From Actively Compliant Lightweight Robots to Intrinsically Compliant Systems

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Outline

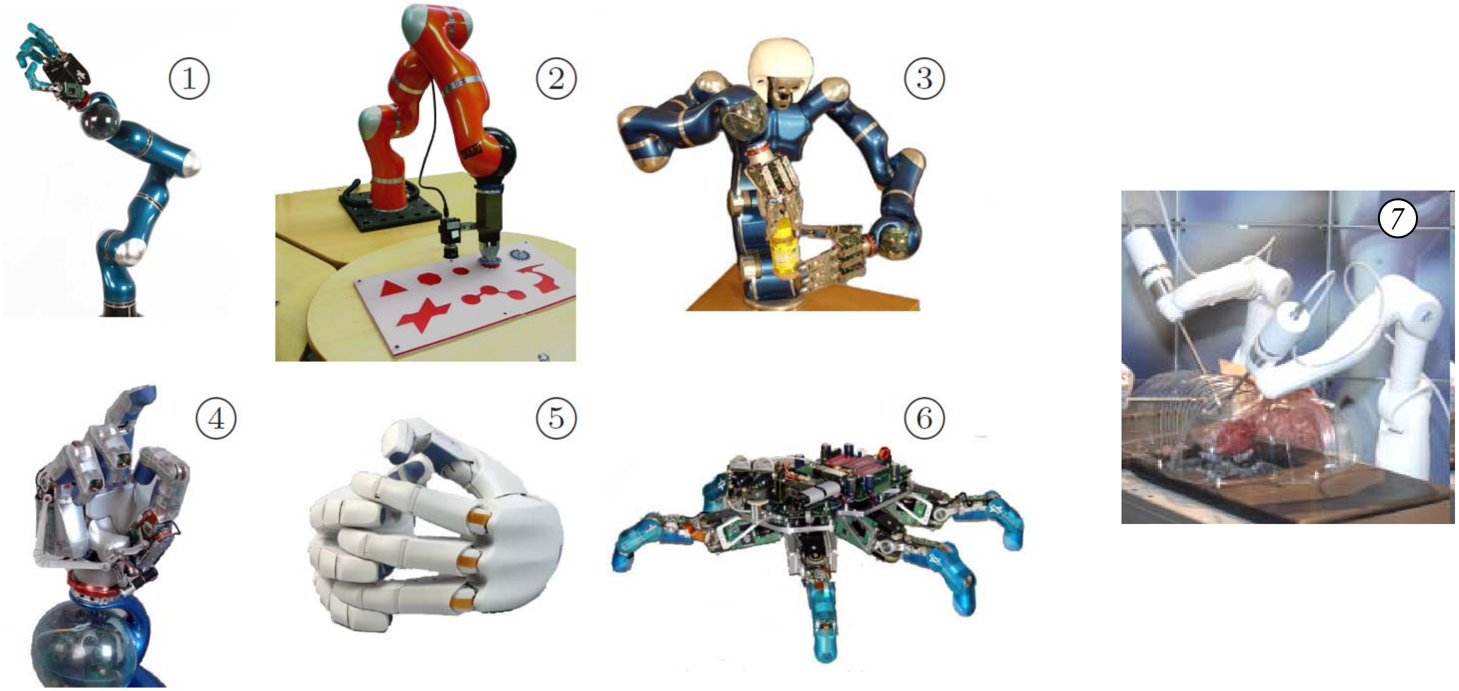
- Active Compliance
  - Assembly
  - Safety Concept
  - Collision Detection and Reaction
- Passive Compliance
  - Goals and Requirements
  - Design Principle
  - System Attributes
  - Throwing a Ball
- Conclusions & Future Work

Torque Control with gravity compensation

DLR-LWR III:

- 7 joints
- ~13.5 kg,
- weight/load ~1/1
- Position sensors at each joint motor and joint output
- Torque sensors at each joint output

Torque-Feedback Controlled Robots



Overview of the torque-feedback controlled DLR Robots:

1 : The DLR-LWRIII equipped with the DLR-Hand II.

2 : The DLR-KUKA-LWR III which is based on the DLR-LWR III.

3 : The DLR Humanoid Manipulator “Justin”.

4 : The DLR-HandII-b, a redesign of the DLR-Hand II.

