Safe Physical Human-Robot Interaction

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Robots designed to work in human environments

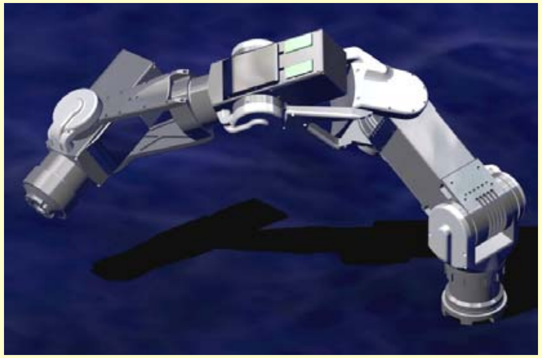
Extreme light-weight arms and hands with 1:1 load-weight ratio

- mobile manipulation
- interaction with unknown environments

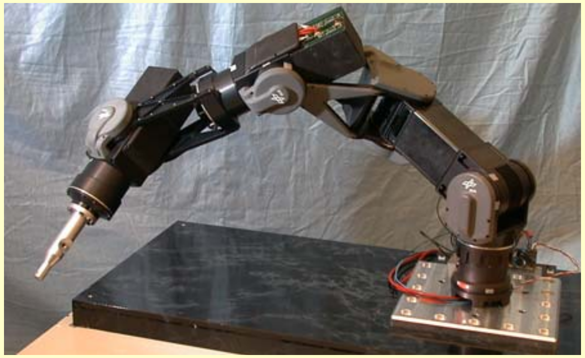
LWR I
(1992)

LWR III real (2002)

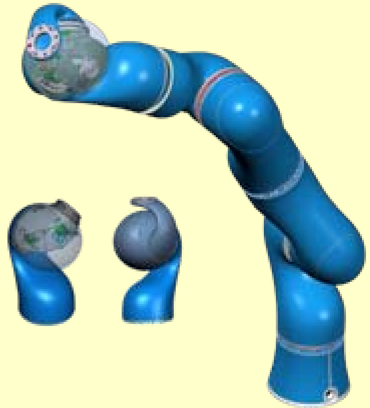
KINEMEDIC (2005)



LWR II virtual (1998)



LWR II real (1999)

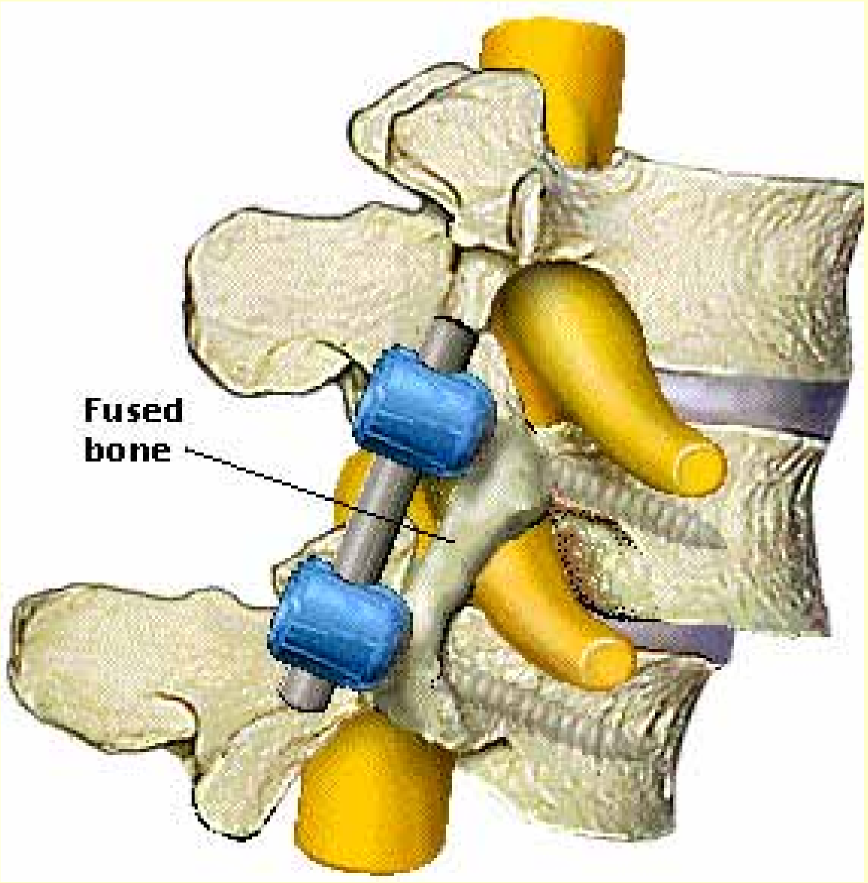


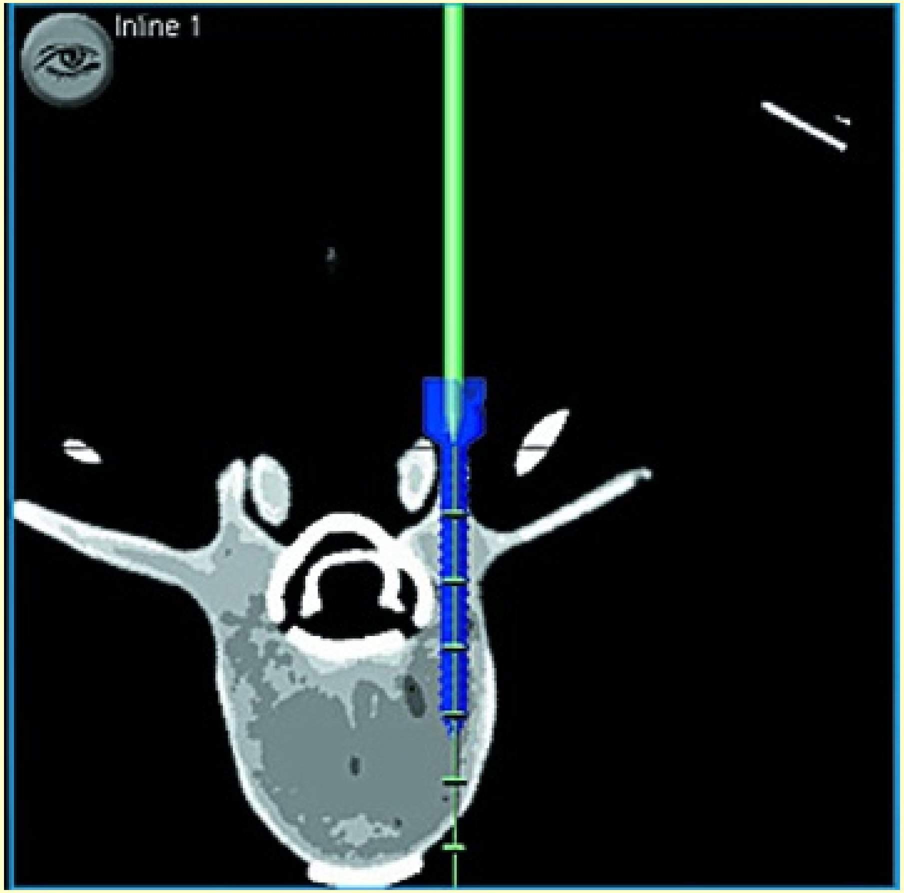
LWR III virtual (2000)


