Design and Control of Compliant Humanoids

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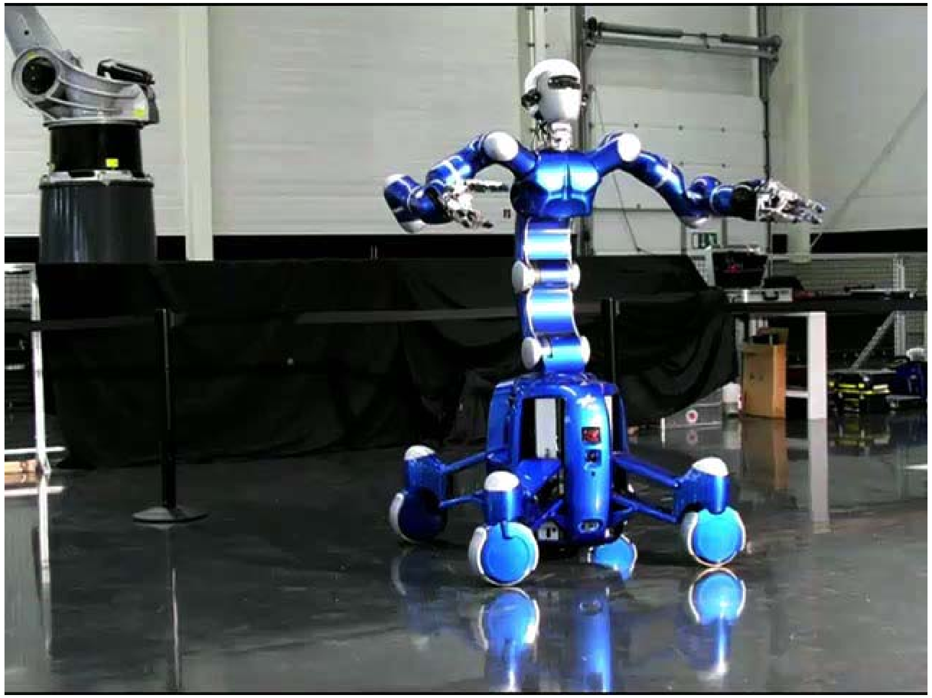
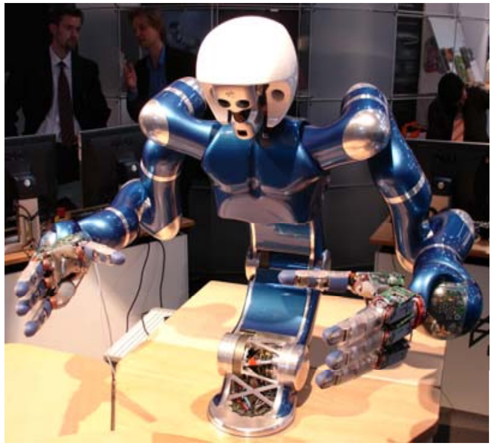
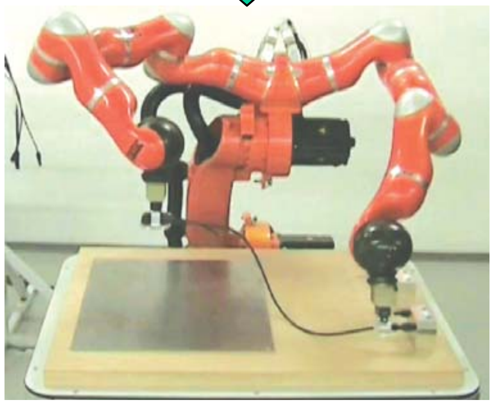
Torque Controlled Light-weight Robots

Torque sensing in each joint
Mature technology for experimental platforms

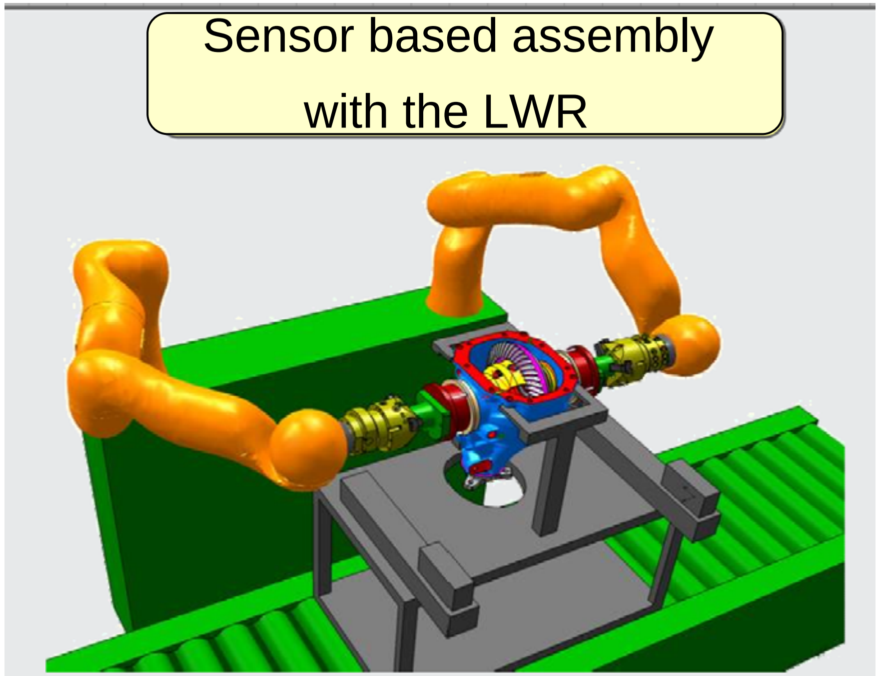


First Applications of the Technology in Automotive Industry





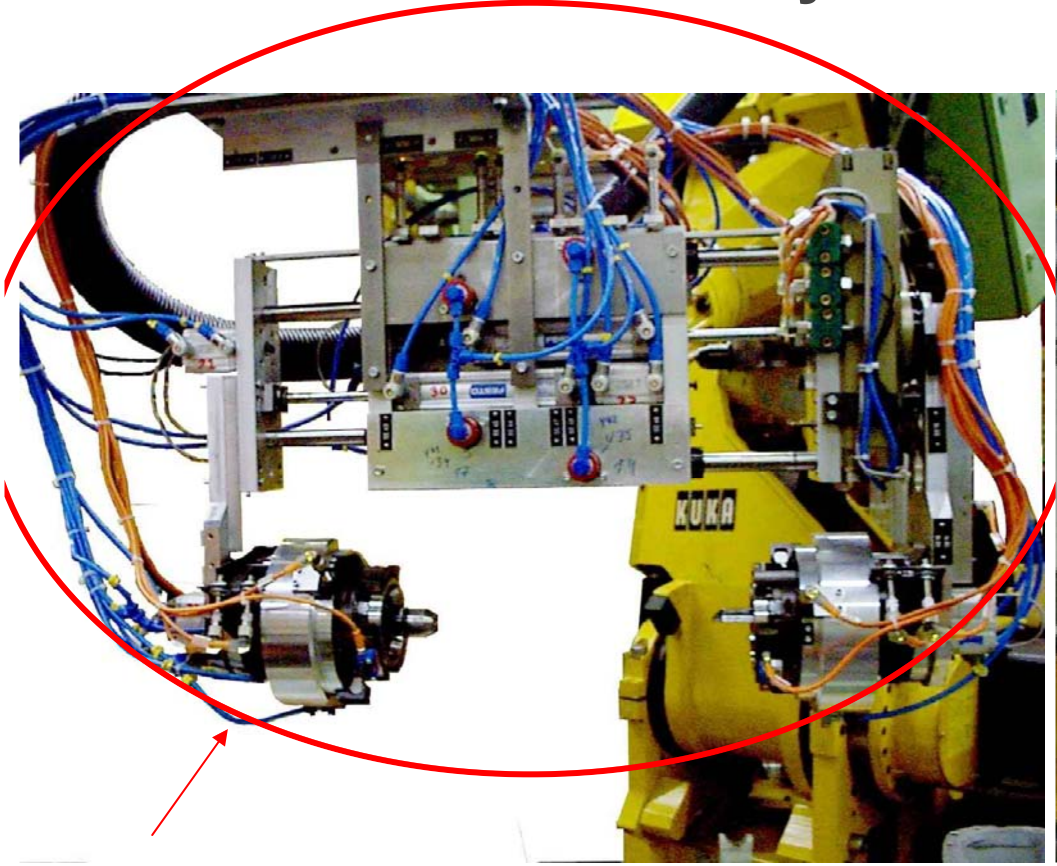
KUKA Demonstrator

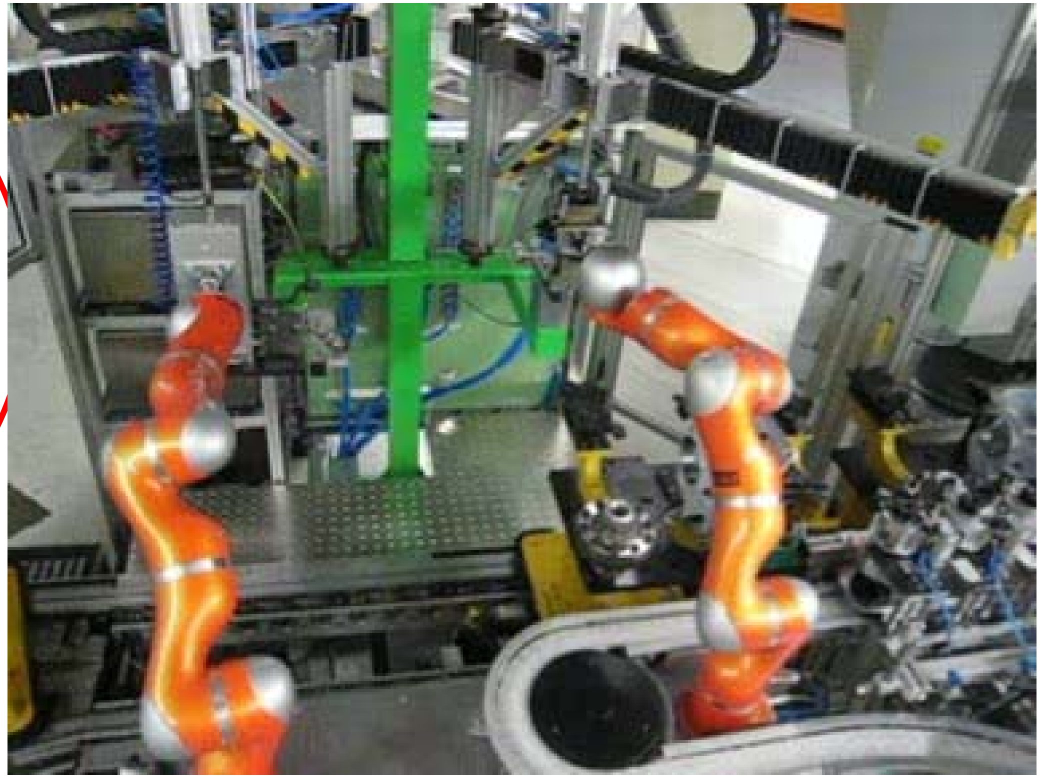


Mercedes-Benz

• Robot commercialized by KUKA since 2008
• Fast, open research software interface (FRI)
Available since 2010

Gearbox Assembly at Daimler





Special Gripper from earlier solutions

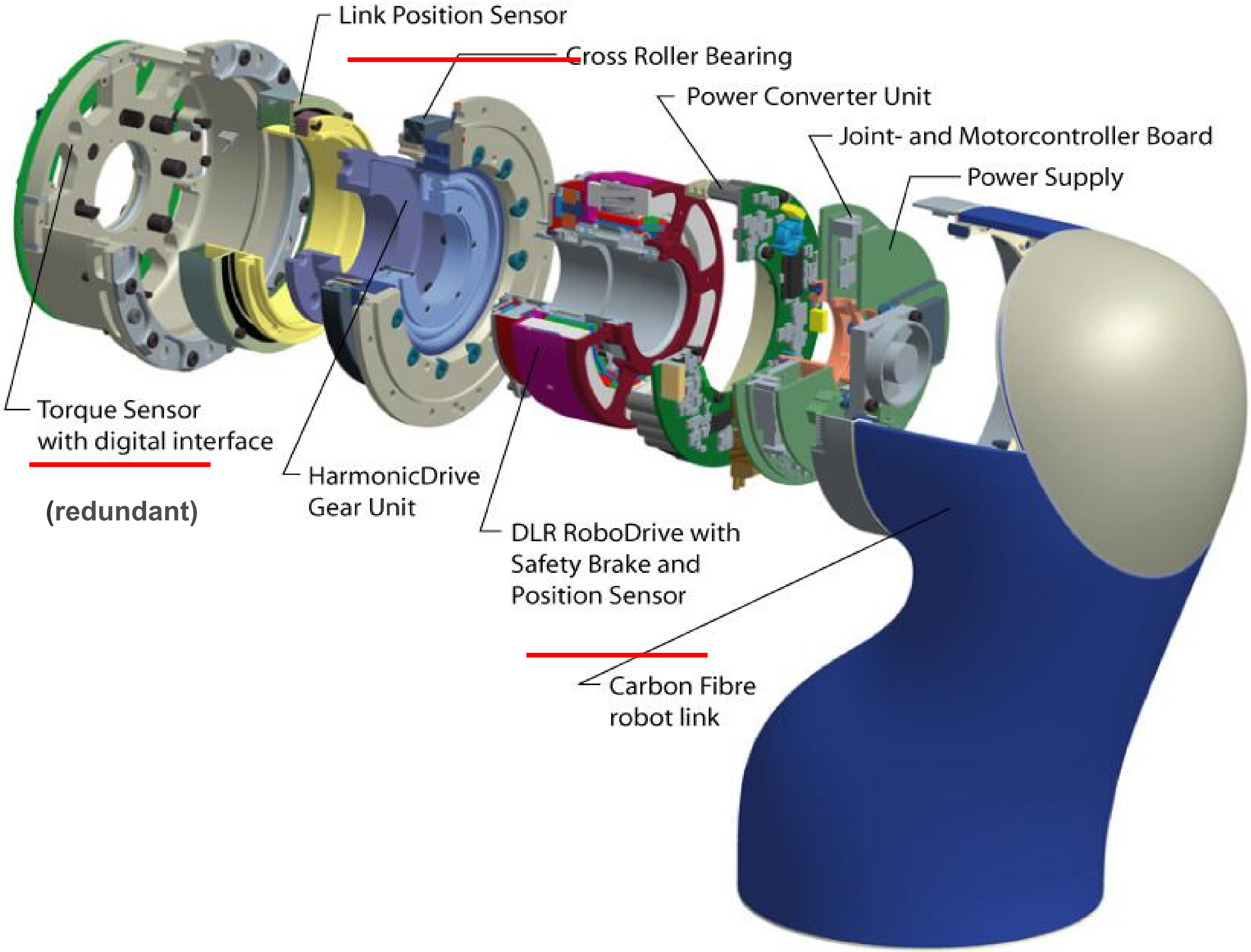
- Production started 2009   24/7 Application with the LWR
- More than 50000 gearbox units in Mercedes cars
- Production without fences. Humans interact with the robot

