Elastic Actuators: From mastering vibrations towards utilization of intrinsic dynamics

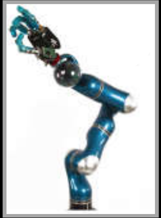
Christian Ott
German Aerospace Center (DLR)

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)

Turboscara (Bosch)



LWR III (DLR)

Spring Flamingo (MIT)

ANYbotics (ETH spin-off)

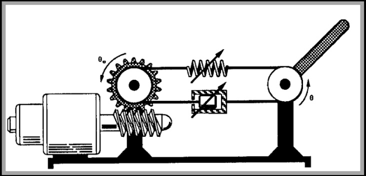
VSA Cubes (Univ. Pisa)

DAVID (DLR)

Dexter (SM)

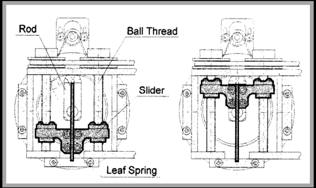
Adjustable Compliance: Some early works

- [Laurin-Kovitz, Colgate, Carnes, 1991]
  Programmable stiffness and damping
  - Hydraulic damper
  - Tunable springs

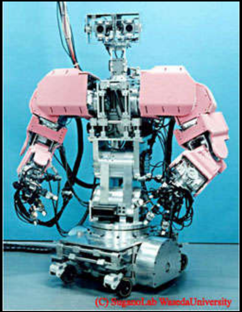


Concept figure from
[Laurin-Kovitz, Colgate, Carnes, 1991]

- [Morita & Sugano, 1995]
  - Based on Leaf springs & brakes
  - Implemented in the 7 DOF MIA arm [1997] and the hand of the robot Wendy



Adjustable stiffness mechanism in
the MIA arm [Morita & Sugano 1997]

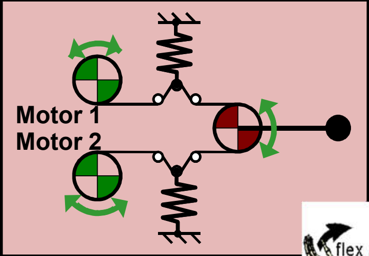


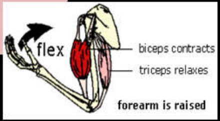
Humanoid robot WENDY, Waseda 1999.

Variable Impedance Actuators

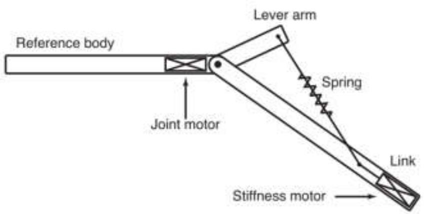
- (Some) actuator impedance parameters can be changed online (either slowly or fast) by control
- Often nonlinear stiffness required by design
- Many possible designs [Viactors project]

Antagonistic Actuation
(inspired by human muscle)



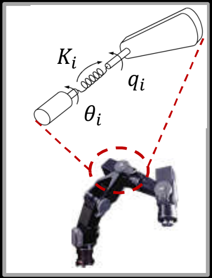


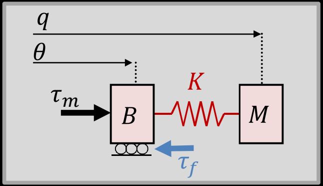
MACCEPA [Van Ham et al, 2007]



Elastic Joint Robots vs. Series Elastic Actuators

- Consider the same physical phenomenon (compliance in actuation)
- Compliance in SEA put on purpose
- Compliance of SEA used to be higher (in newer works not always true any more)
- Literature on SEA is focused often on the actuator level (1DOF)
- Literature on Elastic Joint Robots started from extensions of the rigid body model





Milestones in Modeling of Elastic Robots (1/2)

