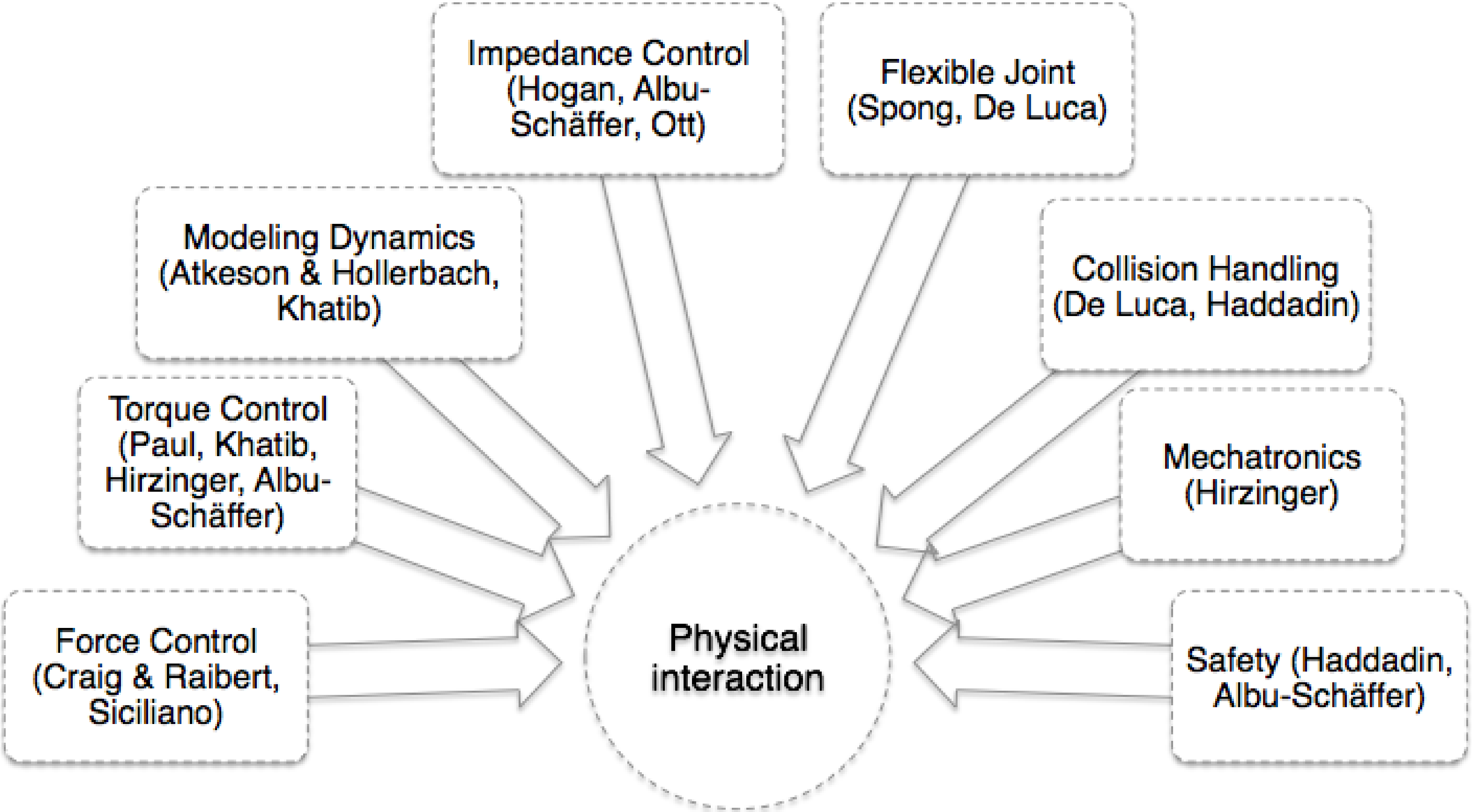
Robot Control

MSRM

Sami Haddadin, Lars Johannsmeier

Physical Interaction



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Overview

Task planning

Motion planning

performing a specific task

Actuation

Sensing

Control Design

Controller choice

Stability analysis

e.g. Model-based control

e.g. Passivity

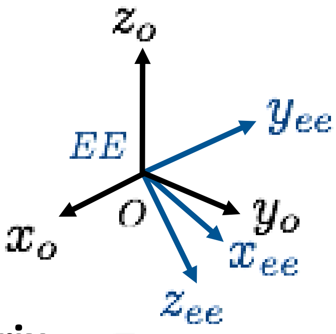
Model Identification

Modeling and essential theories

Modeling and Essential Theories

Kinematics

$^{O}R_{EE}$



Rotation matrix $R_{3\times3}$
Orthonormal matrix

9 elements
-3 orthogonality relationships
-3 unitary relationships
= 3 independent elements

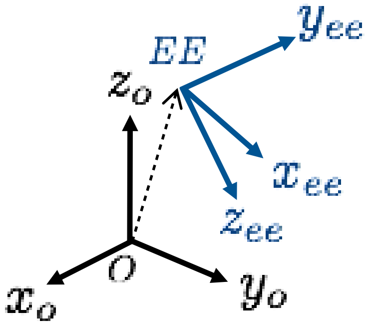
Euler angles $\{\theta, \phi, \psi\}$

Non unique and singularities

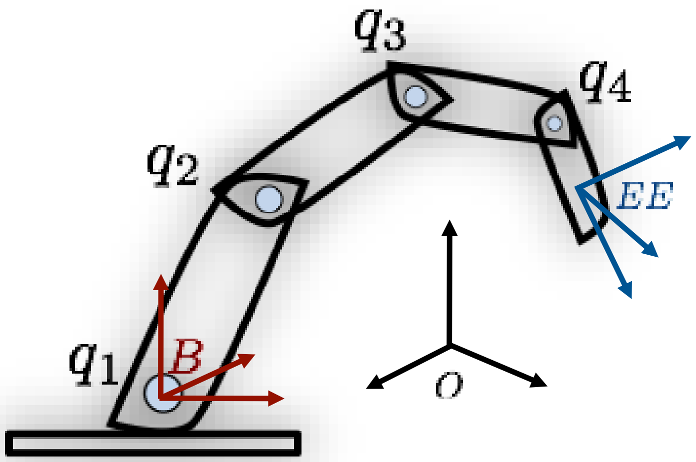
Unit quaternions $(k_0, \boldsymbol{k}_v)$

$$k_0 + k_{v,x}\vec{i} + k_{v,y}\vec{j} + k_{v,z}\vec{k}$$

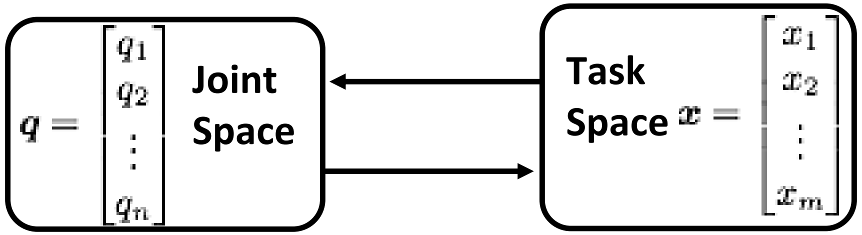
$$\begin{bmatrix} ^{O}R_{EE} & ^{O}p_{EE} \\ 0\,0\,0 & 1 \end{bmatrix}$$



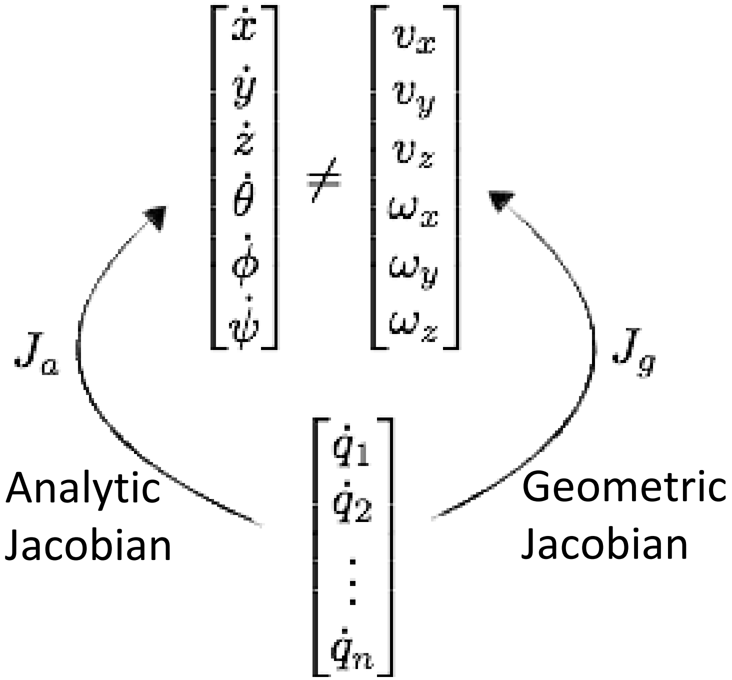
Transformation matrix $T_{4\times4}$
Always invertible
Composition: $^{O}T_{EE} = {}^{O}T_B \, {}^{B}T_{EE}$

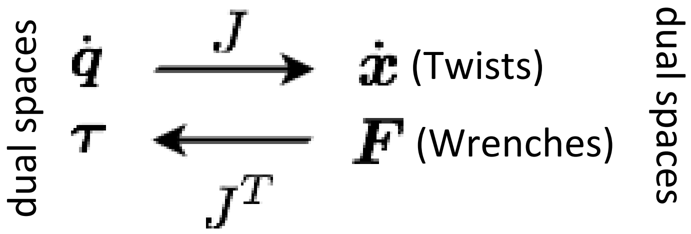


Direct Kinematics



Inverse Kinematics





Space of linear operators on vector space V. $f : V \to \mathbb{R}$

When Jacobian loses rank.

