
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)
Dexter (SM)
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LWR III (DLR)
Spring Flamingo (MIT)
ANYbotics (ETH spin-off)
VSA Cubes (Univ. Pisa)
DAVID (DLR)
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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]
$\tau_i = K_i(\theta_i - q_i)$
q_i
θ_i
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Control approaches for Elastic Robots
Feedback Linearization
static for elastic joints,
dynamic for visco-elastic joints
[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]
Tomei, 91]
Kelly & Santibanez, 98]
$M(q)\ddot{q} + C(q,\dot{q})\dot{q} + g(q) = \tau$
$B\ddot{\theta} + \tau = \tau_m$
Motor Position
Based Control,
e.g. simple PD
Complexity >>
[Spong, 89]
Singular Perturbation:
includes torque feedback
stability properties weak
Energy Based Approaches
[Ott & Albu-Schäffer, 07/08]
[Albu-Schäffer, 00]

Feedback Linearization
• Link side position q presents a flat output
• Full state linearization by output transformation
$\begin{bmatrix} M(q) & 0 \\ 0 & B \end{bmatrix} \begin{pmatrix} \ddot{q} \\ \ddot{\theta} \end{pmatrix} + \begin{pmatrix} C(q,\dot{q})\dot{q} \\ 0 \end{pmatrix} + \begin{pmatrix} g(q) \\ 0 \end{pmatrix} + \begin{pmatrix} K(q-\theta) \\ K(\theta-q) \end{pmatrix} = \begin{pmatrix} 0 \\ \tau_m \end{pmatrix}$
$q^{(4)} = u$
• Linearizing control law (for reduced model):
$\tau_m = BK^{-1}M(q)u + K(\theta - q) + B\ddot{q} + BK^{-1}\left(2\dot{M}q^{(3)} + \ddot{M}\ddot{q} + \frac{d^2}{dt^2}(C\dot{q} + g(q))\right)$
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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
$BK^{-1}\ddot{\tau} + \tau = \tau_m - B\ddot{q}$
• Conventional torque tracking
$\tau_m = BK^{-1}\ddot{\tau}_d + \tau_d + K_T(\tau_d - \tau) + K_S(\dot{\tau}_d - \dot{\tau}) + \alpha B\ddot{q}$
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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 Klügere (Roboter) gibt nach." (misused German Proverb)
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