Design of the DLR Hand Arm System: Benefit of Variable Impedance Actuators (VIA)

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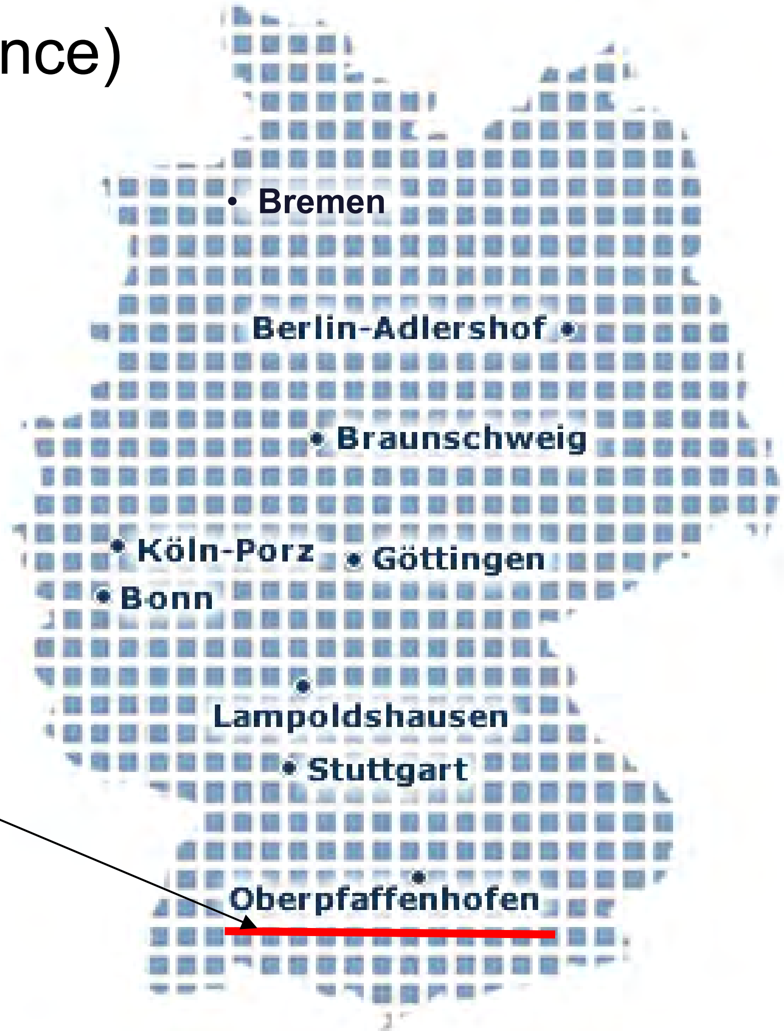
DLR Deutsches Zentrum für Luft- und Raumfahrt e.V.
in der Helmholtz-Gemeinschaft

DLR Deutsches Zentrum für Luft- und Raumfahrt (German Aerospace Center)

DLR (Germany) ⟷ CNES (France)

~ 8000 employees
16 locations

~1700 employees



Institute of Robotics and Mechatronics
research staff:~170 persons

Flight operation

Applied Remote Sensing Cluster

Atmospheric Physics

Space Operations Center

Microwaves and radar

Communications and Navigation

Galileo Control Center

Outline

- Motivation
- Torque controlled robots
- What are Variable Impedance Actuators (VIA)
- Performance of VIA robots
- Reflexes
- Conclusion
- VIA winter school

Motivation

- **Precision**: necessary for fine manipulation
- **Sensitive**: gentle interaction with the environment
- **High dynamics**: fast and controlled movements
- **Robustness**: design to reduce the risk of breaking down

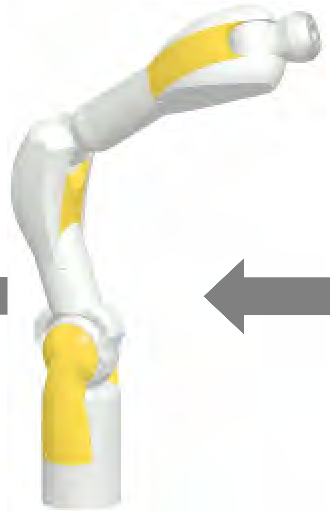
source: youtube.com

source: youtube.com

Torque Controlled Robots

Miro

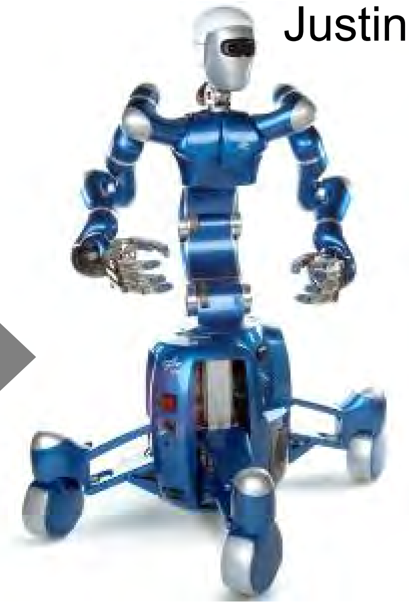
Kinemedic



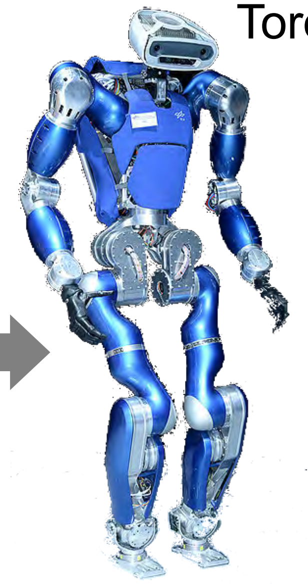
DLR Medical Robot

LWR III

Justin



Toro



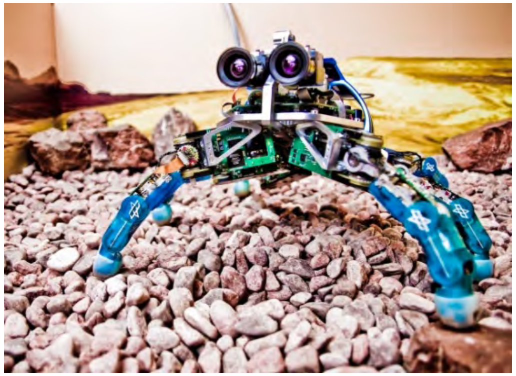
Euron TechTransfer Award 2011

Torque Controlled Hands

DEXHAND (ESA)

DLR Hand II

Justin



6 leg crawler

Commercialization by SCHUNK now by DLR: *Wessling Robotics spin off*

Space Driven Robot Development

Change of paradigm in robotics:

From large, rigid and position controlled to light-weight, compliant, and adaptable

Therefore we coined the name "**Soft Robotics**"

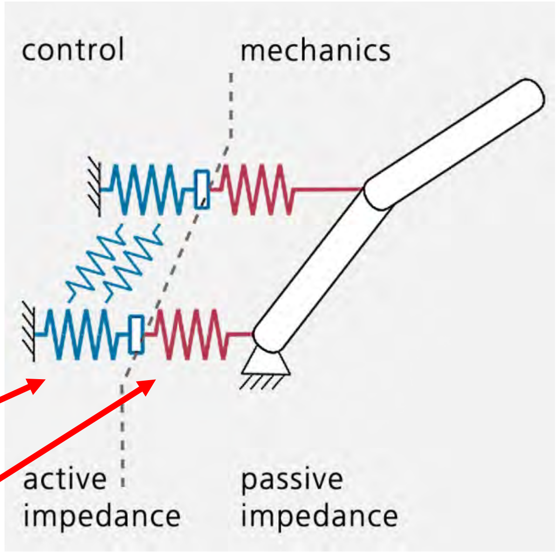
Zero gravity behaviour

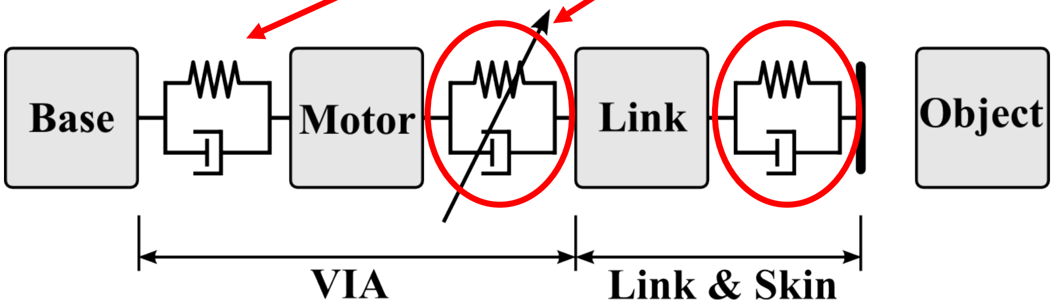
Programmable stiffness and damping

Safety tests

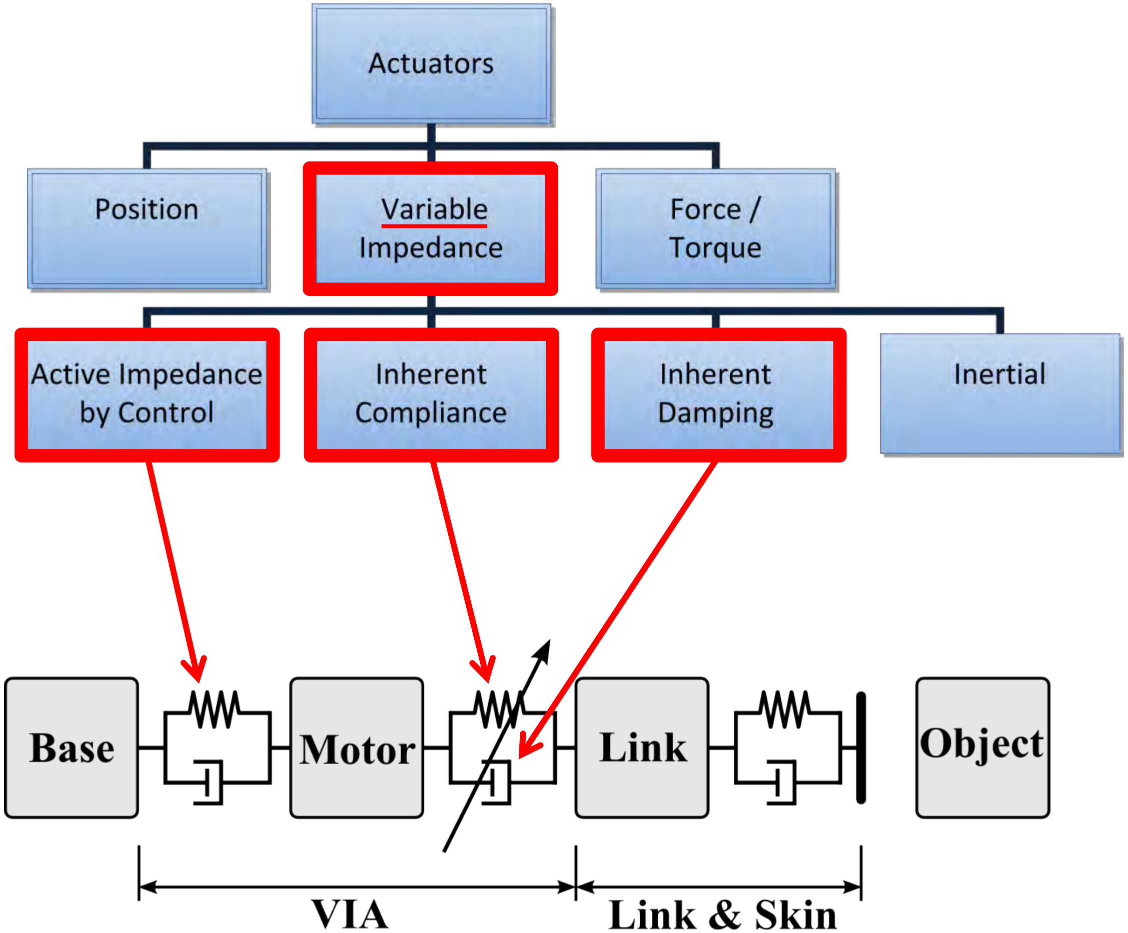
Hardware - Soft Robot Concept

- Decoupling of output and motor inertia
- Stiff link structure
  - Precise position measurement
  - Good dynamic model
  - Dedicated motors for each DoF
- Soft outer hull (skin)
  - Reduce contact forces
  - Gain time to react



