Soft Robotics - Robots Designed to Interact with Humans and Unknown Environments

Alin Albu-Schäffer

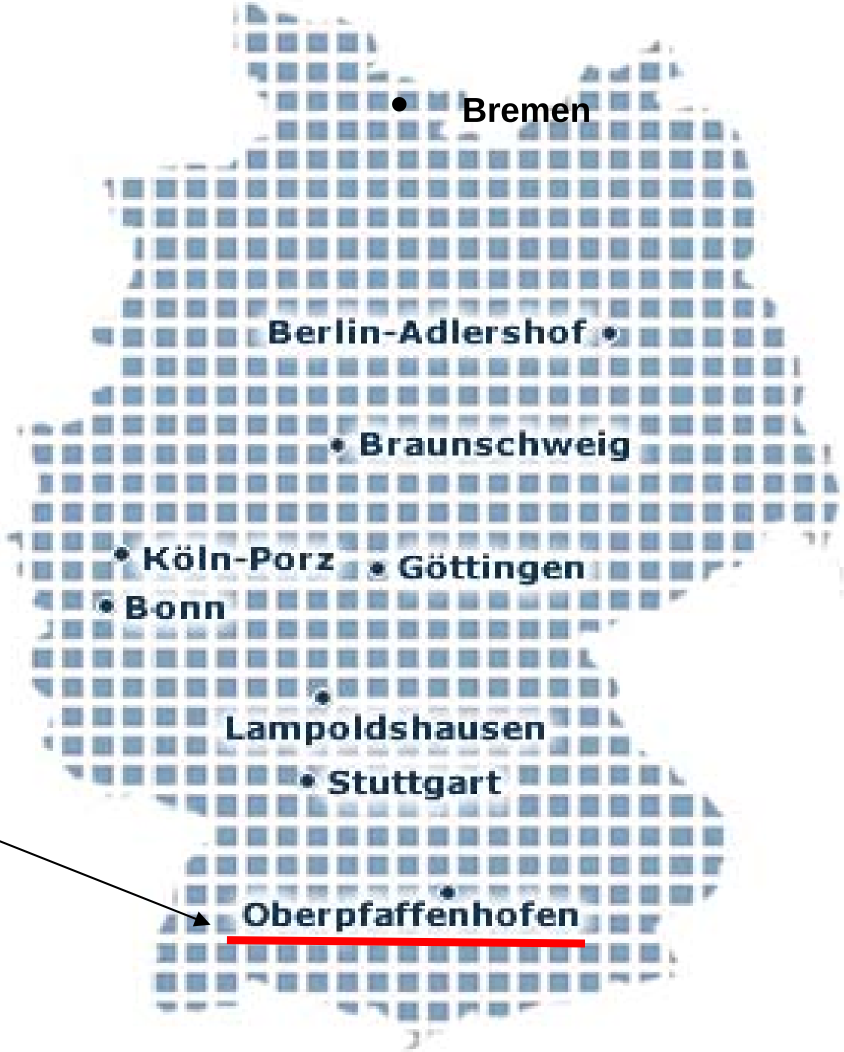
Paris, 22.01.2010

DLR Deutsches Zentrum
für Luft- und Raumfahrt e.V.
in der Helmholtz-Gemeinschaft

DLR Deutsches Zentrum für Luft- und Raumfahrt (German Aerospace Center)

- ~ 5000 employees
- nine locations

~1000 employees



research staff:~180 persons

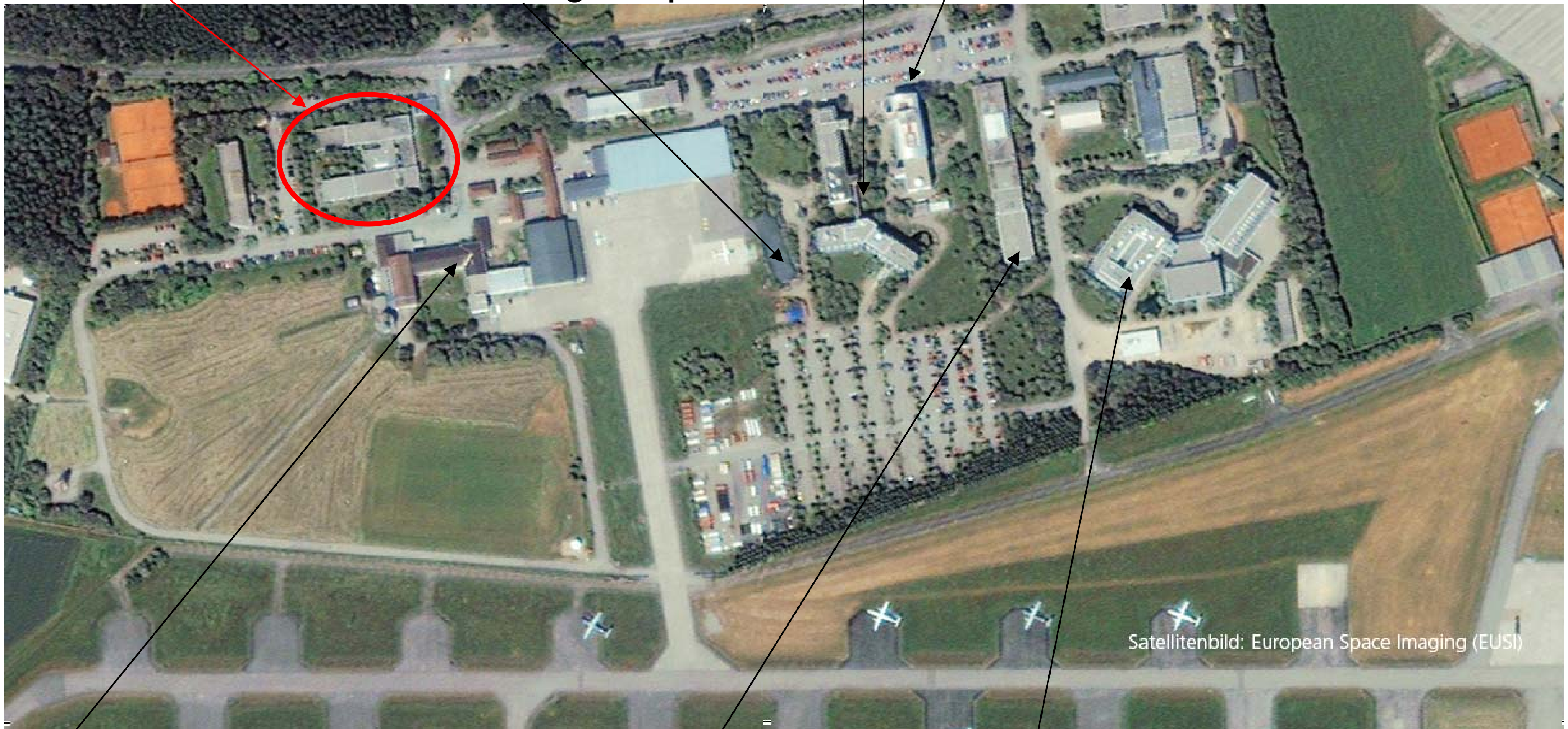
Institute of Robotics and Mechatronics

New Department “Mechatronic Systems”
76 persons

Applied Remote Sensing Cluster

Atmospheric Physics

Flight operation



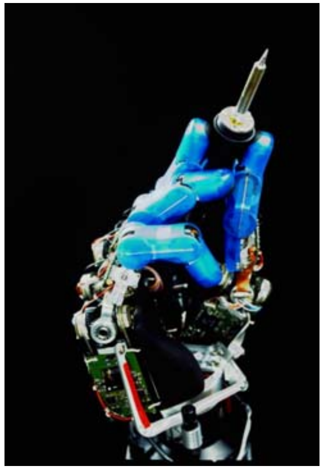
Microwaves and radar

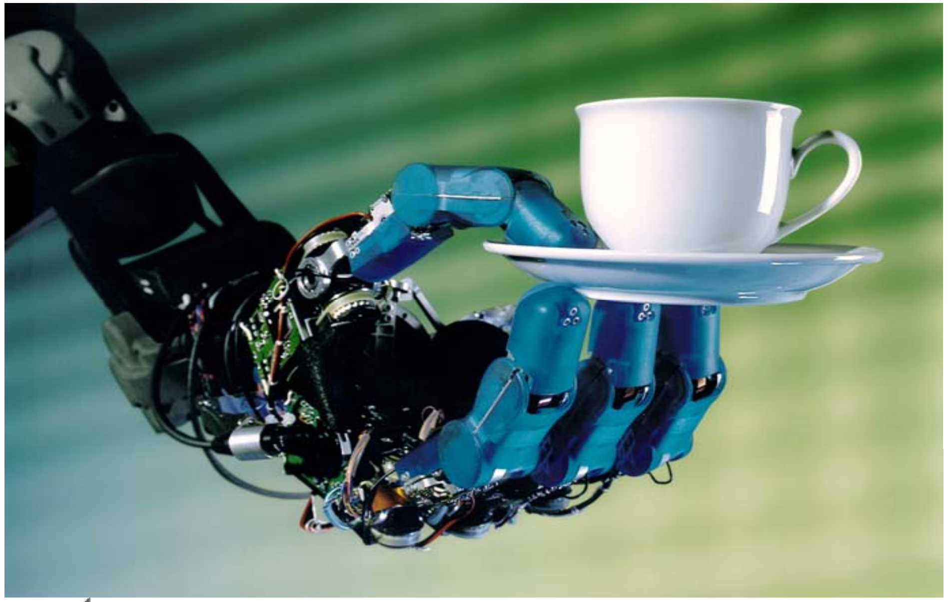
Space Operations Center

Communications and Navigation

Long Experience in Development of Hand-Arm Systems

Hand II: 13 Joints,
3kg finger tip force



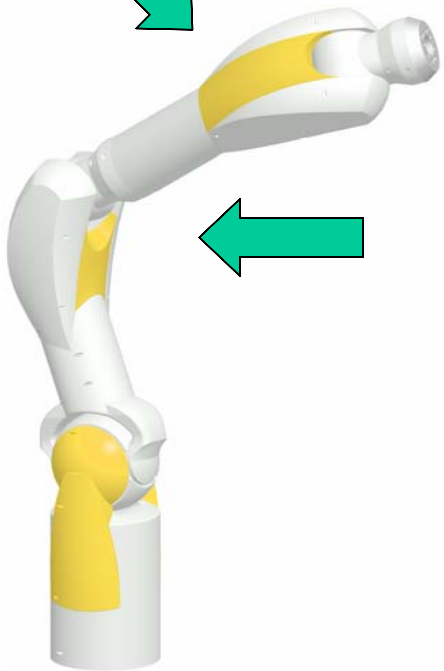


LBRIII
load/weight ~1/1 (14kg)
Consumed power~150 Watt,
Integrated Electronics

Torque Sensor

Mechatronic Developments

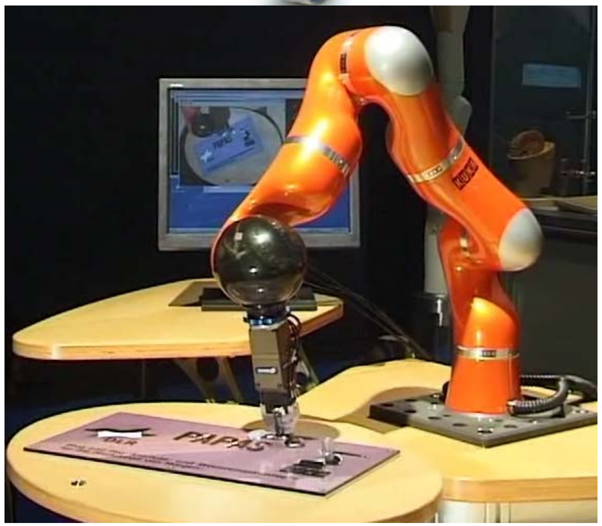
Torque sensing in each joint



DLR Medical robots

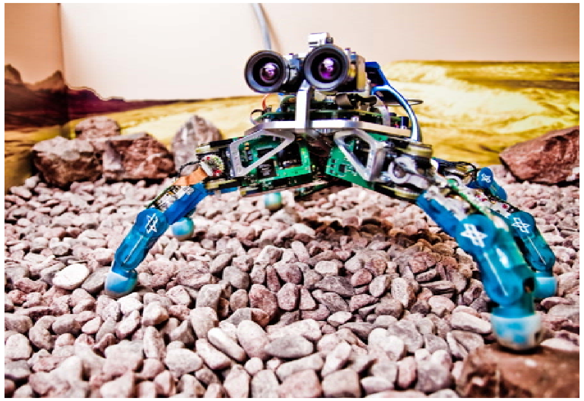
Justin

Commercialized by KUKA



Mechatronic Developments

DLR-Hand IIb



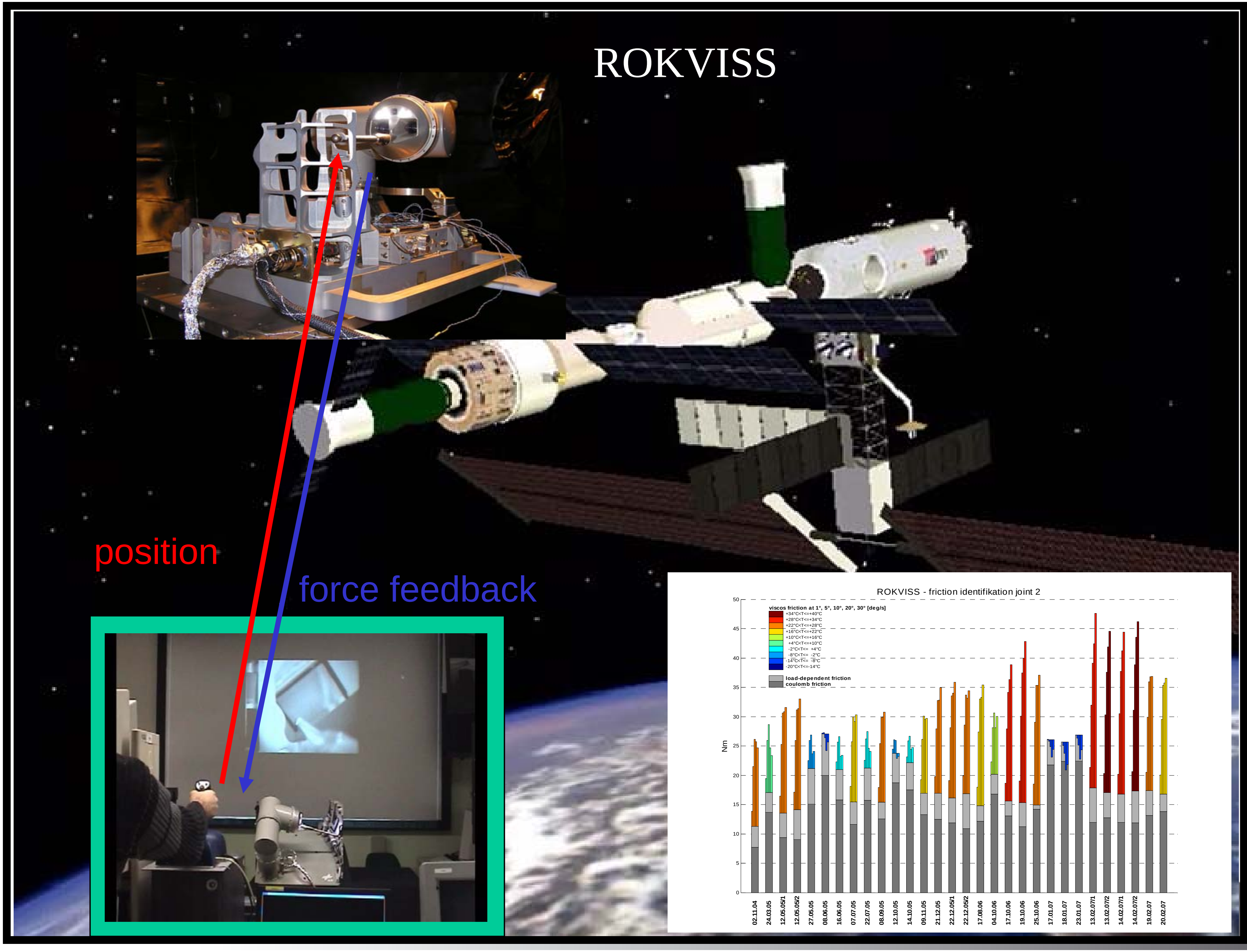
6 legged Crawler

Justin

DEXHAND (ESA-Project)