Working on your Visions
BKM

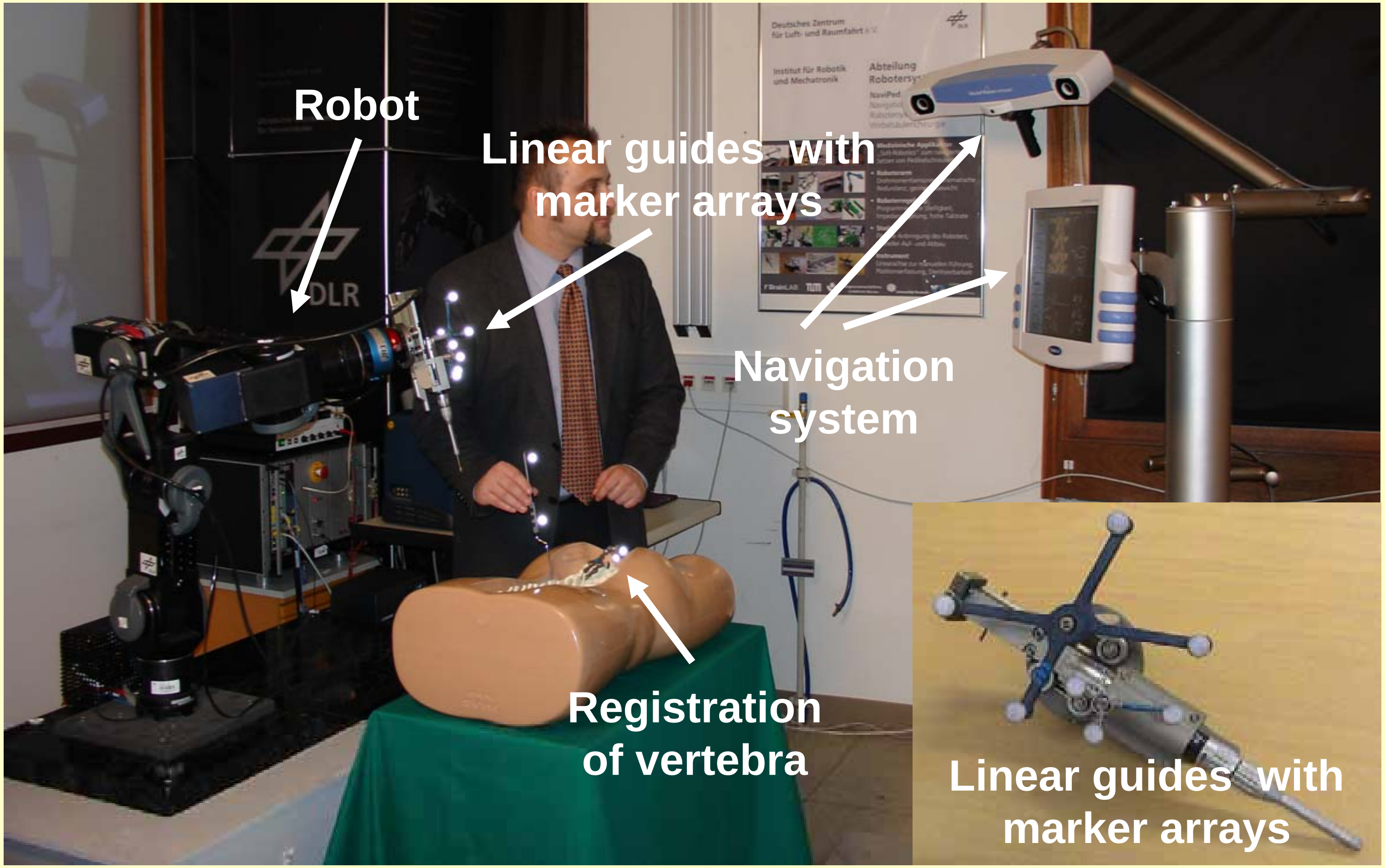

Serving
Water

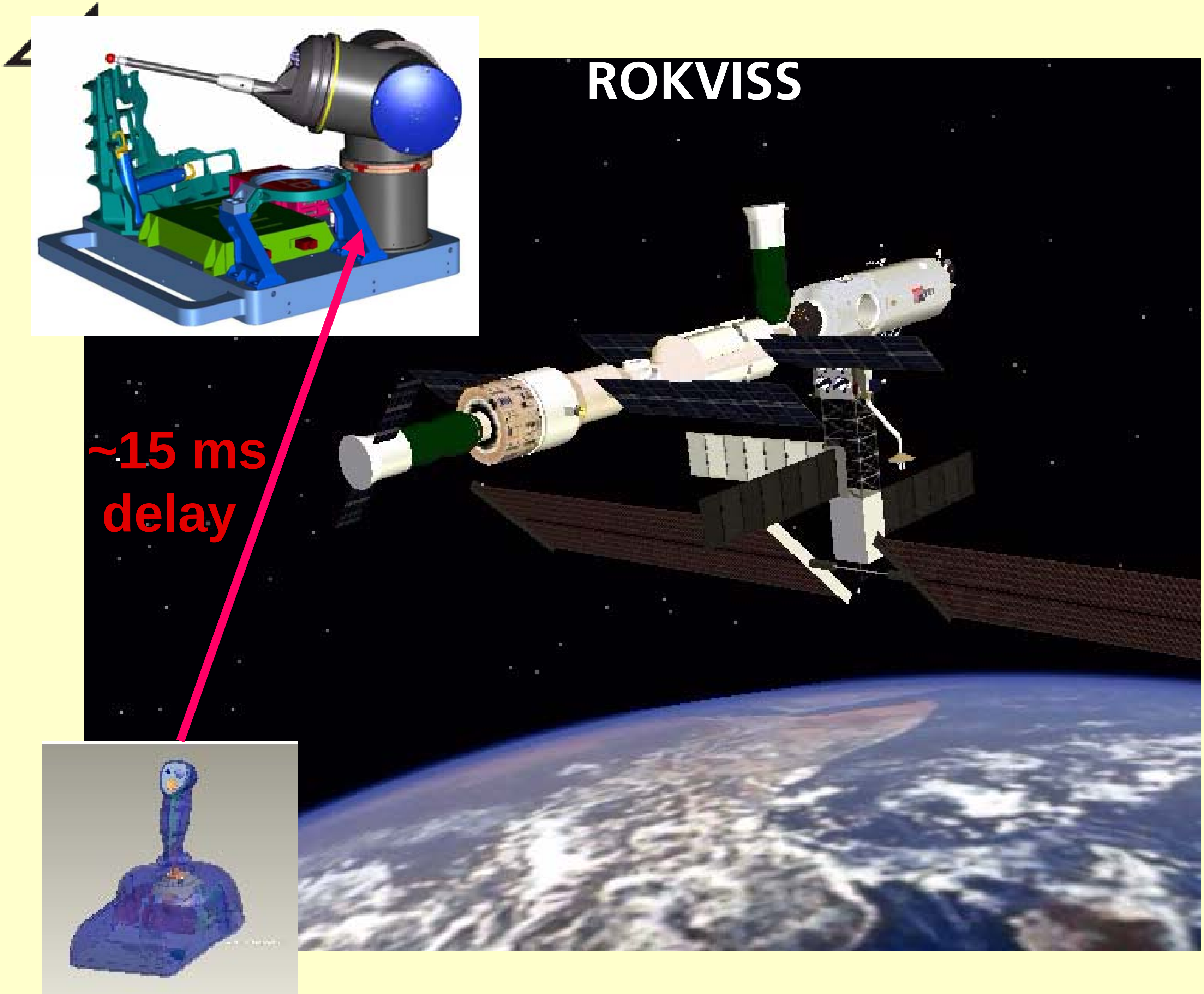
Placing of Pedicle Screws

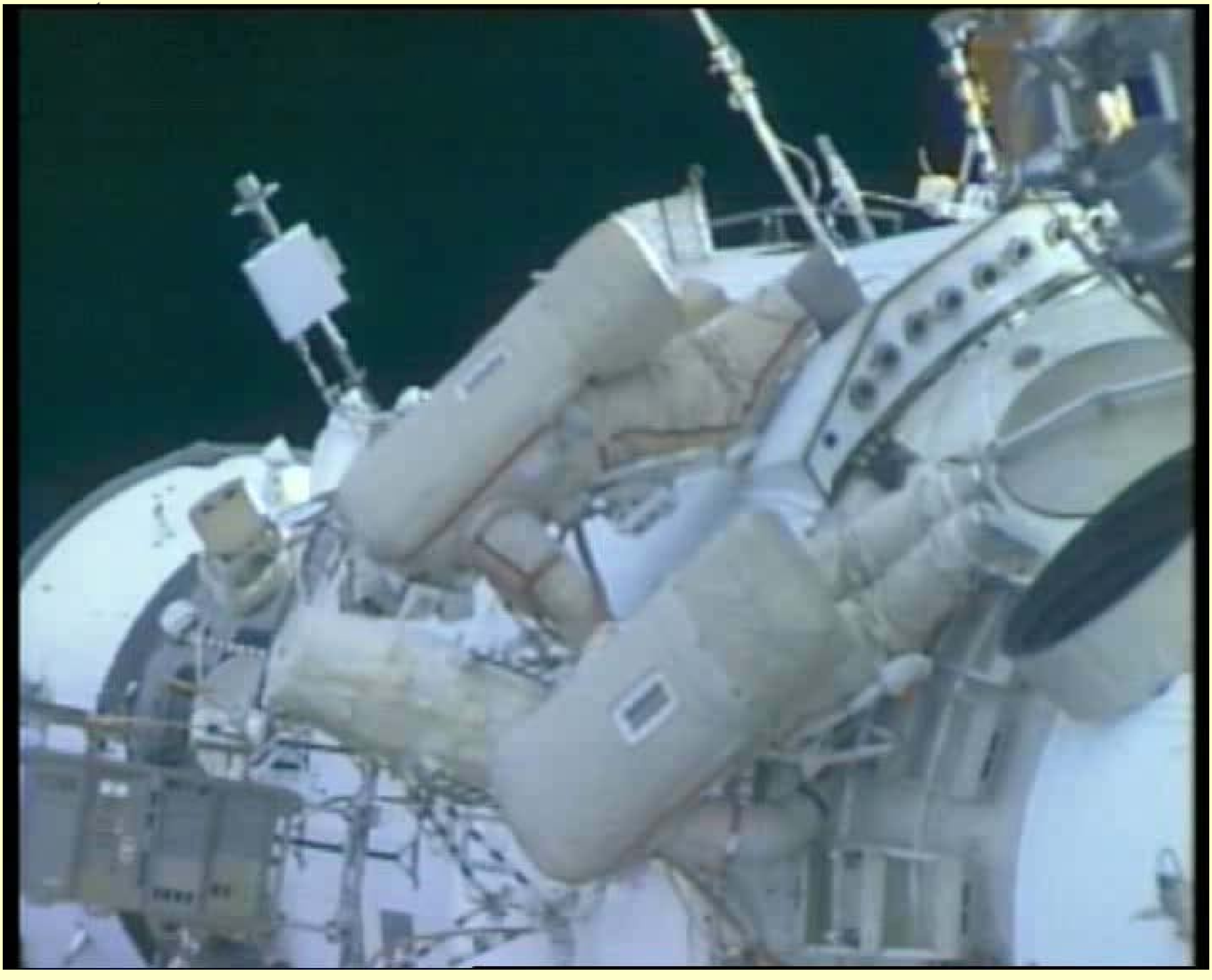




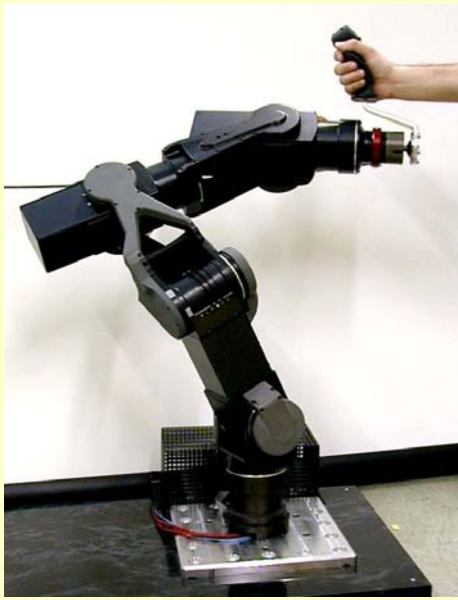
Experimental Setup with LBR II

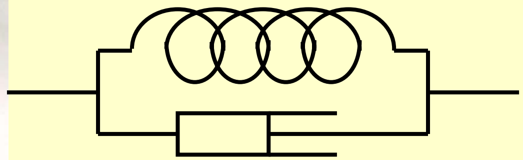


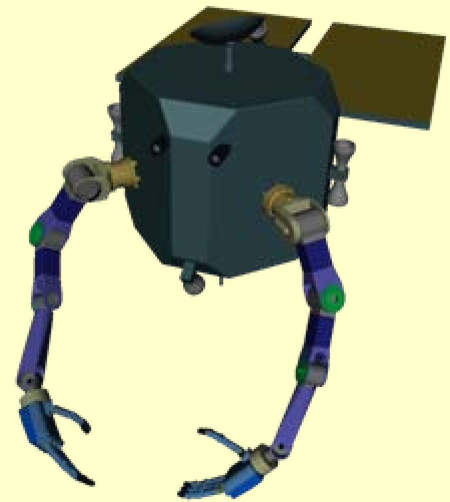

ROKVISS
~15 ms
delay



Tele-Maintenance







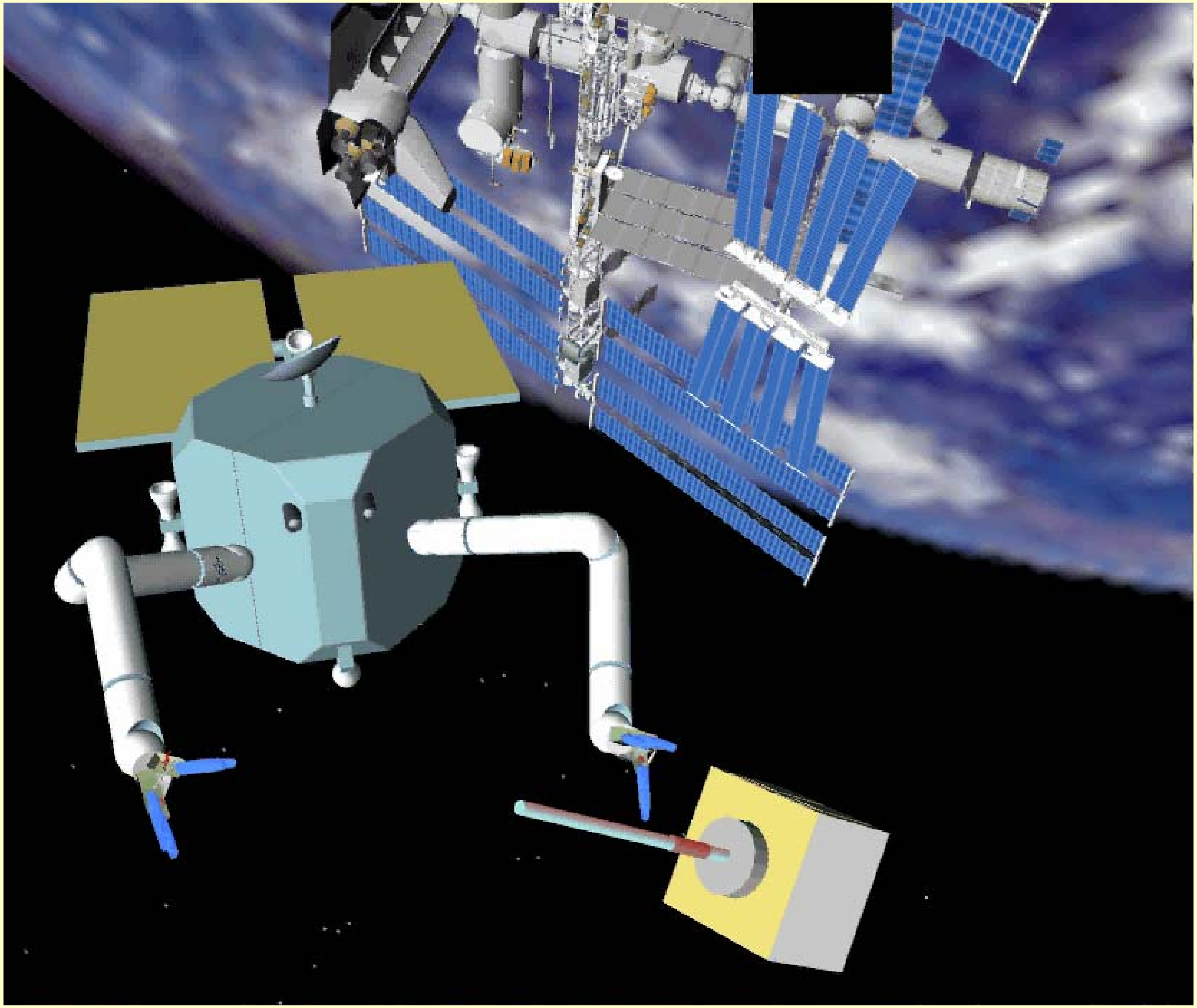
Oberpfaffenhofen **Space**

Force-Feedback: min. 6 DoF

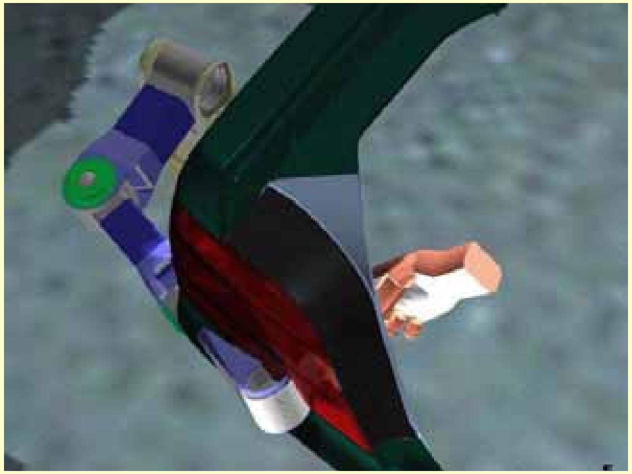
Our Vision

„Affordable“, remotely controlled operations in space with mobile (freeflying) robonauts for

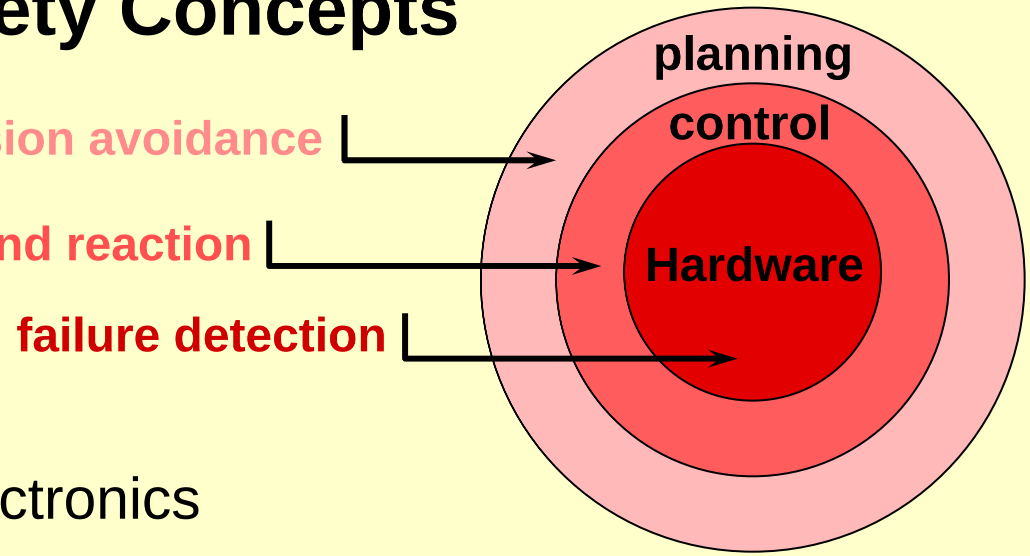
- Servicing
  and
- Exploration



Virtual Product Design: Assembly Scenarios



User Safety Concepts

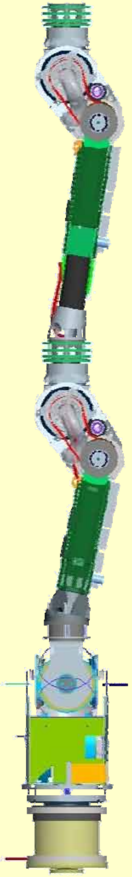


- intrinsically safe robot design
- redundant, error detecting electronics
- redundant sensors
- ”dead-man-switch”, range check for measurements/commands,…
- robust, passivity based control algorithms
- collision detection/reaction with joint torque sensors
- direct control/limitation of exerted forces and torques
- soft robotics – compliance control
- collision avoidance with redundant kinematics