Modularity and light-weight allows the construction of complex kinematics using the arm joints

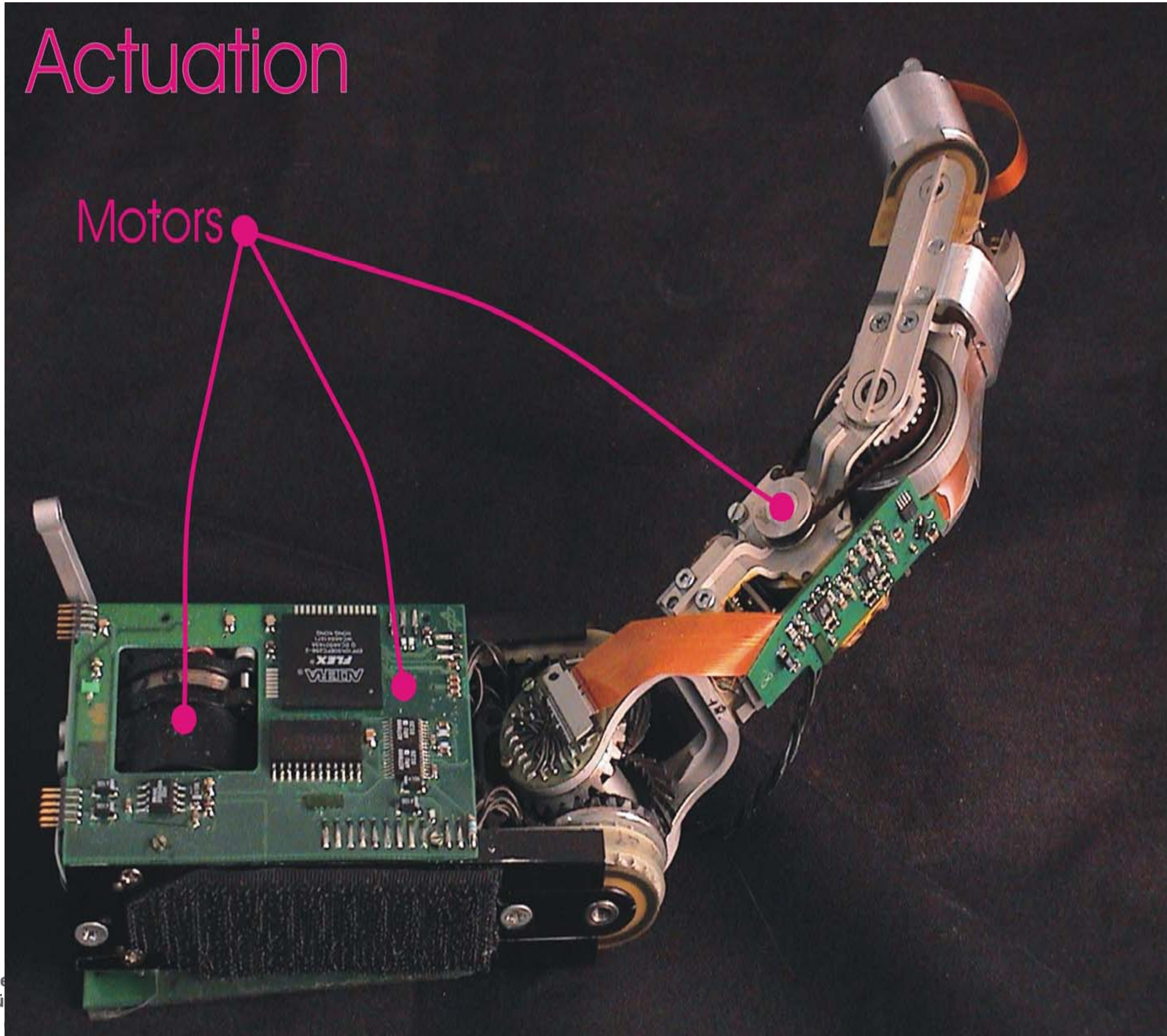
DLR crawler **DLR walker**

[Ott & al. Humanoids 2010, 2011]

Mechatronic Joint Design



(redundant)

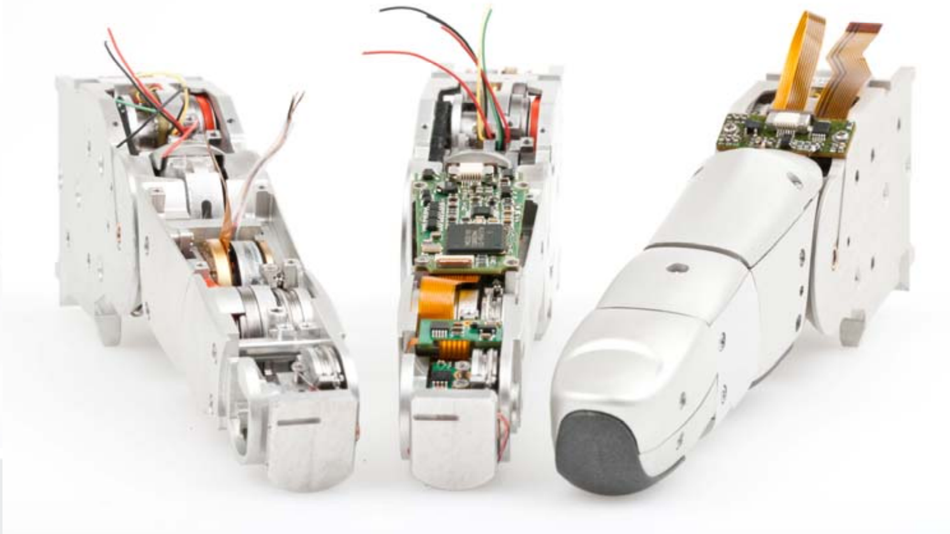

Actuation
Motors

The DLR-HIT-hands on the way to commercialization

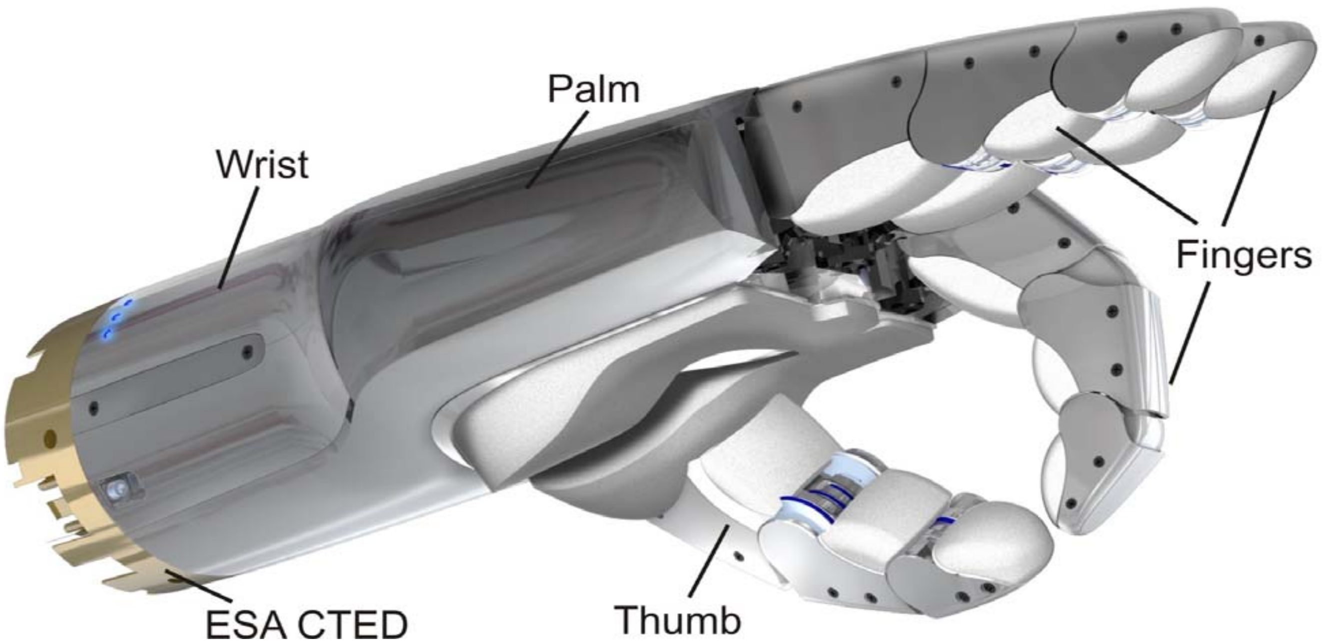
Hand I with four fingers,12 actuators

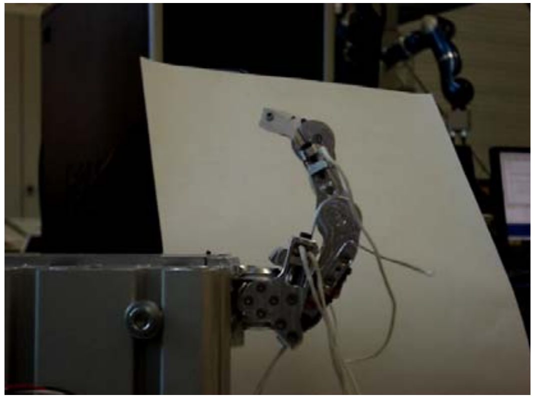
- tooth belt drives
- 1kg finger tip force
- torque control

Hand II with five fingers ,15 actuators



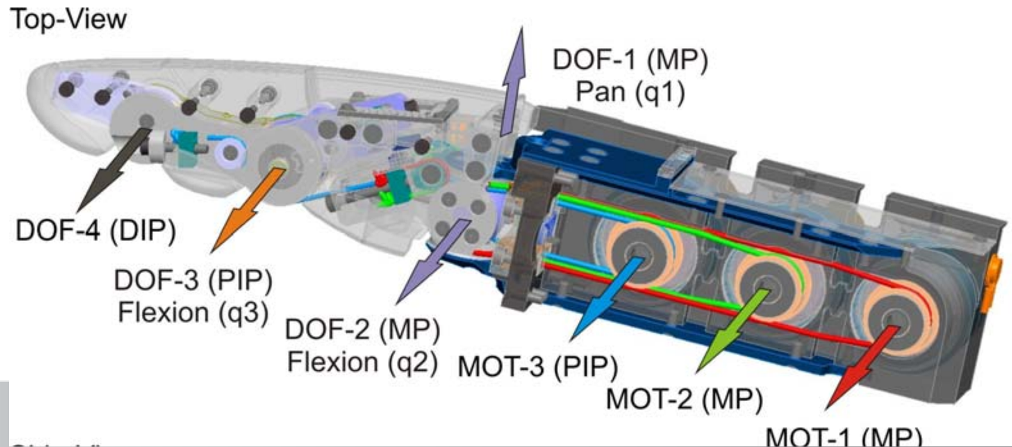
DEXHAND –Europe‘s first Robonaut hand





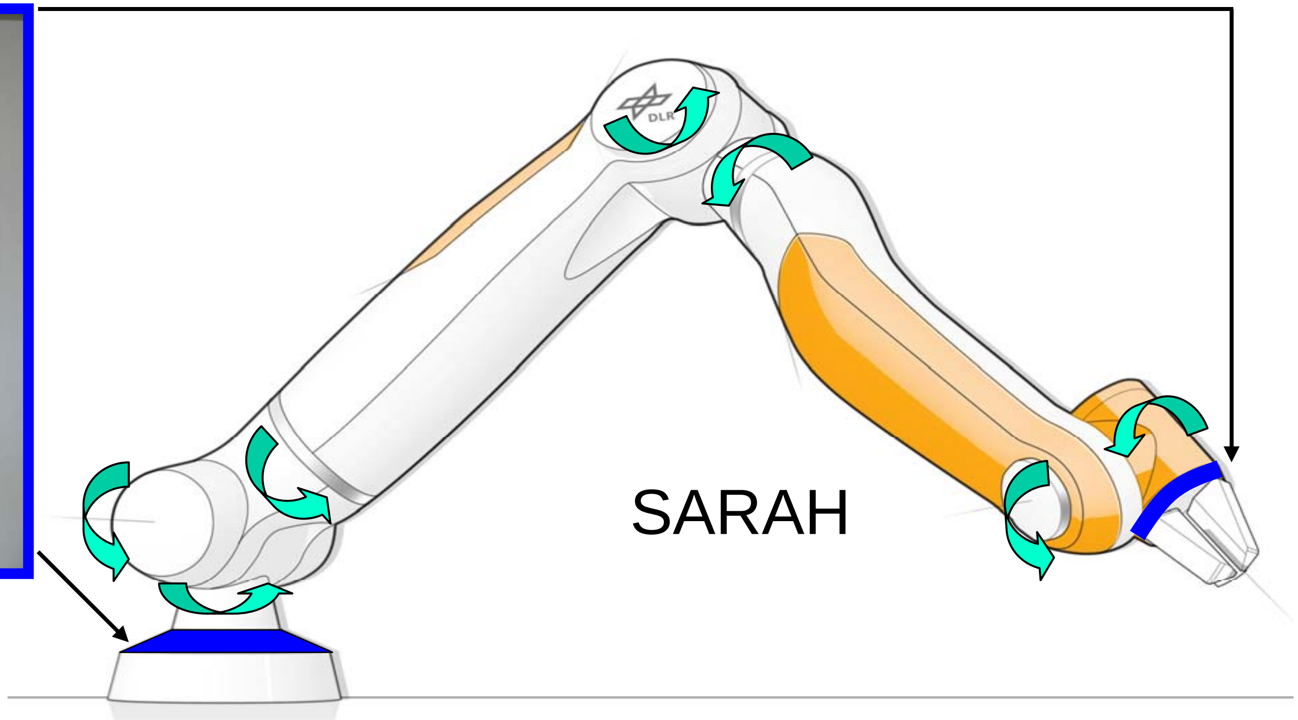
25 N test

- Tendon driven, 12 active dof
- Less than 3.3 kg
- Finger length 93 mm (Thumb 100 mm),
- DEXHAND length 340 mm
- 25 N Fingertip force (Thumb 40 N) – streched out