Commercialized by Schunk

DLR-HIT Hand I, II



ROKVISS
position
force feedback
ROKVISS - friction identifikation joint 2
viscos friction at 1°, 5°, 10°, 20°, 30° [deg/s]
+34°C<T<=+40°C
+28°C<T<=+34°C
+22°C<T<=+28°C
+16°C<T<=+22°C
+10°C<T<=+16°C
+4°C<T<=+10°C
-2°C<T<= +4°C
-8°C<T<= -2°C
-14°C<T<= -8°C
-20°C<T<=-14°C
load-dependent friction
coulomb friction
Nm
0 5 10 15 20 25 30 35 40 45 50
02.11.04 24.03.05 12.05.05/1 12.05.05/2 27.05.05 08.06.05 16.06.05 07.07.05 22.07.05 08.09.05 12.10.05 14.10.05 09.11.05 21.12.05 22.12.05/1 22.12.05/2 17.08.06 04.10.06 17.10.06 19.10.06 25.10.06 17.01.07 18.01.07 23.01.07 13.02.07/1 13.02.07/2 14.02.07/1 14.02.07/2 19.02.07 20.02.07

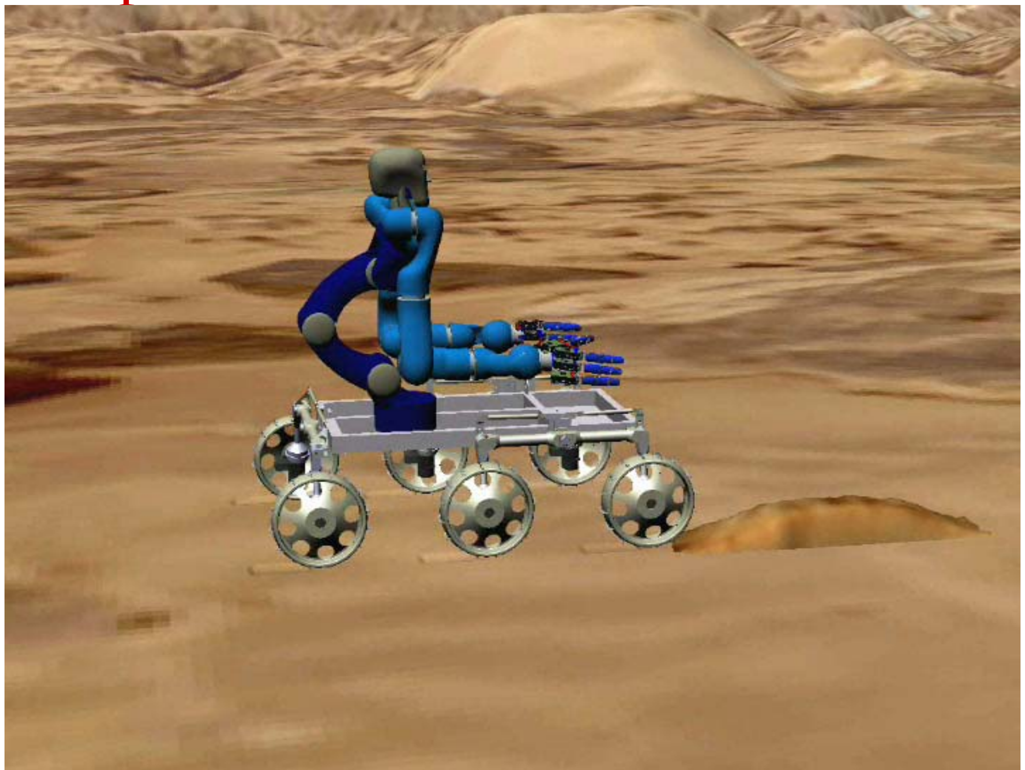
Space Robotics

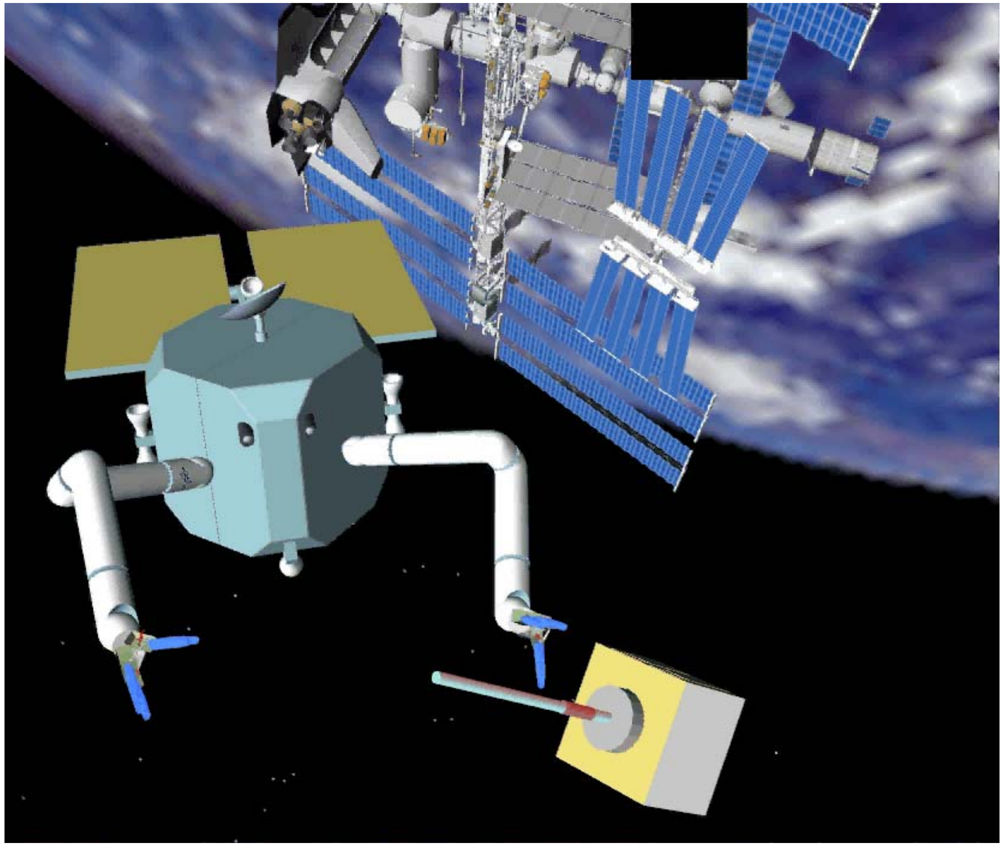
„Affordable“, operations in space with mobile/free-flying robonauts for

- Servicing

  and

- Exploration



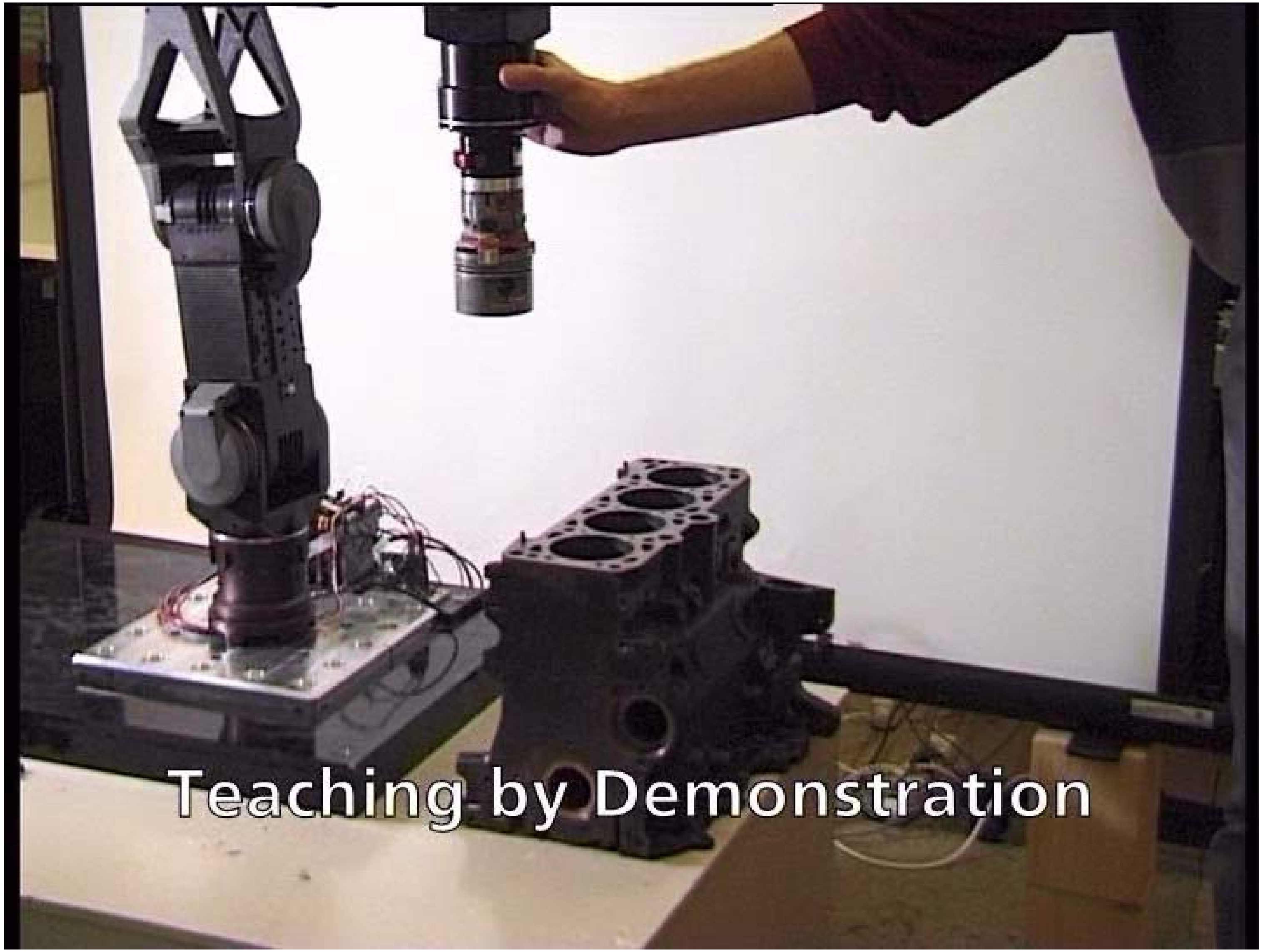


Service Robotics

Medical Robotics

The MIROSURGE System

Industrial Assistan



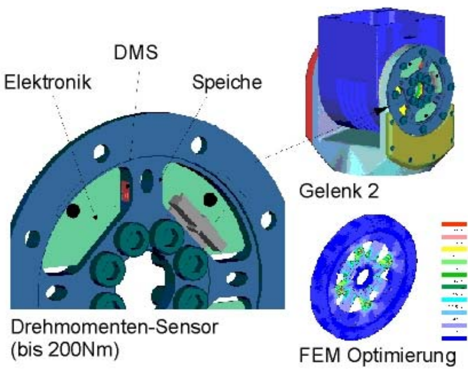
Production Assistant

The “mechatronic” DLR light-weight robots

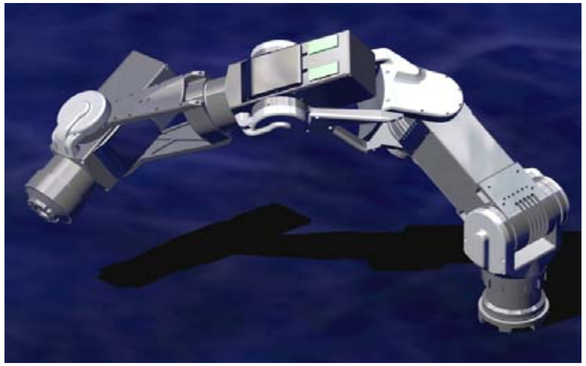
Extreme light arms with high load capabilities and integrated sensor and power electronics

- Harmonic Drives
- motor and load side position sensors
- Joint torque sensors
- Cartesian Force-torque sensor

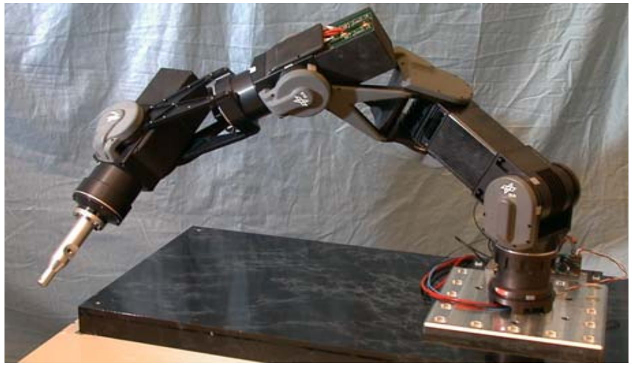
LWR I (ca.1992)



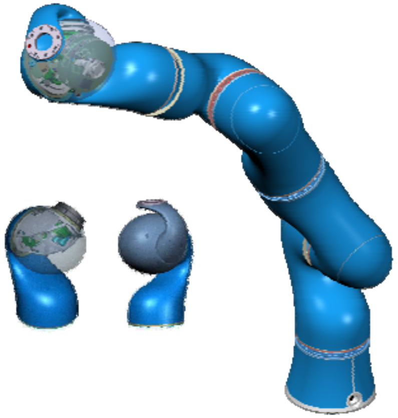
LWR III real (2002)



LWR II virtual (ca.1998)



LWR II real (ca. 1999)

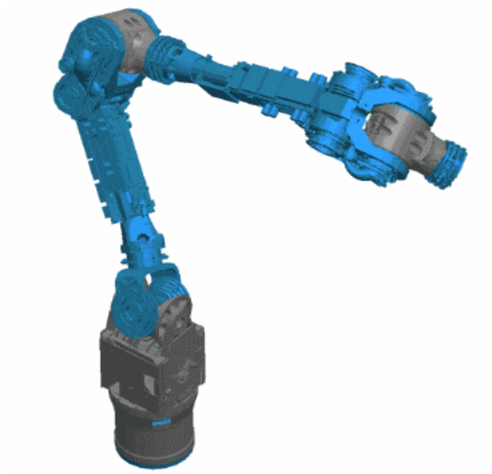


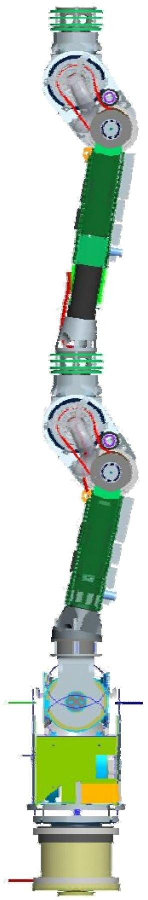
LWR III virtual (2000)

