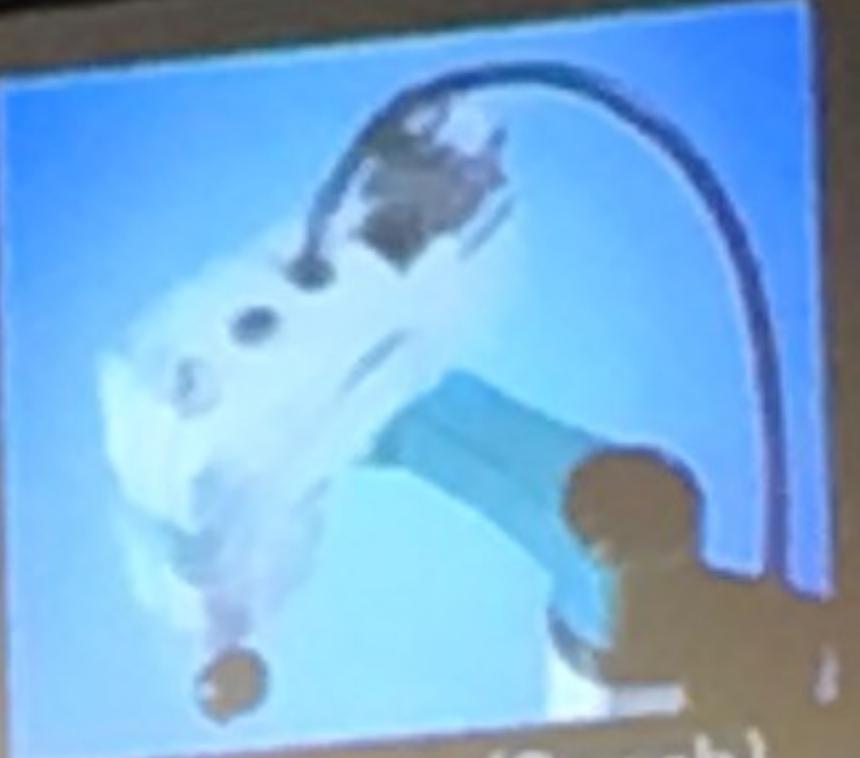


Motivation for Considering Elastic Actuators

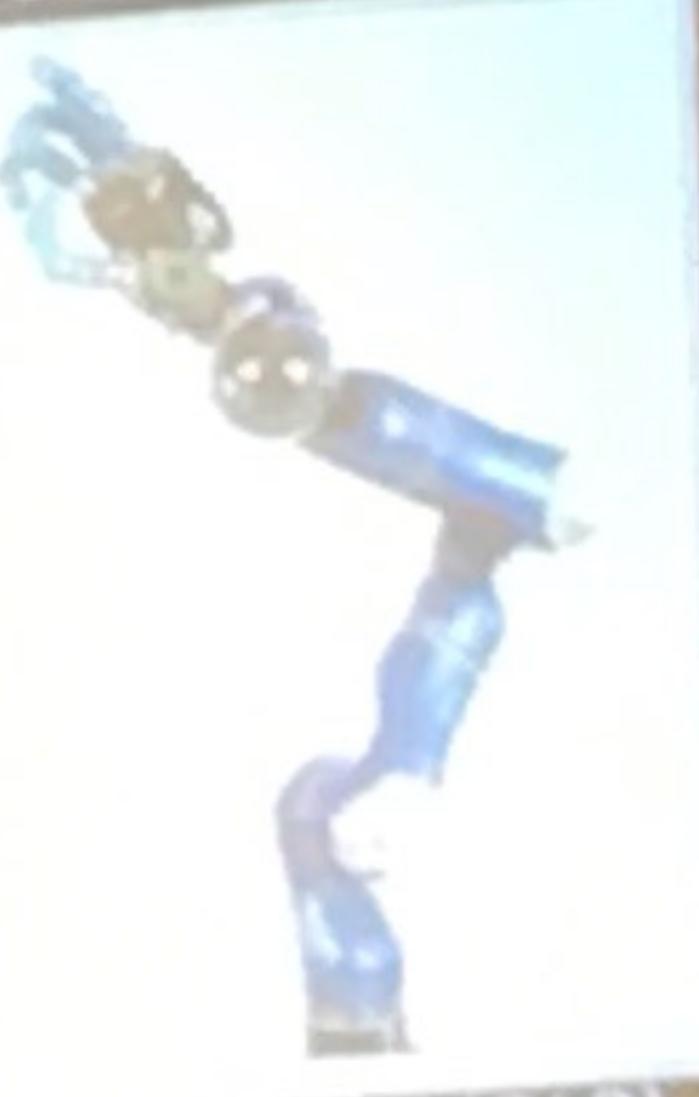
- Elasticity as a disturbance
 - Compliance introduced by transmission elements in the drive unit
 - Cables, belts or long transmission shafts for relocating actuators
 - Harmonic drives
 - Robots with joint torque sensors
- Elasticity on purpose
 - Controlling the joint torque in **Series Elastic Actuators**
 - Protecting the gears from external shocks/impacts
 - Utilizing energy storage in generation of highly dynamic motions
 - Utilizing energy storage in generation of efficient motions
 - Variable stiffness/impedance Actuators (**VIA**)