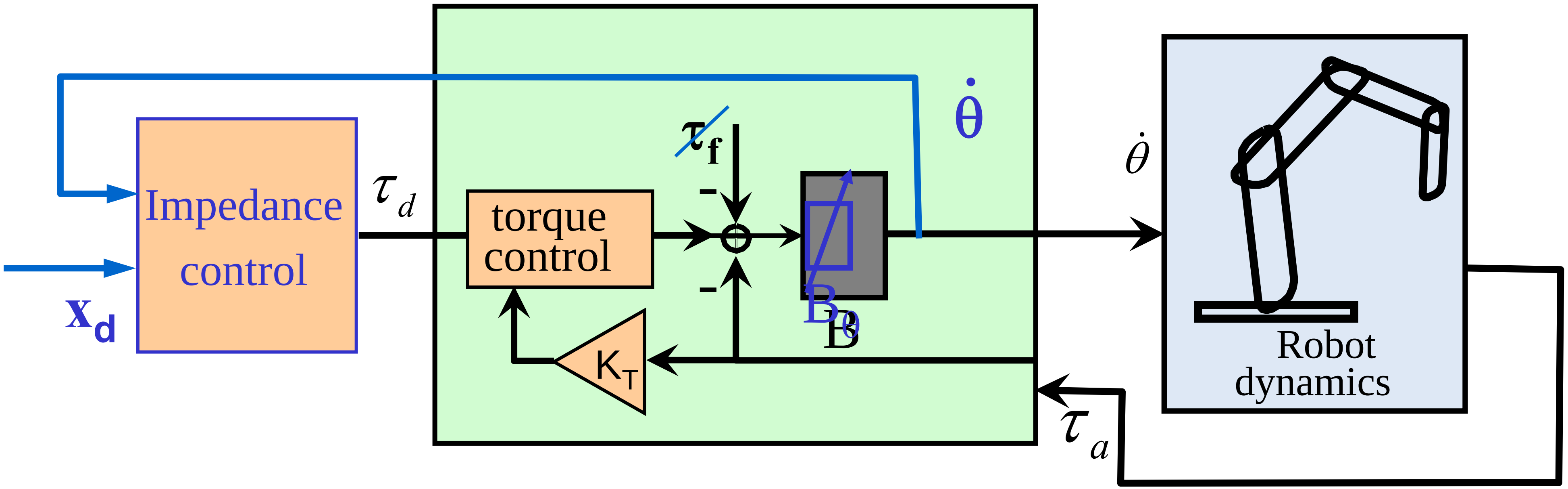
New light-weight robot with
f/t sensing in the joints and
at extremities

- Higher power and speed



Cartesian Impedance Control

Unified approach for torque, position and impedance control on Cartesian and joint level



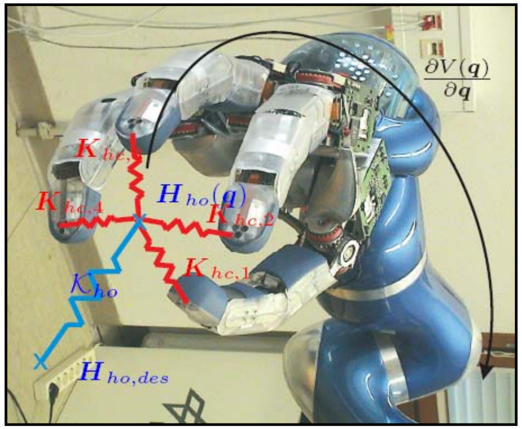
$$\tau_F \rightarrow (1+K_T)^{-1}\tau_F \qquad B \rightarrow B_\theta = (1+K_T)^{-1}B$$

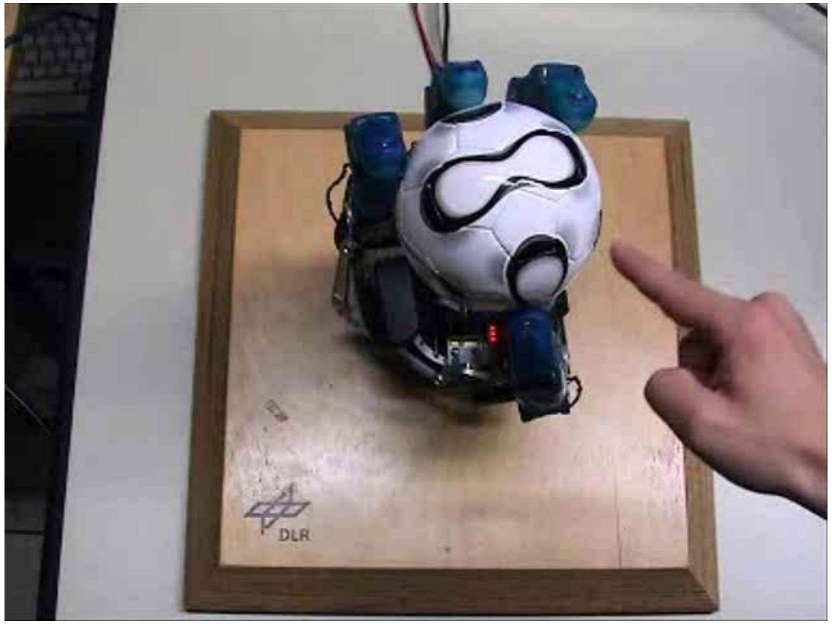
Passivity ⟶ Robustness in contact with the environment

[Albu-Schäffer & al, IJRR 2007]

DLR Hand II – Impedance Control

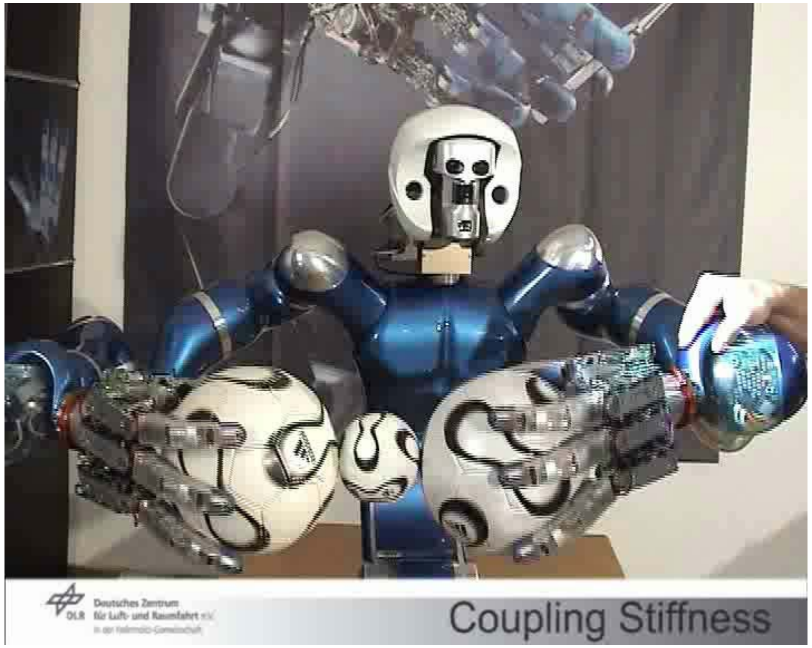
- Joint impedance Control
- Cartesian Impedance Control
- Object Impedance Control

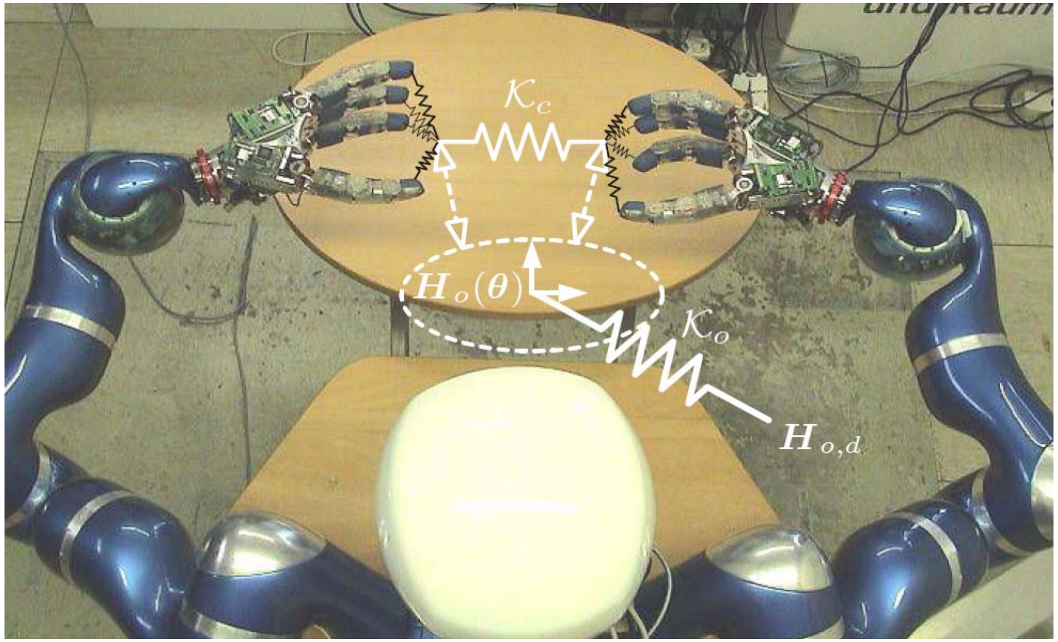




[Wimböck al. IJRR 2010]

Impedance Control for Two Handed Manipulation





$$\tau_d = \overline{g}(\theta) - \frac{\partial V(\theta)}{\partial \theta} - D(\theta)\dot{\theta}$$