Light-Weight Design

DLR medical robot

- 7 Axes
- Weight< 10 kg
- Payload: 3 kg

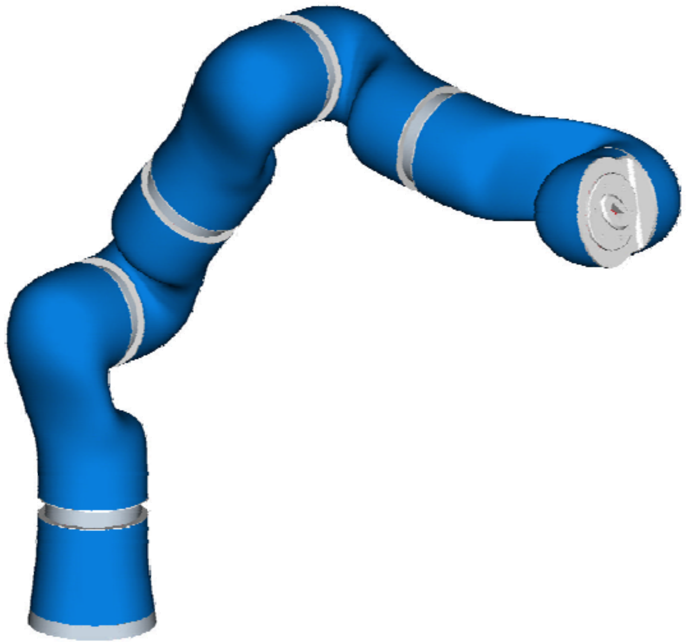


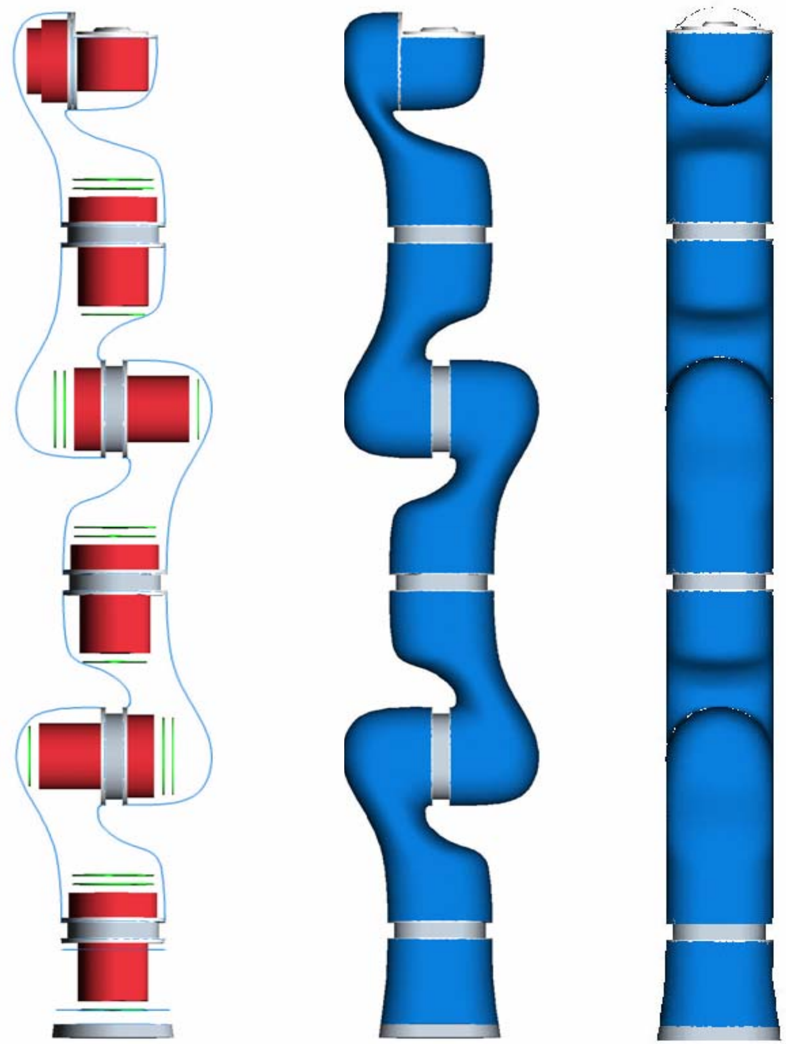


DLR light-weight robot

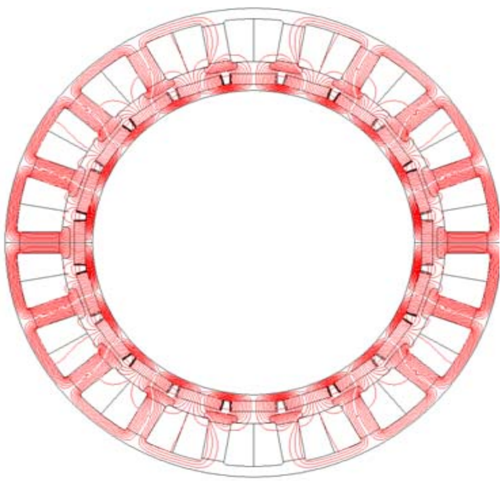
- 7 Axes
- Weight: 13.5 kg
- Payload: 13.5 kg

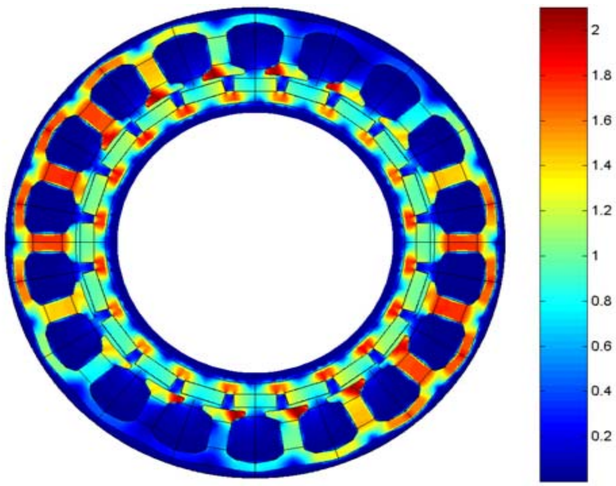
Modular Robot Design

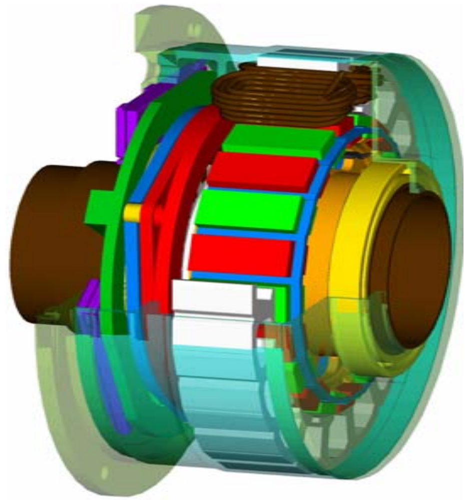




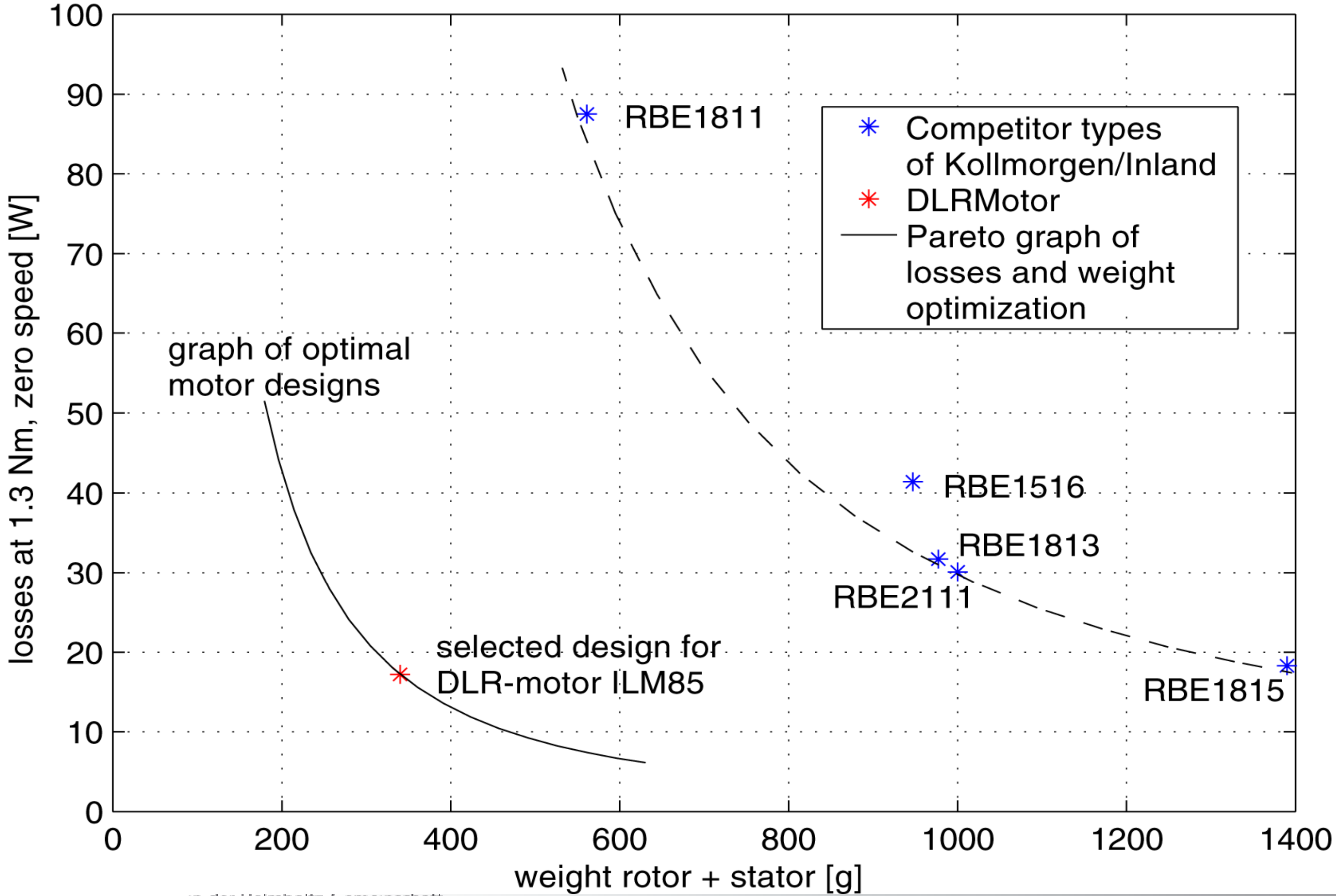
Concurrent Engineering- via multidisciplinary simulation to an optimized motor design