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

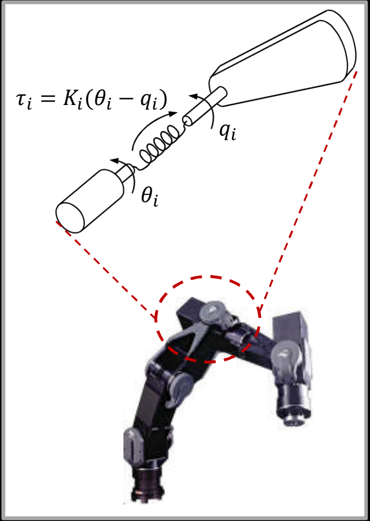
$$\begin{bmatrix} M_L(q) & S(q) \\ S(q)^T & B \end{bmatrix}\begin{pmatrix} \ddot{q} \\ \ddot{\theta} \end{pmatrix} + \begin{pmatrix} c_1(q,\dot{q},\dot{\theta}) \\ c_2(q,\dot{q}) \end{pmatrix} + \begin{pmatrix} g(q) \\ 0 \end{pmatrix} + \begin{pmatrix} K(q-\theta) \\ K(\theta-q) \end{pmatrix} = \begin{pmatrix}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

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

2) „Reduced Model“ [Spong 1987]
- Kinetic energy of the motors only due to own spinning
- Justified for large reduction ratios (e.g. Harmonic Drive gears)

$\Rightarrow$ $S(q) = 0$

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

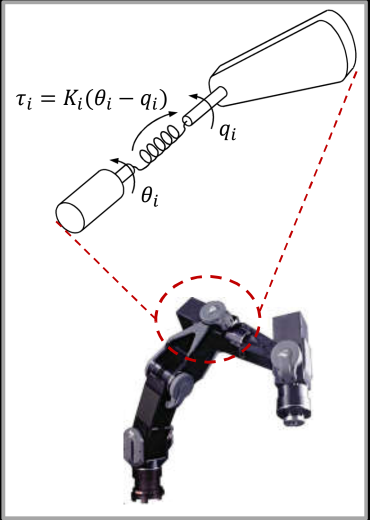


Milestones in Modeling of Elastic Robots (2/2)

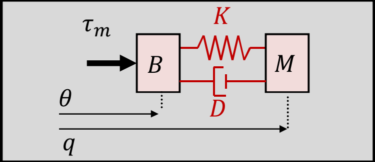
- Comparison of the two standard models

Complete Model	Reduced Model
underactuated	underactuated
Inertial & stiffness couplings	Only stiffness couplings
Linearizable by dynamic state feedback [De Luca, Lucibello 1998]	Linearizable by static state feedback
Always valid	Valid if gear ratio is very high

Small physical effect has a significant impact on the mathematical properties!



Visco-elastic Joints



- Joint damping reduces the relative degree [De Luca 05]

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

- Static I/O linearization still possible (with stable zero dynamics), but ill-conditioned for small damping

Coupling type	Consequence for the model
stiffness	Basic static coupling
damping	Reduced relative degree, static I/O linearization
inertia	Reduced relative degree, only dynamic I/O linearization

Control approaches for Elastic Robots

$$M(q)\ddot{q} + C(q,\dot{q})\dot{q} + g(q) = \tau$$
$$B\ddot{\theta} + \tau = \tau_m$$

Complexity >>

Motor Position Based Control, e.g. simple PD — $\theta, \dot{\theta}$

[Tomei, 91]
[Kelly & Santibanez, 98]

Singular Perturbation: includes torque feedback stability properties weak — $q, \dot{q}, \tau, \dot{\tau}$

[Spong, 89]

Energy Based Approaches — $\theta, \dot{\theta}, \tau, \dot{\tau}$

[Ott & Albu-Schäffer, 07/08]
[Albu-Schäffer, 00]

Feedback Linearization static for elastic joints, dynamic for visco-elastic joints. — $q, \dot{q}, \ddot{q}, q^{(3)}$

[De Luca & Lucibello, 97]

Backstepping [Oh & Lee, 97]

Global Tracking Controllers [Loria & Ortega, 95] [Brogliato et al, 95]

Partial Decoupling, Cascaded Control Theory [Lin&Goldenberg, 95]

$q, \dot{q}, \ddot{q}, q^{(3)}$

Feedback Linearization

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

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

- Linearizing control law (for reduced model):

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

+ Perfectly linear closed loop dynamics

− Requires higher derivatives of q $\quad q, \dot{q}, \ddot{q}, q^{(3)}$

Requires higher derivatives of the dynamics components $\quad \ddot{M}, \ddot{C}, \ddot{g}$