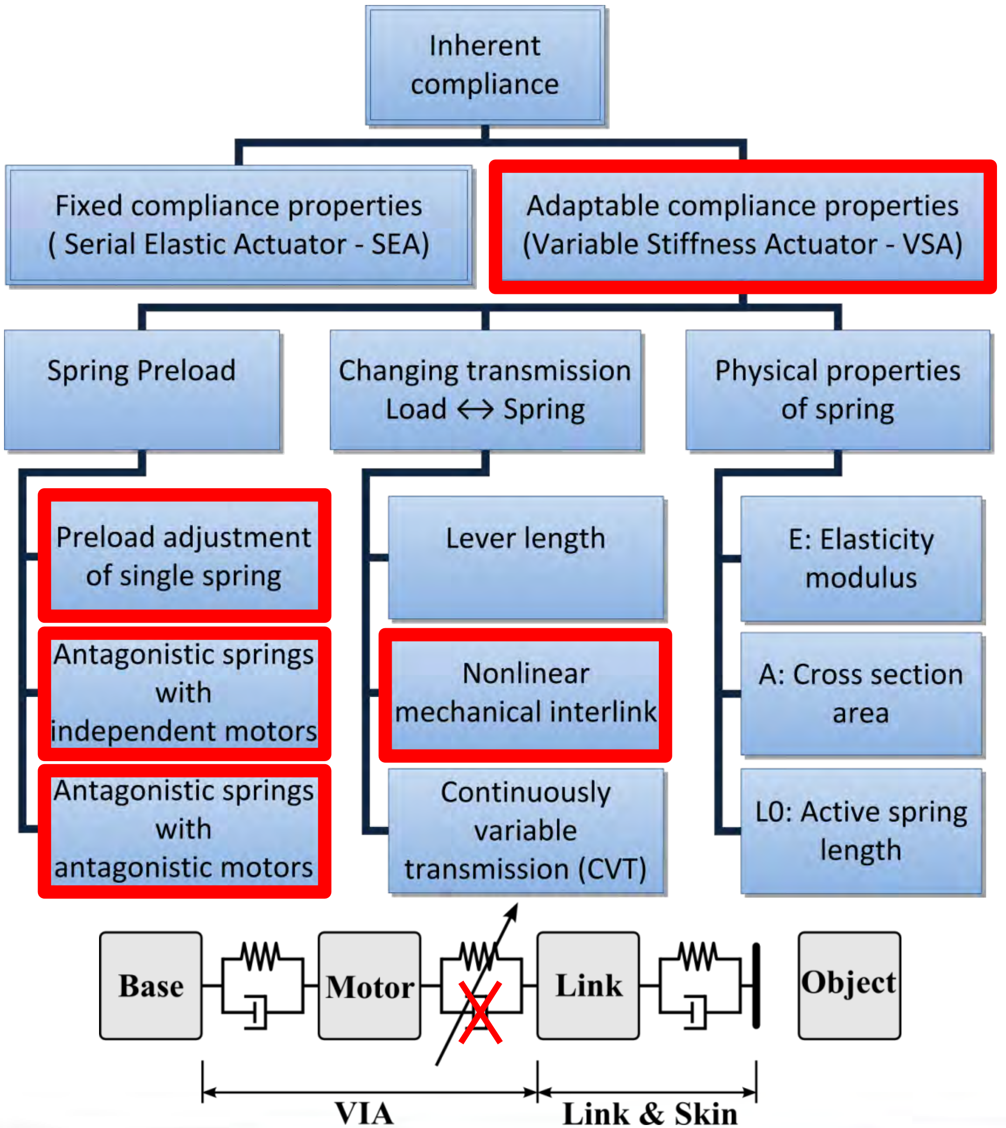


Hardware – VIA Classification



Vanderborght et al., Variable impedance actuators: A review, RAS, 2013

Hardware VSA Classification



Hardware of the DLR Hand Arm System

Vanderborght et al., Variable impedance actuators: A review, RAS, 2013

DLR Hand Arm System

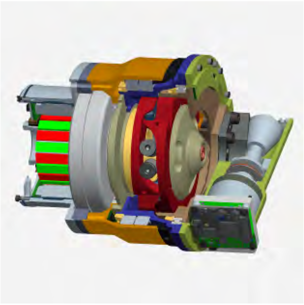
Anthropomorphic light weight robot:

- **size**, **kinematics**, **force** and **dynamics** of human arm and hand
- **variable stiffness** in all joints

- *26 DoF*
- *52 motors*
- *112 position sensors*

Tendon driven fingers

Antagonistic finger actuation



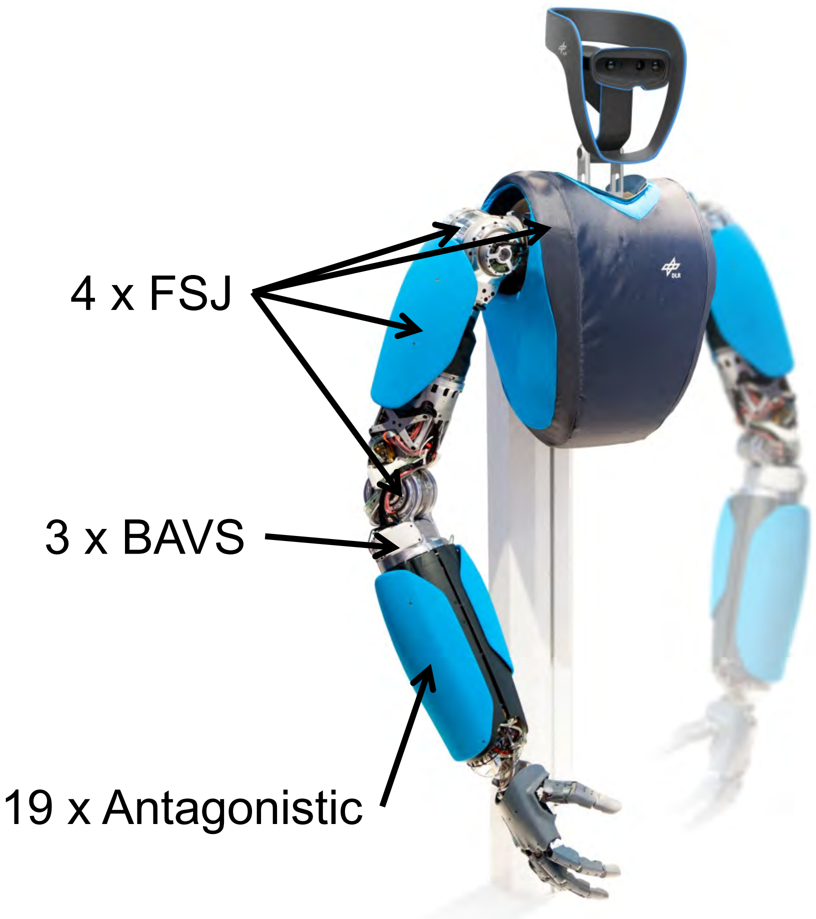
Variable stiffness arm actuators e.g. FSJ

Highly integrated electronics e.g. ILM25 motor module

DLR Hand Arm System

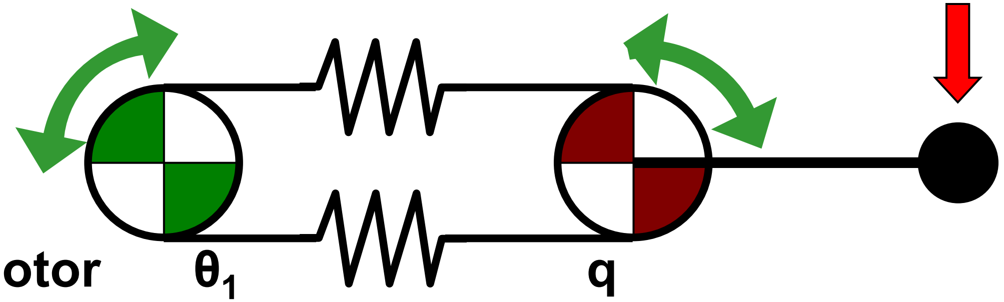
The Hand Arm System is equipped with 3 types of Variable Stiffness Actuators:

- Antagonism (19 DoF Hand)
- BAVS - Bidirectional Antagonism with Variable Stiffness Actuation (2 DoF wrist,1 DoF forearm-rotation
- FSJ - Floating Spring Joint (4 DoF upper arm joints



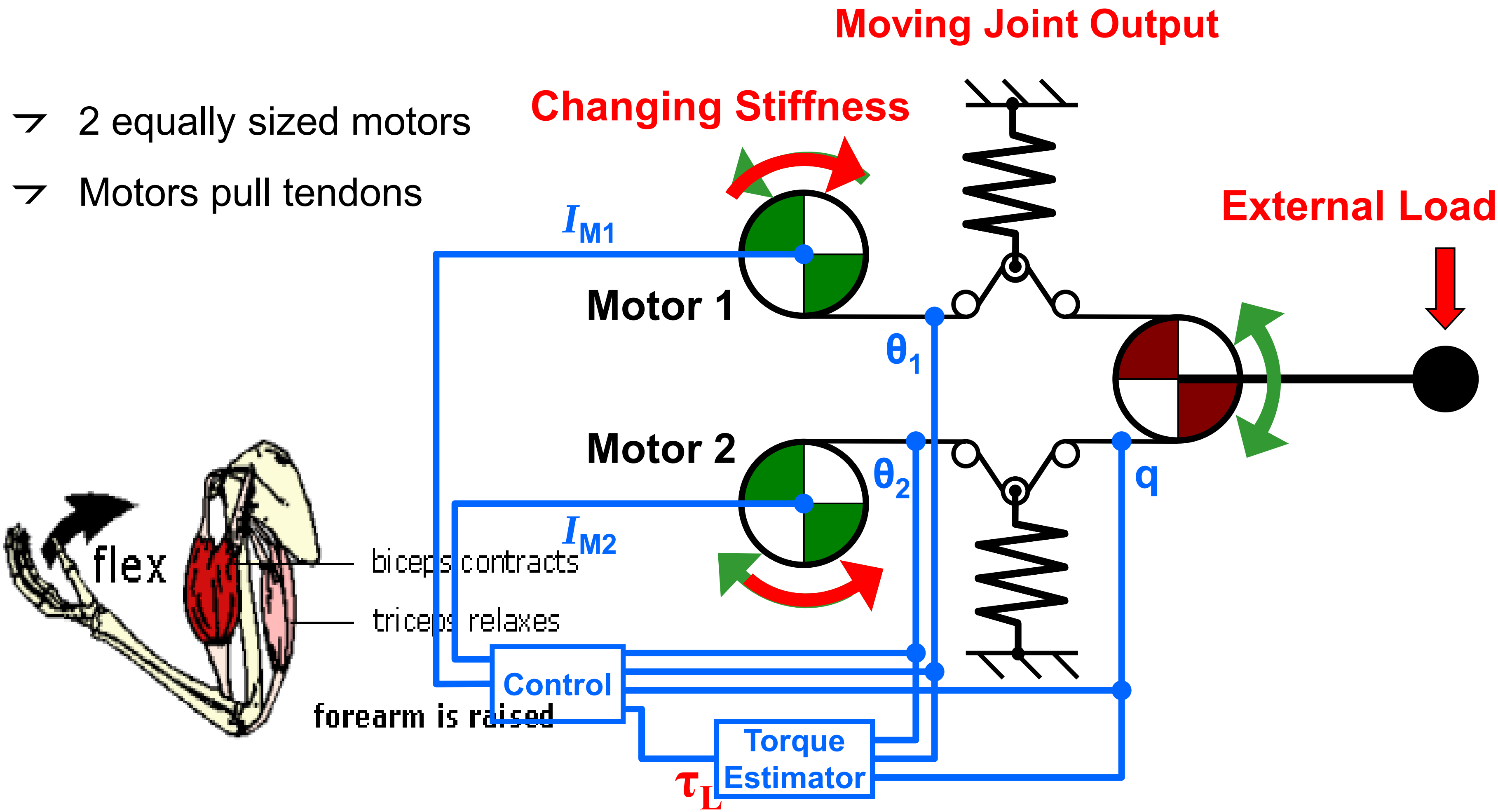
SEA – Serial Elastic Actuator

- one motor
- fixed stiffness



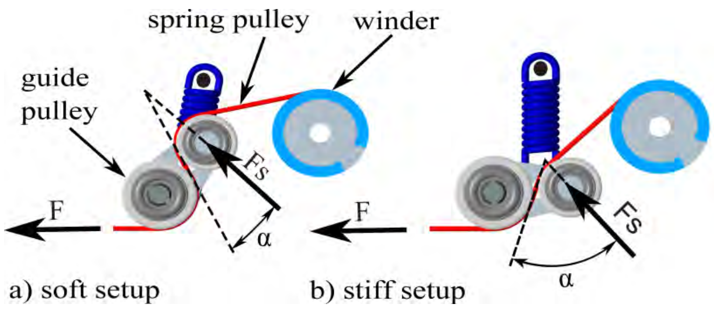
Antagonistic Actuator

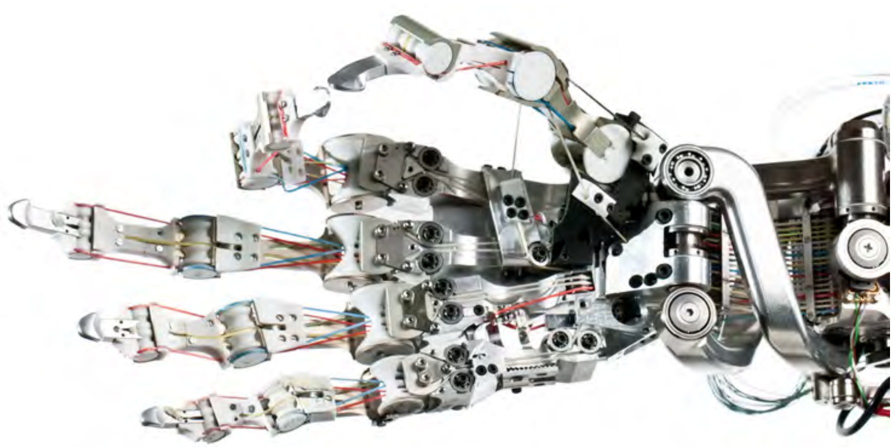
- 2 equally sized motors
- Motors pull tendons

