Understanding, Designing and Controlling "Natural Motion" with Variable Impedance Actuators.

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Robots for Humans

- cooperative manipulation tasks
- domestic applications (*domotics*)
- entertainment
- assistance
- rehabilitation

Robots for Humans

- teleoperation
- human augmentation
- haptic exoskeletons
- mixed environments

The problem

How to make robots that are

- soft yet strong
- simple yet dextrous
- intelligent yet practical

The idea:
Study Intelligence *per* its Embodiment

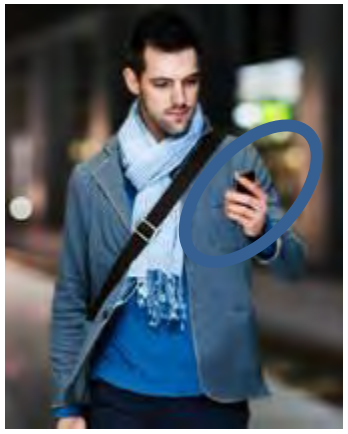
[…] man is the most intelligent of animals because he has hands…

Anaxagoras, cited by Aristotle, De partibus animalium

- The Body as the Organ of Cognition
- How the constraints due to embodiment **affect and determine** learning and control
- What is the **conceptual structure and** the **geometry** of such *enabling constraints* (aka *synergies*)
  - **Understanding** by **building**
  - Trying to reproduce functionality to understand
    - Musculo-skeletal system
    - Biomechanics
    - Sensory motor control
    - Perception
    - Cognition
    - … and their interplay
  - **Re-creating**, one of the basic approaches for human learning – used by children and scientists alike
  - **Motor Synergies** in redundant body mobility
  - **Sensor Synergies** in redundant receptors and the 5+ senses
  - **Sensorimotor Synergies:** How can *the* brain *organize and control* such a complex system as the body, and how could ***our mind emerge*** out of it
  - **Social Synergies**
    - **Human-Robot Interaction** coexistence and cooperation
    - **Robot-Robot Interaction** rules for a Society with Robots

Machine Intelligence

- Yesterday: Puma 560
  - Motorola 68K
  - 8 MHz
  - 160 Kflops
- Today: smartphones
  - Snapdragon S4
  - 1.5 GHz
  - 6.4 Gflops (=40,000X)



Machine Motion

- 1960's robotics
  - Unimate Puma 560
  - Servomotors
- 2010's robotics
  - Servomotors

Motors and Muscles

Robots vs. Humans
(what a difference a body makes)

Motors and Muscles

What makes a muscle different from a motor?

- Motors are accurate – and rigid
- Motors (and gears) are brittle – muscles are resilient
- Muscles absorb energy and restitute it
- Muscles consume little energy
- Muscles are capable of smooth, gentle motion
- but can also be strong and accurate

Robot Muscles for Human-Robot Interaction

• Machines interacting with humans have different requirements than current industrial robots

- ✓ Accuracy less demanding
- ✓ Safety is a must

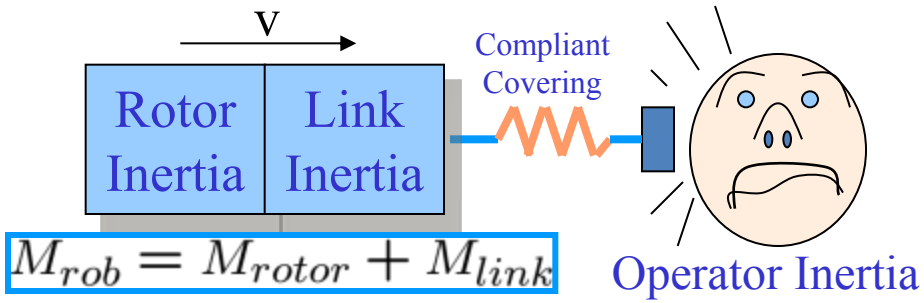
An approach: Design for Accuracy, Control for Safety

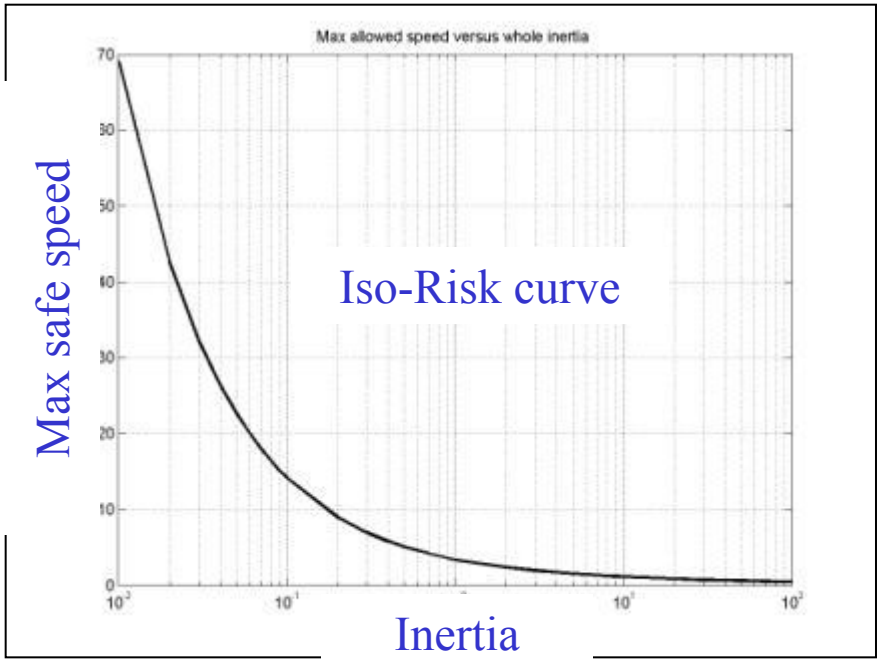
- ✓ Keep using rigid actuators;
- ✓ Increase sensors, bandwidth;
- ✓ Use active control;

Modern approach: Design for Safety, Control for Accuracy

- ✓ Mechanical (passive) compliance;
- ✓ Compensation by control;

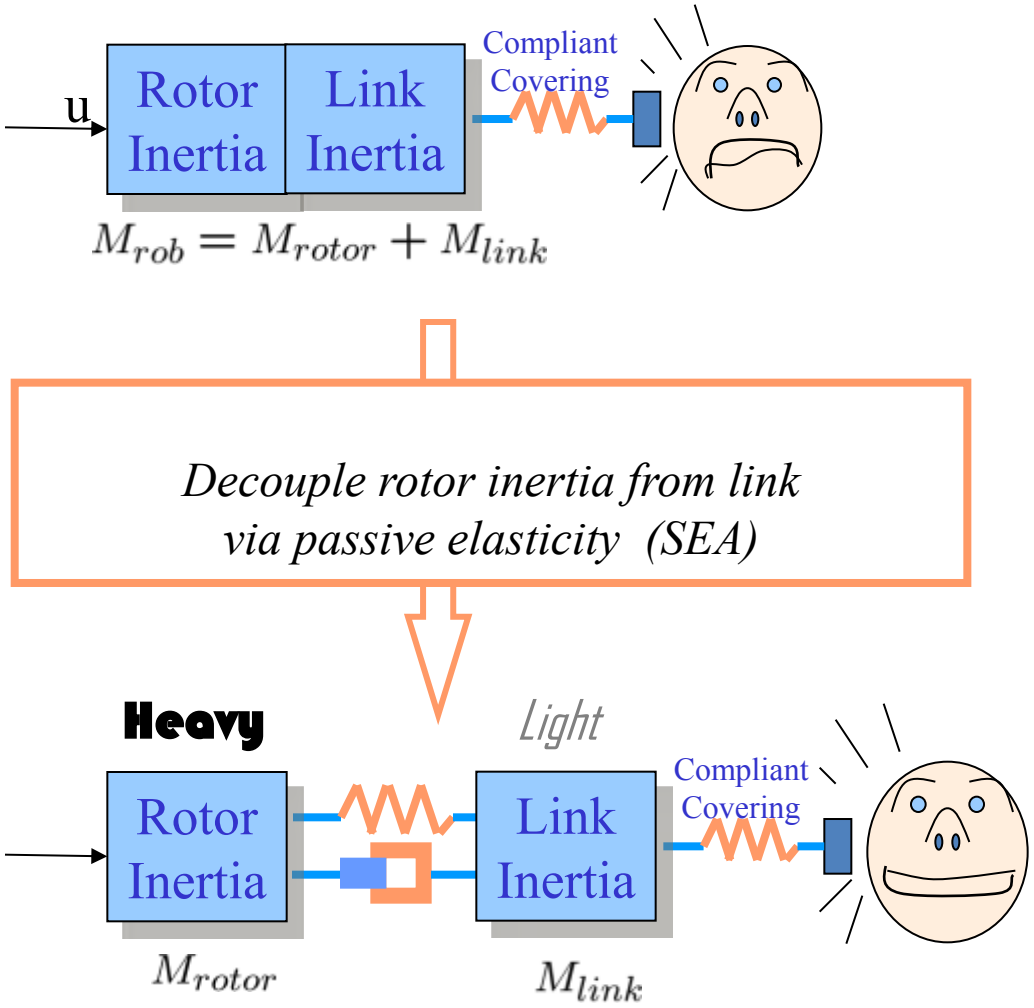
Conventional Rigid Design





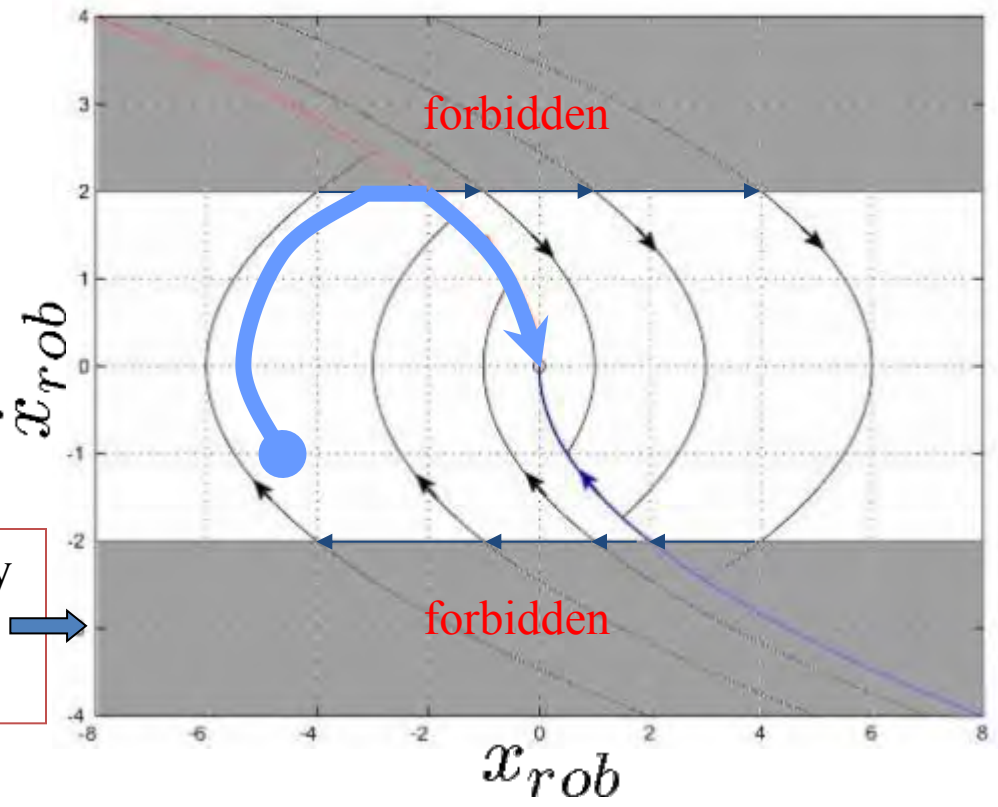
- Given rotor + link inertia, covering, and acceptable risk → max. velocity

How to get beyond rigid robot limitations?



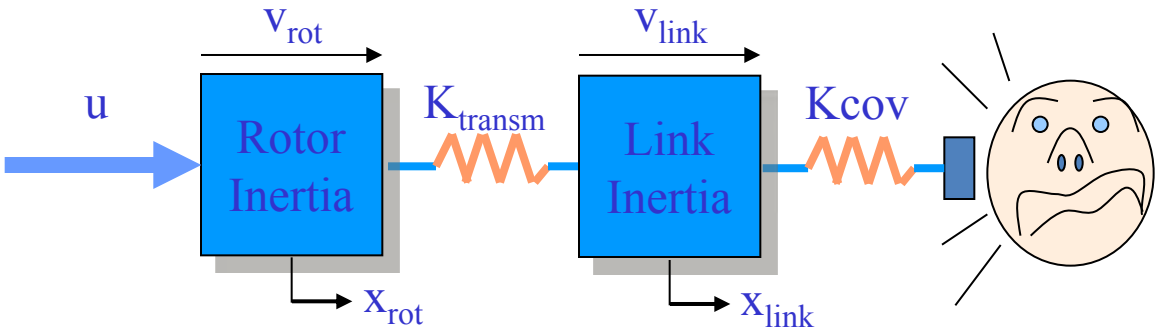
The Safe Brachistocrone: Minimum Time Optimal Control with Safety

$$\begin{cases} \min_T \int_0^T 1 dt \\ M_{rob}\ddot{x}_{rob} = u \\ u \leq U_{max} \\ -u \leq U_{max} \\ v = \dot{x}_{rob} \leq \frac{HIC_{max}}{\beta} \\ -v = -\dot{x}_{rob} \leq \frac{HIC_{max}}{\beta} \end{cases}$$



The safe brachistochrone can be analytically solved in this case by applying Pontryagin's Maximum Principle

The Safe Brachistocrone for Series-Elastic Actuators



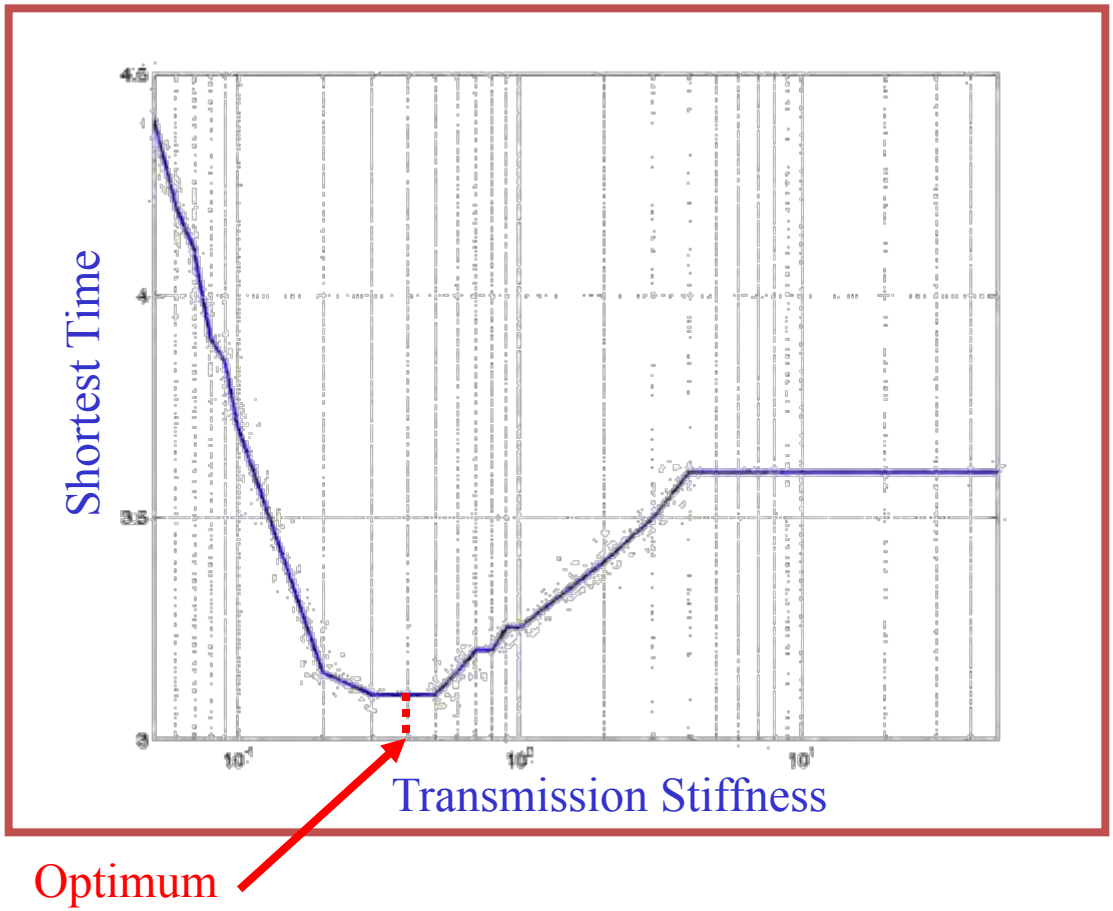
Linear system with linear inequality bounds

$$
\begin{cases}
\min_T \int_0^T 1 dt \\
M_{rot}\ddot{x}_{rot} + K_{transm}(x_{rot} - x_{link}) = u \\
M_{link}\ddot{x}_{link} + K_{transm}(x_{link} - x_{rot}) = 0 \\
|\dot{x}_{link}| \leq \beta H I C_{max}^{\frac{2}{5}} \\
|u| \leq U_{max} \\
(x_{link}, \dot{x}_{link})(0) = (X_{ini}, 0) \\
(x_{link}, \dot{x}_{link})(T) = (0, 0)
\end{cases}
$$

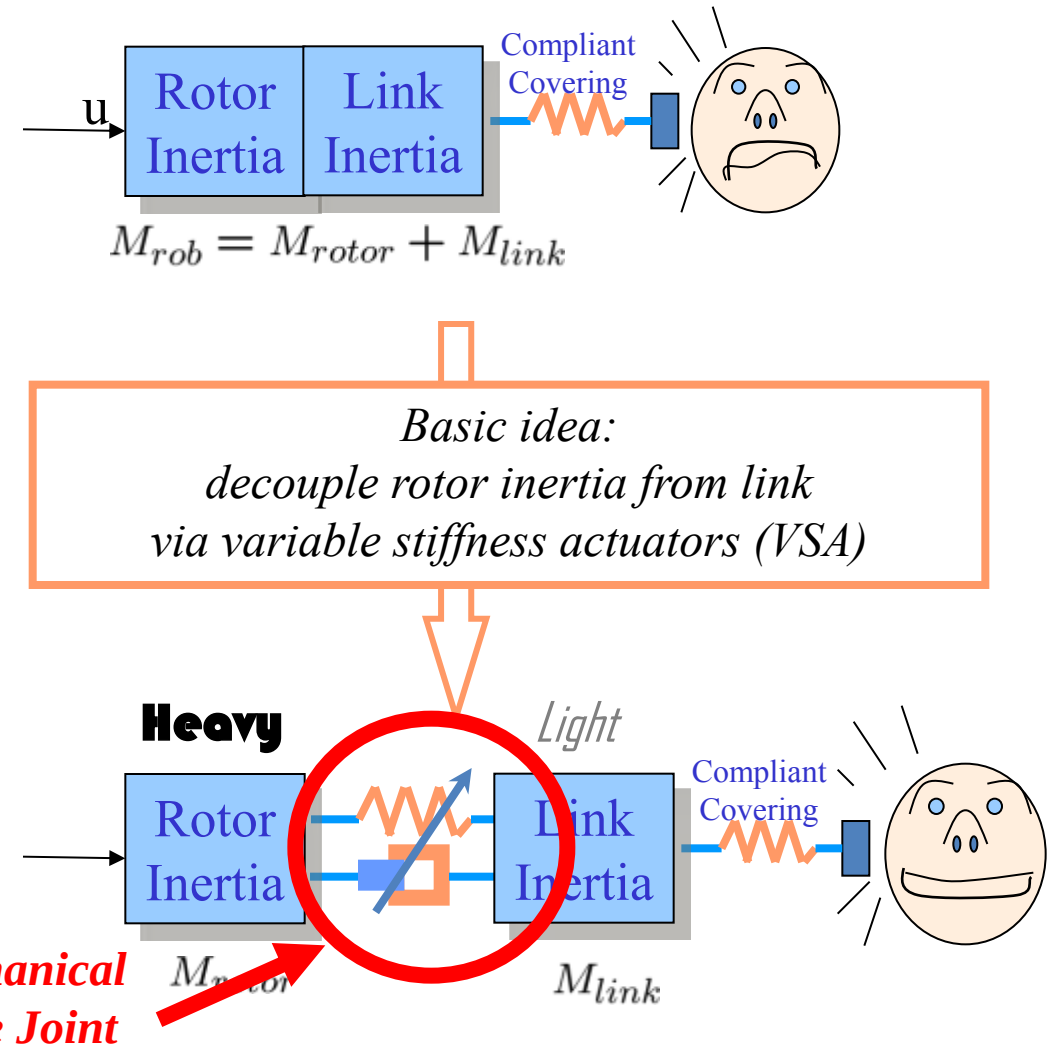
State & Control constraints

The Safe Brachistocrone for Series-Elastic Actuators

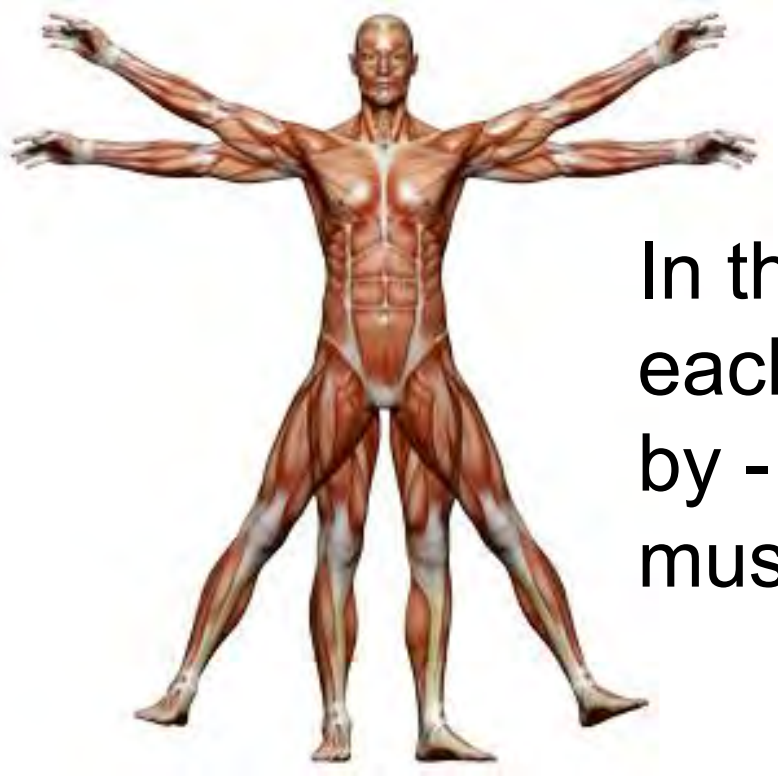
- For high transmission elasticity → slow response (oscillations, low accuracy,…);
- High transmission stiffness, high reflected inertia → low velocities for safety
- An optimum for transmission stiffness design exists
- Performance still limited



How to get beyond these limitations? - 2



Motors and Muscles

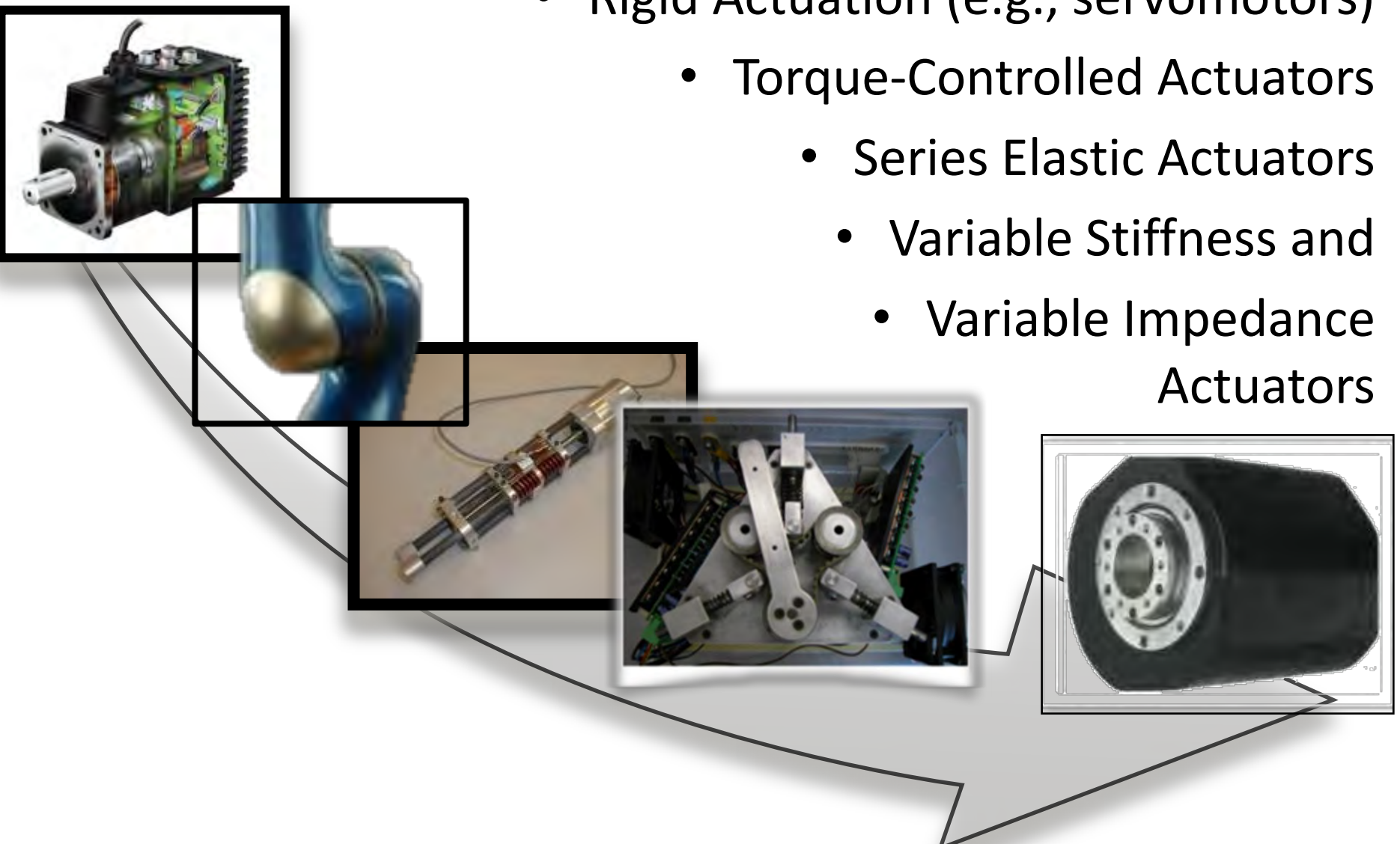


In the human body, each joint is actuated by - *at least* - two muscles

Co-contraction of muscular groups allows for both SOFT and STRONG operations of the arm

Evolution of actuation

- Rigid Actuation (e.g., servomotors)
  - Torque-Controlled Actuators
    - Series Elastic Actuators
      - Variable Stiffness and
      - Variable Impedance Actuators