Manipulability vs. Singularity

How far from singularity?

$\sqrt{\det(JJ^T)}$

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Siciliano, B., Sciavicco, L., Villani, L., Oriolo, G., Robotics: Modelling, Planning and Control, 3rd Edition, Springer, 2009

Redundancy

$$J_W^{\#} = W^{-1}J^T(JW^{-1}J^T)^{-1}$$

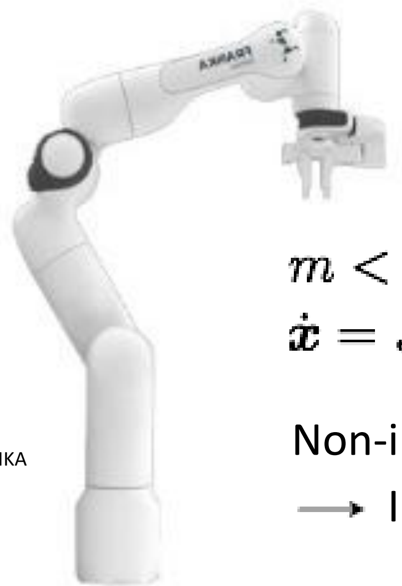
$$J^{\#} = J^T(JJ^T)^{-1}$$

Weighted pseudo-inverse $J_W^{\#}$

Differential inverse kinematics:

Minimization of:

$$\frac{1}{2}\dot{q}^T W \dot{q}$$



FRANKA EMIKA

$m < n$

$\dot{x} = J_{m\times n}\dot{q}$

Non-invertible Jacobian

→ Inverse kinematics problems

Moore-Penrose Pseudo-inverse $J^{\#}$

Unique and always exists

Such that (almost ident. for weighted):

$$JJ^{\#}J = J \qquad J^{\#}JJ^{\#} = J^{\#}$$

$$(JJ^{\#})^T = JJ^{\#} \qquad (J^{\#}J)^T = J^{\#}J$$

Null-space control

No motion $\quad \mathbf{0} = J\dot{q}_N \longrightarrow \dot{q}_N = (I - J_W^{\#}J)\dot{q}'$

No Wrench $\quad \tau_N = J^T\mathbf{0} \longrightarrow J_W^{\#T}\tau_N = \mathbf{0} \longrightarrow \tau_N = (I - J^T J_W^{\#T})\tau'$

Task prioritization

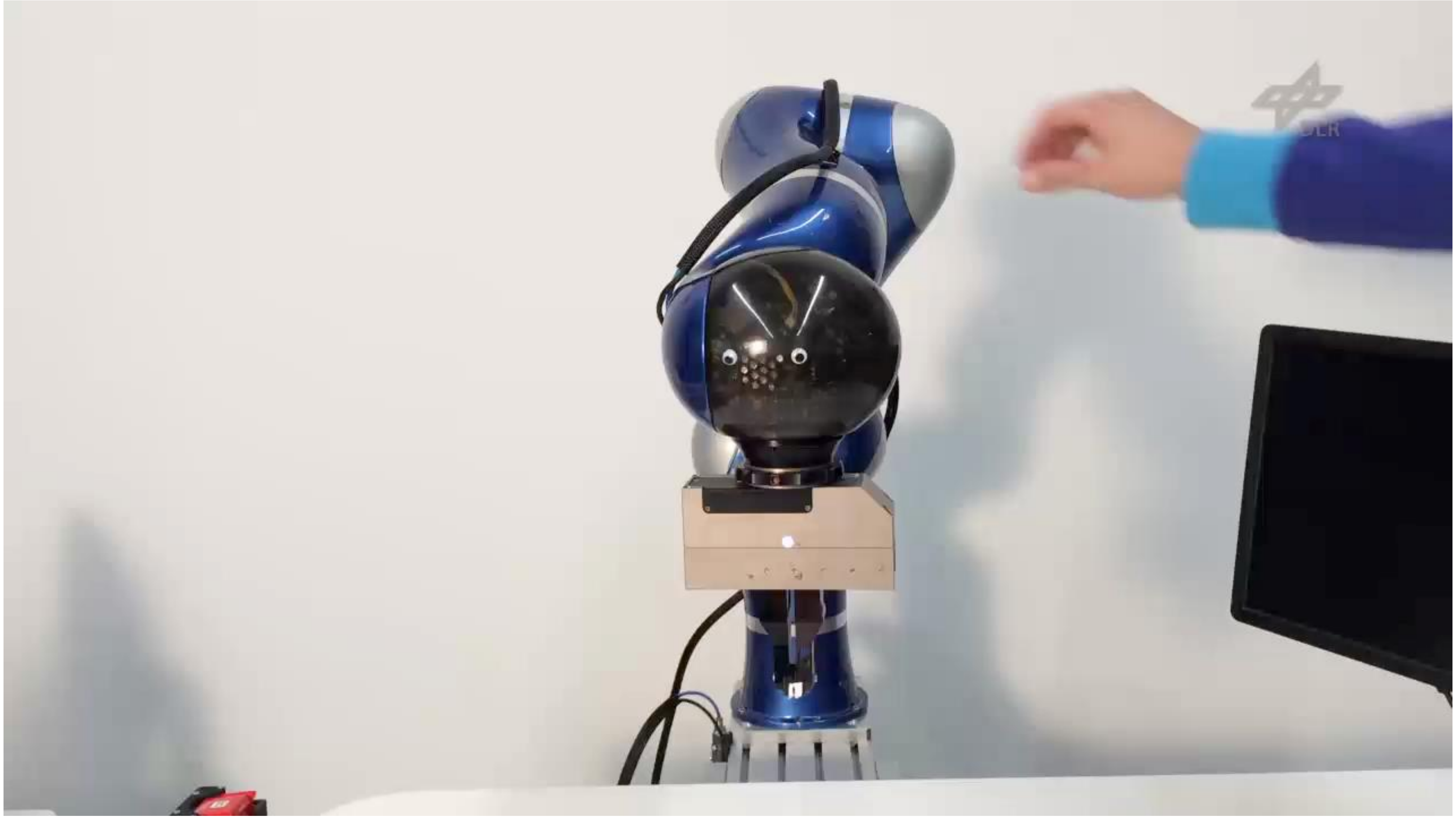
$$\dot{q} = J_W^{\#}\dot{x} + \left(I - J_W^{\#}J\right)\dot{q}'$$ On velocity level

$$\tau = J^T F + \left(I - J^T J_W^{\#T}\right)\tau'$$ On torque level

Primary task ↑ ↑ Secondary task

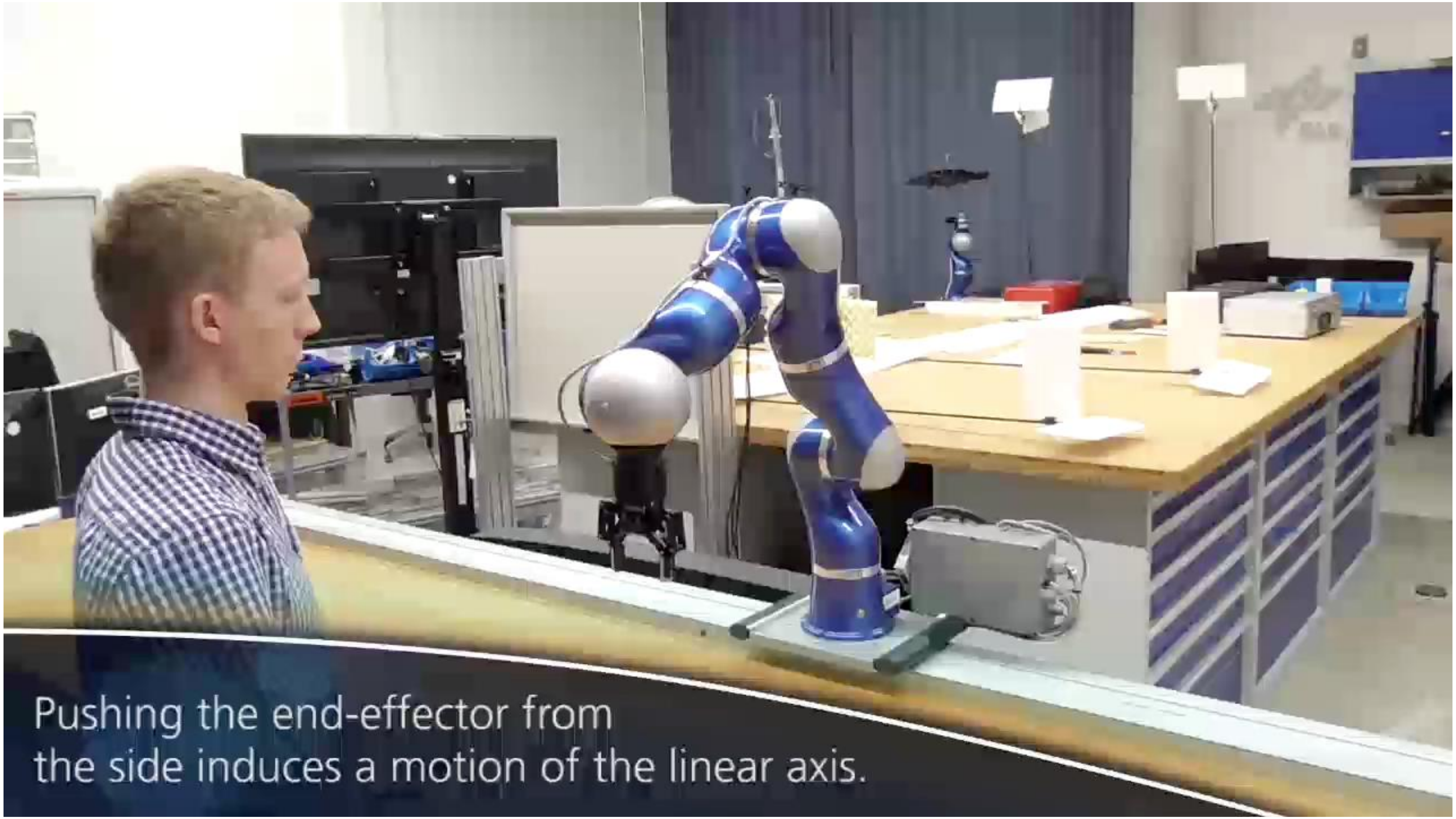
Slotine, S. B. (1991, June). A general framework for managing multiple tasks in highly redundant robotic systems. In proceeding of 5th International Conference on Advanced Robotics (Vol. 2, pp. 1211-1216).