5 : The DLR-HIT Hand, a commercialized version of the DLR-Hand II.

6 : The DLR-Crawler, a walking robot based on the fingers of the DLR-Hand II.

7 : The DLR medical robot MIRO

Physical Human-Robot Interaction with Justin

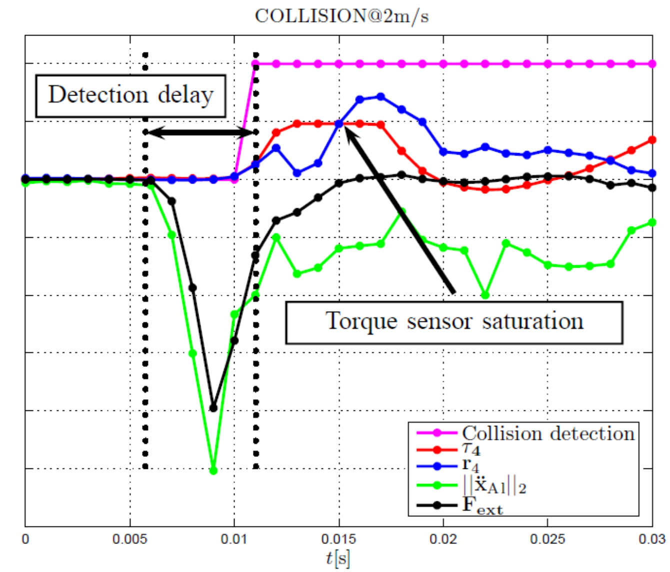
Justin with Mobile Platform at the Automatica fair 2008

Active Compliance in Assembly Job

Collision Detection and Reaction

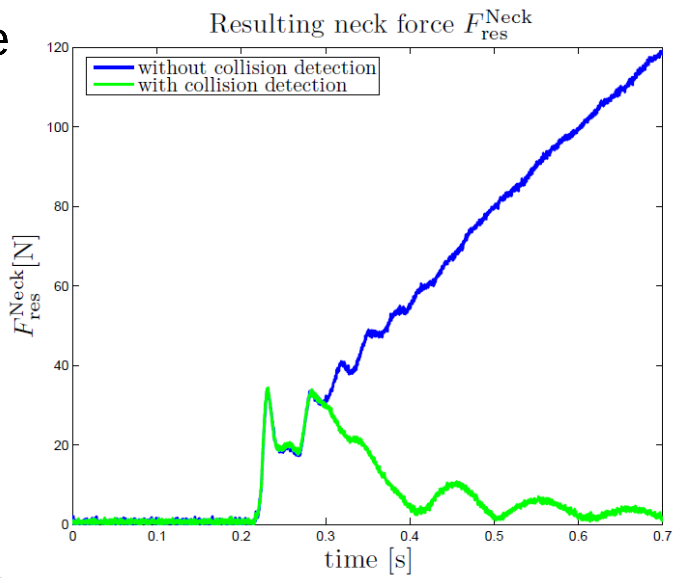
Collision Detection and Reaction

- Hard body impact with dummy head
- Additional force and acceleration sensors at the tip
- Torque controlled with gravity compensation after collision detection



Max. Contact Force 2 kN, max. acceleration 35 g.
All values are scaled to fit into one plot

- Motor and link inertia are decoupled by the intrinsic joint elasticity (~20000 Nm/rad in the first joints)
- No influence of a more compliant joint



Catching a Ball

Goals & Requirements of Passive Compliance

- Robust to fast impacts and contacts with rigid obstacles
- Enhanced performance (velocity, energy efficiency)
- Compliant when deactivated and at malfunction

- Lightweight
- Compact design that can be easily integrated
- High max/min stiffness ratio
- Change stiffness fast and with maximum link load
- Adaptable to different tasks:

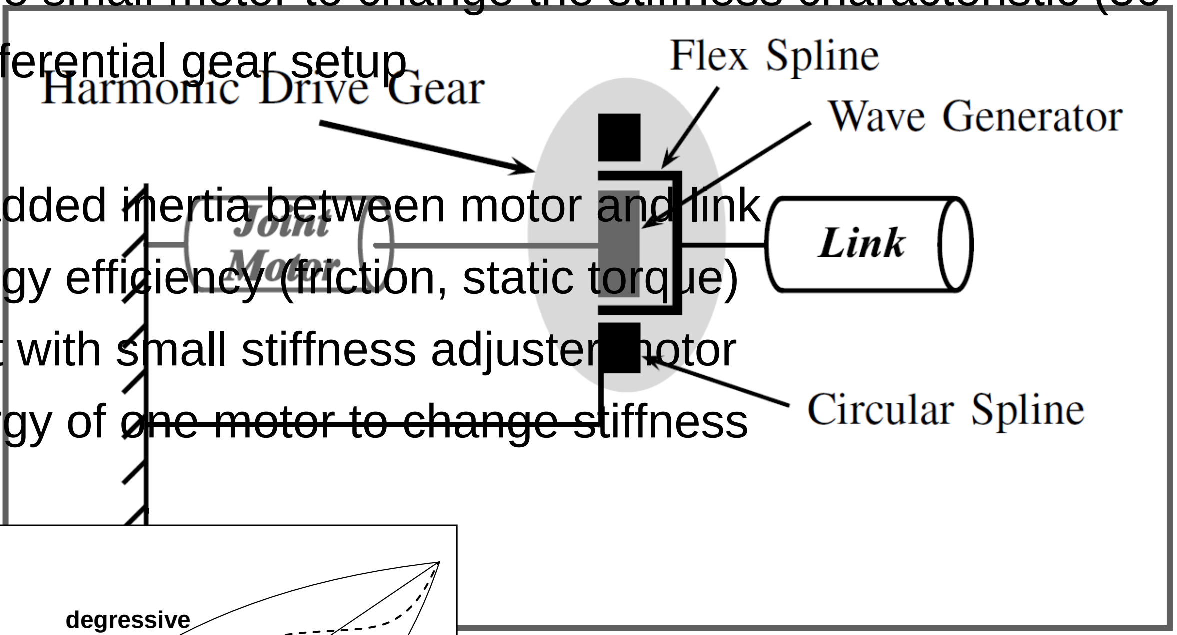
  strong, precise, fast

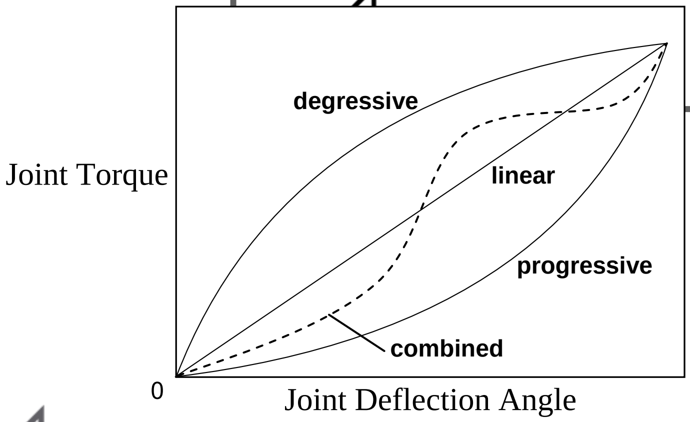
  ➔ stiffness profile, eigenfrequency

Design Principle

- One big motor to change the equilibrium position of the joint (350 W)
- One small motor to change the stiffness characteristic (50 W)
- Differential gear setup

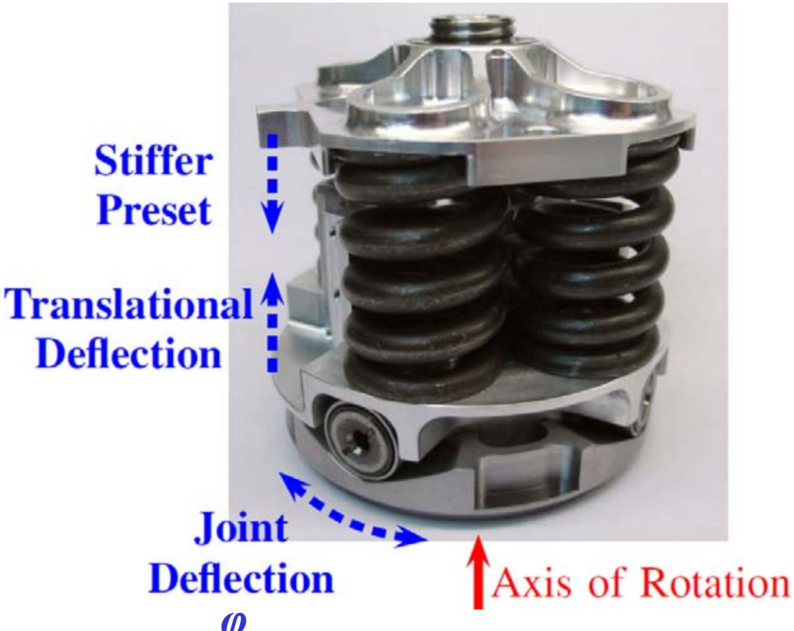
+ No added inertia between motor and link
+ Energy efficiency (friction, static torque)
+ Light with small stiffness adjuster motor
- Energy of one motor to change stiffness