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

Vibration Damping

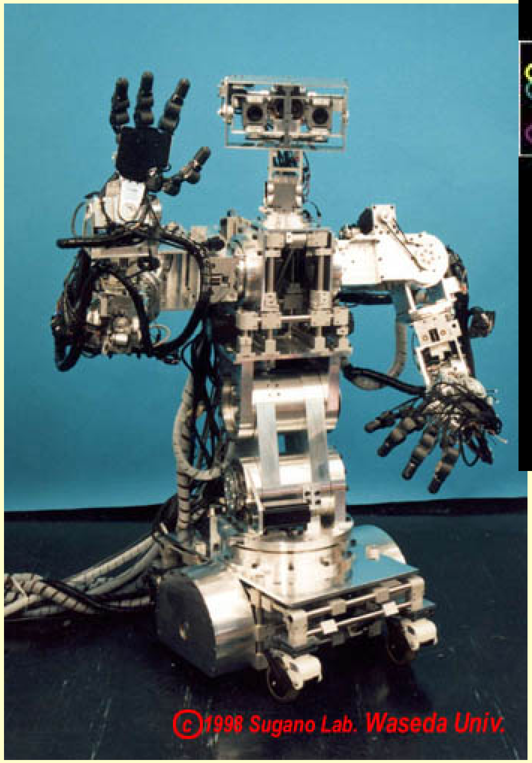
Light-weight ⇨ higher joint compliance ⇨ vibrations

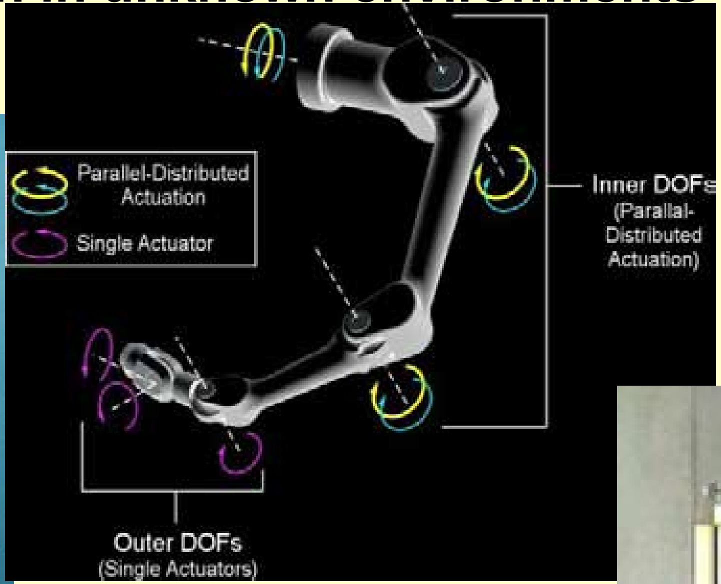
Measurement ⇨ torque sensor ⇨ vibration damping

Joint Flexibility – a Feature, not a Drawback?

YES, for compliance control:

- **Safe interaction with humans**
- **Manipulation in unknown environments**
- **Haptics**

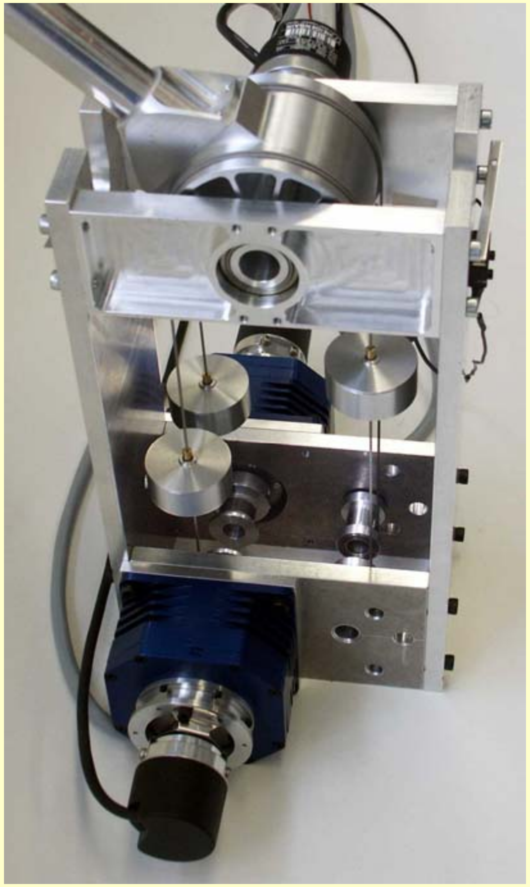




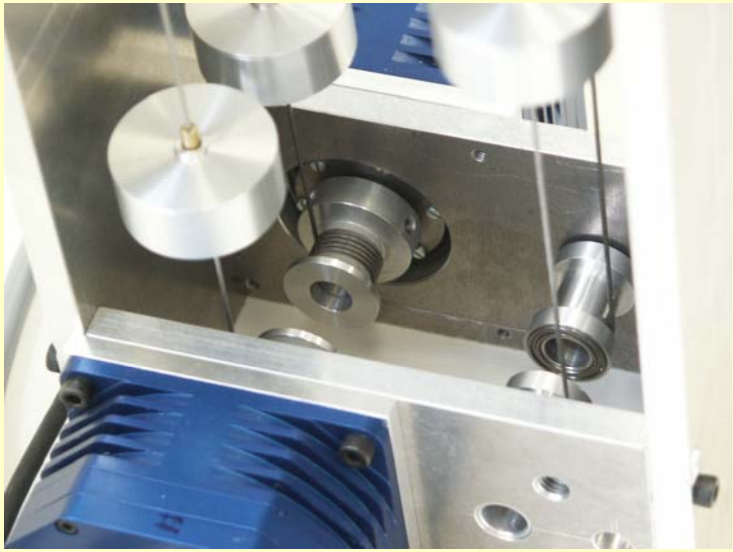
(Khatib Lab, Stanford Univ.)

(Bicchi Lab, Univ. of Pisa)

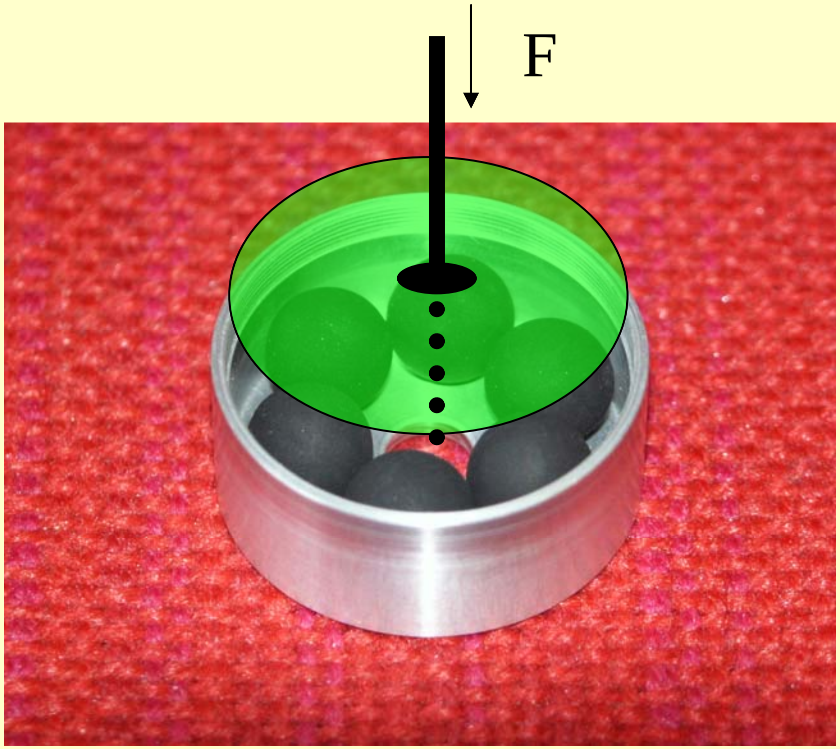
Antagonistic test joint setup



- Every motor used in bidirectional mode
- 4 progressive elastic elements per joint
- direct drive to prevent gear side-effects
- tendon-driven
- motor unit miniaturisable to Ø 28mm
- at least 30N at fingertip