Redundancy



Mansfred, N., Djellab, B., Raldua Veuthey, J., Beck, F., Ott, C., Haddadin, S., Improving the Performance of Biomechanically Safe Velocity Control for Redundant Robots through Reflected Mass Minimization

Redundancy



Mansfeld, N., Beck, F., Dietrich, A., Haddadin, S., Interactive Null space Control for Intuitively Interpretable Reconfiguration of Redundant Manipulators,

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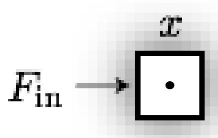
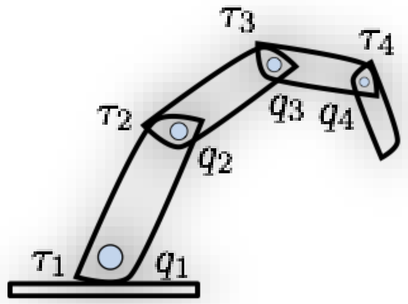
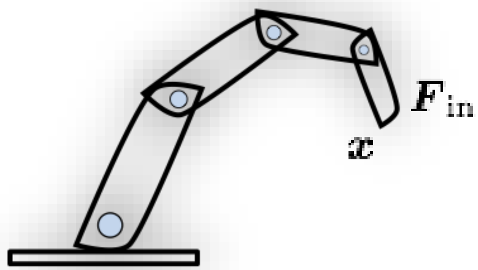
Dynamics



$$F_{\text{in}} = M\ddot{x}$$



$$\boldsymbol{\tau}_{\text{in}} = M(\boldsymbol{q})\ddot{\boldsymbol{q}} + \underbrace{C(\boldsymbol{q},\dot{\boldsymbol{q}})\dot{\boldsymbol{q}}}_{\boldsymbol{c}(\boldsymbol{q},\dot{\boldsymbol{q}})} + \boldsymbol{g}(\boldsymbol{q})$$



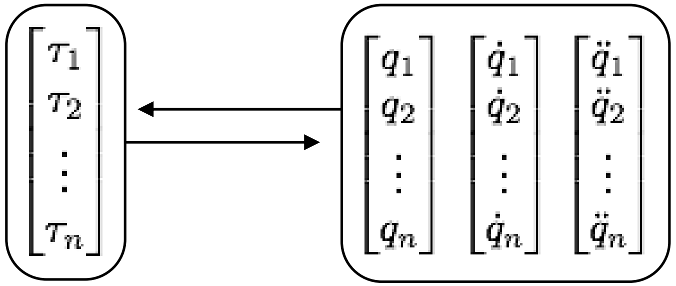
Operational Space Dynamics

$$\boldsymbol{F}_{\text{in}} = J^{\#^T}(\boldsymbol{q})\boldsymbol{\tau}_{\text{in}} = M_x(\boldsymbol{q})\ddot{\boldsymbol{x}} + C_x(\boldsymbol{q},\dot{\boldsymbol{q}})\dot{\boldsymbol{x}} + \boldsymbol{F}_g$$

$$M_x(\boldsymbol{q}) = J^{\#^T}(\boldsymbol{q})M(\boldsymbol{q})J^{\#}(\boldsymbol{q})$$

$$C_x(\boldsymbol{q},\dot{\boldsymbol{q}}) = J^{\#^T}(\boldsymbol{q})C(\boldsymbol{q},\dot{\boldsymbol{q}})J^{\#}(\boldsymbol{q}) - M_x(\boldsymbol{q})\dot{J}(\boldsymbol{q})J^{\#}(\boldsymbol{q})$$

Direct Dynamics



Inverse Dynamics

Euler-Lagrange method
(energy-based approach)
(symbolic)

vs.

Newton-Euler method
(Wrench balance approach)
(numeric)

Skew-symmetry of:

$$\dot{M}(\boldsymbol{q}) - 2C(\boldsymbol{q},\dot{\boldsymbol{q}})$$

$$\dot{M}_K(\boldsymbol{q}) - 2C_K(\boldsymbol{q},\dot{\boldsymbol{q}})$$

$$\Gamma \in \mathbb{R}^{n\times n} \longrightarrow \forall \boldsymbol{v} \in \mathbb{R}^n \implies \boldsymbol{v}^T\Gamma\boldsymbol{v} = 0$$

& skew-symmetric

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Siciliano, B., Sciavicco, L., Villani, L., Oriolo, G., Robotics: Modelling, Planning and Control, 3rd Edition, Springer, 2009

Flexible-joint robots

Fully coupled model

$$\begin{bmatrix} M(\boldsymbol{q}) & S(\boldsymbol{q}) \\ S^T(\boldsymbol{q}) & B \end{bmatrix} \begin{bmatrix} \ddot{\boldsymbol{q}} \\ \ddot{\boldsymbol{\theta}} \end{bmatrix} + \begin{bmatrix} \boldsymbol{c}(\boldsymbol{q},\dot{\boldsymbol{q}}) + \boldsymbol{c}_1(\boldsymbol{q},\dot{\boldsymbol{q}},\dot{\boldsymbol{\theta}}) \\ \boldsymbol{c}_2(\boldsymbol{q},\dot{\boldsymbol{q}}) \end{bmatrix} + \begin{bmatrix} \boldsymbol{g}(\boldsymbol{q}) + K(\boldsymbol{q}-\boldsymbol{\theta}) + D(\dot{\boldsymbol{q}}-\dot{\boldsymbol{\theta}}) \\ K(\boldsymbol{\theta}-\boldsymbol{q}) + D(\dot{\boldsymbol{\theta}}-\dot{\boldsymbol{q}}) \end{bmatrix} = \begin{bmatrix} \boldsymbol{0} \\ \boldsymbol{\tau}_m \end{bmatrix}$$

Reduced model (Large transmission ratio)

$$M(\boldsymbol{q})\ddot{\boldsymbol{q}} + \boldsymbol{c}(\boldsymbol{q},\dot{\boldsymbol{q}}) + \boldsymbol{g}(\boldsymbol{q}) - \boldsymbol{\tau}_J = \boldsymbol{0}$$

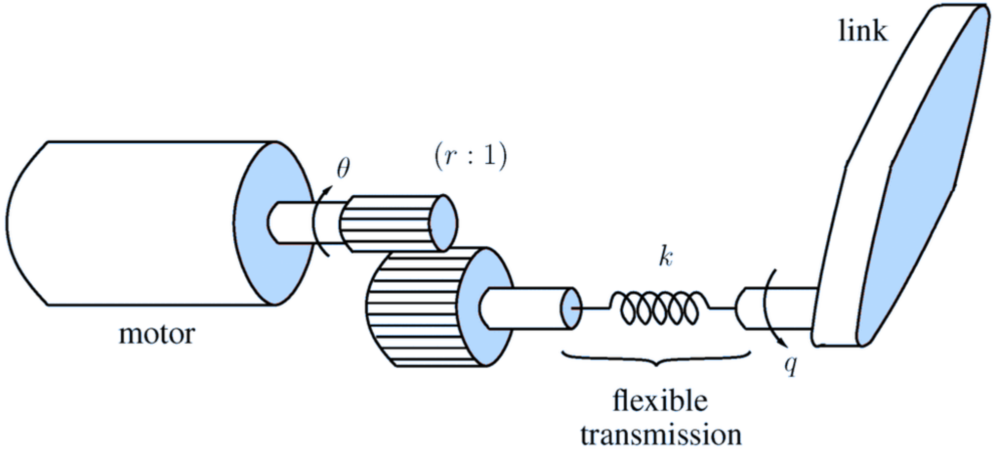
$$B\ddot{\boldsymbol{\theta}} + \boldsymbol{\tau}_J = \boldsymbol{\tau}_m$$

$$K(\boldsymbol{\theta}-\boldsymbol{q}) + D(\dot{\boldsymbol{\theta}}-\dot{\boldsymbol{q}}) = \boldsymbol{\tau}_J$$

←

$$B_\theta\ddot{\boldsymbol{\theta}} + \boldsymbol{\tau}_J = \boldsymbol{\tau}_m$$

$$K(\boldsymbol{\theta}-\boldsymbol{q}) + D_s(\dot{\boldsymbol{\theta}}-\dot{\boldsymbol{q}}) = \boldsymbol{\tau}_J$$



↓ with: Joint torque sensing

$$\boldsymbol{\tau}_m = BB_\theta^{-1}\boldsymbol{\tau}_{\text{in}} + \boldsymbol{\tau}_J - BB_\theta^{-1}(K(\boldsymbol{\theta}-\boldsymbol{q}) + D_s(\dot{\boldsymbol{\theta}}-\dot{\boldsymbol{q}}))$$

Inertia shaping

$B_\theta \leftarrow B$

$D_s \leftarrow D$

Damping shaping

De Luca, A., & Book, W. J. (2016). Robots with flexible elements. In Springer Handbook of Robotics (pp. 243-282). Springer International Publishing.
Albu-Schäffer, A., Ott, C., & Hirzinger, G. (2007). A unified passivity-based control framework for position, torque and impedance control of flexible joint robots. The international journal of robotics research, 26(1), 23-39.