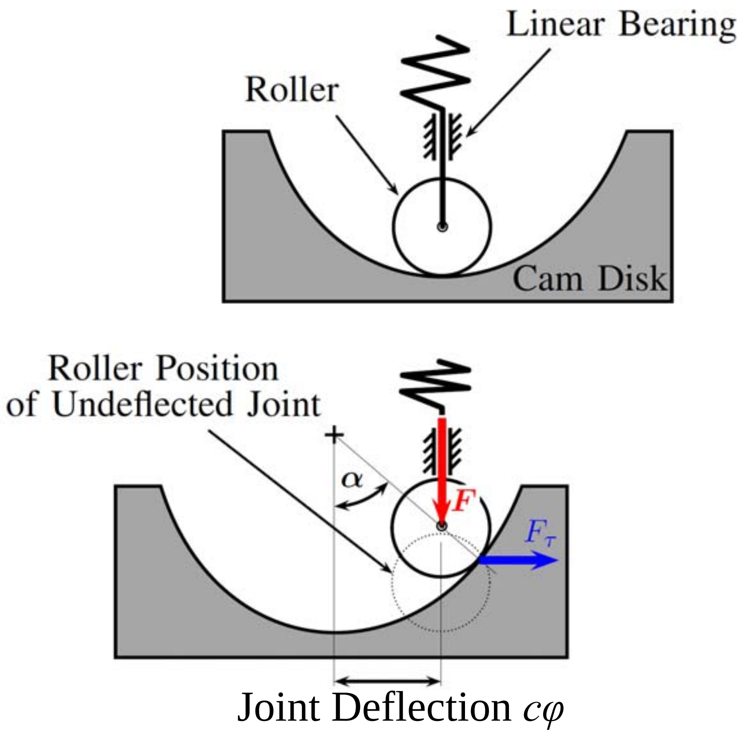
Design Principle

VS-Joint



(patent pending)

Unwinded Model



c : Radius of Cam Disk

System Attributes

- Compact
- Highly integrated
- Very low added inertia at passive compliant joint movement

VS-Joint properties

Max. Torque	160 Nm
Max. Deflection	$\pm 14\,^\circ$
Diameter	97 mm
Length	106 mm
Weight (incl. stiffness adjuster)	1.4 kg
Link Side Inertia	2.34×10^{-4} kg m^2

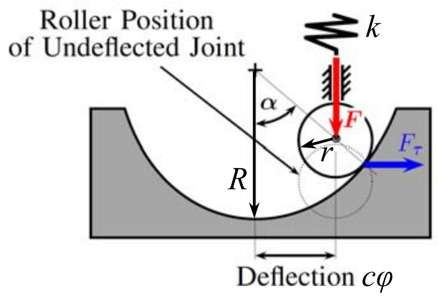
Example: Cam Disk with constant shape radius *R*

$$\alpha = \sin^{-1}\left(\frac{c\varphi}{R-r}\right)$$

$$\tau = Fc\tan\alpha = kc\tan\alpha\left((R-r)(1-\cos\alpha)+\frac{\sigma}{\pi}\right)$$

$$S = \frac{d\tau}{d\varphi} = kc^2\left[-1+\frac{R-r+\frac{\sigma}{\pi}}{(R-r)\cos\alpha}+\frac{\left(R-r+\frac{\sigma}{\pi}\right)c^2\varphi^2}{((R-r)\cos\alpha)^3}\right]$$