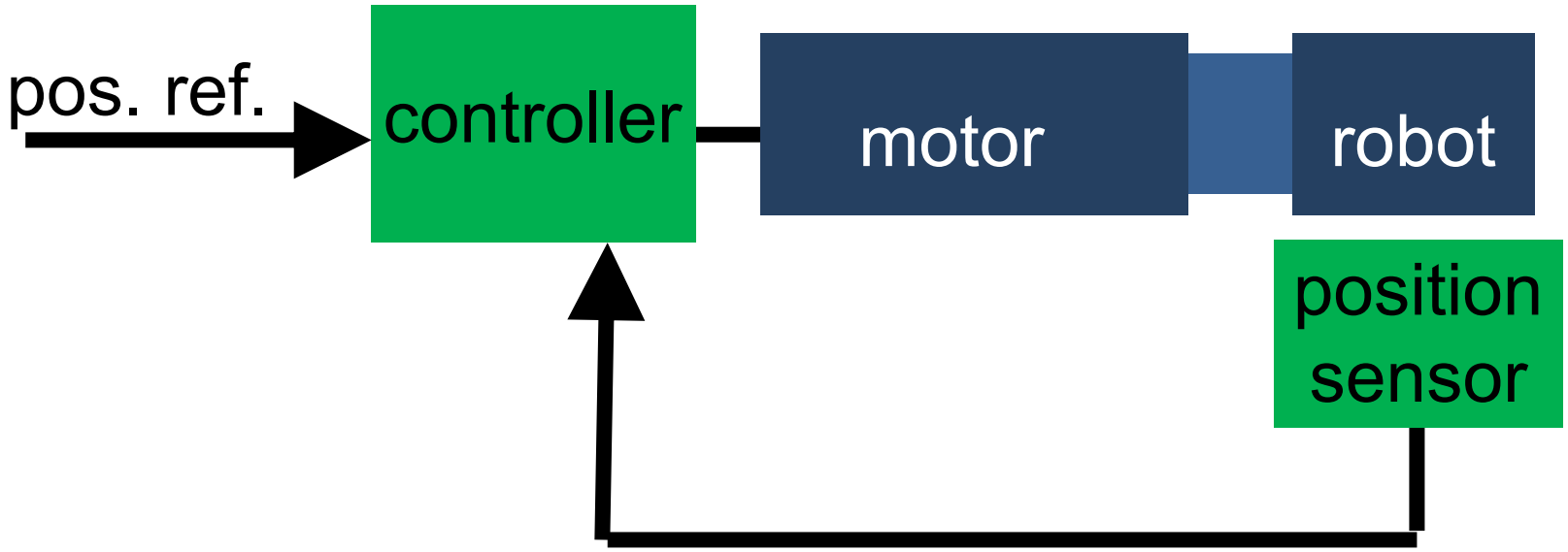
Robotic Actuators

Position Control

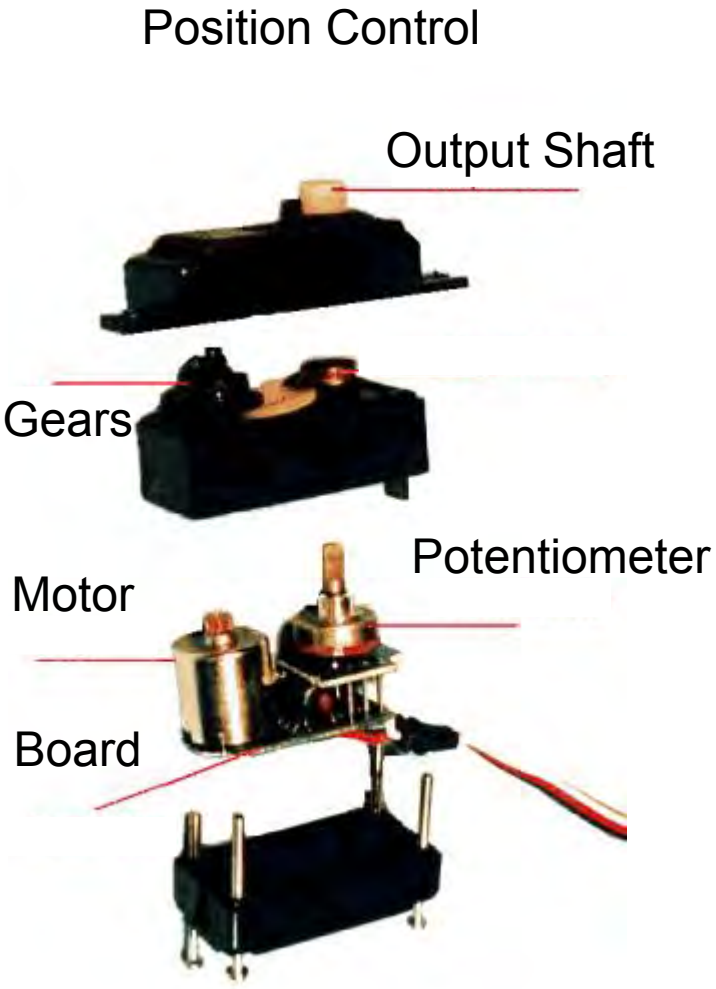
Torque Control

Position and Stiffness Control

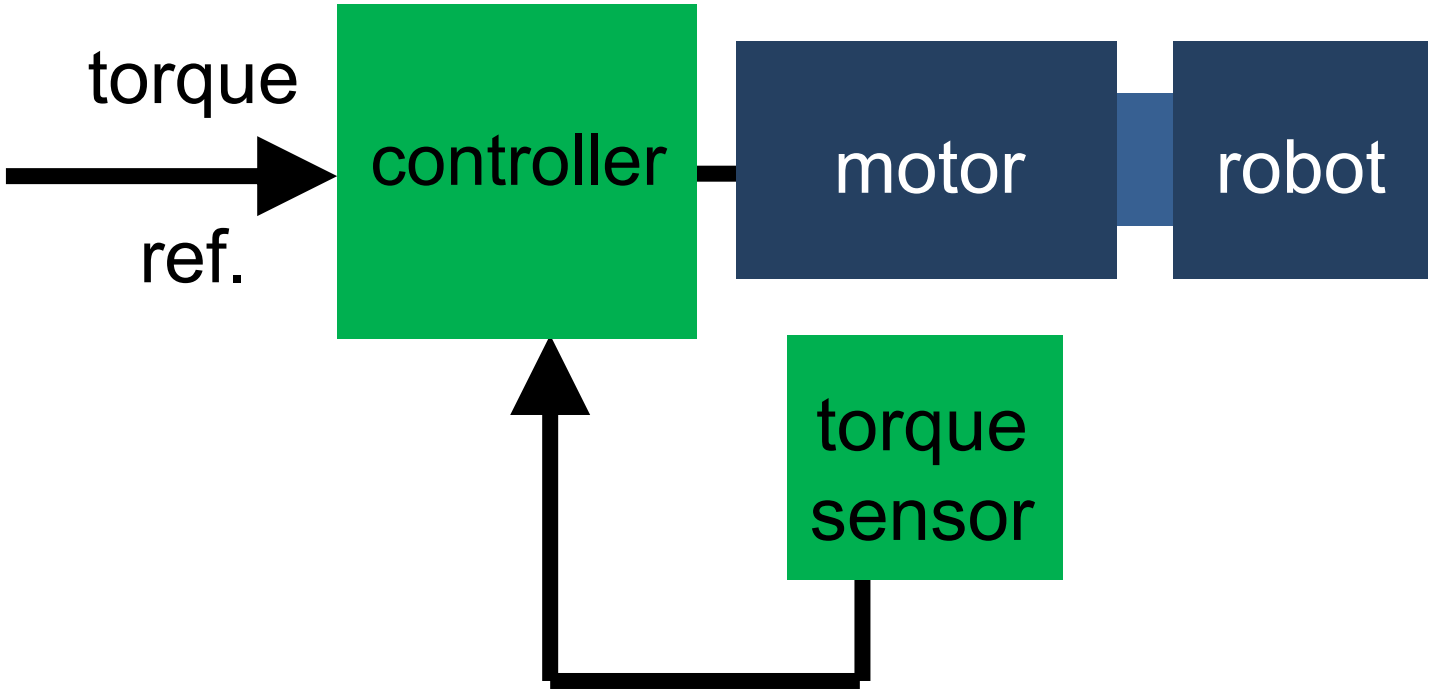
Robotic Actuators: Position Control



Robotic Actuators

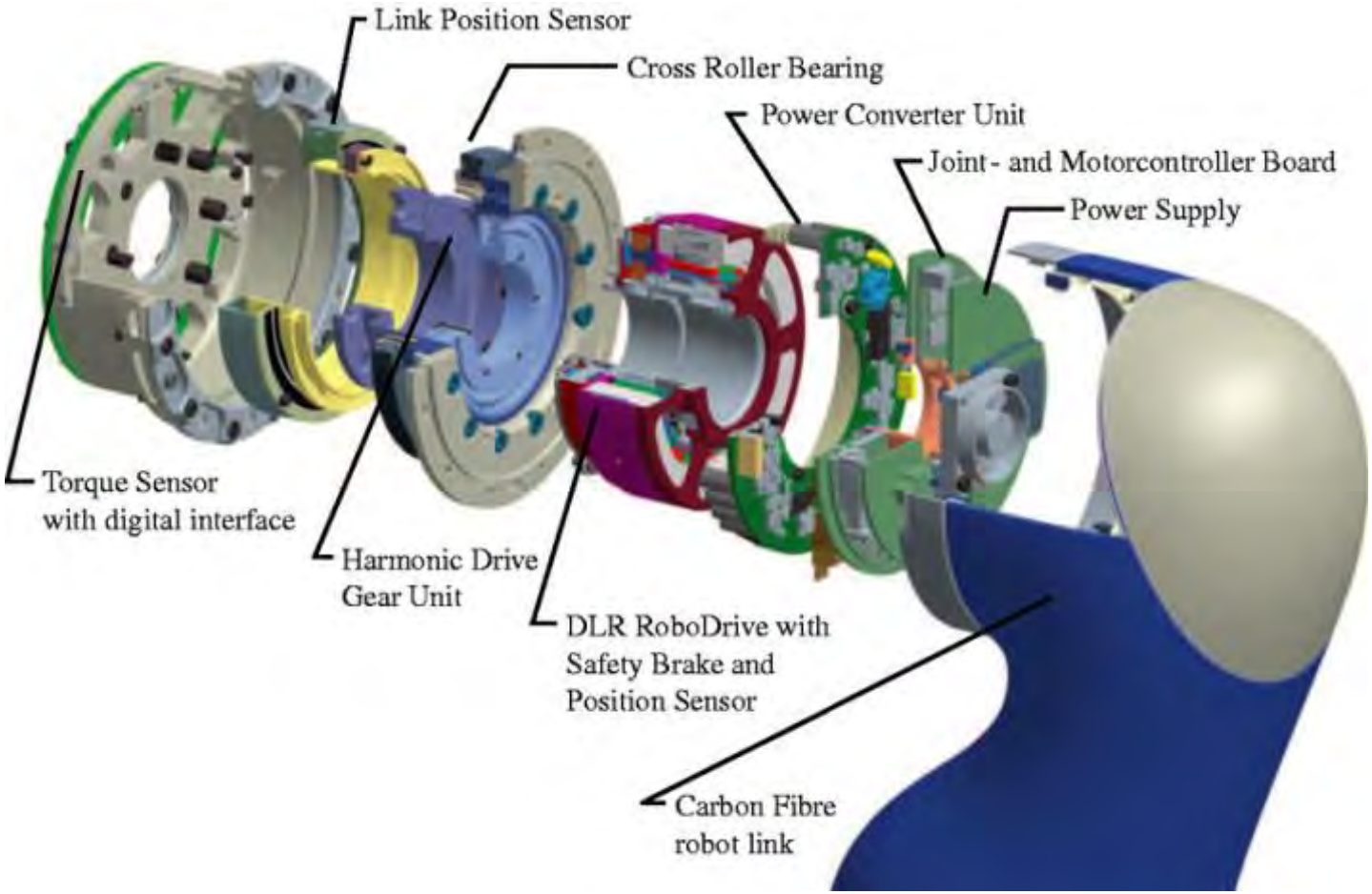


Robotic Actuators: Torque Control

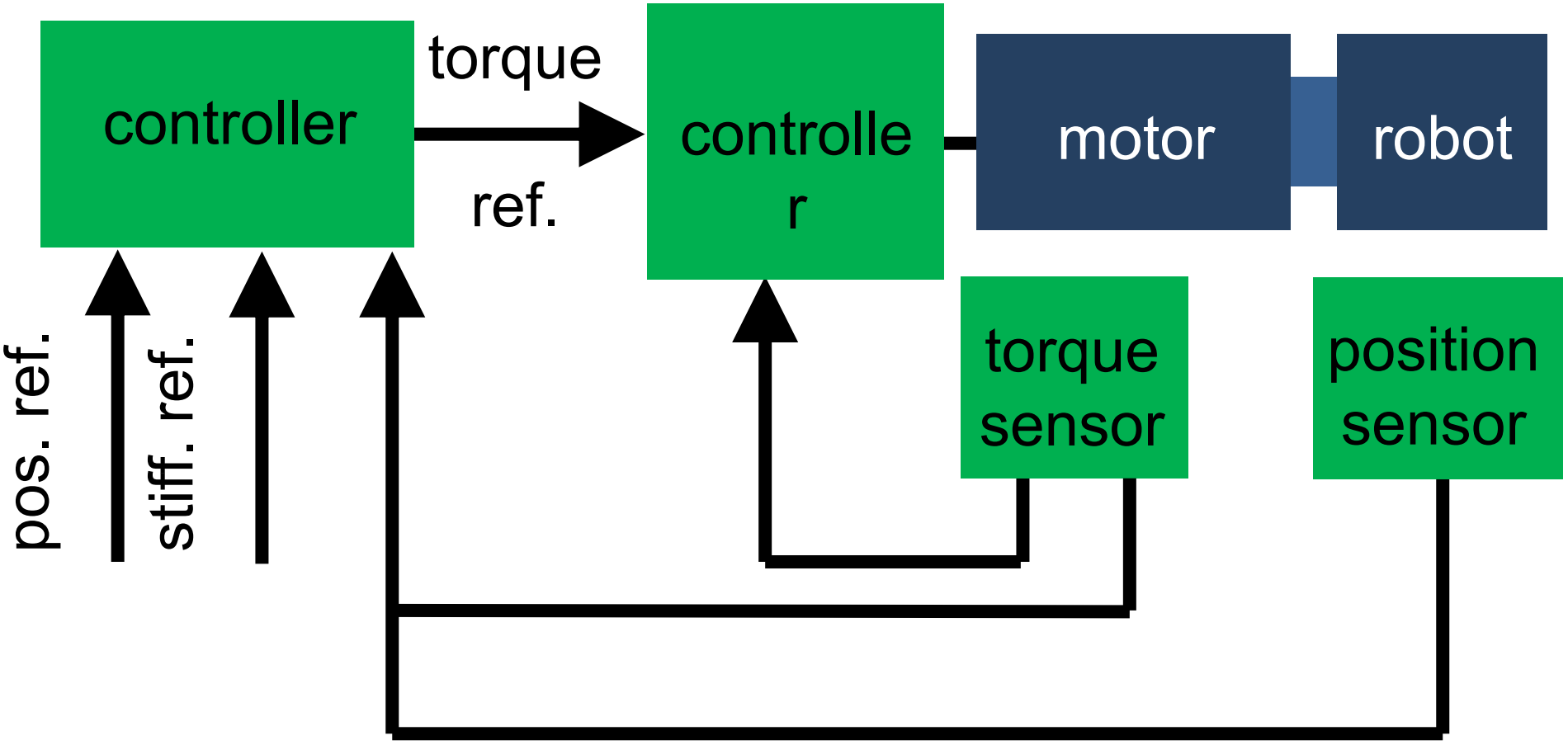


Robotic Actuators: Torque Control

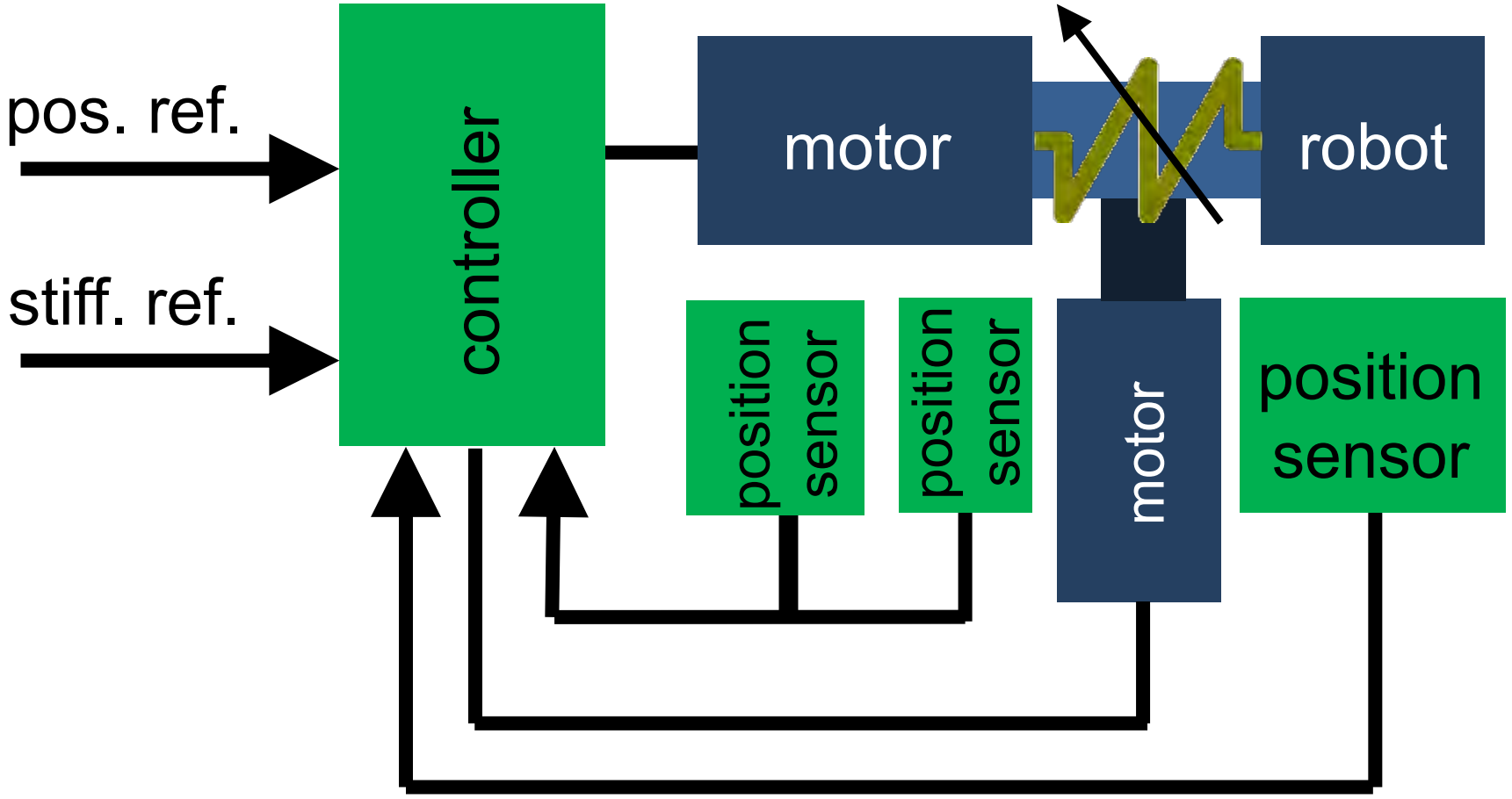
Torque Control



Robotic Actuators: Active Impedance Control



Motion Control:
Position and Stiffness Control



Variable Stiffness Actuators @ Pisa

Soft Arm: 2000

VSA I: 2003

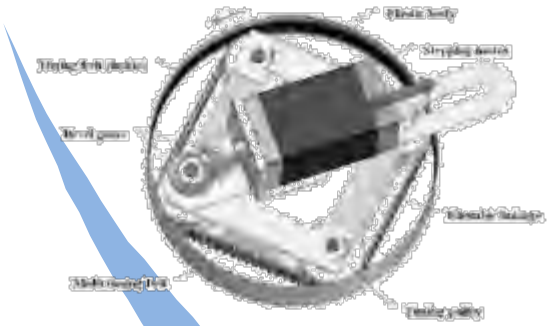
VSA II: 2008

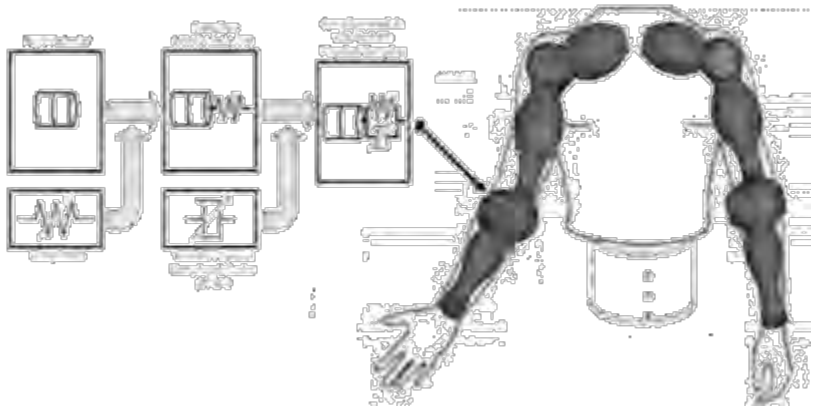
VSA HD: 2010

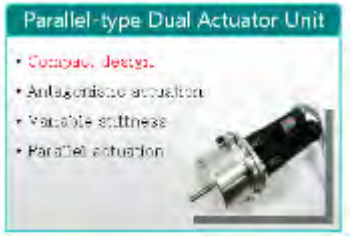
TODAY:

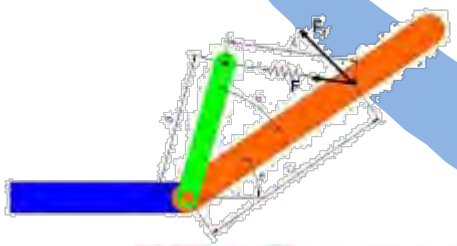
VSA-cubes

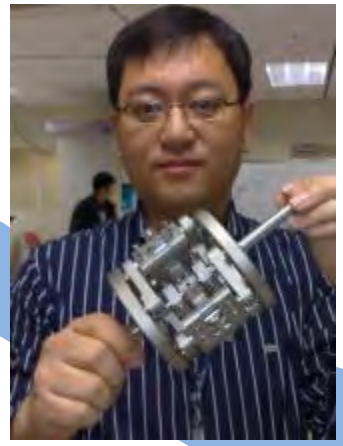
Variable Stiffness Actuators - Worldwide











VSA as muscles for robots

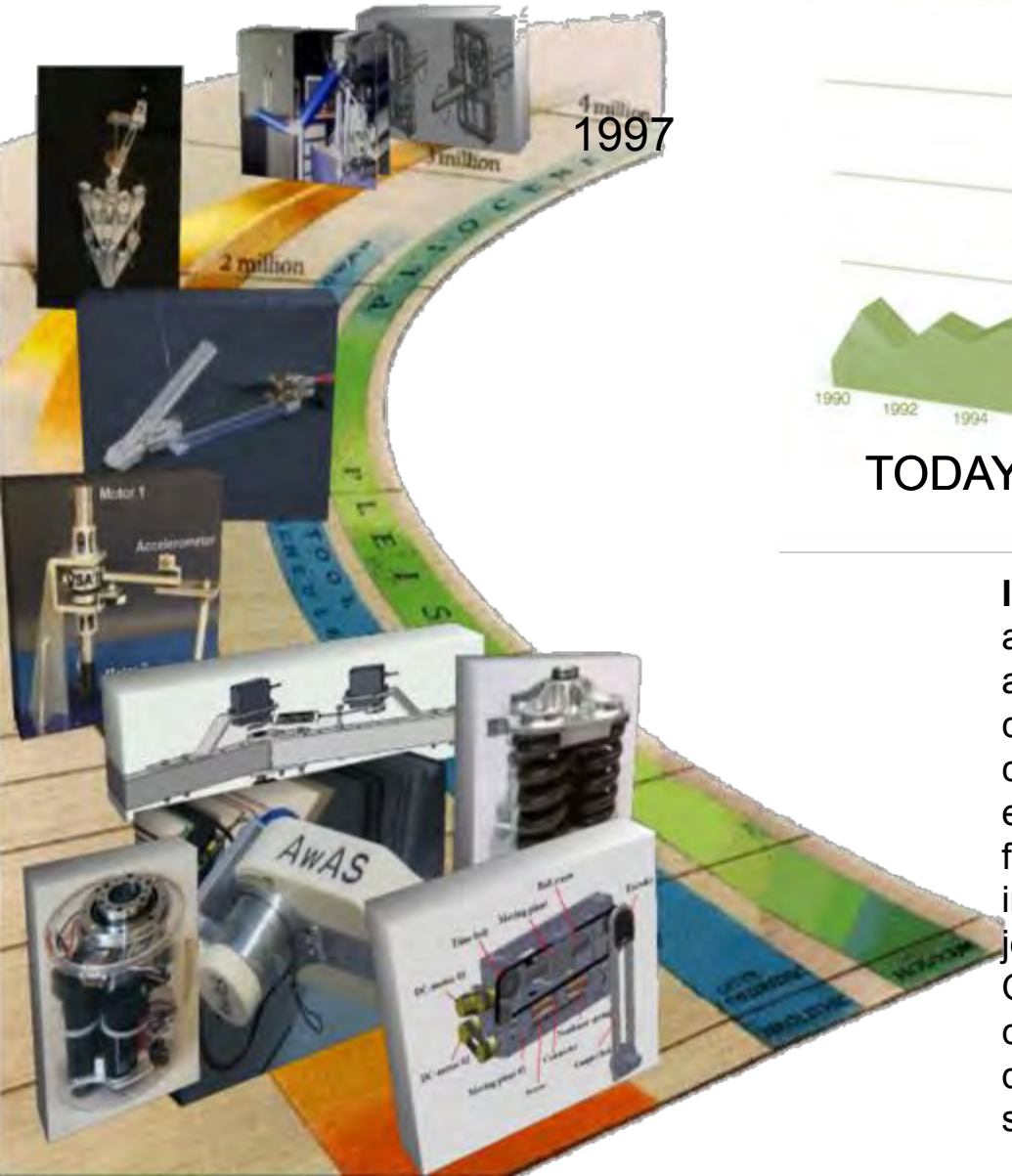
What will future robots look like?

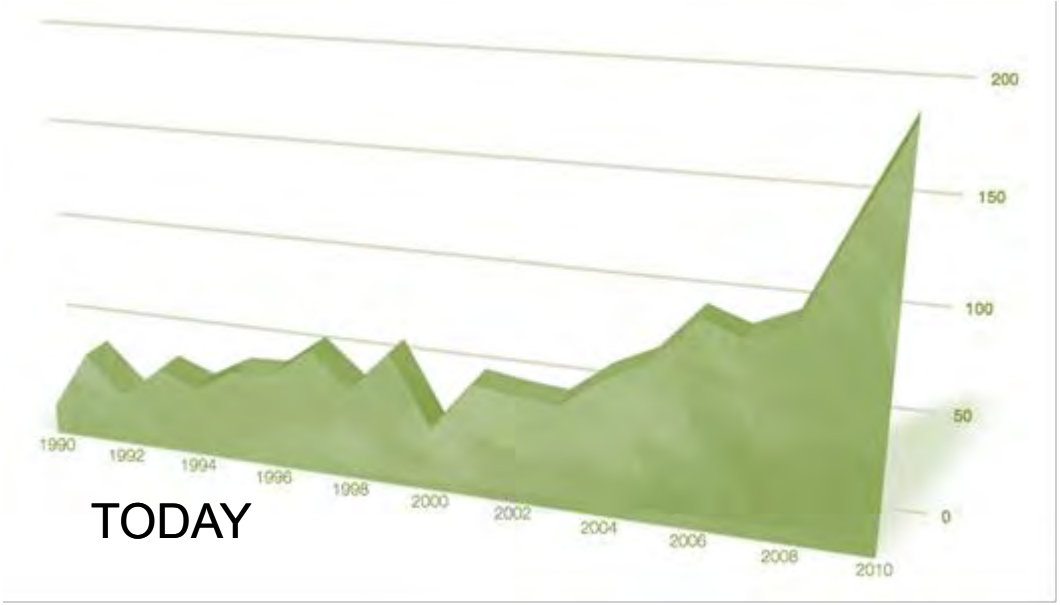
- From Position Control

- To Torque Control

- to Reference Point
  AND
  Stiffness Control

Variable Stiffness Actuators





IEE Xplore Search:
active compliance OR adjustable compliance OR adjustable damping OR compliance controller OR compliant actuation OR compliant actuator OR compliant control OR compliant controller OR elastic actuation OR elastic transmission OR flexible actuation, flexible actuators OR impedance control OR impedance controller OR joint impedance OR joint stiffness OR soft robotics OR soft robot OR soft robotics OR stiffness control OR stiffness controller OR variable damping OR variable compliance OR variable stiffness actuator.

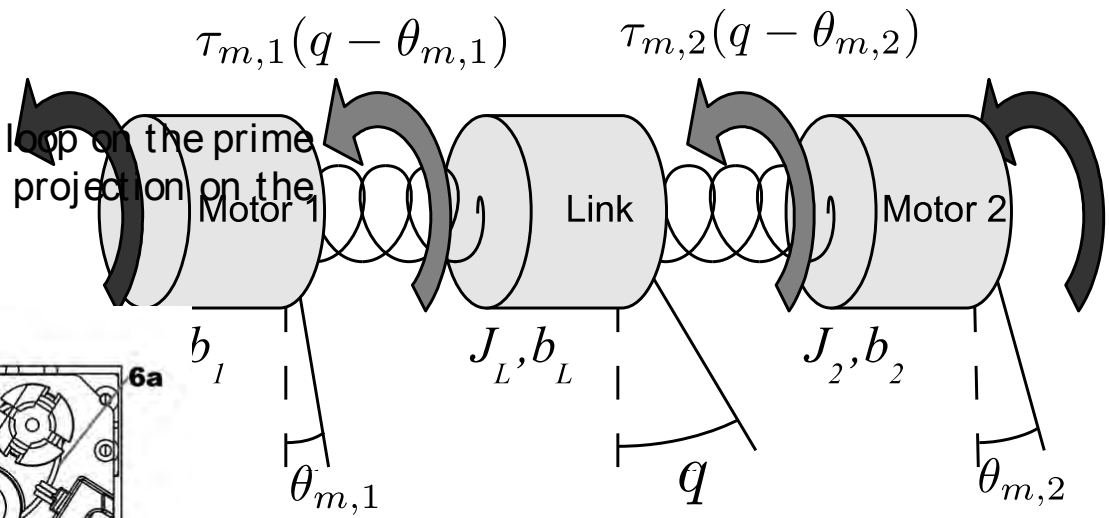
Is Motion Control relevant to Motor Control?

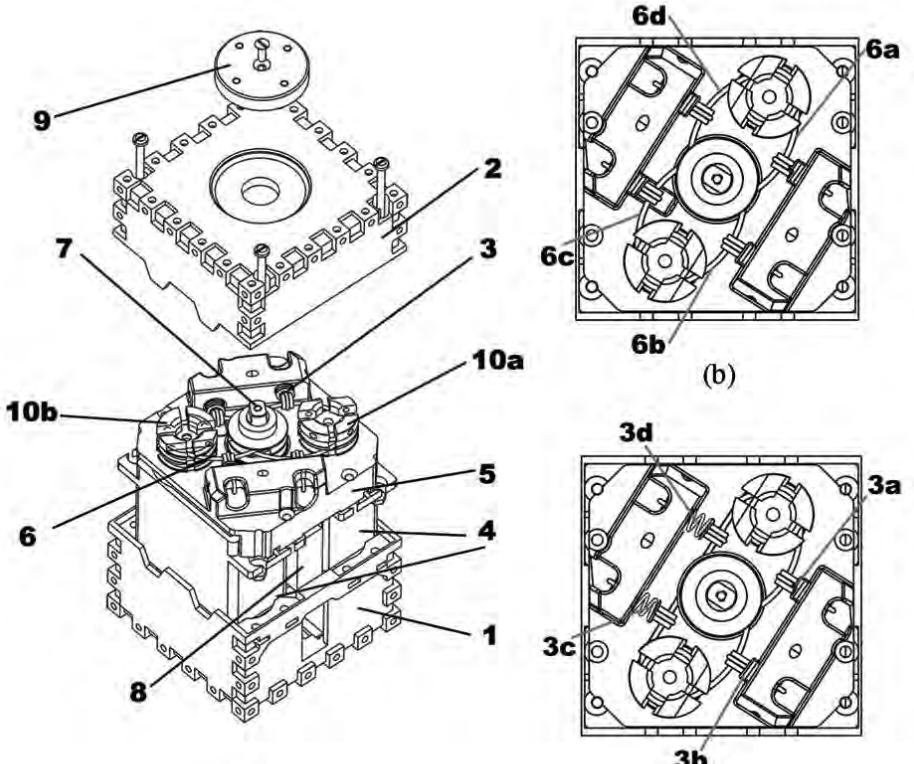
- Are there biologic counterparts to the newest motion control schemes in robotics?
- Does a link exist between the Equilibrium Point Hypothesis and Reference & Stiffness Control?
- Are biologic motor control schemes useful to robotics?
- Can robot muscles be useful to you?

Agonist-Antagonist VSA

-CUBE: Design of a Servo VSA

lowest layer of control, implementing a PID loop on the prime
s (Sec.5.3), this is also reflected in the PEV projection on the
< ω, σ > .



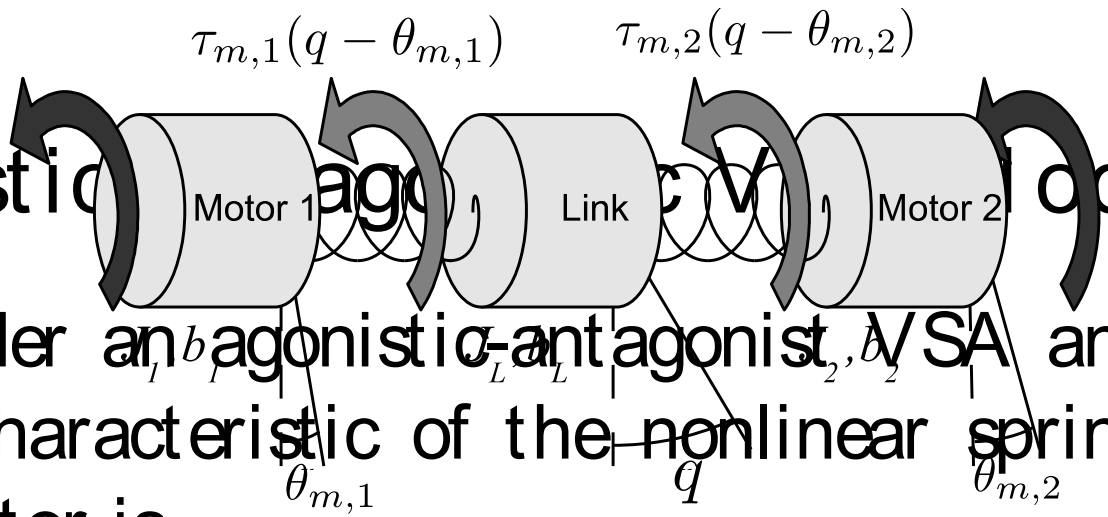


In Fig. 5.15(b) thresholds are changed such that r = 4 an
hence causing only a joint movement while in 5.15(c) thres
changed such that r = 3 and c = 1, hence causing only a joint
change.

VSA Antagonist Model:

Nonlinear springs

qb move



5.7.2 Agonistic-antagonistic VSA model

Let us now consider an agonistic-antagonist VSA and assu
the force-length characteristic of the nonlinear spring bet
link and the actuator is

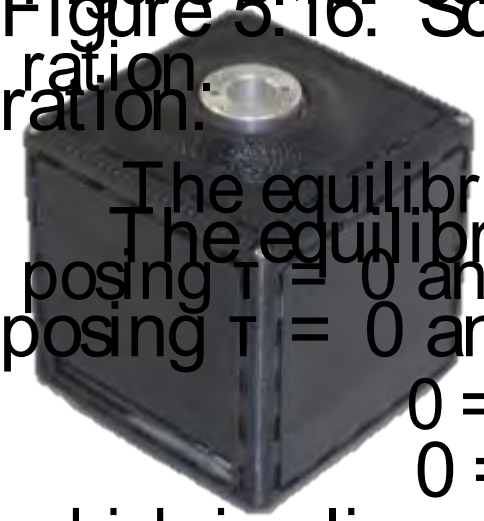
Mechanical characteristic of the nonlinear springs

$$\tau_{m,i} = \alpha(e^{\beta(q-\theta_{m,i}+\eta\dot{q})} - 1)$$

Where α, β, and η are the parameters that determine the mechanical characteristic of the spring; $\theta_{m,I}$ are positions of the motors and q is the link position

VSA Antagonist Model: Equilibrium Position

Figure 5.16: Scheme of a VSA with agonist and antagonist configuration.



Considering zero velocity and no external load

$$\tau = 0 \qquad \dot{q} = 0$$

The equilibrium position $\bar{q}$ of the VSA can be determined by posing $\tau = 0$ and $\dot{q} = 0$ in (5.12), obtaining

$$0 = \tau_{m,1} + \tau_{m,2} = \alpha e^{\beta(\bar{q} - \theta_{m,1})} - \alpha e^{\beta(-\bar{q} + \theta_{m,2})}$$

which implies

$$\bar{q} = \frac{\theta_{m,1} + \theta_{m,2}}{2} = q_l$$

The equilibrium joint position is proportional to the

The stiffness σ can be obtained as a function of $\theta_{m,1}$ and by determining the derivative of the external torque w.r.t. the position q and evaluating it in $\bar{q}$, i.e.:

VSA Antagonist Model: Stiffness

which implies

$$\bar{q} = \frac{\theta_{m,1} + \theta_{m,2}}{2} = q$$

The stiffness σ can be obtained as a function of $\theta_{m,1}$ by determining the derivative of the external torque w.r.t position q and evaluating it in $\bar{q}$, i.e.

The stiffness at the equilibrium position (with no external load) can be evaluated by computing the derivative of the external torque w.r.t. the link position

$$\sigma = \left.\frac{\partial \tau}{\partial q}\right|_{q=\bar{q}} = 2\alpha\beta e^{\beta k}$$

From VSA-C

where $k = \frac{\theta_{m,2} - \theta_{m,1}}{2}$.

Stiffness Preset

In [140] an experimental device implen

The stiffness around the equilibrium position depends on the semi-difference of the motor positions

with two exponential springs acting on t

exponential force-length characteristic of

suitable designing the geometric profile

(see Fig. 5.17).

Equilibrium-Point Hypothesis

"*According to the EP-hypothesis, central control signals change the threshold of activation of alpha-motoneurons to afferent signals related to muscle length (threshold of the tonic stretch reflex, λ)…*"

"*… for each λ (given an external load), there is an instantaneous EP – a combination of muscle length and force that would have been observed if the control process stopped and the system were given time to reach an equilibrium state.*"

"*Control of a simple joint with one kinematic degree of freedom may be viewed as resulting from specifying the control variables for the agonist and antagonist muscles*."

[Latash, Motor Synergies and the Equilibrium-Point Hypothesis, Motor Control. Jul 2010; 14(3): 294–322]

Natural Muscles: Mechanical Characteristics

$$f = \rho\left(e^{\delta A} - 1\right)$$ Muscle Force

ρ Parameter relating to fore-generating capability of the muscle

δ Form parameter

$$A(t) = \left[l(t-d) - \lambda(t) + \mu(t)\dot{l}(t-d)\right]^{+}$$ Muscle Activation

l Muscle Length

$\lambda(t)$ Threshold Length

d Reflex Delay

[P. L. Gribble, D. J. Ostry, V. Sanguineti, and R. Laboissière, “Are complex control signals required for human arm movement?” *Journal of Neurophysiology*]

Muscle Model: Joint

Equilibrium of a system composed of a couple of muscles acting on the same joint (e.g. elbow)

$$\tau + R(f_1 + f_2) = 0$$

τ External Load

R Instantaneous Lever Arm

Assuming that R is constant and ρ and δ are the same for both muscles

$$f_1 = \rho(e^{\delta A_1} - 1) \qquad A_1 = Rq(t-d) - \lambda_1(t) + \mu(t)R\dot{q}(t-d)$$

$$f_2 = -\rho(e^{\delta A_2} - 1) \qquad A_2 = -Rq(t-d) + \lambda_2(t) - \mu(t)R\dot{q}(t-d)$$

q is the forearm angular position w.r.t. the arm

[P. L. Gribble, D. J. Ostry, V. Sanguineti, and R. Laboissière, “Are complex control signals required for human arm movement?” *Journal of Neurophysiology*]

Muscle Model: Joint Equilibrium Position

(a) $l_1 = 1$ and $l_2 = 5$ or, similarly, $r = 3$ and $c = 2$.

$l_1 = 1$ and $l_2 = 5$ or, simi-

$r = 3$ and $c = 2$.

(b) $l_1 = 2$ and $l_2 = 6$, hence changing joint position. Indeed, $r = 4$ and $c = 2$.

(c) $l_1 = 2$ and $l_2 = 4$, hence changing joint stiffness. Indeed, $r = 3$ and $c = 1$.

Fig. 2. Force–length characteristics.

Neglecting the reflex delay and considering

$$\tau = 0 \qquad \dot{q} = 0$$

the equilibrium position $\bar{q}$ (with no external load) of the joint results from the equation

hence obtaining

$$e^{\gamma(R\bar{q}-\lambda_1)} - e^{\gamma(-R\bar{q}+\lambda_2)} = 0$$

$$\bar{q} = \frac{l_1 + l_2}{2R} = \frac{r}{R'} \quad \text{where } r := \frac{l_1 + l_2}{2}. \qquad \text{Reciprocal Command} \quad (6)$$

The stiffness s can be evaluated

computing the derivative of the exte

The equilibrium joint position corresponds to the semi-sum of the threshold lengths of the muscles

∂t

Muscle Model: Joint Stiffness

The stiffness at the equilibrium position (with no external load) can be evaluated by computing the derivative of the external torque w.r.t. the link position

$$\sigma = \left.\frac{\partial \tau}{\partial q}\right|_{q=\bar{q}} = 2\rho\delta R^2 e^{\frac{\delta c}{R}}$$

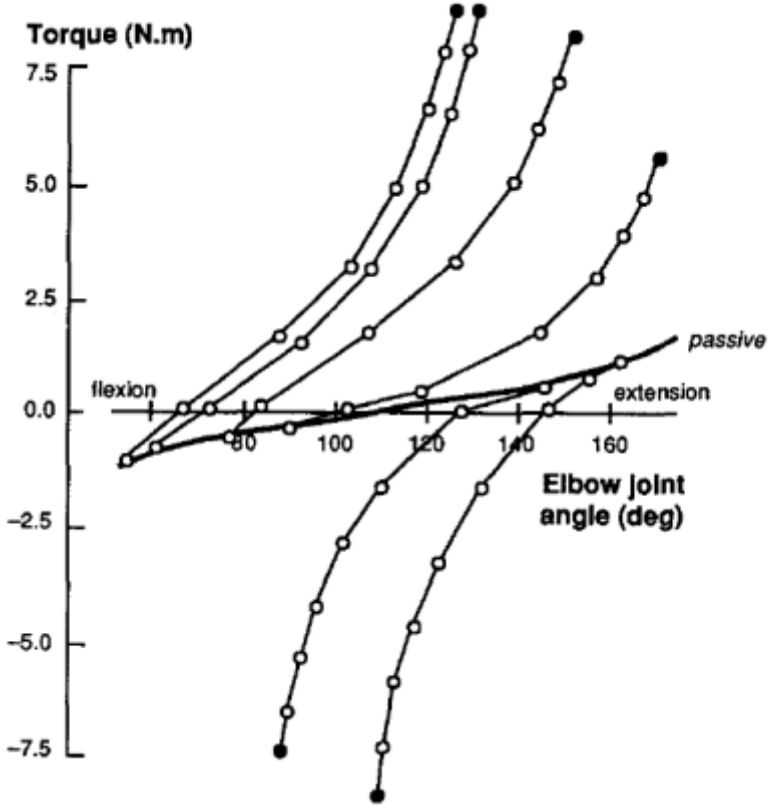
$$c = \frac{\lambda_2 - \lambda_1}{2}$$

Coactivation Command

The stiffness around the equilibrium position depends on the semi-difference of the threshold lengths of the muscles

Muscle experimental data

External Load – Link Position Characteristics of elbow flexors and extensors measured through unloading the arm



[Reza Shadmehr and Michael A. Arbib, A mathematical analysis of the force-stiffness characteristics of muscles in control of a single joint system,Biological Cybernetics, 1992], redrawn from Feldman 1980.

hence obtaining

Natur

which implies

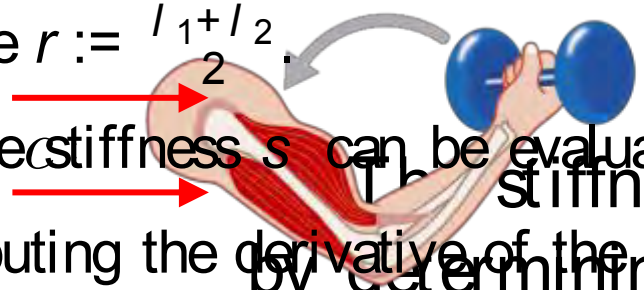
$$0 = \tau_{m,1} + \tau_{m,2} = \alpha e^{\beta(\bar{q} - \theta_{m,1})} - \alpha e^{\beta(-}$$

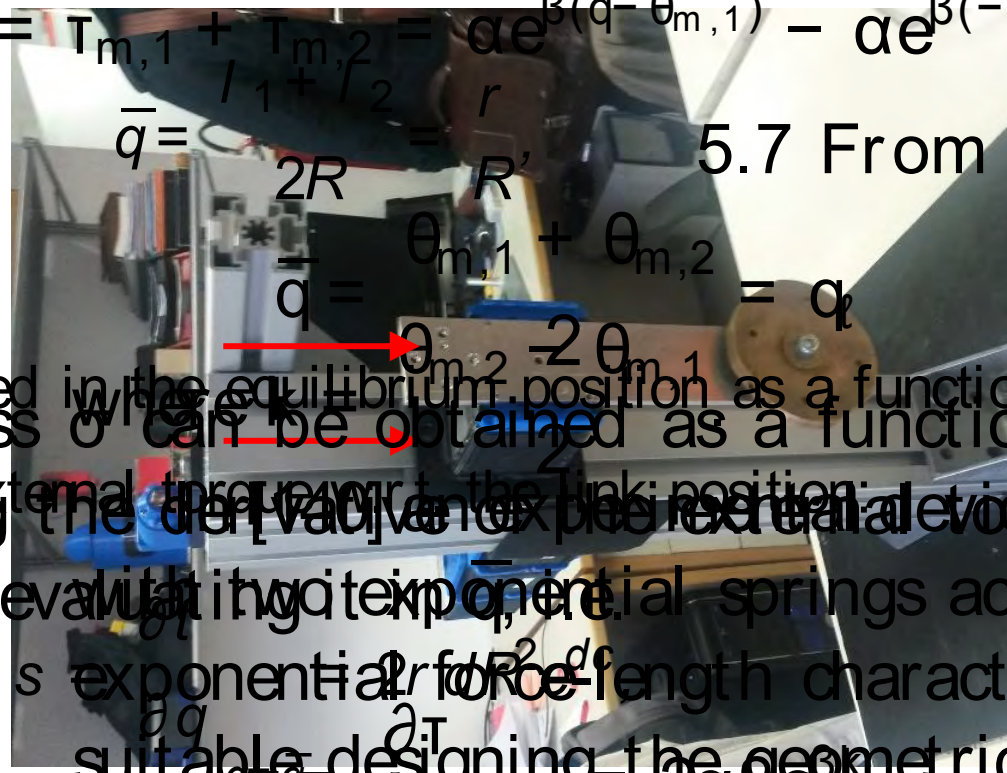
$$\bar{q} = \frac{l_1 + l_2}{2R} = \frac{r}{R},$$

5.7 From

$$\bar{q} = \frac{\theta_{m,1} + \theta_{m,2}}{\theta_{m,2} - \theta_{m,1}} = q_\ell$$

where $r := \frac{l_1 + l_2}{2}$.