Take Me by the Hand!

Albu-Schäffer et. al. ICRA 2002, Albu-Schäffer et. al. IJRR2007

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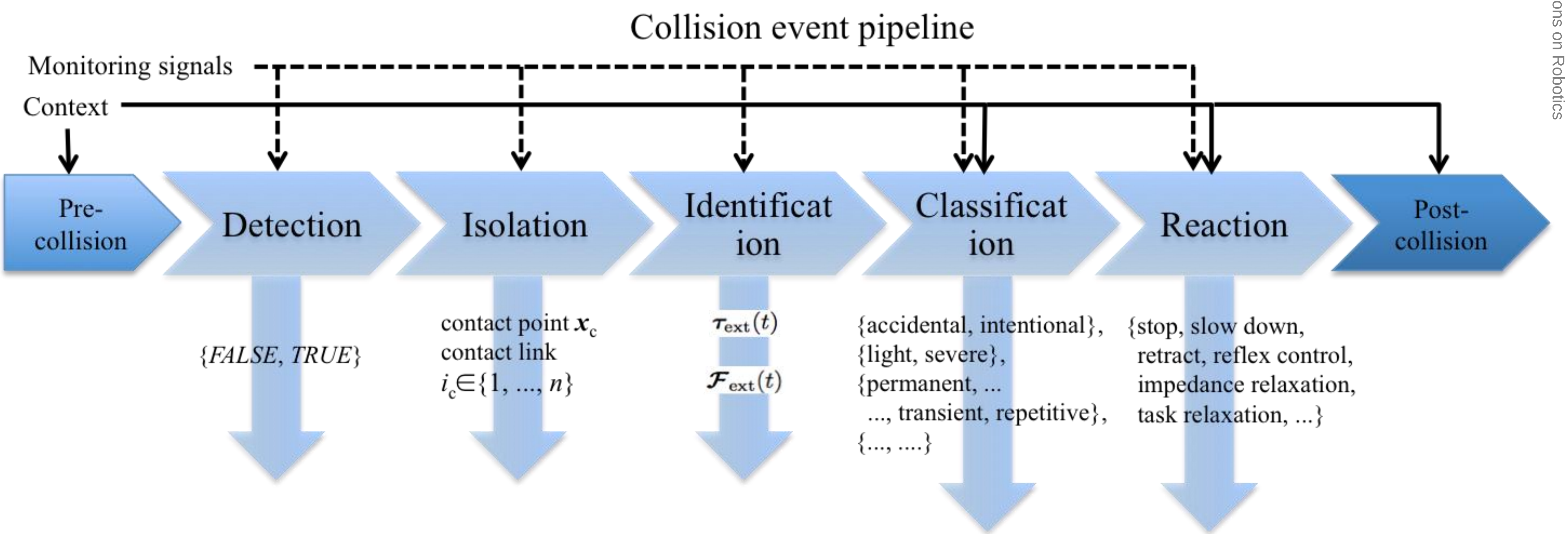
Collision Handling



Haddadin, S., De Luca, A., Albu-Schäffer, A. (2017). Robot Collisions: A Survey on Detection, Isolation, and Identification, Accepted for IEEE Transactions on Robotics

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External Joint Torque Observer

Generalized momentum: $\boldsymbol{p} = M(\boldsymbol{q})\dot{\boldsymbol{q}}$

$$\boldsymbol{r}(t) = K_O \left[\boldsymbol{p}(t) - \int_0^t (\boldsymbol{\tau}_J + C^T(\boldsymbol{q}, \dot{\boldsymbol{q}})\dot{\boldsymbol{q}} - \boldsymbol{g}(\boldsymbol{q}) + \boldsymbol{r}) ds - \boldsymbol{p}(0) \right]$$

$$\longrightarrow \quad \dot{\boldsymbol{r}} = -K_O \boldsymbol{r} + K_O \boldsymbol{\tau}_{\text{ext}}$$

Component-wise: $\dfrac{r_j(s)}{\tau_{\text{ext},j}(s)} = \dfrac{K_{O,j}}{s + K_{O,j}}$

$$K_O \to \infty \quad \longrightarrow \quad \boldsymbol{r} \approx \boldsymbol{\tau}_{\text{ext}}$$

Collision on the i-th link: $\boldsymbol{r} = [* \; \dots \; * \; \underset{\uparrow \atop i+1}{0} \; \dots \; \underset{\uparrow \atop n}{0}]$


DLR Lightweight Robot

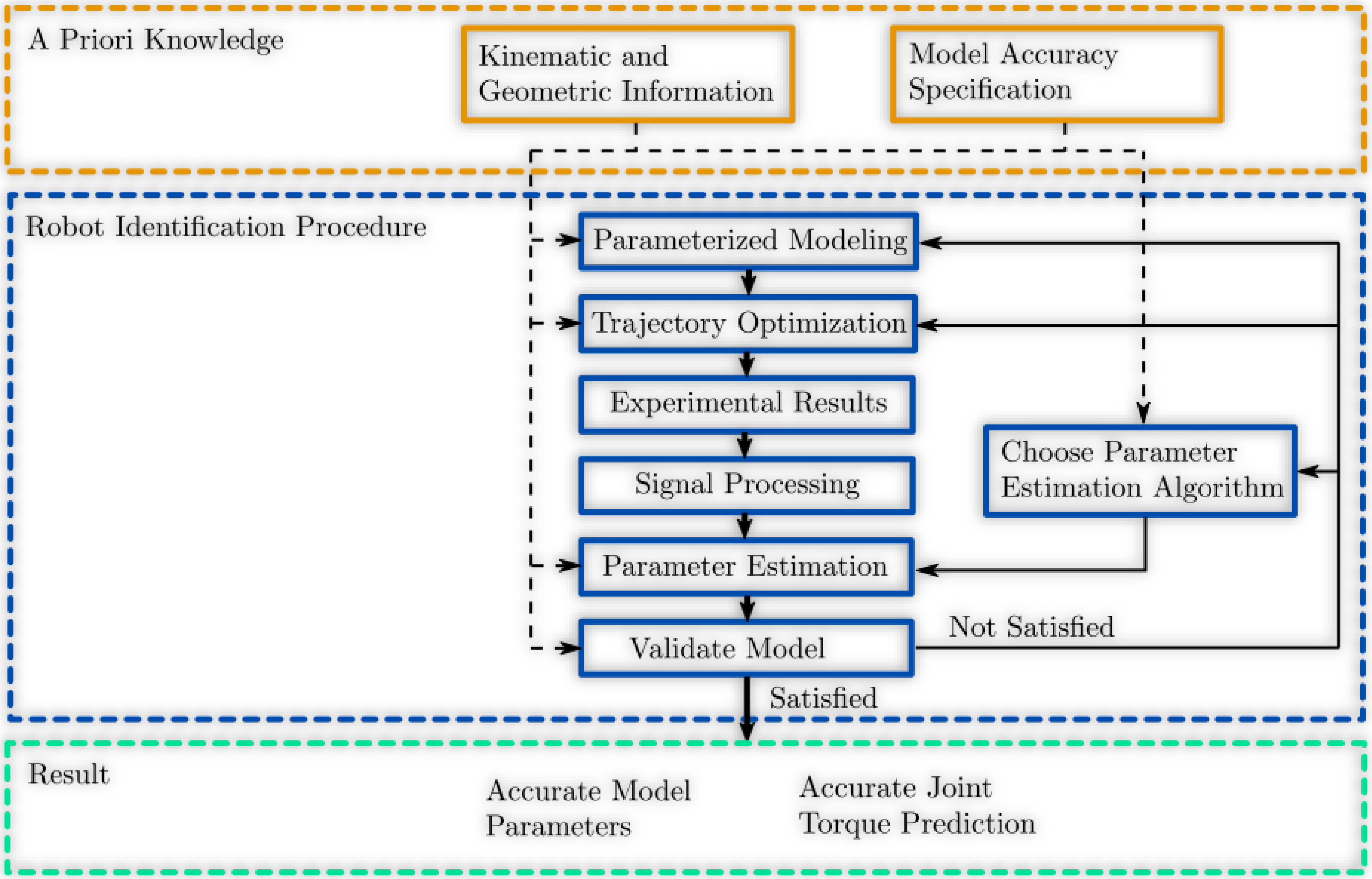
Haddadin, S., De Luca, A., Albu-Schäffer, A. (2017). Robot Collisions: A Survey on Detection, Isolation, and Identification. Accepted for IEEE Transactions on Robotics

Collision Handling

Haddadin et. al. RSS 2007
Haddadin et. al. IJRR 2009
2012 George Giralt PhD Award
ICRA Best Service Robotics Award