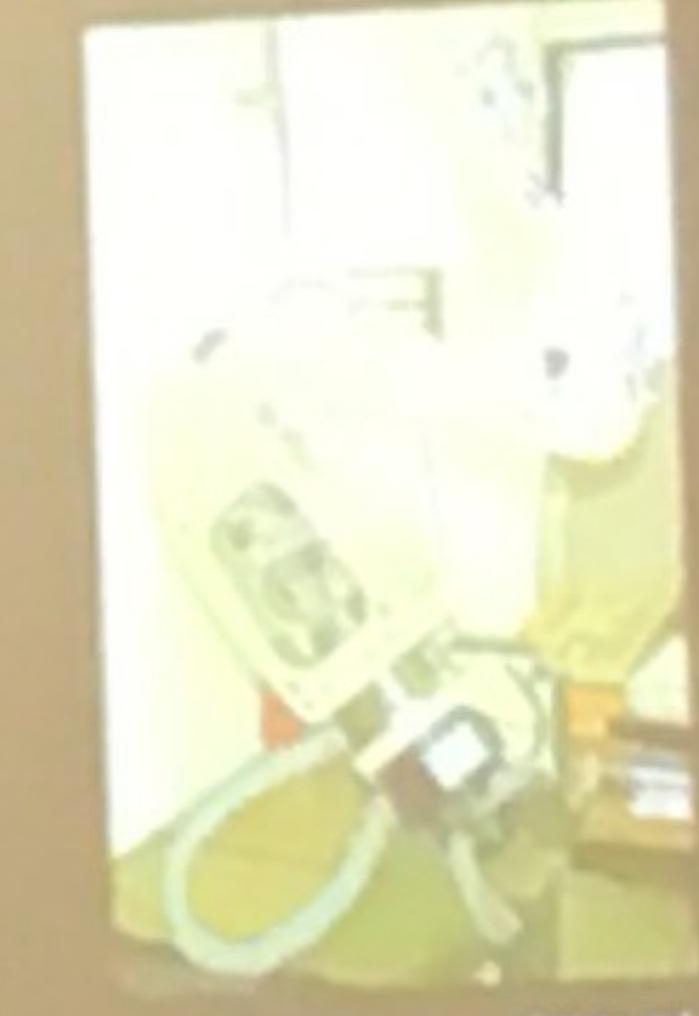
KR 16 (Kuka)



Turboscar (Bosch)



LWR III (DLR)



Dexter (SM)

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B

Motivation for Considering Elastic Actuators

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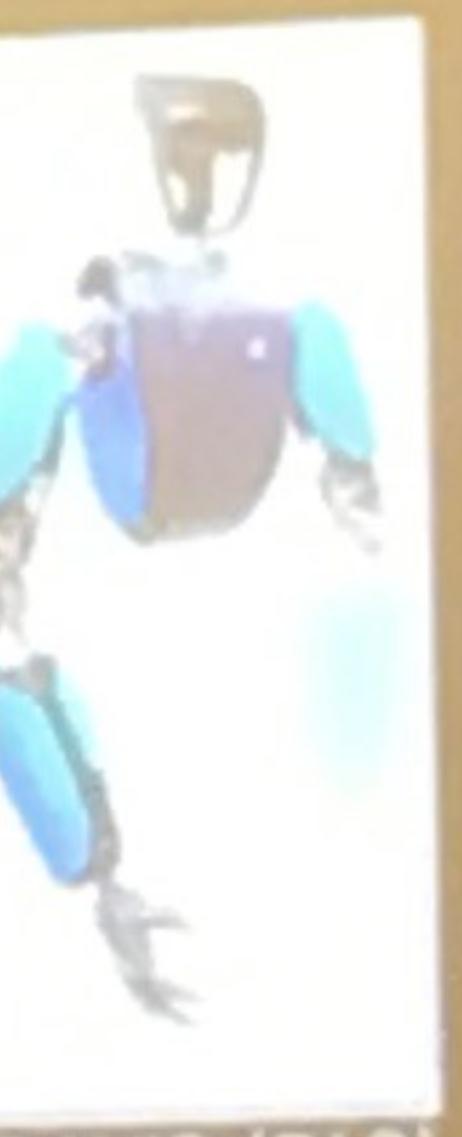
Spring Flamingo (MIT)