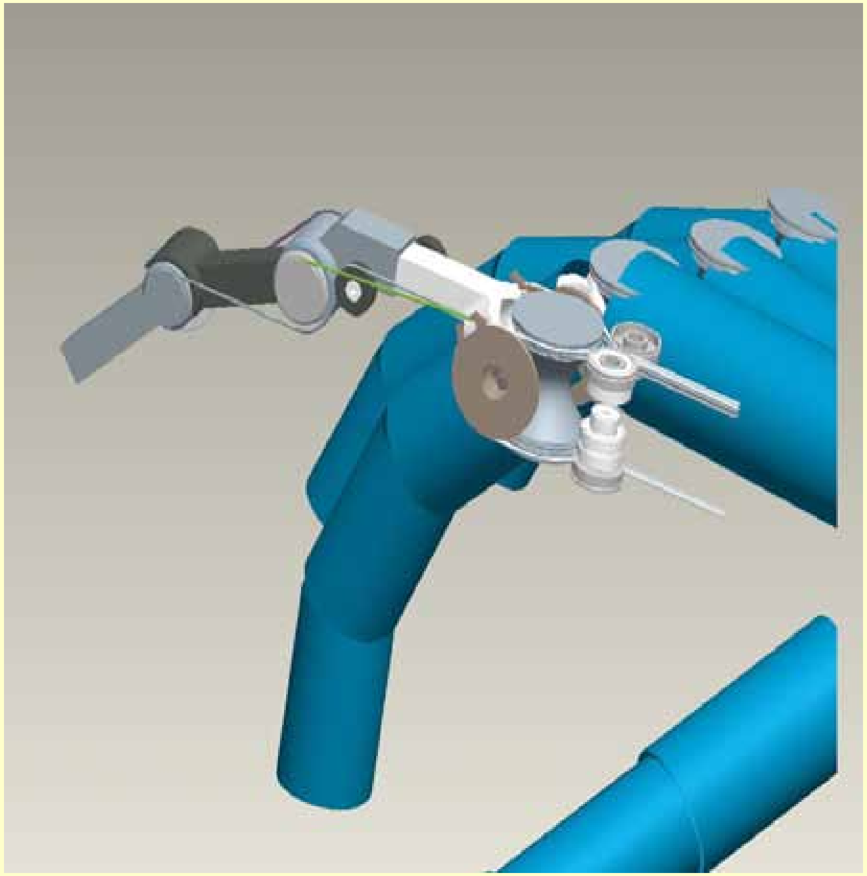


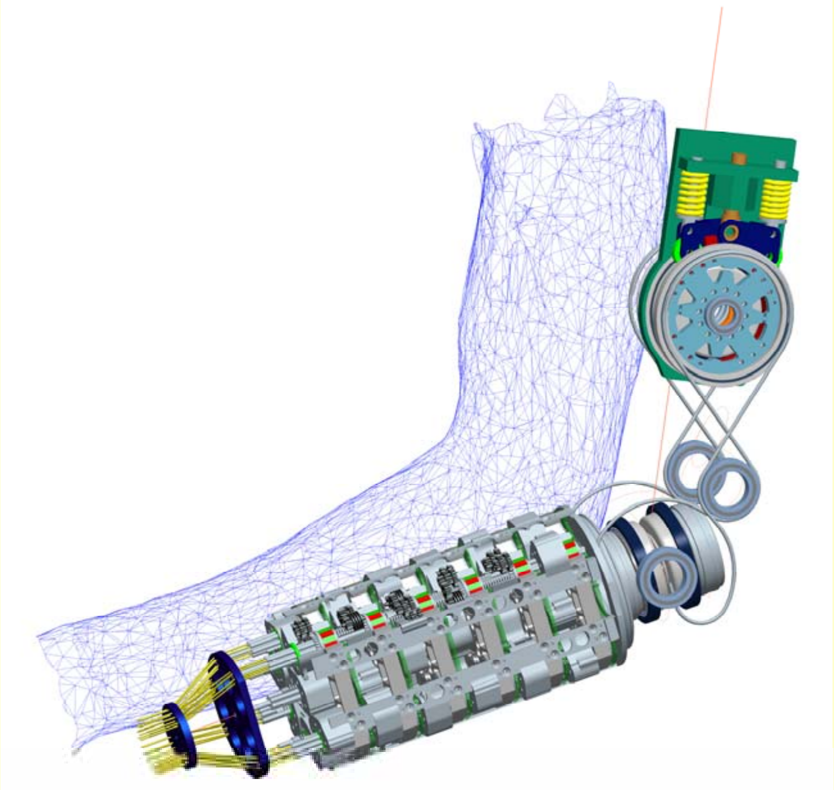
Passively yielding joints



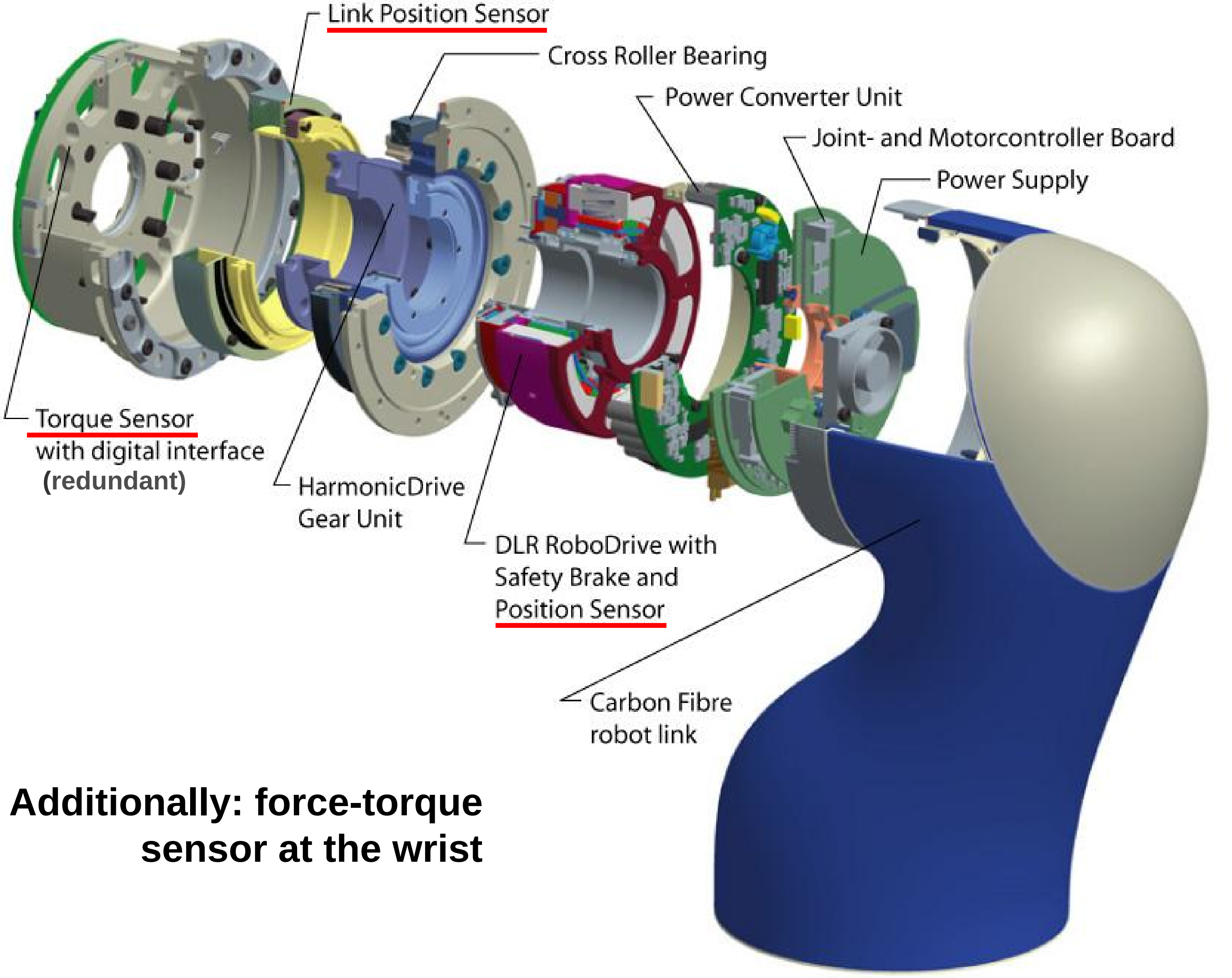
- rubber balls have progressive spring properties with nearly exponential characteristics
- the force with which the balls are squeezed determines the stiffness of the box
- adaptable characteristics through number and diameter of balls

Design Overview





Mechatronic Joint Design



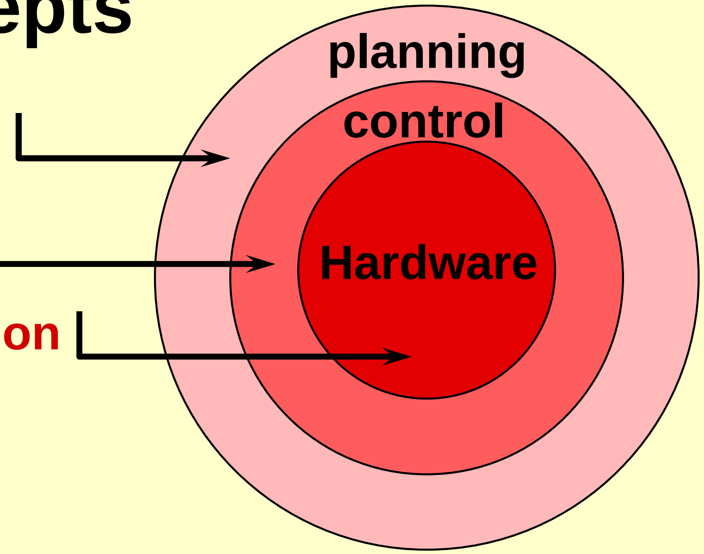
Additionally: force-torque sensor at the wrist

User Safety Concepts

collision avoidance

collision detection and reaction

failure detection



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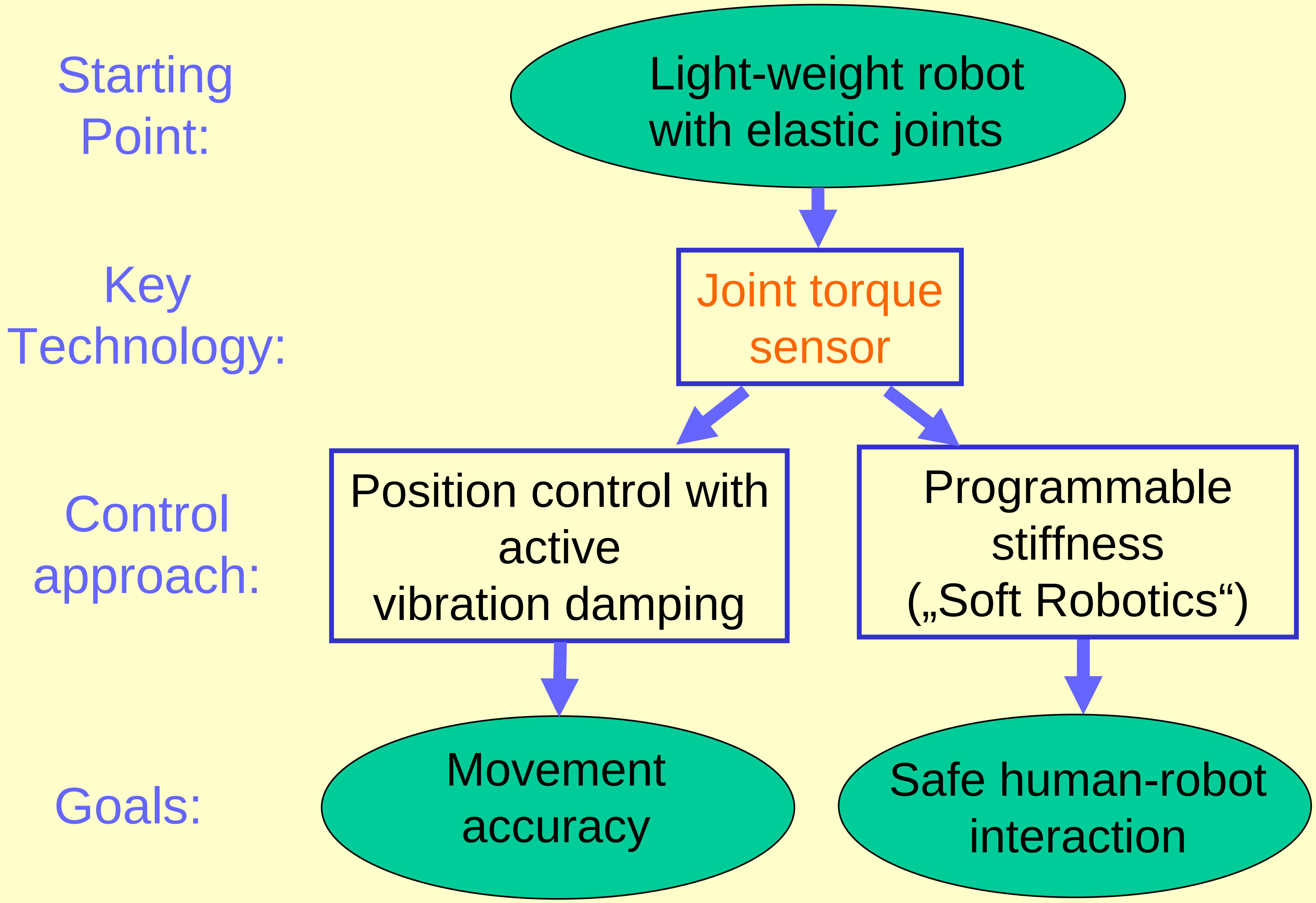
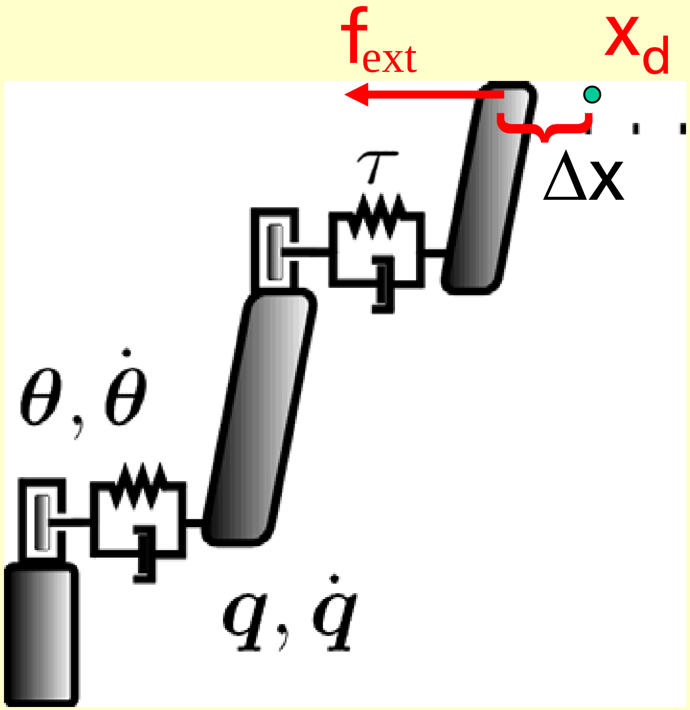
Strategy


Starting Point:
Light-weight robot with elastic joints
Key Technology:
Joint torque sensor
Control approach:
Position control with active vibration damping
Programmable stiffness („Soft Robotics“)
Goals:
Movement accuracy
Safe human-robot interaction

Flexible Joint Robot



State vector:

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

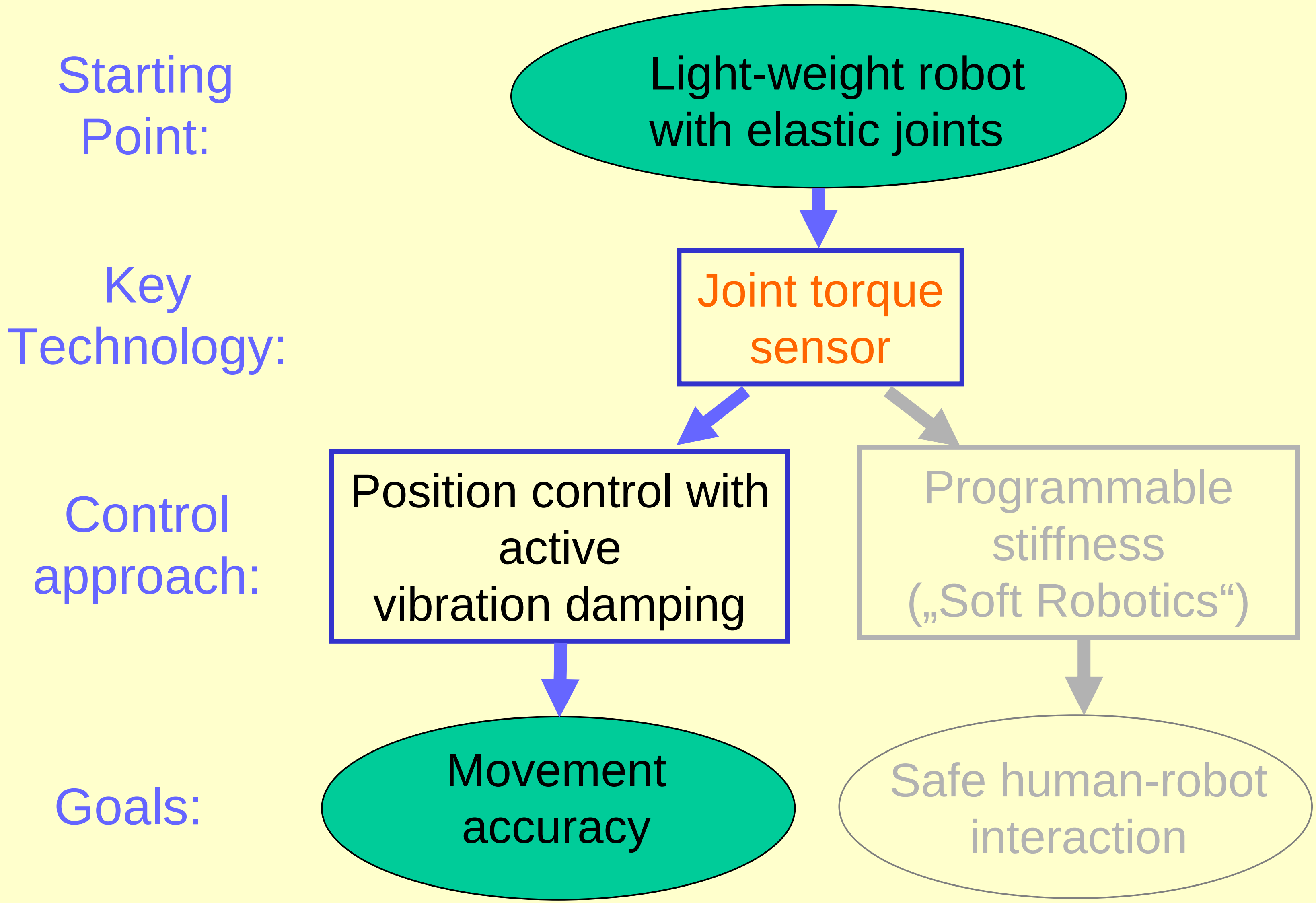
$$M(q)\ddot{q} + C(q,\dot{q})\dot{q} + g(q) = \tau + DK^{-1}\dot{\tau} + \tau_{ext}$$