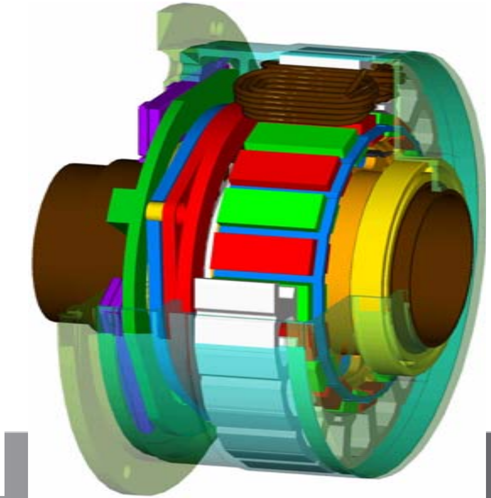




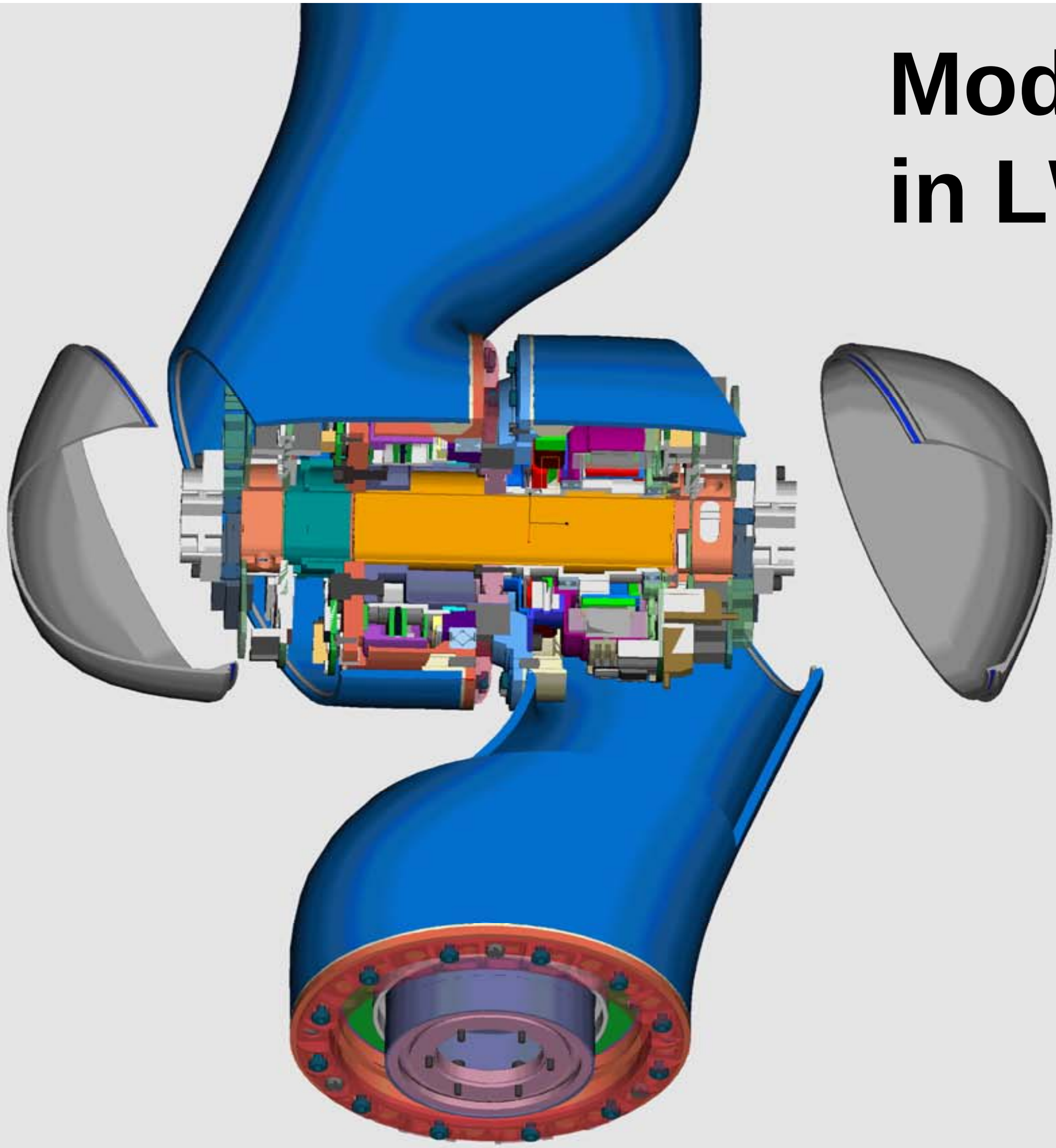


DLR`s new ROBODRIVE-
half weight, half losses

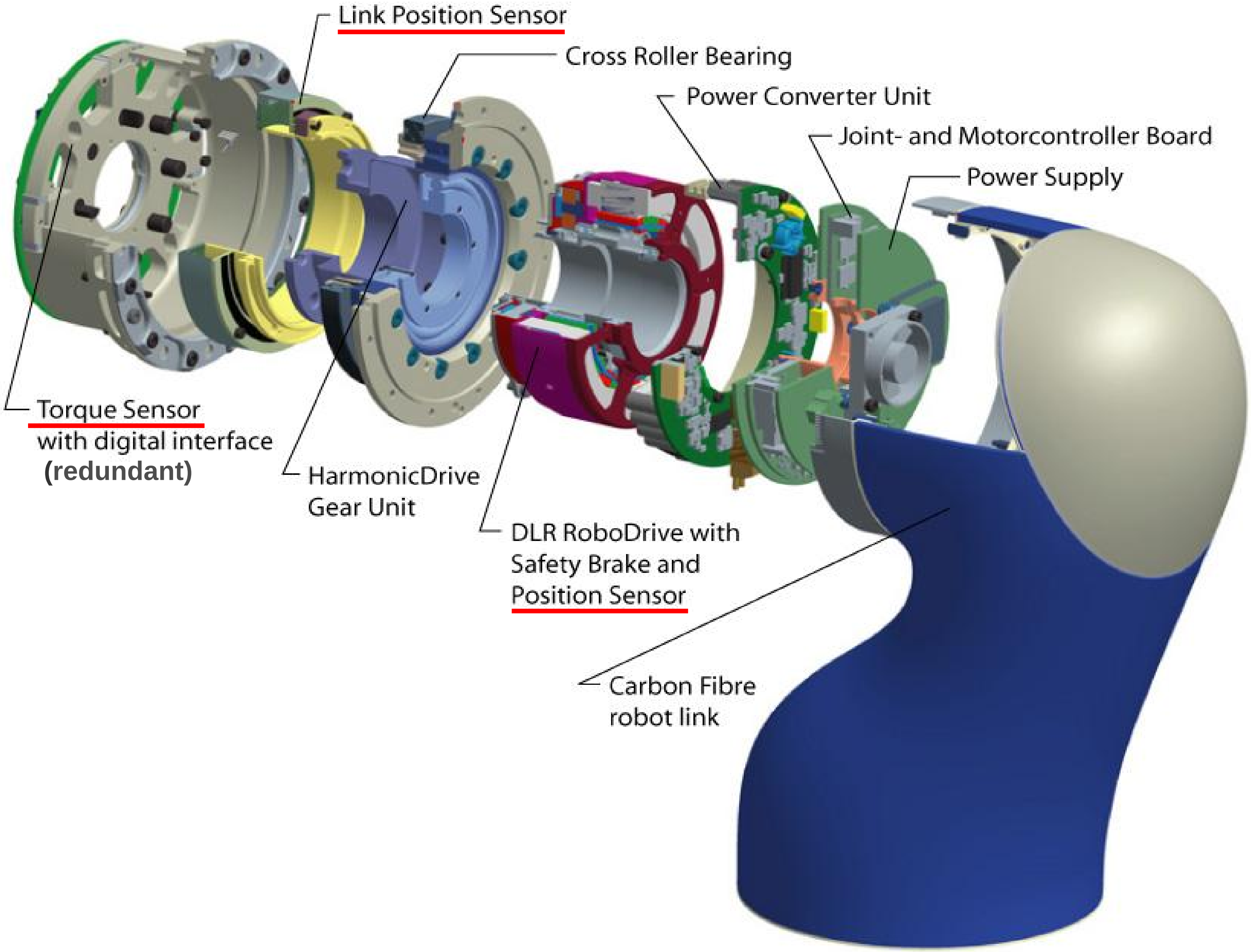




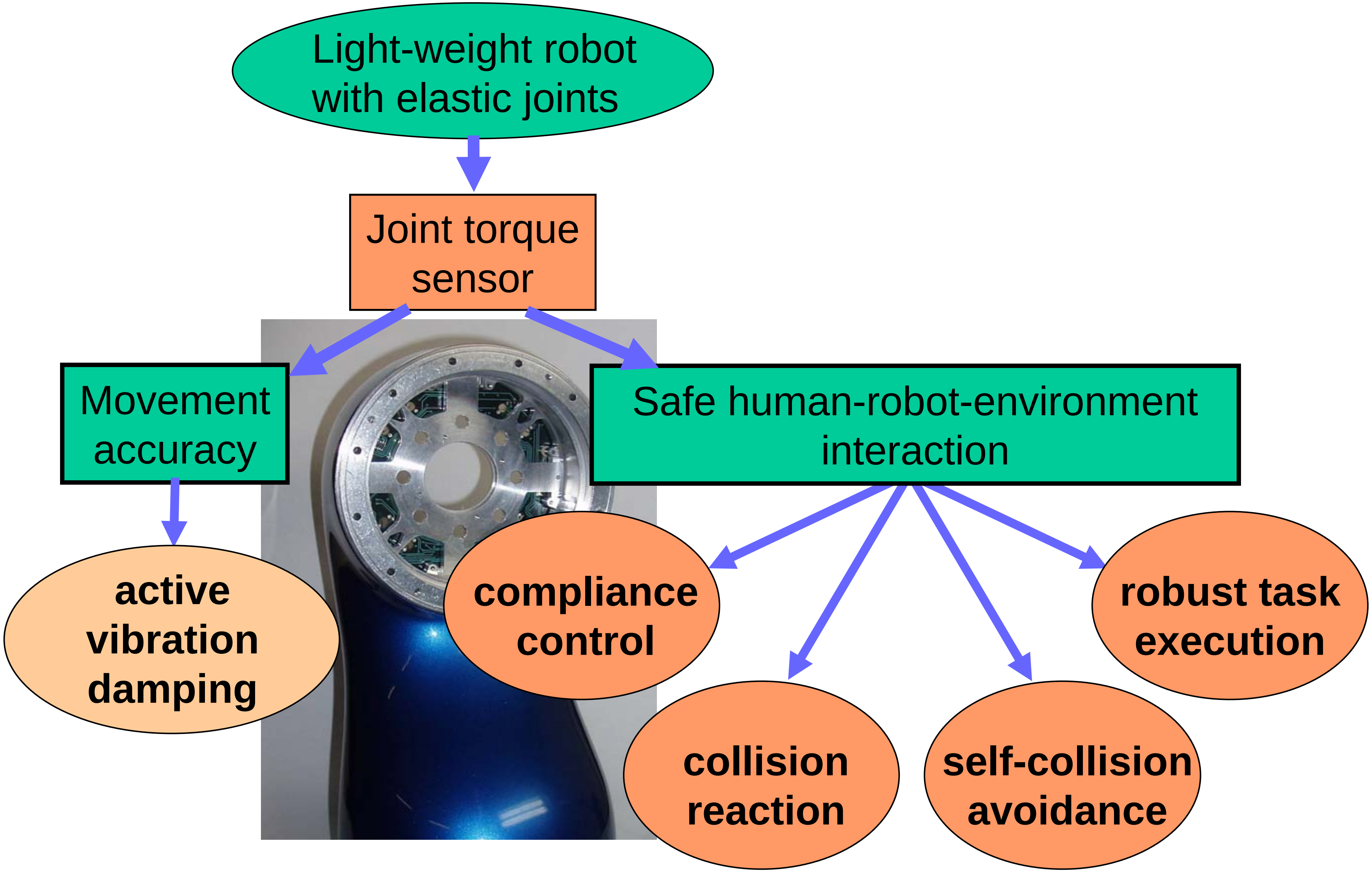
Modular drives in LWR III



Mechatronic Joint Design

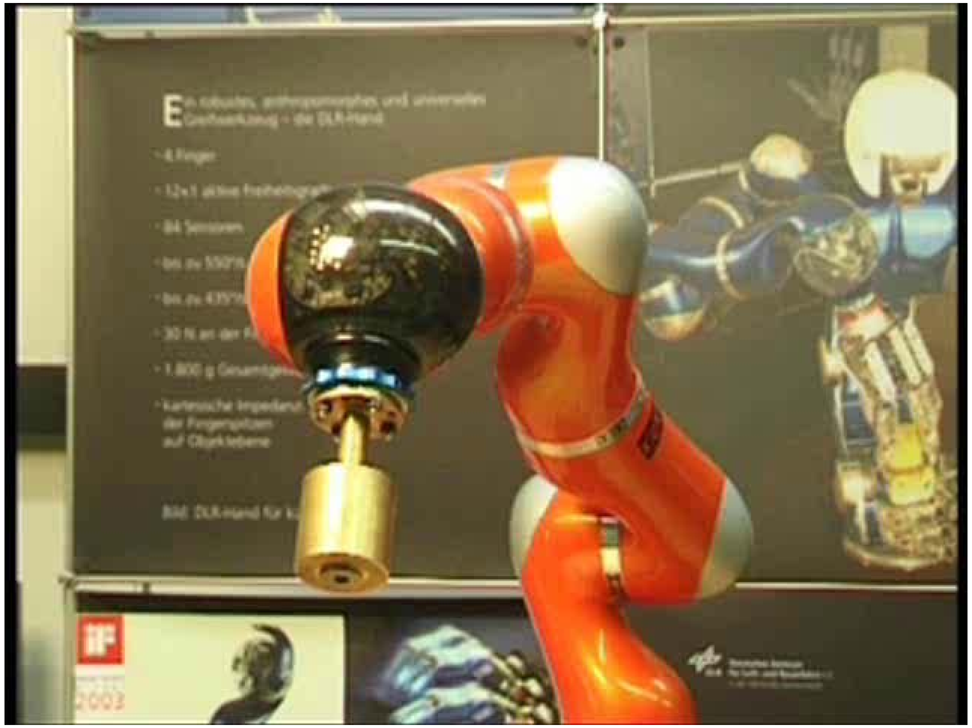


Control components



Vibration Damping

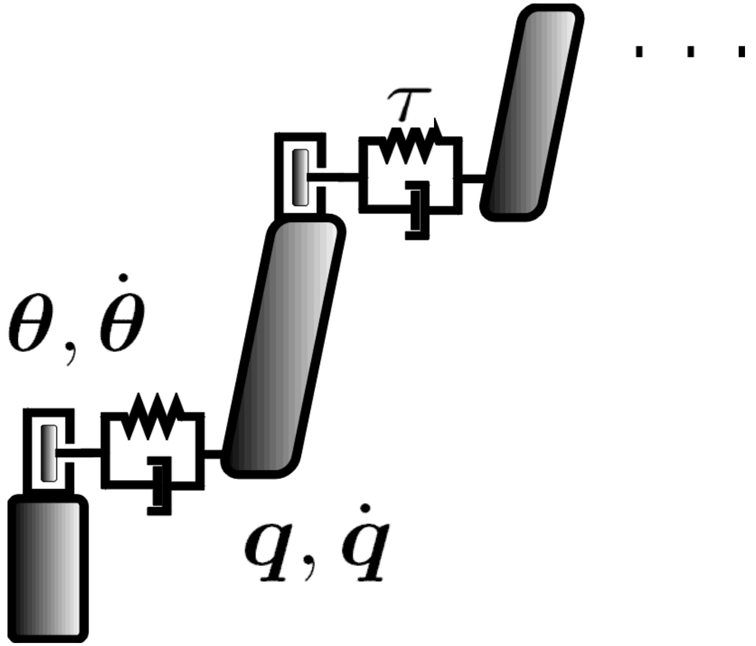
Vibration Damping ON



Vibration OFF

Robot reaches the dynamics and accuracy of an industrial arm (according to KUKA ISO-Tests)

Model of the flexible joint robot



possible state vector:

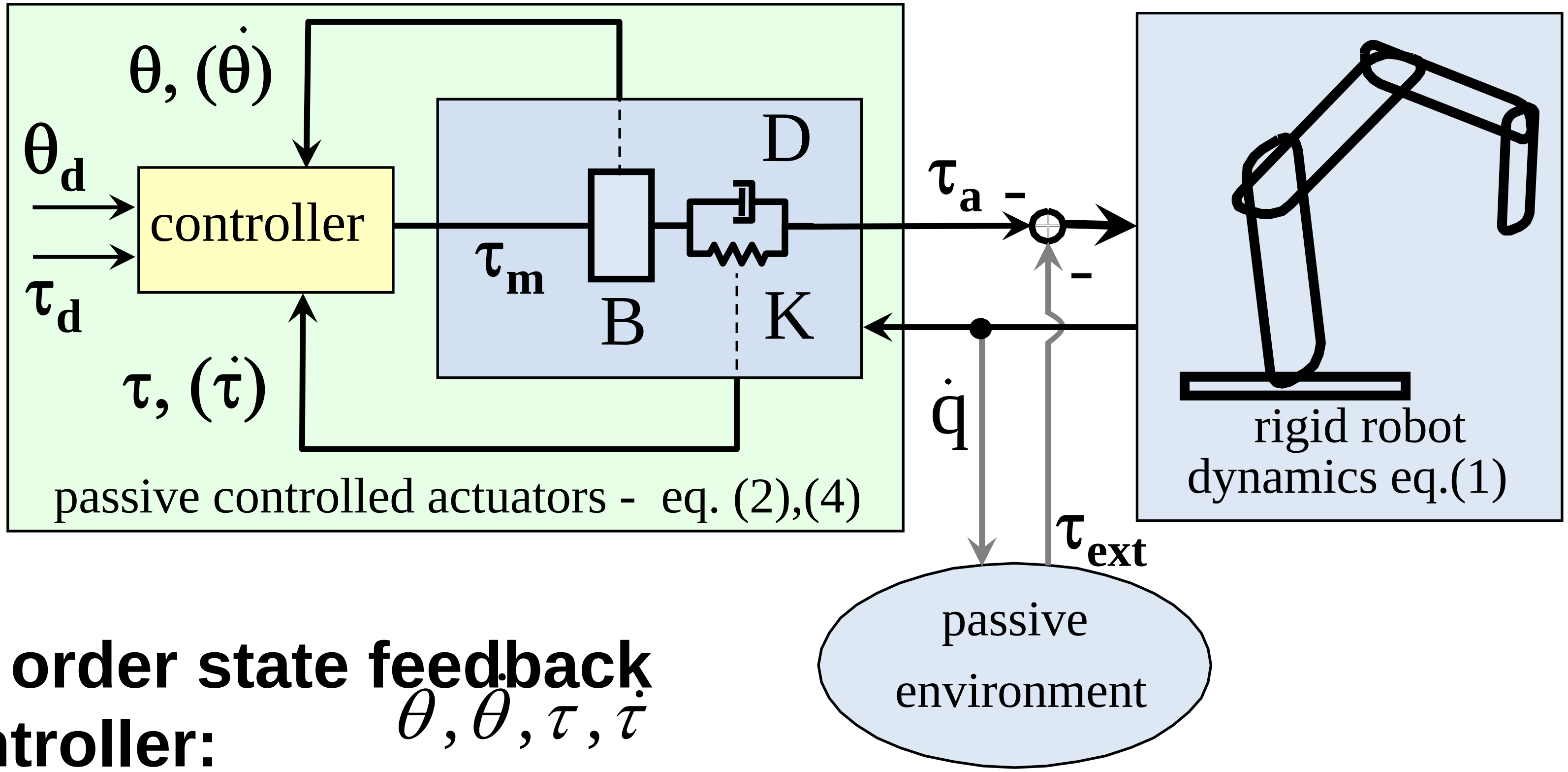
$$x_1^T = \{\theta, \dot{\theta}, q, \dot{q}\}$$

used state vector:

$$x^T = \{\theta, \dot{\theta}, \tau, \dot{\tau}\}$$

$$\begin{aligned} M(q)\ddot{q} + C(q,\dot{q})\dot{q} + g(q) &= \tau + DK^{-1}\dot{\tau} + \tau_{ext} \\ B\ddot{\theta} + \tau + DK^{-1}\dot{\tau} &= \tau_m \\ \tau &= K(\theta - q) \end{aligned}$$