Model Identification

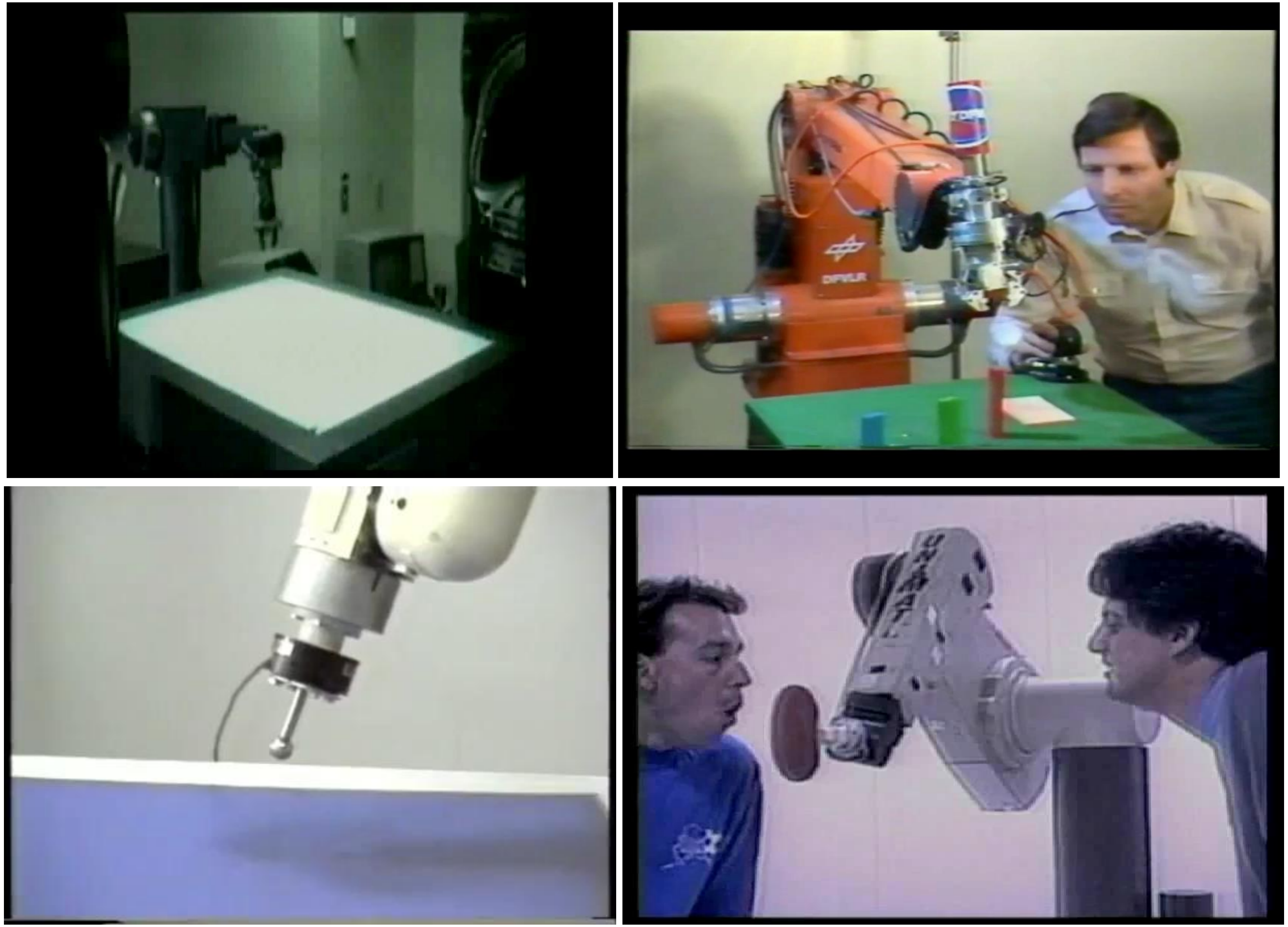
Identification Procedure



Khalil, W., & Dombre, E. (2004). Modeling, identification and control of robots. Butterworth-Heinemann.

Control Design

Early pHRI



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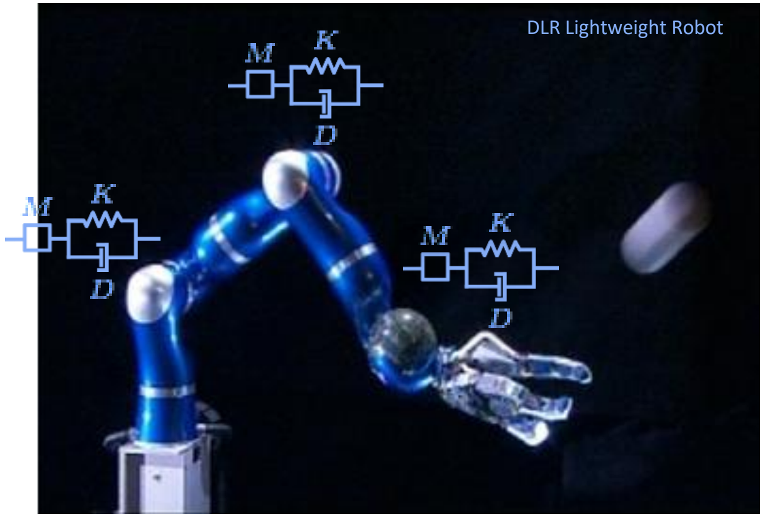
Joint Impedance Control

Desired impedance behavior:

$$\tilde{q} = q - q_d$$

$$M'\ddot{\tilde{q}} + D\dot{\tilde{q}} + K\tilde{q} = \tau_{\mathrm{ext}}$$



Robot dynamics:

$$M(q)\ddot{q} + C(q,\dot{q})\dot{q} + g(q) = \tau_{\mathrm{in}} + \tau_{\mathrm{ext}}$$

Required control input:

$$\tau_{\mathrm{in}} = M(q)\ddot{q}_d + C(q,\dot{q})\dot{q} - M(q)M'^{-1}(D\dot{\tilde{q}} + K\tilde{q}) + (M(q)M'^{-1} - I)\tau_{\mathrm{ext}} + g(q)$$

Avoidance of inertia shaping:

$$M' \longrightarrow M(q)$$
$$D \longrightarrow D + C(q,\dot{q})$$

No need for external joint torque sensing

PD+ controller

$$\tau_{\mathrm{in}} = M(q)\ddot{q}_d + C(q,\dot{q})\dot{q}_d - D\dot{\tilde{q}} - K\tilde{q} + g(q)$$

$\dot{q}_d = 0 \longrightarrow$ **Compliance control**

$$\tau_{\mathrm{in}} = -D\dot{q} - K\tilde{q} + g(q)$$

Closed-loop dynamics:

$$M(q)\ddot{\tilde{q}} + (D + C(q,\dot{q}))\dot{\tilde{q}} + K\tilde{q} = \tau_{\mathrm{ext}}$$

Ott, C. (2008). Cartesian impedance control of redundant and flexible-joint robots. Springer.

Cartesian Impedance Control & Damping Design

Desired impedance behavior (without inertia shaping):

$$M_x(\boldsymbol{q})\ddot{\tilde{\boldsymbol{x}}} + (D_x + C_x(\boldsymbol{q},\dot{\boldsymbol{q}}))\,\dot{\tilde{\boldsymbol{x}}} + K_x\tilde{\boldsymbol{x}} = \boldsymbol{F}_{\text{ext}}$$

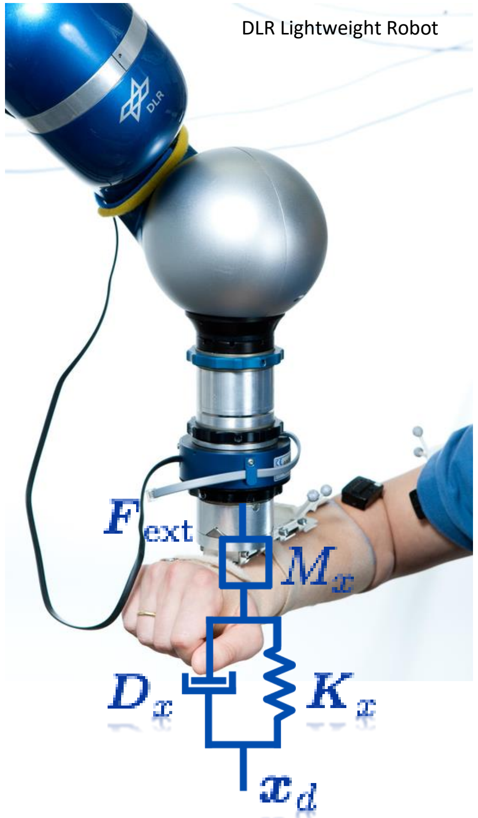
$$\tilde{\boldsymbol{x}} = \boldsymbol{x} - \boldsymbol{x}_d$$

Required control input:

$$\boldsymbol{\tau}_{\text{in}} = J^T(\boldsymbol{q})\left[M_x(\boldsymbol{q})\ddot{\boldsymbol{x}}_d + C_x(\boldsymbol{q},\dot{\boldsymbol{q}})\dot{\boldsymbol{x}}_d - D_x\dot{\tilde{\boldsymbol{x}}} - K_x\tilde{\boldsymbol{x}}\right] + \boldsymbol{g}(\boldsymbol{q})$$

$\dot{\boldsymbol{x}}_d = \boldsymbol{0} \longrightarrow$ **Compliance control**

$$\boldsymbol{\tau}_{\text{in}} = J^T(\boldsymbol{q})\left(-D_x\dot{\boldsymbol{x}} - K_x\tilde{\boldsymbol{x}}\right) + \boldsymbol{g}(\boldsymbol{q})$$



Design of stiffness: Constant & defined by the application (Normally symmetric & positive).

Design of damping: Constant & diagonal not good.

Non-constant & non-diagonal inertia → e.g. based on general eigenvalue decomposition of symmetric matrices

For any positive-definite matrix A and symmetric matrix B, there is a non-singular matrix Q and a diagonal matrix B_0 such that:

$$Q^TQ = A$$
$$Q^TB_0Q = B$$

In quasi-static case, at each position $\boldsymbol{x}_0 = \boldsymbol{f}(\boldsymbol{q}_0)$

$$M_x(\boldsymbol{q}_0)\ddot{\tilde{\boldsymbol{x}}} + D_x(\boldsymbol{x}_0)\dot{\tilde{\boldsymbol{x}}} + K_x\tilde{\boldsymbol{x}} = \boldsymbol{F}_{\text{ext}}$$

$$Q(\boldsymbol{x}_0)^TQ(\boldsymbol{x}_0)\ddot{\tilde{\boldsymbol{x}}} + D_x(\boldsymbol{x}_0)\dot{\tilde{\boldsymbol{x}}} + Q(\boldsymbol{x}_0)^TB_0(\boldsymbol{x}_0)Q(\boldsymbol{x}_0)\tilde{\boldsymbol{x}} = \boldsymbol{F}_{\text{ext}}$$

$$D_x(\boldsymbol{x}_0) = 2Q(\boldsymbol{x}_0)^T\text{diag}(\zeta_i\sqrt{b_{ii}})Q(\boldsymbol{x}_0)$$

b_{ii}: i-th diagonal element of B_0, $i = 1, \ldots, 6$

Damping factor: $0 \leq \zeta_i \leq 1$

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Ott, C. (2008). Cartesian impedance control of redundant and flexible-joint robots. Springer.