Gravity compensation

Stiffness term

Damping term

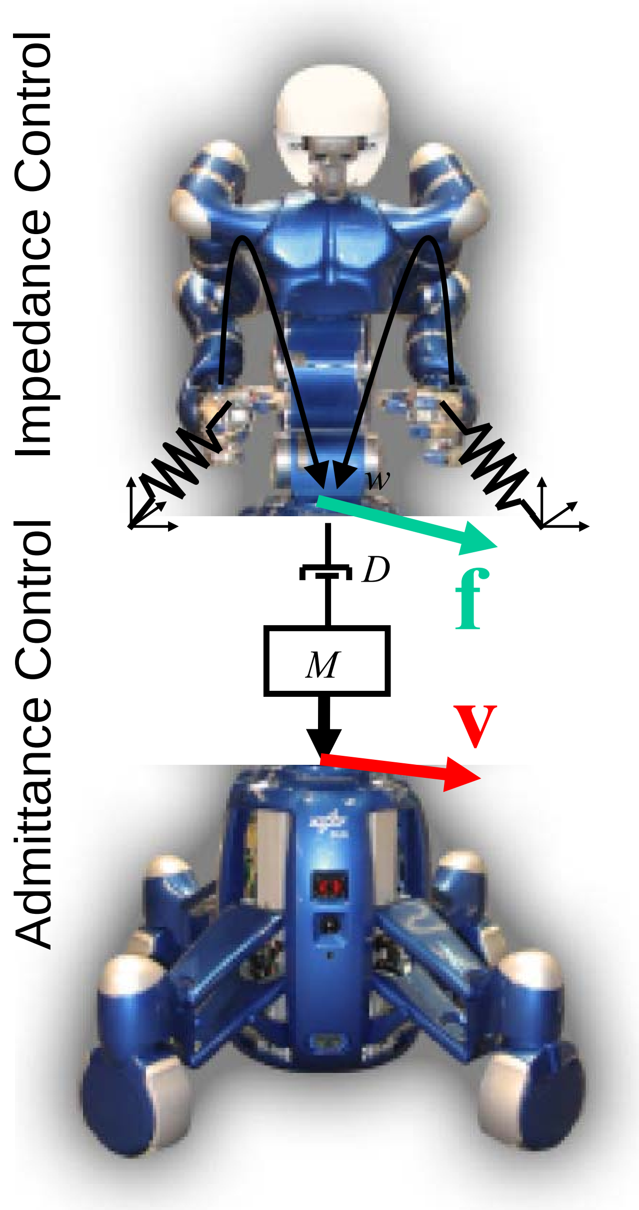
1ms control cycle for the whole system

Human-Robot-Interaction

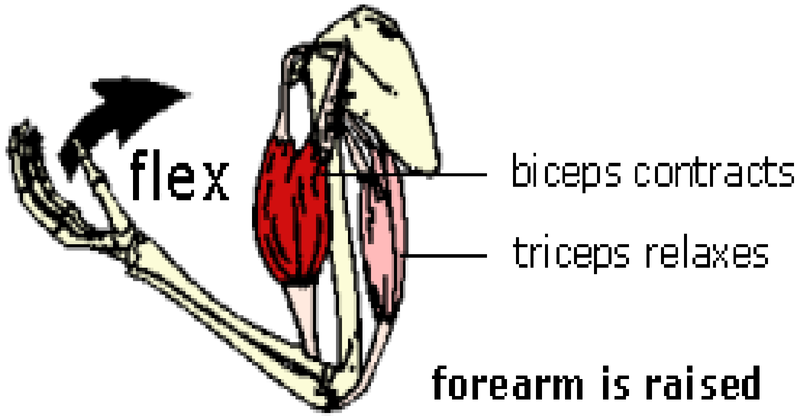
Compliant Control of the entire Robot

Rollin' Justin

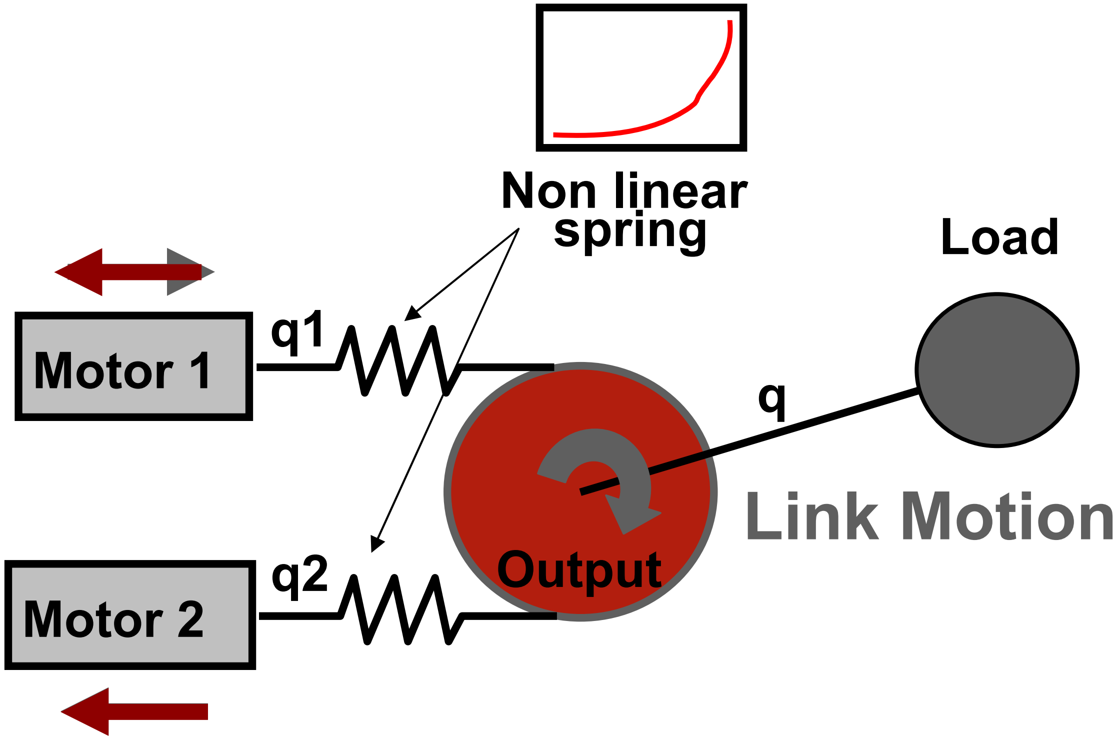
- 53 active dof
- 150 kg



Current Research Plattform based on Variable Compliance Actuation (VIA)



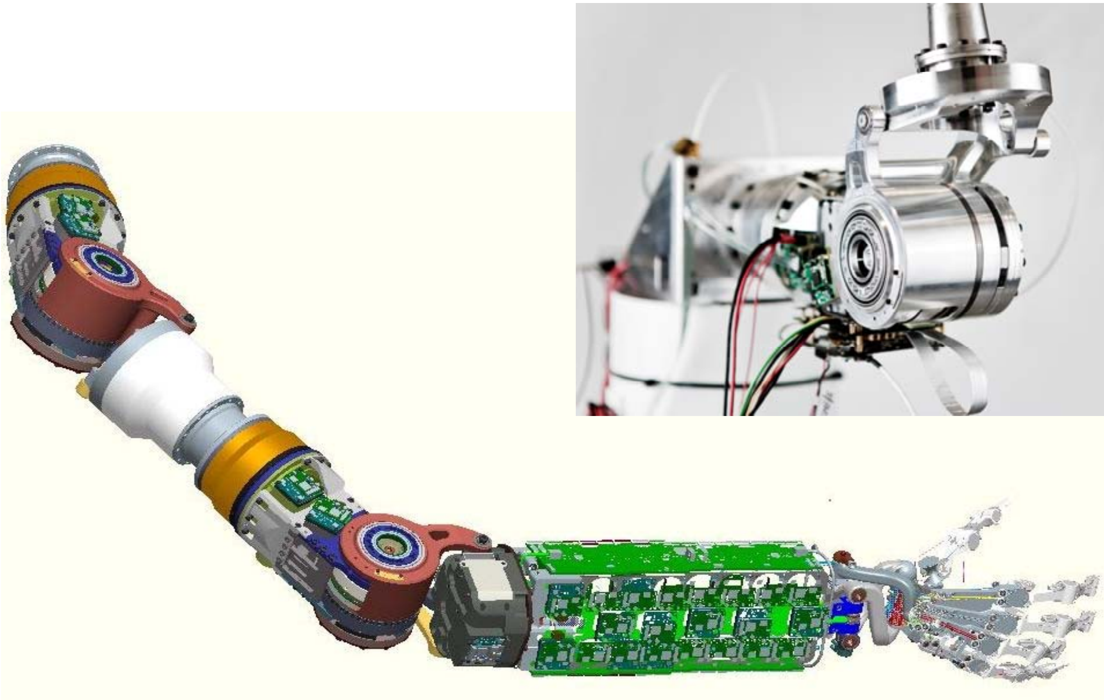
The antagonistic concept

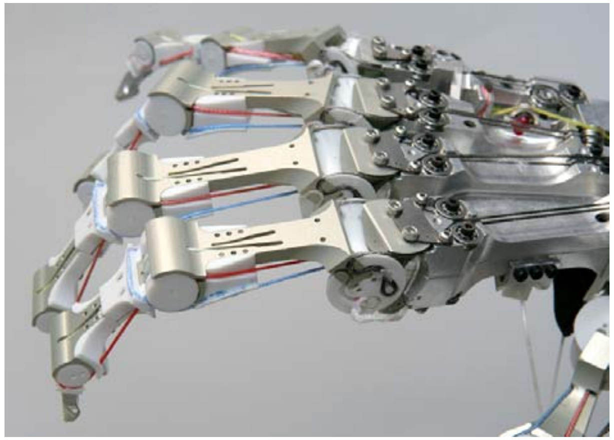


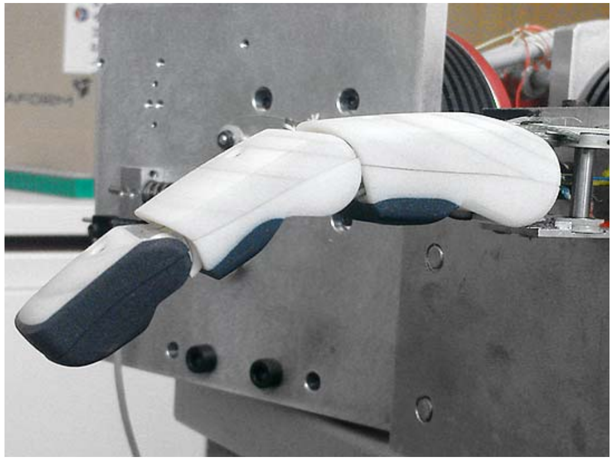
Stiffness adjustment

Anthropomorphic Hand-Arm-System

- Size, force and dynamics of a human arm/hand
- Variable stiffness
- *52 motors,111 position sensors*

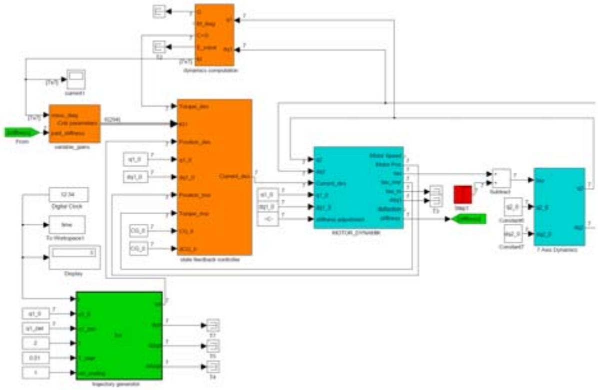


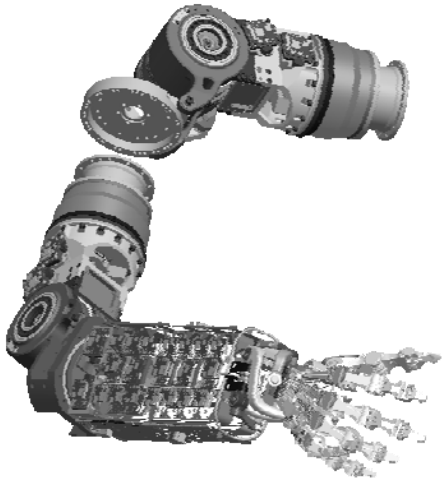


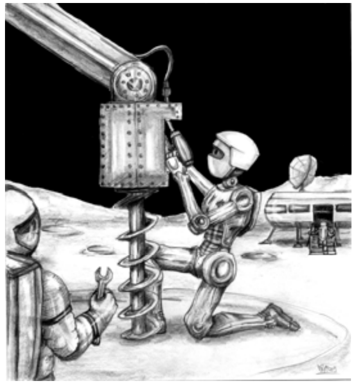


No torque sensing:
torque observed from positions

A Hand-Arm System for Space Robot Assistrance



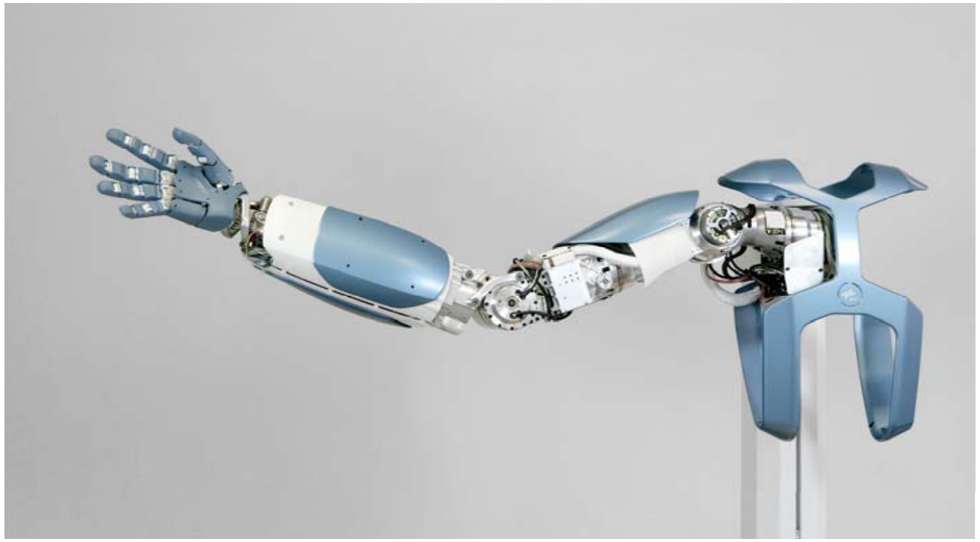


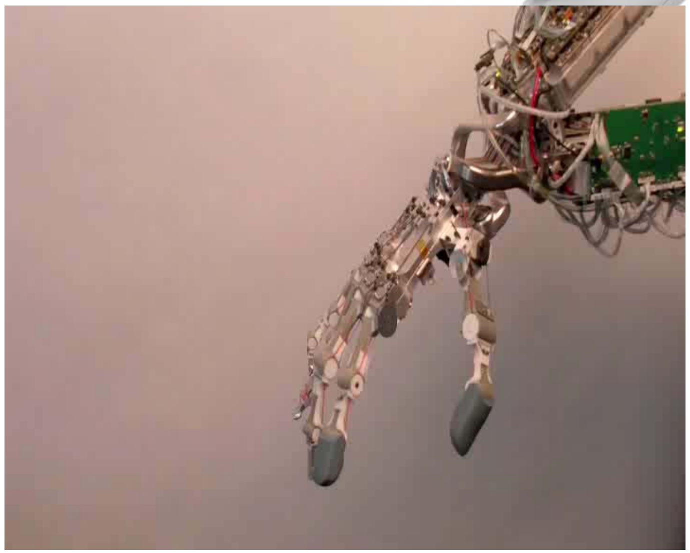


Extension of the passivity based control approaches to the VIA robots:

- Variable, nonlinear stiffness
- Strongly coupled joints

The new integrated hand-arm-system (with variable impedance actuation VIA)