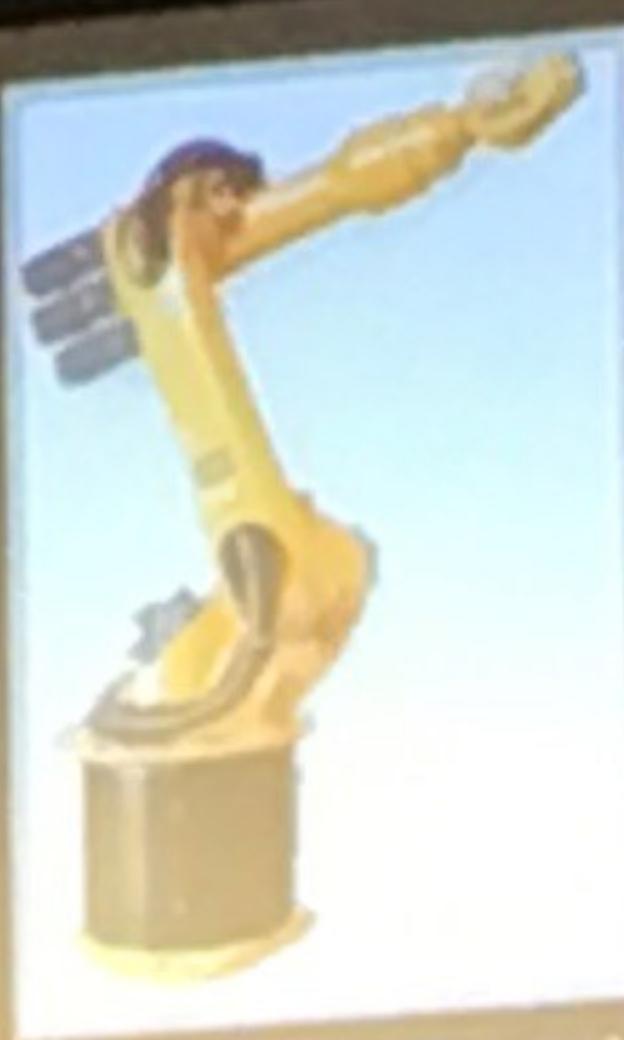
ANYbotics (ETH spin-off)



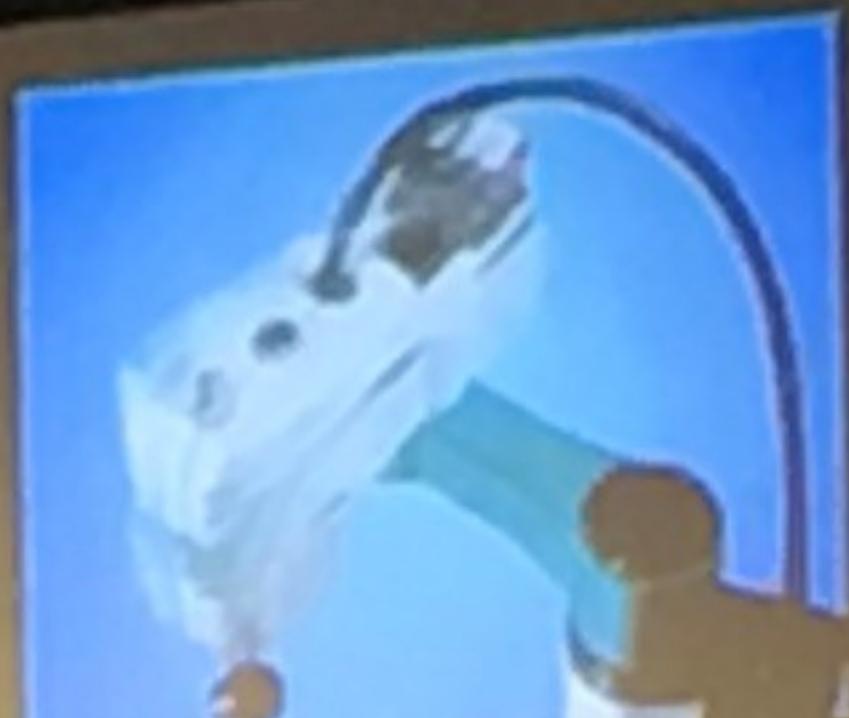
VSA Cubes (Univ. Pisa)