Stiffen up!

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Adaptive Impedance Control

Cartesian impedance control with the feedforward wrench

$$\tilde{\boldsymbol{x}} = \boldsymbol{x} - \boldsymbol{x}_d$$

$$\boldsymbol{\tau}_{\text{in}} = J^T(\boldsymbol{q}) \left[M_x(\boldsymbol{q})\ddot{\boldsymbol{x}}_d + C_x(\boldsymbol{q}, \dot{\boldsymbol{q}})\dot{\boldsymbol{x}}_d - D_x\dot{\tilde{\boldsymbol{x}}} - K_x\tilde{\boldsymbol{x}} - \boldsymbol{F}_{ff} \right] + \boldsymbol{g}(\boldsymbol{q})$$

$$K_x(t) = K_x(t-T) + \delta K_x$$

$$\boldsymbol{F}_{ff}(t) = \boldsymbol{F}_{ff}(t-T) + \delta \boldsymbol{F}_{ff}$$

Similar to the principles of motor adaptation:

$$\delta K_x = \alpha_K(\text{diag}(\boldsymbol{\epsilon} \circ \tilde{\boldsymbol{x}}) - \gamma_K(t) K_x(t))$$

$$\delta \boldsymbol{F}_{ff} = \alpha_F(\boldsymbol{\epsilon} - \gamma_F(t)\boldsymbol{F}_{ff}(t))$$

$$\boldsymbol{\epsilon} = \tilde{\boldsymbol{x}} + \kappa\dot{\tilde{\boldsymbol{x}}}$$

α_K & α_F → Learning rate (positive definite)

γ_F & γ_K → Forgetting factor (positive definite)

→ e.g. $\dfrac{a}{1 + b\|\boldsymbol{\epsilon}\|^2}$


DLR Lightweight Robot with Adaptive Impedance control in peg-in-hole experiment

Yang, C., Ganesh, G., Haddadin, S., Parusel, S., Albu-Schaeffer, A., & Burdet, E. (2011). Human-like adaptation of force and impedance in stable and unstable interactions. IEEE transactions on robotics, 27(5), 918-930.

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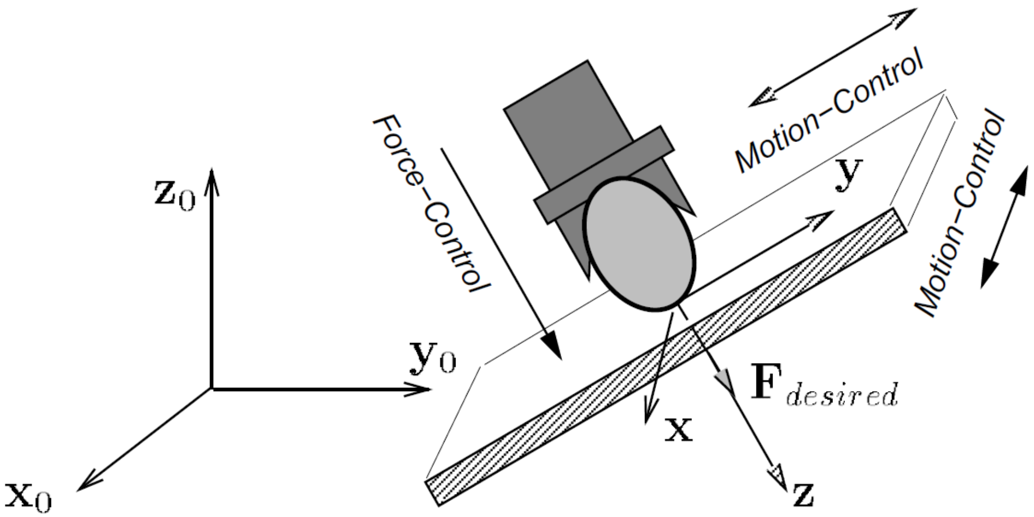
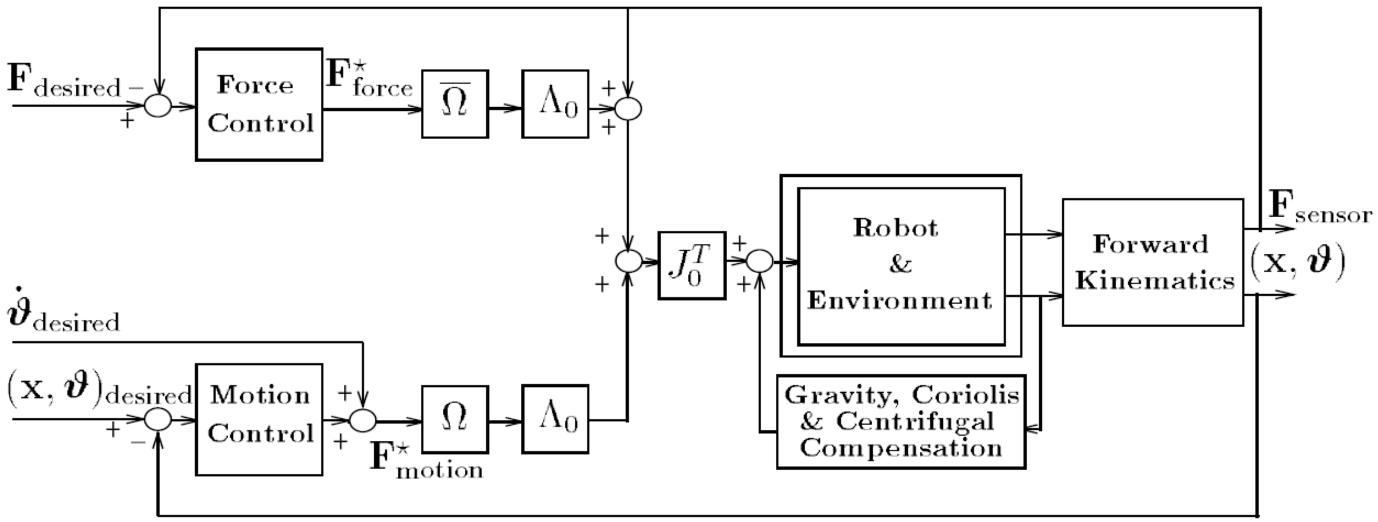
Hybrid Force Position Control

Villani, De Schutter Handbook of Robotics 2008
Khatib IJRR, 1987

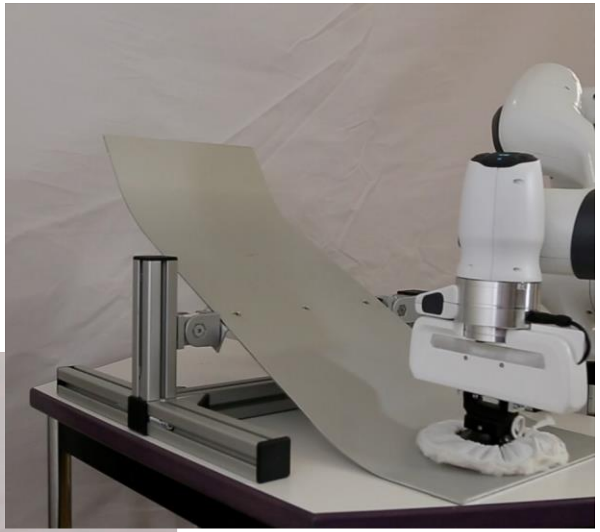
Classical approach: partition motion and force space via selection matrix Ω

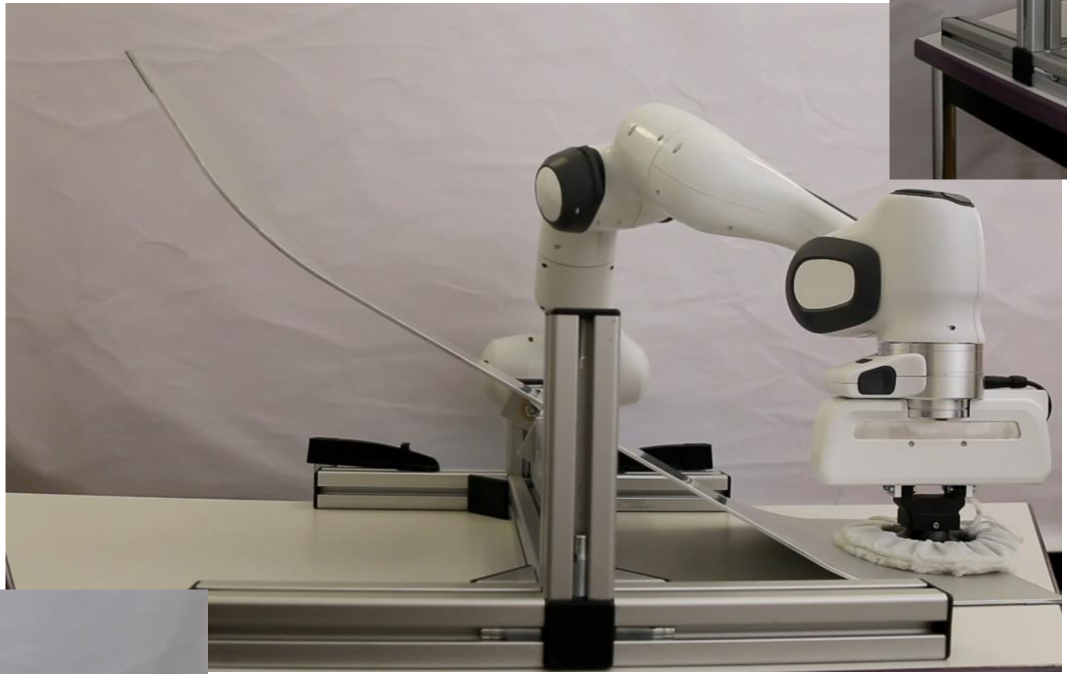




Disadvantage: Exact environment model has to be known!