The stiffness s can be evaluated in the equilibrium position as a functio

The stiffness σ can be obtained as a functio

computing the derivative of the external torque wrt the link position:

by determining the derivative of the external to

position q and evaluating it in $\bar{q}$, i.e.

with two exponential springs ac

exponential force-length charact

suitable designing the geometric

(see Fig. 5.11).

$$s = \frac{\partial \tau}{\partial q}\Big|_{q=\bar{q}} = 2\alpha\beta e^{\beta\kappa},$$

$$\sigma = \frac{\partial \tau}{\partial q}\Big|_{q=\bar{q}} = 2\alpha\beta e^{\beta\kappa},$$

Reciprocal Command (Reference)

Coactivation Command (Stiffness Preset)

Stiffness

where $c := \frac{l_1 - l_2}{2}$.

aracteristichs and

With a fixed Φ we

rom -90 to 90 degrees

order to account

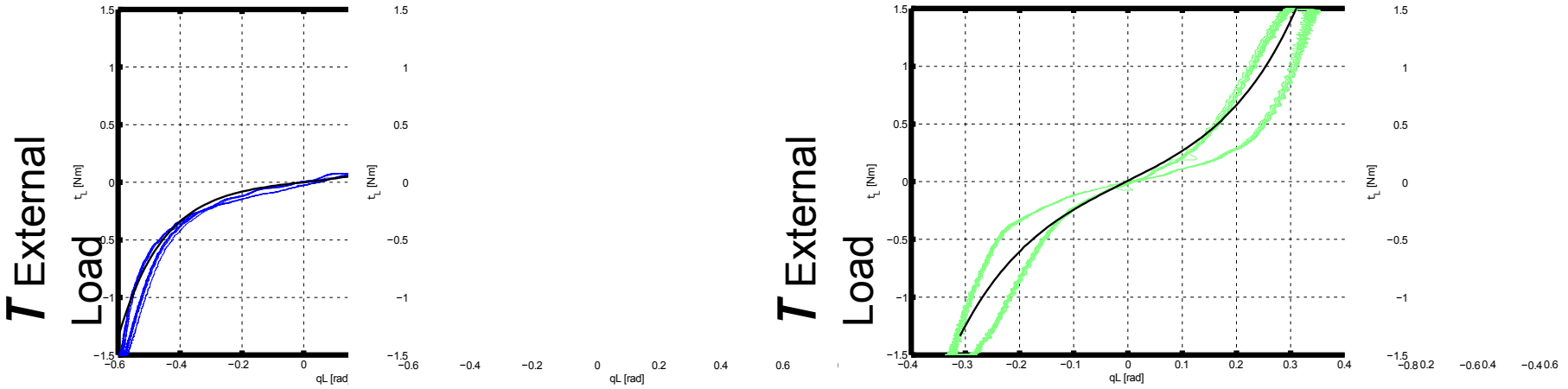
h a 1.8 degree step

ponding ψ.

different values of Φ

Experimental data

External Load = Link Position Characteristics of the VSAcube for different stiffness presets



(a) Case 1. Position $\bar{q} = 0$ $k = 0$

(b) Case 2 $k = 25$

(c)

Figure 5.18: Force-length characteristics

Suitable non-linear springs replicate the human muscle behaviour.

natural motion initiative

*an **open** initiative to foster the diffusion of **soft** actuation in **robotics***

SAPHARI

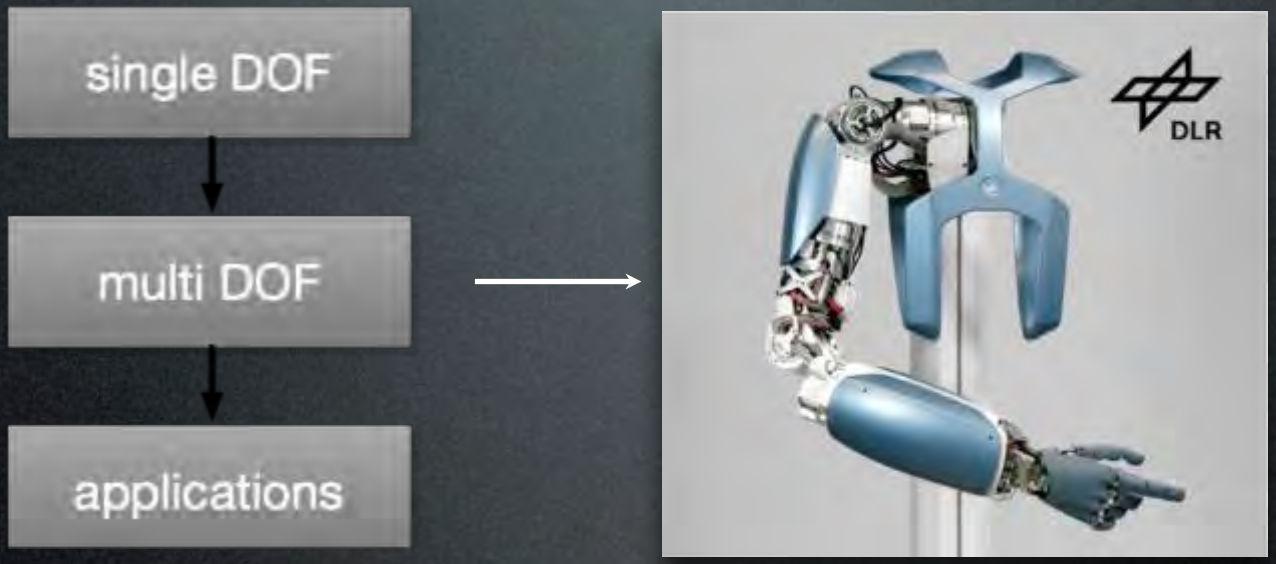
Safe and Autonomous Physical Human-Aware Robot Interaction

qb robotics

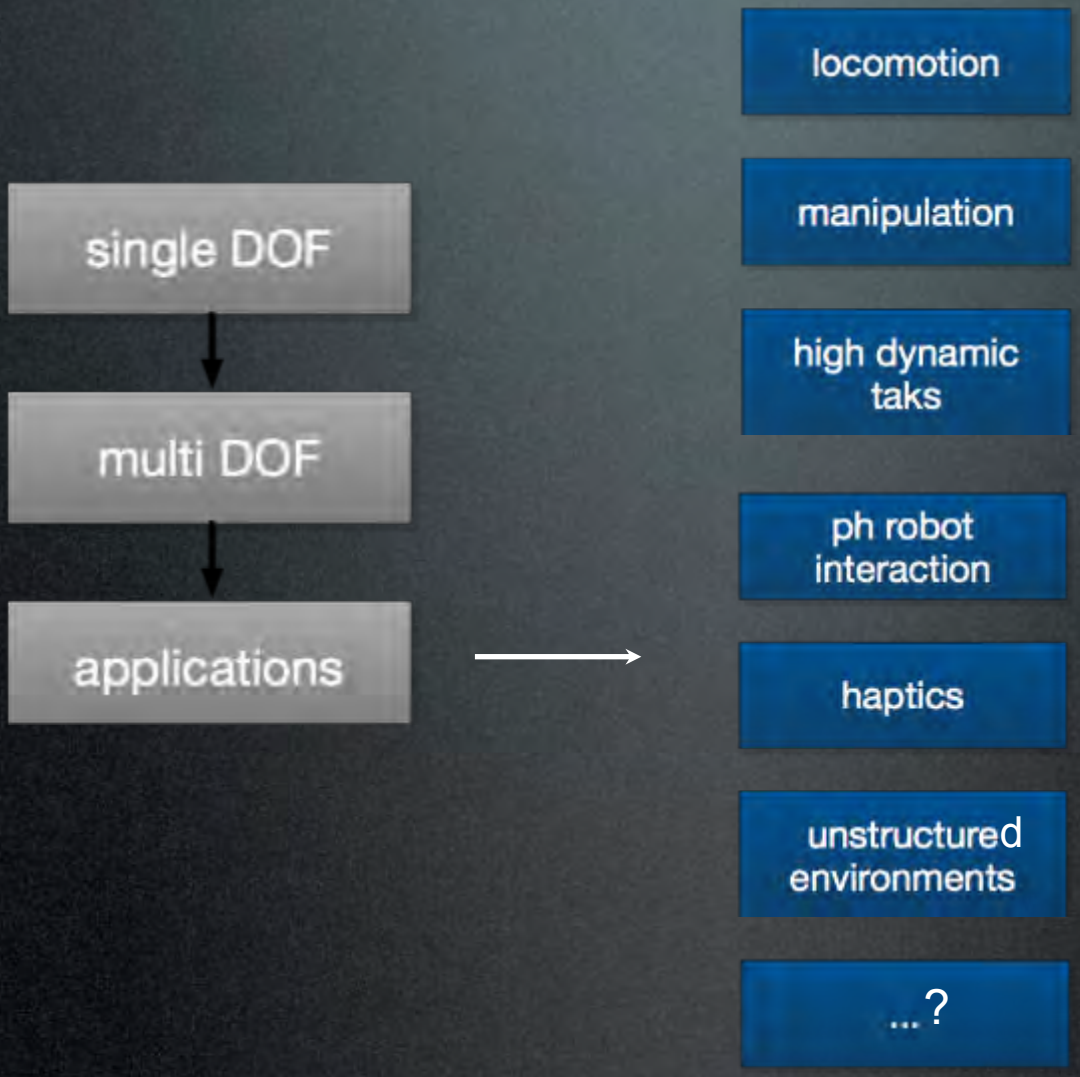
azienda spin-off
Università di Pisa

Applications of VSA & VIA

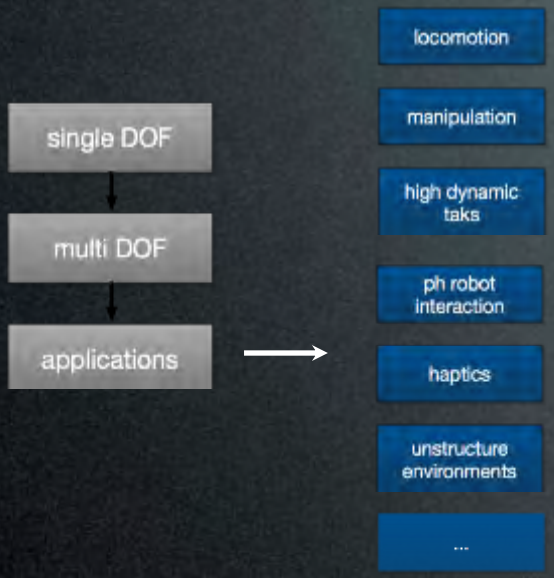
Applications of VSA & VIA



Applications of VSA & VIA



Applications of VSA & VIA



- We suspect there is a much wider range of applications than few researchers alone can explore
- Idea:
  crowdsource the exploration of new territories

Take the Initiative

Main issues

- Cost
- Time
- Know-how
- Diffusion

Solutions

- Lower cost
- Modularity
- Public access, easy utilization
- Open discussion

Full Open Platform

- **SW**
- **Electronics HW**
- **Mechanical HW**

natural motion initiative

- open paradigm
  - BSD & Creative Commons licensing
  - leads to the fast diffusion of the technology
  - best choice for developers
  - create a community to get support and feedback
  - examples: Linux, I-Cub, Arduino

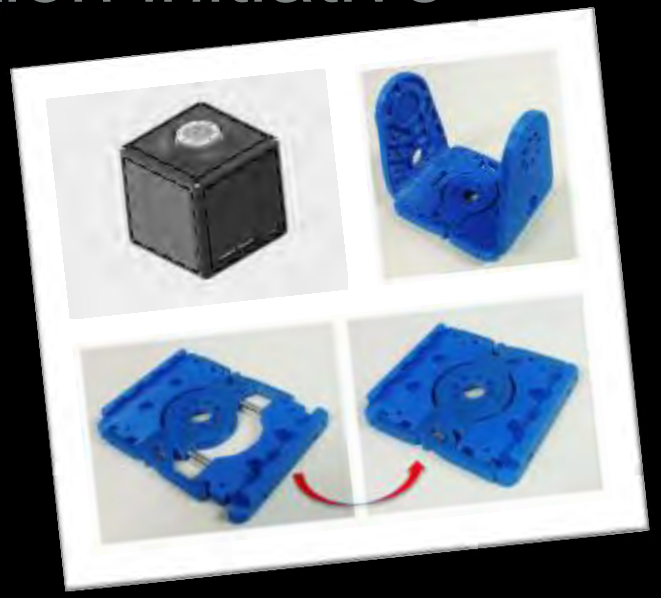
natural motion initiative

- 3 main sections

  - **Learn** – Wiki, Q&A, Forums
  - **Explore** – projects are here (as well as some photos and videos)
  - **Participate** – news, events and registration info

qbmove & qbmate

first fruits of the natural motion initiative



How to Use Variable Siffness

1) Optimal Control
   - Safe Brachistochrone
     ("soft and fast, stiff and slow")
   - Hit maximization (MaxSpeed problem)
   - Motion on a limit cycle (Energy Efficiency)
   - …

Optimal Control and Robotics

There are at least three fundamental reasons why OC is fundamental to robotic studies:

- OC provide a **control synthesis** procedure for complex systems
- OC provides a principled basis to compare the performance of different **system designs**;
- OC represents **a language** to make a dialogue between sciences of natural and artificial systems possible (*bio-aware robotics*)

OC for Abstraction

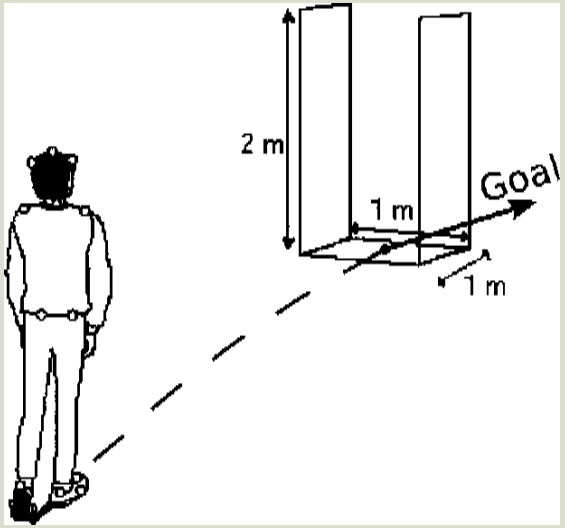
- In the embodied intelligence philosophy, a large part of the functional capabilities of an organ reside in its physical characteristic
- This raises a fundamental question: what can we learn by observing how "body A" works that is relevant to controlling "body B"?
- We need *abstractions* at a sufficiently high level, but still transparently operational, at which ***natural and artificial movement science and technology can meet and share ideas***

Optimality Principles

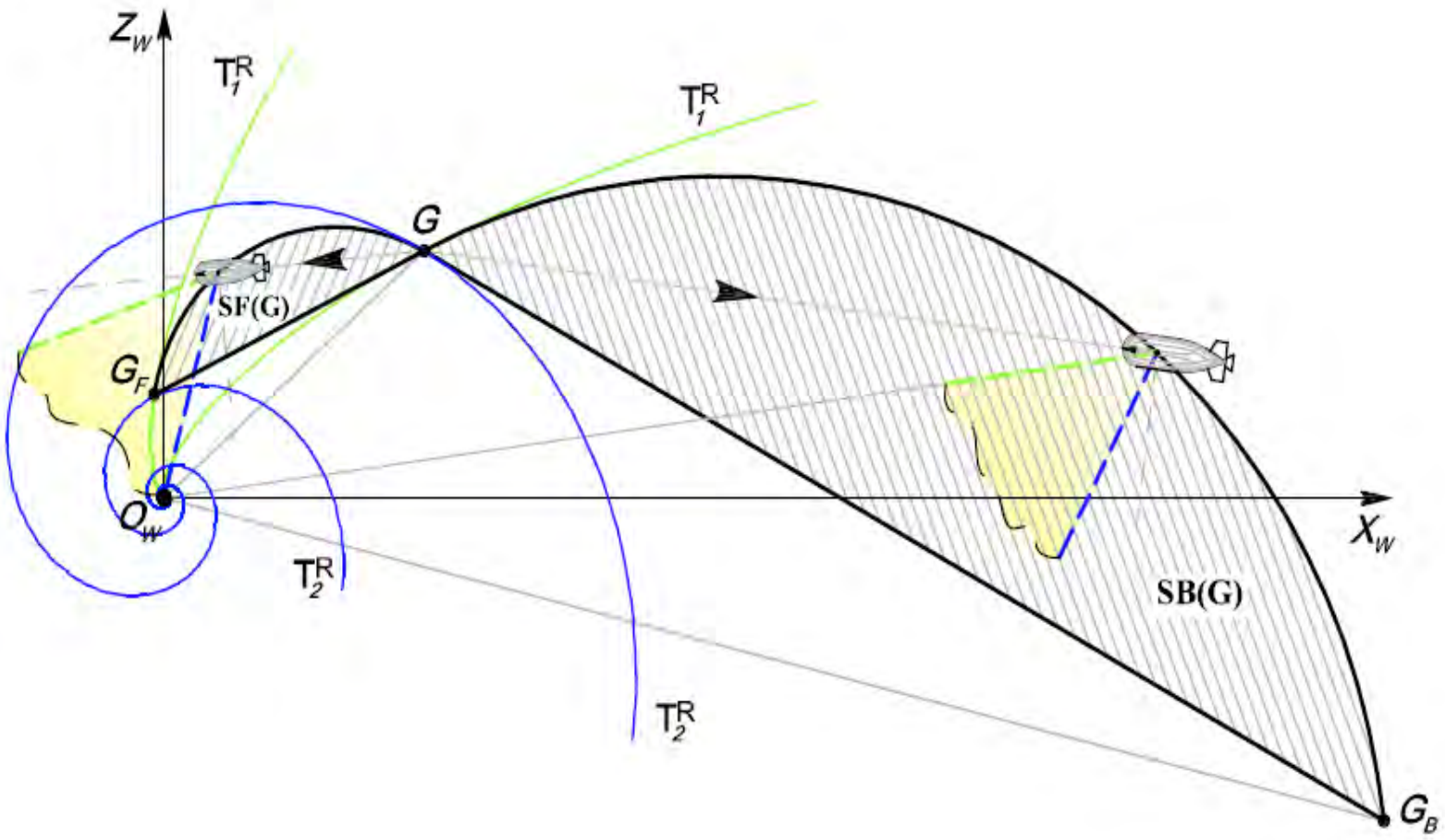
- How should the redundancy implied in the complexity of the bodily implementation and the variability of the environment be managed in the different tasks a robot can be confronted with?
- Notice that the real challenge here, and **the true role of OC is not to solve each and every specific problem** posed by the innumerable different tasks and environment conditions **– rather to understand the basic principles** to adopt, which can be applied in a large class of similar conditions.
- Optimal Control can be used in this function in two main ways
  - Inverse Optimal Control (IOC) applied to natural movements
  - Direct Optimal Control, through either analytic or numerical techniques, to distillate "*principles*" that apply to *classes* of tasks

Inverse Optimal Control

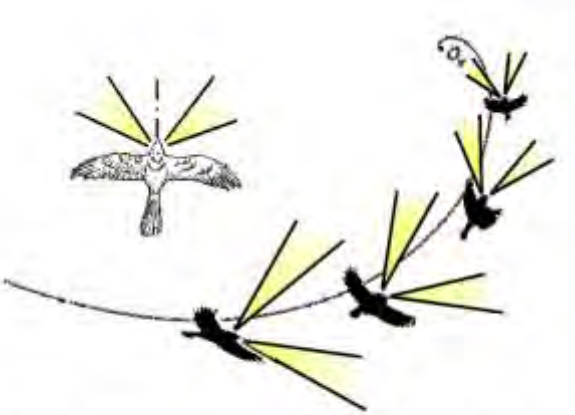
- Mombaur, et al., 2010, showed that a stereotype of locomotor trajectories could be interpreted as the result of application of an optimization index whose weights were found by numerical fitting of experimental data, thus confirming that humans tend to adopt a nonholonomic behaviour, while minimizing the bearing angle so that a spiralling path results



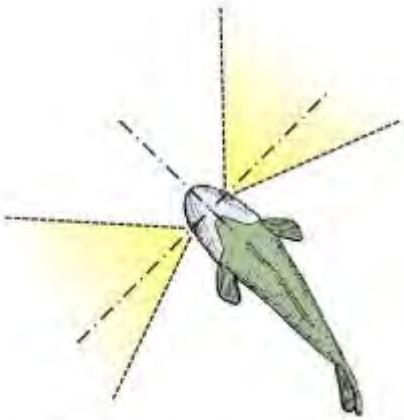
Direct Optimal Control :
Shortest path to a target with limited Field-of-View



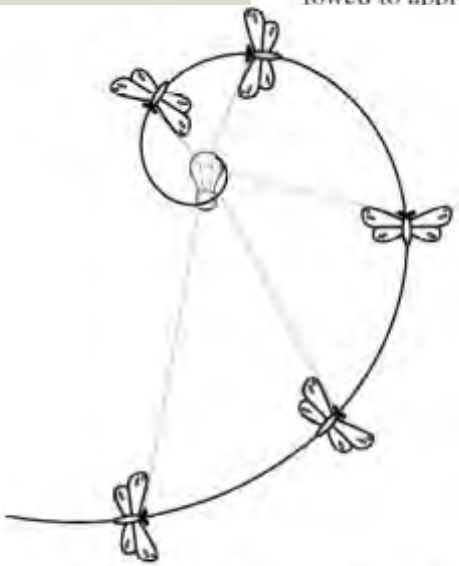
Catching a prey by Finned, Winged, Legged Creatures



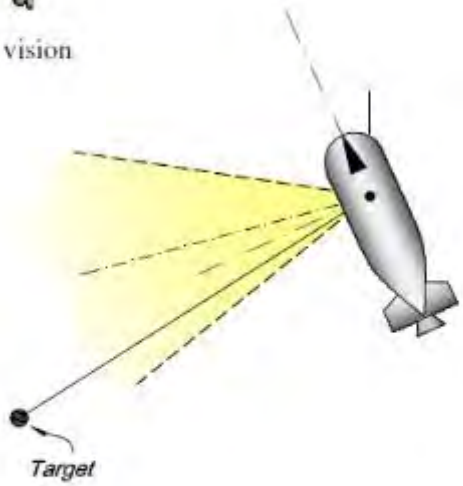
(a) Raptor vision system and trajectories followed to approach a prey.



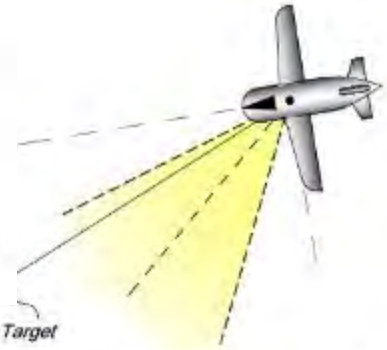
(a) Nurse shark and goldfish vision system.



(b) Trajectories followed by moths to approach an electric light.



(b) Underwater (Finned) vehicle with lateral-looking sensors.



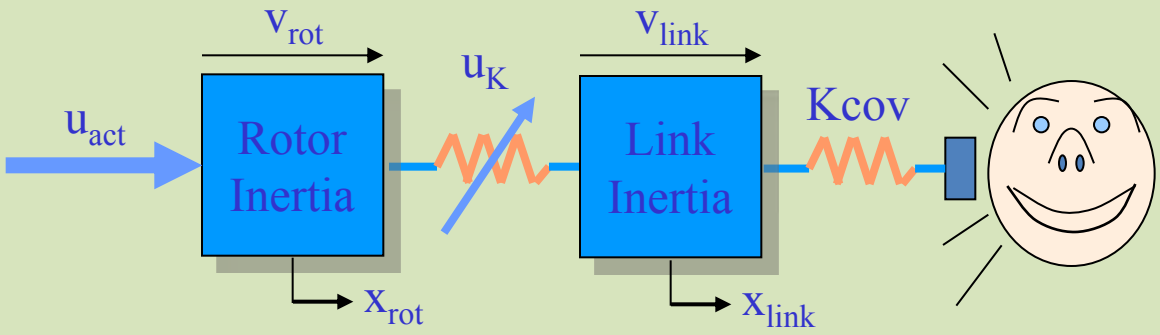
(c) Winged vehicle with side-looking sensors.

DOC and System Design: an Example from Soft Robotics

- We are interested in understanding **how a given design** (e.g. a soft, *variable impedance* actuated robot) **compares with other solutions** (e.g., a conventional elastic joint), **in a specific task** (e.g., safe motion, explosive motion, rhythmic motion)
- In comparisons, we are confronted with the **variability of feedback control policies that could be applied to either systems**, which result in variable performance (to be measured e.g. as energy efficiency or speed)
- Application of the **Optimal Control** solution provides an absolute performance reference that **factorizes the control design out**, and allows for drawing conclusions on the intrinsic worth of the physical system.

Safe Brachistochrone for VSA

Can the control of transmission compliance recover performance?



The Safe Brachistocrone is now nonlinear

$$
\begin{cases}
\min_T \int_0^T 1 dt \\
M_{rot}\ddot{x}_{rot} + u_K(x_{rot} - x_{link}) = u_{act} \\
M_{link}\ddot{x}_{link} + u_K(x_{link} - x_{rot}) = 0 \\
|\dot{x}_{link}| \leq \beta(u_K) HIC_{max}^{\frac{2}{5}} \\
|u_{act}| \leq U_{max} \\
u_{K,min} < u_K < u_{K,max} \\
(x_{link}, \dot{x}_{link})(0) = (X_{ini}, 0) \\
(x_{link}, \dot{x}_{link})(T) = (0, 0)
\end{cases}
$$

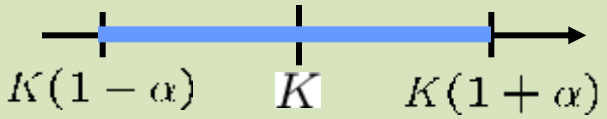
Safety & Control bounds

VST Bounds

Comparison of VSA, SEA and DM^2

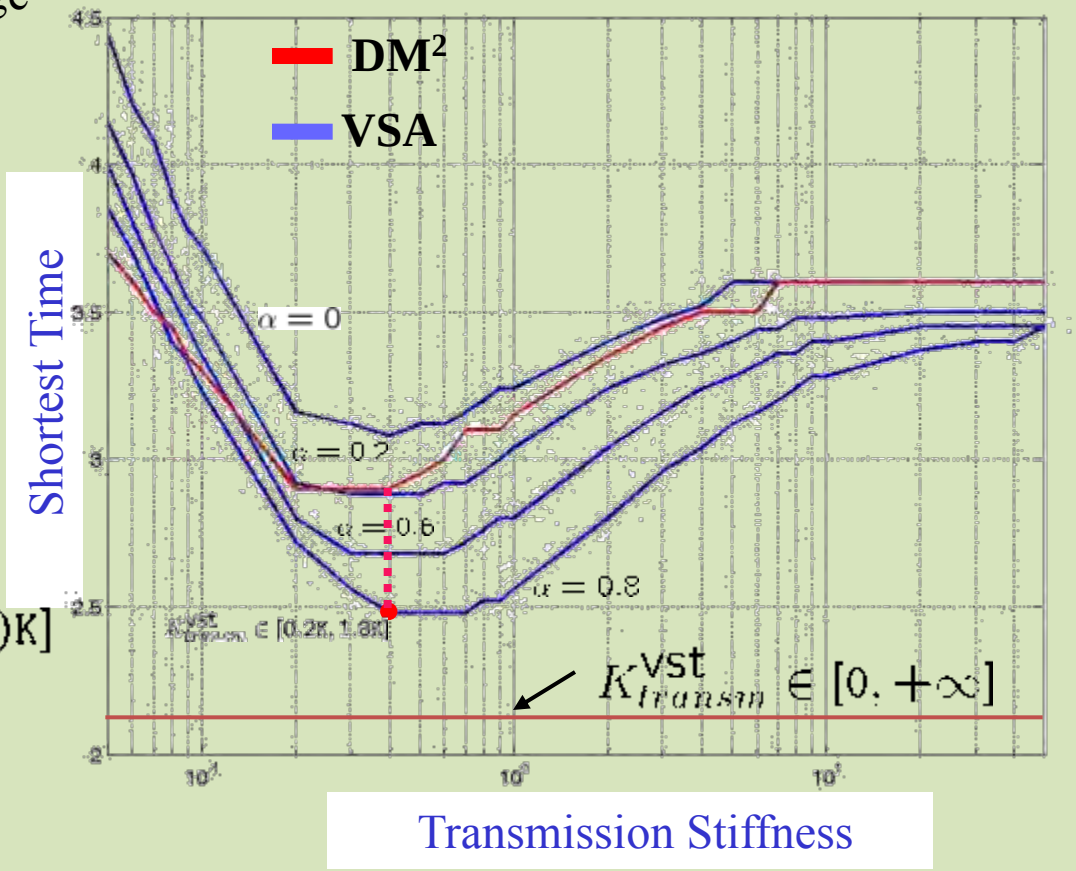
- VST performance recovery highest when transmission stiffness varies in broad range (ideally, 0 to ∞).

- Technology imposes bounds on range

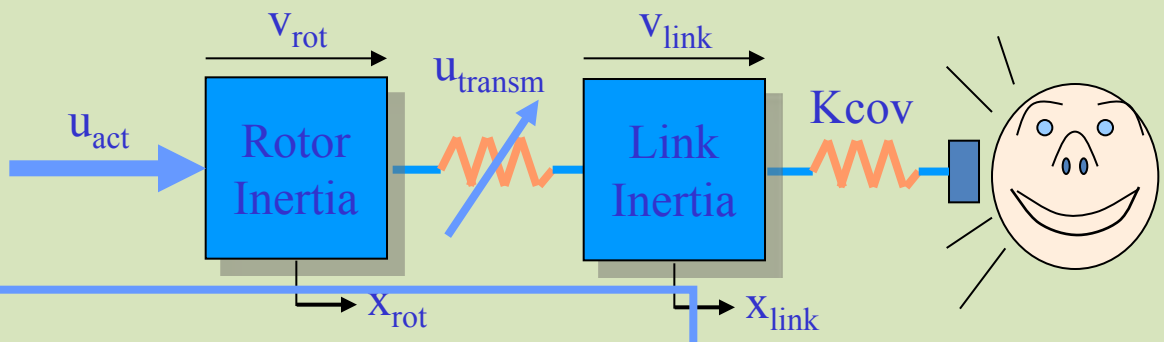


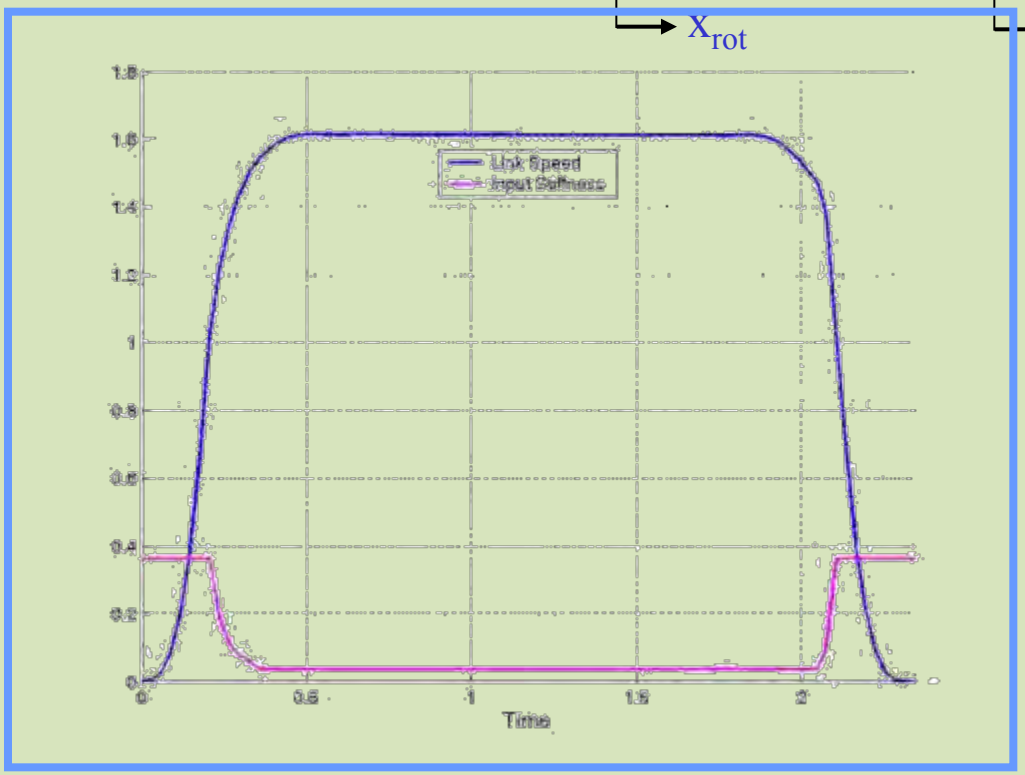
$$u_K = K^{vst}_{transm} \in [(1-\alpha)K, (1+\alpha)K]$$