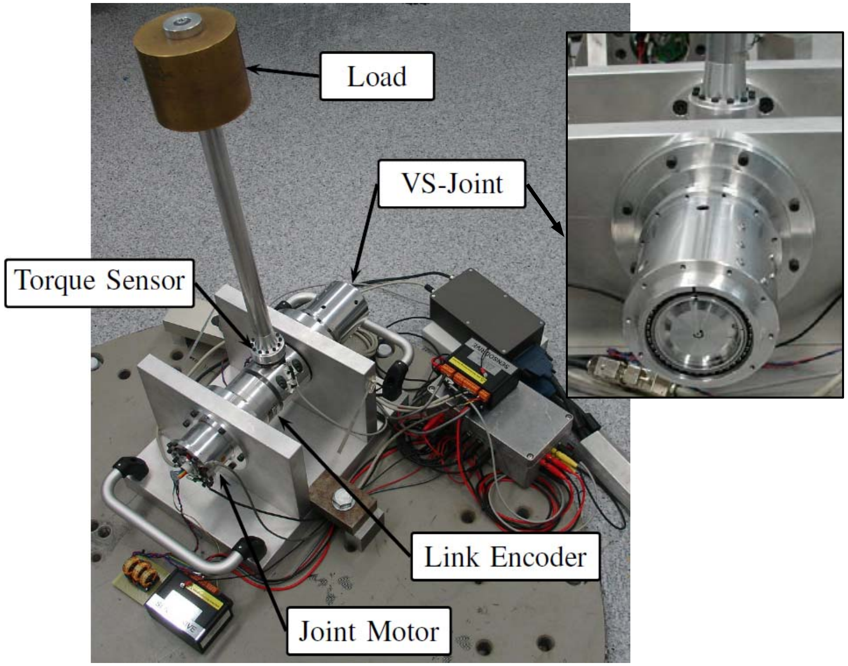
$$E = \int_0^{\varphi}\tau d\varphi = -k\left[\frac{1}{2}c^2\varphi^2(R-r)\left(\left(1+\frac{\sigma}{\pi}\right)\cos\alpha+\frac{\sigma}{\pi}-R+r\right)\right]$$