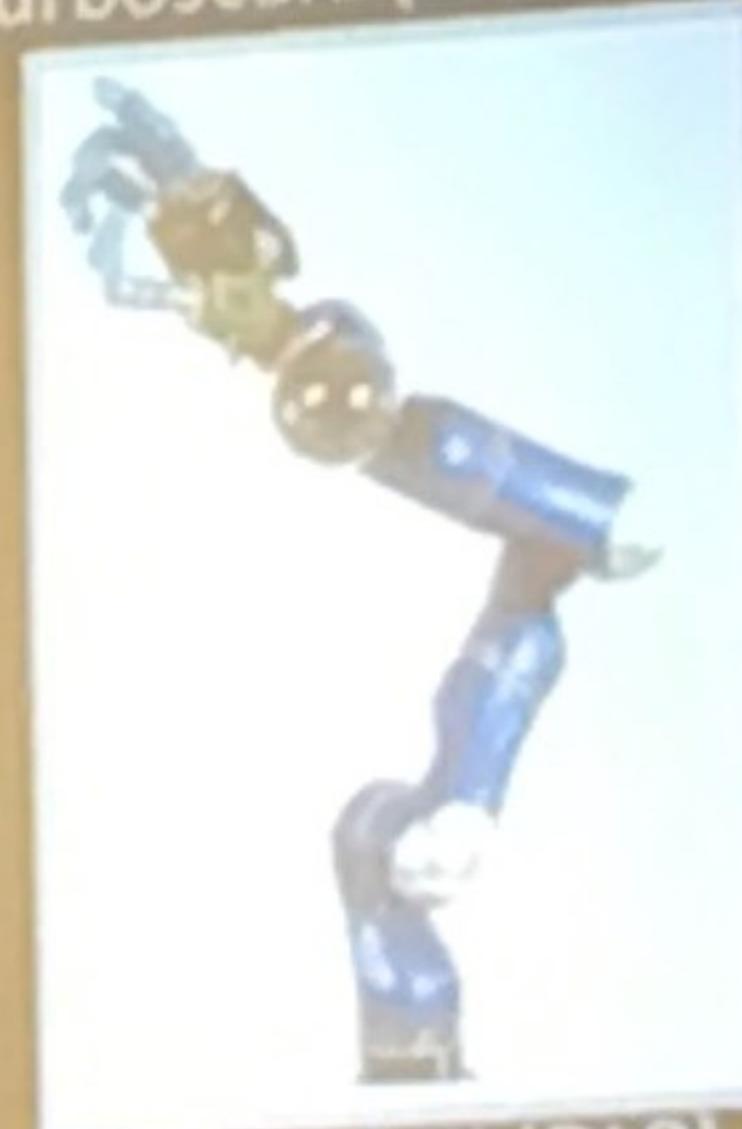
DAVID (DLR)



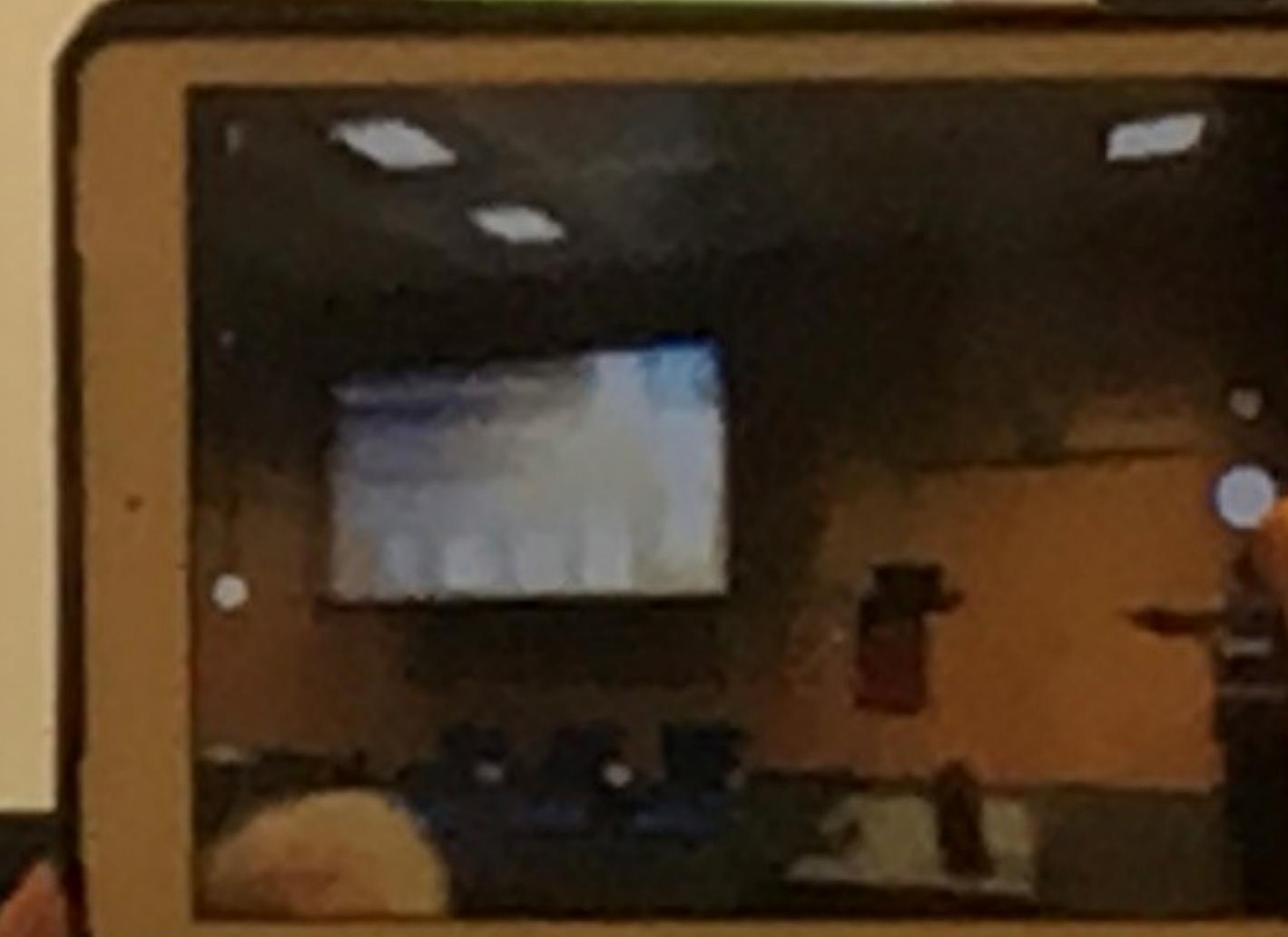
KR 16 (Kuka)