Joint Level Control

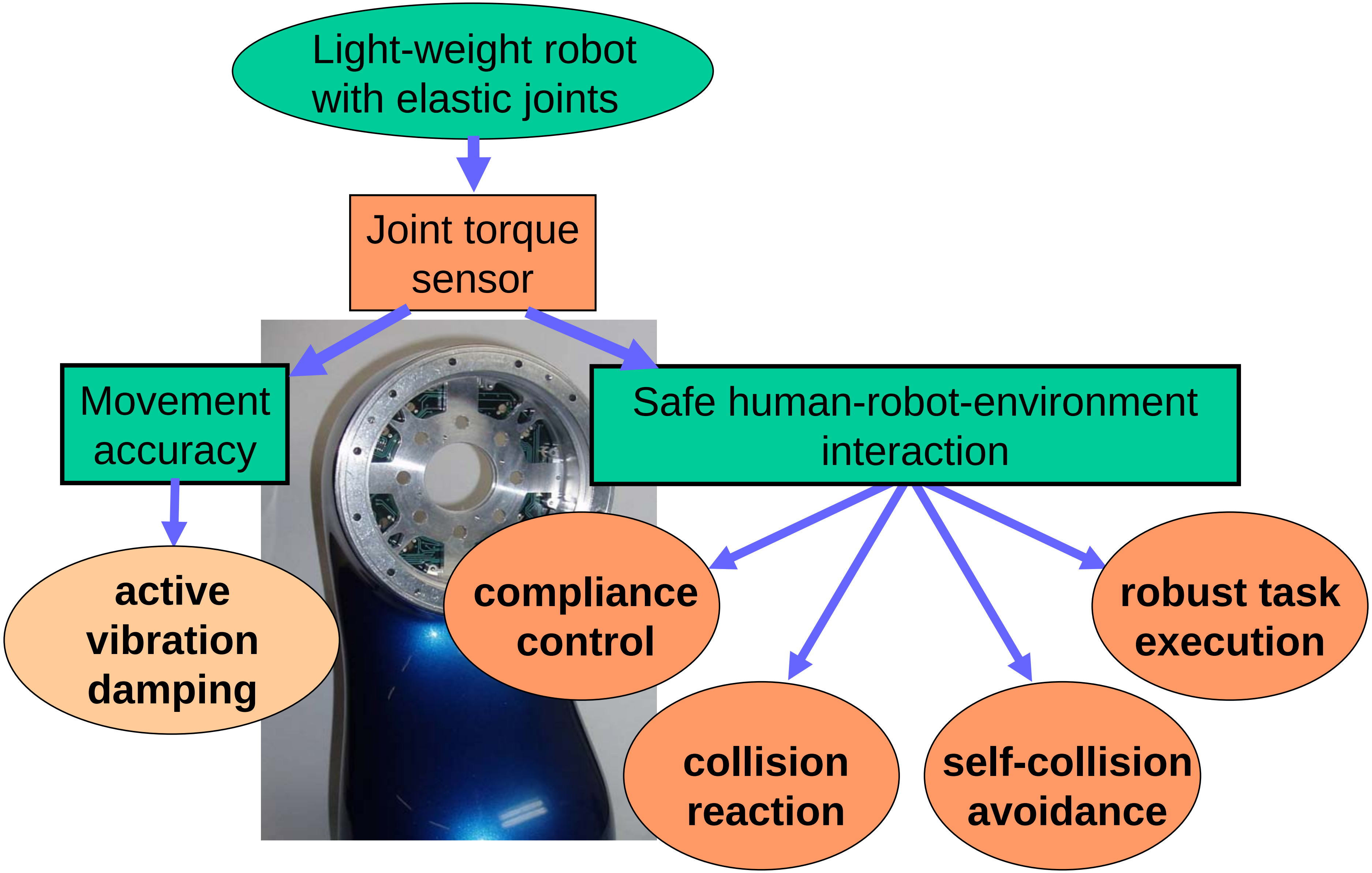


4th order state feedback controller: $\theta, \dot{\theta}, \tau, \dot{\tau}$

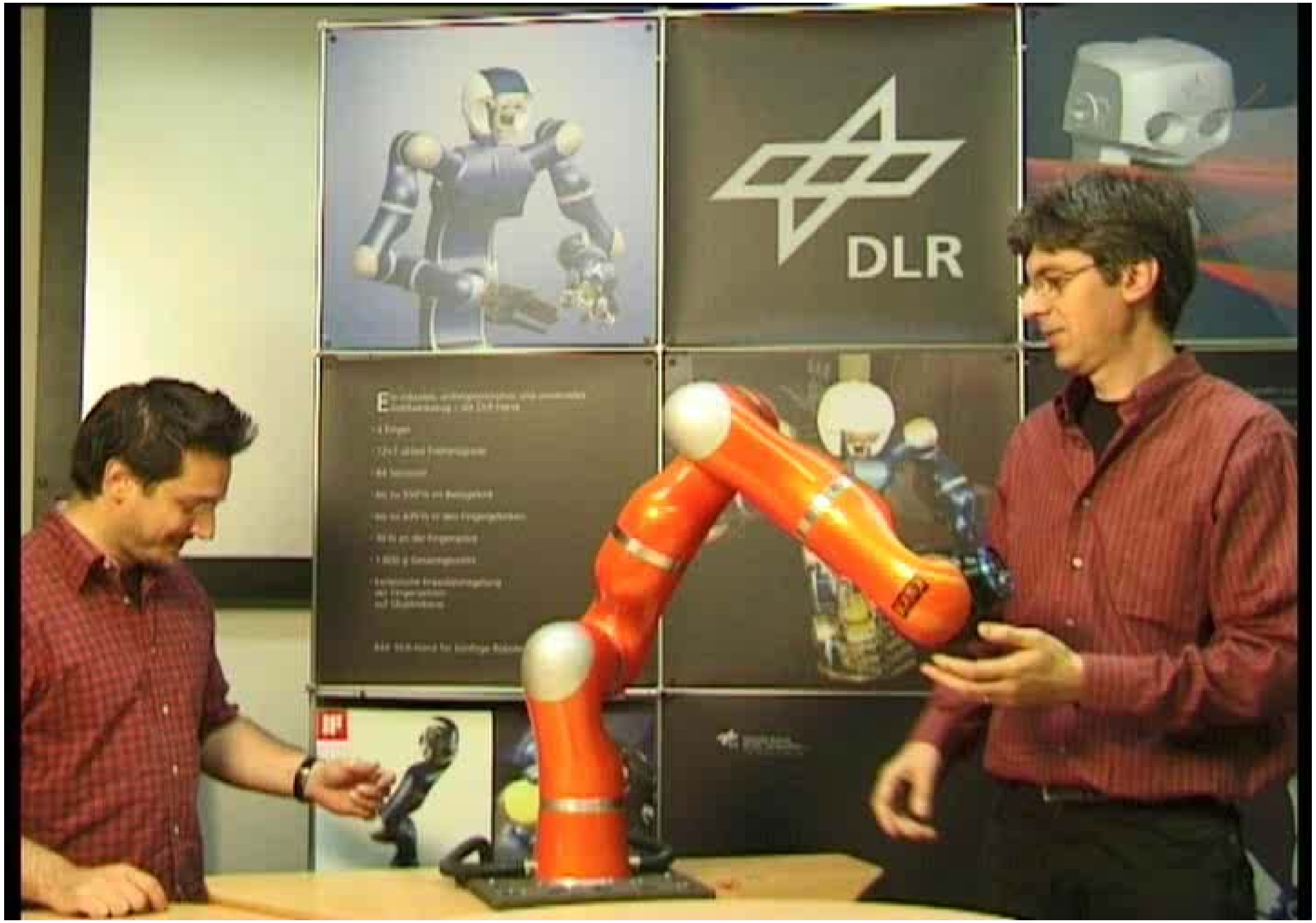
same structure used for

- **toque control**
- **position control**
- **impedance control**

Control components



Torque Control with Gravity Compensation



Cartesian Impedance Controller

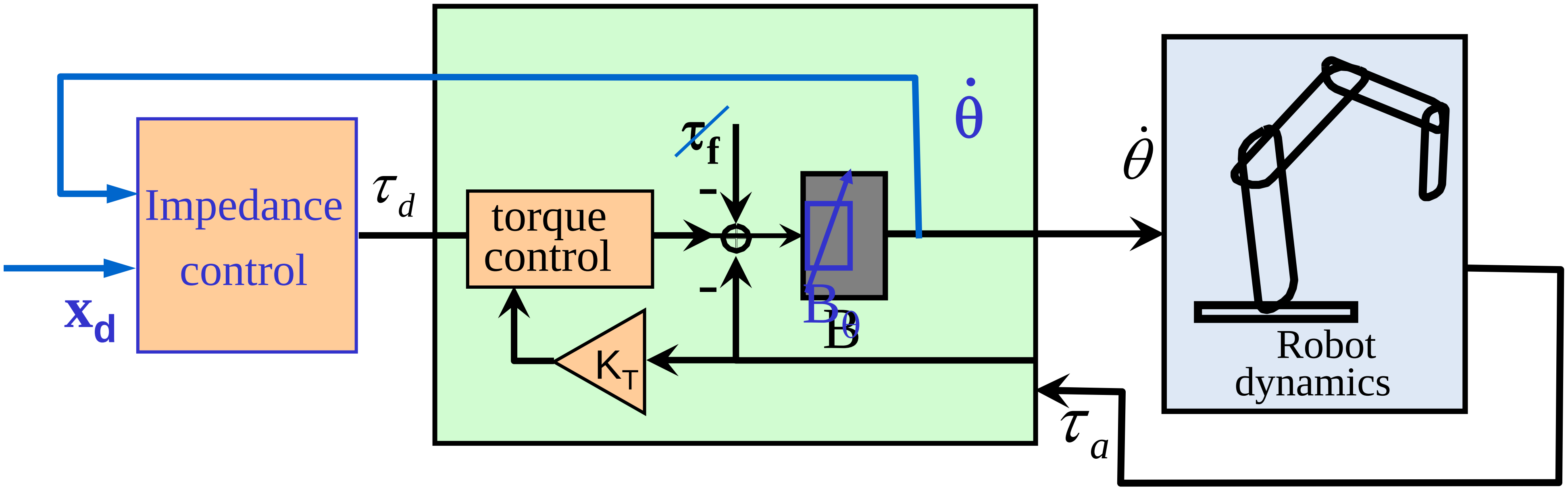
Generalization of approaches from rigid robots to the flexible case

- Shaping the potential energy - collocated feedback
  - Asymptotic stabilization around $\boldsymbol{x}_\mathbf{d}$ ($\boldsymbol{\tau}_{ext} = \mathbf{0}$)
  - Implementation of the desired compliance relationship ($\boldsymbol{\tau}_{ext} \neq \mathbf{0}$
  - Feedback of $\boldsymbol{\theta}, \dot{\boldsymbol{\theta}}$
- Shaping of the kinetic energy - noncollocated feedback
  - Damping of vibrations => increased performance
  - Feedback of $\boldsymbol{\tau}, \dot{\boldsymbol{\tau}}$ (torque controller)

=> Full state feedback

Cartesian Impedance Control

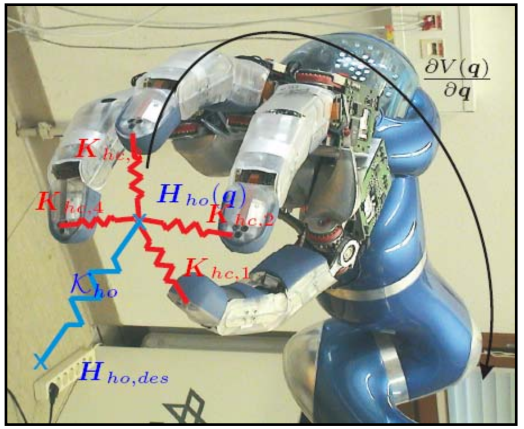
Unified approach for torque, position and impedance control on Cartesian and joint level

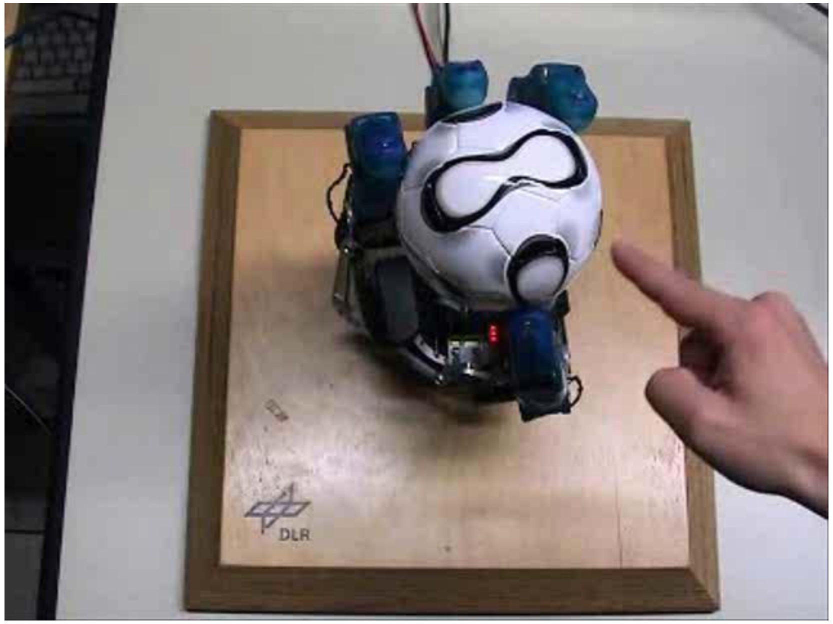


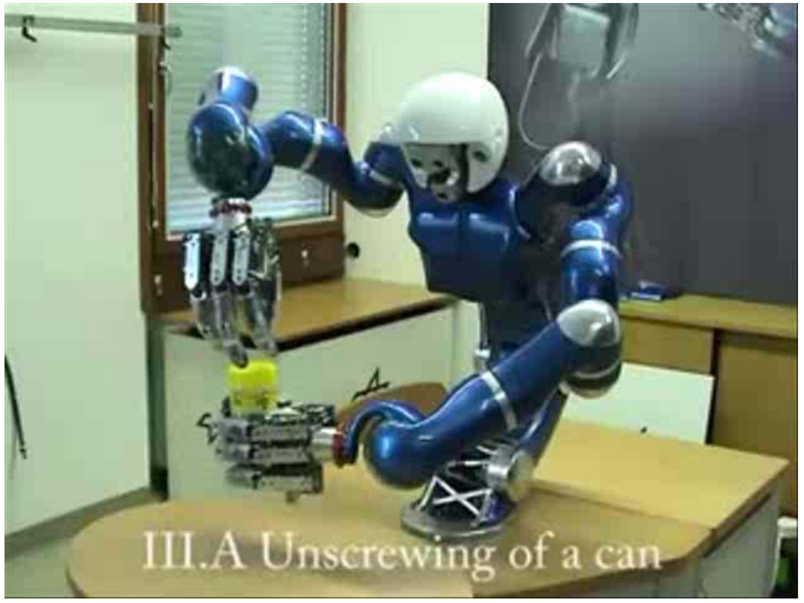
Passivity ⟶ Robustness in contact with the environment

DLR Hand II – Impedance Control

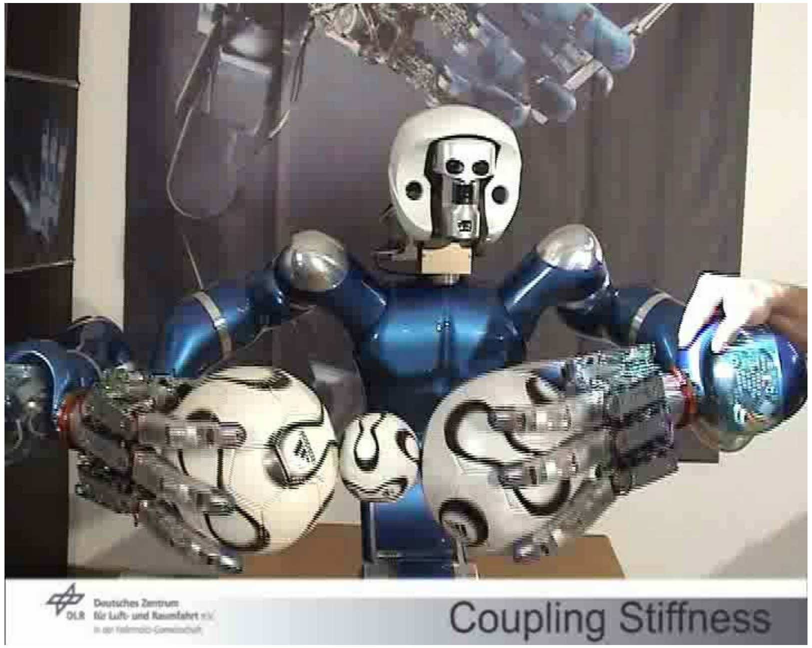
- Joint impedance Control
- Cartesian Impedance Control
- Object Impedance Control

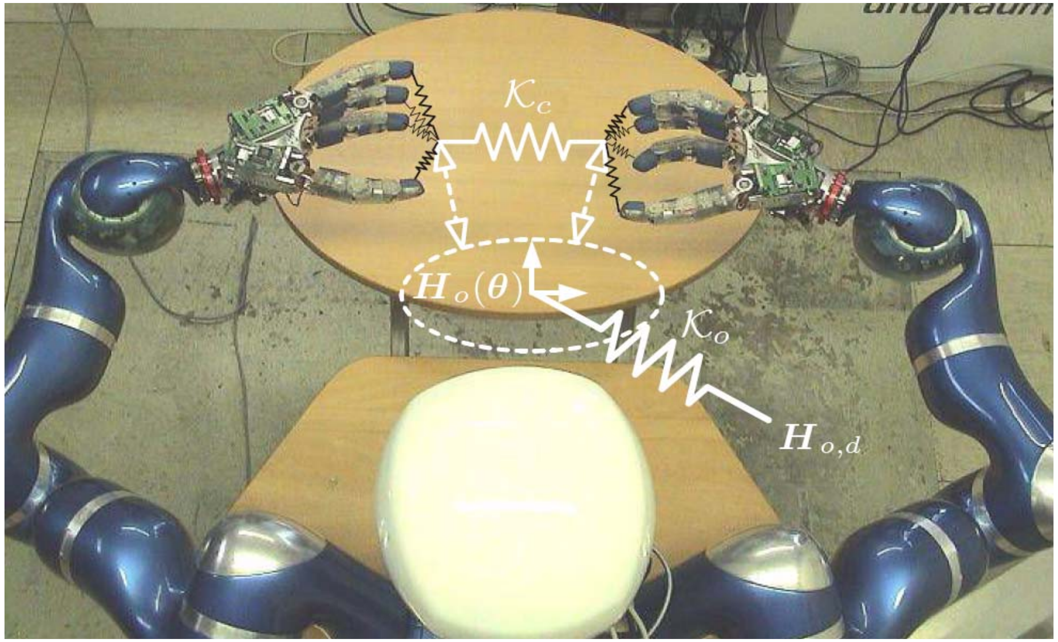






Impedance Control for Two Handed Manipulation





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

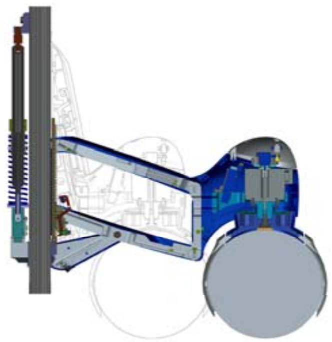
Gravity compensation

Stiffness term

Damping term

1ms control cycle for the whole system

Development and Control of the Omni-Directional, Mobile Platform



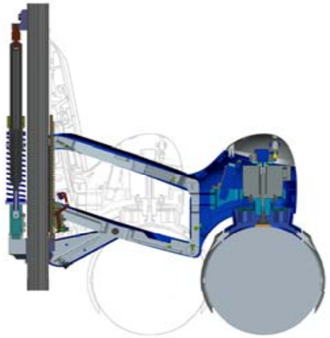
- Wheels can be independently retracted

  (variable support area)
- 8 actuators
  - 4 steering actuators
  - 4 wheel actuators
- Passive suspension - lockable

Fixed leg length: all joint axes intersect in the Instantaneous Center of Rotation (ICR)

For leg extension while moving no ICR exists – controller generalizations were needed