Regulation

- A minimalistic controller (PD) for regulation: $\tau_m = u_g + K_\theta(\theta_d - \theta) - D_\theta \dot{\theta}$
- Intuitive physical interpretation: stiffness & damping → Energy based stability analysis.
- For passivity: Only collocated feedback
- Focus on the gravity compensation term: compensation of link side potential from the motor side

u_g	Gain criteria for stability	
$g(q_d)$	$\lambda_{min}\begin{bmatrix} K & -K \\ -K & K + K_\theta \end{bmatrix} > \alpha$	[Tomei 91]
$g(\theta + K^{-1} g(q_d))$	$\lambda_{min}\begin{bmatrix} K & -K \\ -K & K + K_\theta \end{bmatrix} > \alpha$	[Zollo & De Luca 04]
$g(\bar{q}(\theta))$, $\bar{q}(\theta)$: $g(\bar{q}) = K(\theta - \bar{q})$	$K_\theta > 0$, $\lambda_{min}(K) > \alpha$	[Ott & Albu-Schäffer 04]
$g(q) + BK^{-1}\ddot{g}(q) + D_\theta K^{-1}\dot{g}(q)$	$K_\theta > 0$, $\lambda_{min}(K) > \alpha$	[De Luca 10] [Ott 08]

$$\alpha = \max\left(\left\|\frac{\partial g(q)}{\partial q}\right\|\right)$$

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

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

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

- Conventional torque tracking

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

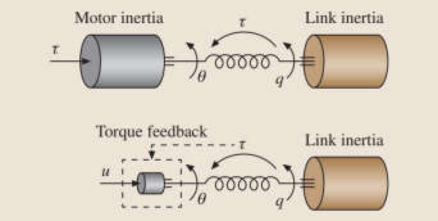
  - $\alpha < 1$ for avoiding over-compensation
  - Friction compensation
  - Motor side disturbance observer

  - Basis for many cascaded controller designs that start from a rigid body control law $\tau_d(q,\dot{q})$.
  - Higher derivatives are required $(\ddot{\tau}_d, \ddot{q})$

A Passivity Based View on Torque Feedback

- Consider a purely proportional torque feedback

$$\tau_m = BB_d^{-1}u + \underbrace{\left(I - BB_d^{-1}\right)}_{K_T}\tau + \underbrace{\left(I - BB_d^{-1}\right)DK^{-1}}_{K_S}\dot{\tau}$$



Original motor dynamics

$$B\ddot{\theta} + K(\theta - q) = \tau_m$$

After torque feedback

$$B_d\ddot{\theta} + K(\theta - q) = u$$

Visco-elastic case

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

$$B_d\ddot{\theta} + \tau + DK^{-1}\dot{\tau} = u$$

- Physical interpretation: Torque feedback = Scaling of the motor inertia and motor friction! [Ott&Albu-Schäffer 08]

Full State feedback Control

- Inertia scaling via torque feedback: $\tau_m = (I + K_T)u - K_T\,\tau - K_S\dot{\tau}$
- Regulation via motor PD: $u = g(\bar{q}(\theta)) + K_\theta(\theta_d - \theta) - D_\theta\dot{\theta}$

dynamics feed forward &
Desired torque command

Setpoint control

(+ Integral actions)

$$\tau_m = \tau_d - K_T\,(\tau - \tau_d) - K_S\dot{\tau} - K_P(\theta_d - \theta) - K_D\dot{\theta} + \tau_f + \tau_{dob}$$

Motor inertia scaling

Vibration damping

Friction comp. & dist. obs.

Torque Control	Position Control	Impedance Control
$K_P = 0$	$K_P > 0$	$K_P = K_T K_\theta$
$K_D = 0$	$K_D > 0$	$K_D = K_T D_\theta$
$K_T > 0$	$K_T > 0$	$K_T = (BB_d^{-1} - I)$
$K_S > 0$	$K_S > 0$	$K_S = \left(BB_d^{-1} - I\right)DK^{-1}$
τ_d	$\tau_d = g(q)$	$\tau_d = g(\bar{q}(\theta))$

Joint level control structure of the DLR lightweight robots.

Vibration damping with full state feedback control

Vibration Damping OFF

Vibration Damping ON

No cascaded control, but 4th order controller design! [Albu-Schäffer 02]

Some examples

- Using Task Level Compliance instead of joint level PD.