Turboscara (Bosch)



LWR III (DLR)



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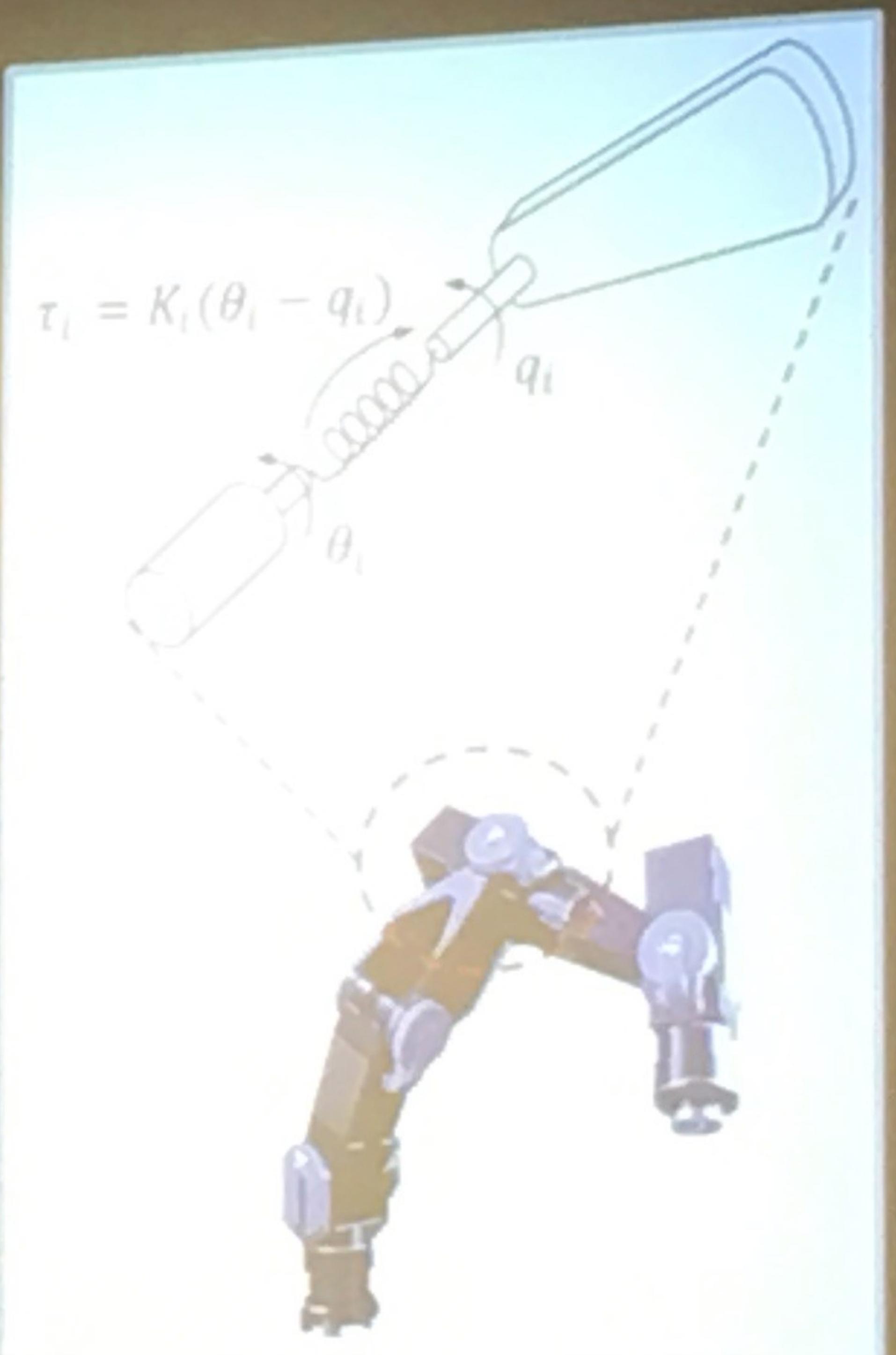
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Milestones in Modeling of Elastic Robots (1/2)

- 1) „Complete Model“ (derived from classical Lagrangian mechanics)

$$\begin{bmatrix} M_L(q) & S(q) \\ S(q)^T & B \end{bmatrix} \begin{pmatrix} \ddot{q} \\ \ddot{\theta} \end{pmatrix} + \begin{pmatrix} c_1(q, \dot{q}, \dot{\theta}) \\ c_2(q, \dot{q}) \end{pmatrix} + \begin{pmatrix} g(q) \\ 0 \end{pmatrix} + \begin{pmatrix} K(q - \theta) \\ K(\theta - q) \end{pmatrix} = \begin{pmatrix} 0 \\ \tau_m \end{pmatrix}$$