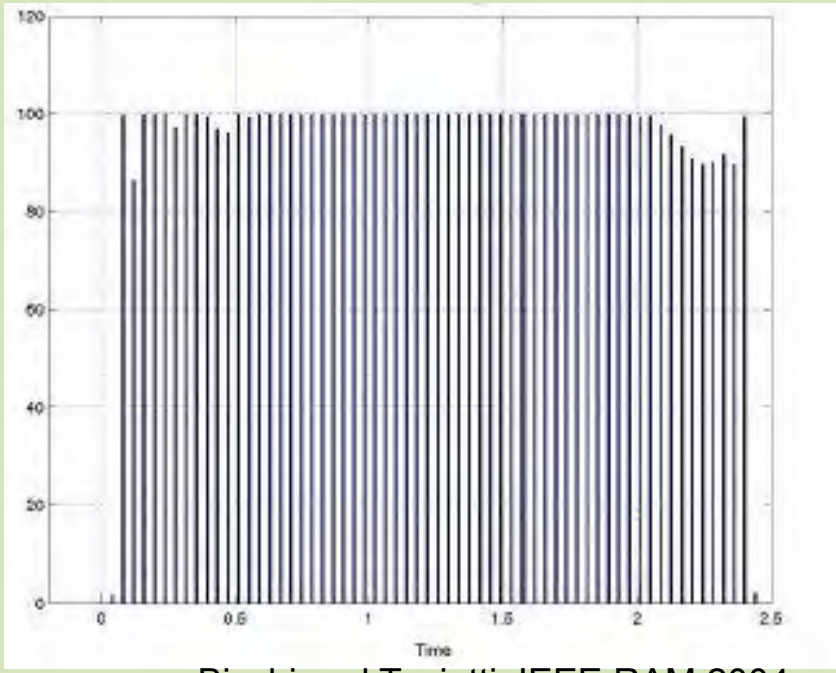
$$K = K^{sea}_{transm}$$



Optimal Control Policy for VSA

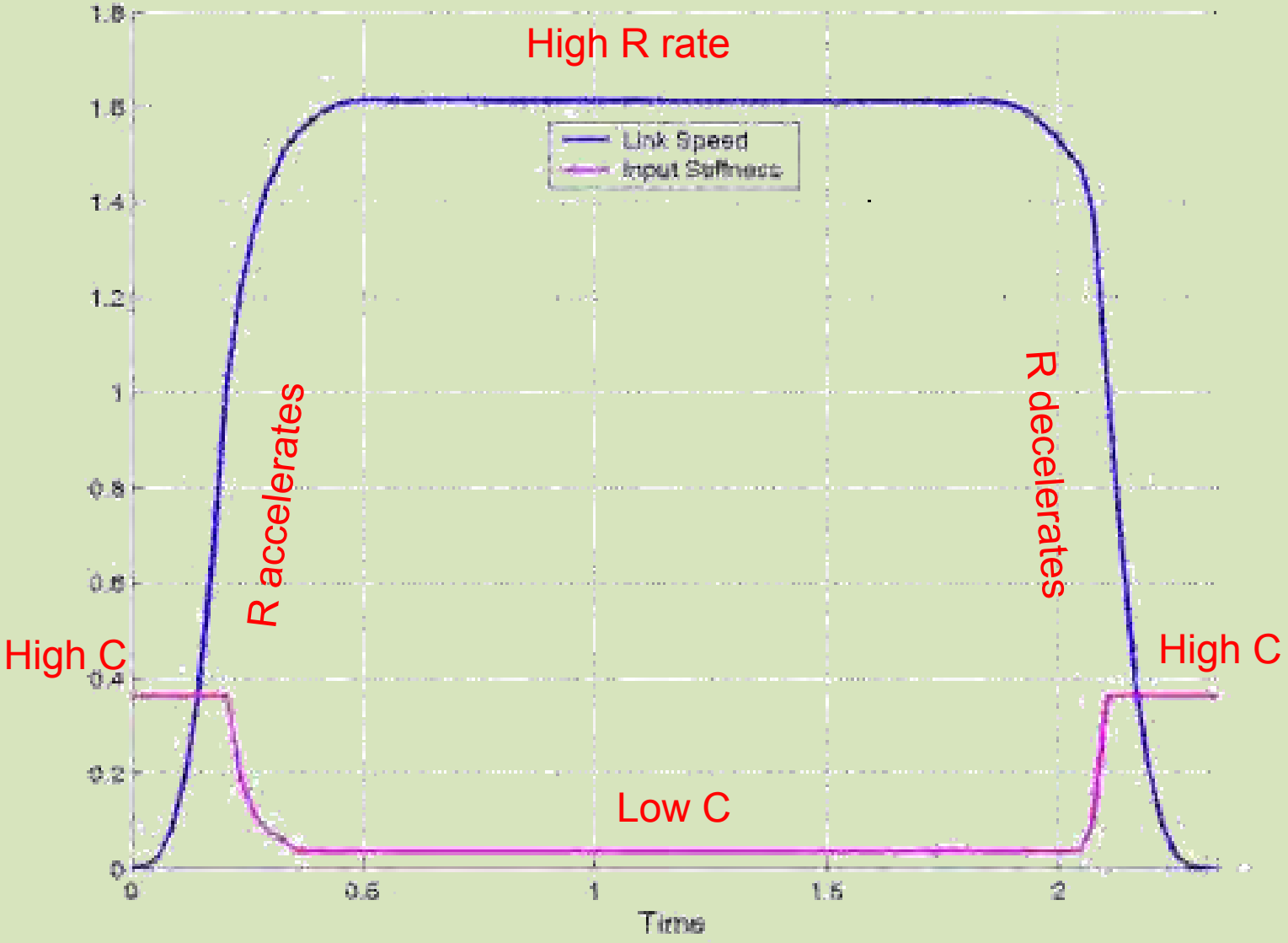






→ ***Fast & Soft, Stiff & Slow***

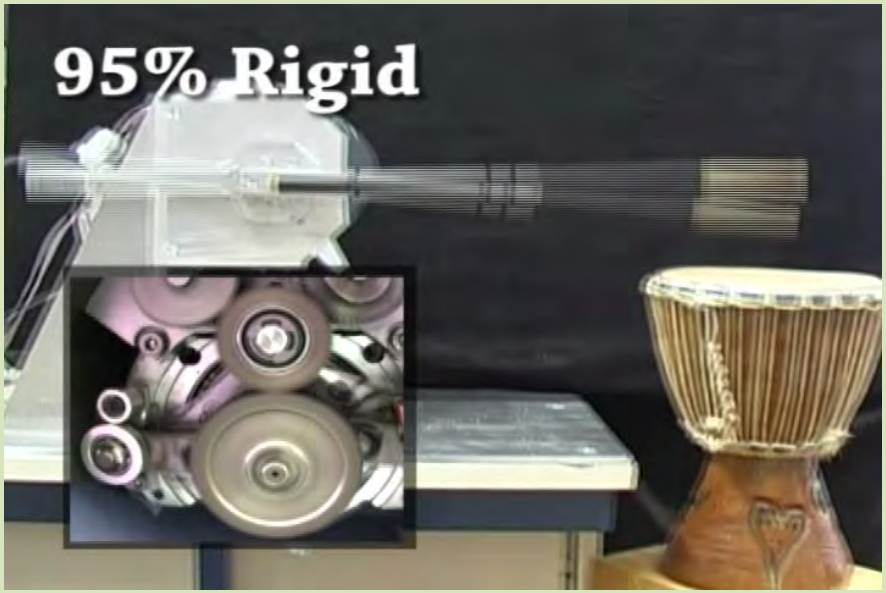
Bicchi and Tonietti, IEEE RAM 2004

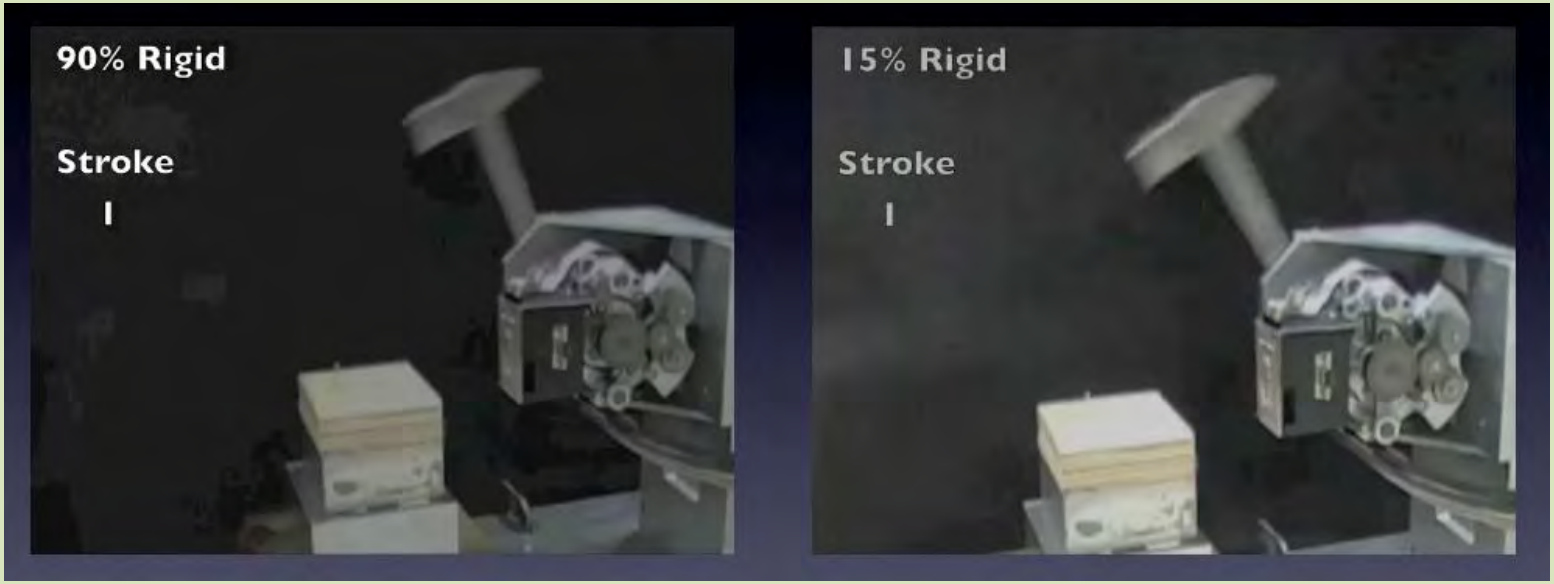

High R rate
Link Speed
Input Stiffness
R accelerates
R decelerates
High C
High C
Low C
Time
0
0.5
1
1.5
2

How to Plan Variable Impedance

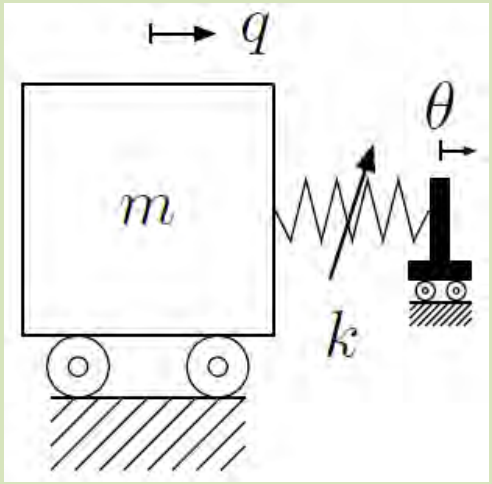
- Optimal Control
  - Safe Brachistochrone
  - Hit maximization (MaxSpeed problem)

Exploiting the Dynamics of VSA





The MaxSpeed Problem (The *VSA Hammer*)



$$|u| \leq u_{max}$$

Index $J = \phi(x(T)) = x_2(T) = \dot{q}(T)\,.$

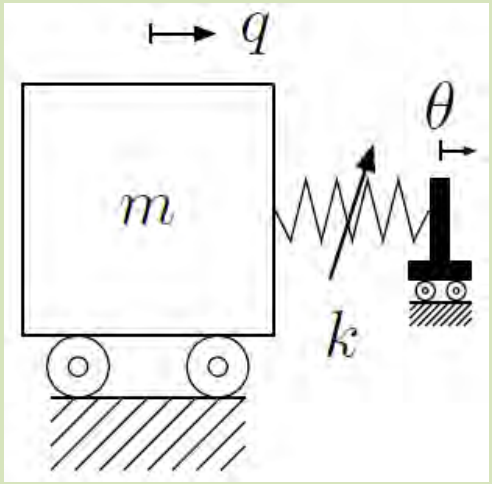
Dynamics $\dot{x} = f(x,u),$

Initial conditions $q(0) = 0$

Terminal const. $\psi(x(T)) = x_1(T) = q(T) = 0$

Hamiltonian $H(x(t),\lambda(t),u(t)) = \lambda^T(t) f(x(t),u(t))$

The MaxSpeed Problem (The *VSA Hammer*)



$$q(0) = 0$$
$$q(T) = 0$$

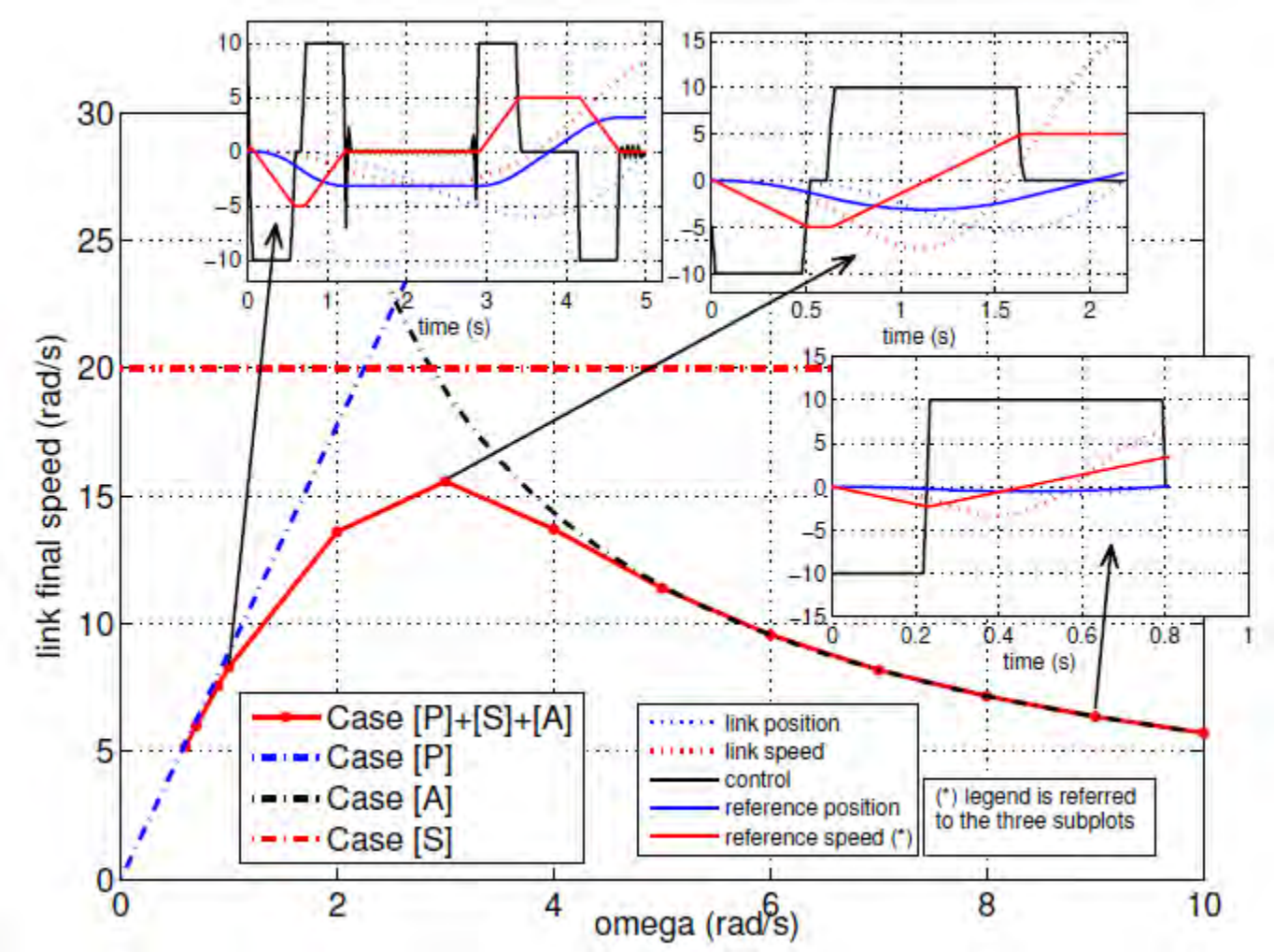
$$|u| \leq u_{max}$$

$$\omega = \sqrt{k/m}$$

Constant K (SEA)

Position control (P)	Speed control (S)	Acceleration control (A)
$\begin{cases} x^T = [q \quad \dot{q}] \\ u = \theta \\ \dot{x} = \begin{bmatrix} x_2 \\ \omega^2 (u - x_1) \end{bmatrix} \end{cases}$	$\begin{cases} x^T = [q \quad \dot{q} \quad \theta] \\ u = \dot{\theta} \\ \dot{x} = \begin{bmatrix} x_2 \\ \omega^2 (x_3 - x_1) \\ u \end{bmatrix} \end{cases}$	$\begin{cases} x^T = [q \quad \dot{q} \quad \theta \quad \dot{\theta}] \\ u = \ddot{\theta} \\ \dot{x} = \begin{bmatrix} x_2 \\ \omega^2 (x_3 - x_1) \\ x_4 \\ u \end{bmatrix} \end{cases}$
$v_{max} = 2\sqrt{2} u_{max} \omega$	$v_{max} = 4 u_{max}$	$v_{max} = 5.74 \frac{u_{max}}{\omega}$

Single Stroke MaxSpeed Problem: Is There a Best Constant Stiffness?



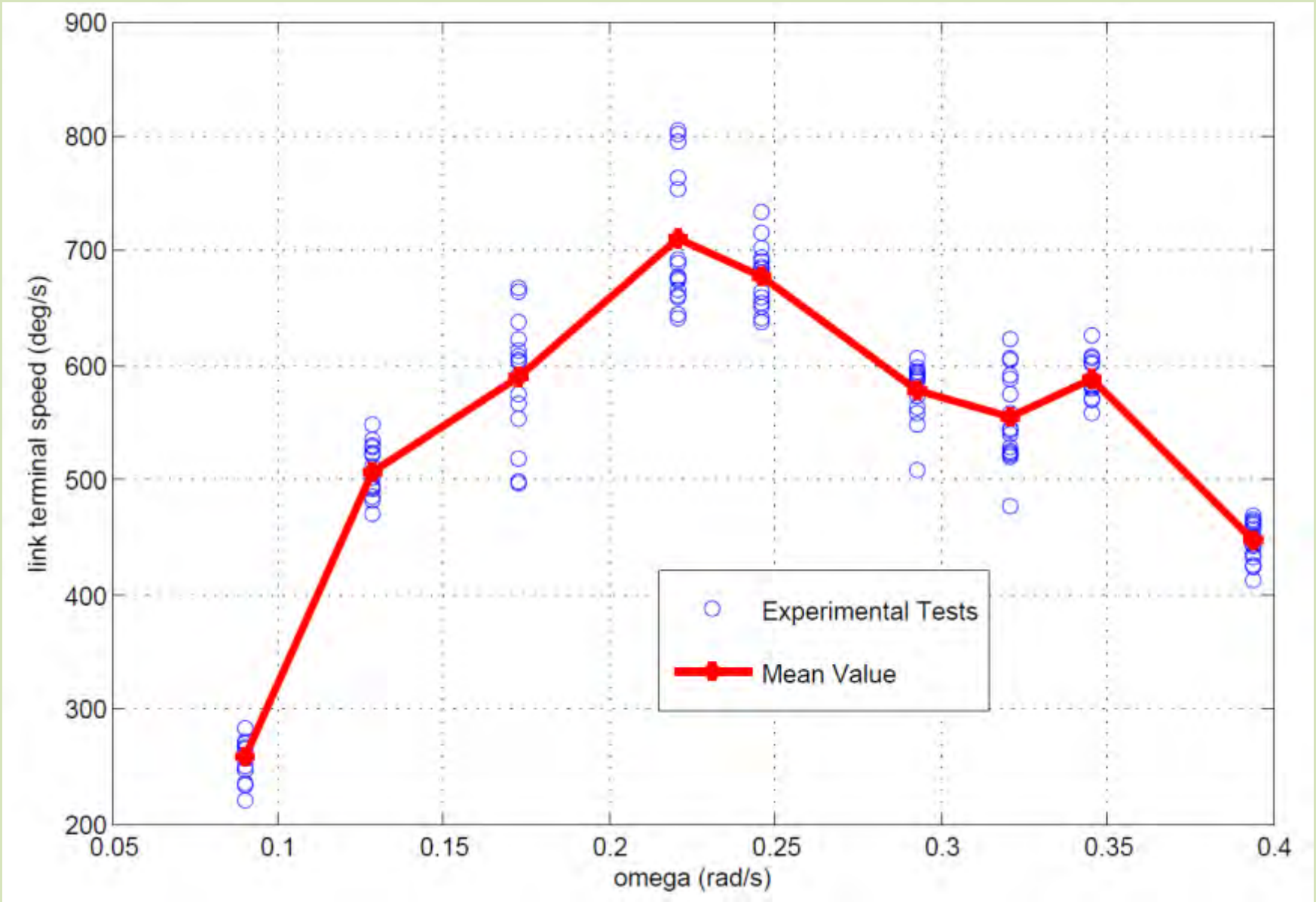
Position control: the stiffer, the better

Velocity control: *k*-invariant

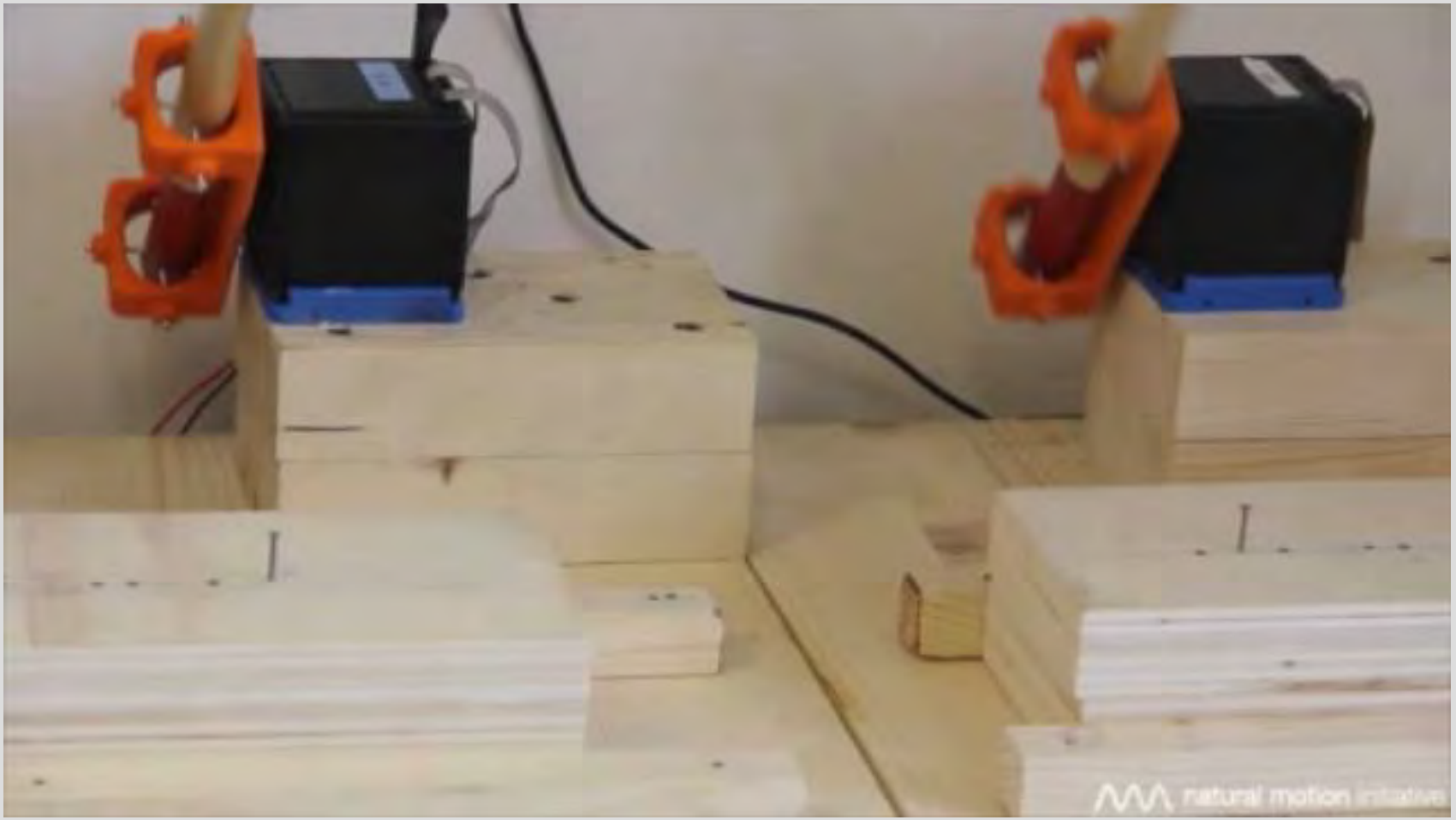
Acceleration control: the softer, the better

Realistic Conditions (Acc.Ctrl. s.t. Pos., Speed constraints) → k^{opt} *exists!*

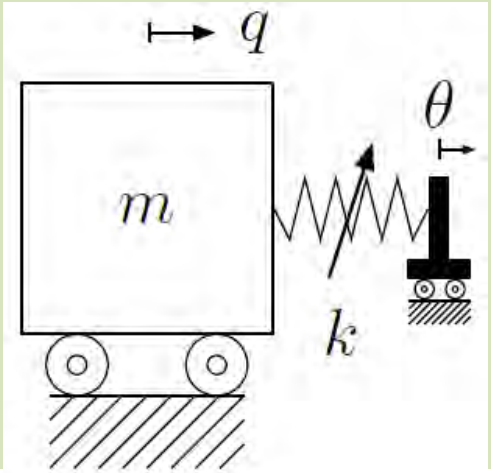
Experimental Results



the *qb* hammer



MaxSpeed Problem:
Can VSA improve further?



$$\begin{cases} x^T = [q \quad \dot{q}] \\ u^T = [\theta \quad k] \\ \dot{x} = \begin{bmatrix} x_2 \\ \frac{u_2}{m}(u_1 - x_1) \end{bmatrix} \end{cases}$$

State space definition

$$\begin{cases} x^T = [q \quad \dot{q}] \\ u^T = [\theta \quad k] \\ \dot{x} = \begin{bmatrix} x_2 \\ \frac{u_2}{m}(u_1 - x_1) \end{bmatrix} \end{cases}$$

Hamiltonian

$$H = \lambda_1 x_2 - \lambda_2 \frac{u_2}{m}(x_1 - u_1)$$

Co-State dynamics

$$\begin{cases} \dot{\lambda}^T = \begin{bmatrix} \frac{u_2}{m}\lambda_2 & -\lambda_1 \end{bmatrix} \\ \lambda(T)^T = [0 \quad 1] \end{cases}$$

Optimal control law

$$u_1^* = \begin{cases} u_{1,max} \text{ if } \lambda_2 > 0 \\ -u_{1,max} \text{ if } \lambda_2 < 0 \end{cases}$$

$$u_2^* = \begin{cases} u_{2,max} \text{ if } \lambda_2 (u_1 - x_1) > 0 \\ u_{2,min} \text{ if } \lambda_2 (u_1 - x_1) < 0 \end{cases}$$

Main Results (IROS 2011)

Theorem 1: The optimal control is characterized by the following properties:

1) the switching sequence is

$$\{S_2; S_{1,2}; S_2; \ldots; S_2; S_{1,2}\}, \tag{14}$$

2) the time between S_2 and $S_{1,2}$ is

$$t_{S_{1,2}} = \sqrt{m/k_{min}}\pi/2, \tag{15}$$

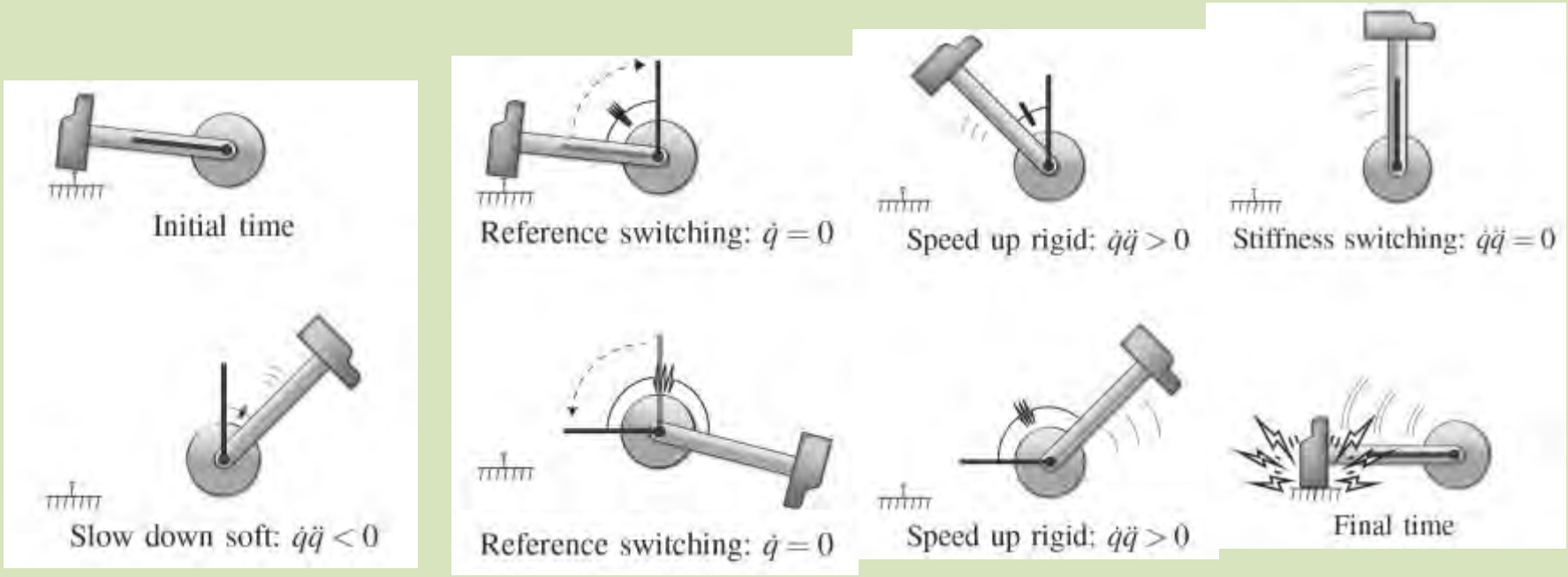
3) the time between $S_{1,2}$ and S_2, the time of the first period and the time of the last period are:

$$t_{S_2} = \sqrt{m/k_{max}}\pi/2, \tag{16}$$

Theorem 2: The stiffness optimal control is:

$$u_2 = \begin{cases} u_{2,\max} & \text{if } \dot{q}\ddot{q} > 0 \\ u_{2,\min} & \text{if } \dot{q}\ddot{q} < 0 \end{cases}$$

VSA Optimal control

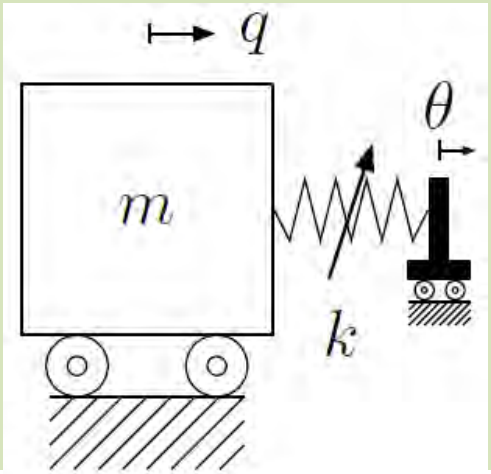


Theorem 2: The stiffness optimal control is:

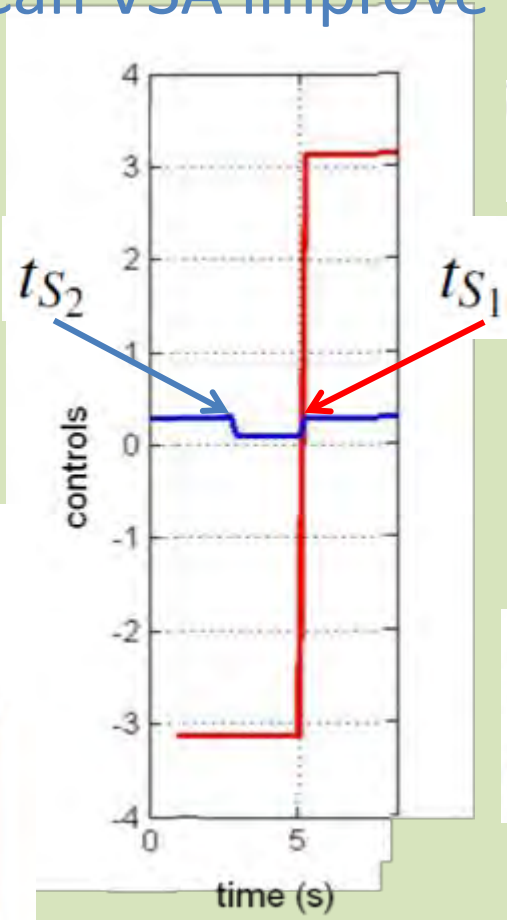
$$u_2 = \begin{cases} u_{2,\max} & \text{if } \dot{q}\ddot{q} > 0 \\ u_{2,\min} & \text{if } \dot{q}\ddot{q} < 0 \end{cases}$$

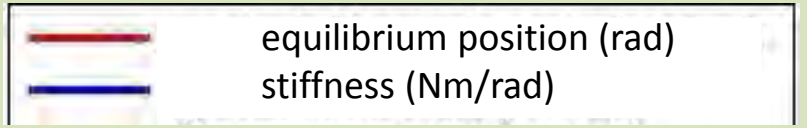
Stiff speed-up, soft slow-down

Single Stroke MaxSpeed Problem: Can VSA improve further?



$$\begin{cases} x^T = [q \quad \dot{q}] \\ u^T = [\theta \quad k] \\ \dot{x} = \begin{bmatrix} x_2 \\ \frac{u_2}{m}(u_1 - x_1) \end{bmatrix} \end{cases}$$





$$t_{S_1} = \sqrt{m/k_{min}}\,\pi/2$$

$$t_{S_2} = \sqrt{m/k_{max}}\,\pi/2$$

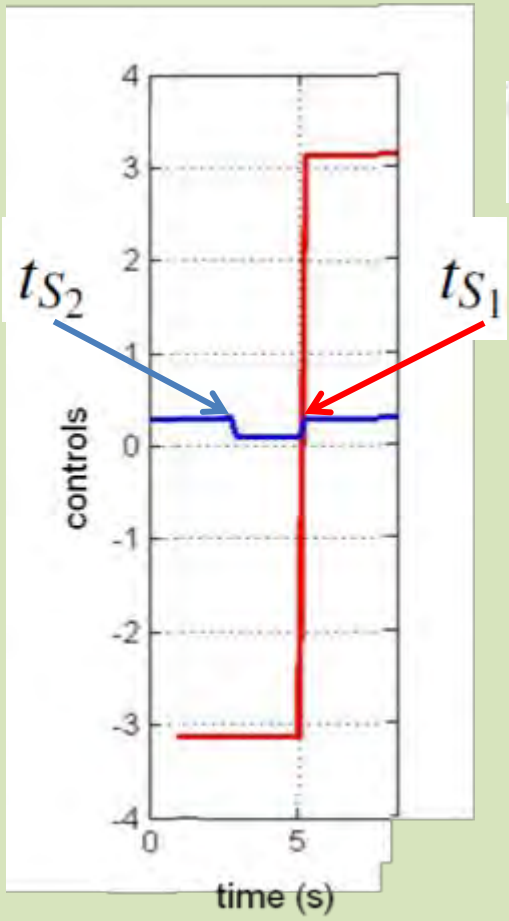
t_{S_2} link acceleration changes sign

t_{S_1}: link velocity changes sign

$$\frac{v_{VSA}}{v_{SEA}} = \frac{1 + (k_{max}/k_{min})^{1/2}}{2}$$

Yes, up to 30% in our setup !