Autonomous manipulation (2005)


Whole body manipulation (2006)

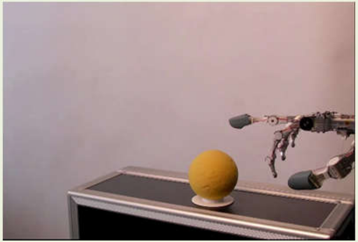

Multi-contact control (2014)

Highly elastic robots

Energy storage in highly elastic robots

Robustness

Performance

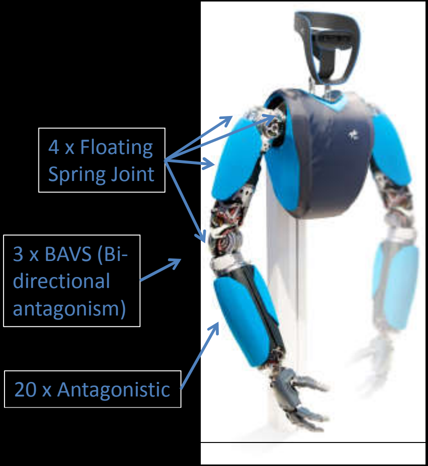


Vibration damping in highly elastic robots

- Stiffness in DAVID: ~200-500 Nm/rad
- Stiffness in LBR: ~10.000 Nm/rad

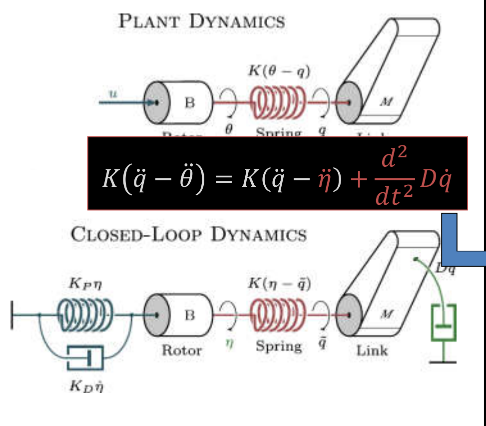
- Vibration damping via torque feedback & pure motor damping not sufficient for high performance!

- Intrinsic dynamics:



[Grebenstein, Albu-Schäffer et al, ICRA 2011]

Vibration damping in highly elastic robots



$$K(\ddot{q}-\ddot{\theta}) = K(\ddot{q}-\ddot{\eta}) + \frac{d^2}{dt^2} D\dot{q}$$

[Keppler et al., 2016]

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

$$K(q-\theta) = K(q-\eta) + D\dot{q}$$

State transformation

$$\frac{d^2}{dt^2}$$

$$\tau_m = u - K(\eta - q) + BK^{-1}\frac{d^2}{dt^2} D\dot{q}$$

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

- → Generalization to trajectory tracking
- → Nonlinear springs in the joints [ICRA 2016]
- → Viscoelastic Joints [ECC 2017]

$$u = K_P\eta + K_D\dot{\eta}$$


Challenge
The intrinsic oscillatory behavior and the under actuation of the system
make control of the link configuration variables a challenging task.

From Damping to Impedance Control

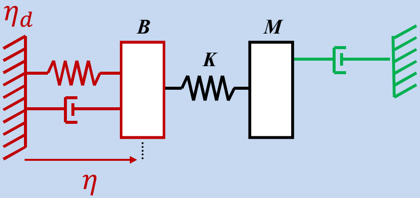
Desired Damping on the link side

Vibration damping

$$M(q)\ddot{q} + C(q,\dot{q})\dot{q} + g(q) = K(\eta - q) + D\dot{q}$$

$$B\ddot{\eta} + K(\eta - q) = D_\eta \dot{\eta} + K_\eta \eta$$

Stabilization

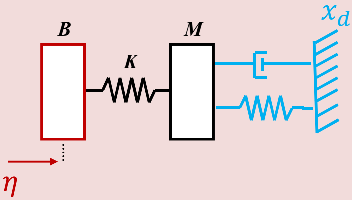


Impedance Control on the link side

$$M(q)\ddot{q} + C(q,\dot{q})\dot{q} = K(\eta - q) + J(q)^T \left(D_x \dot{x} + K_x \tilde{x}\right)$$

$$B\ddot{\eta} + K(\eta - q) = 0$$

Compliance



→ [ThATS4.2] *„Elastic Structure Preserving Impedance (ESPi) Control for Compliantly Actuated Robots", Keppler et al.*