Unified Force/Impedance Controller





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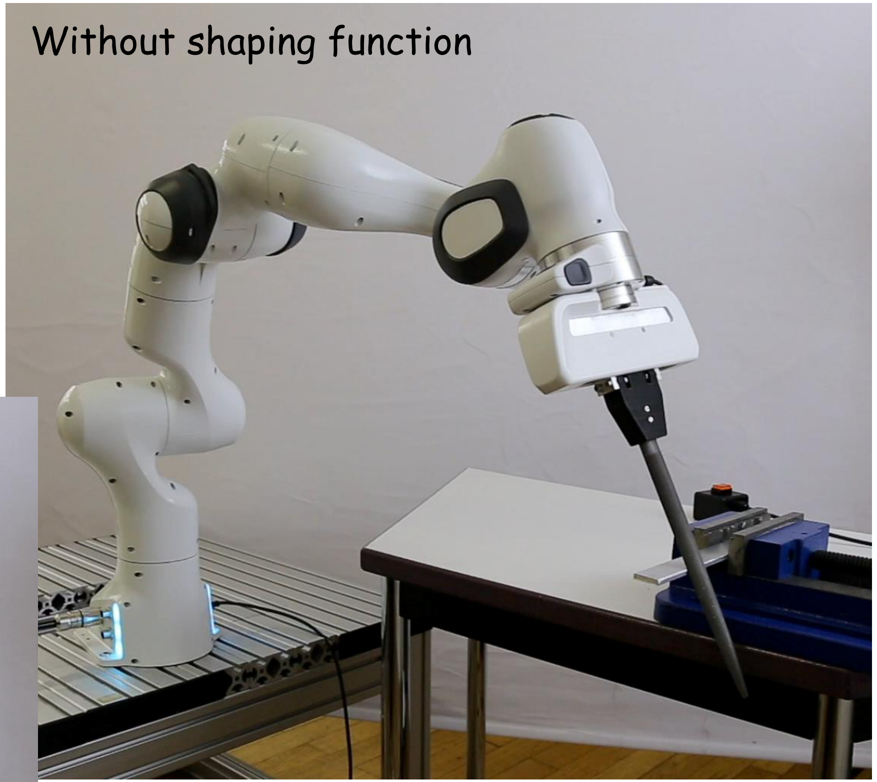
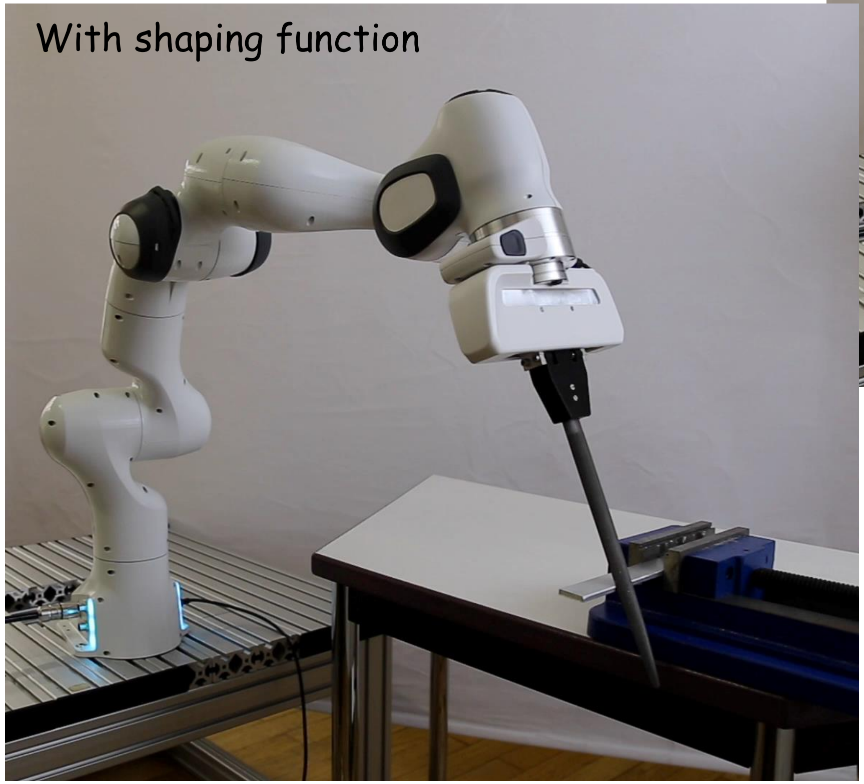
Unified Force/Impedance Controller