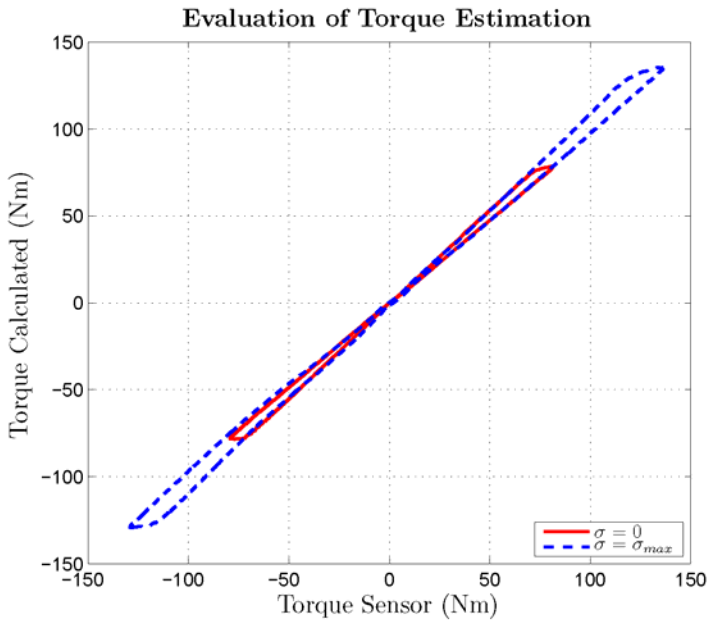


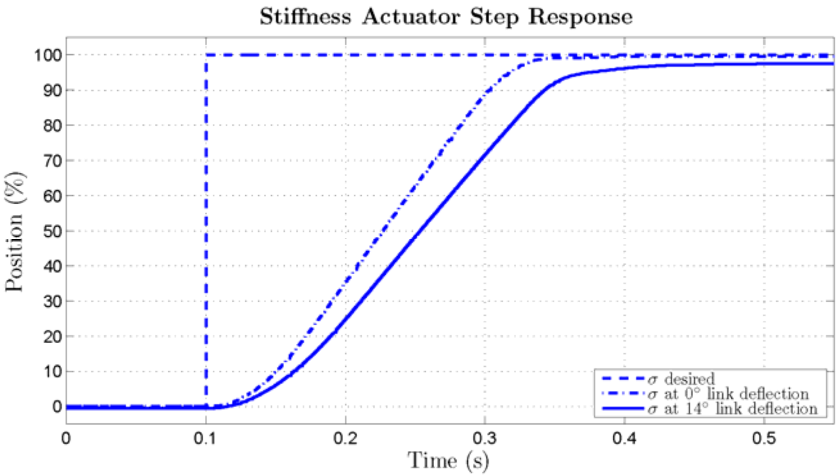
c : Radius of Cam Disk
r : Radius of Roller
R : Radius of Cam Shape
k : Spring Constant
F : Spring Force
σ : Stiffness motor position including transmission ratio

Testing Setup & Results

- Unmodeled structure elasticity
  → linear factor of 0.81 on torque
- Friction and sensor hysteresis
- Stiffness actuator dynamics

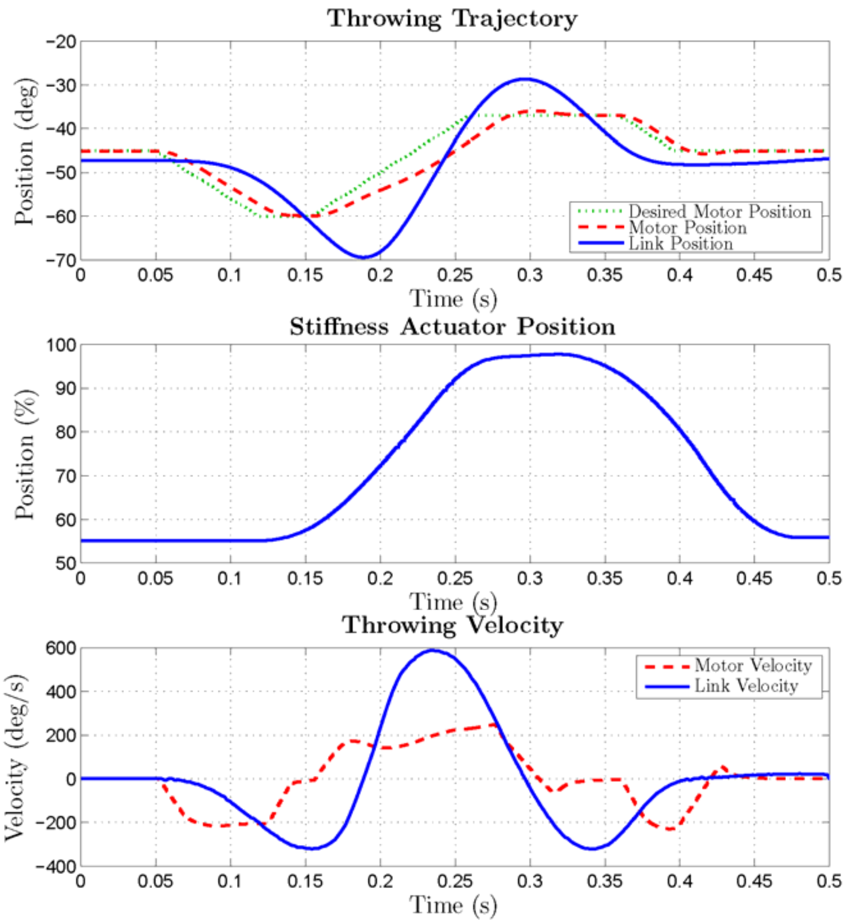






Throwing a Ball - Demonstration of Velocity Gain

- Attached Lacrosse-Stick-Head
- 0.78 m lever length
- Strike out trajectory (bang - bang)
- Stiffness increase to add extra energy to the system