Development and Control of the Omni-Directional, Mobile Platform



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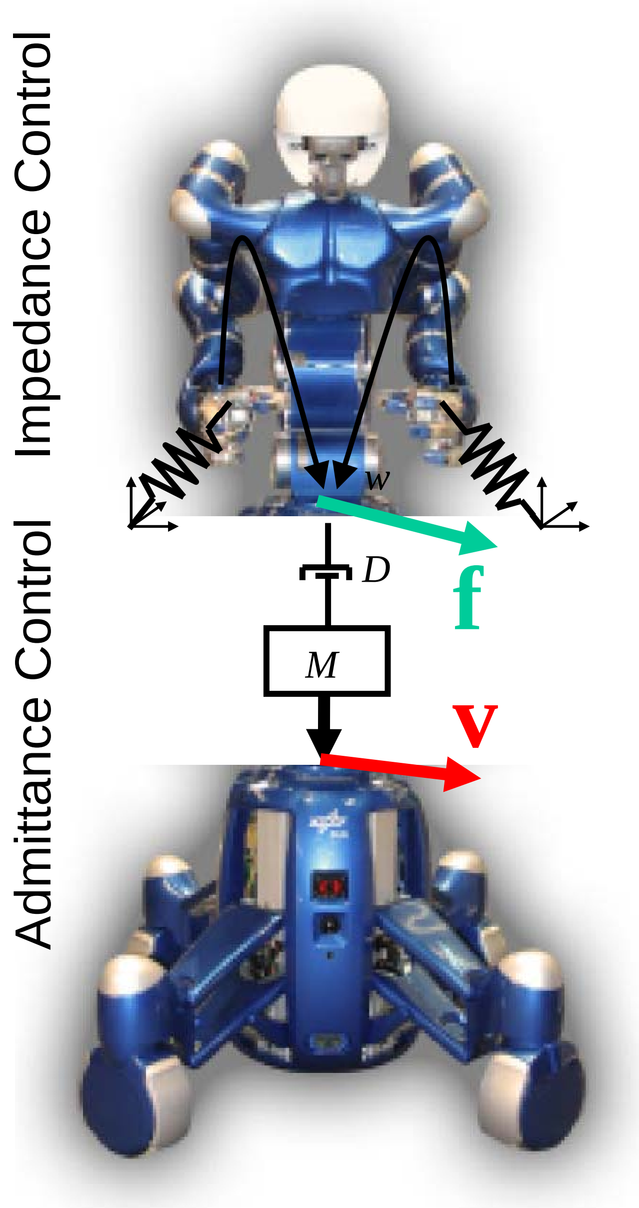
Human-Robot-Interaction

Compliant Control of the entire Robot



Rollin' Justin

- 53 active dof
- 150 kg

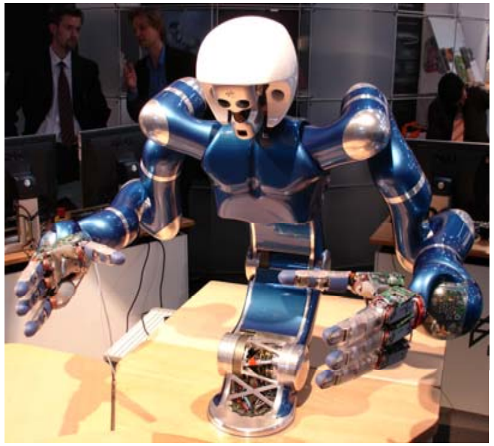
Collision Avoidance

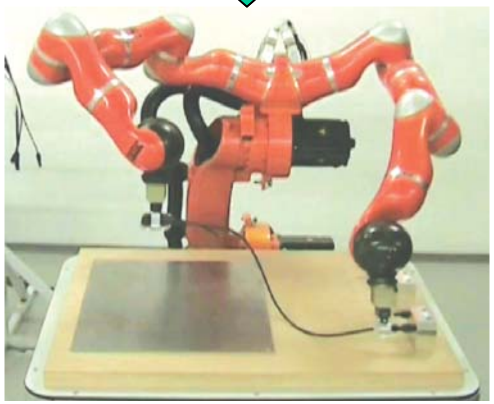
Avoidance of collisions with repulsive potentials

Compatible with the passivity based approach

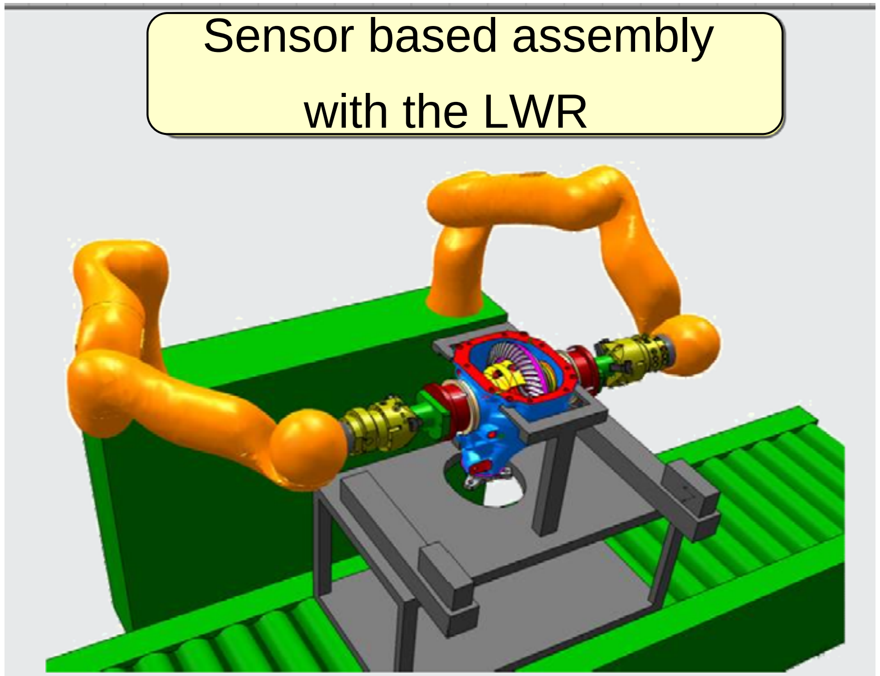
Cooperation with Univ. of Naples
(Lab of Bruno Siciliano)

First Application of the Technology in Automotive Industry





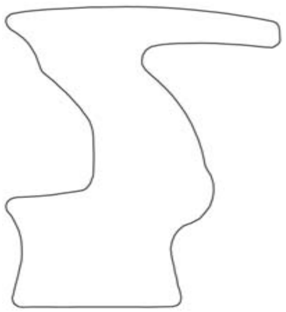
KUKA Demonstrator



Mercedes-Benz

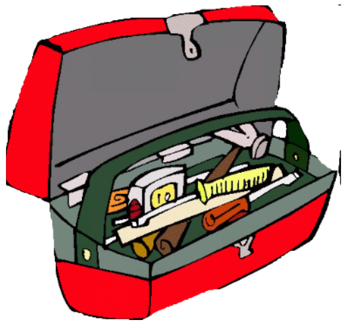
- Gearbox assembly tests since March 2009
- Production starting from September 2009

Basic Idea

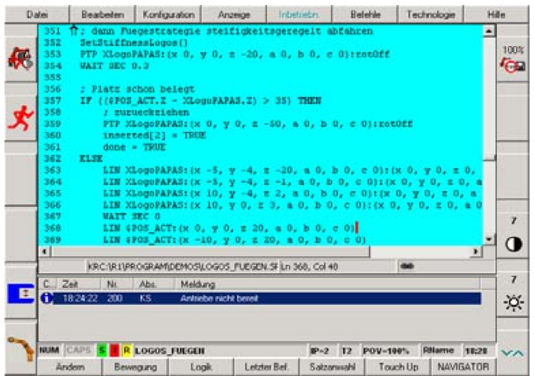


Geometrical Model
(from image processing / CAD)

Additional information:
- tolerance
- material properties
- Robot and camera accuracy
- additional constraints



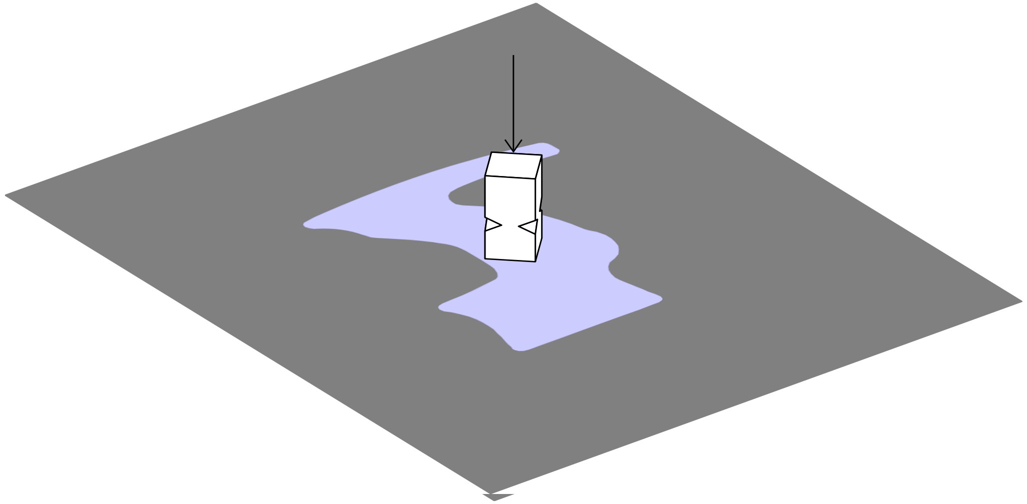
Assembly Planning Toolbox



KRL code

Online-Data:
- Position estimation
- Workspace limitations
- Robot configuration
- additional sensor data

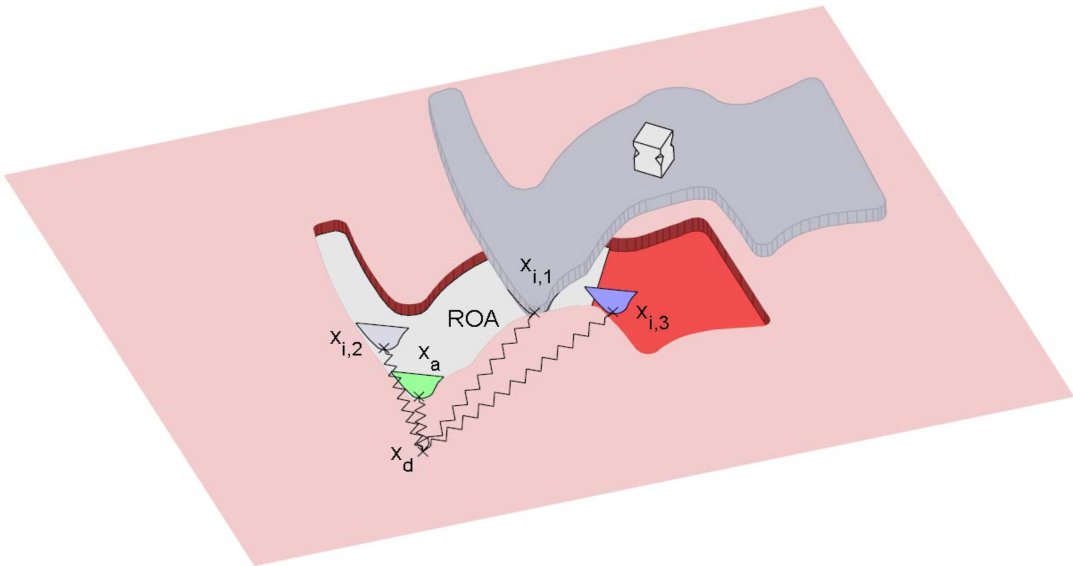
Vision and Impedance Based Assembly



$$F = -K(x - x_d) - D\dot{x}$$

- Problem statement : Automatically find and program the optimal strategy

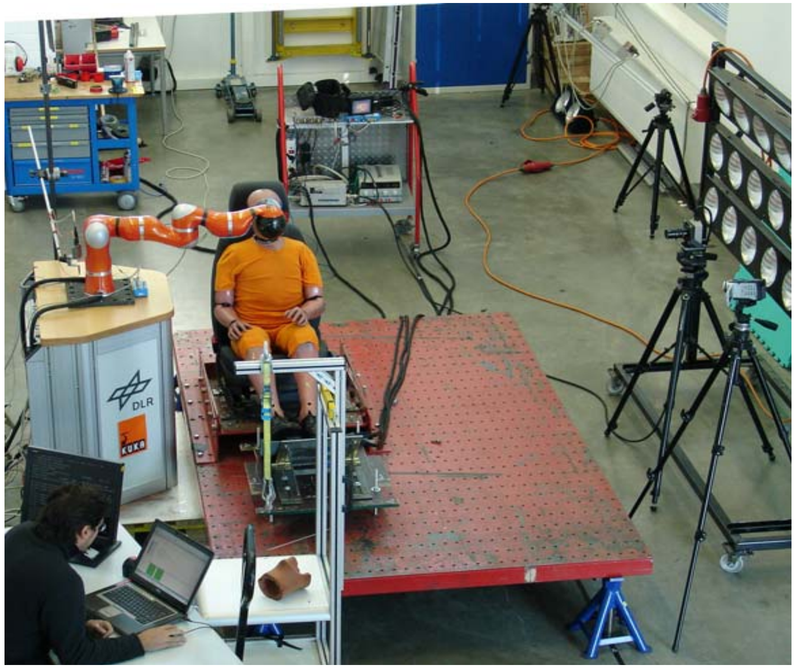
Regions of Attraction (ROA)

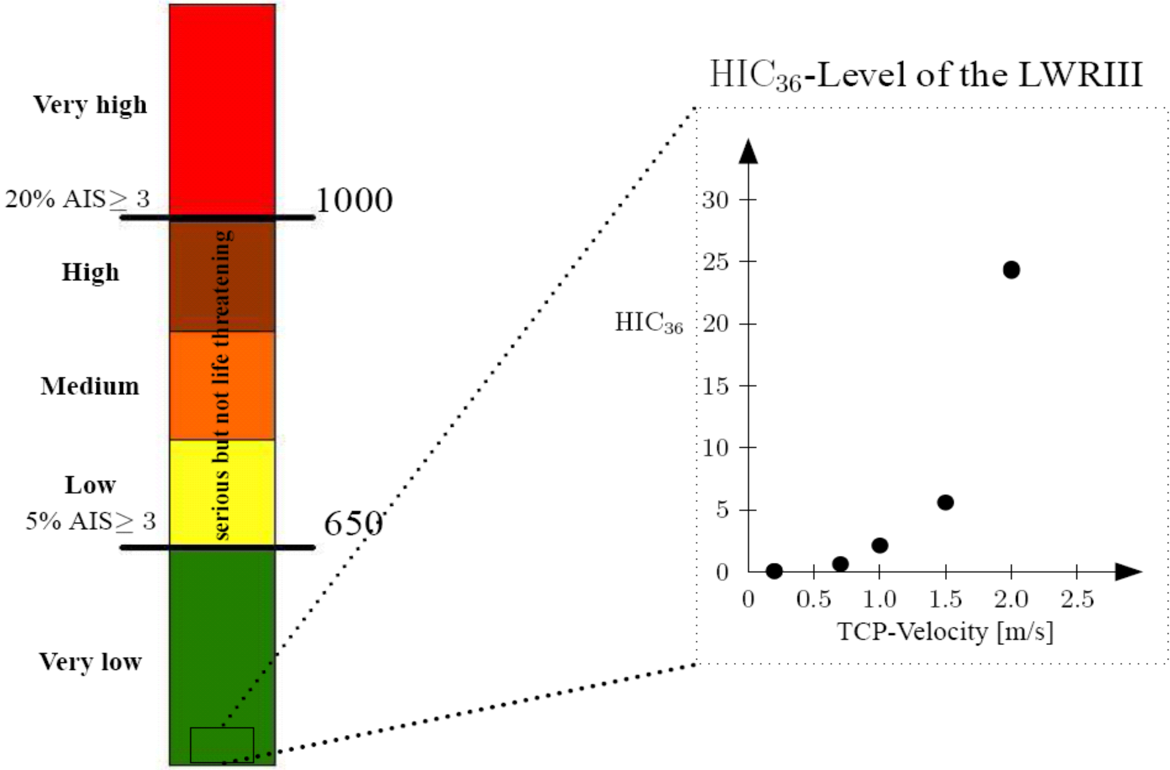


- The contact point with maximal ROA provides maximal robustness w.r.t. sensor and mode uncertainties
- A local Lyapunov Based convergence analysis is possible based on the impedance controlled robot and the contour geometry

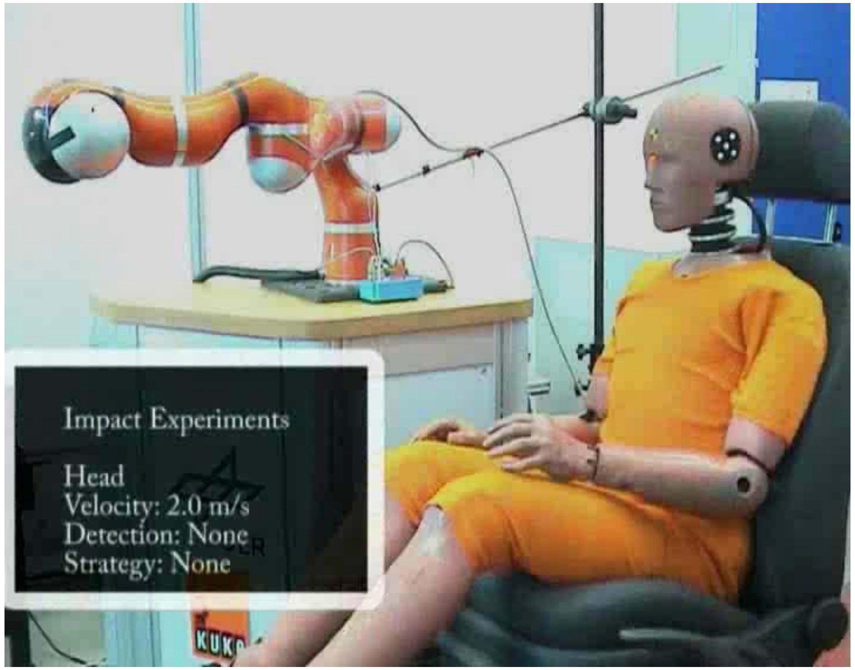
How Dangerous is the Robot Really?