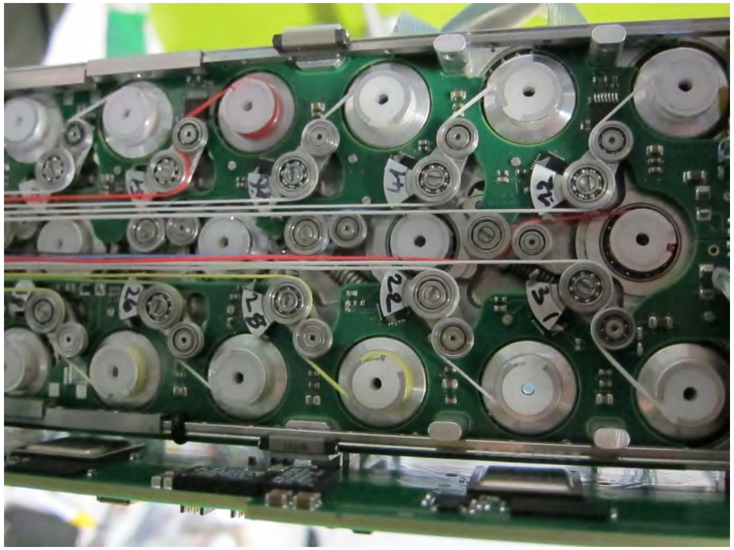


Finger Actuation (FAS)

- Simple and small
- Few parts
- Compensates geometric inaccuracies



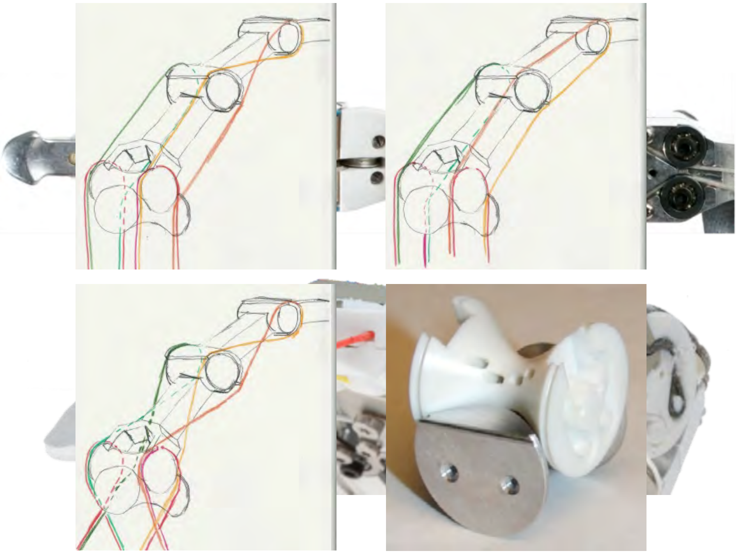


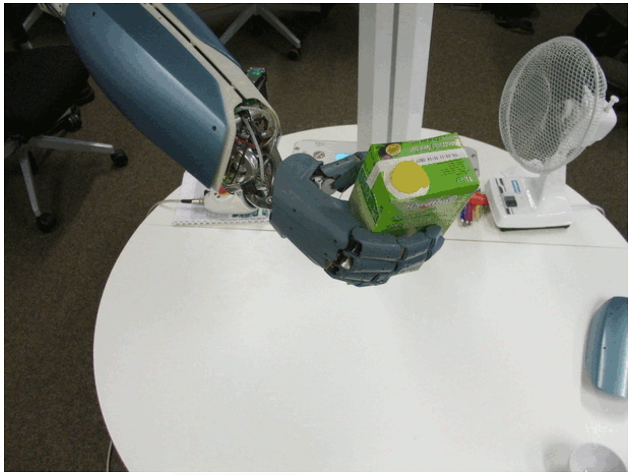


Friedl, W., Chalon, M., Reinecke, J. and Grebenstein, M., *FAS A flexible antagonistic spring element for a high performance over*, Intelligent Robots and Systems (IROS), 2011 IEEE/RSJ International Conference on, 2011, pp. 1366-1372

Hand Design (Awiwi Hand)

- 38 Motors drive 19 DoFs antagonistically
- Nonlinear spring mechanism in each tendon path
- Robust to impacts
- Adjustable stiffness
- Suitable for grasping objects made for the human



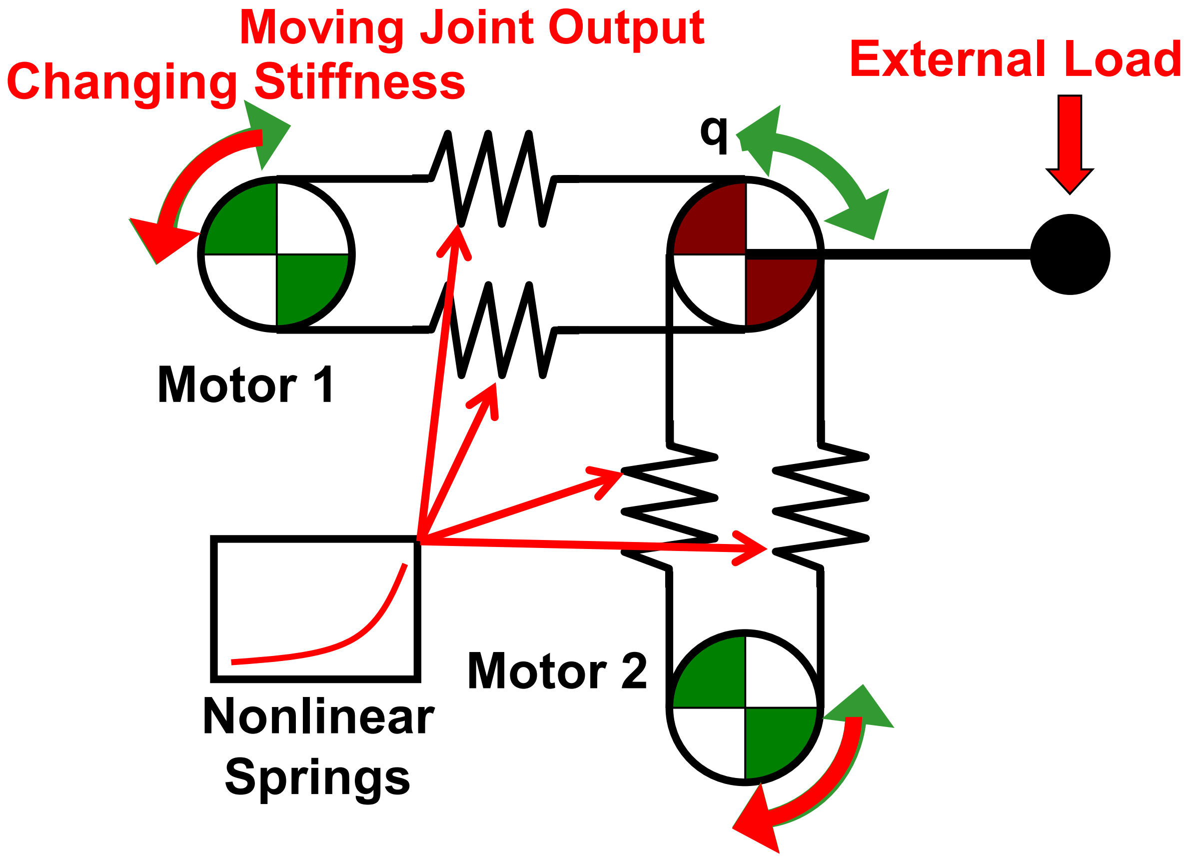


Markus, Grebenstein (2012) Approaching human performance: The functionality driven Awiwi robot hand. Dissertation, ETH Zurich

Reinecke et al., Experimental Comparison of Slip Detection Strategies by Tactile Sensing with the BioTac the DLR Hand Arm System, ICRA, 2014

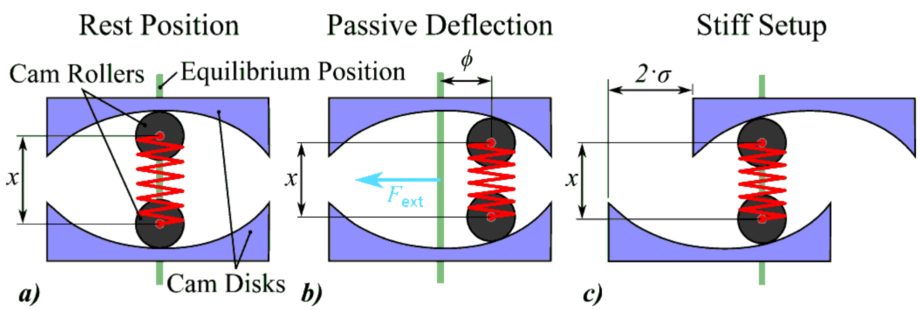
Bidirectional Antagonistic Actuator

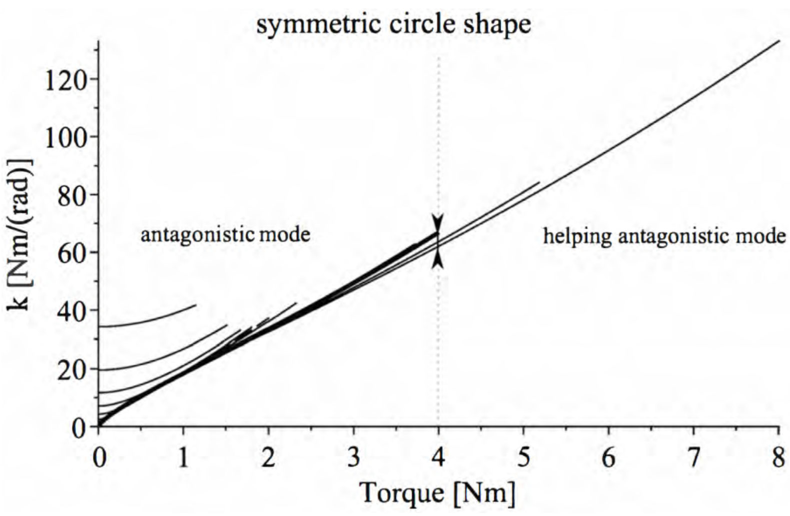
- 2 equally sized motors
- both motors push and pull (bidirectional)
- Add both motor torques

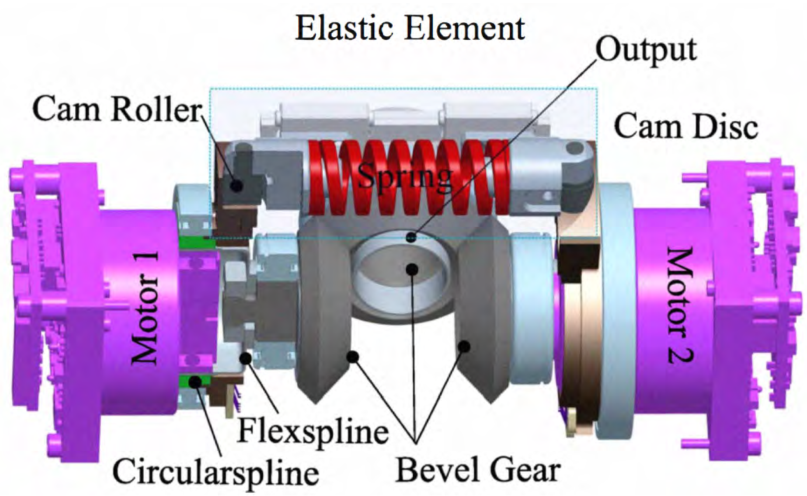


Wrist and Forearm Actuation (BAVS)

- Motor torques sum up to 8 Nm
- Symmetric or asymmetric cam disk design



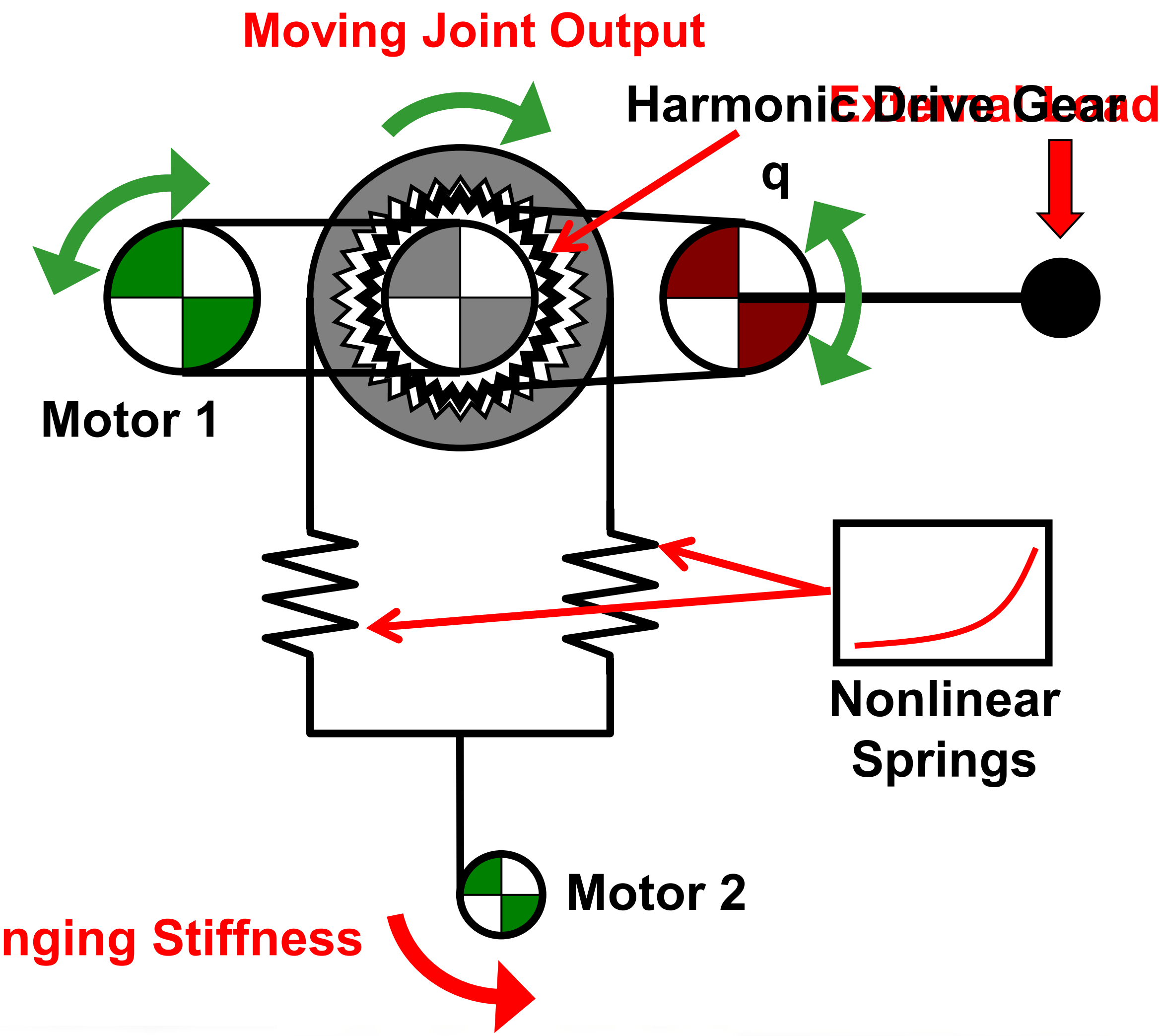




Friedl, W., Hoppner, H., Petit, F. and Hirzinger, G., *Wrist and forearm rotation of the DLR Hand Arm System: Mechanical design, shape analysis and experimental validation*, Intelligent Robots and Systems (IROS), 2011 IEEE/RSJ International Conference on, IEEE/RSJ, 2011, pp. 1836-1842