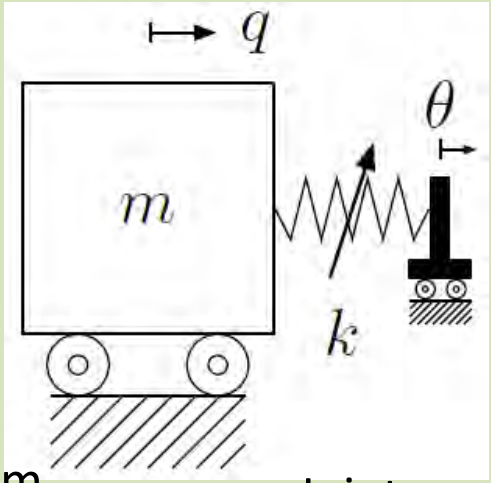
Note: assume SEA with optimal K



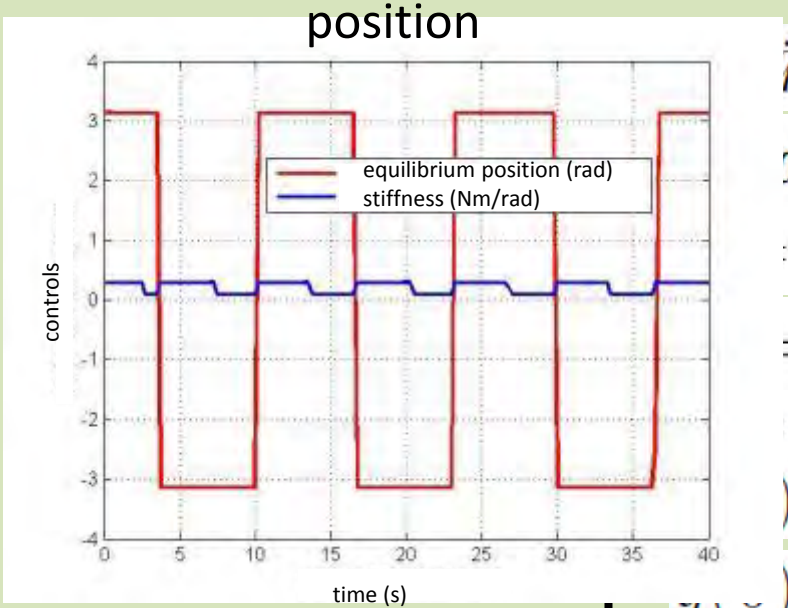
equilibrium position (rad)
stiffness (Nm/rad)

Initial time

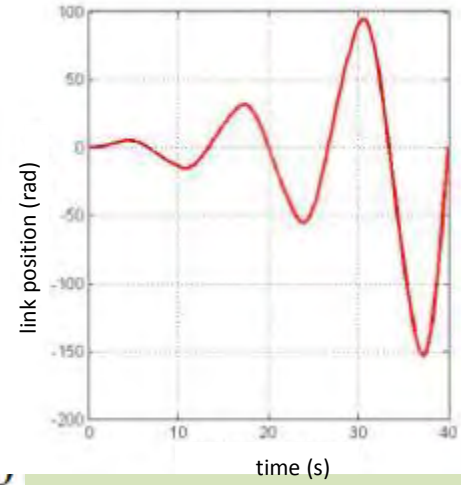
MultiStroke MaxSpeed Problem



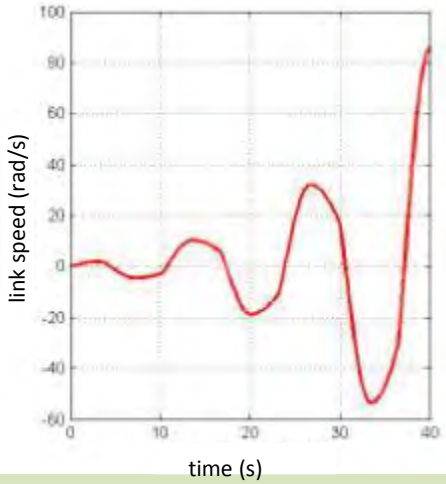
Optimal stiffness and equilibrium position



Joint position Vs time

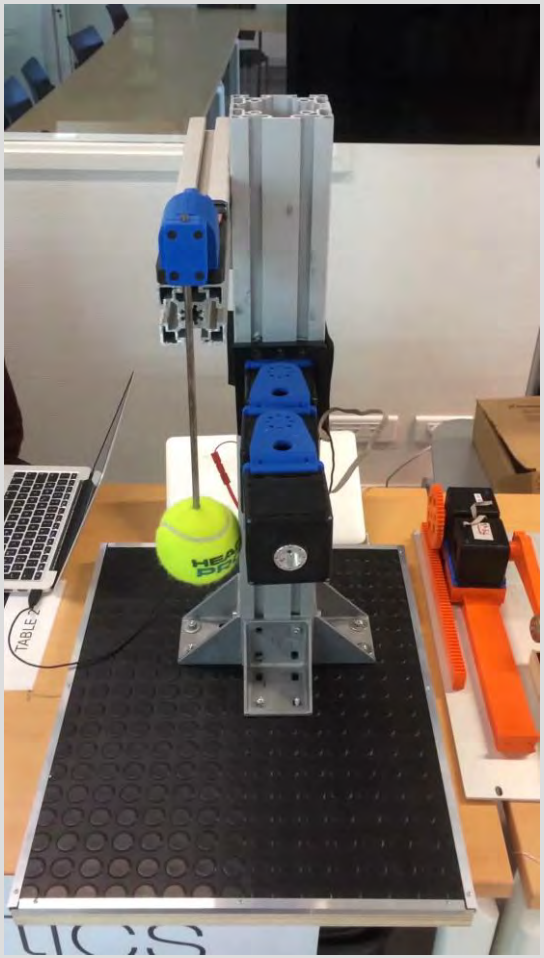


Joint speed Vs time



2DoF hitting

Stiff



VSA

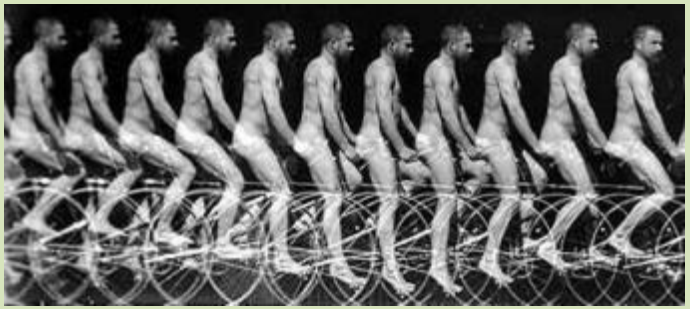
Summing up

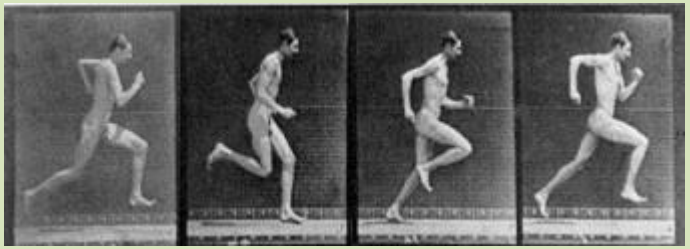
- Optimal Control gives insight in physical properties of embodied behaviors, by factorizing control and physical performance
- More than open-loop optimal control, we believe lessons learned are important
- For safe fast motion, STIFF should go with SLOW, and SOFT with FAST
- For impact, STIFF goes with SPEED-UP, and SOFT with SLOW-DOWN
- …

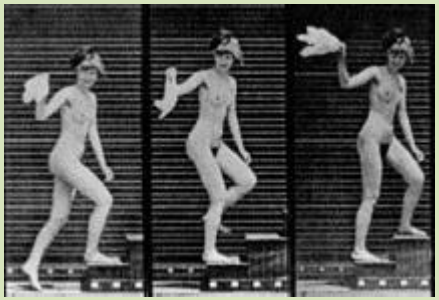
Cyclic tasks

Humans perform efficently tasks that:

- Are cyclic
- Are complex
- Involve interaction with unknown, complex dynamical systems

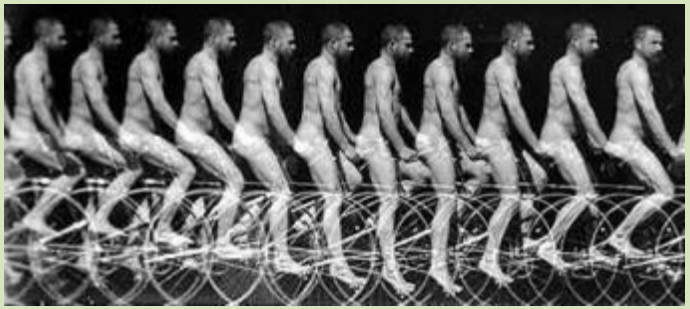


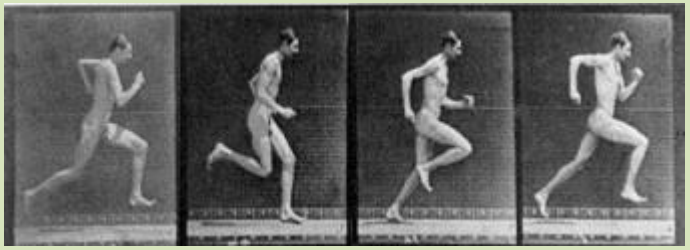


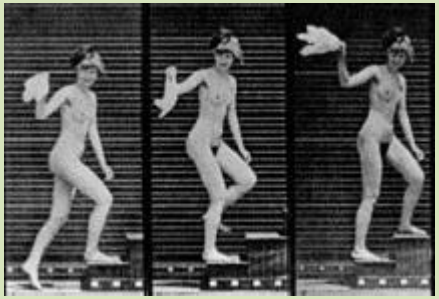


Cyclic tasks

How to accomplish these tasks with robots?
how to induce stable limit cycles in complex robots exploiting their intrinsic dynamics?

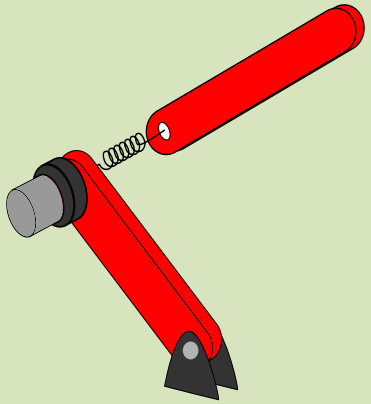




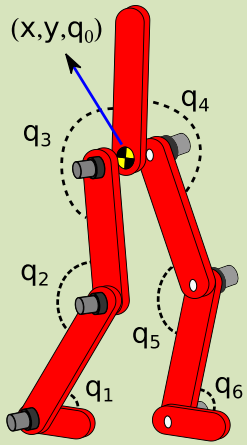


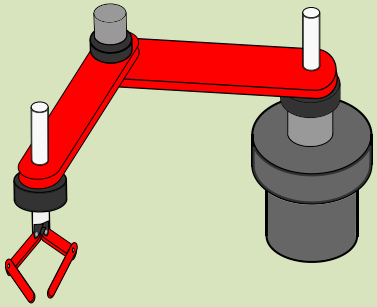
Cyclic Tasks

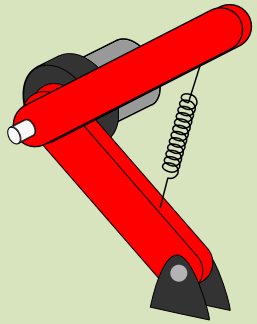
- What role does soft actuation play in the reduction of energy cost for mechanical systems that perform cyclic motions?



Joint with SEA

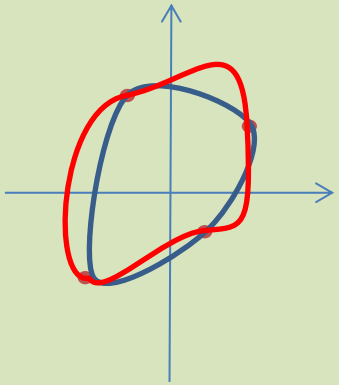






Joint with PEA

Objective: Determine optimal actuation parameters



Find the

- Cyclic trajectory
- Stiffness (K) and
- Spring pre-load (q_e)

which minimize a cost functional (J_i) given a number of viapoints in state space, where

- J_1 : Squared power
- J_2: Squared torque

Problem Formulation

$$\min_{\tau(t),\beta,\, q} J_i$$

$$J_1 = \sum_{j=1}^{n} \int_0^T (\tau_j(t)\dot{\theta}_j(t))^2 dt$$

$$J_2 = \sum_{j=1}^{n} \int_0^T \tau_j^2(t) dt$$

$$s.t. \begin{cases} f(\ddot{q}, \dot{q}, q, t) = K(q_e - q) + \tau \\ q(t) = q(t+T) \\ \xi_1(q, \dot{q}, \ddot{q}) \leq 0 \\ \xi_2(q, \dot{q}, \ddot{q}) = 0 \\ \beta_m \leq \beta \leq \beta_M \end{cases}$$

Cyclic motion

Physical constraints

$$f_u(\ddot{x}, \dot{x}, x, \ddot{q}, \dot{q}, q, t) = 0$$
$$f_a(\ddot{x}, \dot{x}, x, \ddot{q}, \dot{q}, q, t) = -K(q - \theta)$$
$$J_m\ddot{\theta} = K(q - \theta) + \tau$$

β is a vector containing joint stiffness K and pre-load q_e $\beta_M = [K_M; q_e; \beta_M]$ and $\beta_m = [K_m; q_e; \beta_m]$,

Actuation Parameter Optimization

- Hypothesis: $K = \mathrm{diag}[K_1, \ldots, K_n]$
- We show that the problem can be decoupled
  - Optimize actuation parameters
    - SEA: Stiffness (K)
    - PEA: Stiffness and Pre-load (K, q_e)
  - Then, optimize trajectory:

$$q(t) = q_d(t),\ \dot{q}(t) = \dot{q}_d(t)\ ,\ \ddot{q}(t) = \ddot{q}_d(t)$$

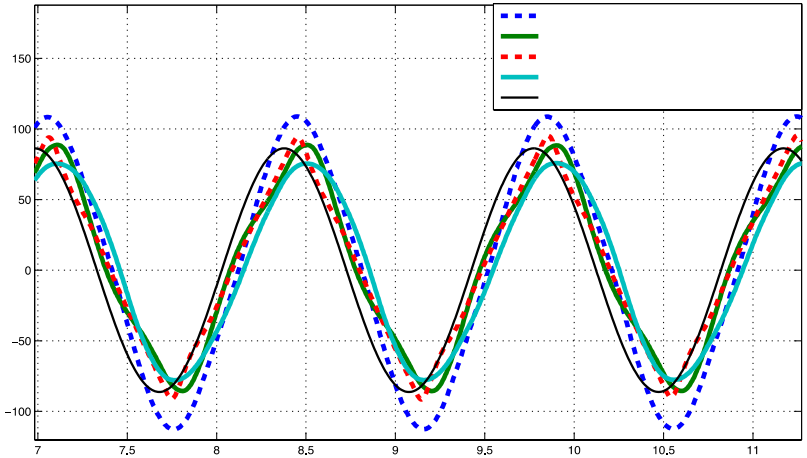
Actuation parameters: Analytical Optimal solution

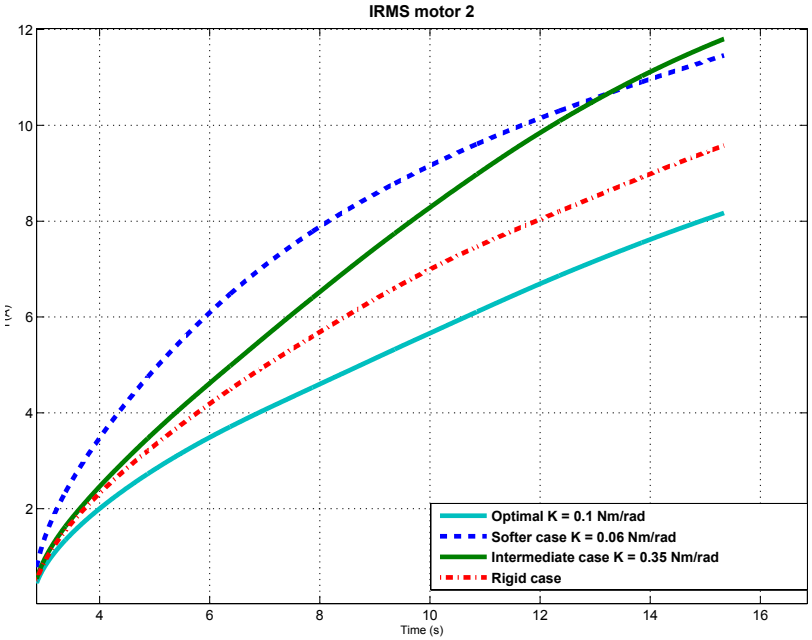
	J_1	J_2
SEA	A Solution of $4\,A_{S,j} + 3K_j B_{S,j} + 2C_{S,j}K_j^2 + D_{S,j}K_j^3 = 0$	$\hat{K}_j = -2\frac{F_{S,j}}{G_{S,j}}$
PEA	$\hat{K}_j = \frac{B_{P,j}E_{P,j} - 2C_{P,j}D_{P,j}}{4D_{P,j}F_{P,j} - E_{P,j}^2}$ $\hat{q}_{e,j} = \frac{C_{P,j}E_{P,j} - 2B_{P,j}F_{P,j}}{2C_{P,j}D_{P,j} - B_{P,j}E_{P,j}}$	$\hat{K}_j = \frac{\hat{q}_{e,j}H_{P,j} - I_{P,j}}{2(\hat{q}_{e,j}^2 T + L_{P,j} - \hat{q}_{e,j}M_{P,j})}$ $\hat{q}_{e,j} = \frac{H_{P,j} + \hat{K}_j M_{P,j}}{2\hat{K}_j T}$

A, B, C, D, F, G, E, H, I, M, L are integrals that depend on the trajectories and on the mechanical model

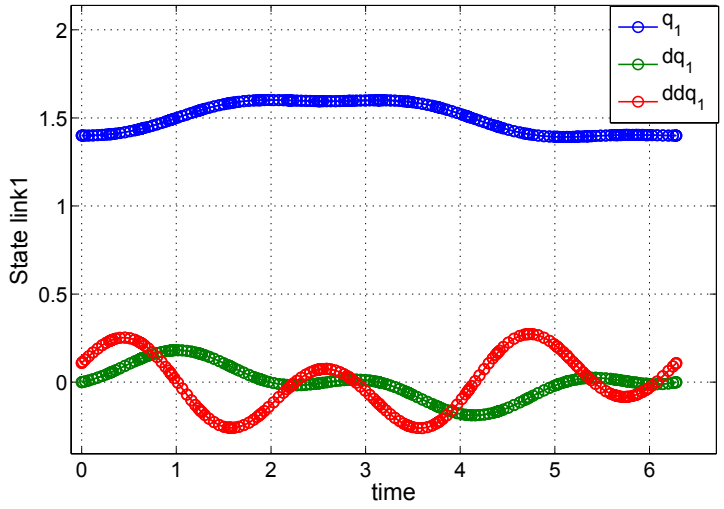
Experiments

	$\hat{K}$	$K < \hat{K}$	$K > \hat{K}$	Stiff
$J_{1_{TOTAL}}$	0.1542	0.7964	0.3154	0.5672
$I_{RMS_{Total}}$ (A)	1.37	2.95	1.79	1.68
K_1 [Nm/rad]	0.2	0.08	0.57	Stiff
K_2 [Nm/rad]	0.1	0.06	0.35	Stiff





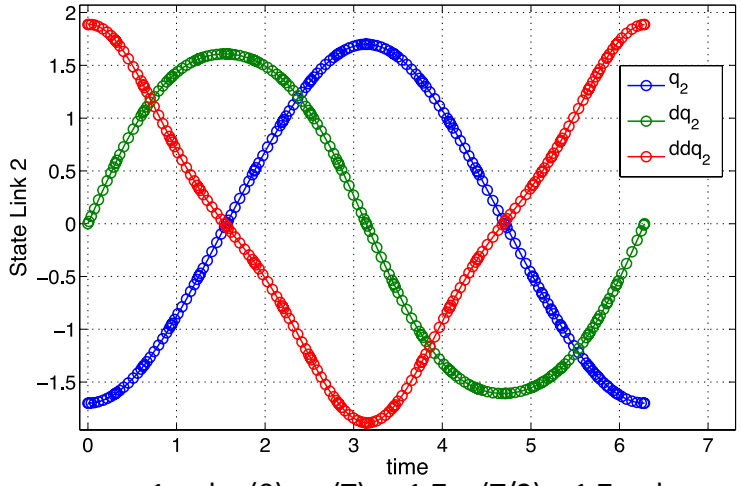
Trajectory optimization



ω = 1 rad; q(0) = q(T) = 1.3; q(T/2) = 1.6 rad

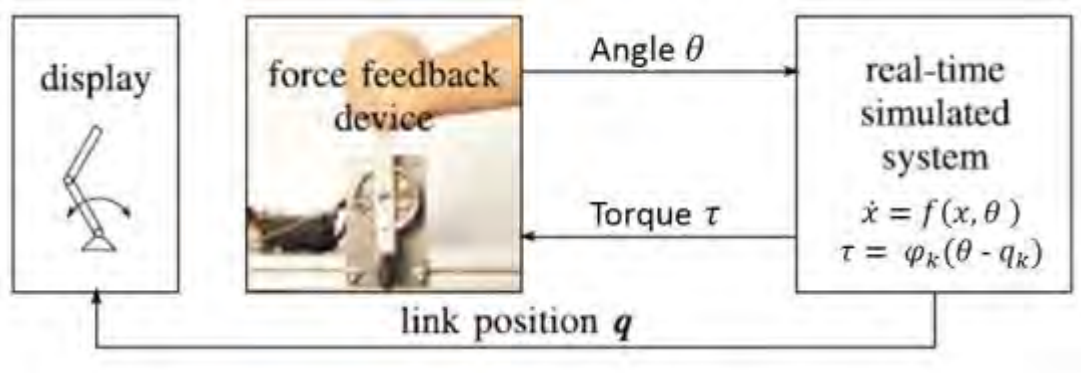
- Replace the analytical solution of stiffness in the problem formulation
- Solve using nonlinear programming methods
- Optimize the trajectory (with GPOPS II)

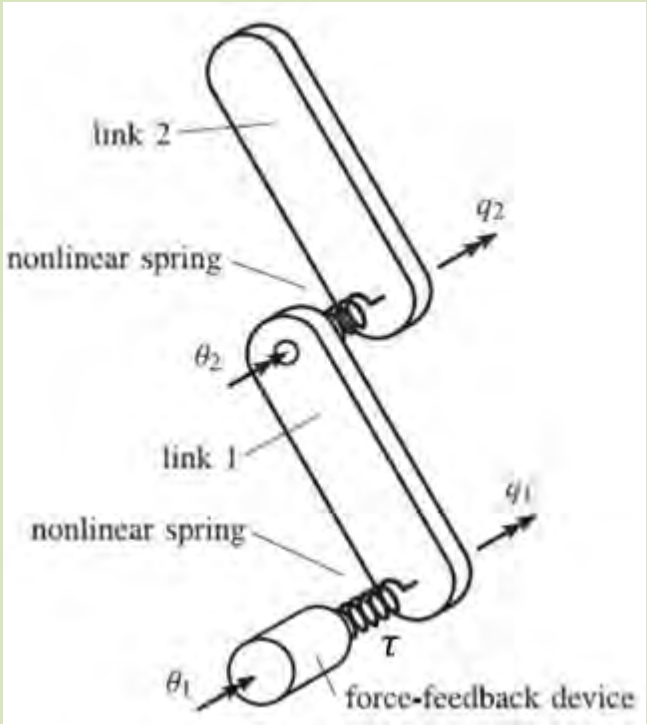
K_1 = 0.001 Nm/rad
K_2 = 0.002 Nm/rad
J = 3.5 x 10^{-4}



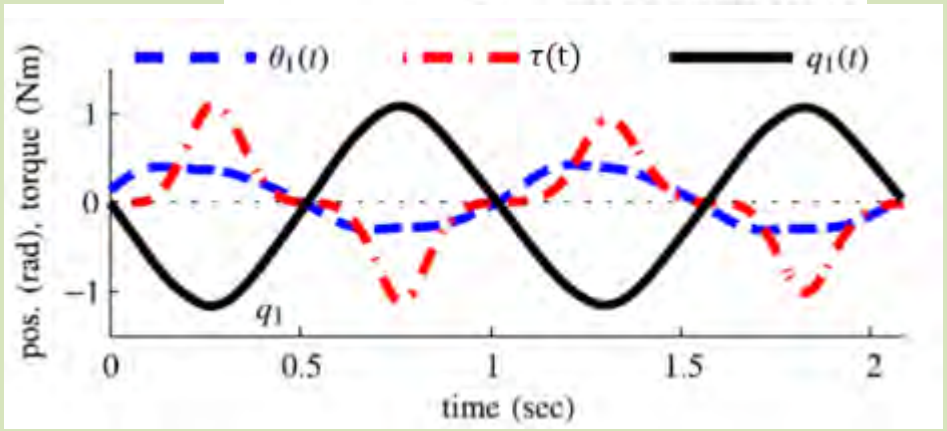
ω = 1 rad; q(0) = q(T) = -1.7; q(T/2) = 1.7 rad

How do humans excite limit cycles?





Human behaviour in exciting natural cycles has been explored via a force feedback device.

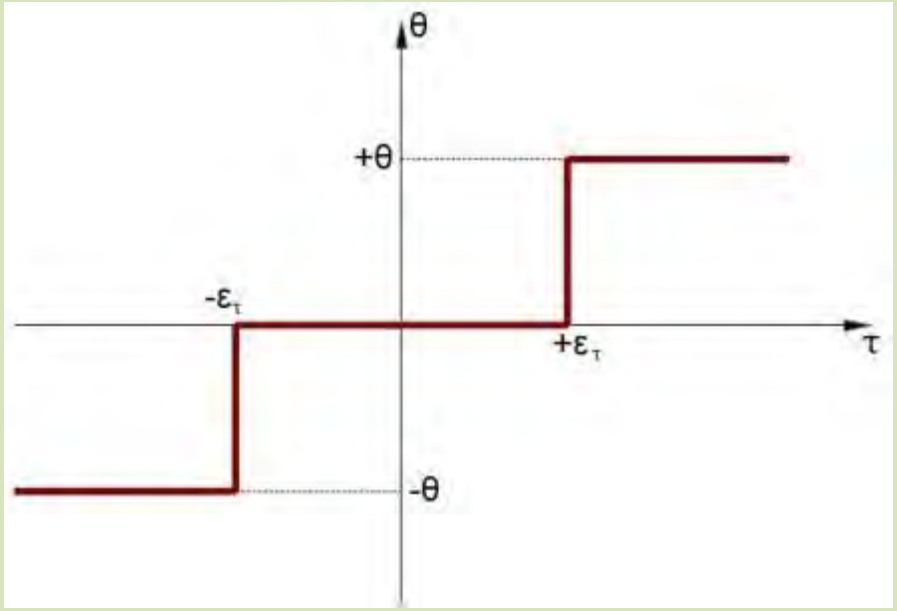


Dominic Lakatos et al. - Nonlinear Oscillations for Cyclic Movements in Human and Robotic Arms, 2014

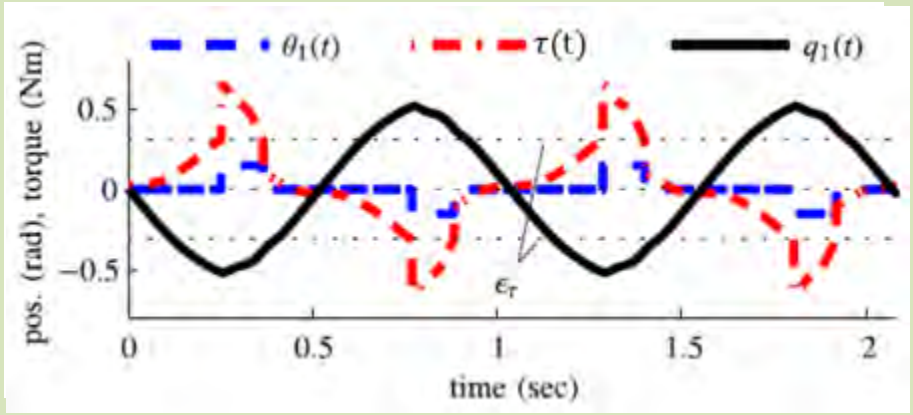
From human measurements to a model-free bang-bang control law

Thresholded Bang-Bang law approximating human behavior:

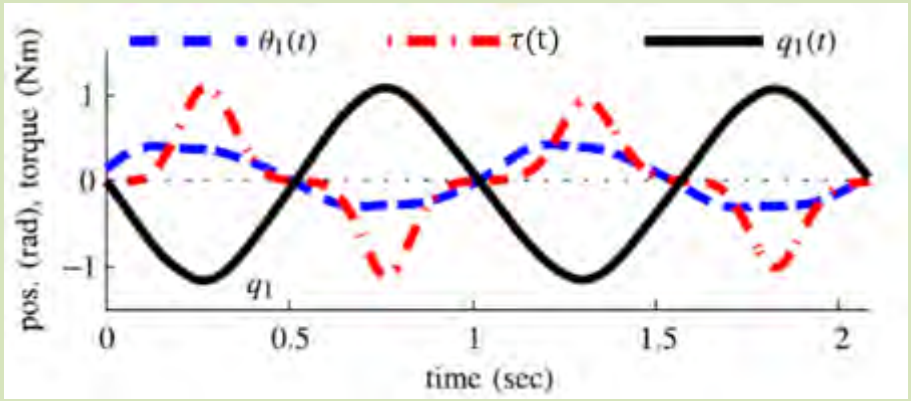
$$\theta = \begin{cases} \hat{\theta}\ \mathrm{sign}(\tau), & |\tau| > \epsilon_\tau \\ 0, & \text{otherwise} \end{cases}$$



Using control law



Natural motion



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Thresholded Bang-Bang law approximating human behavior:

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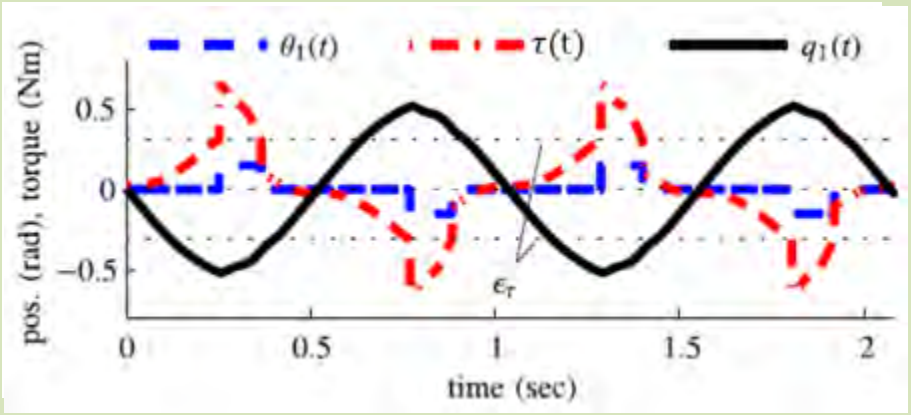
This control law induces cyclic movements in non-linear systems

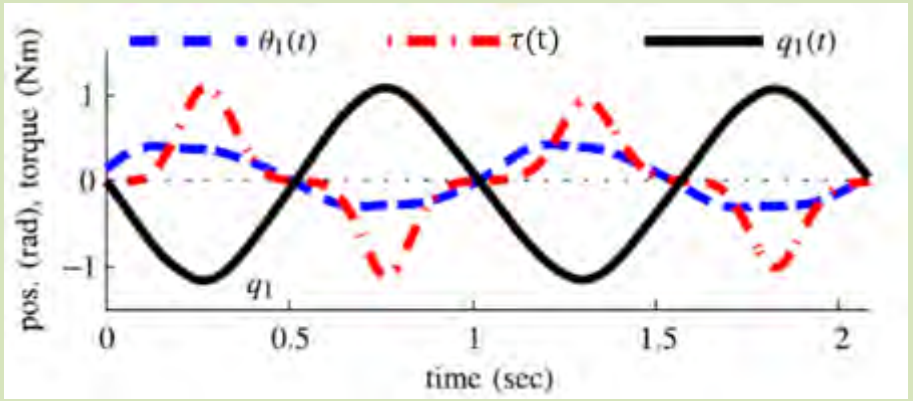
Cyclic motion features:

- Stable
- Natural: they depend on intrinsic physical characteristics
- Robust: control law is model free

Using control law



Natural motion

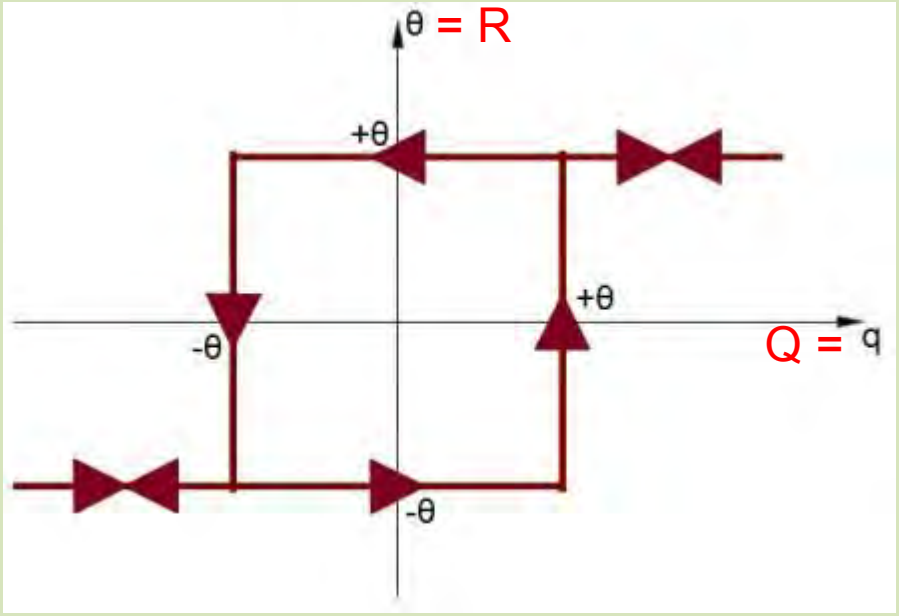


Dominic Lakatos et al. - Nonlinear Oscillations for Cyclic Movements in Human and Robotic Arms, 2014

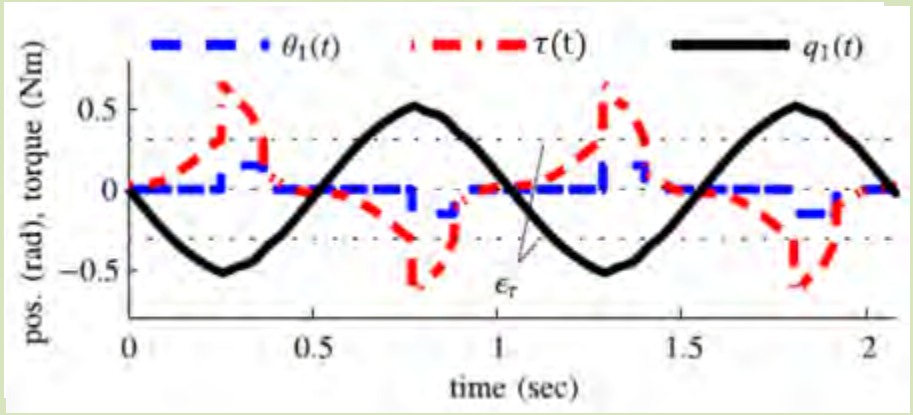
From human measurements to a model-free bang-bang control law

Replacing τ with $\varphi(\theta - q)$ (monotone):

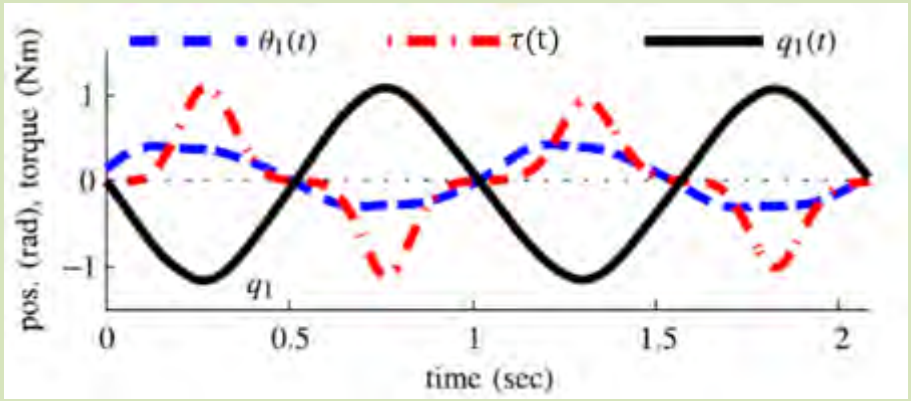
$$\theta = \begin{cases} \hat{\theta}\ \mathrm{sign}(\theta - q), & |\theta - q| > \epsilon \\ 0, & \text{otherwise} \end{cases}$$



Using control law



Natural motion



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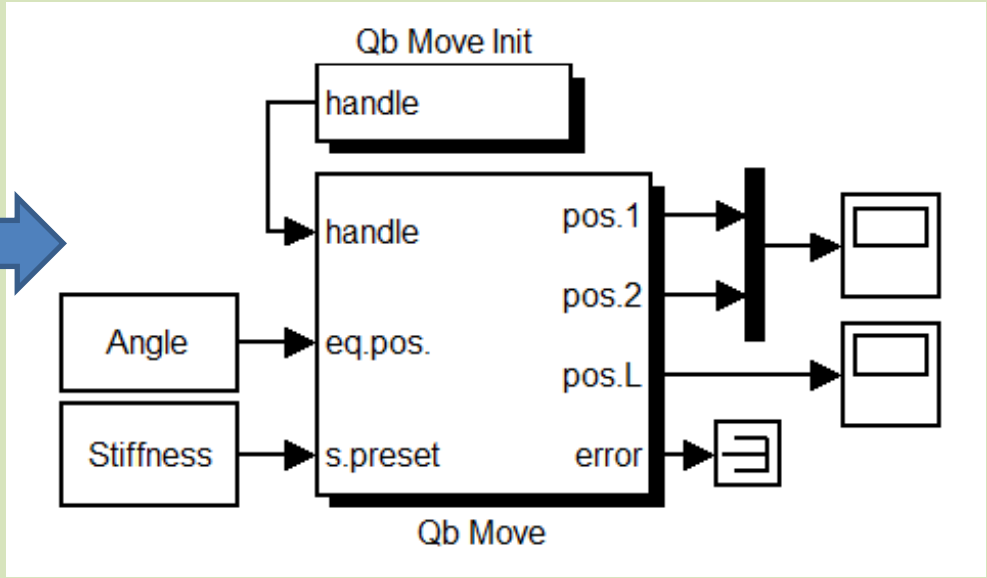
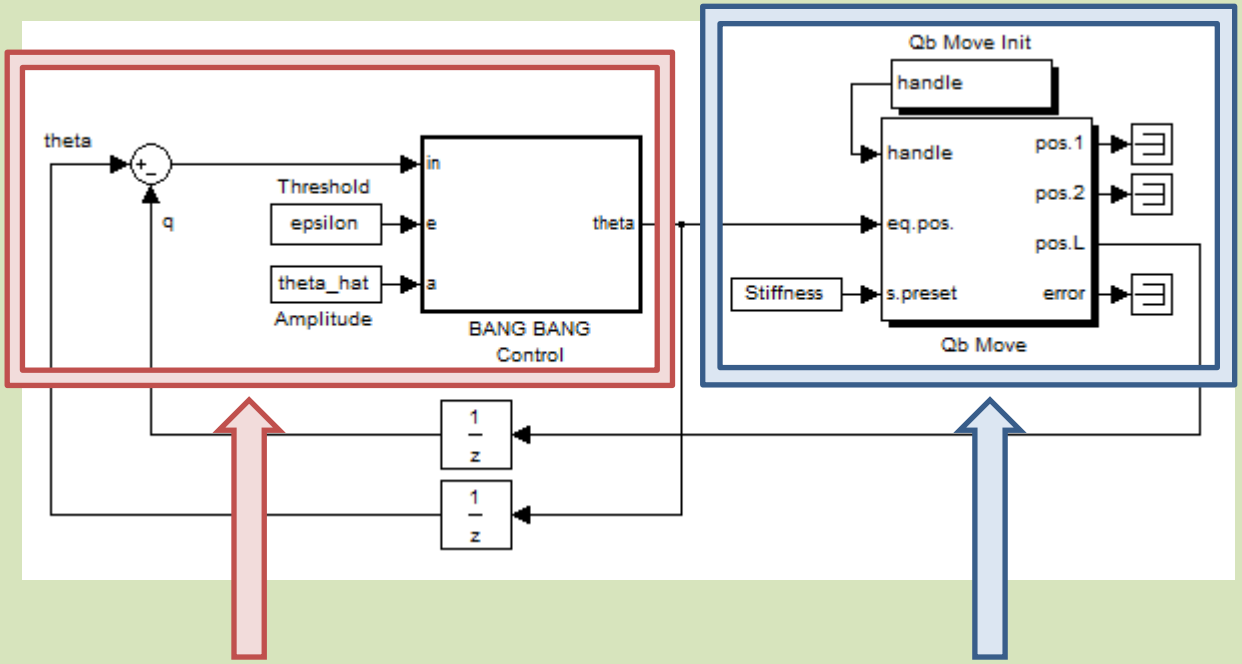
From theory to experiment



The VSA cubes are provided of a simple interface in simulink that permits to command position and stiffness and measure actual positions.