$$B\ddot{\theta} + \tau + DK^{-1}\dot{\tau} = \tau_m$$

τ_a

$$\tau = K(\theta - q)$$

Strategy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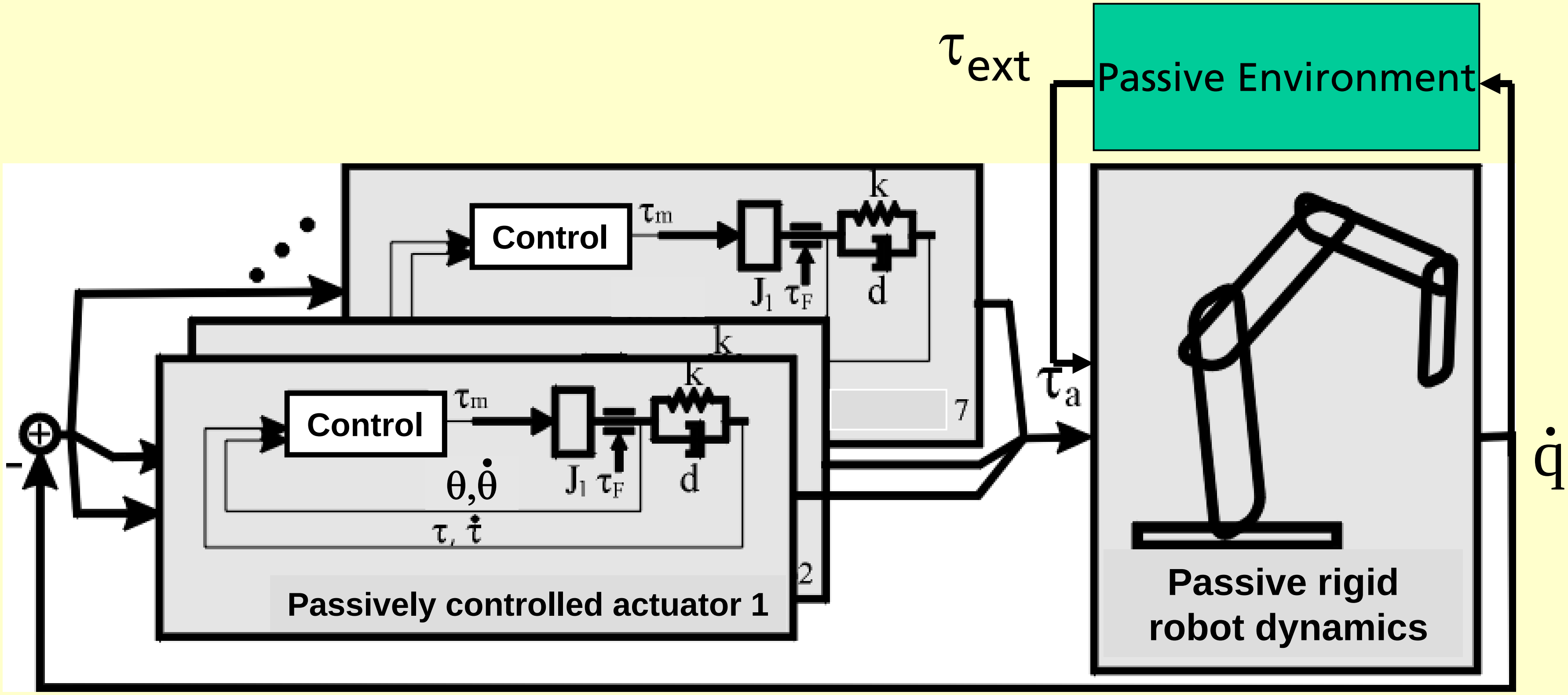
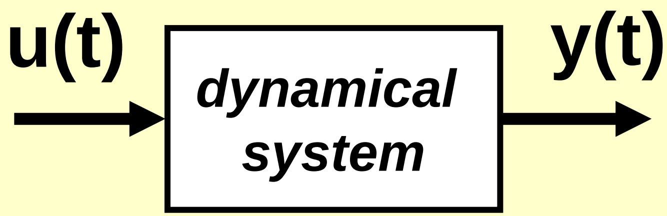
Position Control with Full State Feedback

- global asymptotically stable (Lyapunov-Analysis)
- passive => robust with respect to parameter uncertainties



Model error may cause performance degradation but not in instability

Passivity



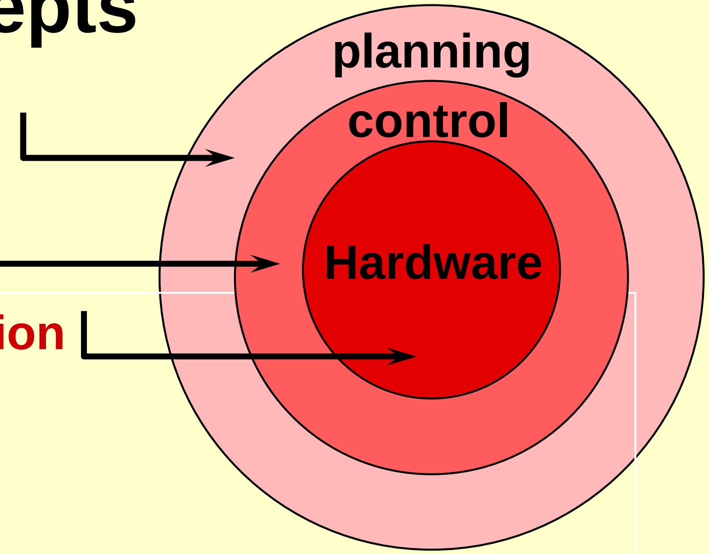
$$u^T(t)y(t)$$ - **Power**

System is passive, if

$$\exists \alpha > 0 \qquad \int_0^t u^T(t)y(t)dt > -\alpha$$

The energy which can be extracted from the system is bounded

User Safety Concepts



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Quantization of Severity of Impact Injury

No standards for robotics

Some “borrowed” indices

Head

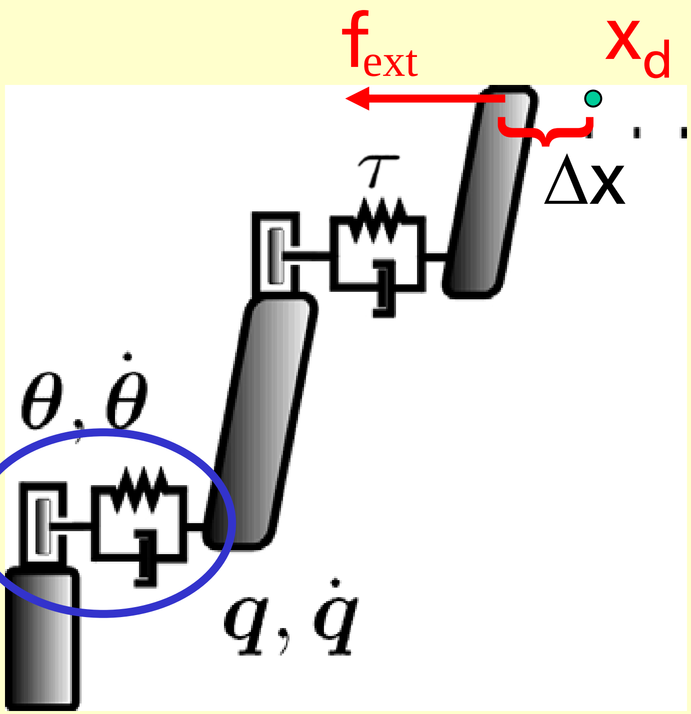
- **H**ead **I**njury **C**riterion - HIC (car crash tests)
- Maximum Impact Power
- Maximum Mean Strain Criterion
- Vienna Institute Index, Effective Displacement Index, Revised Brain Model

!?

$$\mathrm{HIC} = \max_{(t_{2,v}-t_{1,v})} \left((t_{2,v} - t_{1,v}) \cdot \left(\frac{1}{t_{2,v}-t_{1,v}} \int_{t_{1,v}}^{t_{2,v}} \ddot{\mathbf{x}}_{M_{av}} \, \mathrm{d}t \right)^{\left(\frac{5}{2}\right)} \right) \leq 1000$$

mean acceleration

Collision Detection



measured signals:

$$\theta, \tau$$

computed signals:

$$q, \dot{\theta}, \dot{q} \qquad \tau_m$$

observable:

collision torque

$$M(q)\ddot{q} + C(q, \dot{q})\dot{q} + g(q) = \tau + DK^{-1}\dot{\tau} + \tau_{ext}$$

$$B\ddot{\theta} + \tau + DK^{-1}\dot{\tau} = \tau_m - \tau_F$$

gearbox friction torque / actuator failure

Observer Implementation

(De Luca et. al., 2005)

$$\hat{\boldsymbol{\tau}}_{ext} \quad = \quad \boldsymbol{K}_I \left[\boldsymbol{p}(t) - \boldsymbol{p}(0) - \int_0^t \dot{\hat{\boldsymbol{p}}}(t) \, \mathrm{d}\boldsymbol{s} \right]$$

$\boldsymbol{p}(t) = \boldsymbol{M}(\boldsymbol{q})\dot{\boldsymbol{q}}$ - generalized momentum

$$\dot{\hat{\boldsymbol{p}}}(t) \quad = \quad \boldsymbol{\tau} - \boldsymbol{C}^T(\boldsymbol{q}, \dot{\boldsymbol{q}})\dot{\boldsymbol{q}} - \boldsymbol{g}(\boldsymbol{q}) - \hat{\boldsymbol{\tau}}_{ext}$$

Linear resulting observer dynamics:

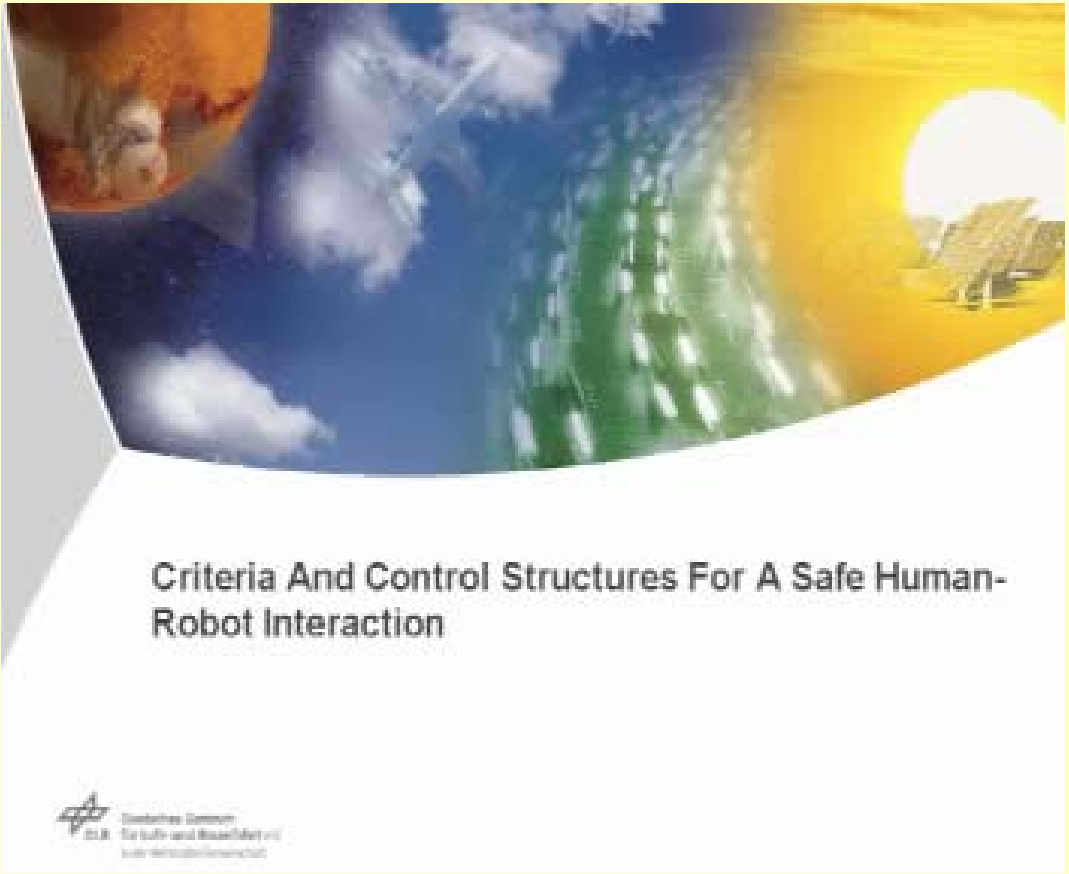
$$\dot{\hat{\boldsymbol{\tau}}}_{ext} + \boldsymbol{K}_I \hat{\boldsymbol{\tau}}_{ext} = \boldsymbol{K}_I \boldsymbol{\tau}_{ext}$$