First collision experiments with standardized methods for evaluation of injury potential and related safety measures in robotics



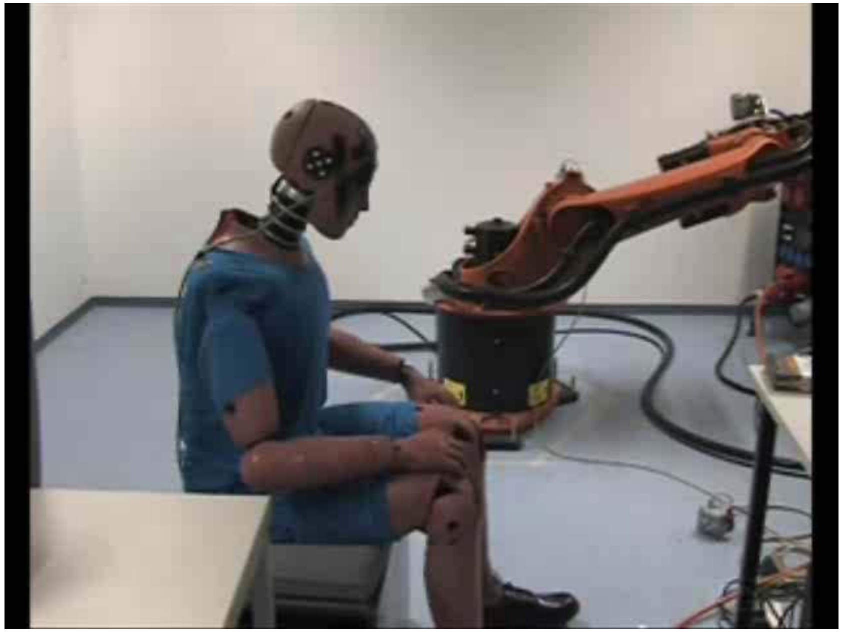


For all evaluated criteria, the LWR proved to be in the lower quarter of the green, uncritical area

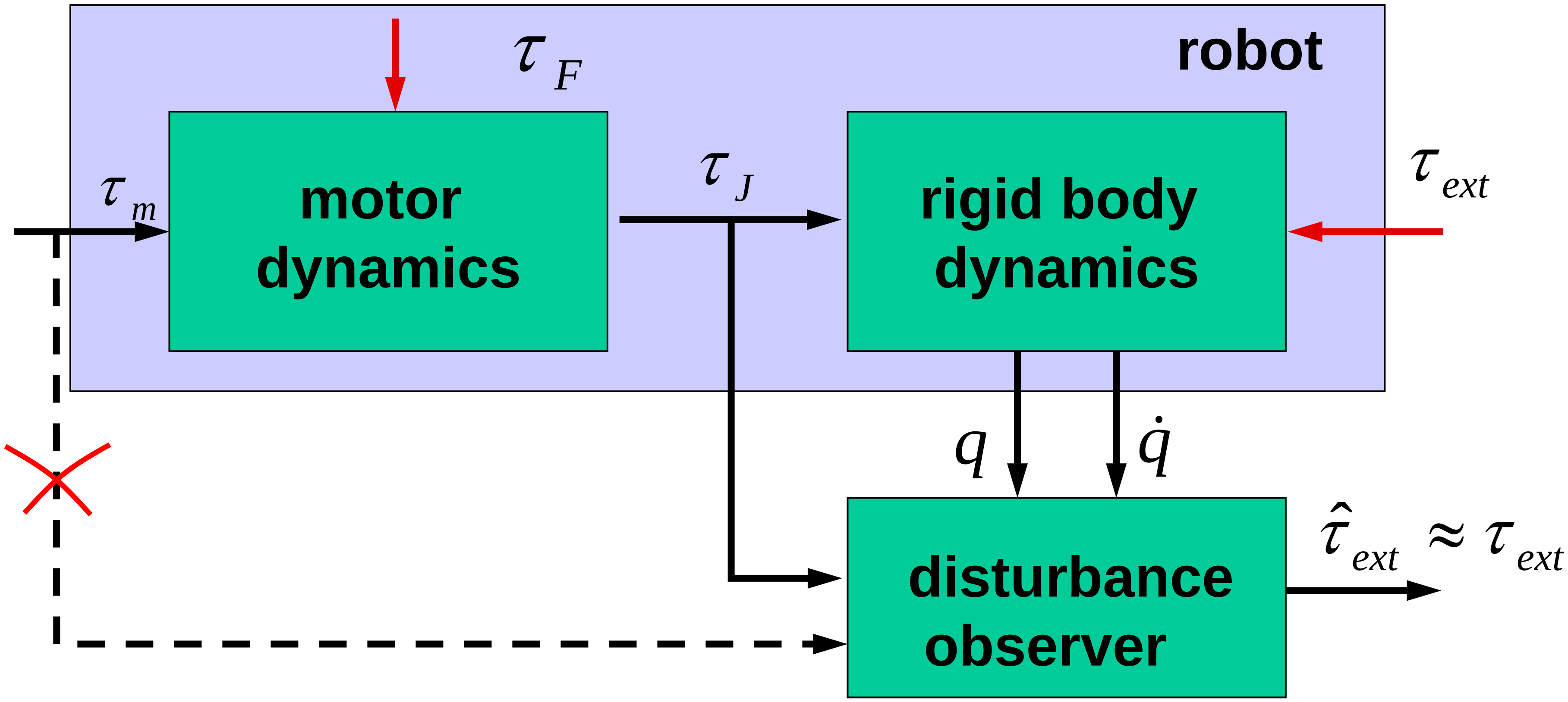

Impact Experiments
Head
Velocity: 2.0 m/s
Detection: None
Strategy: None


DLR
No Collision Detection
DLR


DLR
III. Impact Experiments LWRIII - Human

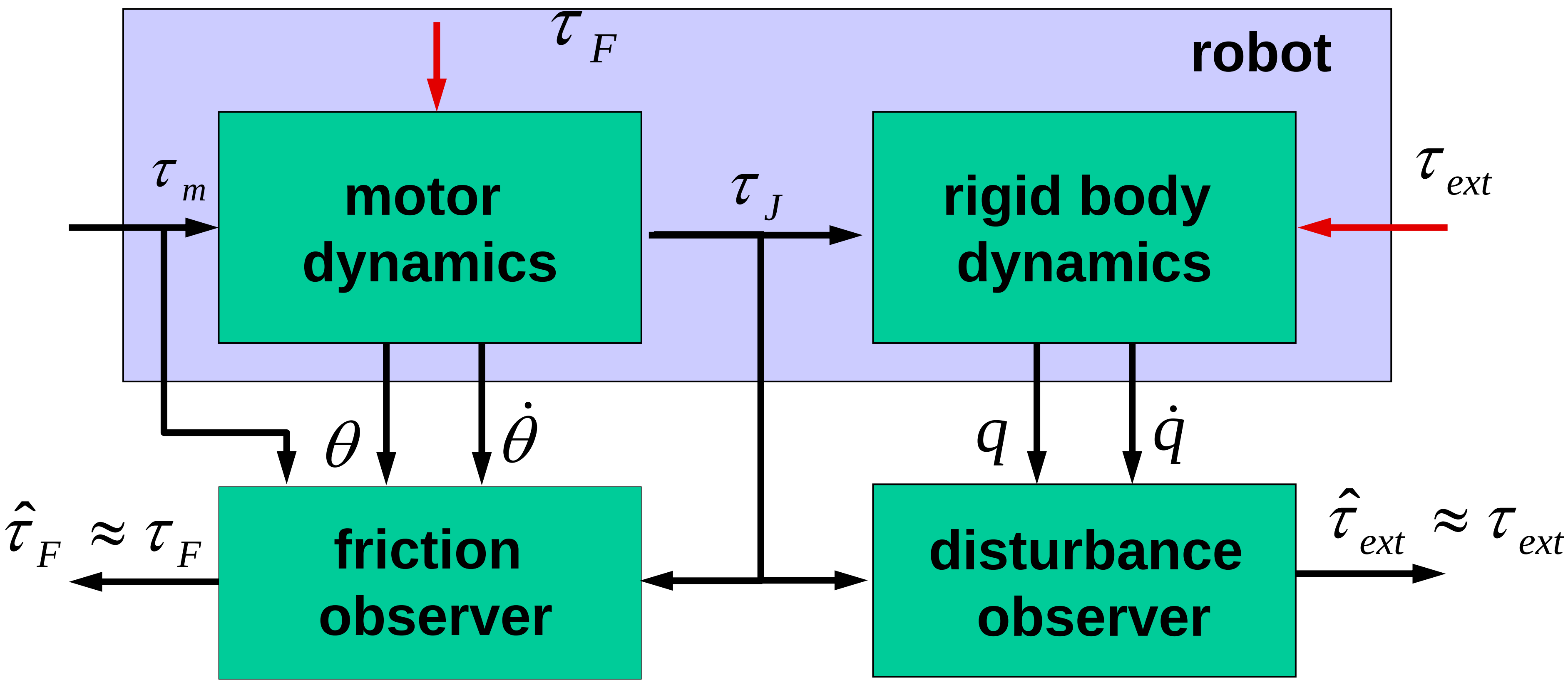


Disturbance Observer for Collision Detection



IROS'06
with Alessandro De Luca

Disturbance Observer for Collision Detection and Friction Compensation



IROS'08
with Alessandro De Luca

Joint Flexibility – a Feature, not a Drawback

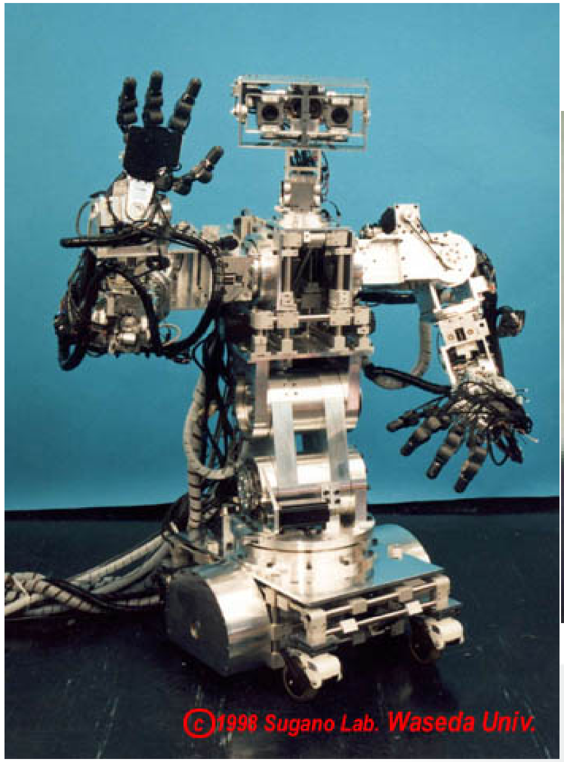
•Constant Compliance:

Series Elastic Actuators (G. Pratt)

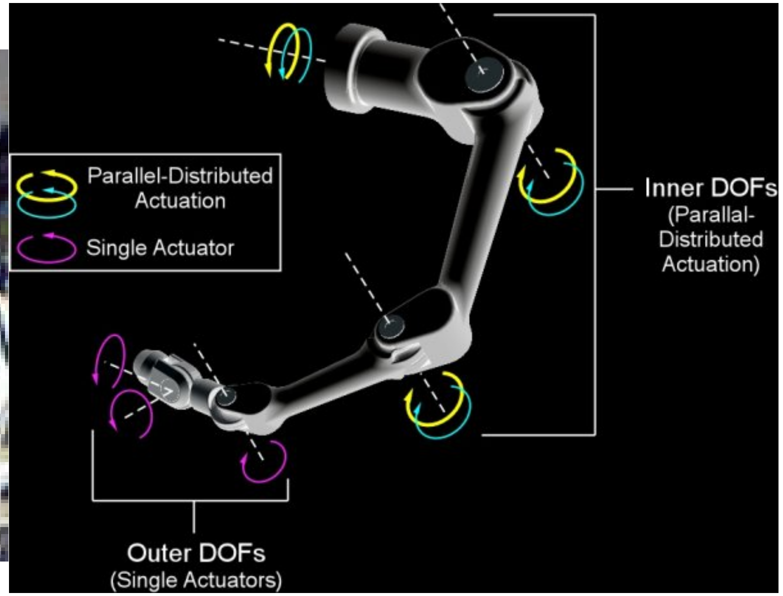
Benefits are INTRINSIC to the arm design w.r.t.:

- Robust manipulation in unknown environments
- Dynamic Performance and energy efficiency
- Mechanical robustness in case of failure or impact
- Safe interaction with humans

•Variable Impedance Actuators (VIA):



(Bicchi, Univ. of Pisa)



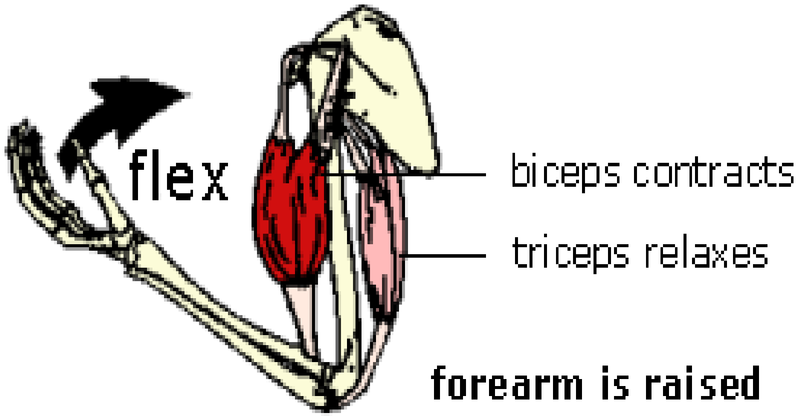
(Khatib, Stanford Univ.)