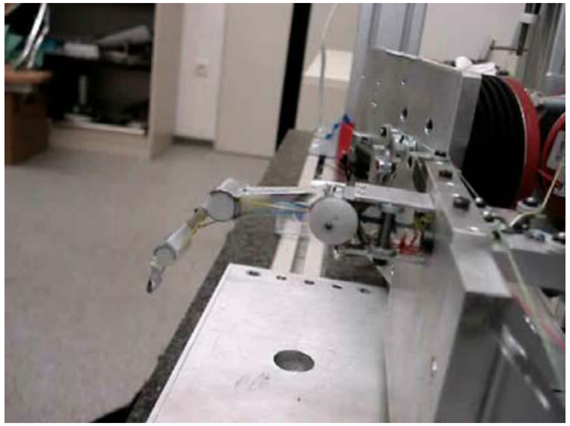


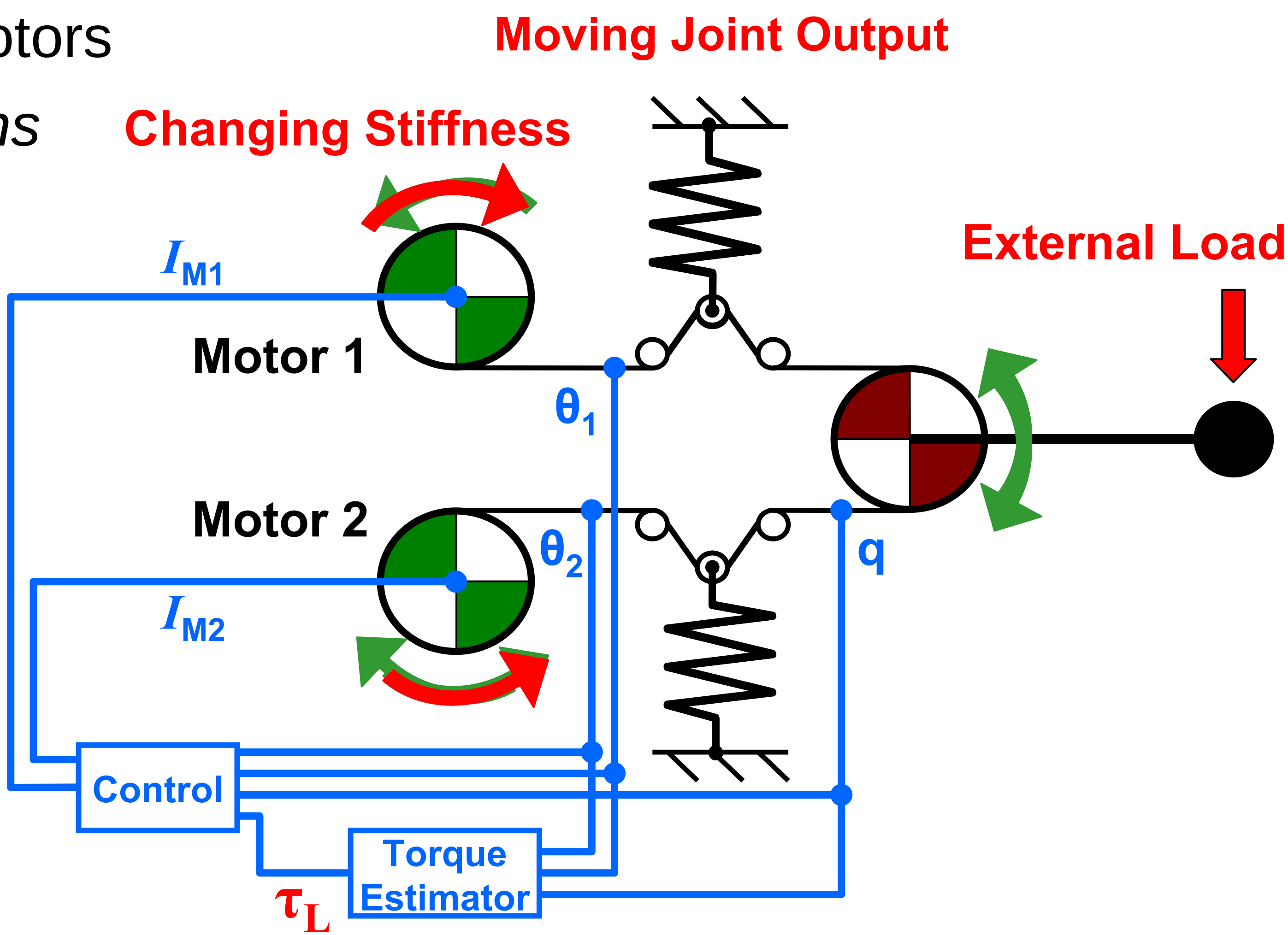
Grebenstein & al. Humanoids 2010]

VIA – Variable Impedance Actuators 1

Antagonistic Actuator (fingers)

- 2 equally sized motors
- *motors pull tendons*

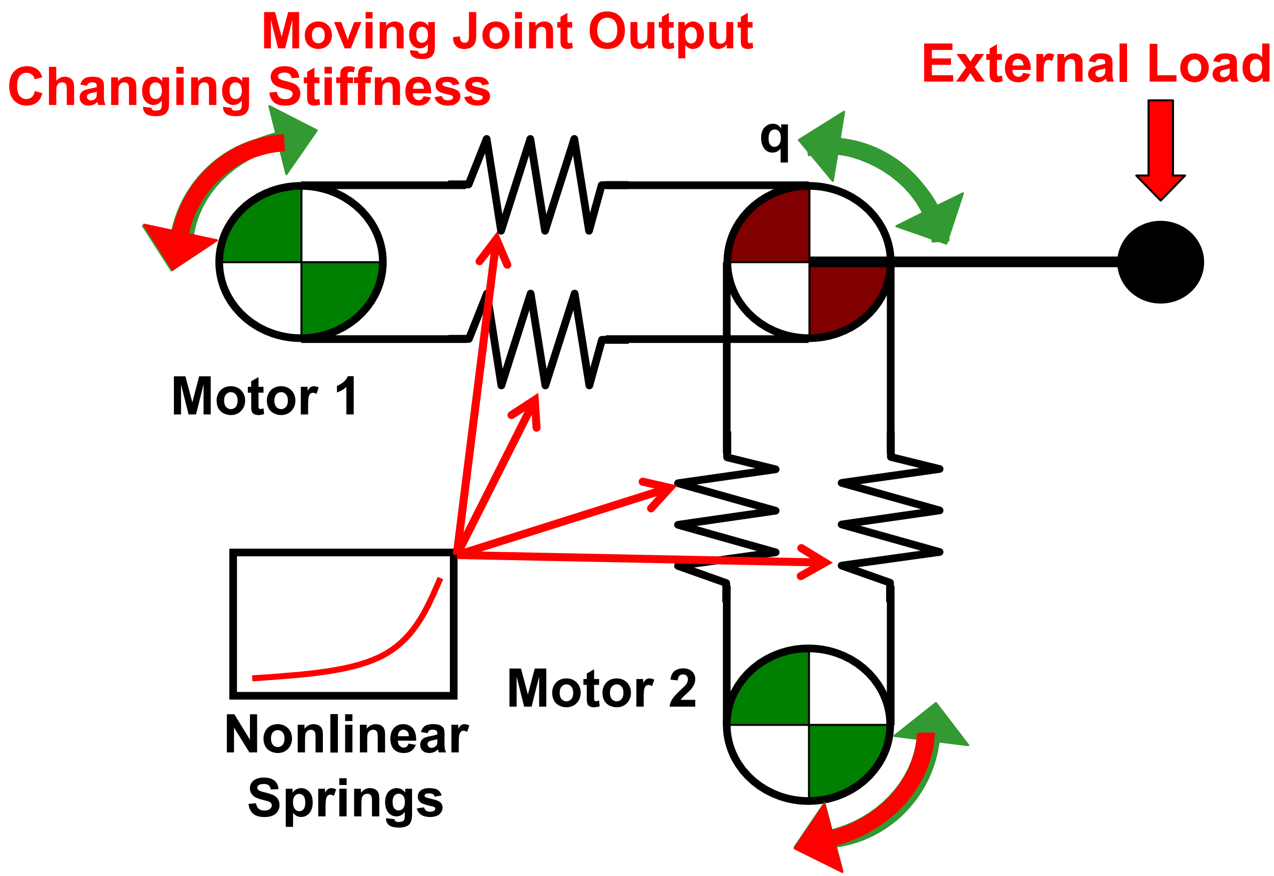




VIA – Variable Impedance Actuators 2

Bidirectional Antagonistic Actuator (underarm rotation and wrist)

- 2 equally sized motors
- *both motors push and pull (bidirectional)*

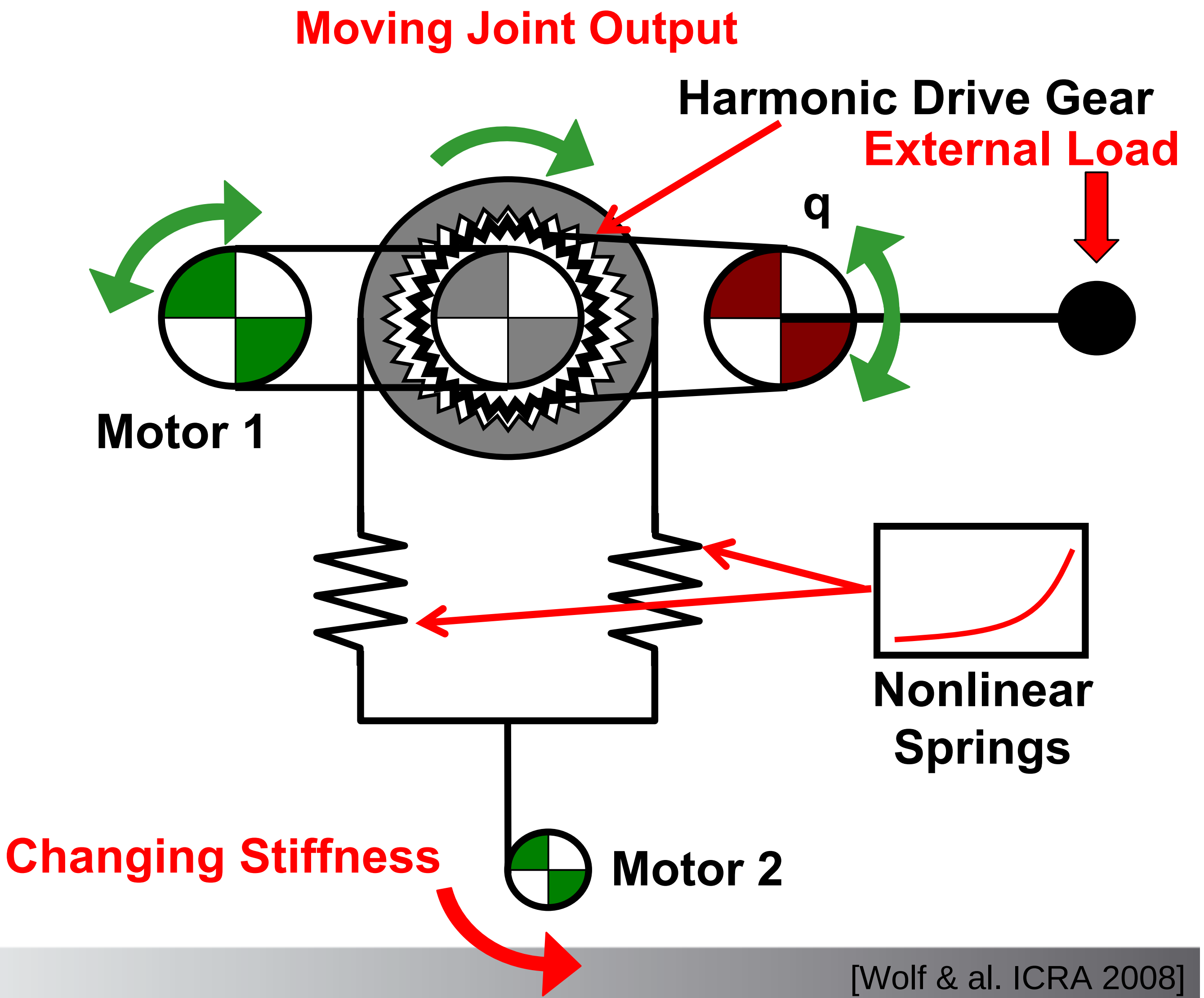


[Petit & al. ICRA 2010]

VIA – Variable Impedance Actuators 3

Adjustable Stiffness Actuator (upper arm)

- one big motor1 moves the joint
- *one small motor2 changes joint stiffness*
- ***without motor2 we have a serial elastic joint***

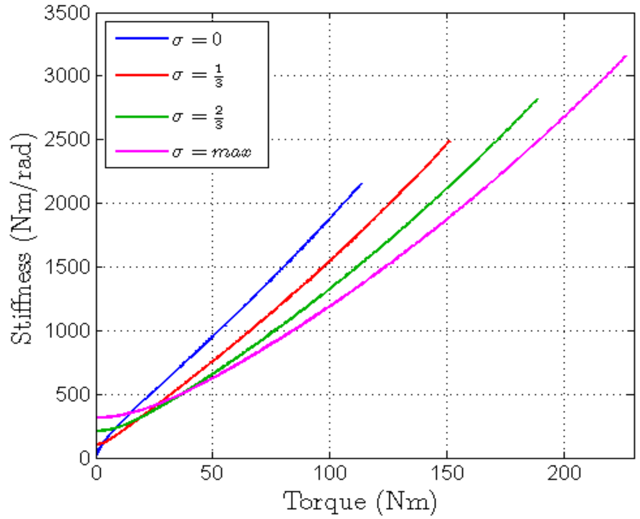


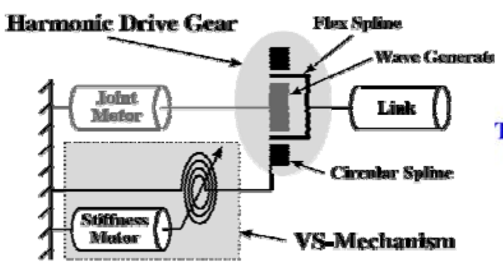
[Wolf & al. ICRA 2008]

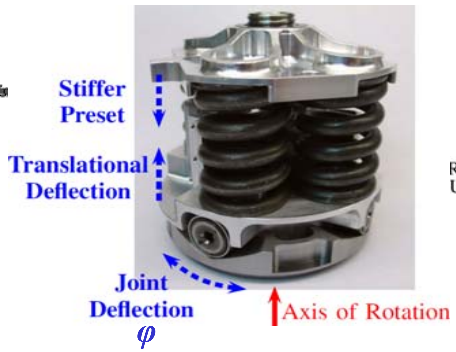
Joint Data Sheet: DLR VS-Joint

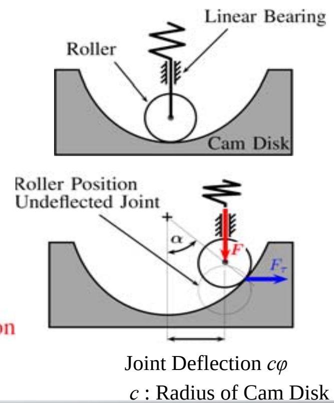
VIACTORS

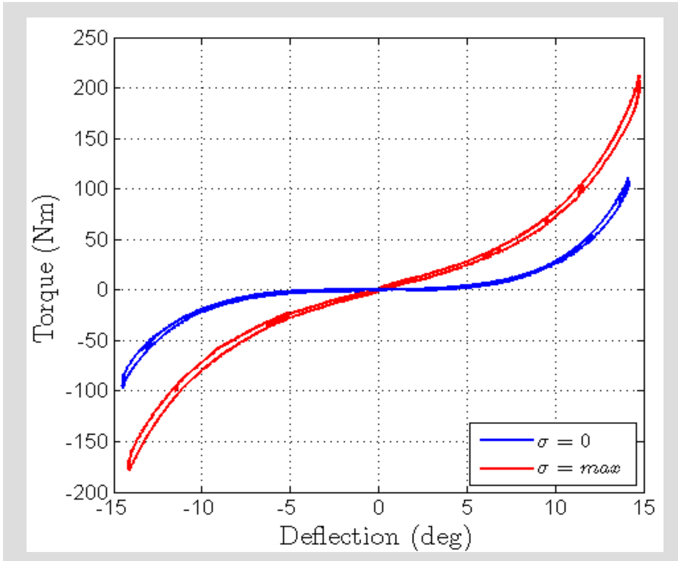
Actuator Type	Variable Stiffness
Maximum Joint Torque (repeatable, evaluated by measurement)	± 180 Nm
Min./Max. Stiffness (no external load)	0 / 315 Nm/rad
Max. Storable Energy	16.8 J
Max. Equilibrium Velocity	217°/s
Nominal Power (not max./peak!)	270 + 50 = 320 W
Min. Stiffness Adjusting Time (from 3% to 97% stiffness)	0.2 s
Torque Hysteresis at Max. Torque	7.3%
Weight (w/wo Motors)	1.4 / ~ 2.0 kg
Size (w/wo Motors)	Ø97x106 / ~ Ø97x166 mm
Max. Deflection Range (min./max Stiff.)	± 14° / ± 14°