Triangular structure of the coupling matrix! [De Luca, Tomei 1996]



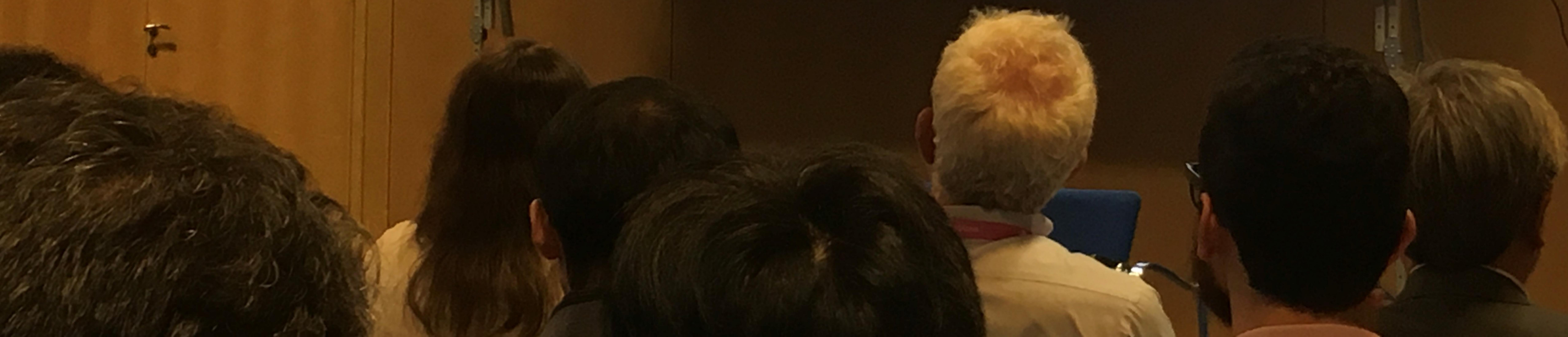
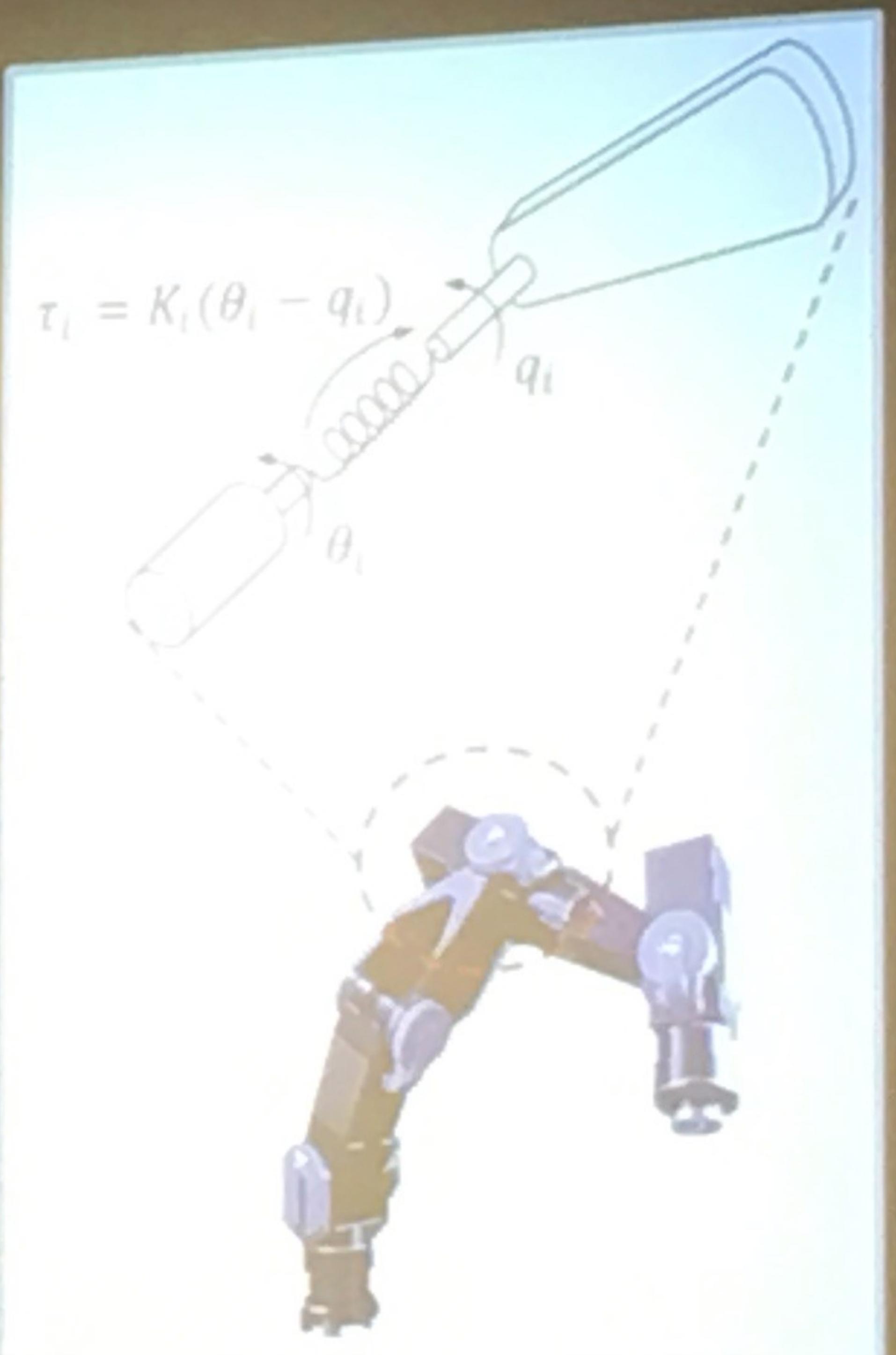
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Milestones in Modeling of Elastic Robots (1/2)