Adjustable Stiffness Actuator

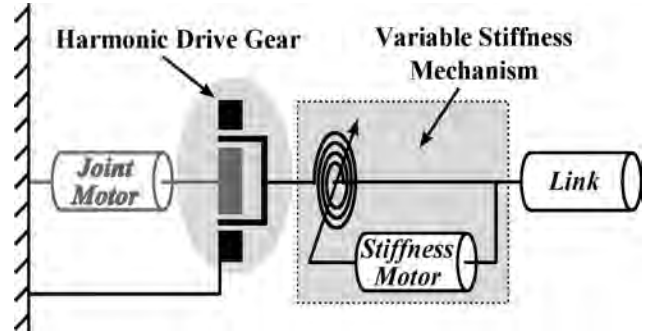
- one big motor moves the joint
- one small motor changes joint stiffness

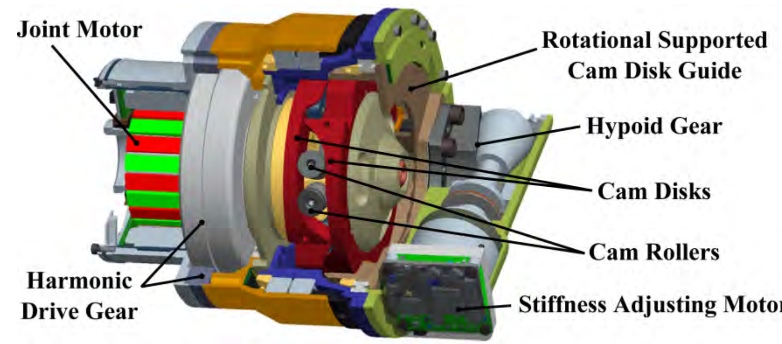


Shoulder and Elbow Actuation (FSJ)

- One big joint motor for positioning
- One small motor for stiffness change
- Serial setup

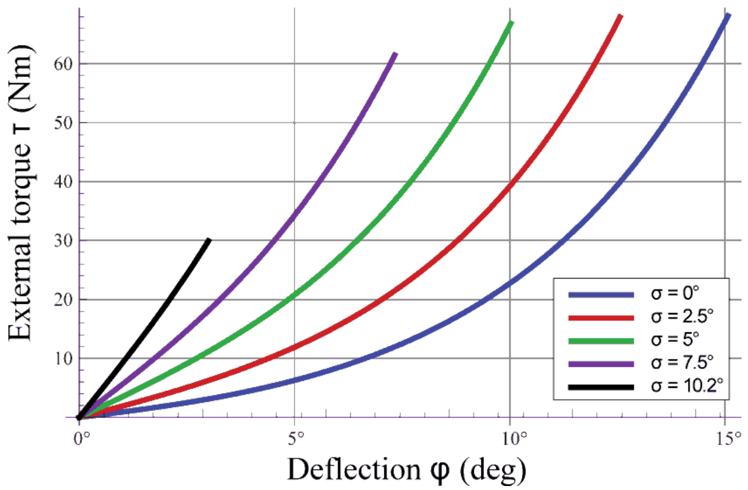
Max. torque	67 Nm
Drive speed	490°/s
Max. Stiffness	826 Nm/rad
Min. Stiffness	52 Nm/rad
Peak Input Power	1.3 kW
Weight	1.4 kg

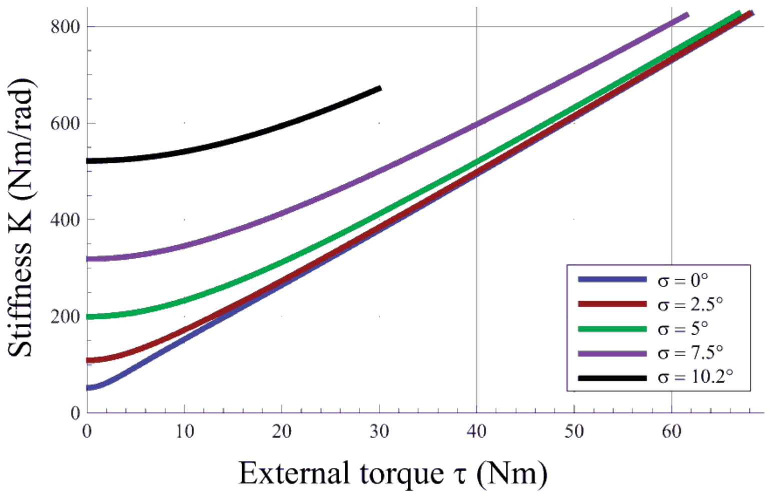


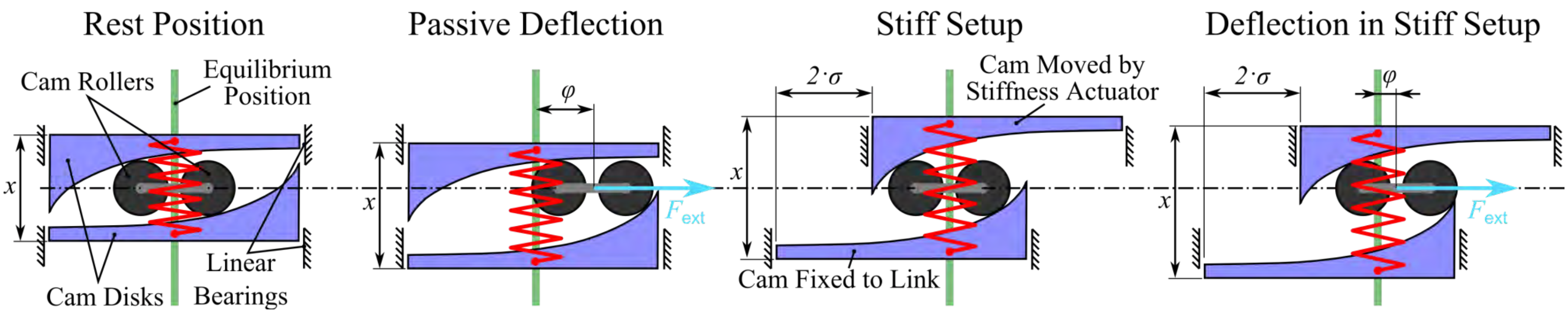


Wolf, S., Eiberger, O. and Hirzinger, G., *The DLR FSJ: Energy based design of variable stiffness joints*, Robotics and Automation (ICRA), 2011 IEEE International Conference on, IEEE, 2011, pp. 5082 - 5089

The FSJ Mechanism







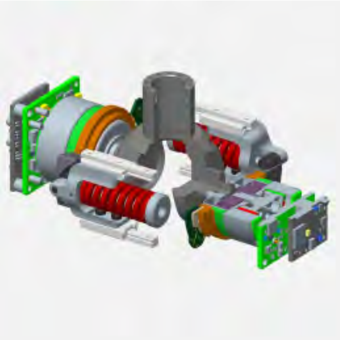
Wolf, S., Eiberger, O. and Hirzinger, G., *The DLR FSJ: Energy based design of variable stiffness joints*, Robotics and Automation (ICRA), 2011 IEEE International Conference on, IEEE, 2011, pp. 5082 - 5089

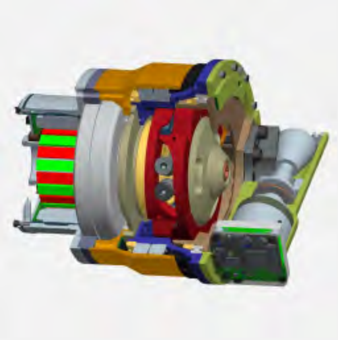
Types of VSAs of the DLR Hand Arm System

- Antagonism (19 DoF Hand):
  - -2 equivalent motors adjusting joint stiffness and position
  - -in-tendon progressive spring mechanism

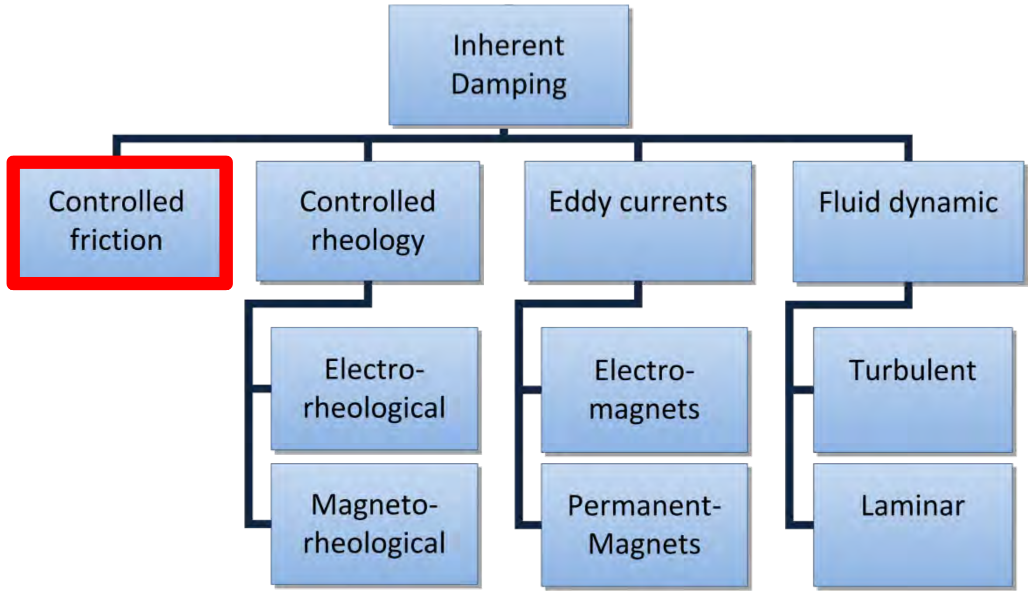
- BAVS - Bidirectional Antagonism with Variable Stiffness Actuation (2 DoF wrist,1 DoF forearm-rotation):
  - -2 equivalent motors adjusting joint stiffness and position
  - -Asymmetric cam disc shape
  - -Redundant joint actuation

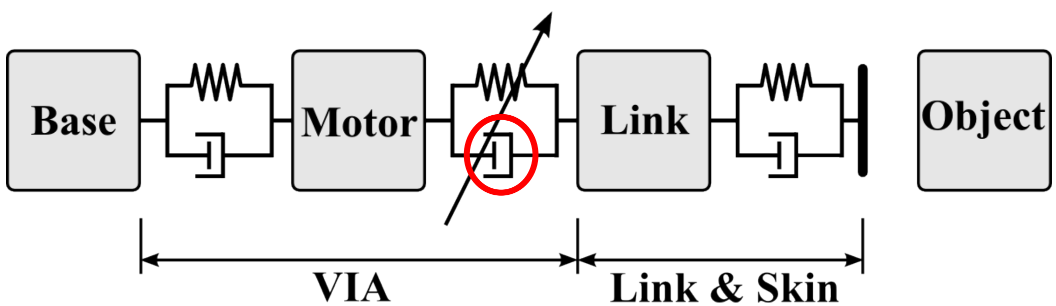
- FSJ - Floating Spring Joint (4 DoF upper arm joints):
  - -one big motor for joint positioning
  - -one small motor to change the stiffness
  - -one single spring





Hardware VDA Classification



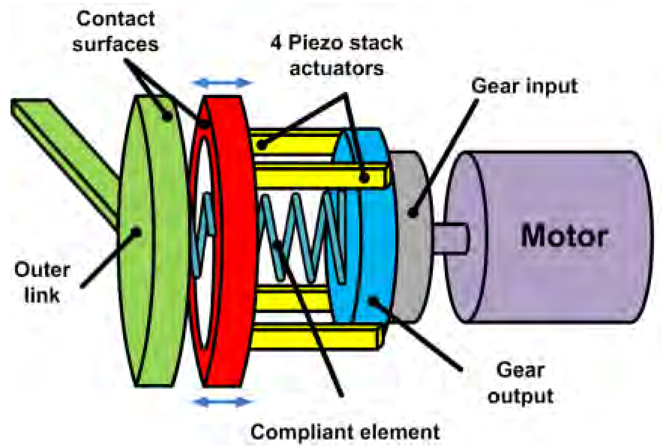


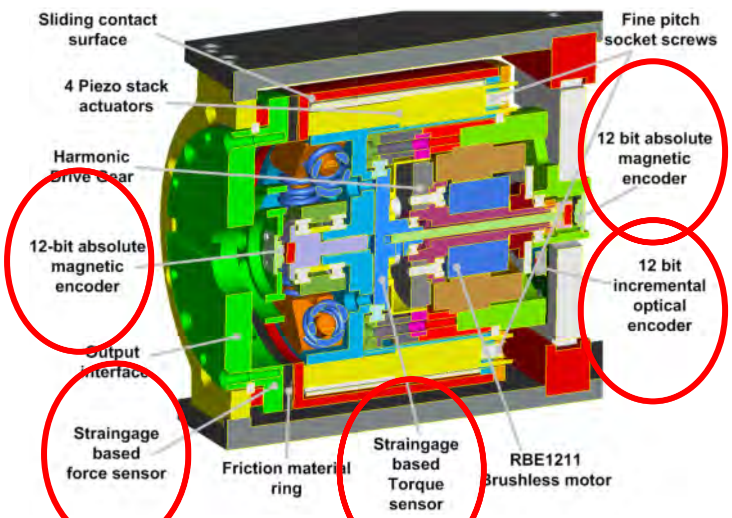
Vanderborght et al., Variable impedance actuators: A review, RAS, 2013

Variable Damping Actuator (VDA)

- Variable damping (actuated)
- Constant spring rate
- Force AND torque sensors

CompAct Arm





M. Laffranchi, N. G. Tsagarakis and D. G. Caldwell, "A Variable Physical Damping Actuator (VPDA) for Compliant Robotic Joints," in International Conference on Robotics and Automation, Anchorage, Alaska, 2010.