How to test the control law



Bang Bang Control Law

```
function out = control(in,e,a)

    out = 0;
    if abs(in)>e
        out = a*sign(in);
    end

end
```

Cube Interface

VSA implementation

Using the described system is possible to test the control law behaviour in different sytuations:

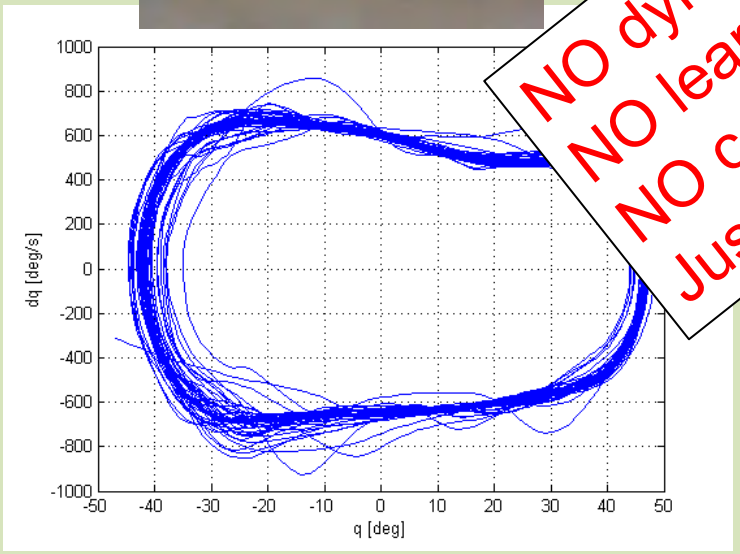
- With or without inpact
- With dynamically varying dynamics
- As $\hat{\theta}$ varies
- As stiffness varies

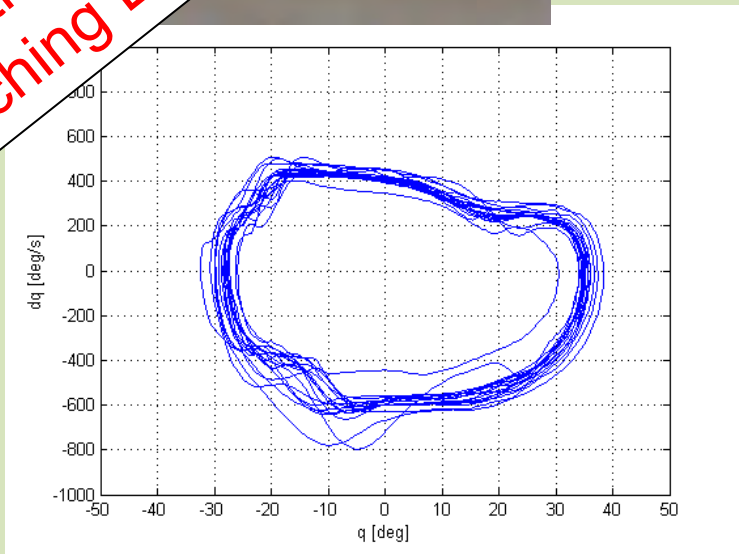
Testing robustness of behavior

Without impacts

With impacts

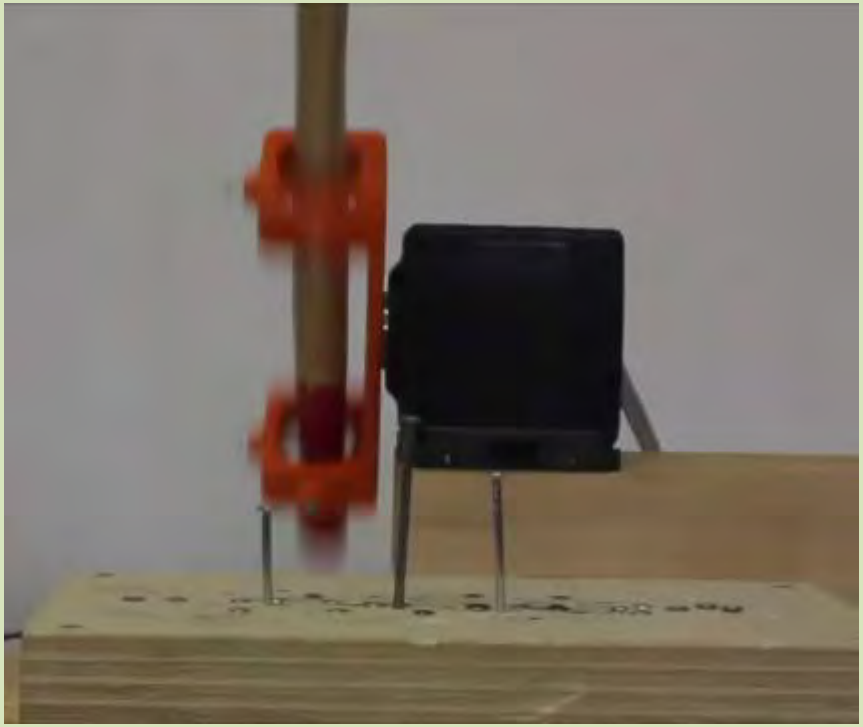
NO dynamical models
NO learning
NO computations
Just a switching EP law

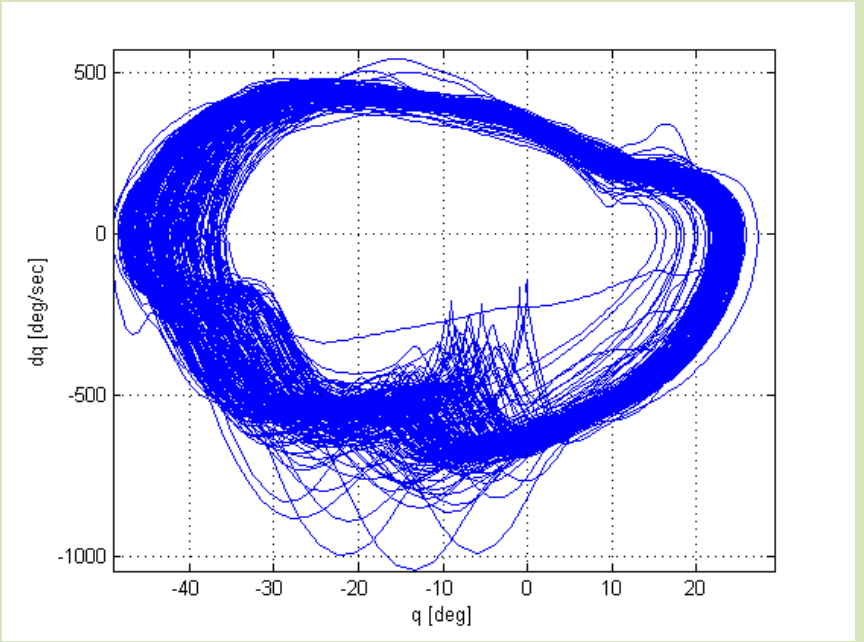




The control mantains the system in oscillation also under strong variations, such as an impact, adapting the cycle.

Testing robustness to impacts

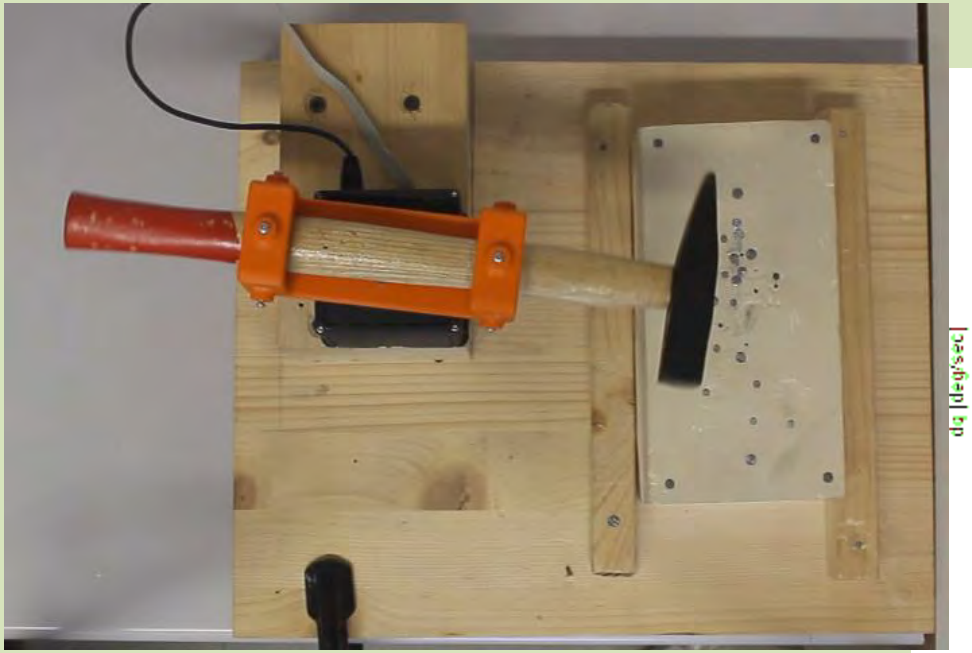


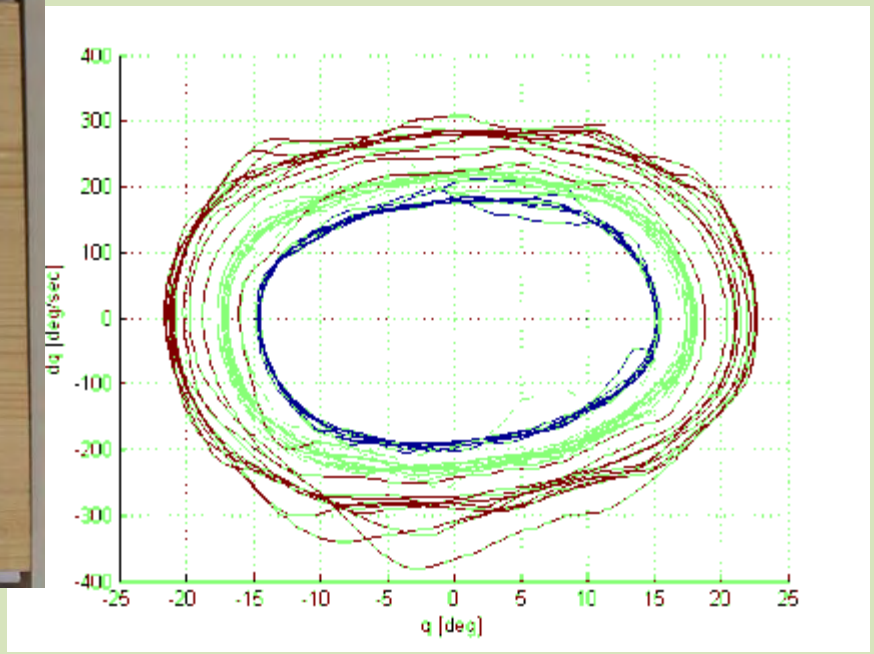


For
$\hat{\theta} = 20°$
$\varepsilon = 4°$
Preset = 10°

Hammering nails imply a dynamics that change during the task. Bang bang control continues to mantain the system on stable cycles even as the dynamics change

Changing Amplitude

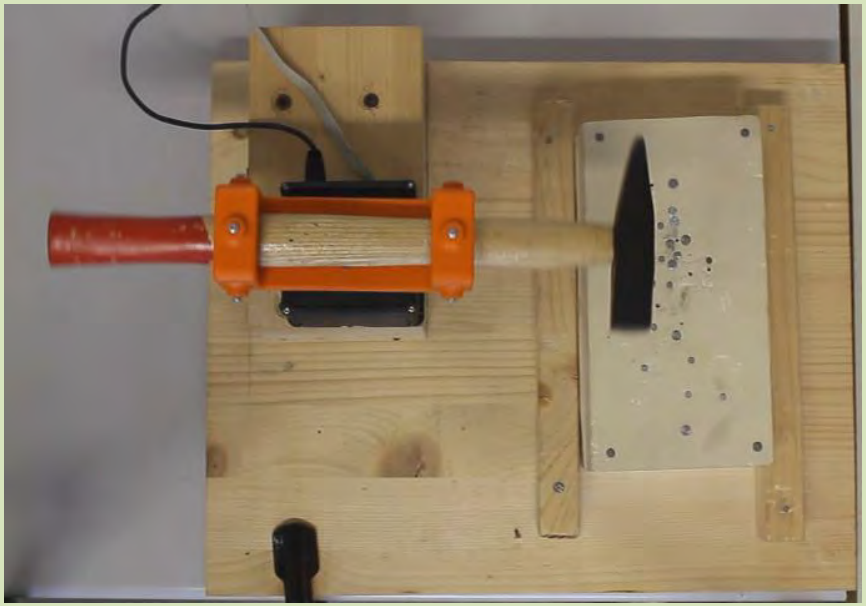


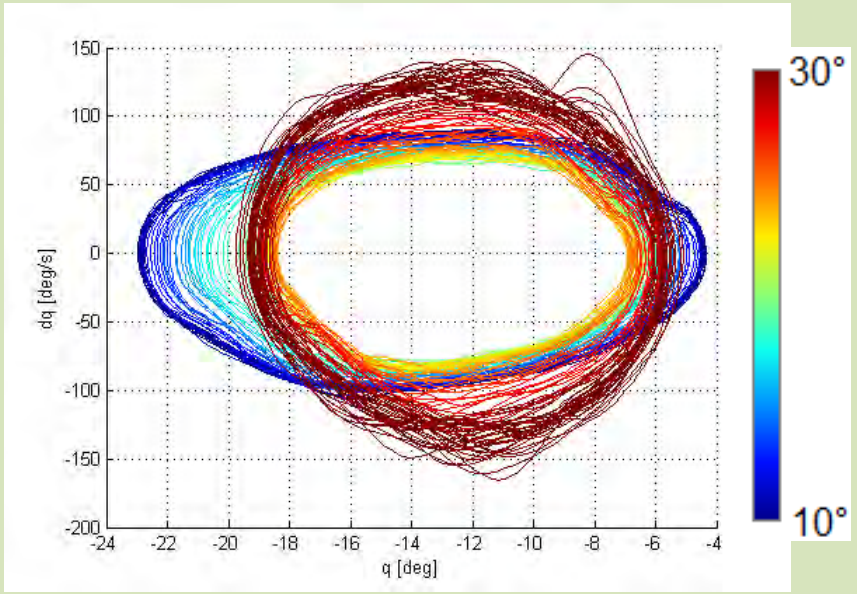


For
$\hat{\theta}\epsilon\{6,7,8\}°$
$\varepsilon = 4°$
Preset = 10°

The cycle 'size' increases with $\hat{\theta}$.

Changing Stiffness





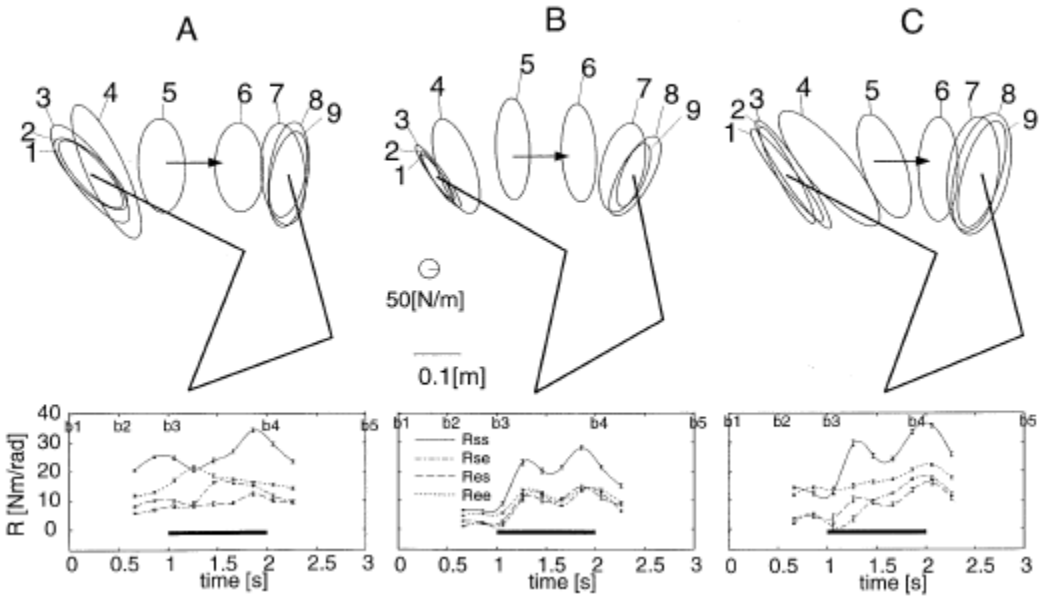
For
$\hat{\theta} = 6°$
$\varepsilon = 4°$
Preset ϵ [10,30]°

If the stiffness preset increases:

- first the maximum displacement decreases
- after the maximum speed increases

How do humans use variable impedance?

- Human subject studies
  - Arm stiffness is adapted to tasks and force fields [Kawato, Hogan, Burdet, Gomi, Franklin, Shadmer, …]
  - Results look at impedance in one configuration after several learning trials
  - How do humans vary their stiffness while throwing, drumming, walking?



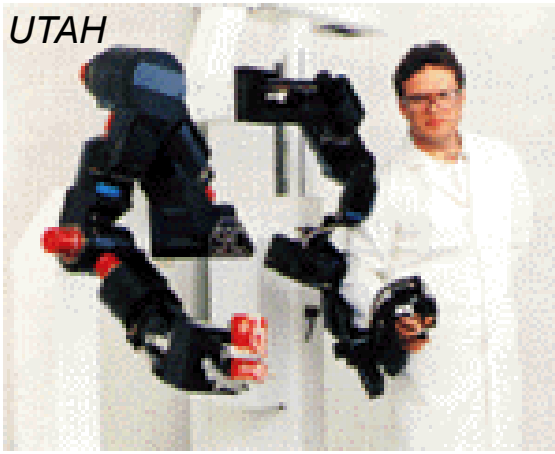
How to Plan Variable Impedance

- … let the human do it
  - Not general
  - Makes sense in applications where you need to replicate some skills at a distance

→ Teleoperation of Impedance

Teleoperation

- Teleoperation consists of measuring motor control parameters in human, and replicating in robots
- Remote position control is rather easy – used to be done with exoskeletons as “master” and robot arms as “slave”
- Position control is not enough because of interaction with unknown remote environments



Teleimpedance

- Remote control with force feedback
  - needs force sensors on the robot
  - may have stability problems because of transmission delays in the control loop
- Can we instead do remote impedance control?
  - use human arm position and impedance as references for robot
  - use local controllers (no delays, very stable) to make the robot track those plans

Teleimpedance

- The operator moves the hand and adapts his/her arm impedance to solve the task based on visual information from the scene

Three questions:

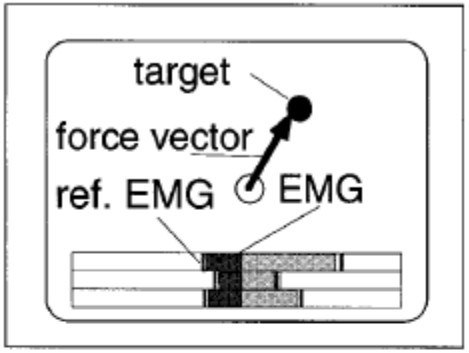
- How do we sense position and impedance on the master?
- How do we control them on the slave?
- Is this useful to solve the task?

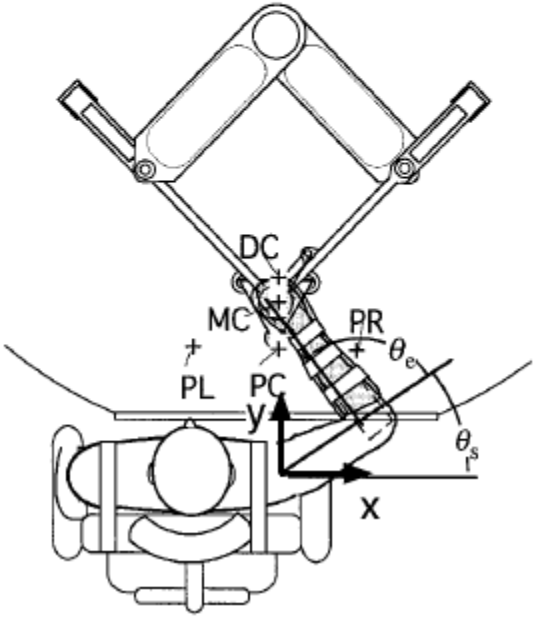
EMG

- Electromyographic signals correspond to muscle activation, hence are strongly correlated with muscle force
- Very easy to implant, not invasive, relatively cheap (compared to force-reflecting exoskeletons)
- The command signal of choice for prostheses
- Signals are noisy and not too stable – good processing needed

EMG and Stiffness

Previous work on joint torque and stiffness estimation from EMG signals demonstrated feasibility, and indicated methods





"Estimation of MultiJoint Limb Stiffness from EMG Duirng Reaching Movements",
D.W. Franklin,F. Leung, M. Kawato, T. E. Milner 2003

"Multijoint Muscle Regulation Mechanisms Examined by Measured Human Arm Stiffness and EMG Signals"
R. Osu and H. Gomi, J. Neurophysiol., 2005

EMG and Stiffness

- Muscle tensions correspond to the rectified EMGs of the arm muscles (Basnajian and De Luca 1984)
- The relationship between EMGs of agonistic and antagonistic muscles to the generated torques and stiffness in joints can be assumed linear in isometric conditions (Osu, Gomi Kawato *et al.* 2001). Neglecting cross-joint stiffness w.r.t. homologous joint stiffness (Gomi and Osu 1998) →

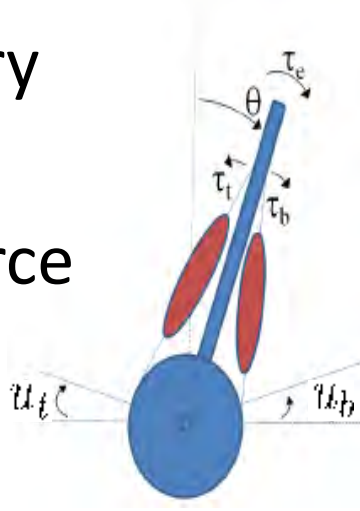
$$\tau = T(q)f, \quad \tau, q \in R^3, f \in R^6$$

$$\sigma = S(q)f, \quad \sigma = \left(\frac{\partial \tau_i}{\partial q_i} \right) \in R^3$$

EMG and Position Control

- EMG related to muscle force – not to displacement - indeed, a person can relax muscles at arbitrary positions (Wachholder)
- How to control slave position from master force information?
  - Control the robot force (with dynamic scaling)
  - Integrate the human arm dynamics to find position
  - Use gravity compensating forces
  - Forget it

    There exist very cheap and accurate endpoint position sensors



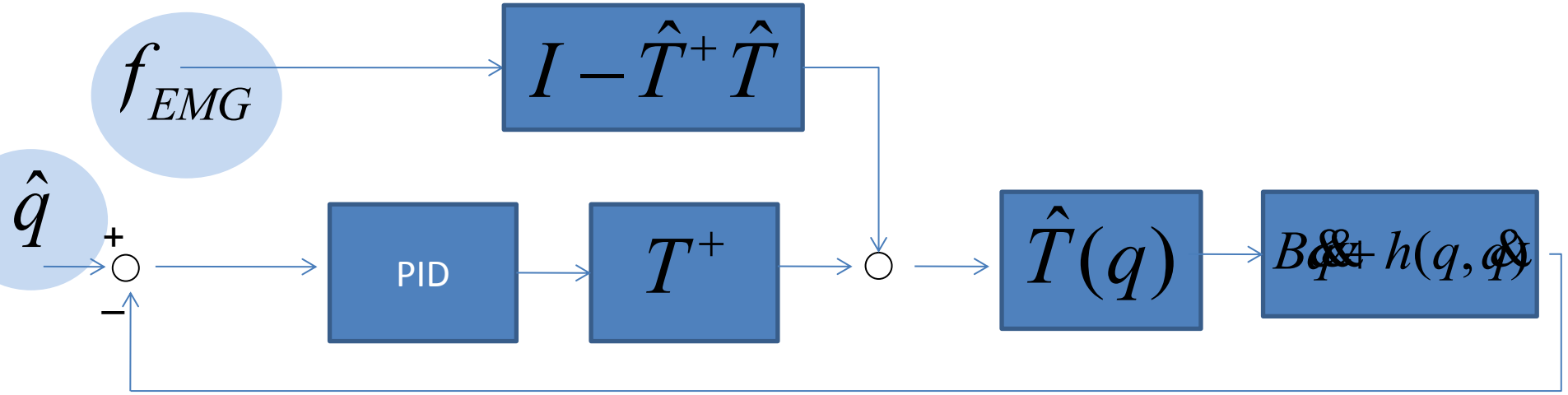
Decoupling Position and Impedance Remote Control

- Our approach:
  - use absolute Cartesian position reference from reliable sensors, and
  - use EMG for stiffness reference generation
- Cascaded control scheme:
  - control position with higher priority
  - control impedance in the nullspace of position control inputs.

Decoupled Position and Impedance Remote Control

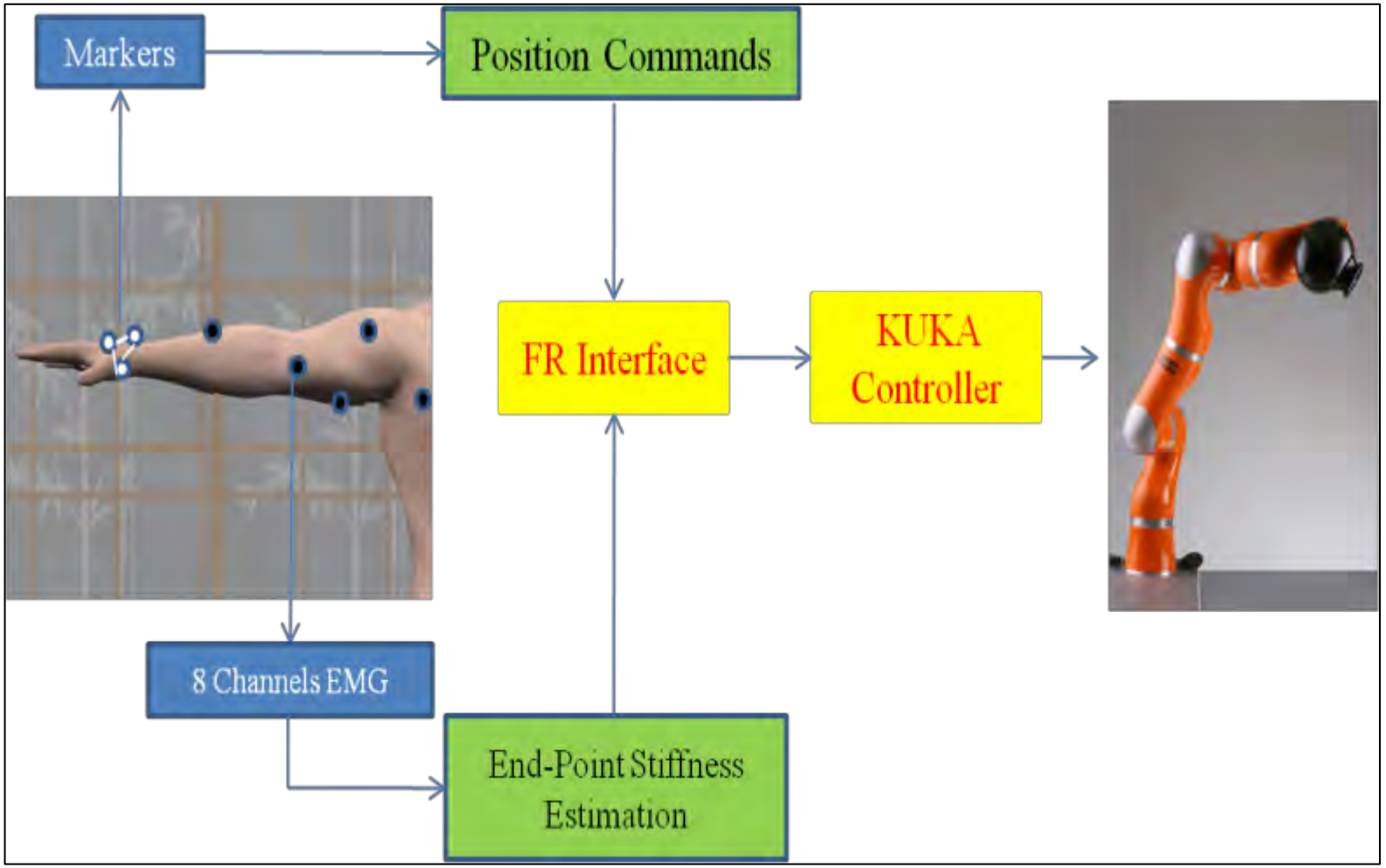
- Control is decoupled so that the error-prone EMG impedance measurements will not spoil the accurate position tracking control
- True only as far as there are no external forces: if there are, the control of stiffness will have implications on the position tracking error (by definition)

Decoupled Position/Stiffness Control of Robot Arms

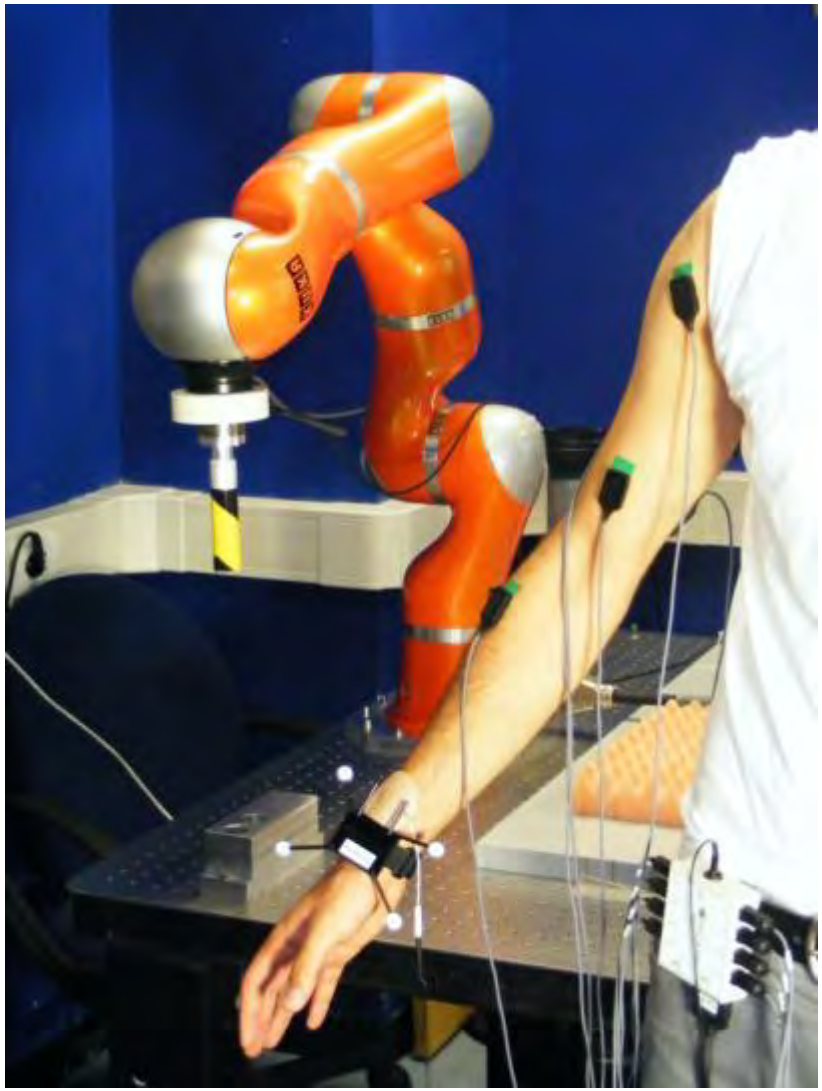


$$T^{+} = T^{T}(T\,T^{T})^{-1}$$

Teleimpedance Control Scheme

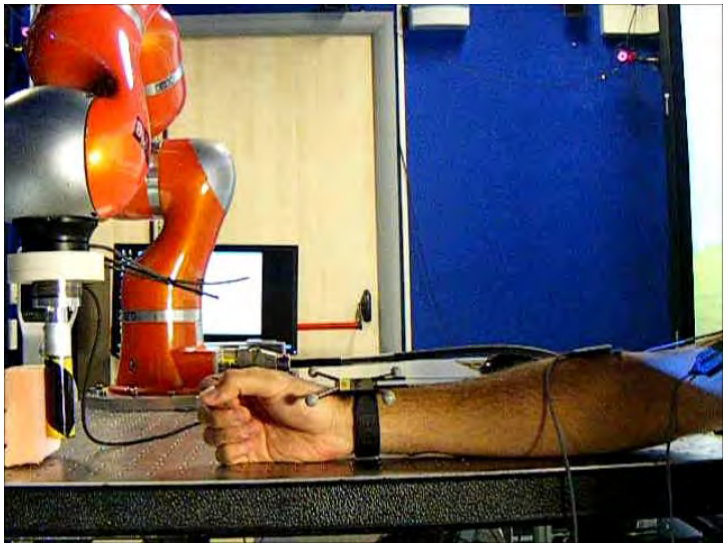


Experimental Setup

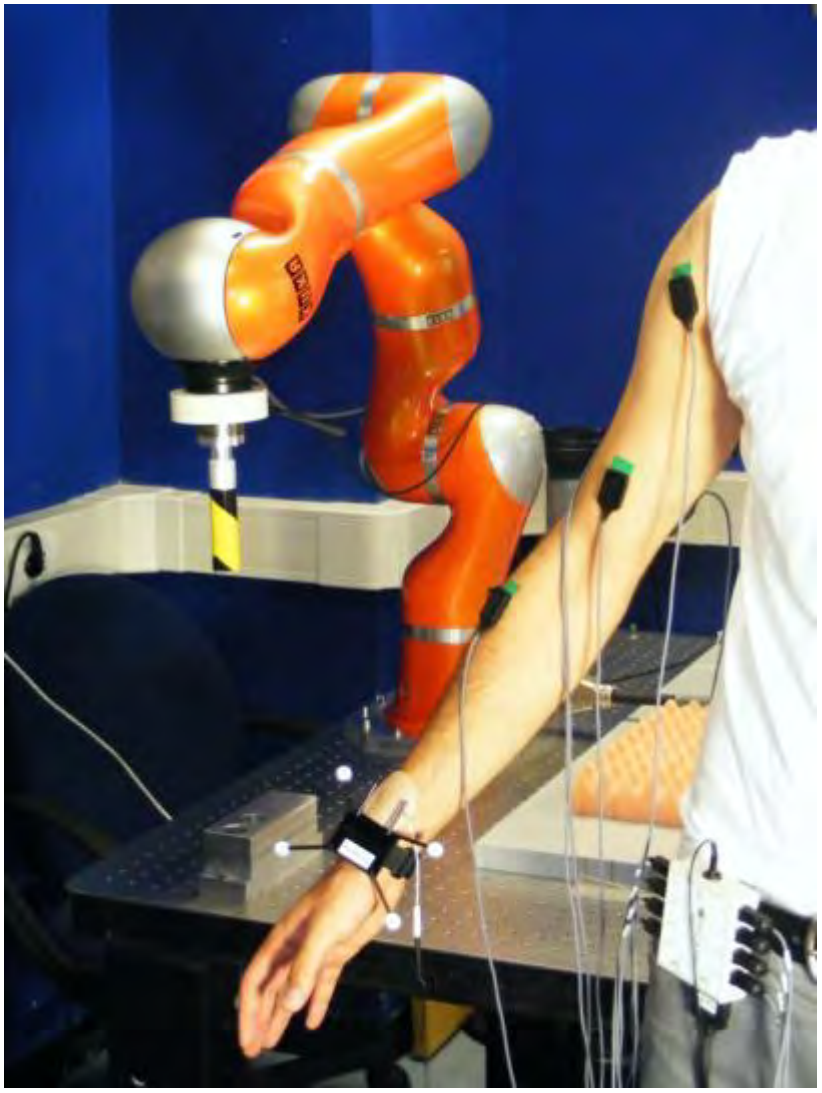


- Kuka LW Arm
- FR interface (Schreiber *et al* 2011)
- Advanced end-point Impedance Controller