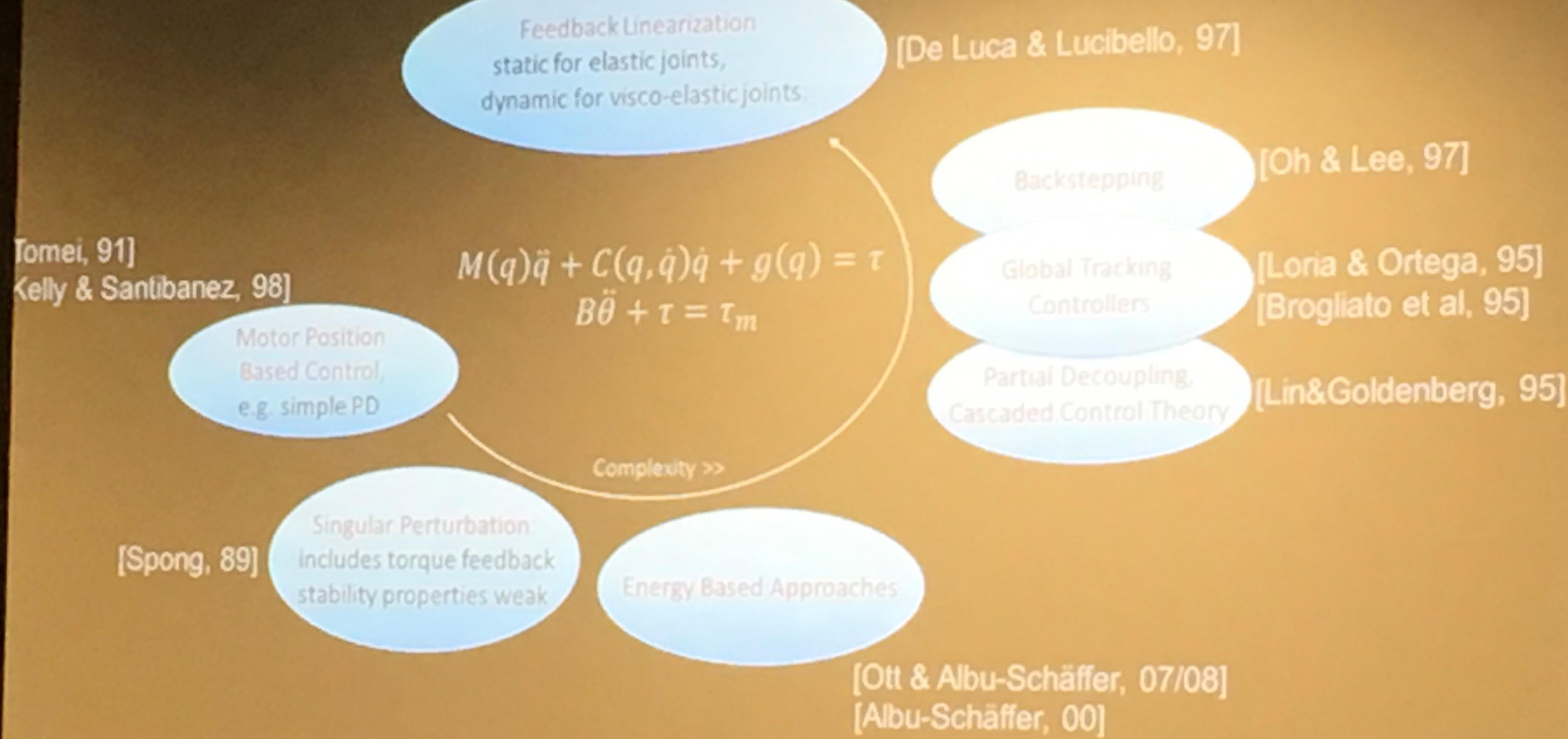
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Control approaches for Elastic Robots