Ideal situation (no noise) $\boldsymbol{K}_I \rightarrow \infty \quad \Longrightarrow \quad \boxed{\hat{\boldsymbol{\tau}}_{ext} \approx \boldsymbol{\tau}_{ext}}$

Reaction Strategies

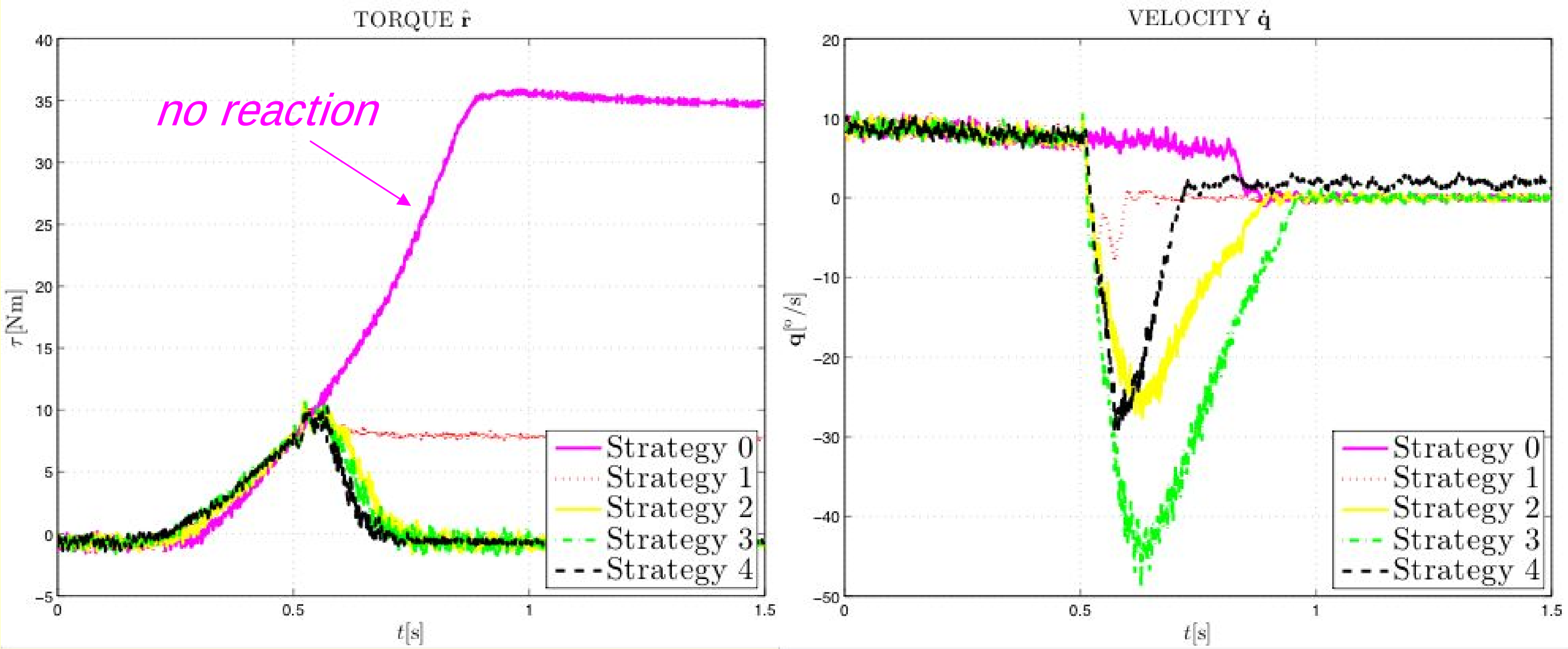
- strategy 1: stopping the trajectory
- strategy 2: gravity compensated torque mode
- strategy 3: impedance control mode using $\boldsymbol{\tau}_{ext}$
- strategy 4: admittance control mode using $\boldsymbol{\tau}_{ext}$

Impact Tests



Results on Balloon Impact

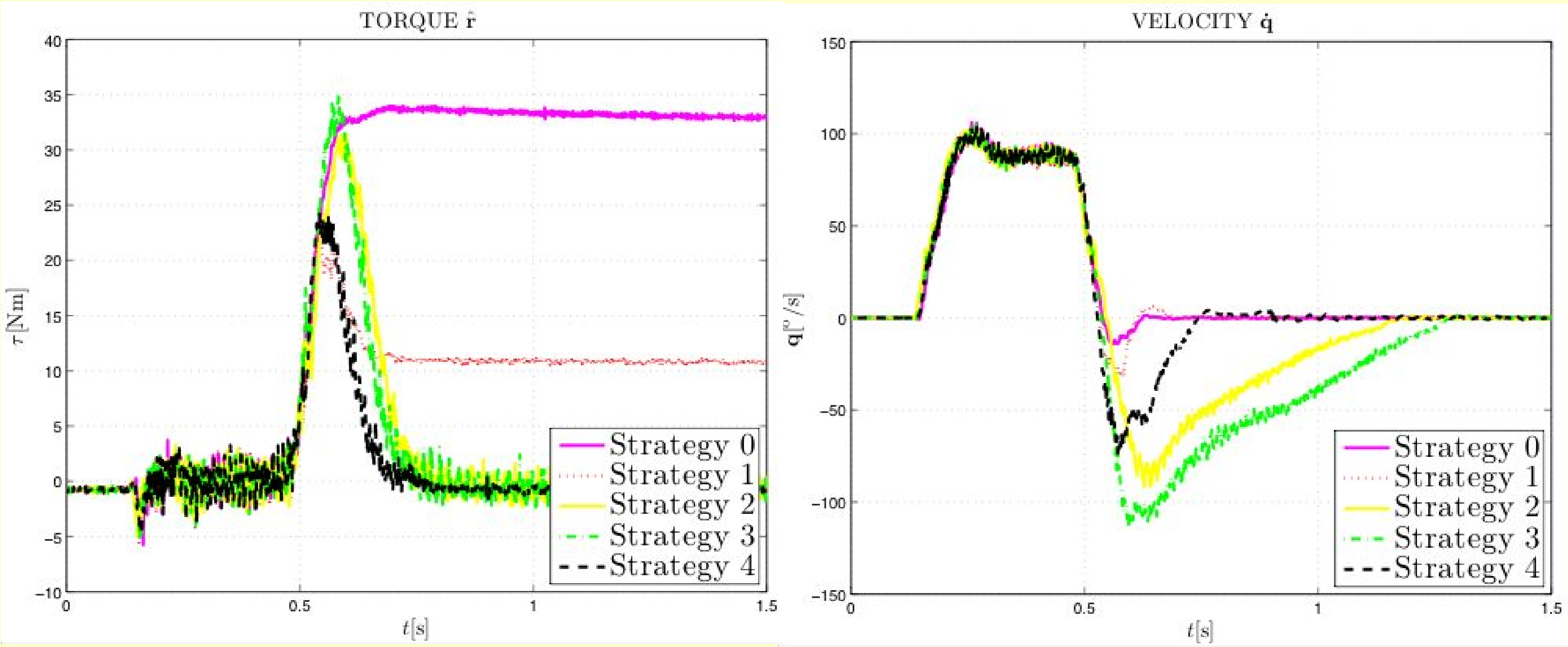
- residual & velocity on joint 4 for different reaction strategies



impact at 10°/s with coordinated joint motion

Results on Balloon Impact (cont'd)

- residual & velocity on joint 4 for different reaction strategies



impact at 100°/s with coordinated joint motion

Results on Dummy Head Impact

- approaching at 30°/s with each joint
- residual gains K_I = diag{25}

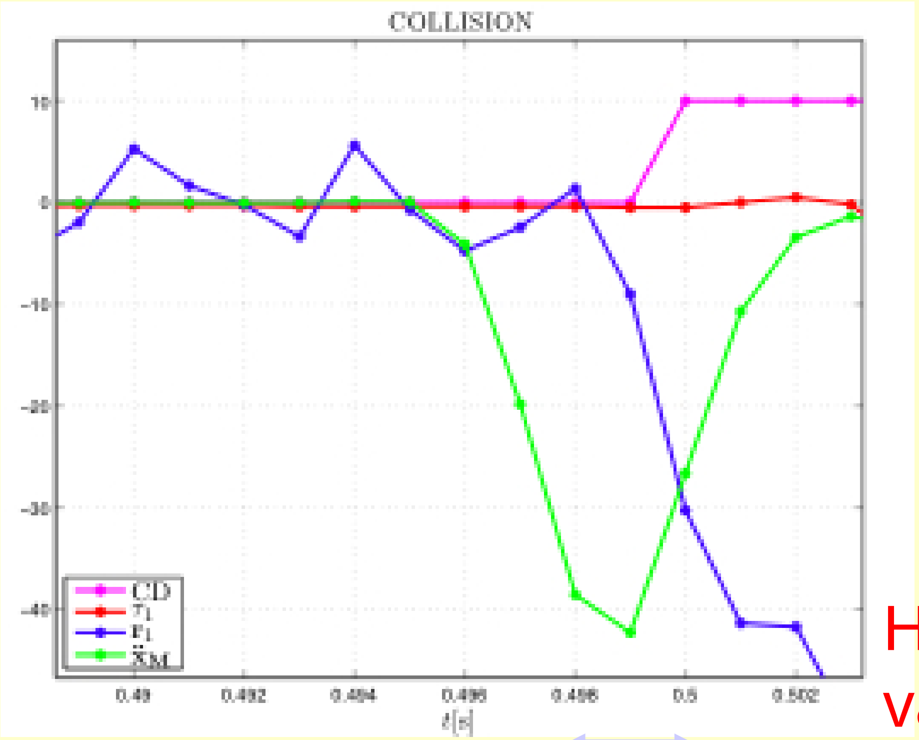
joint torque

observer

0/1 detection

acceleration

joint 1



2 ms

HIC < 400

HIC approaches critical value at 70°/s

Strategy

Starting Point:

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Key Technology:

Joint torque sensor

Control approach:

Position control with active vibration damping

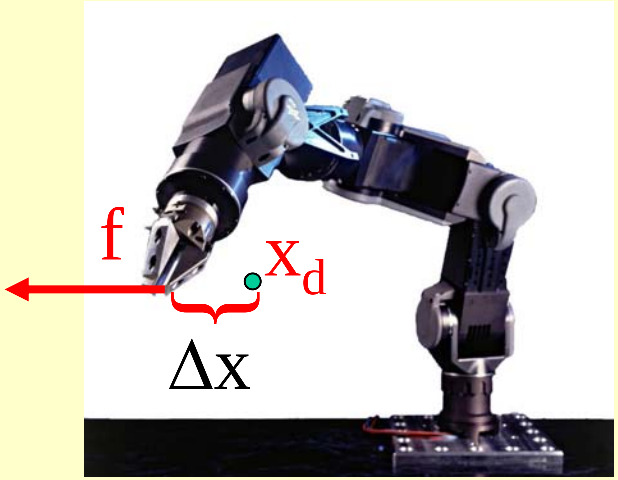
Programmable stiffness („Soft Robotics“)

Goals:

Movement accuracy

Safe human-robot interaction

Cartesian Stiffness Control



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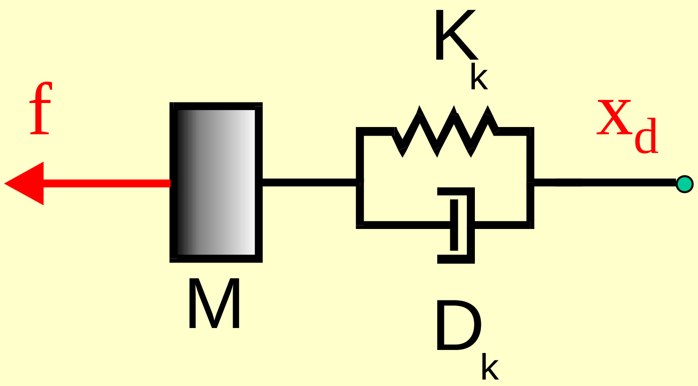
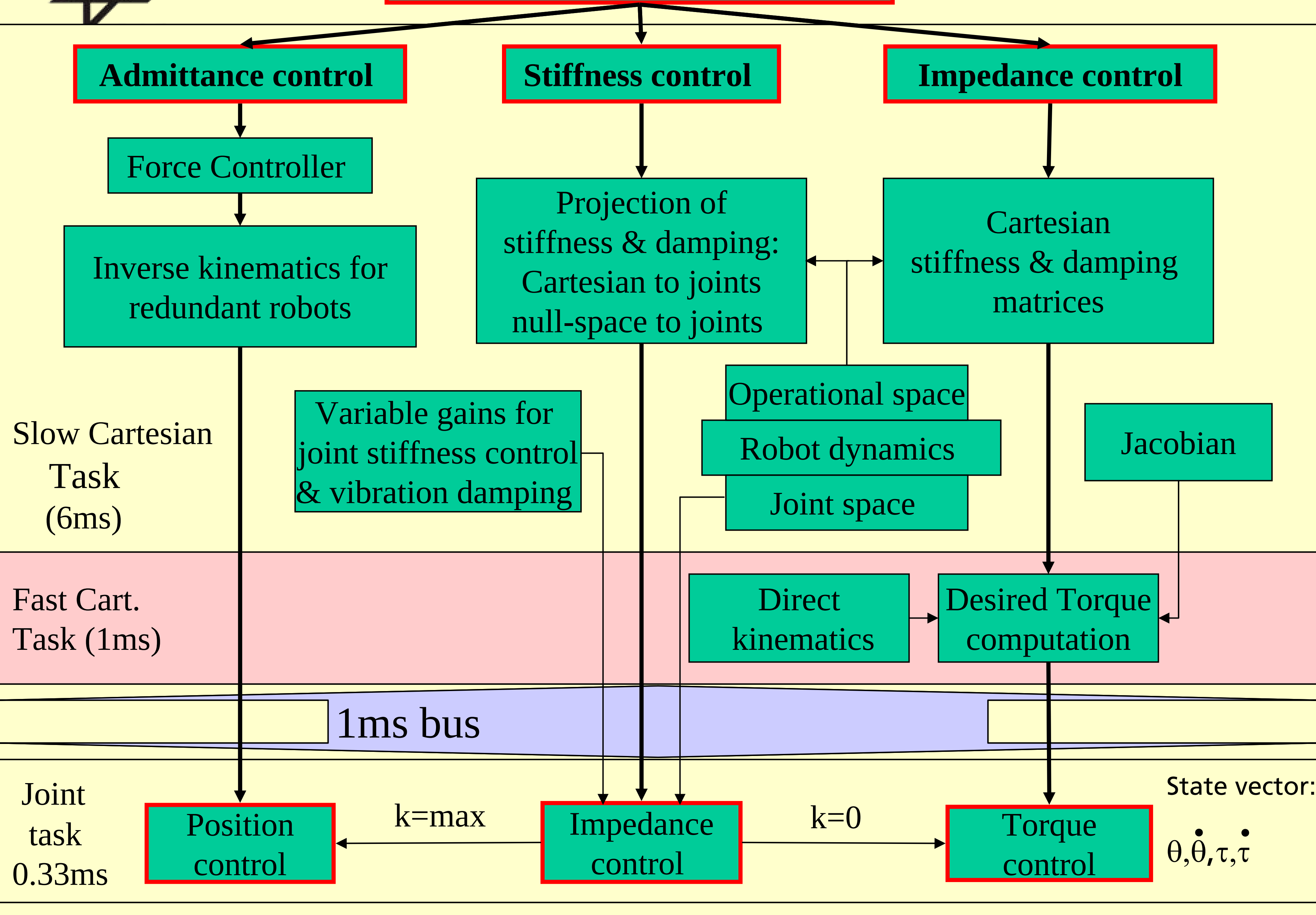
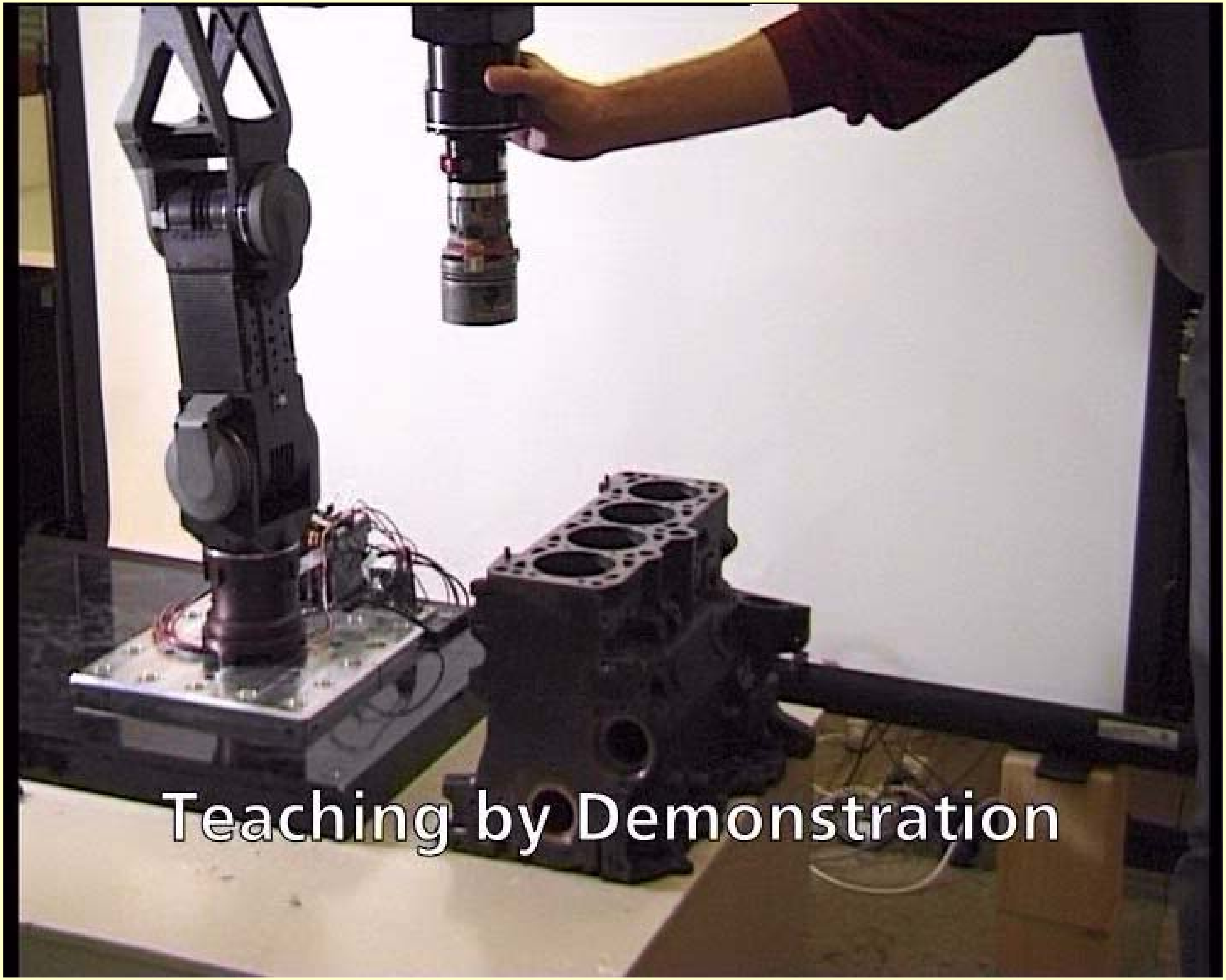


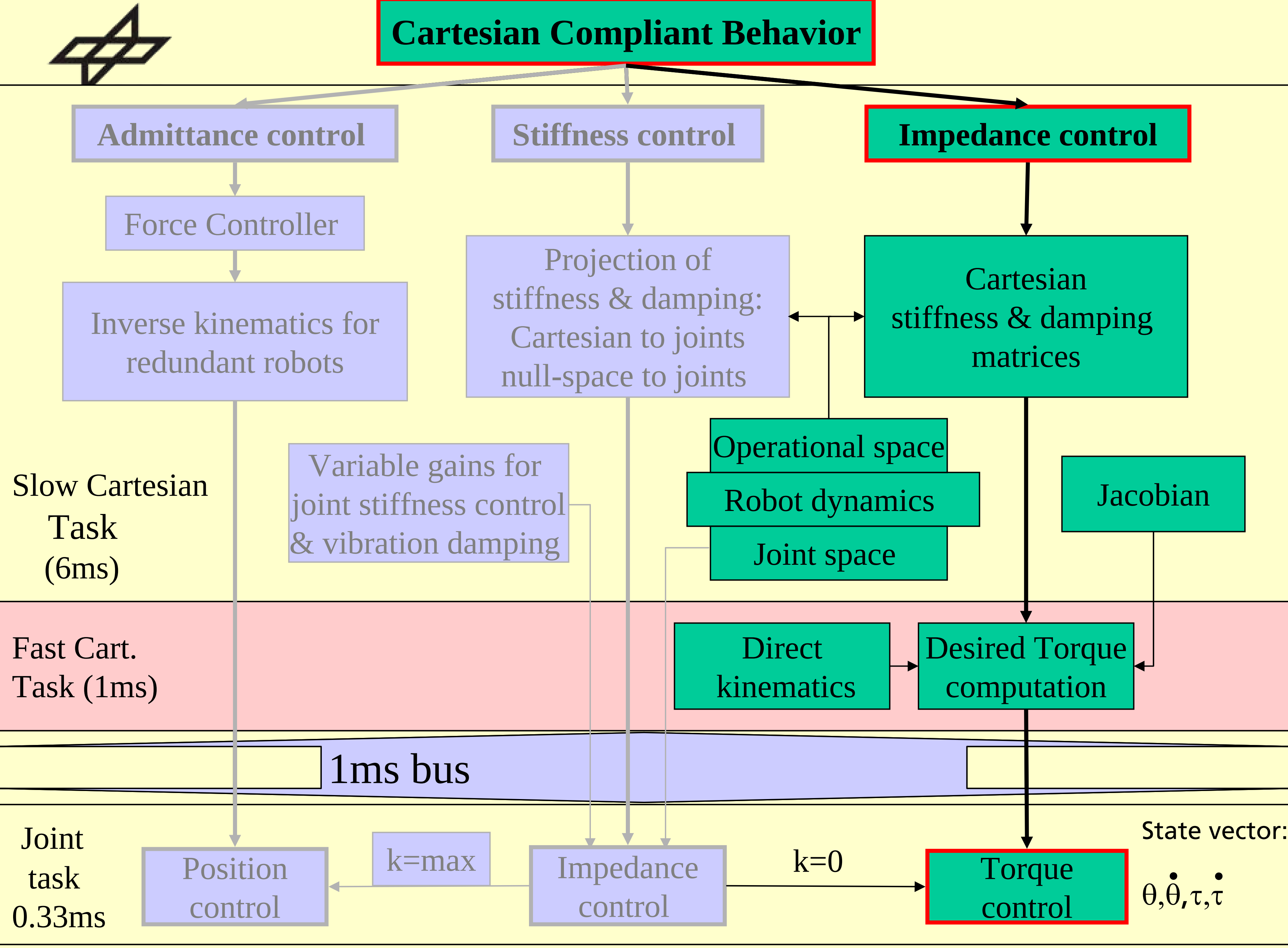
$$f = M\Delta\ddot{x} + D_k\Delta\dot{x} + K_k\Delta x$$

Cartesian Compliant Behavior



Application: Piston Insertion




Cartesian Compliant Behavior
Admittance control
Stiffness control
Impedance control
Force Controller
Inverse kinematics for redundant robots
Projection of stiffness & damping: Cartesian to joints null-space to joints
Cartesian stiffness & damping matrices
Operational space
Robot dynamics
Joint space
Jacobian
Variable gains for joint stiffness control & vibration damping
Slow Cartesian Task (6ms)
Fast Cart. Task (1ms)
Direct kinematics
Desired Torque computation
1ms bus
Joint task 0.33ms
Position control
k=max
Impedance control
k=0
Torque control
State vector:
θ,θ̇,τ,τ̇

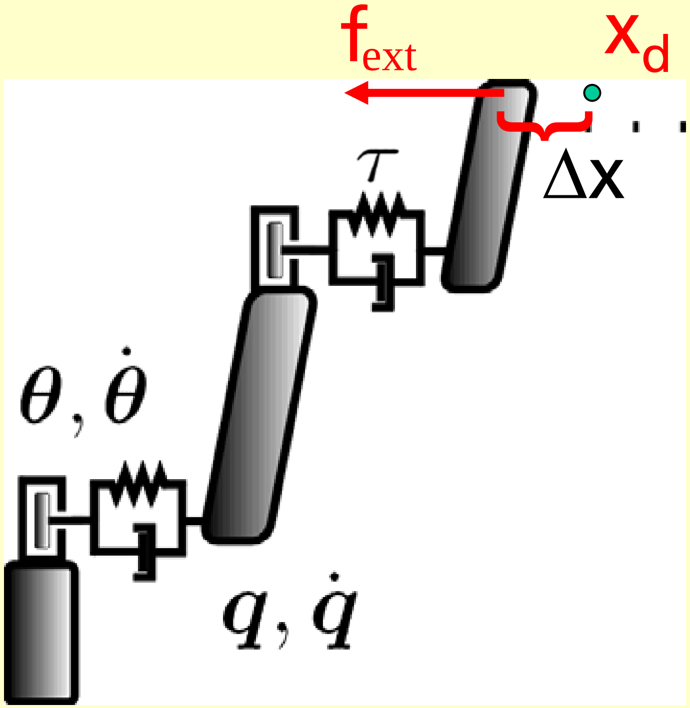
Cartesian Impedance Controller

Two step concept for noncollocated systems:

- Shaping the potential energy - collocated feedback
  - Asymptotic stabilization around x_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

Main Idea for Energy Shaping



- At equillibrium:

  1 to 1 correspondence

  $$\bar{q}(\theta)$$

  Between θ and q

A controller based on $\bar{q}(\theta)$ instead of q

- is collocated ➡ **passivity**
- **satisfies** static requirements related to q:
  - **desired equilibrium point**
  - **desired stiffness**

Conditions for Energy Shaping

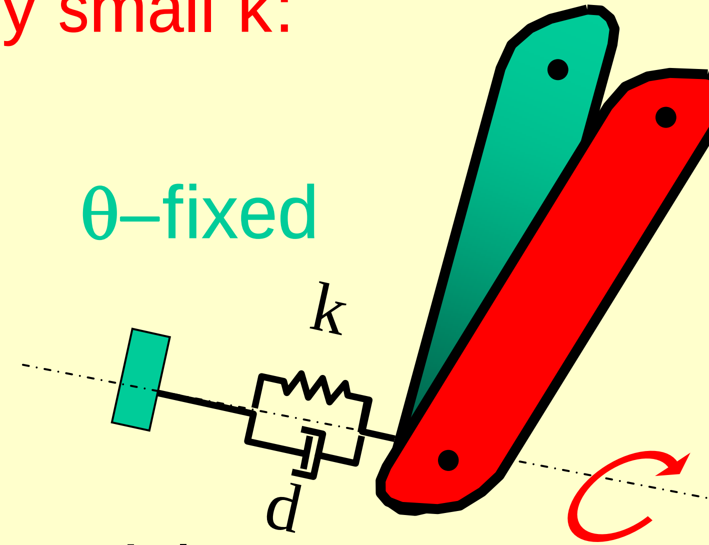
In any equilibrium position $q=\bar{q}(\theta)$ if k not too small