Active Damping for Variable Stiffness Actuators

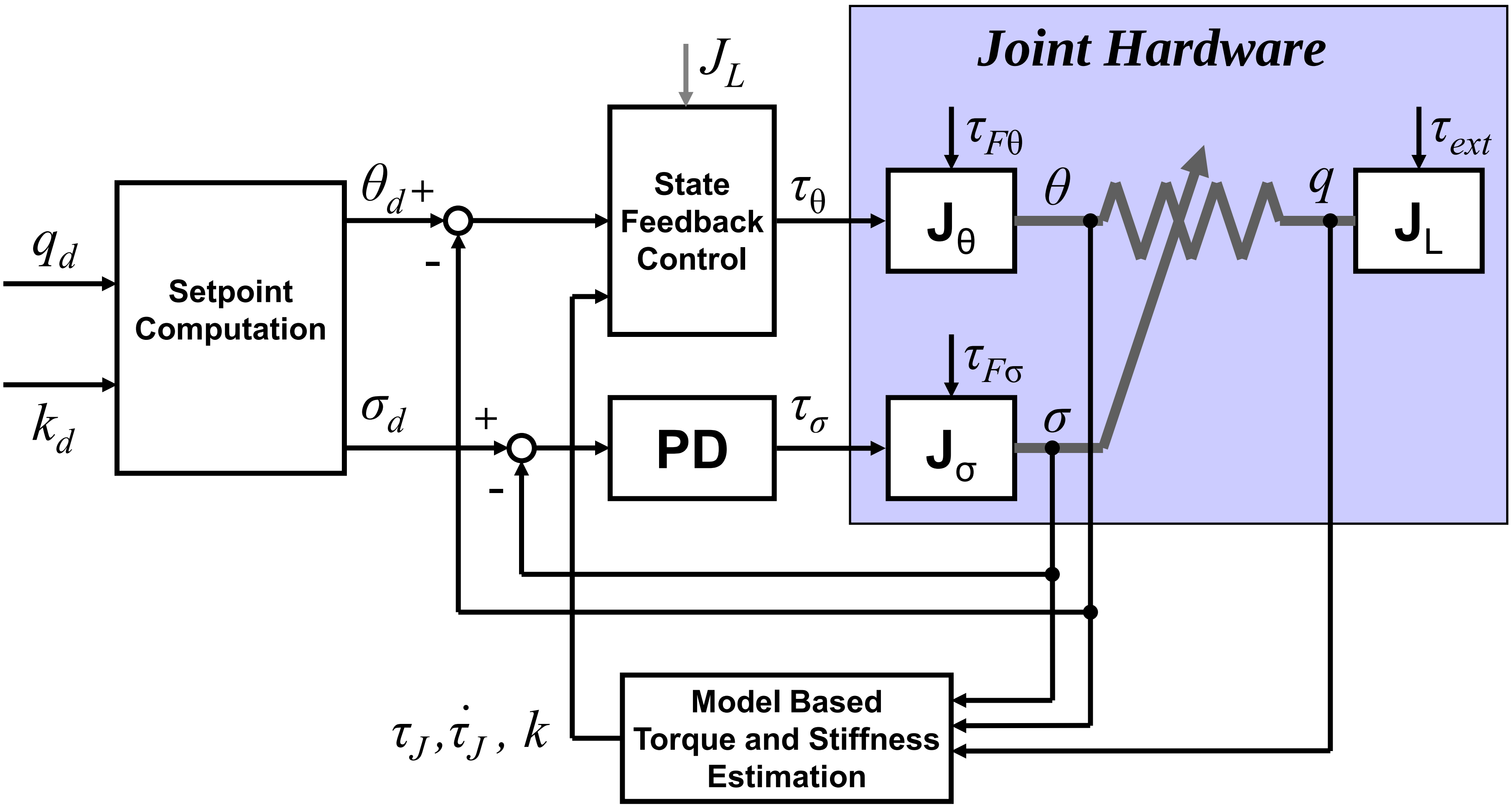
Variable Stiffness Actuators
have very low intrinsic damping

useful for cyclic movements involving energy storage (running or throwing)

damping of the arm for fast, fine positioning tasks has to be realized by control

- Vibration damping
- Ensuring the achievement of the desired link position with motor position based control
- Providing the desired stiffness property

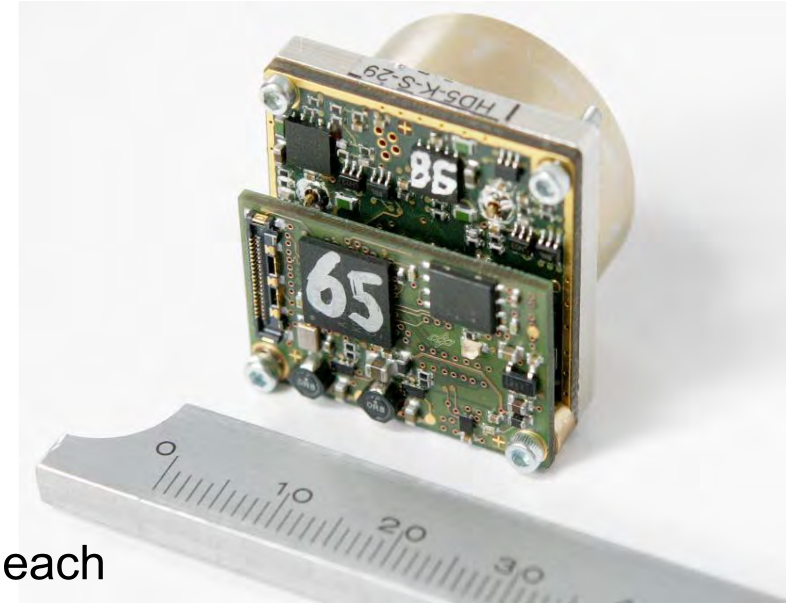
Active Damping



Actuation of the DLR Hand Arm System:

DLR brushless DC ILM Drives & Harmonic drive gears

- ILM 25 (ServoModules)
  - Forearm actuation and stiffness actuators
  - 44 Motors at 5 A, 24 V (hardware limit: 9 A) ⇨ 4,8 kW
  - Power density > 15 mW/ mm^2 (electronics included)
  - Full integration of electronics
    - Position controller
    - Motor controller
    - Power electronics
    - Communication Interface



- ILM 50 (Arm joint actuation)
  - Elbow and shoulder
  - Maximum input power 1.15 kW each

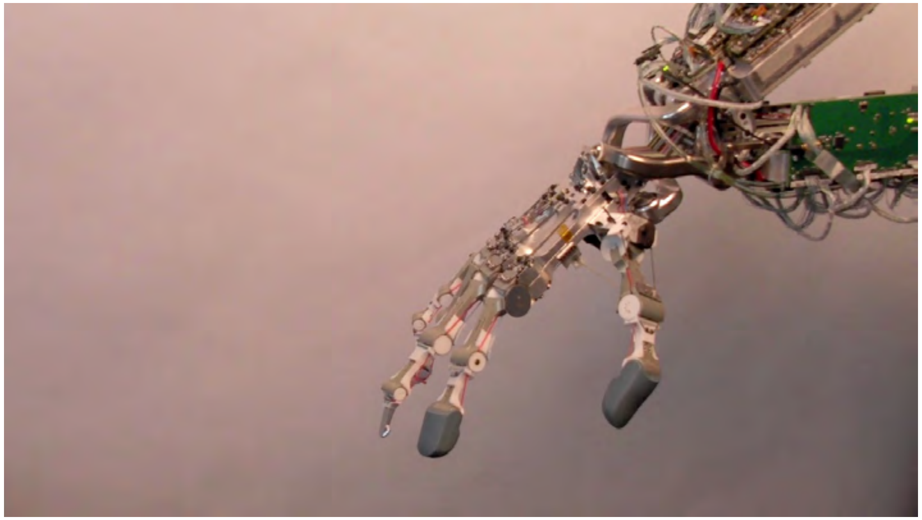
Performance of the Hand Arm System

Demonstrations on:

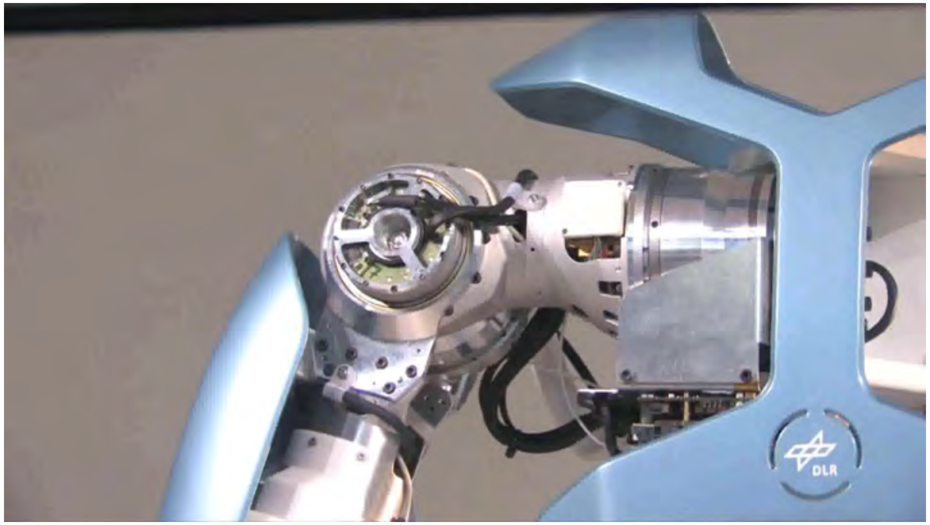
- **Precision**: necessary for fine manipulation
- **Sensitive**: gentle interaction with the environment
- **High dynamics**: fast and controlled movements
- **Robustness**: design to reduce the risk of breaking down

Precision

- Precise in movements and dynamics
- High resolution output and spring deflection sensors with rigid structure
- Known inertial properties for good dynamic models



Coordinated finger movement



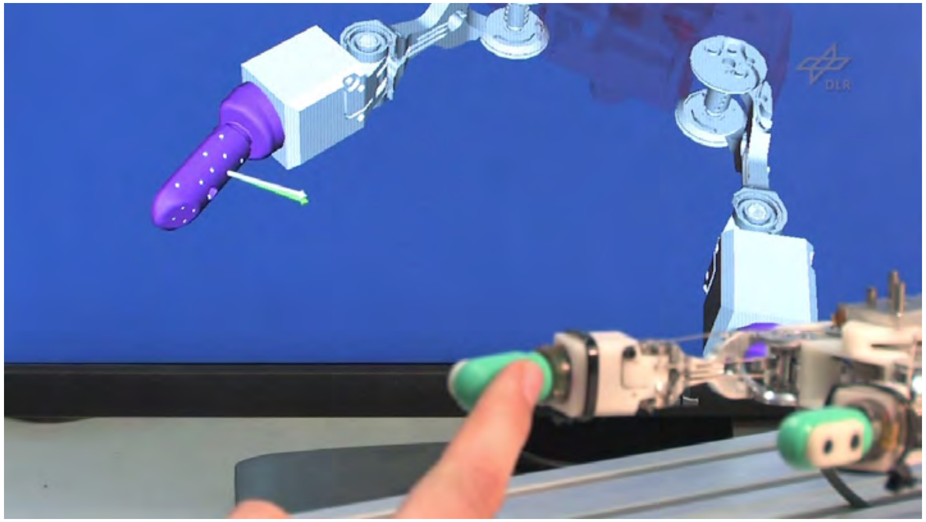
Active damping control

Petit et al., State feedback damping control for a multi DOF variable stiffness robot arm, ICRA, 2011