Feedback Linearization

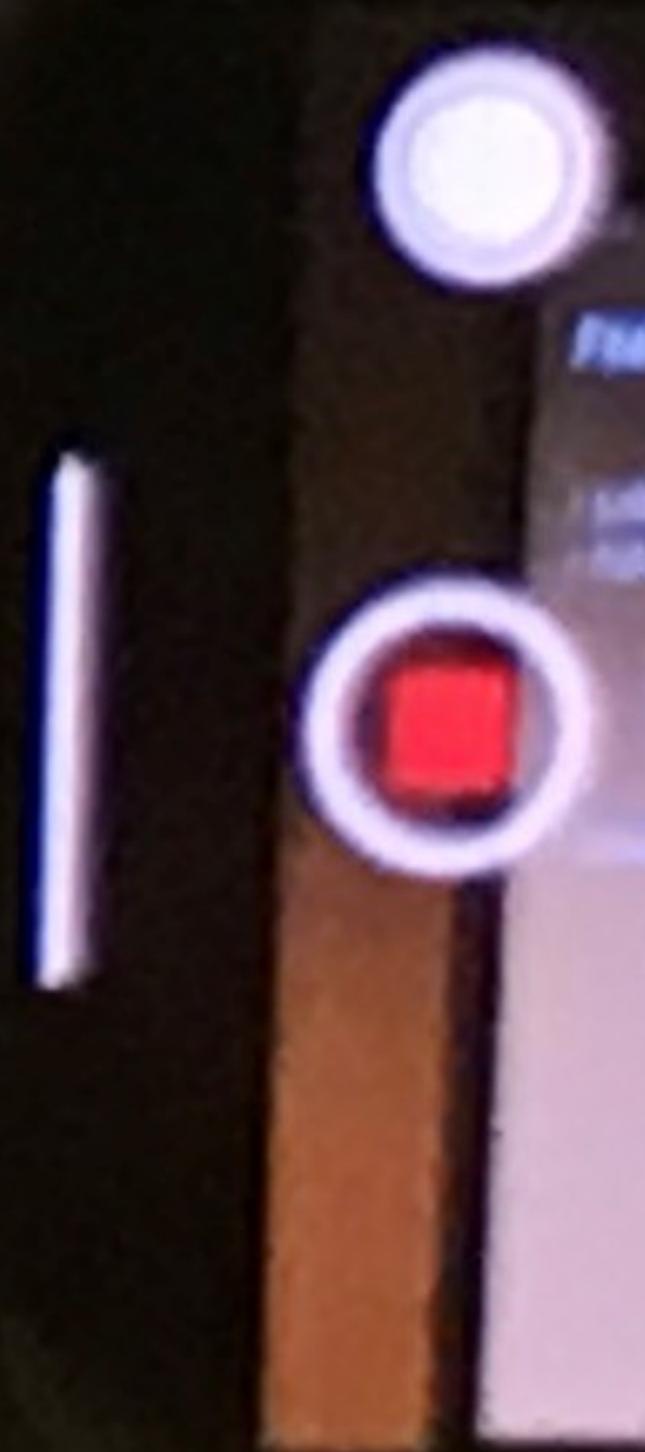
- Link side position q presents a flat output
- Full state linearization by output transformation

$$\begin{bmatrix} M(q) & 0 \\ 0 & B \end{bmatrix} \begin{pmatrix} \ddot{q} \\ \ddot{\theta} \end{pmatrix} + \begin{pmatrix} C(q, \dot{q})\dot{q} \\ 0 \end{pmatrix} + \begin{pmatrix} g(q) \\ 0 \end{pmatrix} + \begin{pmatrix} K(q - \theta) \\ K(\theta - q) \end{pmatrix} = \begin{pmatrix} 0 \\ \tau_m \end{pmatrix} \rightarrow q^{(4)} = u$$

- Linearizing control law (for reduced model):

$$\tau_m = BK^{-1}M(q)u + K(\theta - q) + B\ddot{q} + BK^{-1} \left(2\dot{M}q^{(3)} + \dot{M}\ddot{q} + \frac{d^2}{dt^2}(C\dot{q} + g(q)) \right)$$

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Torque Control

$$\begin{bmatrix} M(q) & 0 \\ 0 & B \end{bmatrix} \begin{pmatrix} \ddot{q} \\ \ddot{\theta} \end{pmatrix} + \begin{pmatrix} C(q, \dot{q})\dot{q} \\ 0 \end{pmatrix} + \begin{pmatrix} g(q) \\ 0 \end{pmatrix} + \begin{pmatrix} K(q - \theta) \\ K(\theta - q) \end{pmatrix} = \begin{pmatrix} 0 \\ \tau_m \end{pmatrix}$$

- Torque Dynamics

$$\ddot{q} = K(\theta)$$

$$BK^{-1}\ddot{q} + \tau = \tau_m - B\dot{q}$$

- Conventional torque tracking

$$\tau_m = BK^{-1}\ddot{\tau}_d + \tau_d + K_T(\tau_d - \tau) + K_S(\dot{\tau}_d - \dot{\tau}) + \alpha B\dot{q}$$

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Summary

- 1) Foundations of Control of elastic robots
- 2) Some new results on control of highly elastic robots
- 3) Open Challenges

„Der Kämpfer (Robot) gibt nach.“ (misused German Proverb)

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