For very small k:

q_1

q_2 -second equilibium

θ–fixed



One turn

For a general potential energy $\boldsymbol{U}$

$$\left\| \frac{\partial^2 U(\boldsymbol{q},\boldsymbol{\theta})}{\partial \boldsymbol{q}^2} \right\| > \alpha$$ ← **Uniqueness of the solution**

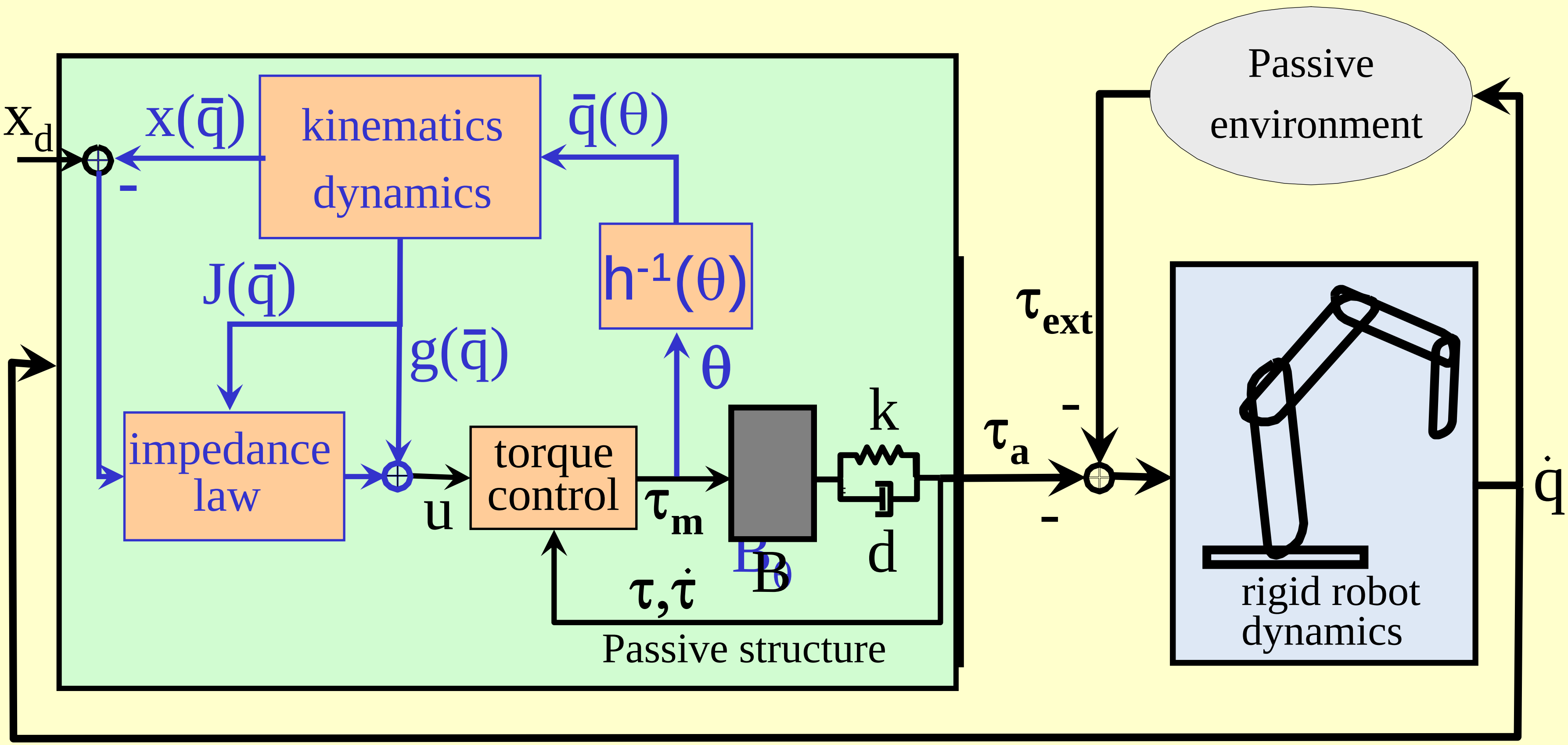
$$\left| \frac{\partial^2 U(\boldsymbol{\theta},\boldsymbol{q})}{\partial \boldsymbol{\theta} \partial \boldsymbol{q}} \right| \neq 0$$ ← **Invertibility**

} $\bar{q}(\theta)$ diffeomorphism

Extendable to a broad class of noncollocated E-L systems

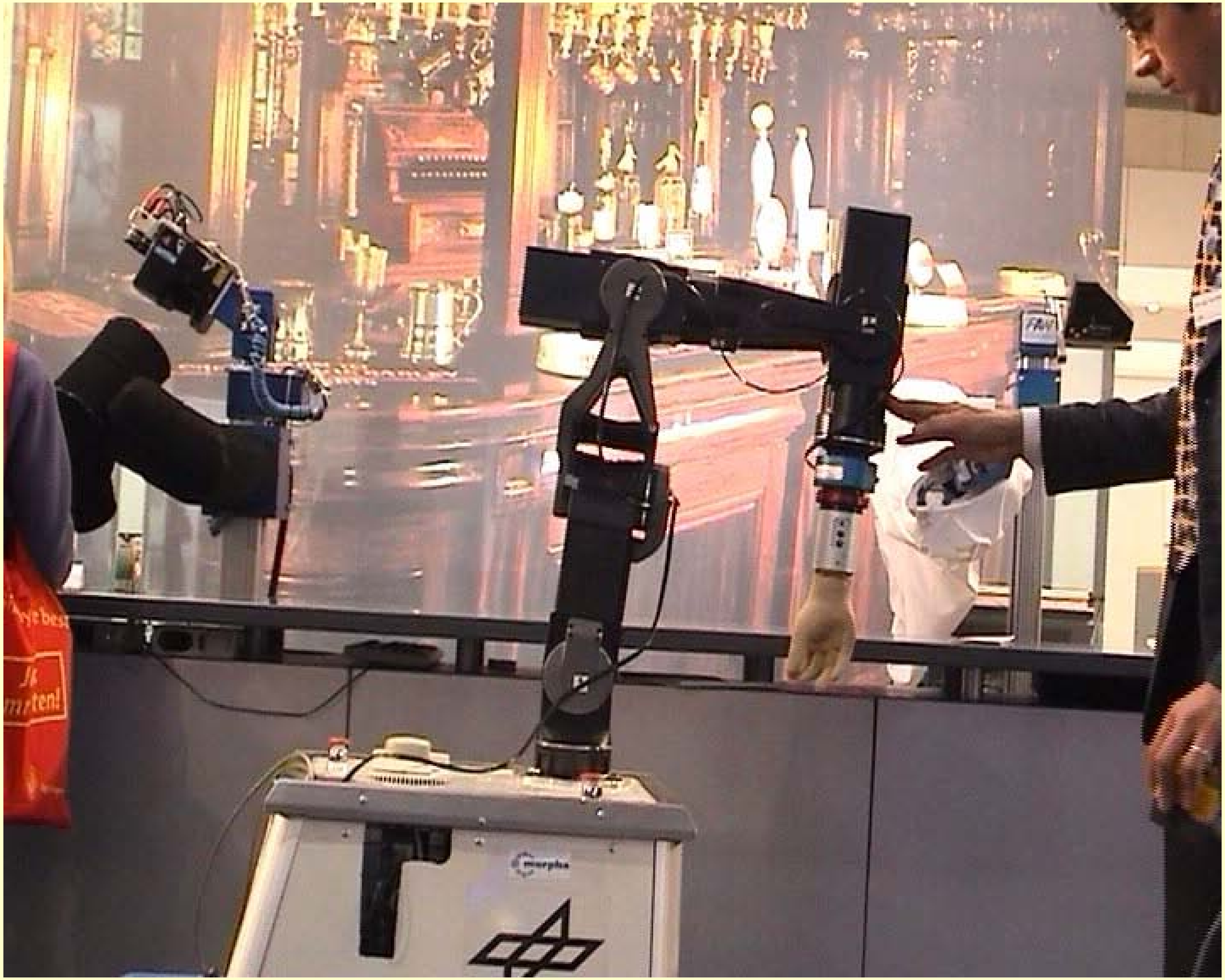
Cartesian Impedance Control

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

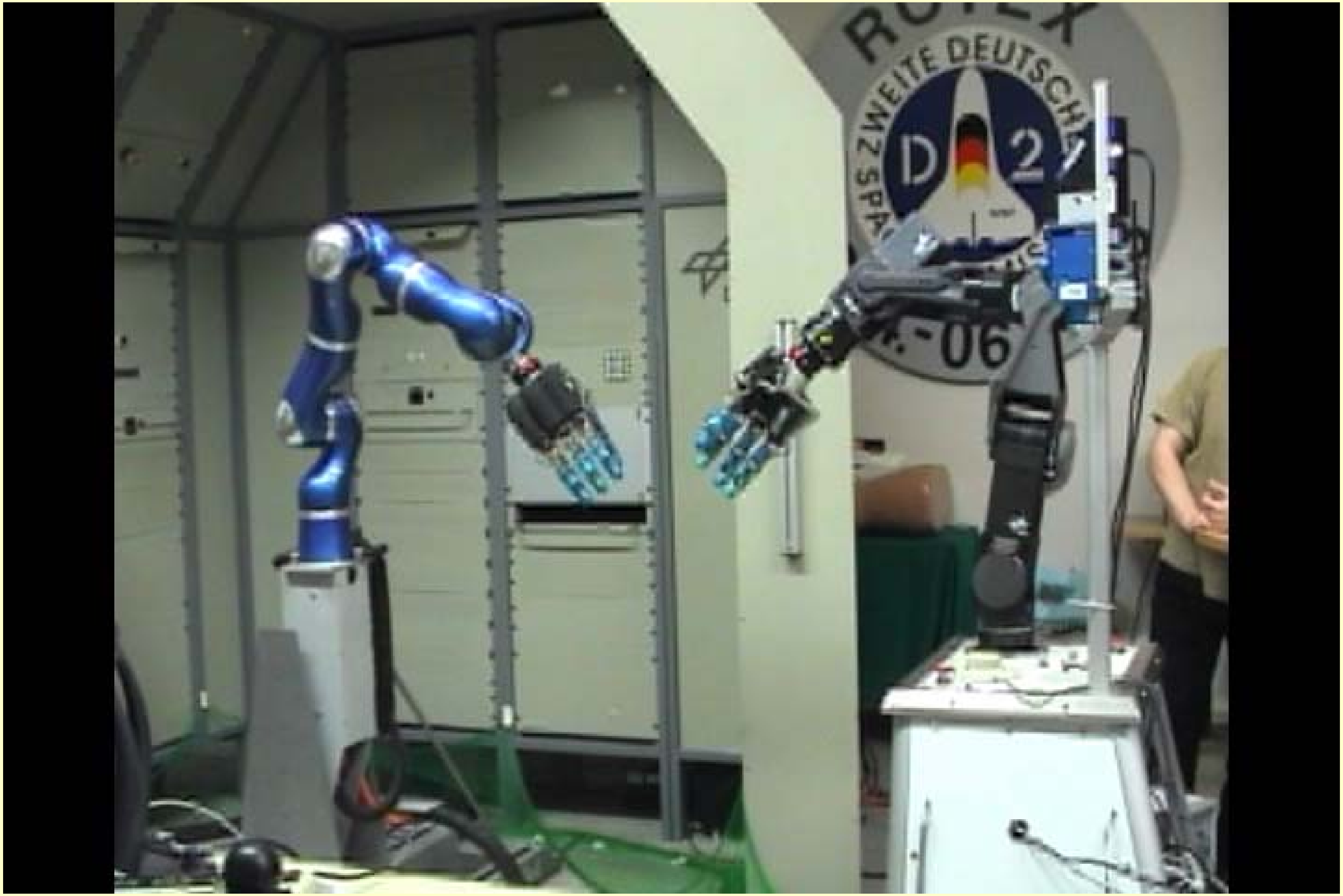


Torque Control

Impedance Control



DLR



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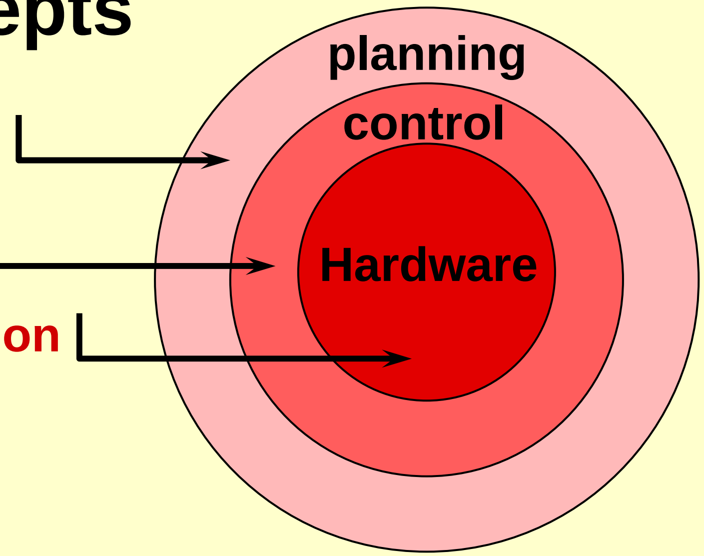

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Inverse Kinematics for Redundant Robots

- Constrained optimization
  - Singularity avoidance
  - Multiple constraints
  - Nonlinear mobile systems
- Interactivity
- Reactivity

Collision Detection Using Redundancy

Collision Detection Using Redundancy