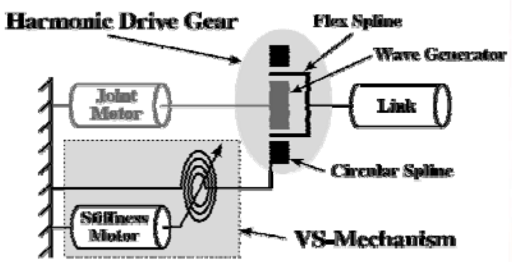


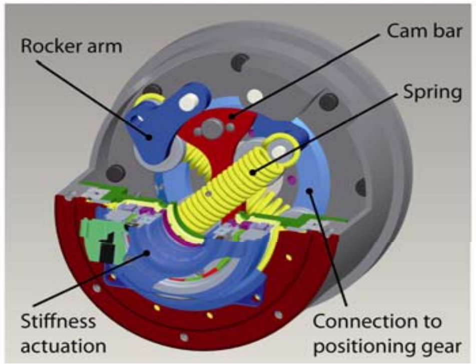




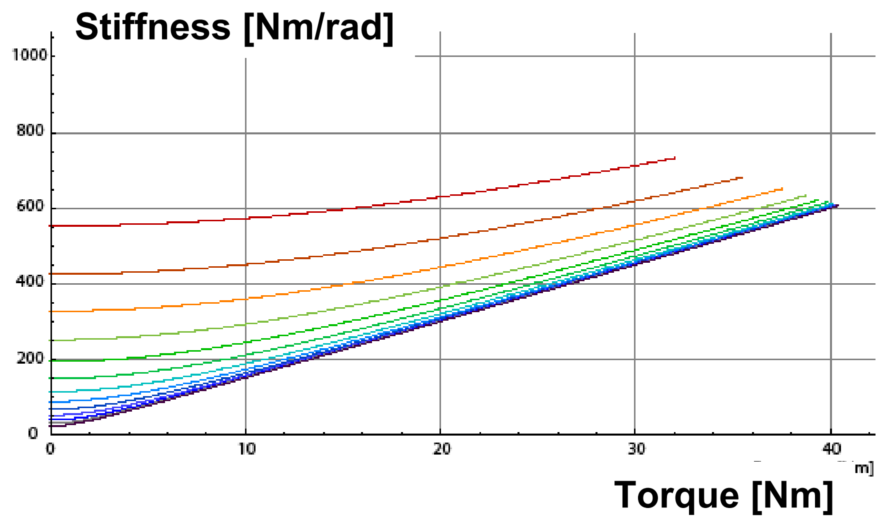
Joint Data Sheet: DLR QA-Joint

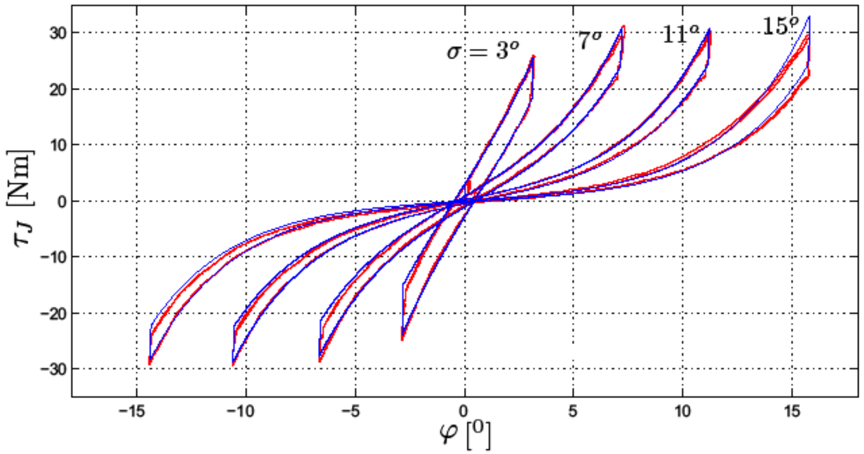
Actuator Type	Quasi Antagonistic
Maximum Joint Torque (repeatable, evaluated by measurement)	± 40 Nm
Min./Max. Stiffness (no external load)	20 / 550 Nm/rad
Max. Storable Energy	2.7 J
Max. Equilibrium Velocity	217°/s
Nominal Power (not max./peak!)	270 + 50 = 320 W
Min. Stiffness Adjusting Time (from 3% to 97% stiffness)	0.15 s
Torque Hysteresis at Max. Torque	+/-12.5%
Weight (w/wo Motors)	1.4 / ~ 2.0 kg
Size (w/wo Motors)	Ø90x100 / ~ Ø90x160 mm
Max. Deflection Range (min./max Stiff.)	± 15° / ± 3°





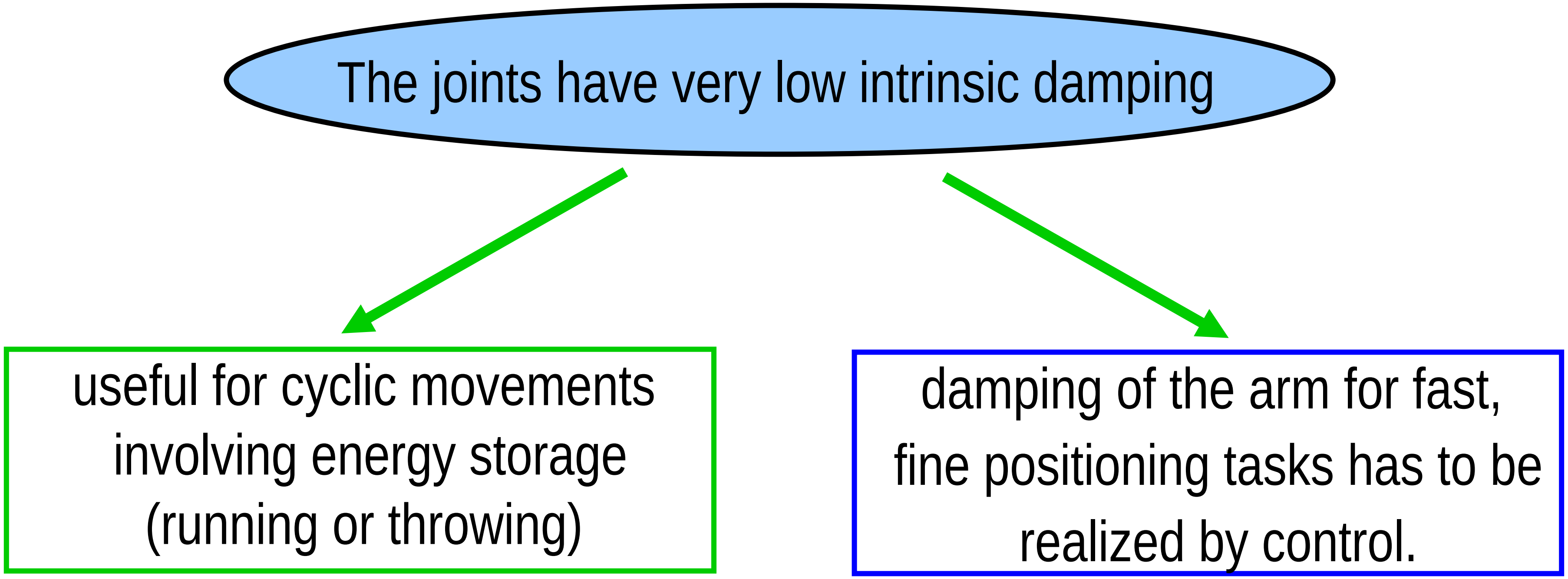
Stiffness over ext. torque, preset + / - 3° to +/-15°





Validation of Arm Robustness

Control of VIA Joints



- Ensuring the achievement of the desired link position with motor position based control.
- Providing the desired stiffness property.

General Model

For all considered actuator types so far, following model structure holds

$$\boldsymbol{M}(\boldsymbol{x})\ddot{\boldsymbol{x}} + \boldsymbol{c}(\boldsymbol{x}, \dot{\boldsymbol{x}}) + \frac{\partial V(x)}{\partial x} = \begin{bmatrix} \tau_1 \\ \tau_2 \\ \tau_{\mathrm{ext}} \end{bmatrix}$$

τ_{ext} ← External disturbance torque

Main properties:

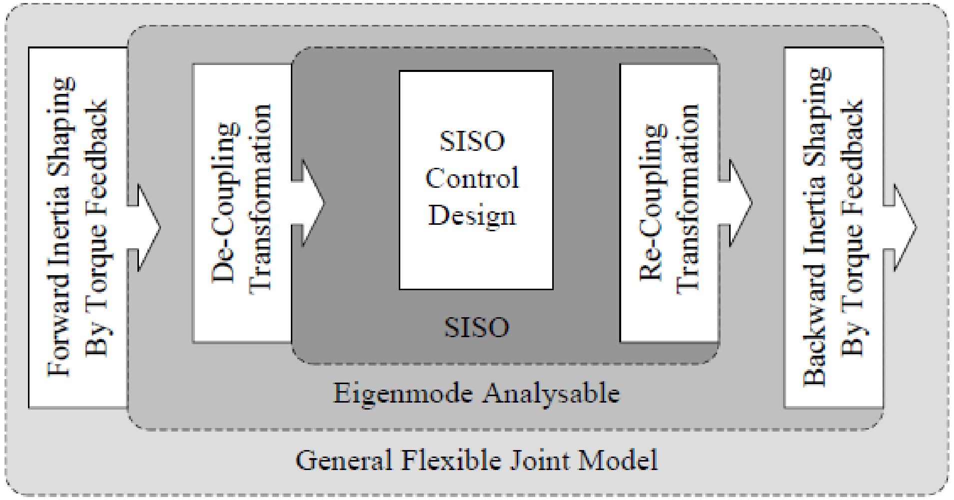
- **under-actuation**: less control inputs (τ_1, τ_2) than dimension of configuration space
- positive definiteness of $V(x)$

We propose this generic model for controller design of VIA joints

Flexible joint model is a particular case

[Albu-Schäffer at ICRA 2010]

Decoupling in Modal Coordinates



back to link coordinates

$$\begin{cases} K_P = Q K_{PQ} Q^T \\ K_D = Q\ K_{DQ} Q^T \\ K_T = Q\ K_{TQ} Q^T \\ K_S = Q\ K_{SQ} Q^T \end{cases}$$

symmetric,
nondiagonal
p.d

state feedback controller in link coordinates.

$$u = K_P \tilde{\theta}\ - K_D \dot{\theta} - K_T K^{-1} \tau - K_S K^{-1} \dot{\tau}$$

[Petit at ICRA 2010]

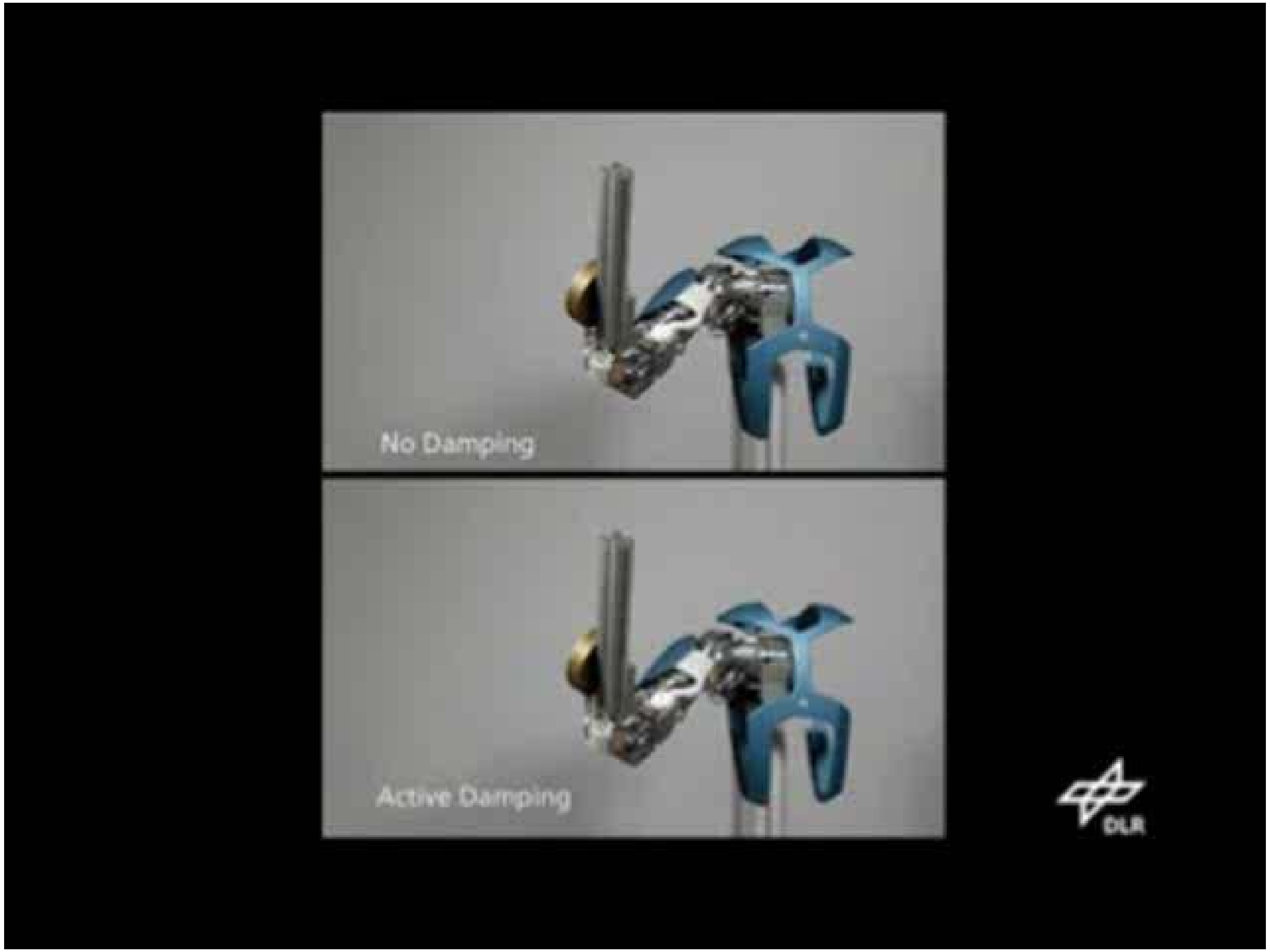
Experimental Validation

Point to Point trajectory

Vibration Damping OFF

Vibration ON

Experimental Validation



Cartesian Impedance Control

Implementation of a simple Cartesian impedance

$$\tau_m = g(q) - \frac{\partial V(q)}{\partial q} - D(q)\dot{q}$$

Potential: $V(q) = V_S(H(q), H_d, \kappa_d)$

Damping design:

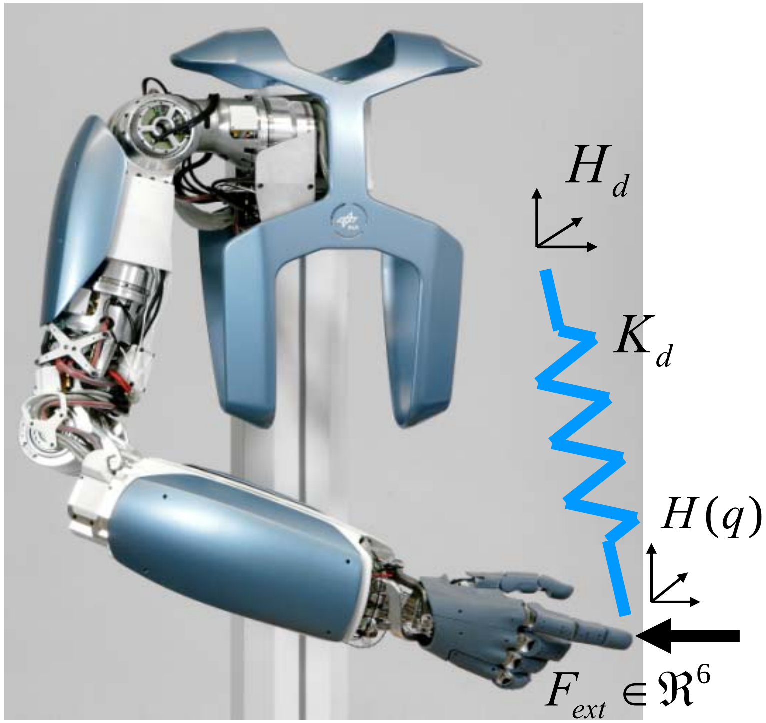
Double diagonalization of the inertia matrix
and the Hessian of the potential function.

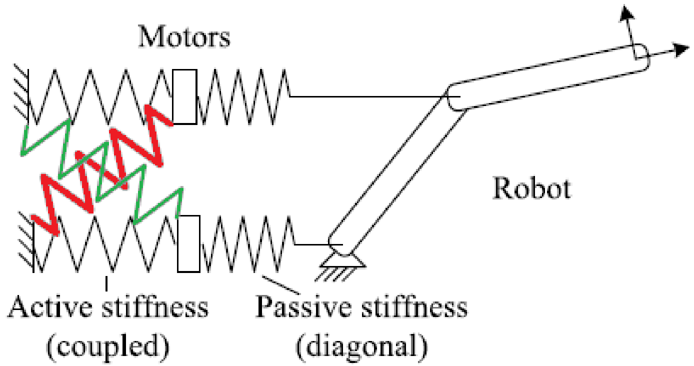
Extension for variable stiffness joints

Combine active and passive impedance

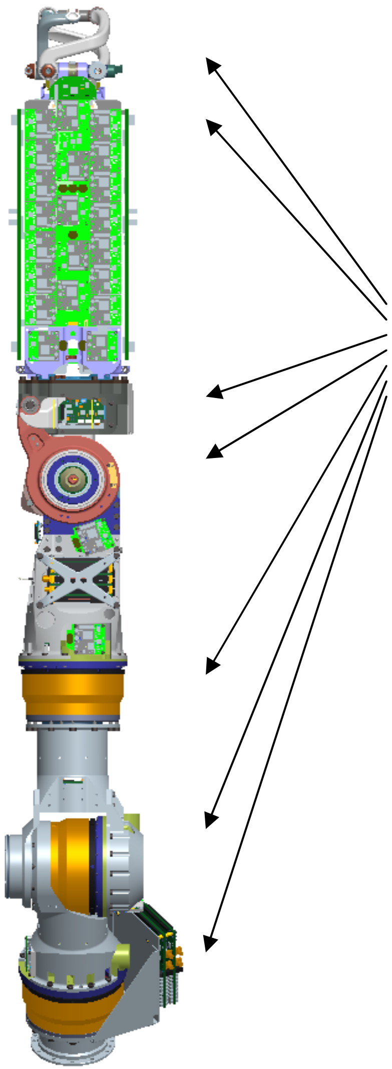
$$\boldsymbol{K_s^{-1}} = \boldsymbol{K_a^{-1}} + \boldsymbol{K_a^{-1}}$$

[Petit at IROS11]





Passive Joint Elasticities & Cartesian Stiffness



generate $\mathbf{K}_C$ by passive joint stiffness

- diagonal

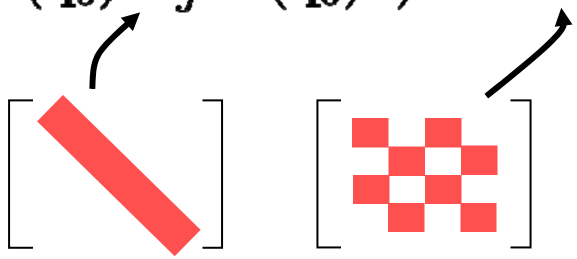
$$\mathbf{K}_{Jp} = \mathrm{diag}(\mathbf{k}_{Jp}) \in \Re^{n \times n}$$

- bounded

$$\mathbf{k}_{Jp}^{\min} < \mathbf{k}_{Jp} < \mathbf{k}_{Jp}^{\max}$$

- Cartesian transformation

$$(\mathbf{J}(\mathbf{q}_0)\,\mathbf{K}_J^{-1}\,\mathbf{J}(\mathbf{q}_0)^T)^{-1} = \mathbf{K}_C$$

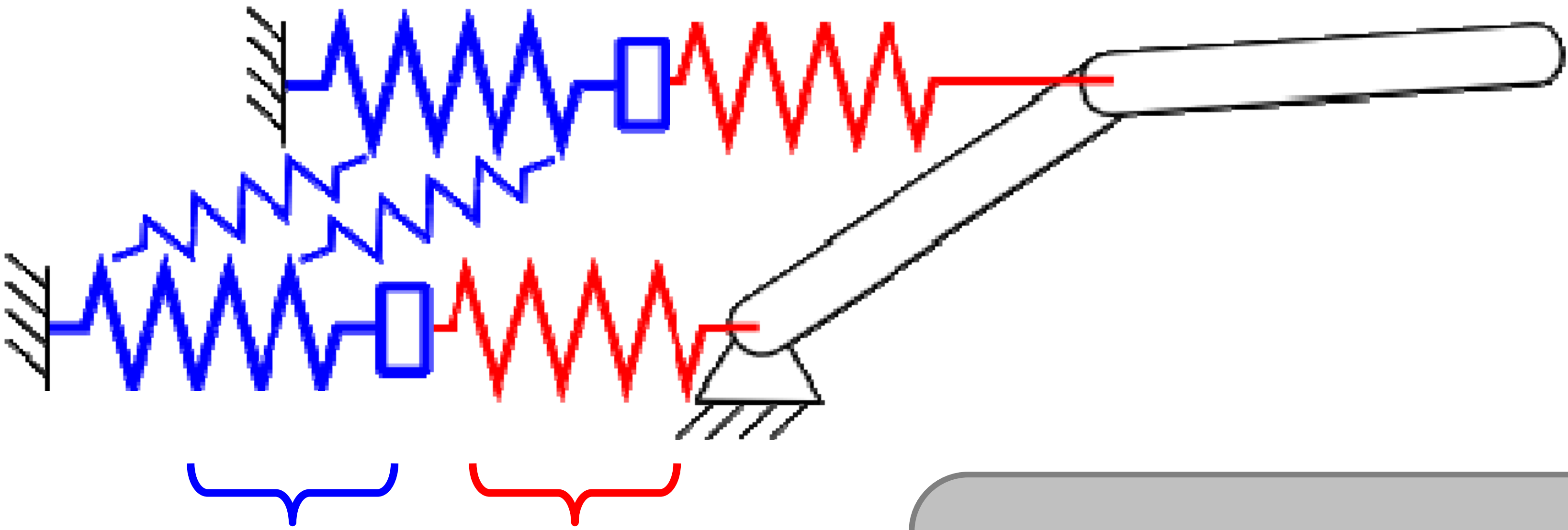


[Albu-Schäffer et al. 03]

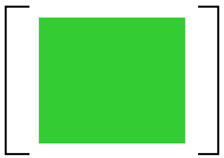
- severe limitation of achievable Cartesian stiffness

error: 25-55%

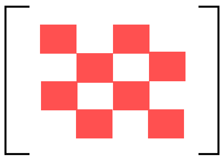
Combining Active & Passive Impedances



active impedance controller



passive joint stiffness



best of both worlds:

- overcome limitations of passive stiffness
- get VSA features

1. Step: Passive Compliance Optimization

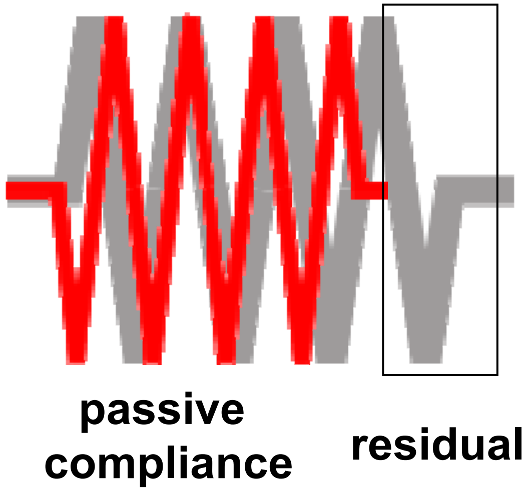
- achieve Cartesian compliance as good as possible by passive compliance

- least-squares problem

$$\min_{\mathbf{c}_{Jp}} \quad \|\mathbf{A} \cdot \mathbf{c}_{Jp} - \mathbf{b}\|_2^G$$

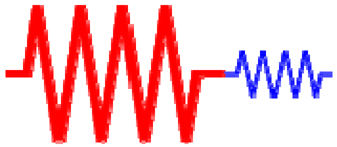
$$\text{subject to} \quad \mathbf{c}_{Jp}^{\min} < \mathbf{c}_{Jp} < \mathbf{c}_{Jp}^{\max}$$

- solution by active-set algorithm
- efficient (pseudo inverse)
- fast (366Hz for 4 joints)



2. Step: Active Compliance Optimization

- remove residual by active compliance



$$\mathbf{C}_d = \mathbf{C}_s = \mathbf{C}_p + \mathbf{C}_a$$

$$\tau = -\mathbf{J}(\mathbf{q}_0)^T \mathbf{C}_a^{-1}(\mathbf{x} - \mathbf{x}_d)$$

possibly negative definite ⇔ stability issues

- optimization formulation:

$$\min_{\mathbf{C}_a} \quad \|\mathbf{X} - \mathbf{C}_a\|_F$$
$$\text{subject to} \quad \mathbf{C}_a > 0$$

$\mathbf{X}$ .. goal matrix

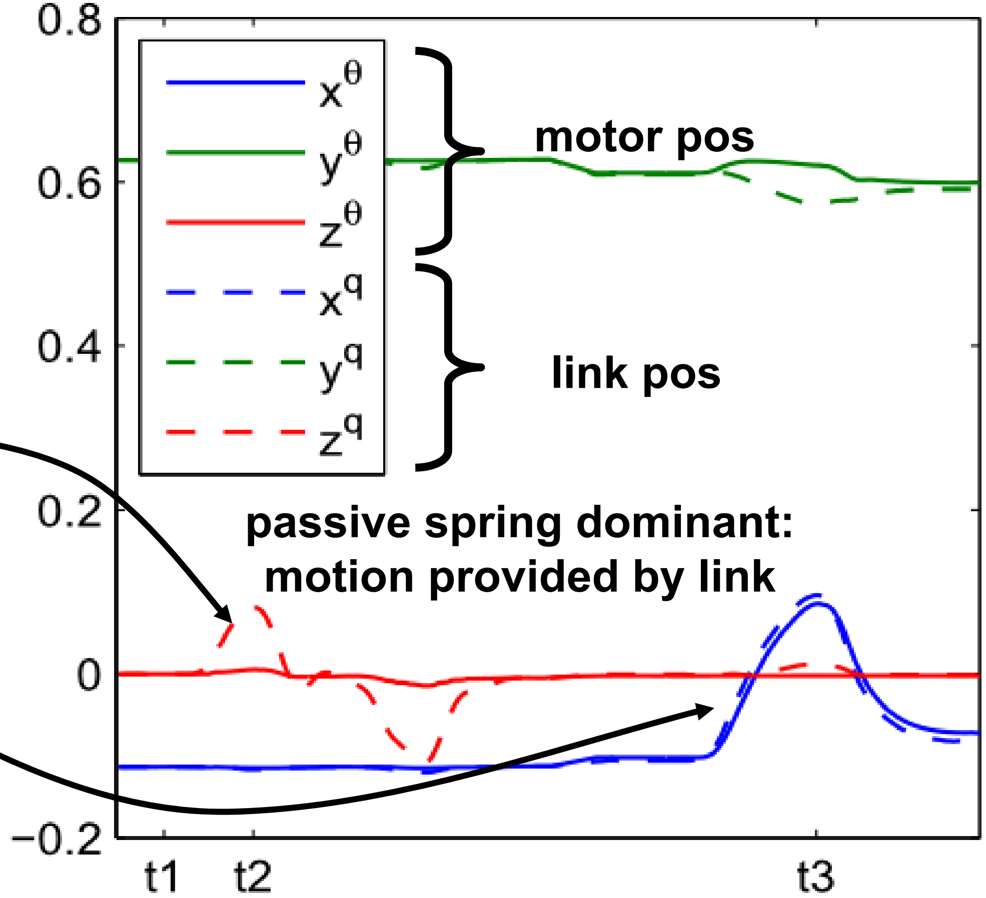
$\mathbf{C}_a$ .. positive definite

- solution by matrix nearness problem
- efficient (eigenvalue problem)