Sensitivity

- Precise torque mesurement
- Contact force control
- Robust grasping of objects

Robust grasping



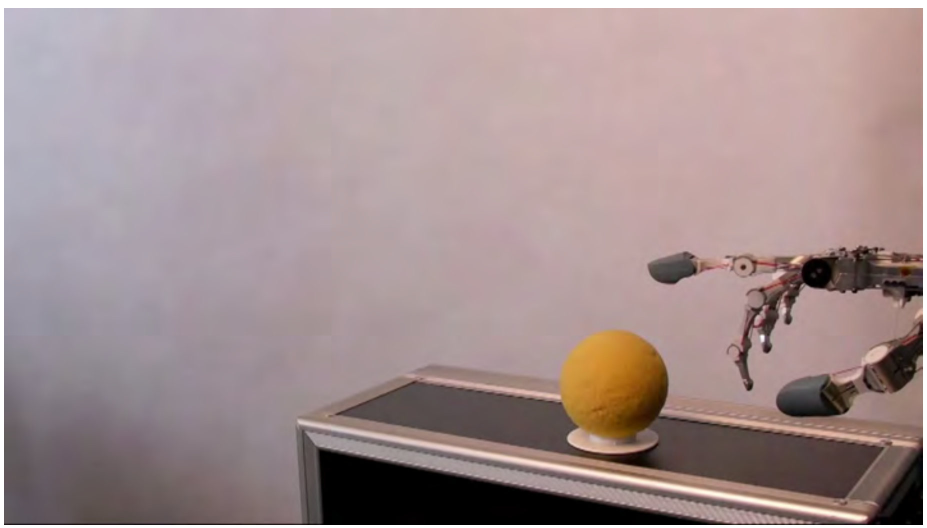
Control of contact force when grasping

Reinecke et al., Experimental Comparison of Slip Detection Strategies by Tactile Sensing with the BioTac the DLR Hand Arm System, ICRA, 2014

Object manipulation

Performance

- Store energy in the springs
- Use the spring energy in additional to motor torque as acceleration source



Acceleration by spring preload

Friedl et al., FAS A flexible Antagonistic spring element for a high performance over actuated hand, IROS, 2011

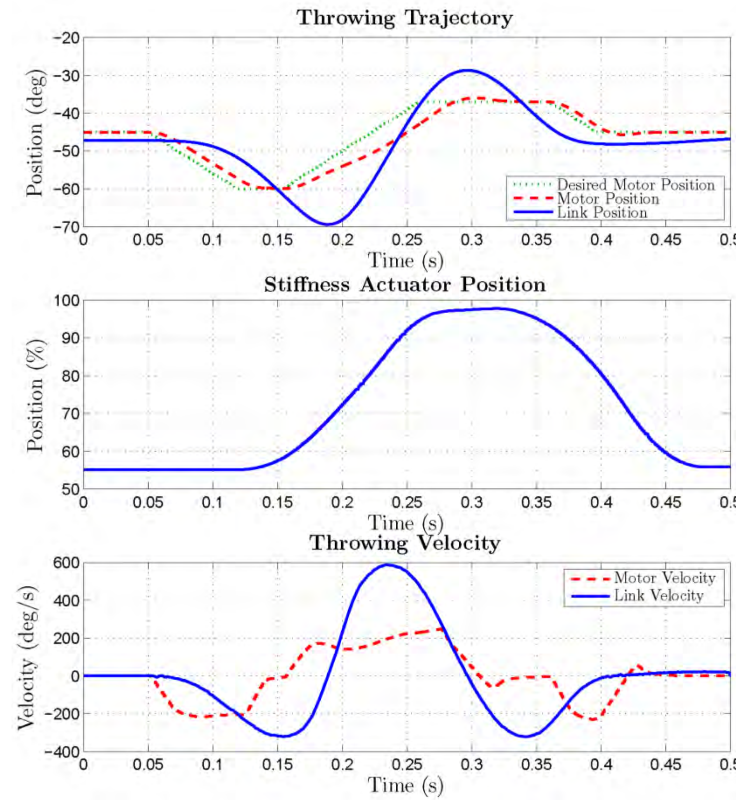
Strike out trajectory

DLR Robotics Symposium, Challenges in Robotics: Down to Earth, 2011

Throwing a Ball

- Difference between stiff and flexible drive train
- Link velocity gain of 272%

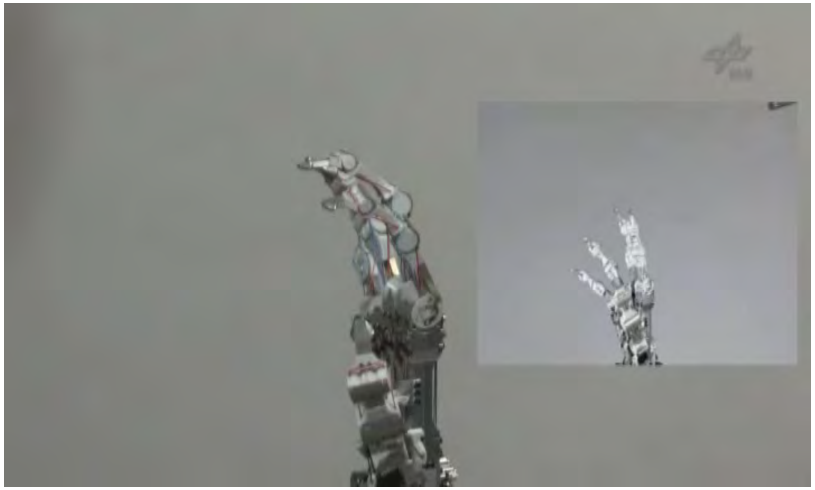
	Sitff Joint	VS-Joint
Link Velocity	216°/s	588°/s
Calc. Throwing distance	0.88 m	6.52 m



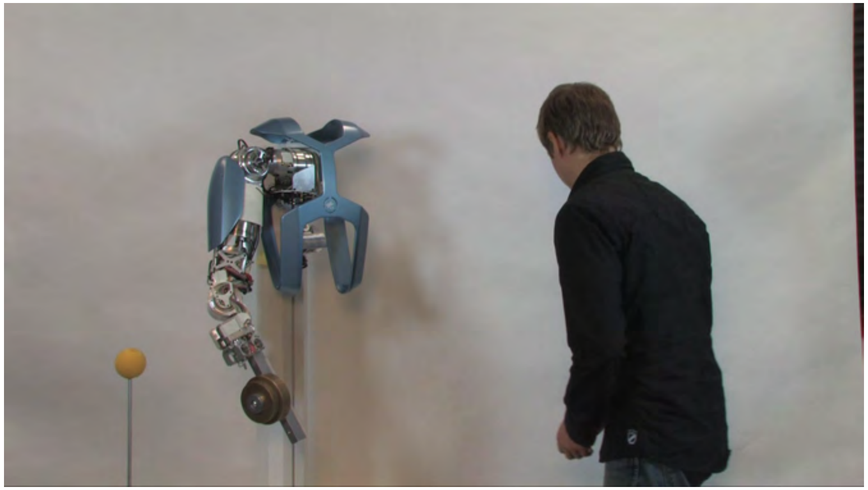
Wolf, S. & Hirzinger, G., A New Variable Stiffness Design: Matching Requirements of the Next Robot Generation, Robotics and Automation (ICRA), IEEE International Conference on, 2008, 1741-1746

Mechanical Robustness

- Decoupling the link mass from motor mass
- Avoid high peak torques during impact
- Independent of control (always on)



Impact on finger

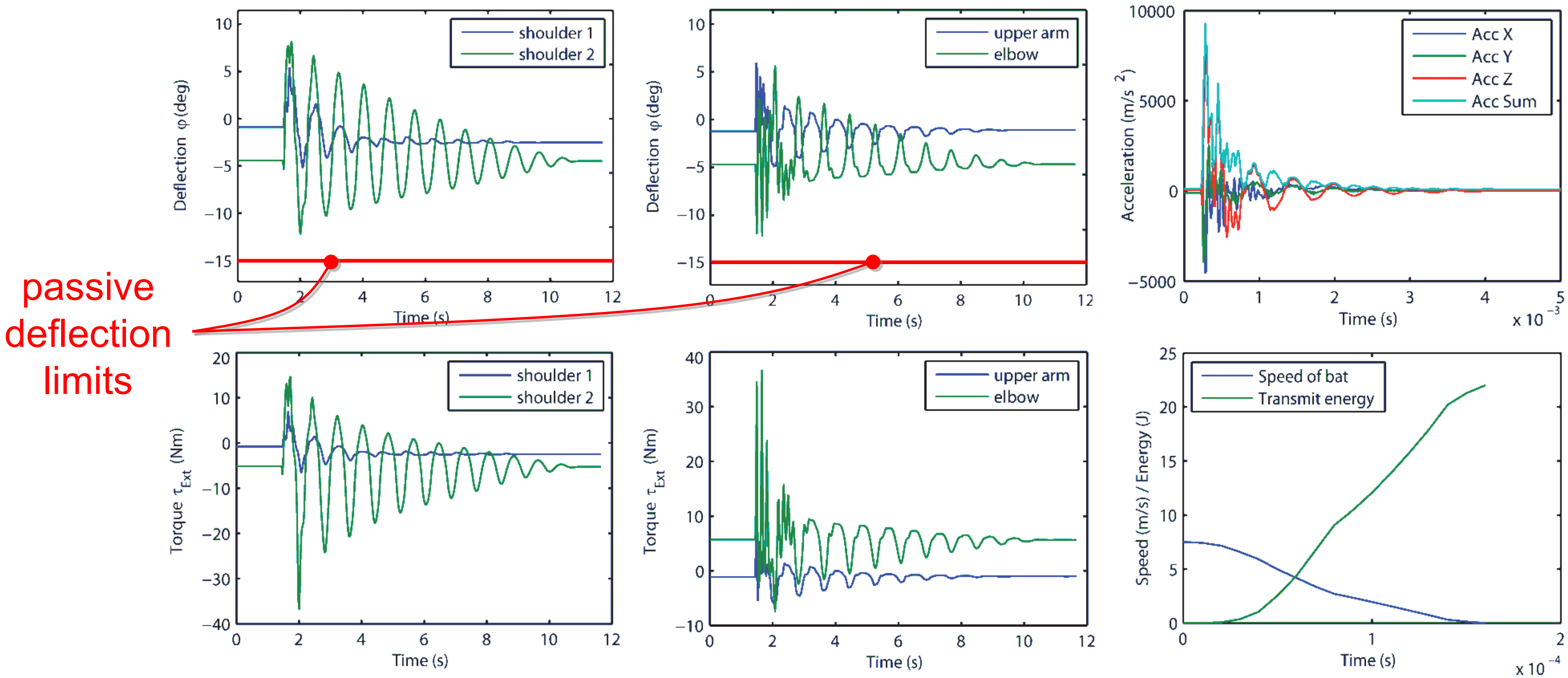


Impact on arm

Wolf et al., The DLR FSJ: Energy based design of variable stiffness joints, ICRA, 2011

Results / Evaluation

- Impact Energy of 22 Joule
- Joint limits of the passive deflection are not approached



Task with Combined Requirements

- Robust grasp
- Withstand impacts
- Requirement of mechanism precision

- Oscillation excitation via bang-bang controller
- Machine learning approach for contact point control
- Result: high accuracy & repeatability

Enhance Robustness by Control

- When passive elastic energy capacity is not sufficient
- Enhance by active control
    - Reactions
    - Reflexes

Reactions

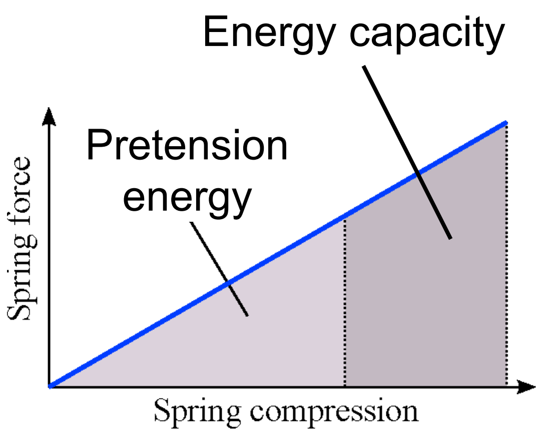
Active reactions:

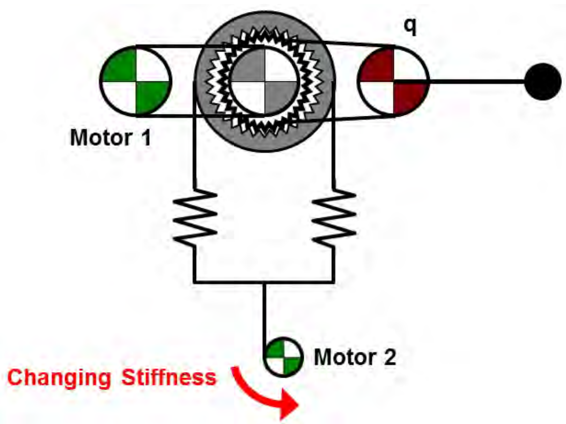
Goal: Prevent spring from overload

Implementation: 1) Stiffness setup
2) Motor position
(Equilibrium position)