- 3D Optitrack motion capture system



Experiments



Disturbances

Interaction with soft, sticky surface

Position and Stiffness Control

Sponge

Assembly Task

Position Control, Constant Low Stiffness

Position Control, Constant High Stiffness

Teleimpedance Control (1)

Teleimpedance Control (2)

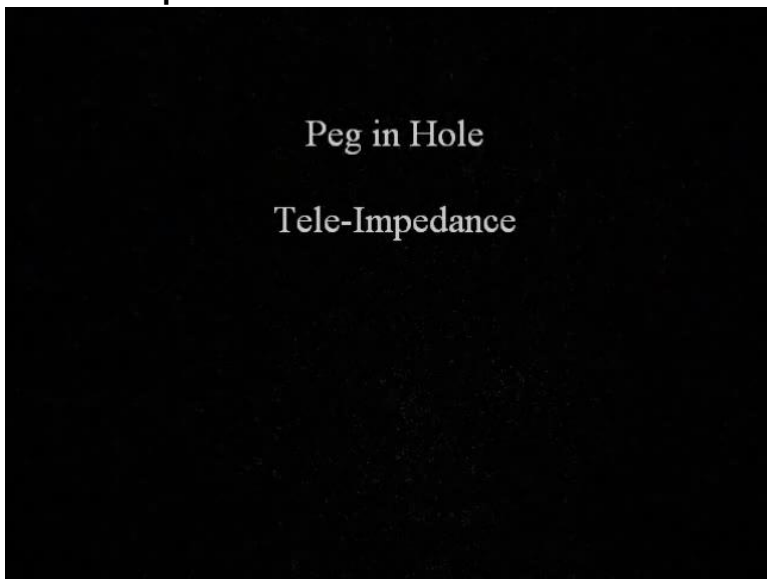
Me

Experiments: Peg in Hole

High impedance

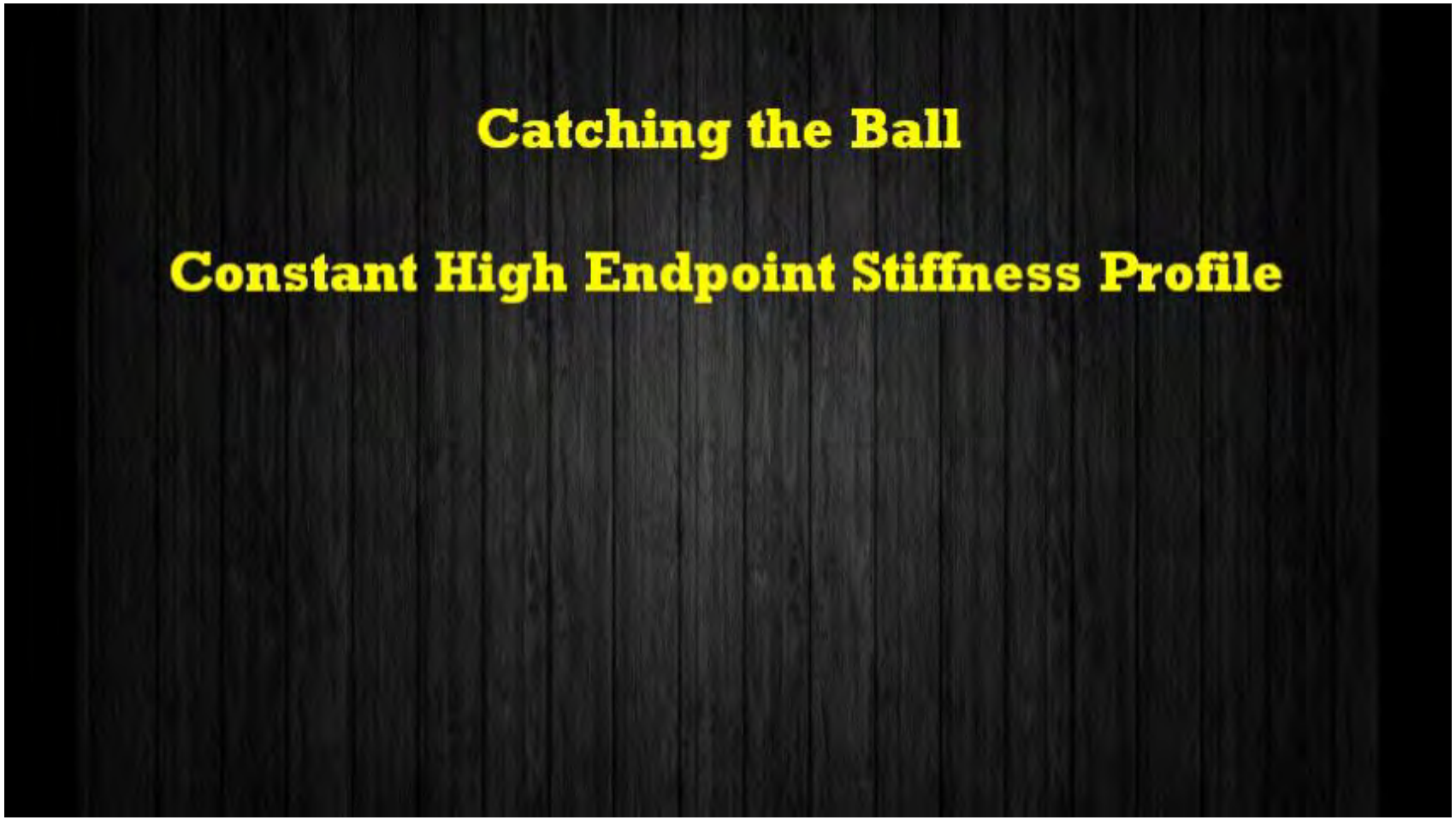
Low impedance

Tele impedance



Me

Experiments: Ball Catching

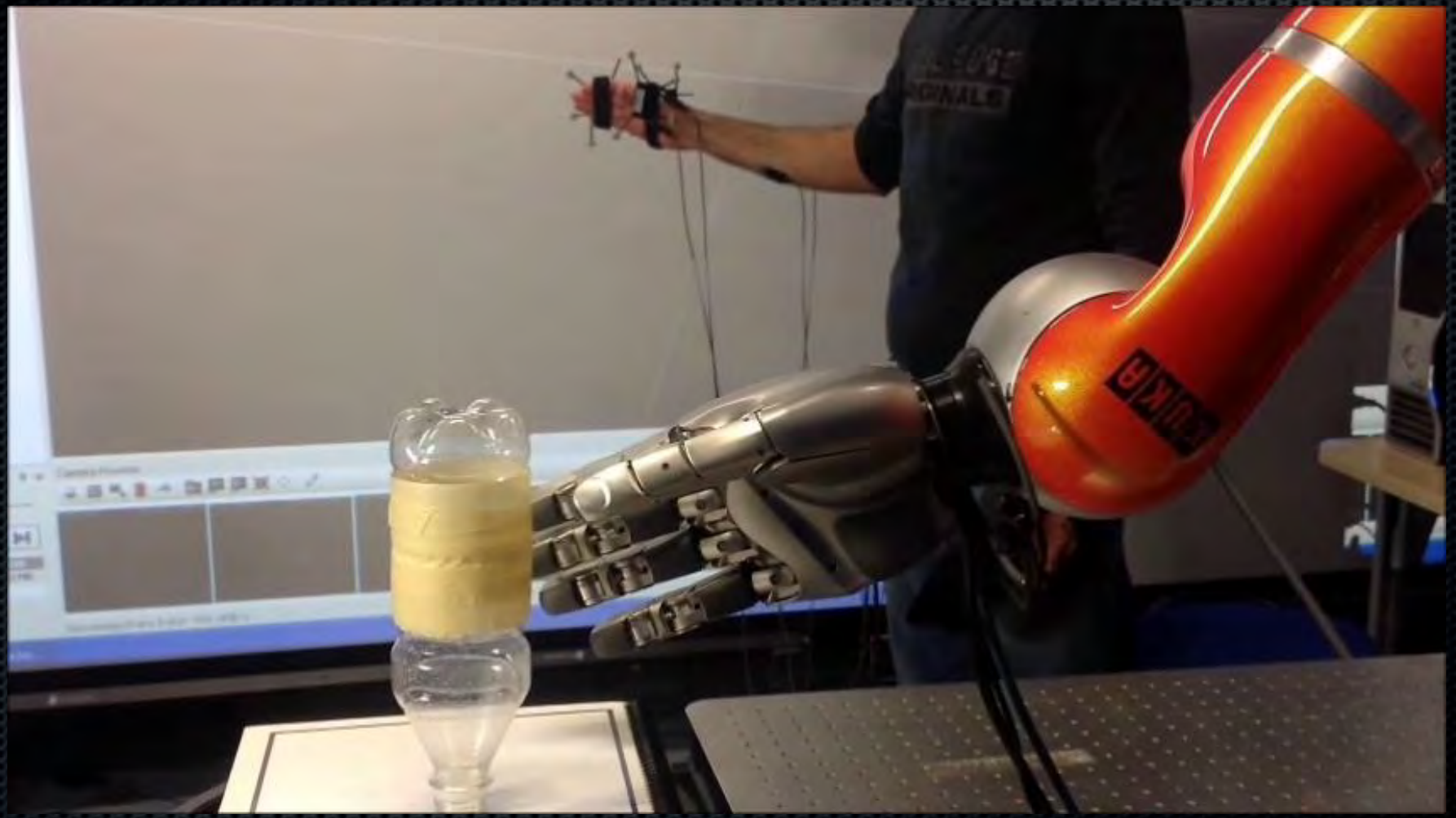


Body-Robot Interfaces: Teleoperation

Teleoperation consists of measuring motor control parameters in human, and replicating in robots

- Unilateral (Position Control)
  - Very stable
  - Difficult interactions with uncertain environments

Body-Robot Interfaces: Position Control



Body-Robot Interfaces: Teleoperation

Teleoperation consists of measuring motor control parameters in human, and replicating in robots

- Unilateral (Position Control)
  - Very stable
  - Difficult interactions with uncertain environments
- Bilateral (Force Feedback)
  - Needs force sensors and actuators (e.g. exoskeleton)
  - Difficult stability/transparency trade-off

Body-Robot Interfaces: Teleimpedance

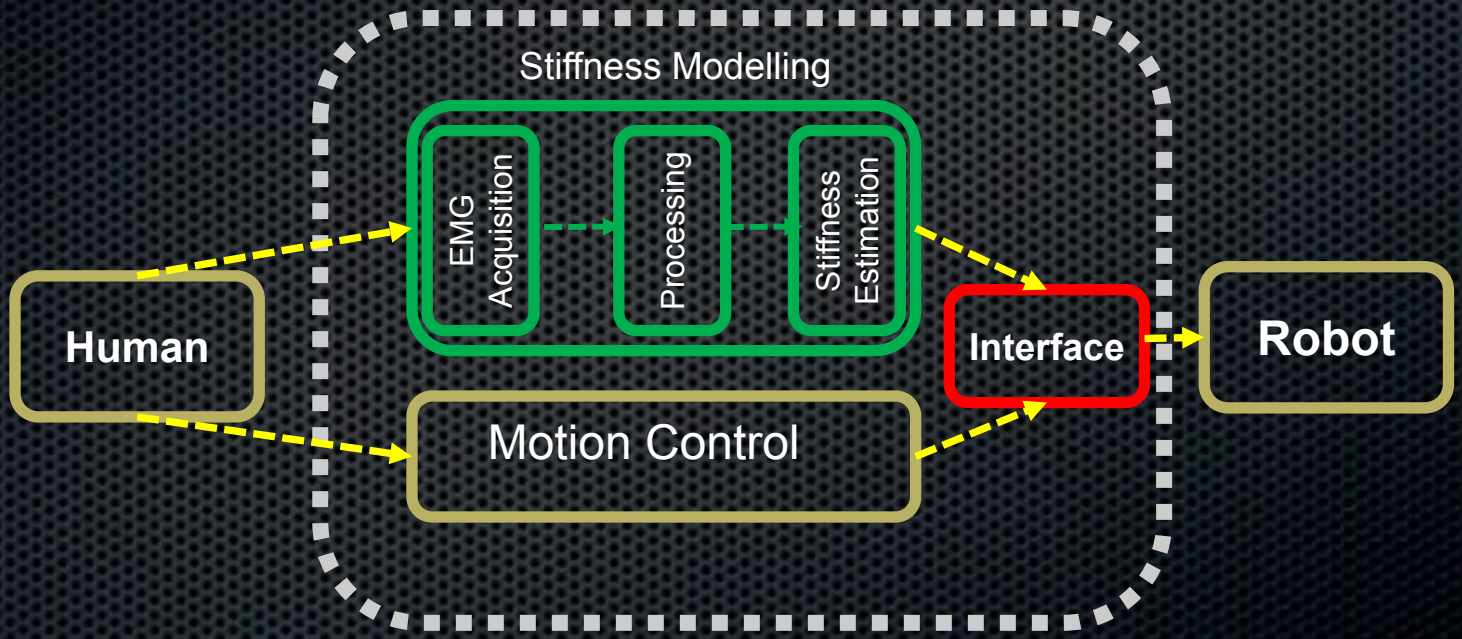
- Can we instead do remote impedance control?

  - use human arm position and impedance as references
  - use local robust controllers to make the robot track those plans: no delays, very stable

- How do we sense position and impedance on the master?
  - Position
  - Impedance

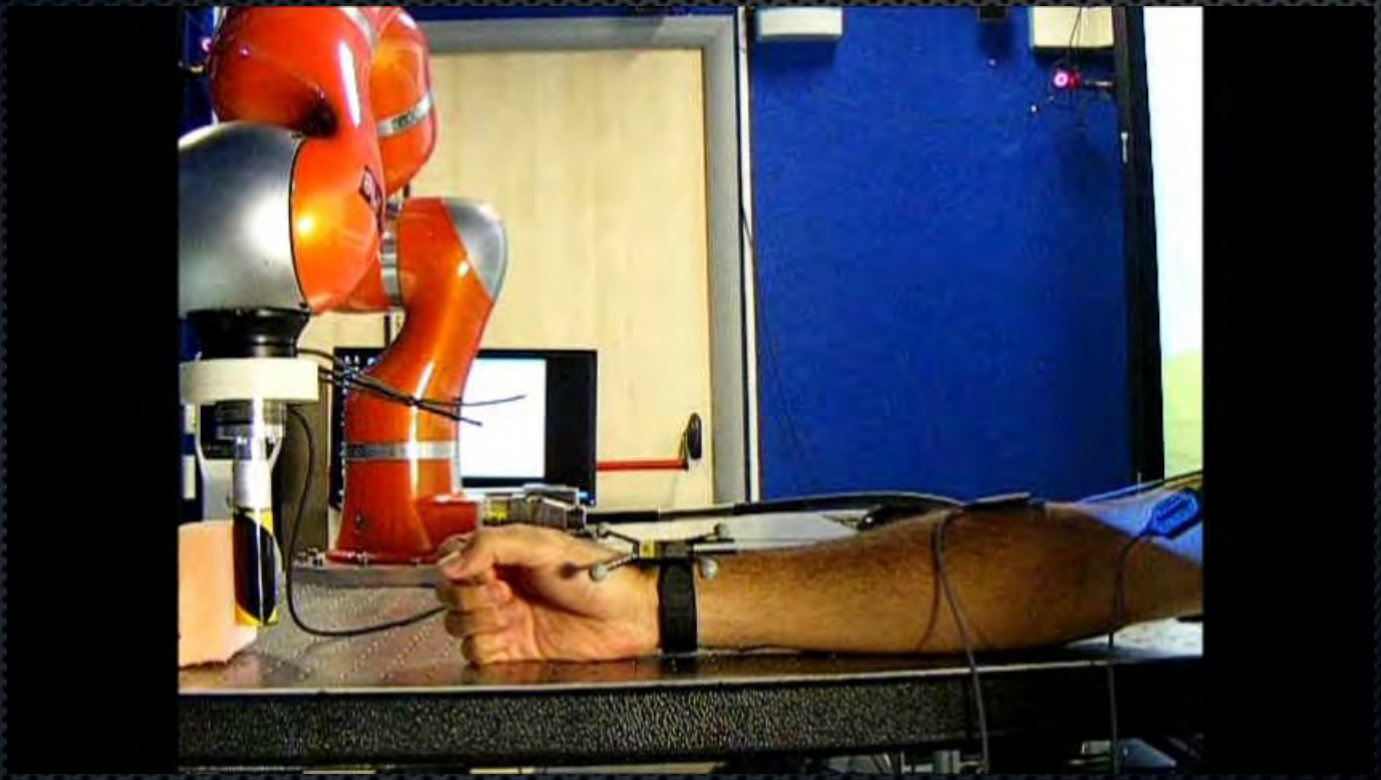
Teleimpedance Control

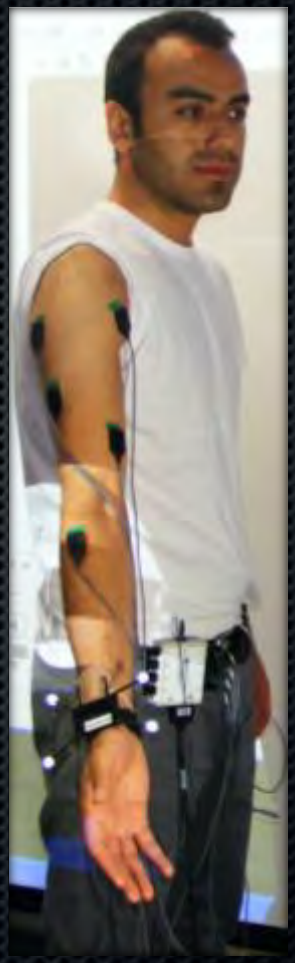
- use human arm position and impedance as references for robot
- use local robust controllers (no delays, very stable) to make the robot track those plans

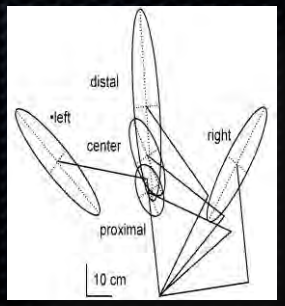


Ajoudani et. al, IJRR 2012

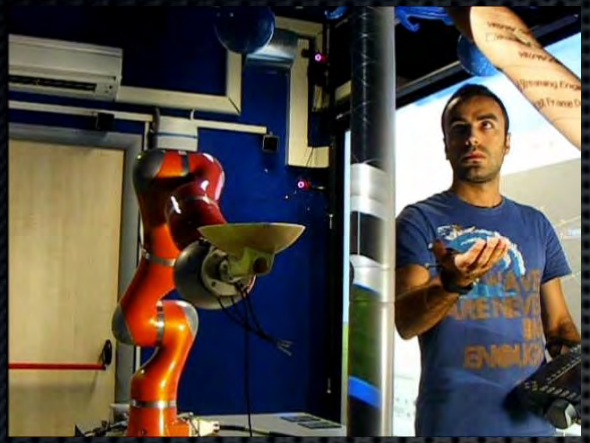
Body-Robot interfaces: Tele-Impedance control



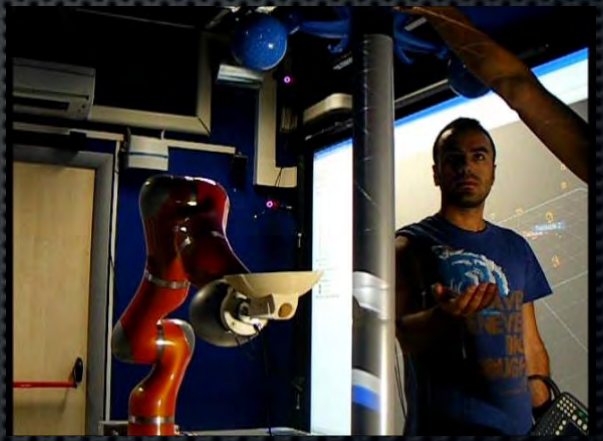




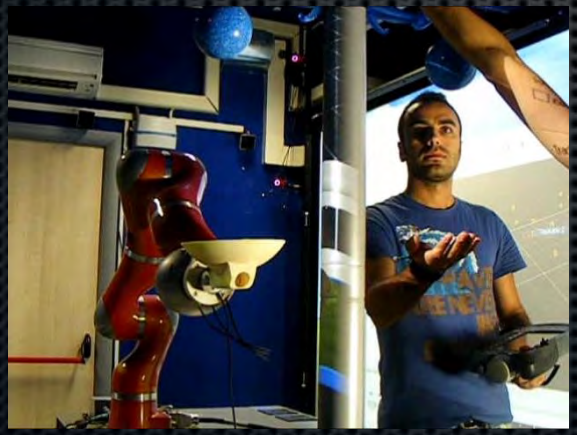
Body-Robot interfaces: Tele-Impedance Control



High Impedance:
too much bouncing

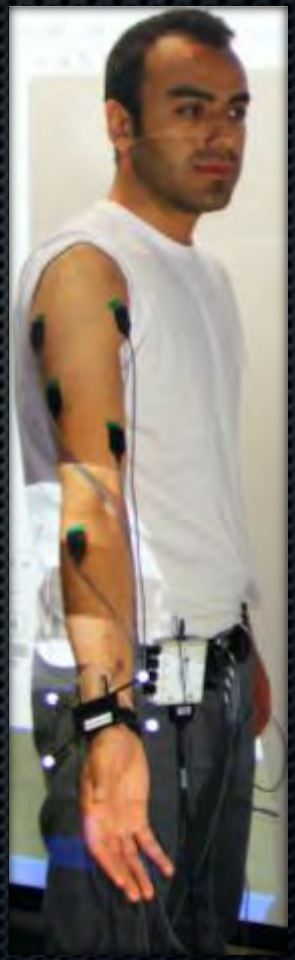


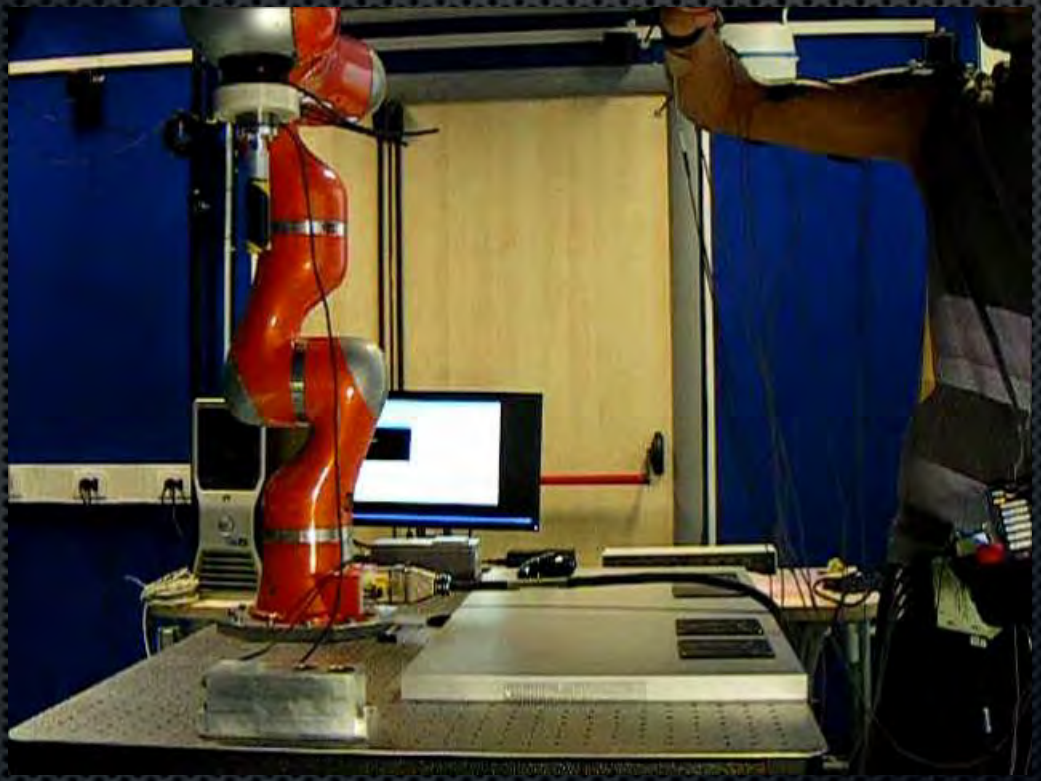
Tele Impedance



Low Impedance:
too deep bowing

Body-Robot interfaces: Tele-Impedance control





Peg-in-hole with Teleimpedance

Impedance estimation

- *Task-efficient* modifications of the endpoint arm *impedance* and endpoint *force* fluctuations in humans are shown to have high correlations with patterns of (co)activations in the involved muscles (Osu et al., 2002; Selen et al. 2002; Tsuji et al. 2004)

- Based on above observations and their
  - Adaptivity
  - Accessibility
  - Stability

EMGs

Best Candidate...

- Drawbacks?
  - Drift, calibration, crosstalk, sensitivity,...

Stiffness Modeling

- Modeling of EMG to impedance at endpoint

$$\begin{pmatrix} F \\ \sigma \end{pmatrix} = \begin{pmatrix} T_F \\ T_\sigma \end{pmatrix} P + \begin{pmatrix} 0 \\ \sigma_0 \end{pmatrix}$$

F : Endpoint Forces

σ : Endpoint stiffness where σ_0 is the intrinsic part

P : Muscular activities (Processed EMGs)

T_F : Mapping from P to F

T_σ : Mapping from P to σ

- Inspired by human impedance-force regulation skills, T_F is decoupled from T_σ, therefore EMGs are mapped to two subspaces corresponding to range and null-space of the EMG to Force mapping

$$P = T_F^R T_F P + (I - T_F^R T_F) P = P_F + P_K$$

R : Right inverse

I : Identity matrix

- Stiffness-generating component is a projection of measured EMG in the Kernel of T_F

Stiffness Modeling

Let N_F denote a basis matrix for the Kernel of T_F

and let

$$\lambda = N_F^+ P_k = QP \qquad Q \overset{def}{=} N_F^+ (I - T_F^R T_F)$$

NOTE: The kernel of T_F is generally larger than the subspace of stiffness regulating activations (in our case the ratio is 5 to 3).

So we write: $\sigma - \sigma_0 = M_\sigma QP$

$M_\sigma \in \Re^{3\times 5}$ is the mapping from kernel of T_F to stiffness variations

An embodied intelligence approach to taming the complexity of hands

Antonio Bicchi

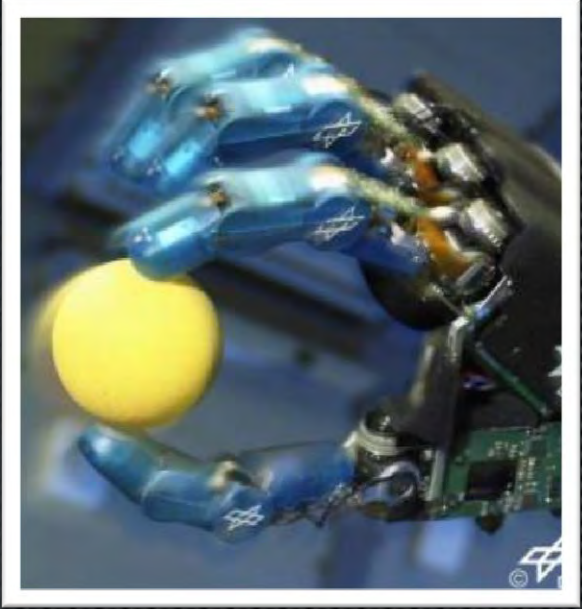
with

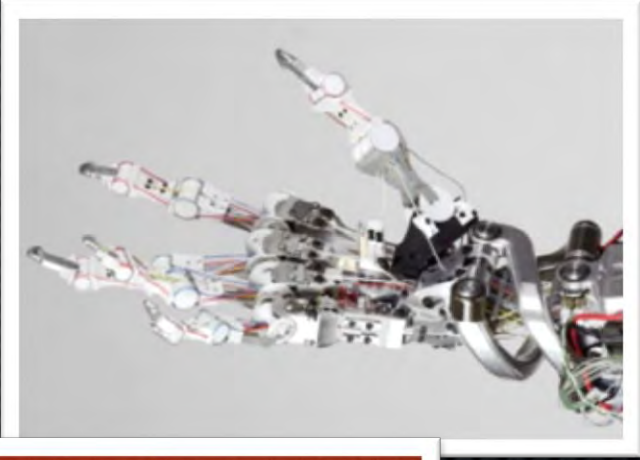
M. G. Catalano A. Ajoudani S.B. Godfrey M. Bianchi
G.Grioli A. Serio E. Farnioli C. Piazza
M. Bonilla M. Garabini M. Gabiccini

thanks to

M. Santello (ASU), D. Prattichizzo (UNISI), N. Tsagarakis (IIT)

(complex) Hands for Robots





JPL-Stanford Hand at MIT AI Lab
Clips from a 1989 Videotape

Measure Friction Coefficients

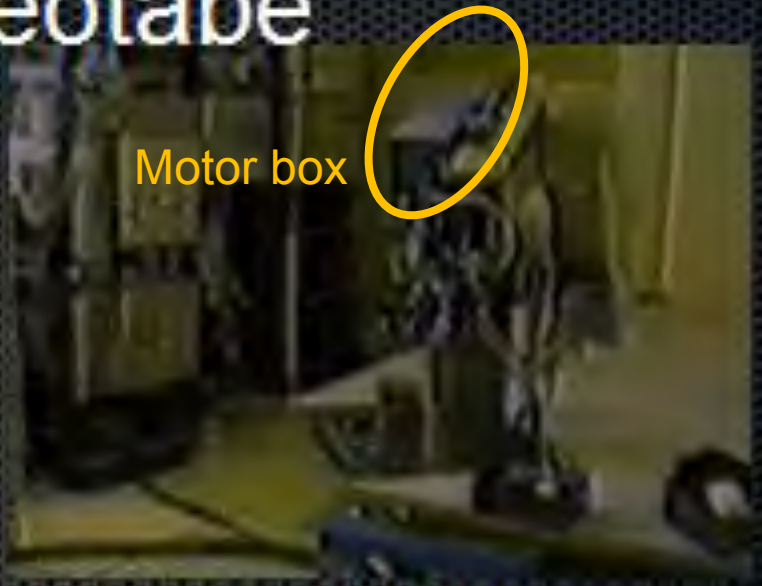
Detect Objects by Texture

Reflex Control of Grasping

Follow and Reconstruct Shape

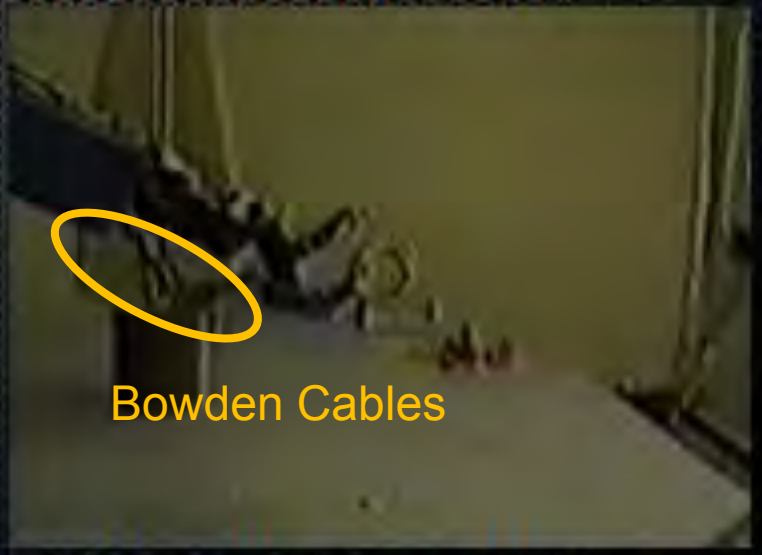
JPL-Stanford Hand at MIT AI Lab
Clips from a 1989 Videotape

Measure Friction Coefficients



Detect Objects by Texture

Reflex Control of Grasping



Follow and Reconstruct Shape

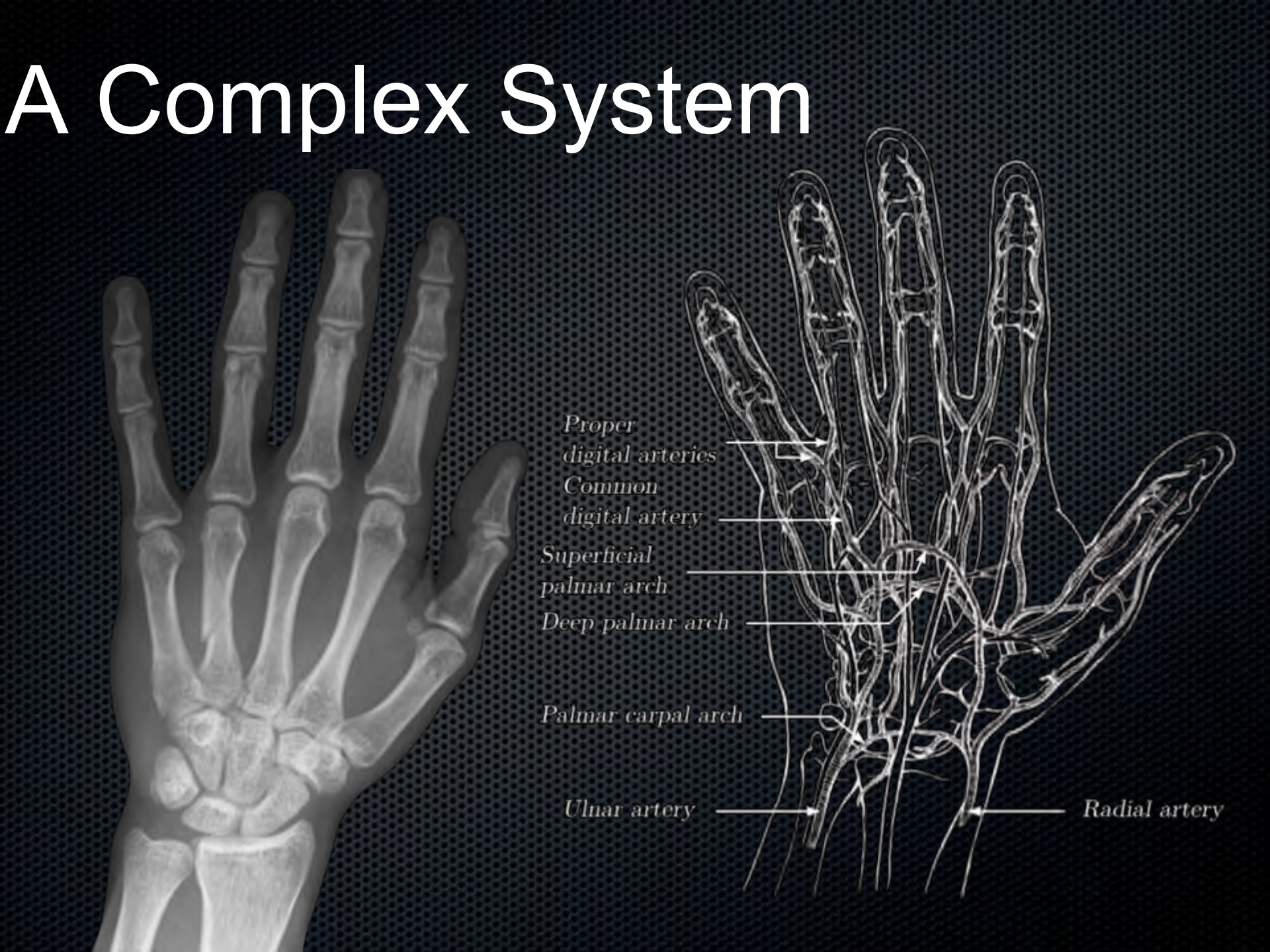
The real problem

How to make robots that are
- soft yet strong
- simple yet dextrous
- intelligent yet practical