[Higham 98]

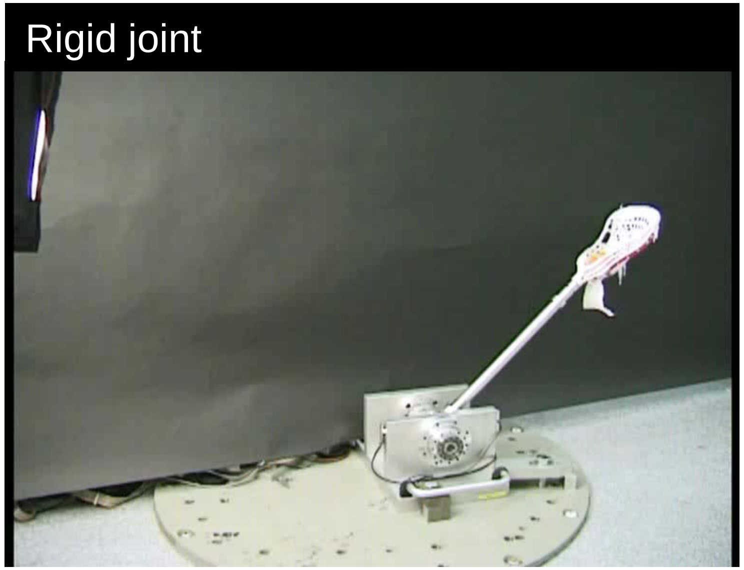
Results

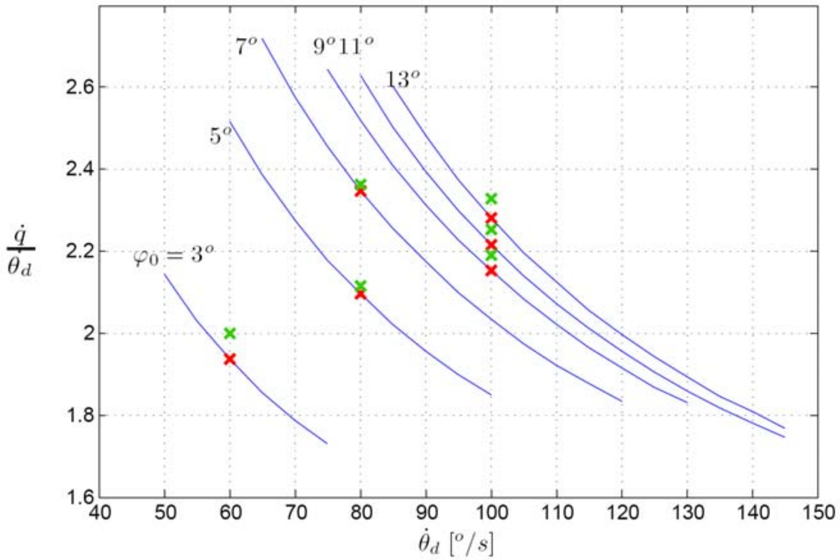
Direction	x
$\mathbf{K}_d$ (N/m)	100
$\mathbf{K}_p$ (N/m)	922
$\mathbf{K}_a$ (N/m)	116
$\mathbf{K}_s$ (N/m)	96



active spring dominant:
motion provided by motor

Performance Validation



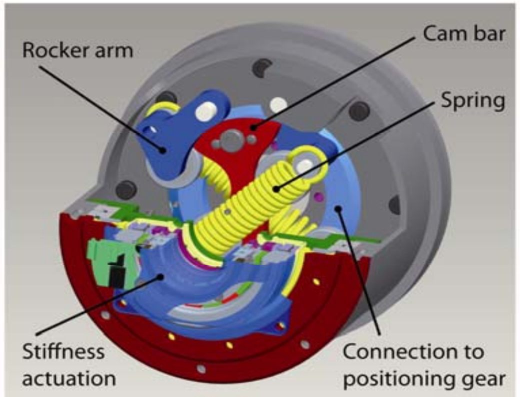


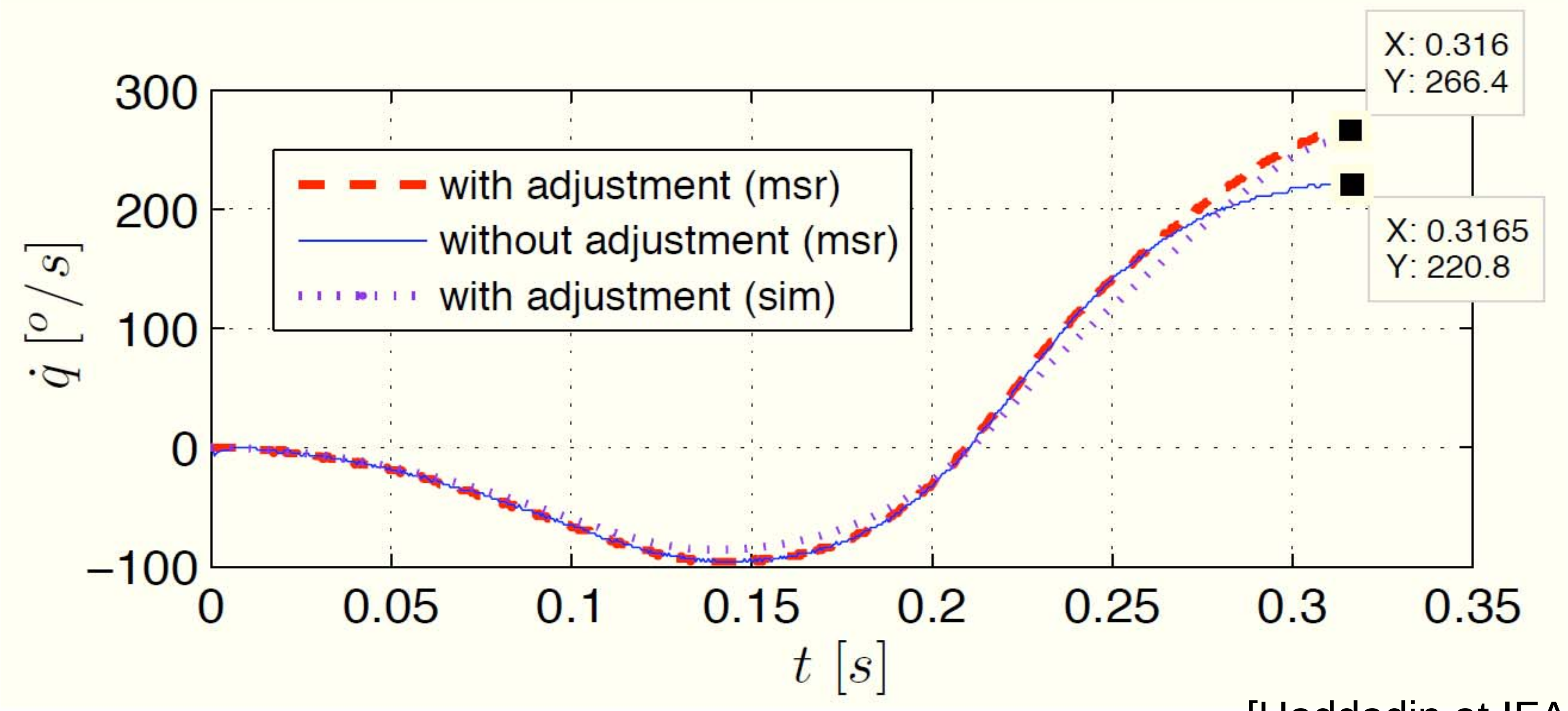
Optimal control for maximizing end velocity.

- Analytical solutions for 1dof, linear case
- Extension to nonlinear case with dynamic constraints

Constant vs. Variable Stiffness

Increase in velocity for the QA joint



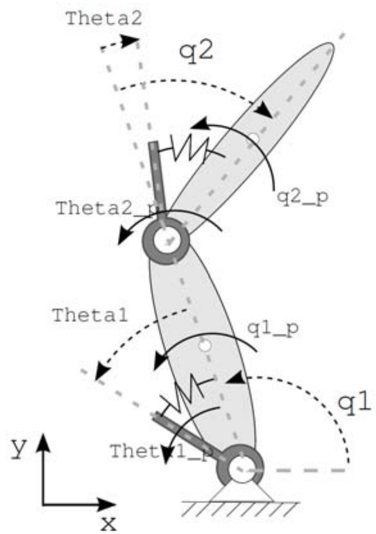


[Haddadin at IFAC 2011]

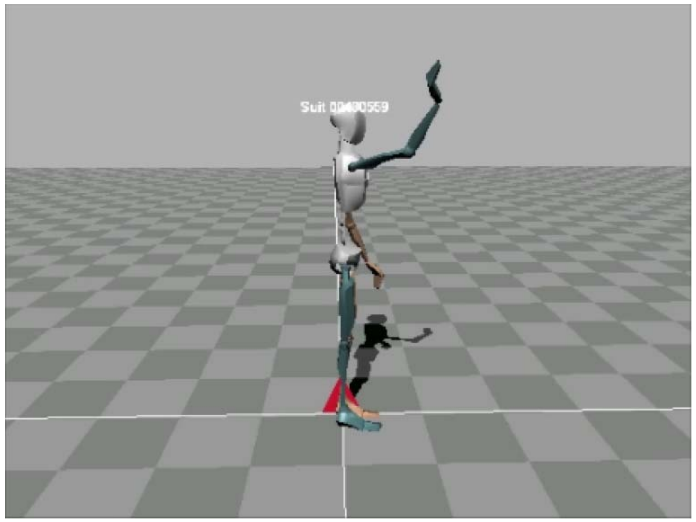
Performance Validation for multi dof

2 dof system

ball throwing



Evaluation of human-inspired throwing motion generation



Performance Demonstration with the Hand

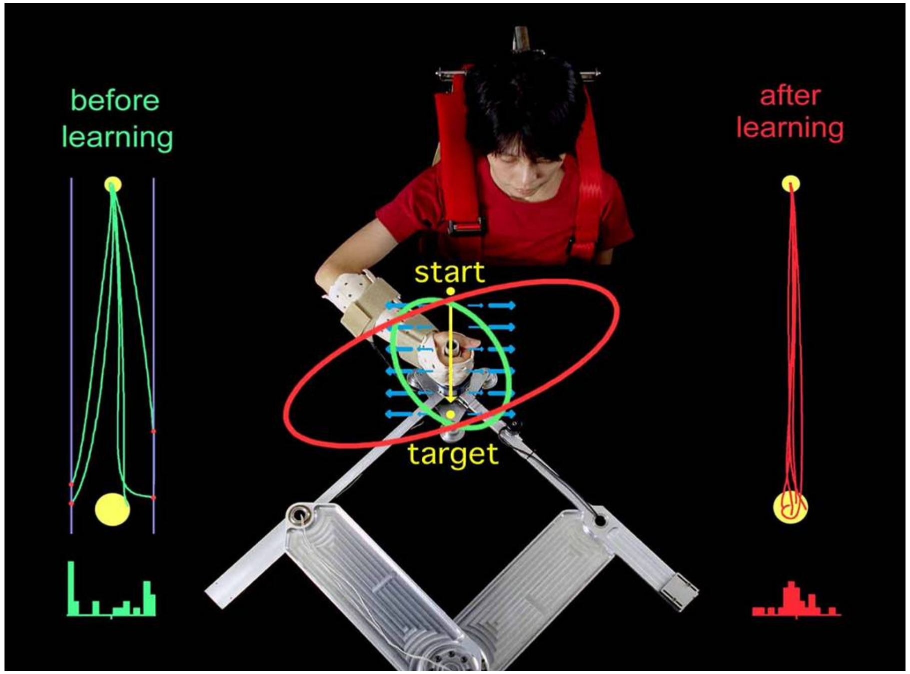
Chalon & al. IROS 2011

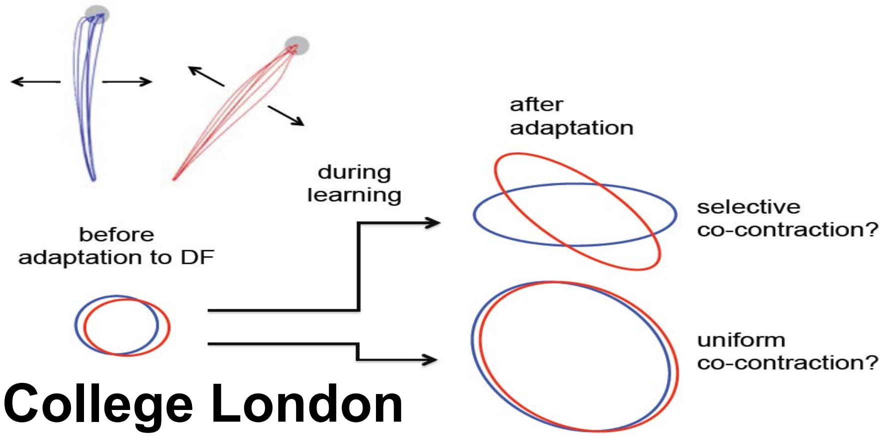
Performance Validation: Kicking Experiments

Experimental Results

	Stiff Joint	VS-Joint
Speed	3.06 m/s	6.35 m/s
Kicking range	1.6 m	4.05 m
Impact joint torque	85 Nm	10 Nm

WP2- Robotics of Biological Neuro-mechanical Control





[Ganesh & al., TRO 2011]

The DLR Hand-Arm System