Rigid vs. Compliant Actuation

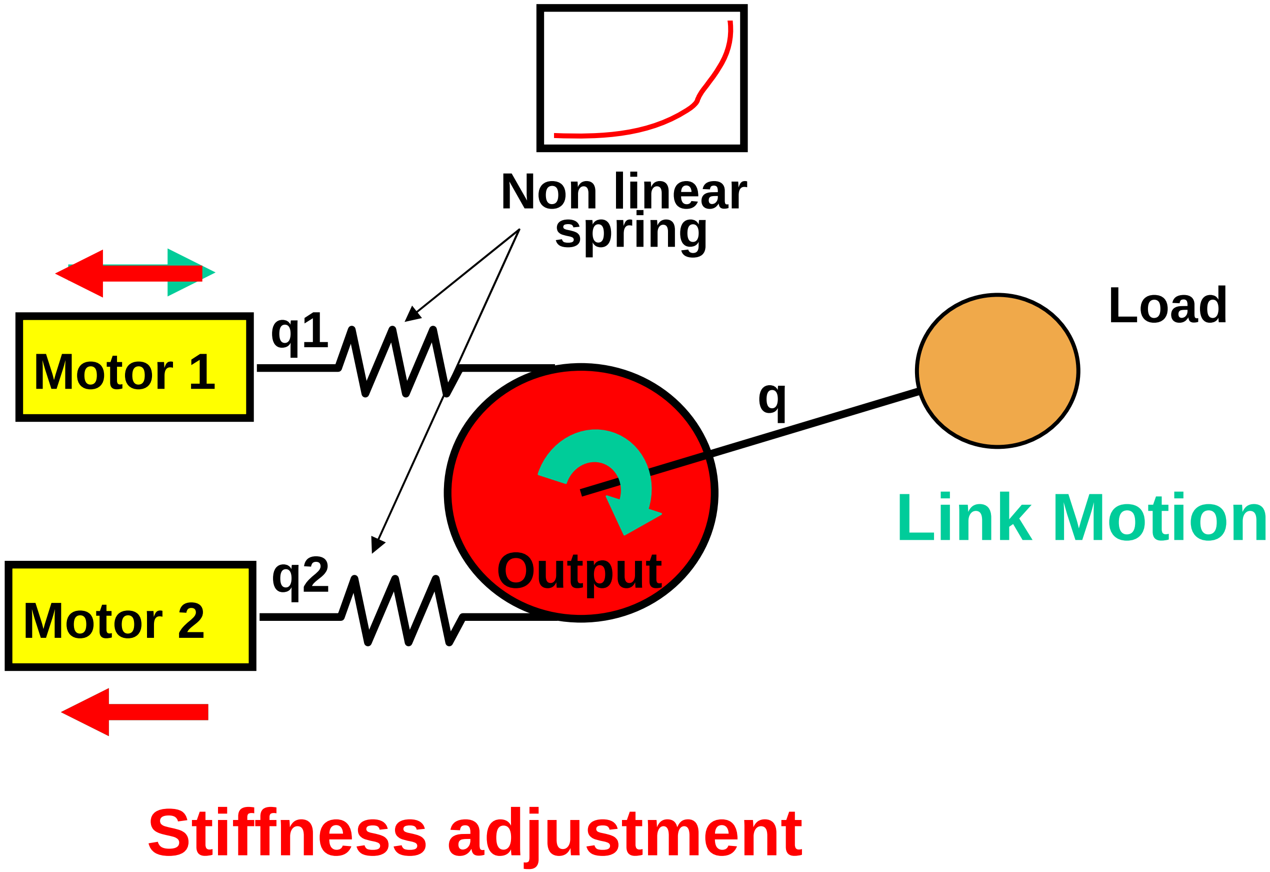
One of today's most advanced humanoid

Human top performance

The Principle of VIA

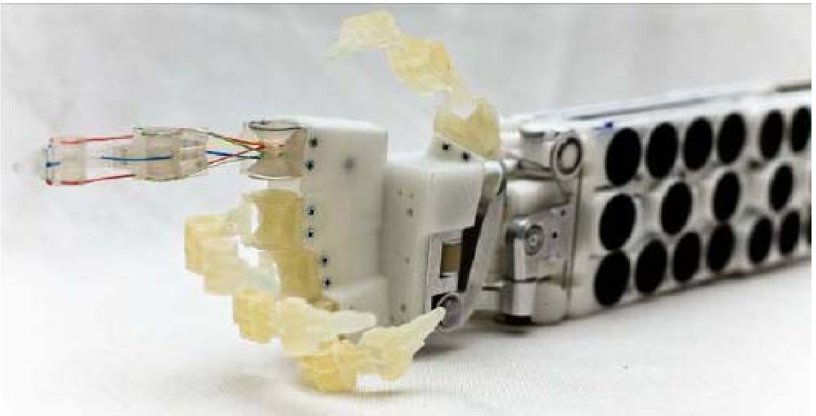


The antagonistic concept

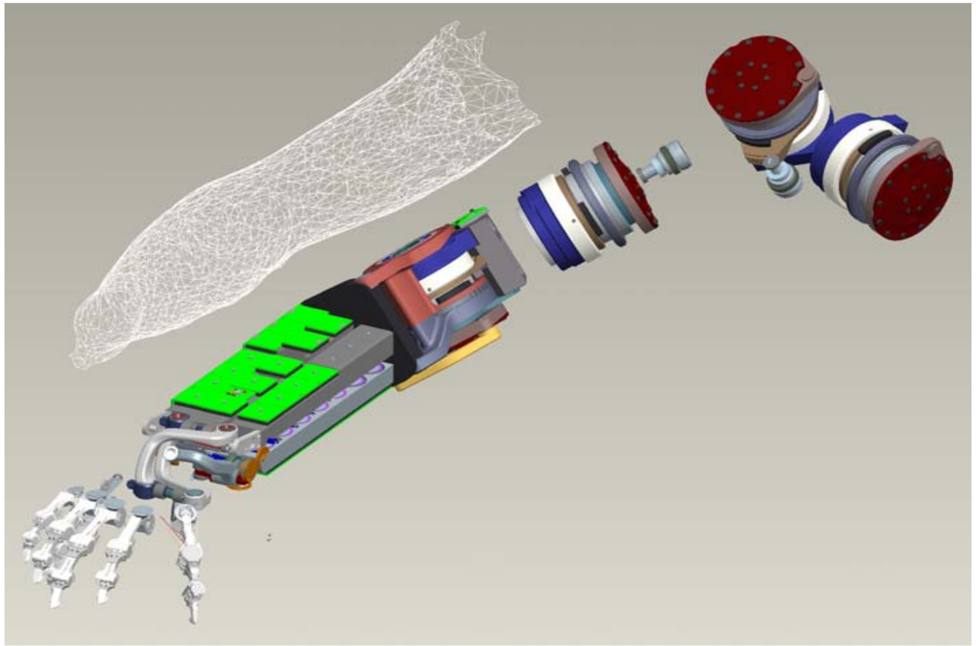


The New DLR Hand-Arm-System

VIA – **V**ariable **I**mpedance **A**ctuation



new VIA Hand
(38 Motors)



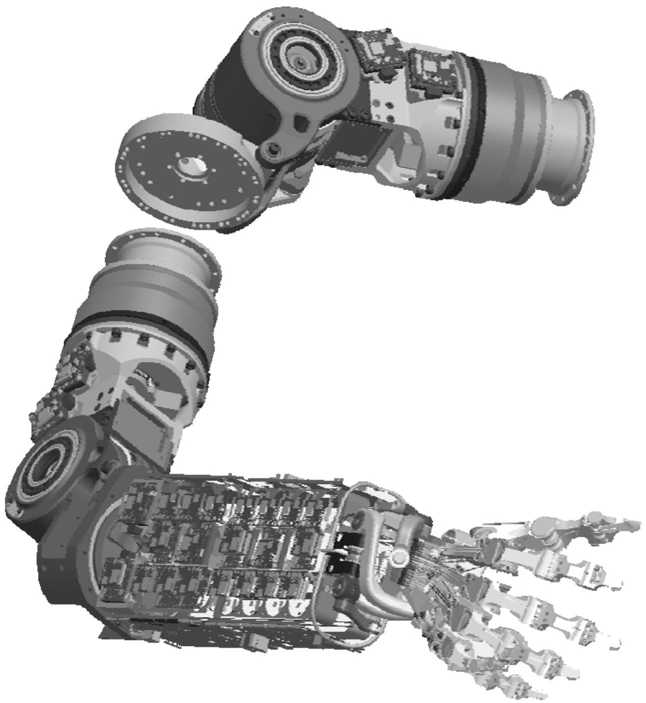
Sketch of VIA Arms

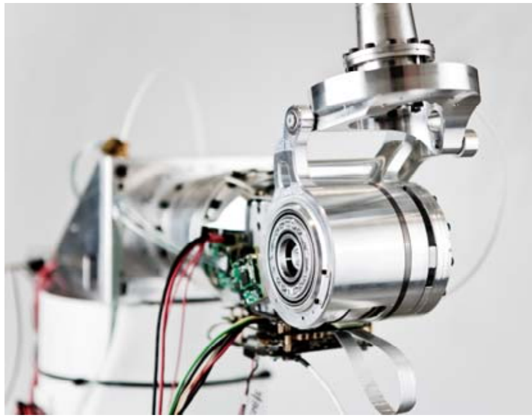
Extension of the passivity based control approaches to the VIA robots:

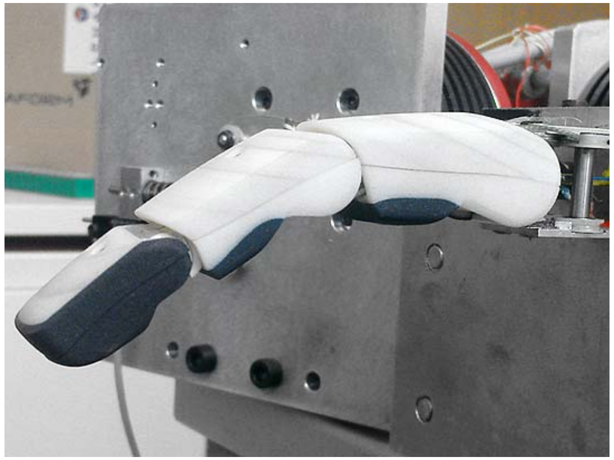
- Variable, nonlinear stiffness
- Strongly coupled joints

Anthropomorphic Hand-Arm-System

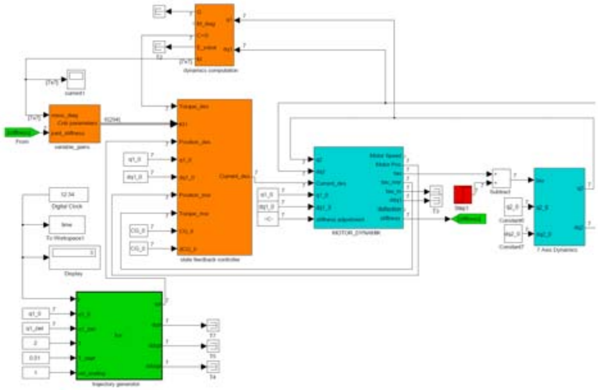
- Size, force and dynamics of a human arm/hand
- Variable stiffness
- *54 motors,108 position sensors*

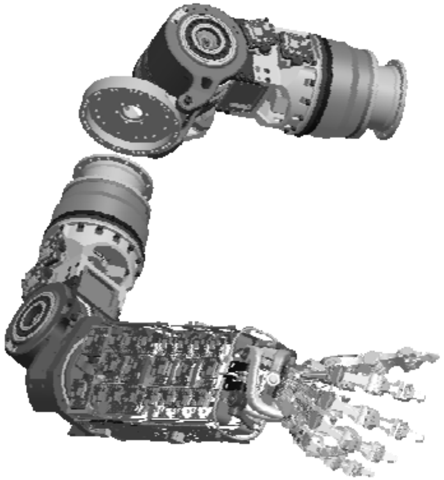


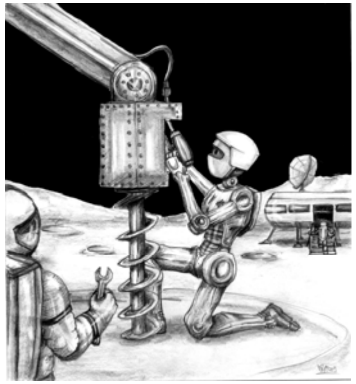




A Hand-Arm System for Space Robot Assistrance







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

- Variable, nonlinear stiffness
- Strongly coupled joints

Control of VIA Joints

The joints have very low intrinsic damping

useful for cyclic movements involving energy storage (running or throwing)

damping of the arm for fast, fine positioning tasks has to be realized by control.

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

Active Vibration Damping for VIA Joints

Extension of the passivity based approaches to systems of the form

$$M(q)\ddot{q} + C(q,\dot{q})\dot{q} + \frac{\partial U(q)}{\partial q} = \begin{bmatrix} \tau_m \\ 0 \end{bmatrix}$$

No damping

Active damping

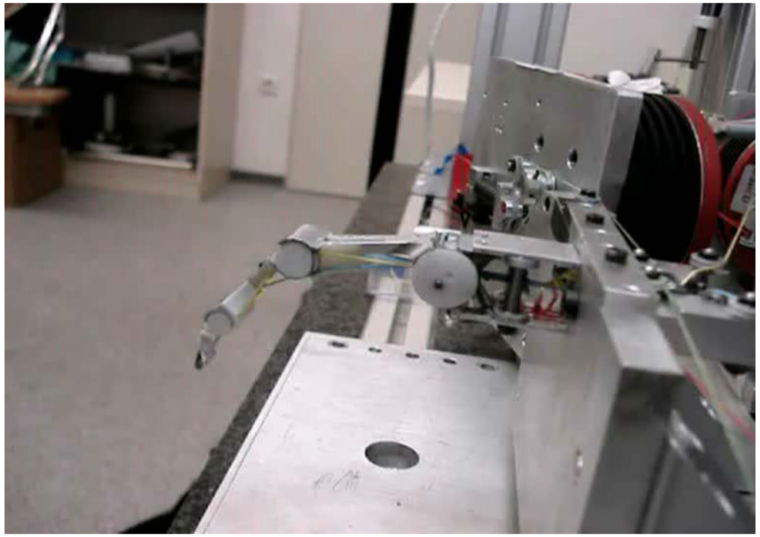
Performance Validation

Finger:

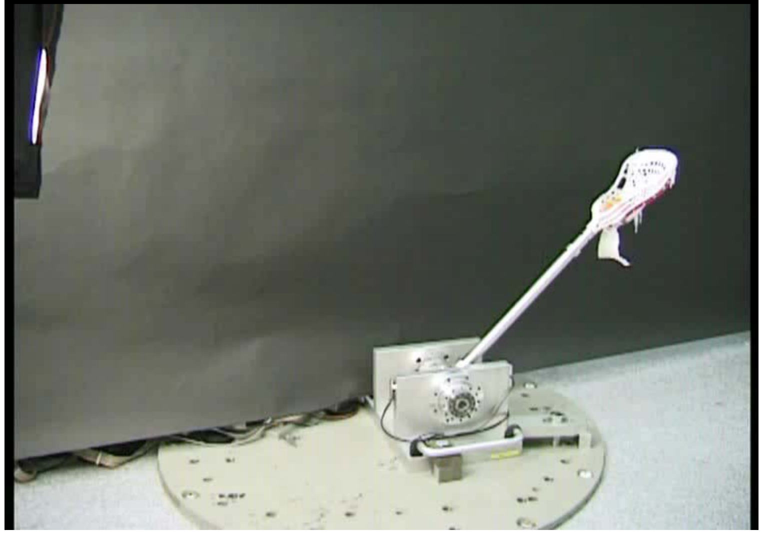
- Robust w.r.t. impacts

Arm Joints:

- Increase of performance due to energy storage

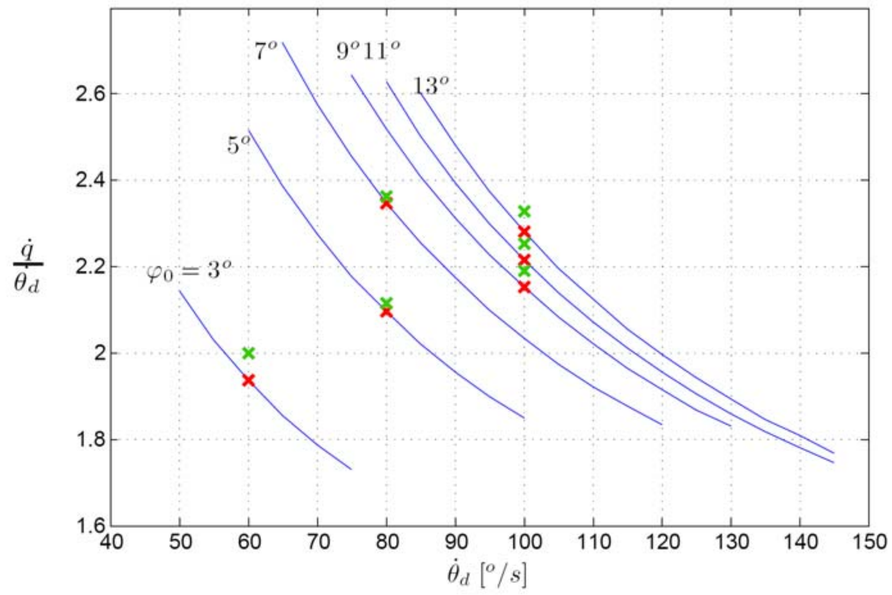


Rigid joint



VIA joint

Optimal Control for Maximal Performance



Optimized
stiffness and motion trajectory

Kicking Performance: Motivation

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

Justin at AUTOMATICA Fair