Characteristics: Activation only in critical situations

Different triggers: Deflection angle
Energy capacity
Percentage of max torque

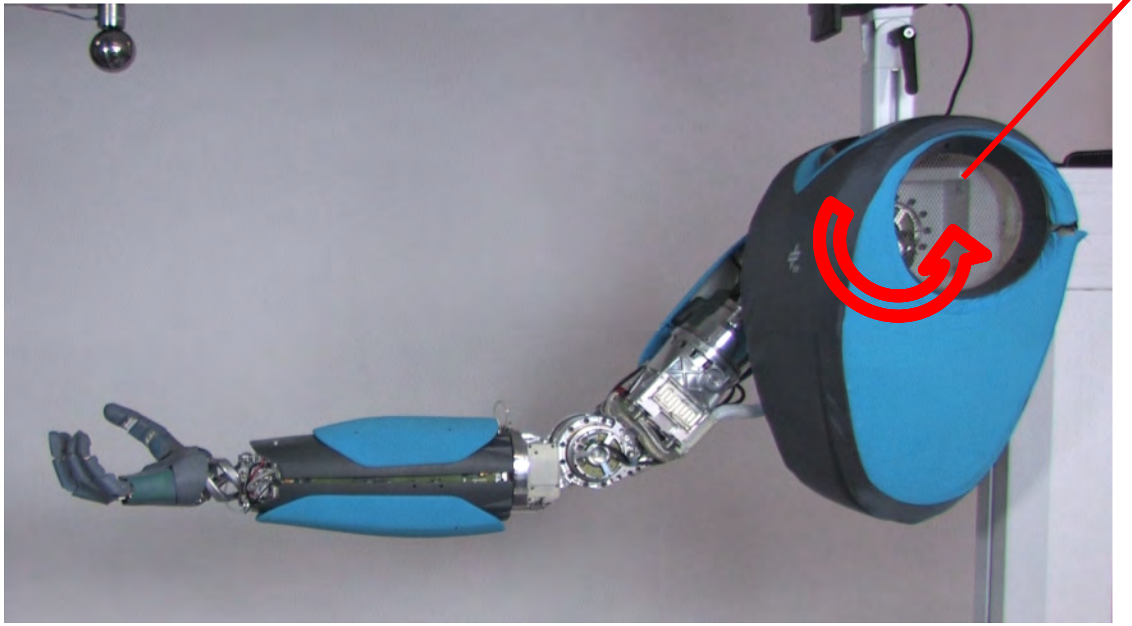




Wolf et al., Towards a Robust Variable Stiffness Actuator, IROS, 2013

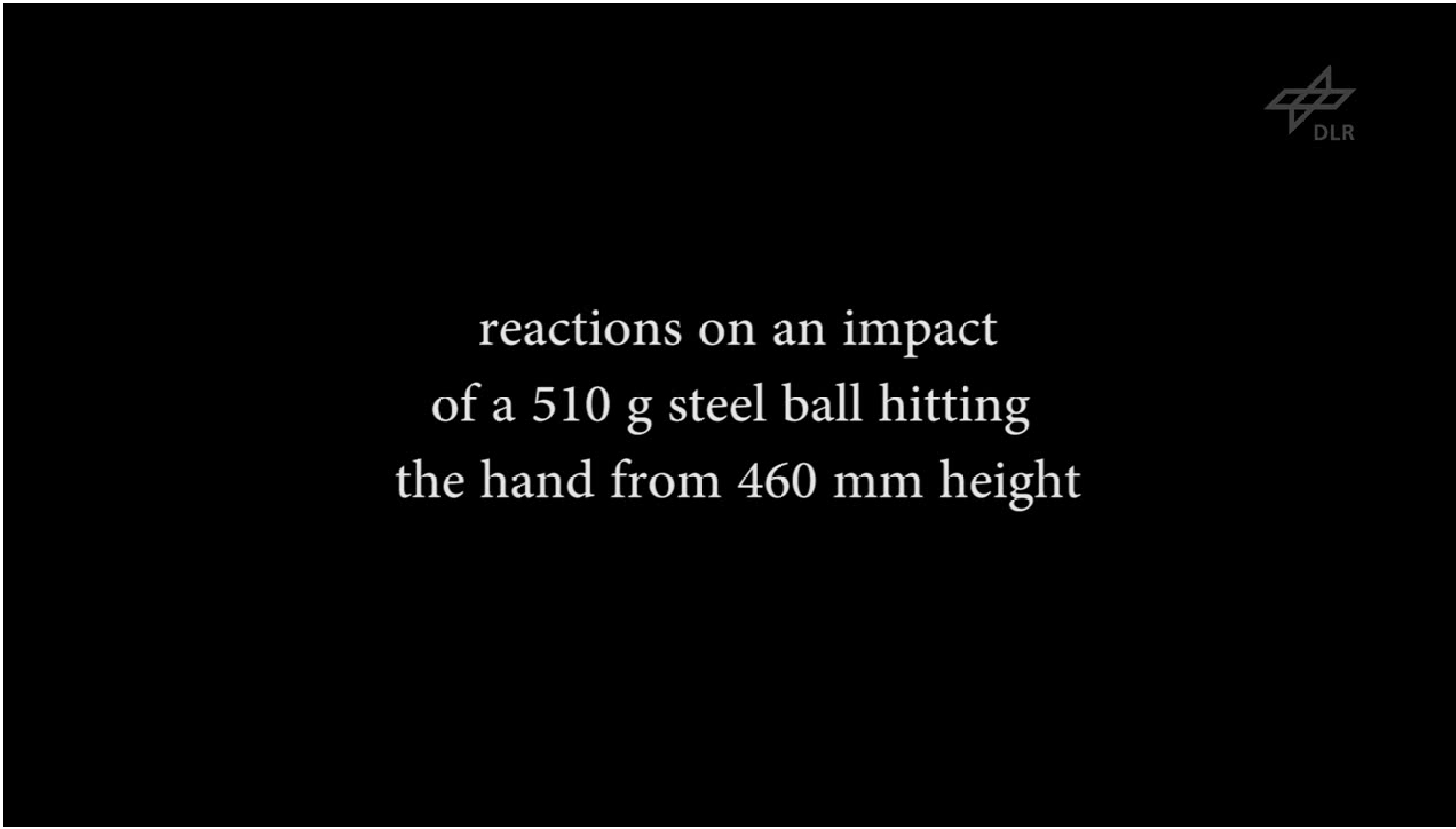
Evaluation of reactions

- Reaction trigger at 2° remaining spring deflection
- 35.4 Nm preload by gravitation
- 510 g steel ball
- 2.3 J impact energy



Wolf et al., Towards a Robust Variable Stiffness Actuator, IROS, 2013

Reactions Video



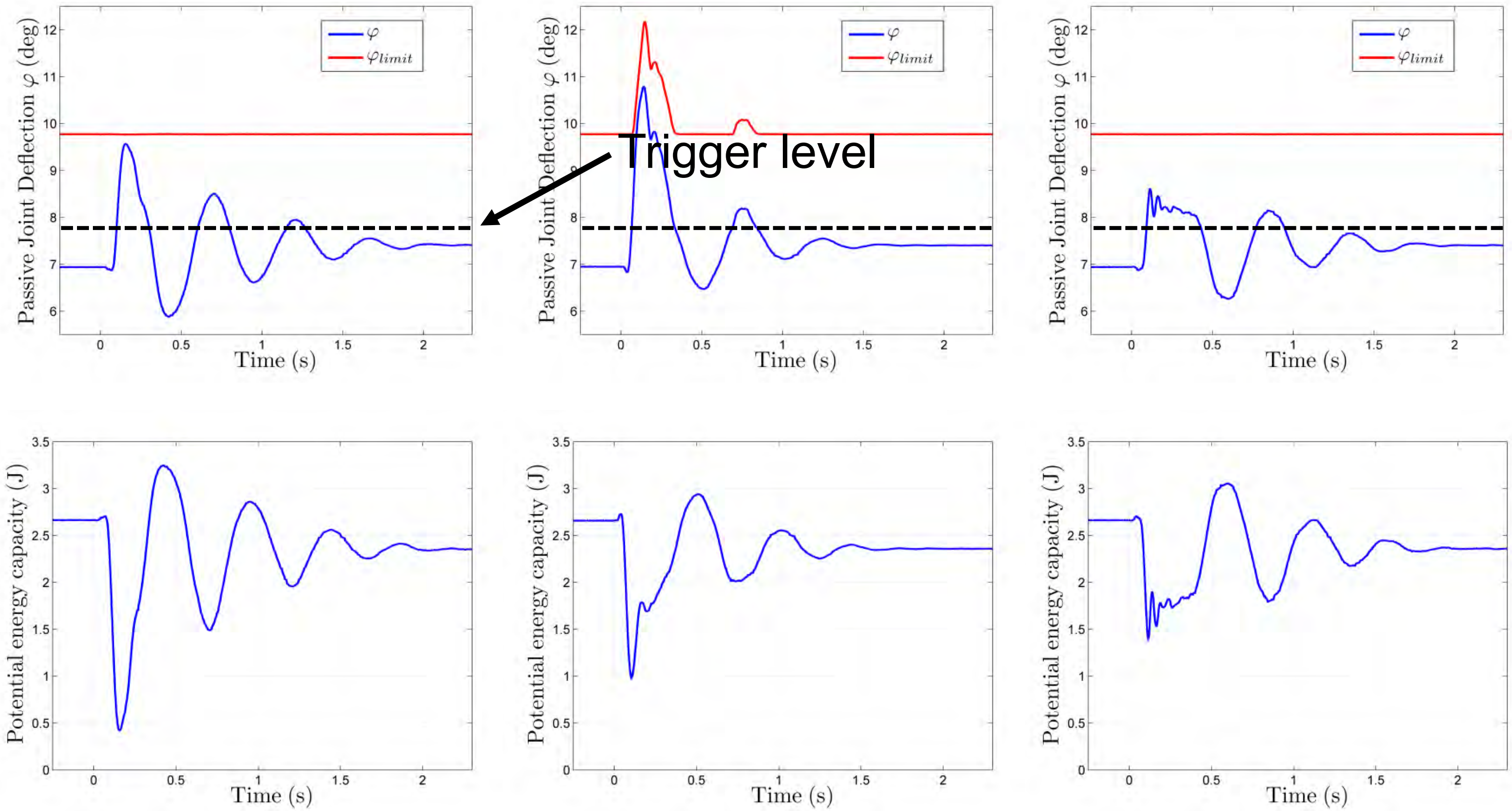
Wolf et al., Towards a Robust Variable Stiffness Actuator, IROS, 2013

Experimental Results

No reaction | Stiffness reaction | Motor reaction

Passive deflection

Energy capacity

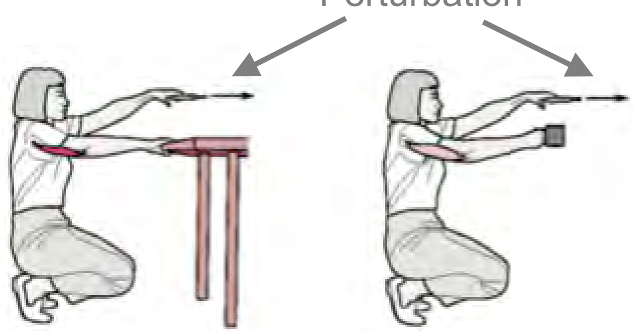


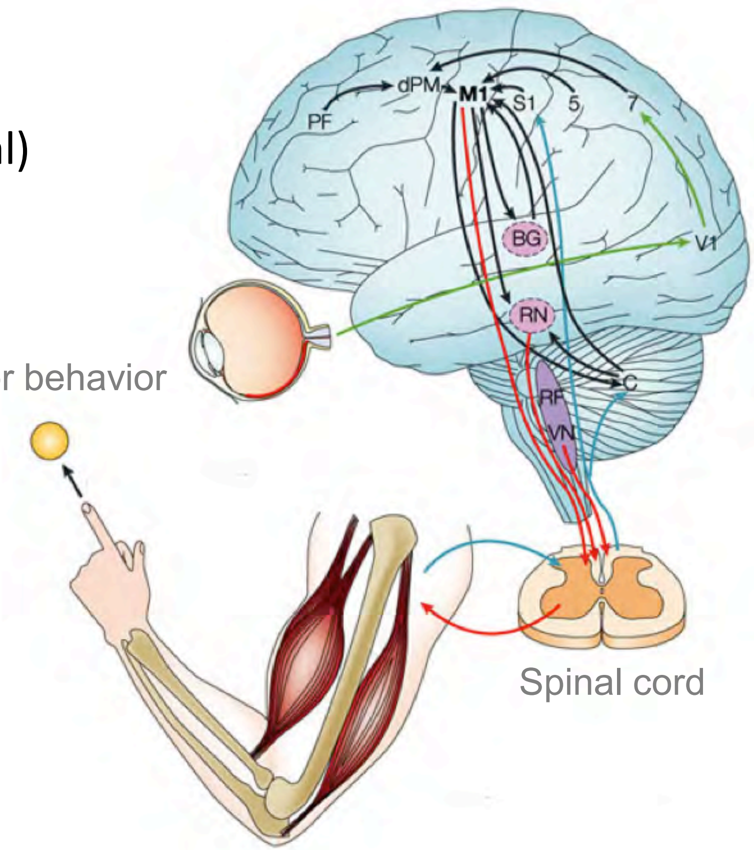
Wolf et al., Towards a Robust Variable Stiffness Actuator, IROS, 2013

Human Motor Control

Common Properties

- Hierarchical Organization
- Situation/Task dependent (reflex-reversal)
- Irradiation principle (passive/active)
- Maintenance of stability
- Action on joint level