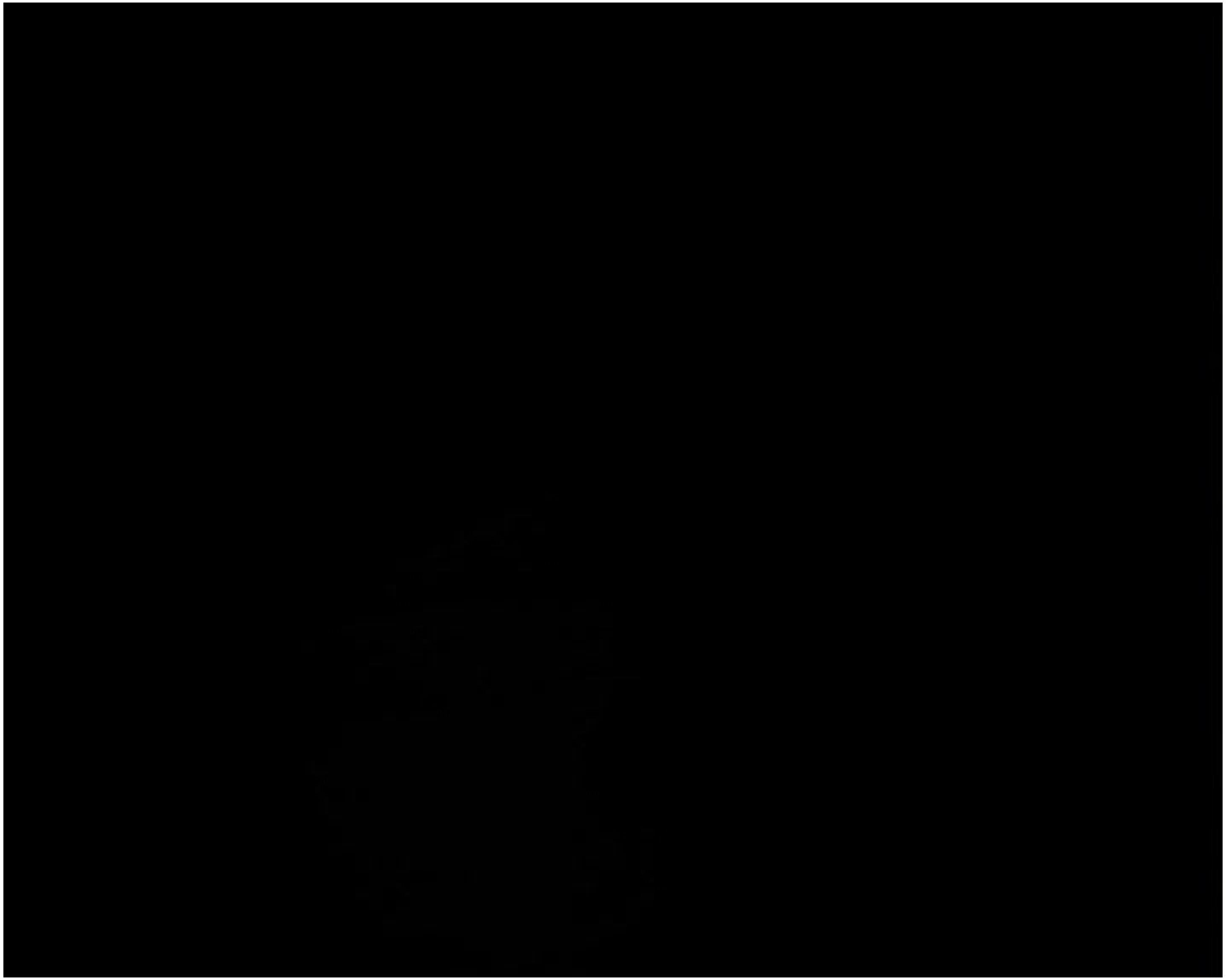
Comparison of flexible to stiff joint:

- Same maximum motor velocity and setup of soft and stiff joint

	Sitff Joint	VS-Joint
Link Velocity	216°/s	588°/s
Calc. Throwing distance	0.88 m	6.52 m

- Link velocity gain of 272%

Demonstration: Throwing a Ball with the Joint Test Bed



Conclusions

- Active Compliance
  - In hard impacts the link and motor inertias are decoupled
  - The force peak at an impact can not be influenced by the joint stiffness
  - Compliance bandwidth is important at hard impacts

- Passive Compliance
  - Development of a joint prototype with variable stiffness
  - Easily adaptable system characteristic by changing the cam disk
  - High dynamic stiffness adjuster
  - Mechanical energy storage
  - Enhanced performance in terms of maximum velocity

Future Works

- Ideal passive compliance characteristic
- Development of a compact joint module
- Integration in a robotic system

Thank you for listening!