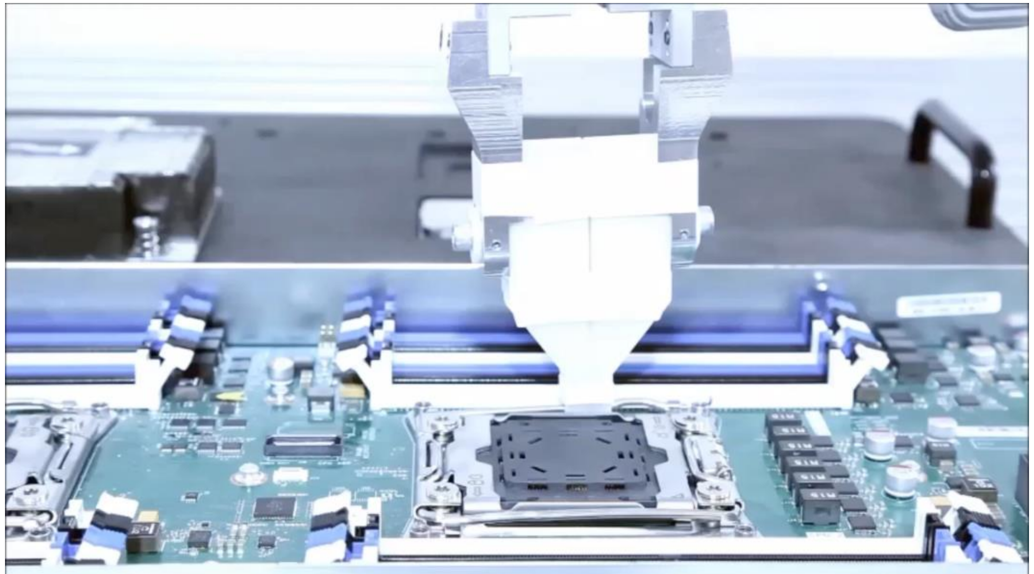


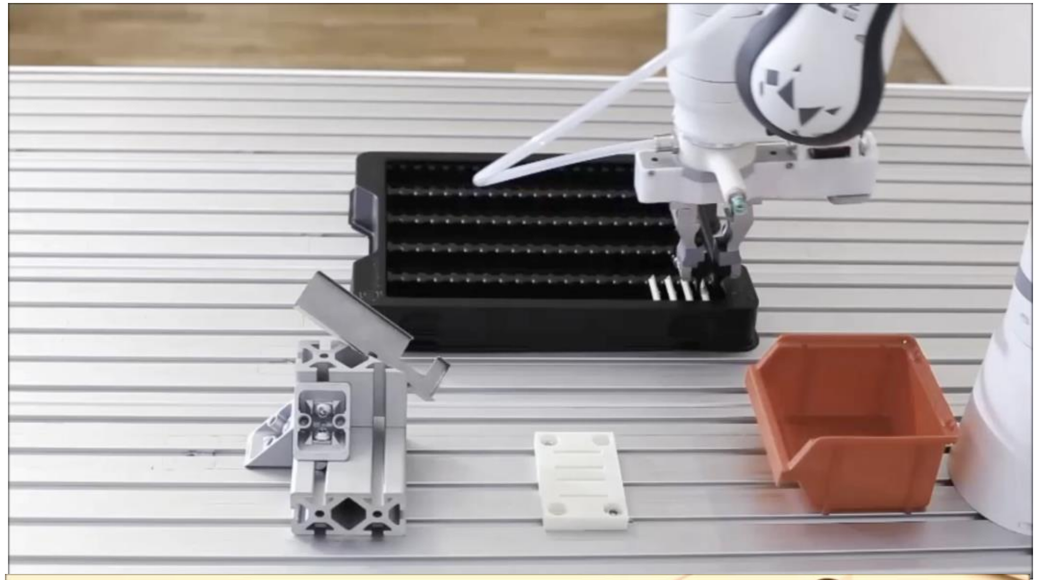


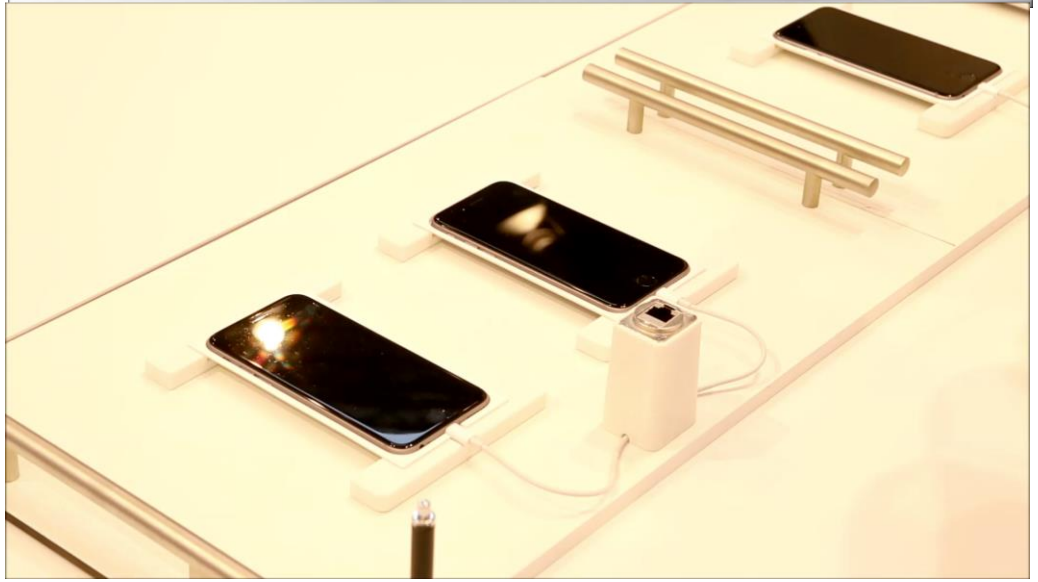
Assembly and Soft Manipulation

Assembly and Soft Manipulation

Assembly and Soft Manipulation







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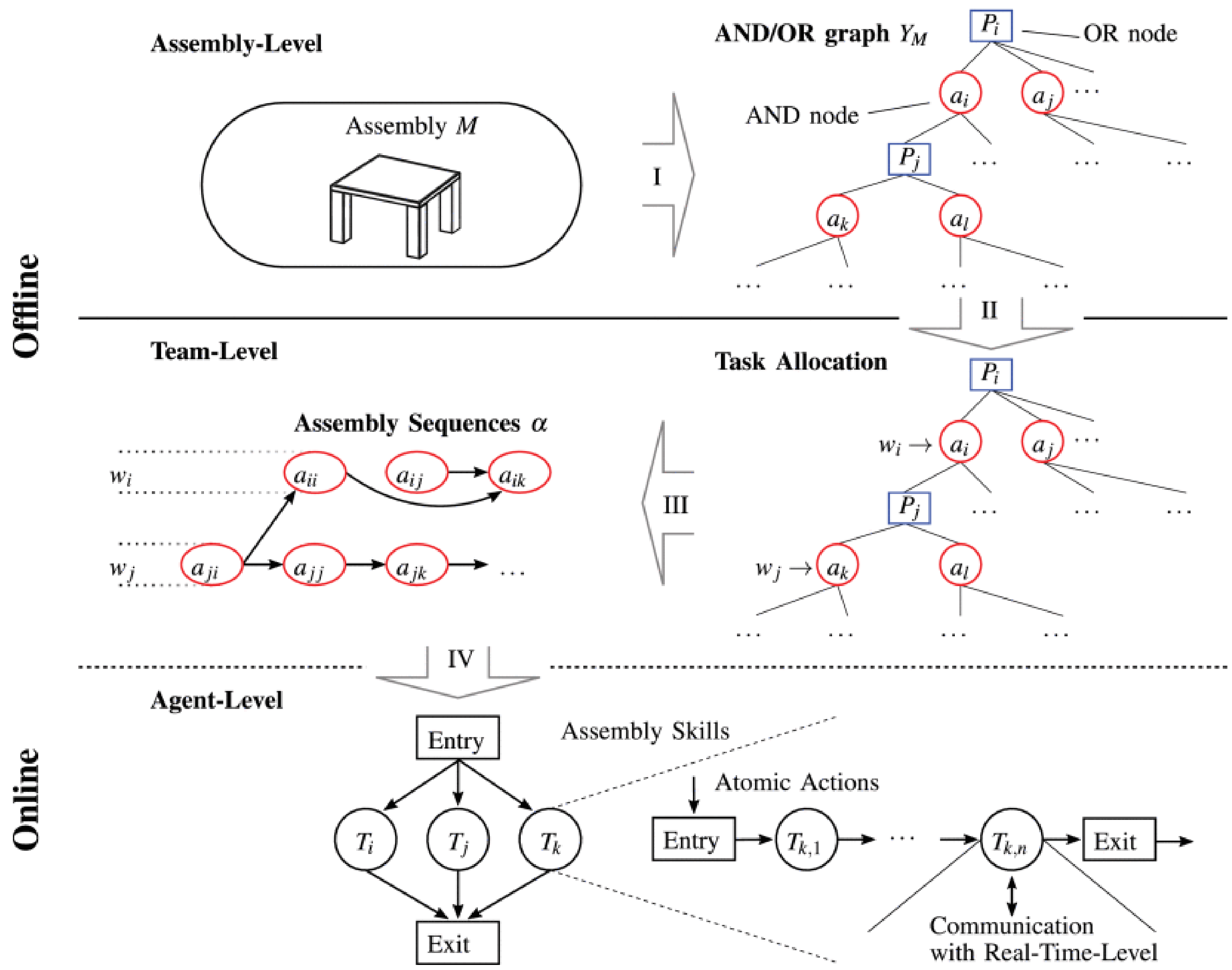
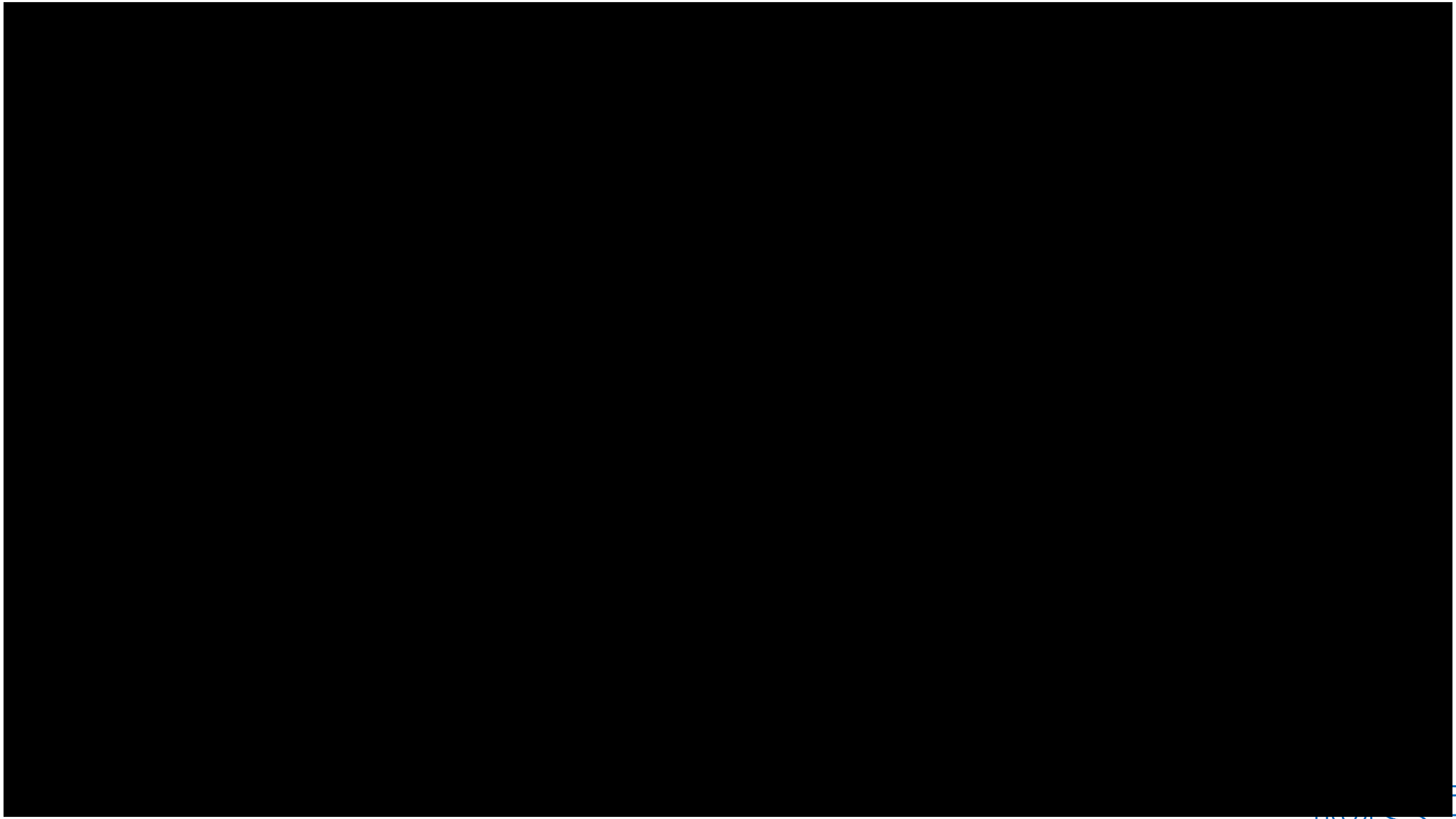
Assembly Planning



- Framework for multi-agent assembly
- Optimal assignment of agents to tasks is planned
- Local motion and manipulation planning

Assembly Planning



Assembly Planning

A Framework for Robot Manipulation:
Skill Formalism, Meta Learning and Adaptive Control

Lars Johannsmeier, Malkin Gerchow and Sami Haddadin

Institute of Automatic Control
Gottfried Wilhelm Leibniz Universität Hannover

Leibniz Universität Hannover

- Robot knows a general strategy
- Controller and skill parameters are learned
- Parameter space limits are derived from known system limits and task context

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