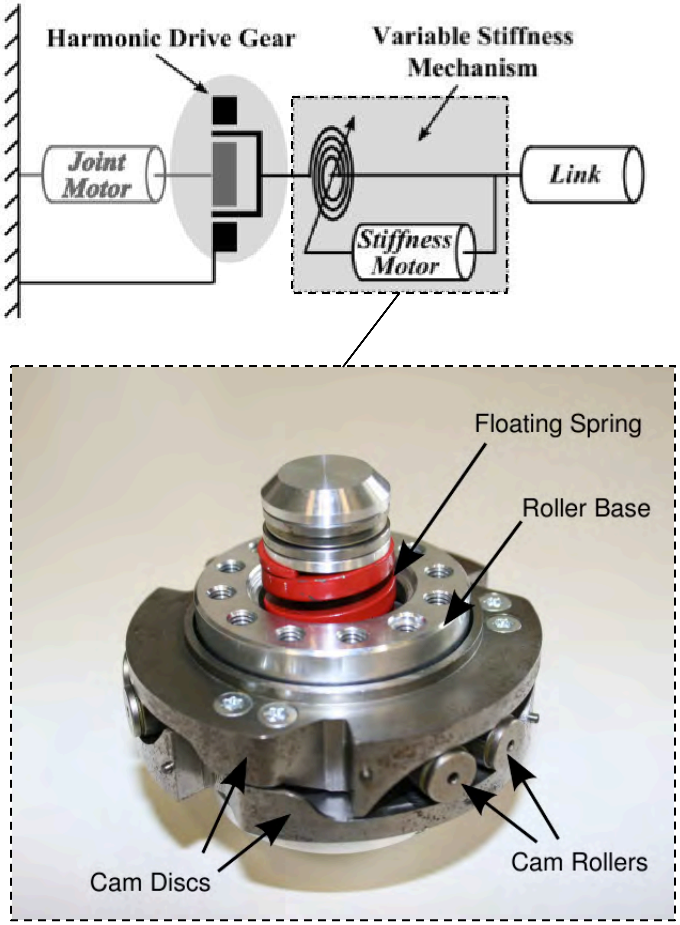


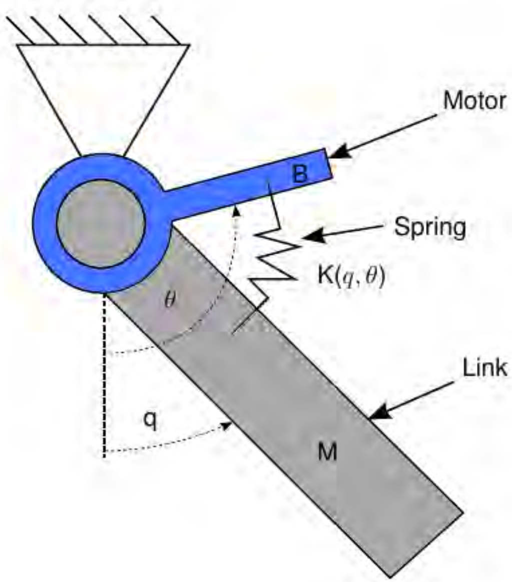


Markus Kühne, Reflexes in variable stiffness actuators, 2013

Actuator Model

Floating Spring Joint (FSJ) → **Model: General VSA**





$$M\ddot{q} + g(q) = \tau_{el} + \tau_{ext} \quad (1)$$

$$B\ddot{\theta} + \tau_{el} = \tau_m \quad (2)$$

$$\tau_{el} = A(\theta - q)^3 + C(\theta - q) \quad (3)$$

Reflex Test Setup

DLR Hand Arm System

Actuated axis of rotation S1

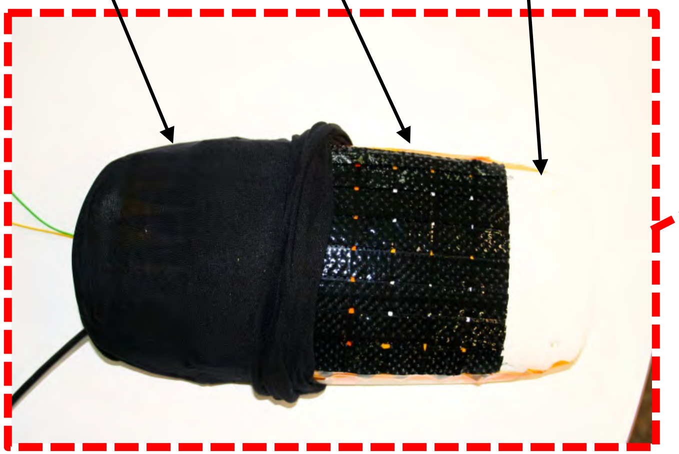
Link position q

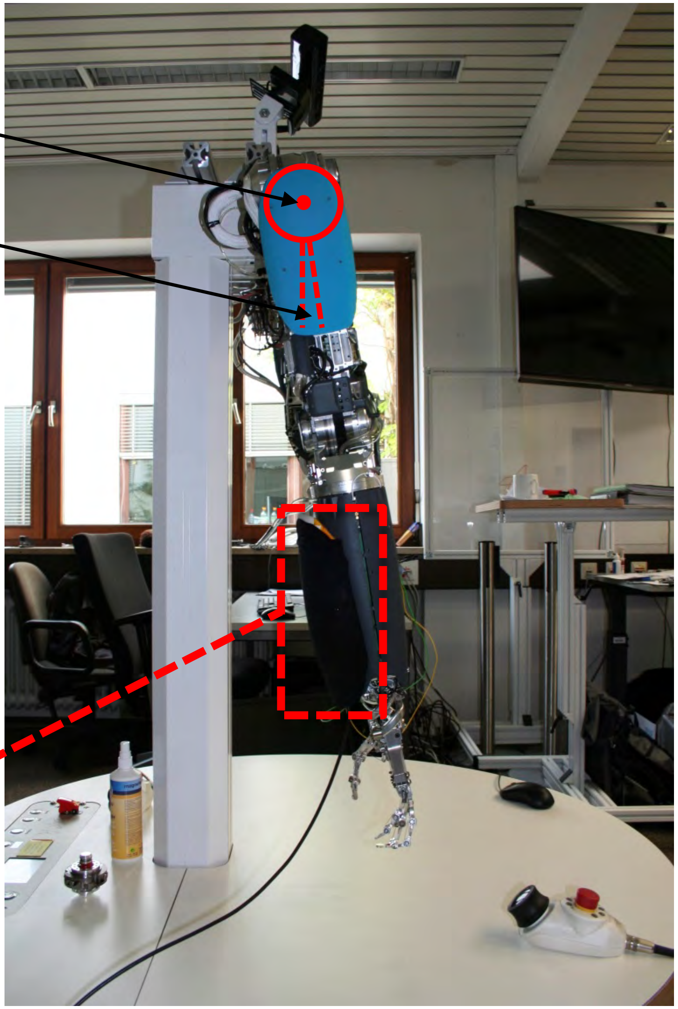
DLR Artificial Skin

Polymer based tracks (64 taxels)

Cover

Support





Markus Kühne, Reflexes in variable stiffness actuators, 2013

Conclusion

VIA based robots promise to have:

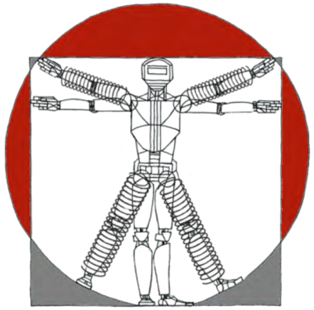
- **Precision**
- **Sensitive**
- **High dynamics**
- **Robustness**
- **Enhanced performance by control**

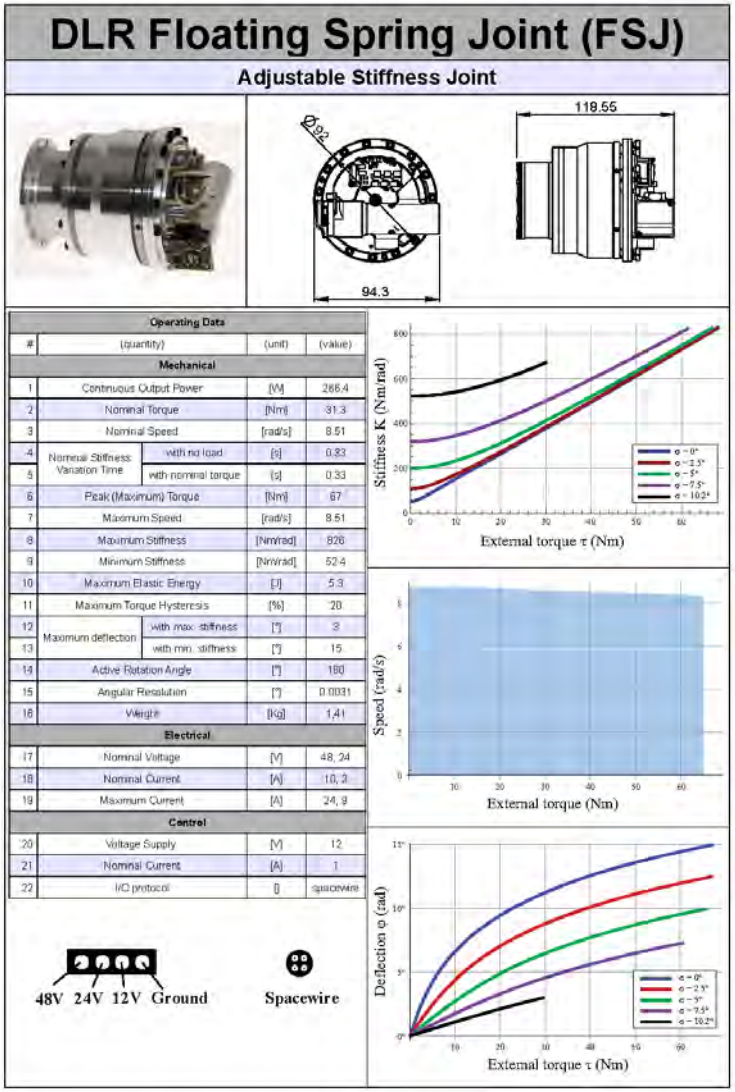
- **Supplementary sensor information helps**

VIACTORS Variable Stiffness Joint Data Sheet

- Basis for the exchange of information of different VSAs
- **Template** and **data sheets** of the VIACTORS consortium:

www.viactors.org

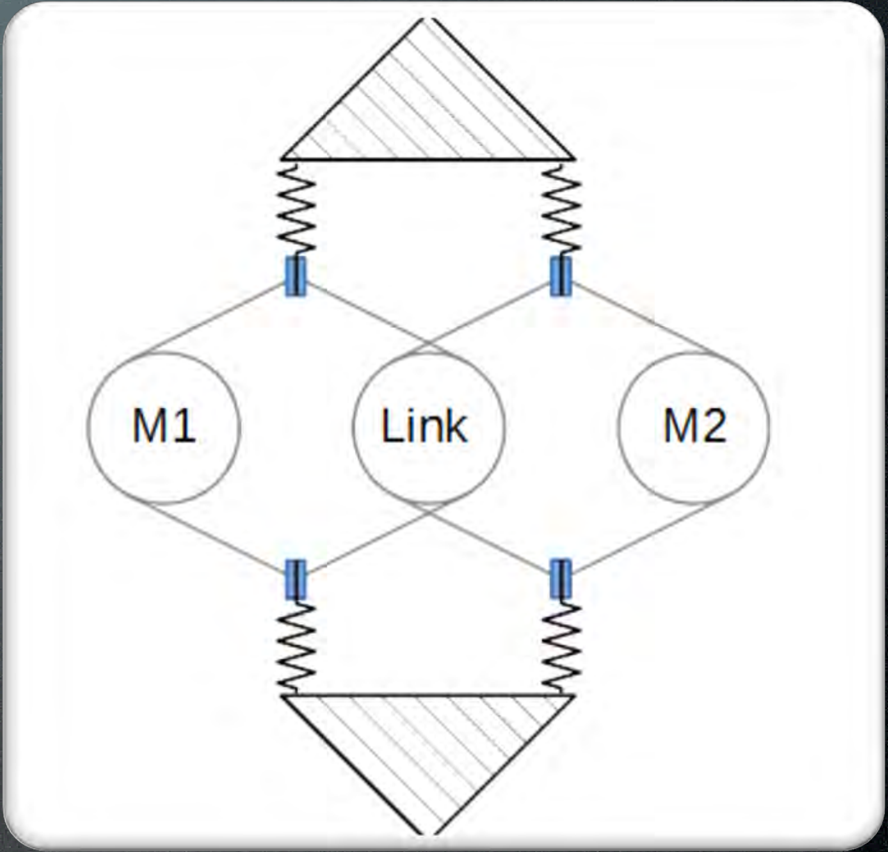




Operating Data				
#	(quantity)		(unit)	(value)
Mechanical				
1	Continuous Output Power		[W]	266.4
2	Nominal Torque		[Nm]	31.3
3	Nominal Speed		[rad/s]	8.51
4	Nominal Stiffness Variation Time	with no load	[s]	0.33
5		with nominal torque	[s]	0.33
6	Peak (Maximum) Torque		[Nm]	67
7	Maximum Speed		[rad/s]	8.51
8	Maximum Stiffness		[Nm/rad]	826
9	Minimum Stiffness		[Nm/rad]	52.4
10	Maximum Elastic Energy		[J]	5.3
11	Maximum Torque Hysteresis		[%]	20
12	Maximum deflection	with max. stiffness	[°]	3
13		with min. stiffness	[°]	15
14	Active Rotation Angle		[°]	180
15	Angular Resolution		[°]	0.0031
16	Weight		[Kg]	1,41
Electrical				
17	Nominal Voltage		[V]	48, 24
18	Nominal Current		[A]	10, 3
19	Maximum Current		[A]	24, 9
Control				
20	Voltage Supply		[V]	12
21	Nominal Current		[A]	1
22	I/O protocol		[]	spacewire

qbmove – working principle

an open-source modular variable-stiffness servo-actuator



Symmetric Agonist-Antagonist VSA

qb move
specs

nominal torque [Nm]	0.6	1.3	6.0
nominal speed [rad/s]	3	7	10
VS range [Nm/rad]	[0.2 – 2]	[0.6 – 8]	[0.6 – 30]
rotation range [°]	+/- 90	+/-180	+/-180
electronics	100% Arduino Comp.	Custom	Custom
communication BUS	USB (with HUB)	RS485	RS485
daisy-chain	no	yes	yes

NMMI & SAPHARI

SAFE AND AUTONOMOUS PHYSICAL HUMAN-AWARE ROBOT INTERACTION

organize the

VIA Winter School

Rome, February 20-25, 2015

Programme:

Friday, Feb. 20th : School
Saturday, Feb. 21st : School
Sunday, Feb. 22nd: OFF
Monday, Feb. 23rd: School
Tuesday, Feb. 24th: School
Wednesday, Feb 25th: Workshop
Wednesday, Feb. 25th: Competition