ESπ Control

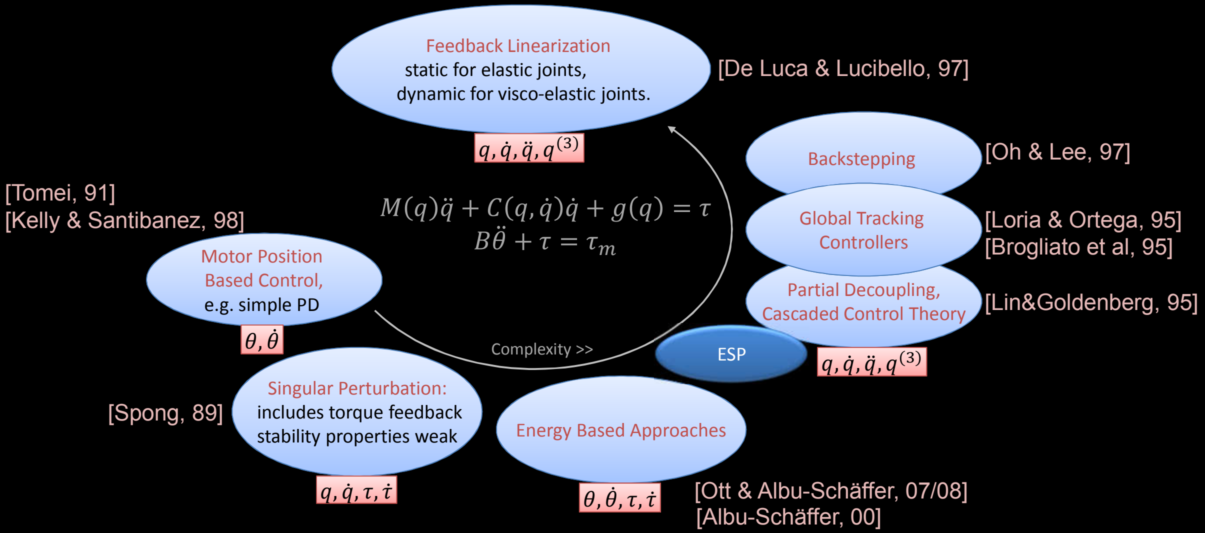
Cartesian

We implement <u>Cartesian springs</u> with <u>no active damping</u>.
The stiffness values are set to:

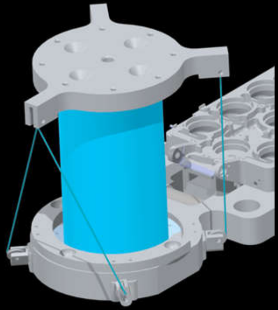
kx: 3000 N/m
ky: 3000 N/m
kz: 3000 N/m

The bars indicate the forces exerted by the user.

Control approaches for Elastic Robots



Elastic Actuators based on Soft Material

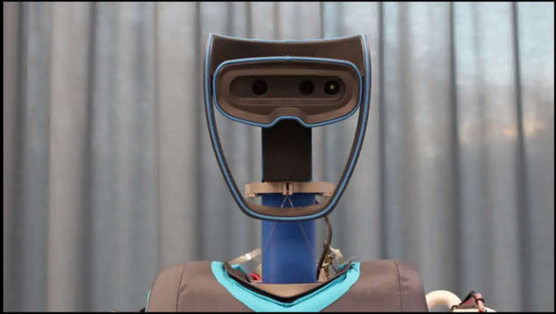


- Elastic component made of silicon
- Tendon actuation (underactuated)

- Approximation of the silicone by massless nonlinear spatial compliance

$$\Rightarrow \quad M(q)\ddot{q} + C(q,\dot{q})\dot{q} + g(q) + k(q) = P(q)f$$

- Enables model based control approaches for soft material actuators!
  - Partial feedback linearization
  - Passivity based control [Deutschmann 17]
  - Fractional order control [Monje 16]



Some Open Challenges

1) How to use variable impedance parameters for specific applications?
   - Locomotion
   - Manipulation
   - Periodic vs aperiodic tasks

2) How to integrate the desired compliance directly into the structure?
   - Link to Soft Material Robotics
   - Compliant actuators → Compliant robots

3) How to preserve performance indices like energetic efficiency from open loop design in closed loop control?
   - Utilize natural dynamics in feedback
   - Balance embodiment & controllability

4) Find a balance between the predicted performance increase and the increased system complexity

Summary

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

„Der Klügere (Roboter) gibt nach.“ (misused German Proverb)