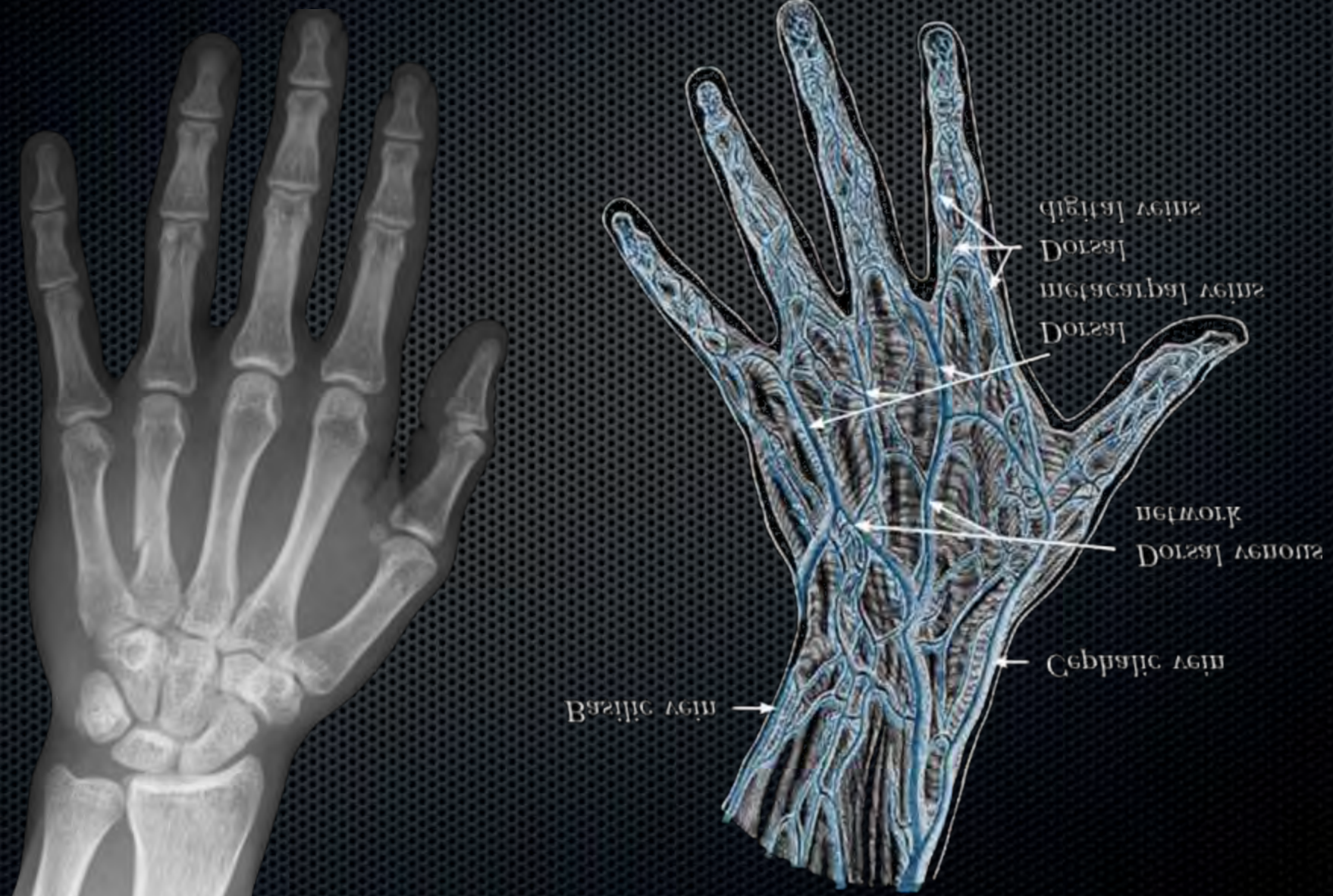
Our Approach

- Soft Robotics
- Synergies

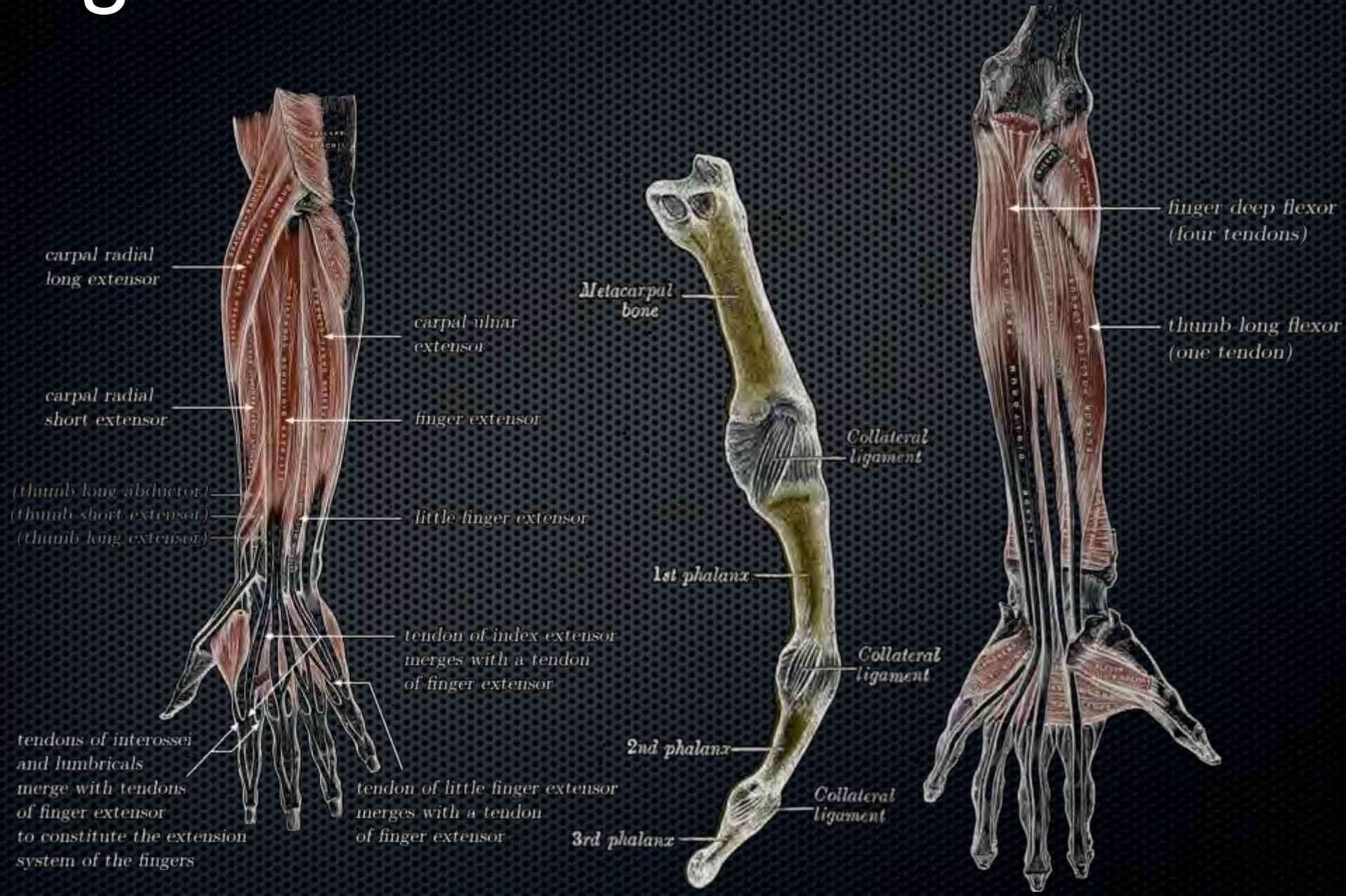
A Complex System



A Complex System



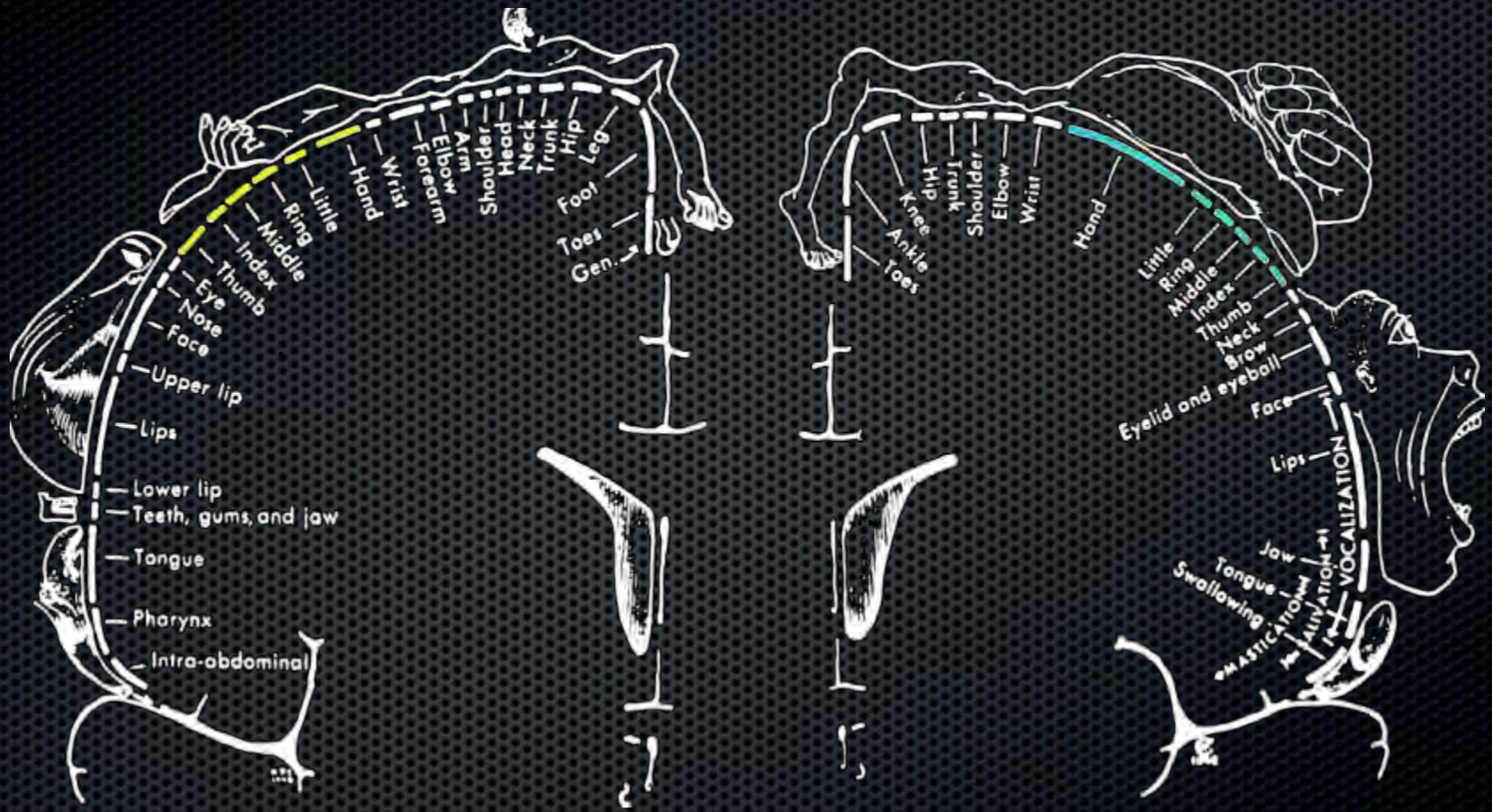
Ligaments and Muscles



Numbers

29	major joints
≥ 29	major and minor bones
≥ 123	named ligaments
34	muscles moving fingers and thumb
–17	in the palm of the hand
–18	in the forearm
48	named nerves
–3	major nerves
–24	named sensory branches
–21	named muscular branches
30	named arteries (+ ~30 smaller branches)

How can the brain cope?



Synergies in the Hand Motor System

- Extensive neuroscientific evidence for the ***existence of sensorimotor synergies and constraints*** Babinski (1914!), Bernstein, Latash, Bizzi, Arbib, Jeannerod, Wolpert, Flanagan, Soechting, Sperry, …
- Quantitative work on hand postural synergies dates back ~15 years
- Santello, Flanders and Soechting (1998, J. Neuroscience) collected and analyzed the statistics of a large database of human grasps

The Shape of Synergies

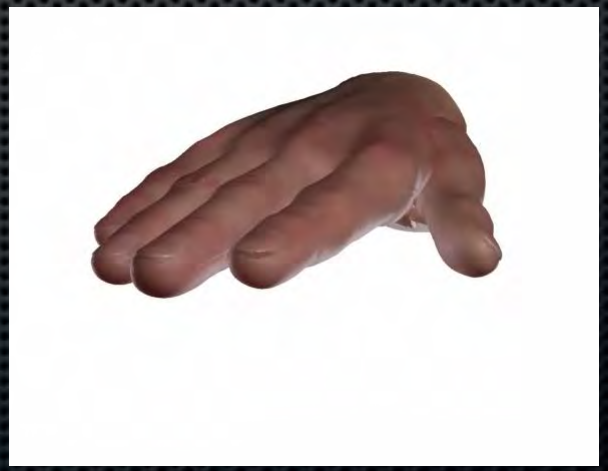
Glossary: "Postural Synergies"
= Principal Components
of Grasp Covariance Matrix

First two synergies explain ~84%,
first three ~90% of the covariance.

First synergy alone more than 50%

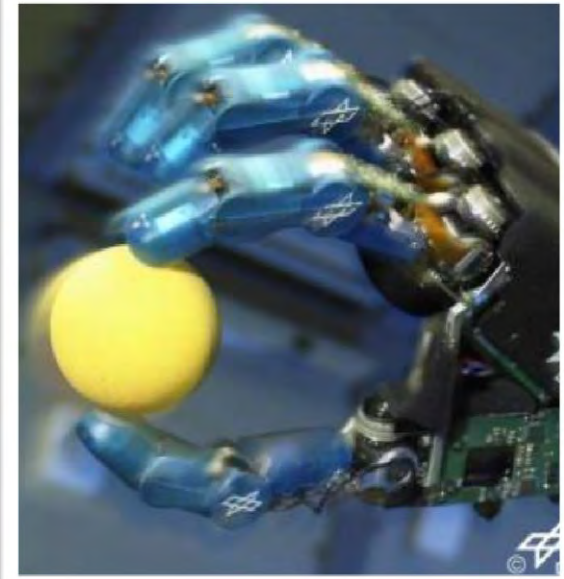
$$S = \begin{bmatrix} \vdots & \vdots & \vdots & \vdots & \vdots \\ S_1 & S_2 & S_3 & \cdots & S_n \\ \vdots & \vdots & \vdots & \vdots & \vdots \end{bmatrix}$$

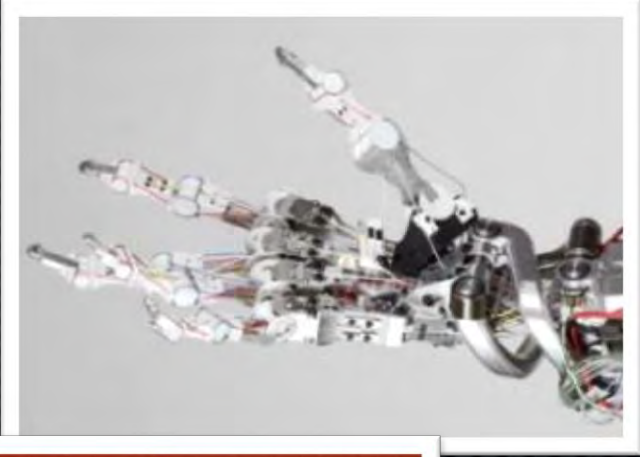
(1-st synergy) (2-nd synergy) (3-rd synergy)



Human Hands

Robot Hands





The problem

How to make and use hands that are

– soft yet strong
– simple yet dexterous
– intelligent yet practical

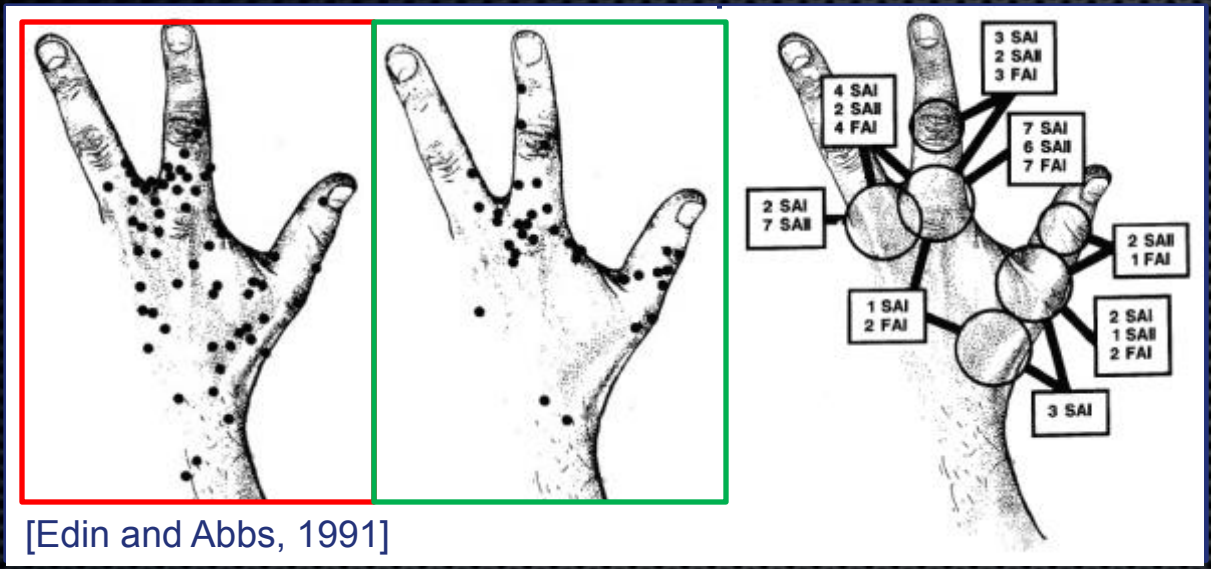
Our Approach

- Soft Robotics Technology
- Theory of Human Synergies

Synergies for reconstructing the hand pose from limited measures

Bianchi Salaris Bicchi IJRR 2013-1

If you were the designer...



[Edin and Abbs, 1991]

- **SA units (SAI, SAII):**
  - non-localized response (several joints involved);
  - rather uniformly distributed
- **FA units (FAI):**
  - localized response to one/two joints;
  - denser near joints

Different typologies of proprioceptive sensors are distributed in the dorsal skin with different densities

A non–uniform map of sensitivities to joint angles

Application of Optimal Glove Design Techniques: Noisy Case

MVE with H_s				
e_i	7.28°	7.86°	7.34°	8.47°
MVE with H_d^*				
e_i	6.47°	4.28°	5.38°	7.59°

Non-Optimal

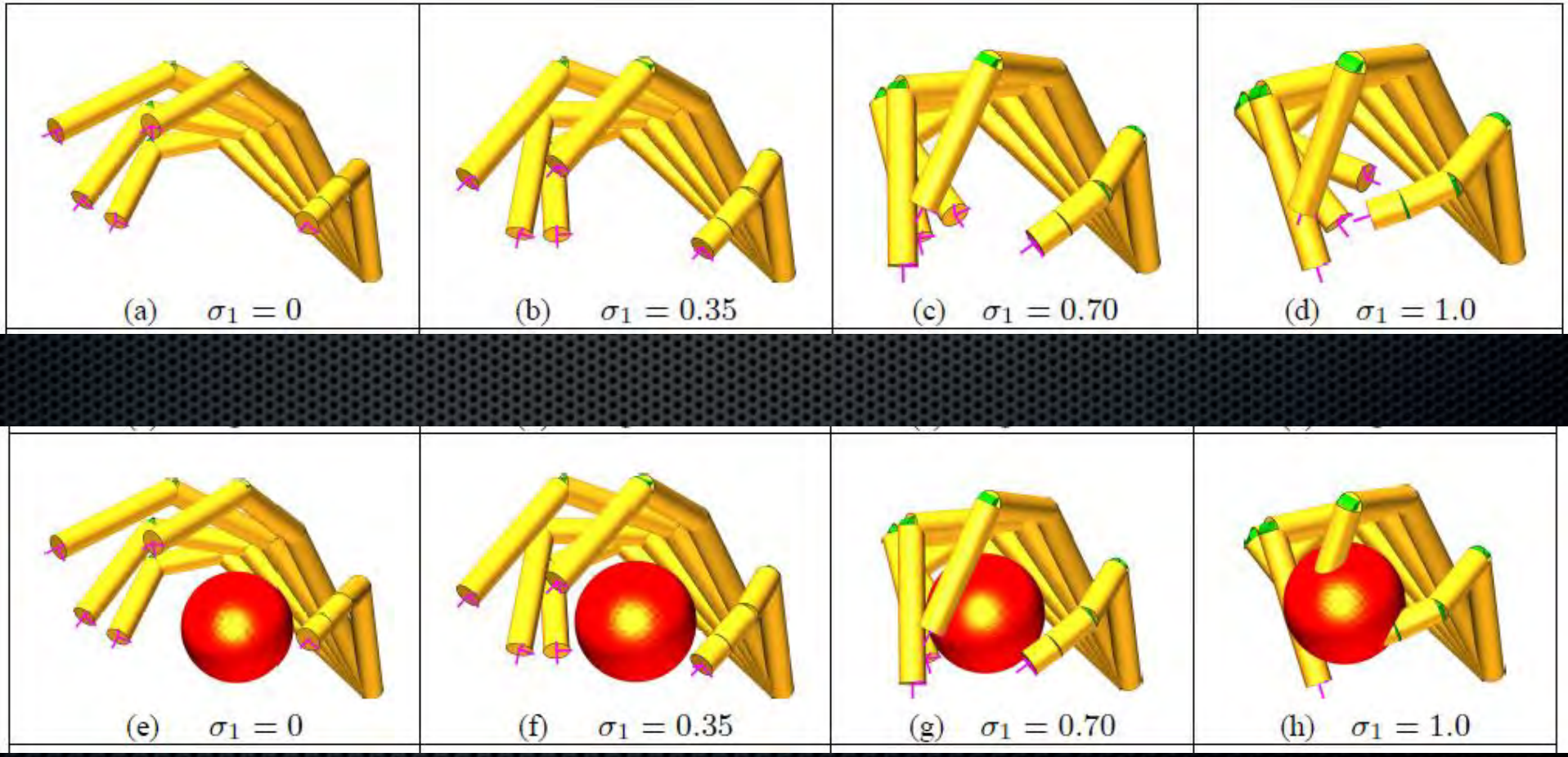
Optimal

Bianchi Salaris Bicchi IJRR 2013-2

Geometric Synergies

Grasping a ball with one synergy

IMPOSSIBLE!

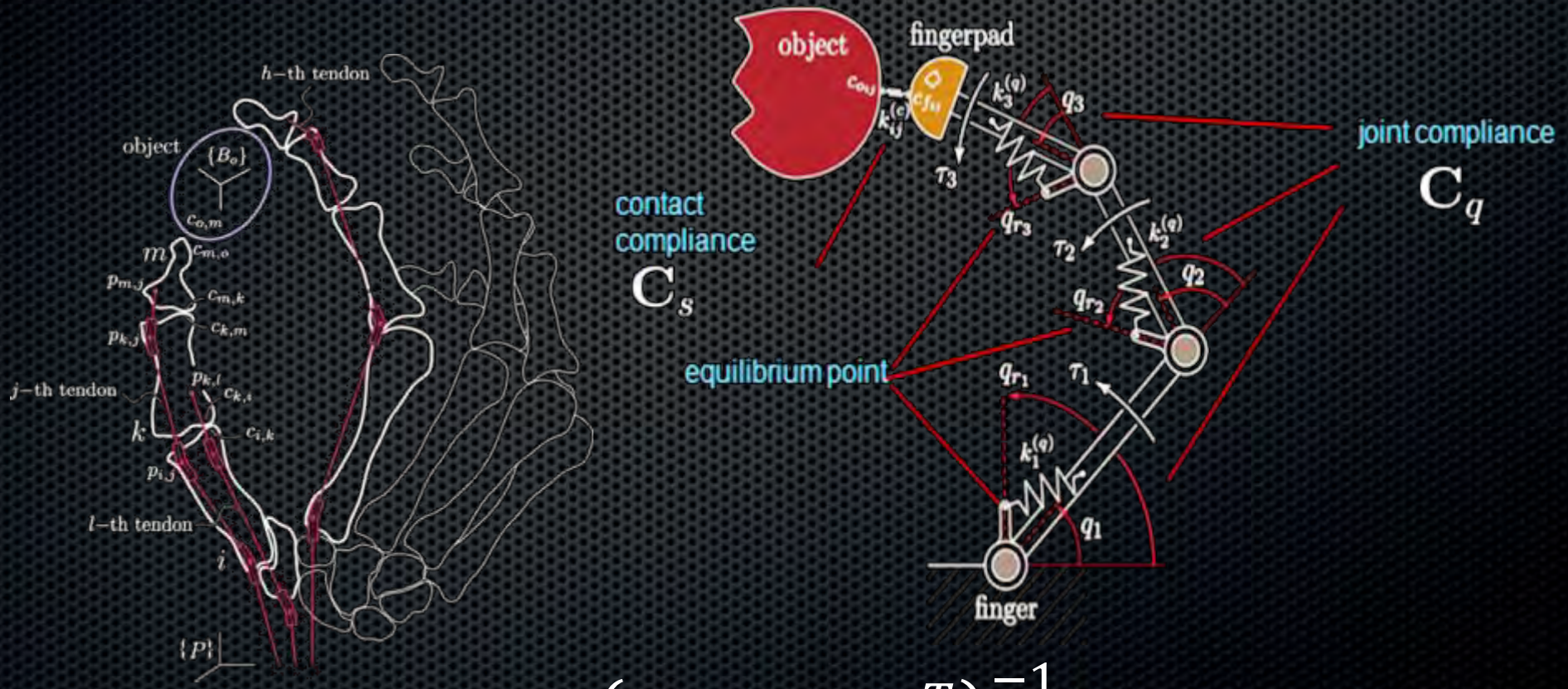


How to Get a Grasp?

- Key point in grasping is *how forces are applied and controlled*
- Geometric synergy model can not account for grasping force generation
- What relation is there between grasping forces, grasping postures, and synergies?
- Human hands are not rigid!

Synergies and Hand Compliance

Human hands are not rigid: Compliance of the musculoskeletal system, of the skin, and of the object combine in an overall grasp stiffness matrix K



$$K = \left(C_s + J\, C_q J^T\right)^{-1}$$

Internal Forces in Grasping with Synergies

- Internal Forces: $\mathbf{p} \in ker(\mathbf{G})$
- Not all internal forces are independently controllable acting through the joints

TH: The set of contact forces which can be actively controlled is a linear subspace of $ker(\mathbf{G})$

PLV → $$\mathbf{A}\mathbf{x} = \mathbf{K}\mathbf{J}\mathbf{S}\Delta\sigma - \mathbf{K}\mathbf{G}^T\Delta\mathbf{u}$$

hence $$\begin{bmatrix}\mathbf{A} & -\mathbf{K}\mathbf{J}\mathbf{S} & \mathbf{K}\mathbf{G}^T\end{bmatrix}\begin{pmatrix}\mathbf{x}\\ \Delta\sigma\\ \Delta\mathbf{u}\end{pmatrix} = 0.$$

$$\mathbf{p}_a = (\mathbf{I} - \mathbf{G}_K^R\mathbf{G})\mathbf{K}\mathbf{J}\mathbf{S}\Delta\sigma$$

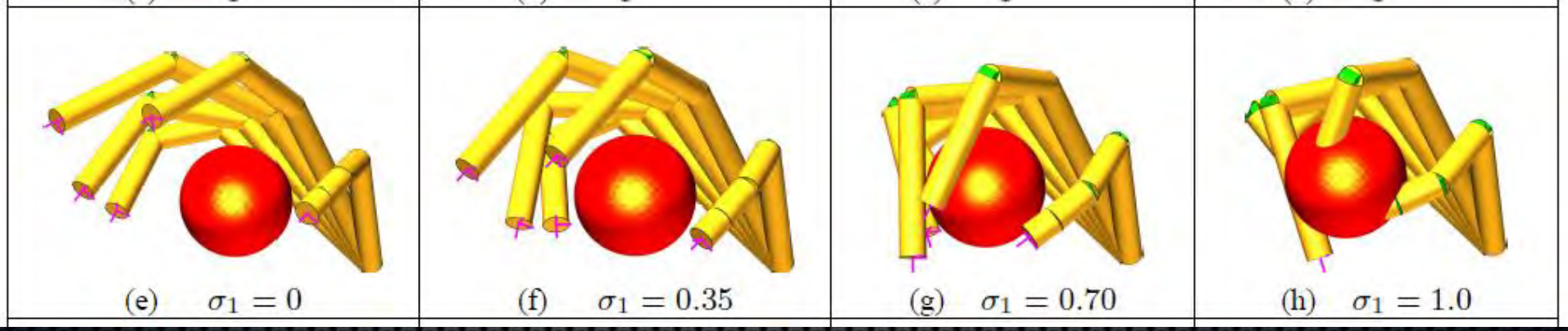
or $$\mathbf{p}_a = \mathbf{E}_\sigma\mathbf{y}$$

The Soft Synergy Paradigm

- The posture (kinetic) synergy model only rules an internal "reference" representation of the hand configuration
- The higher level control of the hand commands this internal representation within the synergy manifold
- The actuator system of the hand is controlled towards this *reference hand* set-point
- The hand fingers and palm interact with manipulated objects and environment through contact
- The *physical hand* reaches an equilibrium under the effect of
  - attraction towards the synergy-driven reference hand
  - repulsion by contact forces
  - stiffness of actuators, tendons, and deformable bodies

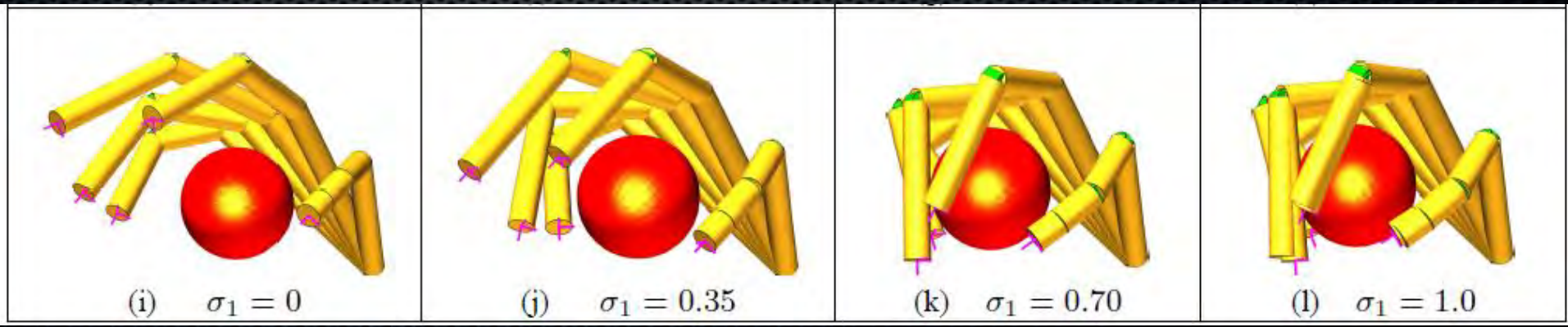
Soft Synergies

Geometric Synergies drive an “inner” hand reference



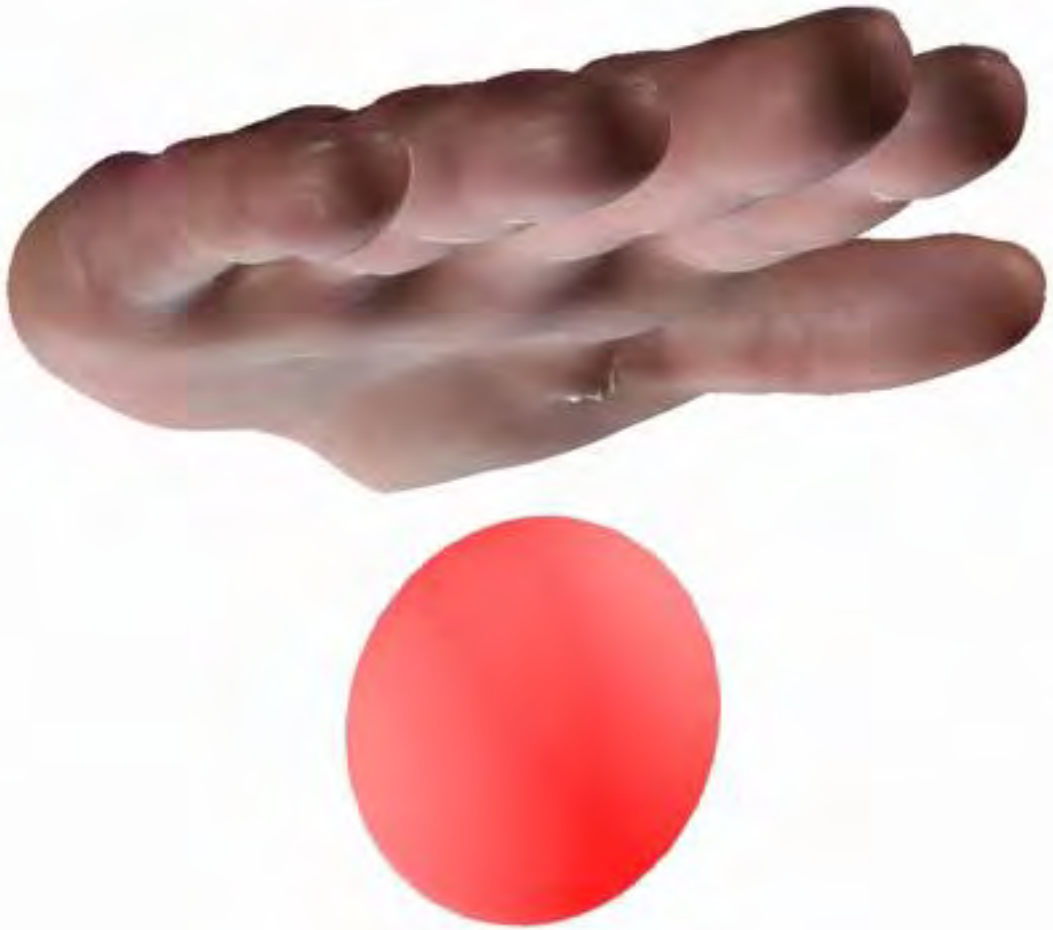
(e) $\sigma_1 = 0$ (f) $\sigma_1 = 0.35$ (g) $\sigma_1 = 0.70$ (h) $\sigma_1 = 1.0$

The real, compliant hand is attracted by the internal reference but repelled by contact forces, reaching an equilibrium configuration



(i) $\sigma_1 = 0$ (j) $\sigma_1 = 0.35$ (k) $\sigma_1 = 0.70$ (l) $\sigma_1 = 1.0$

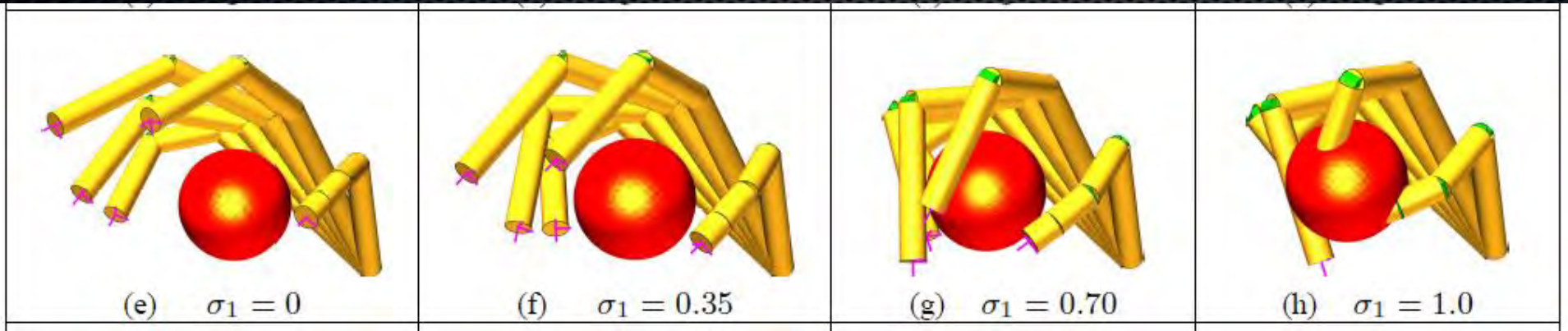
Small Red Object



Gray Ashtray

Soft Synergies

Geometric Synergies drive an “inner hand”



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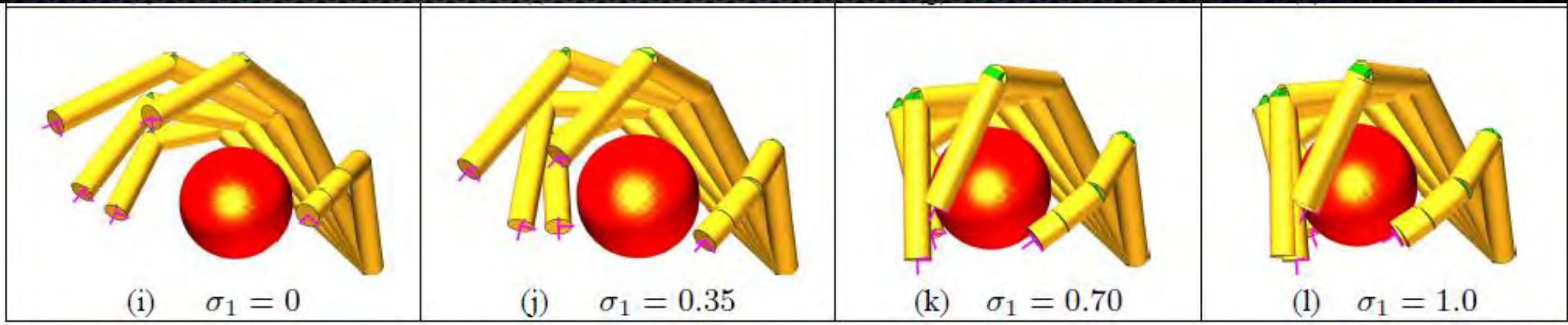
Soft Synergies and the “Equilibrium Hand”



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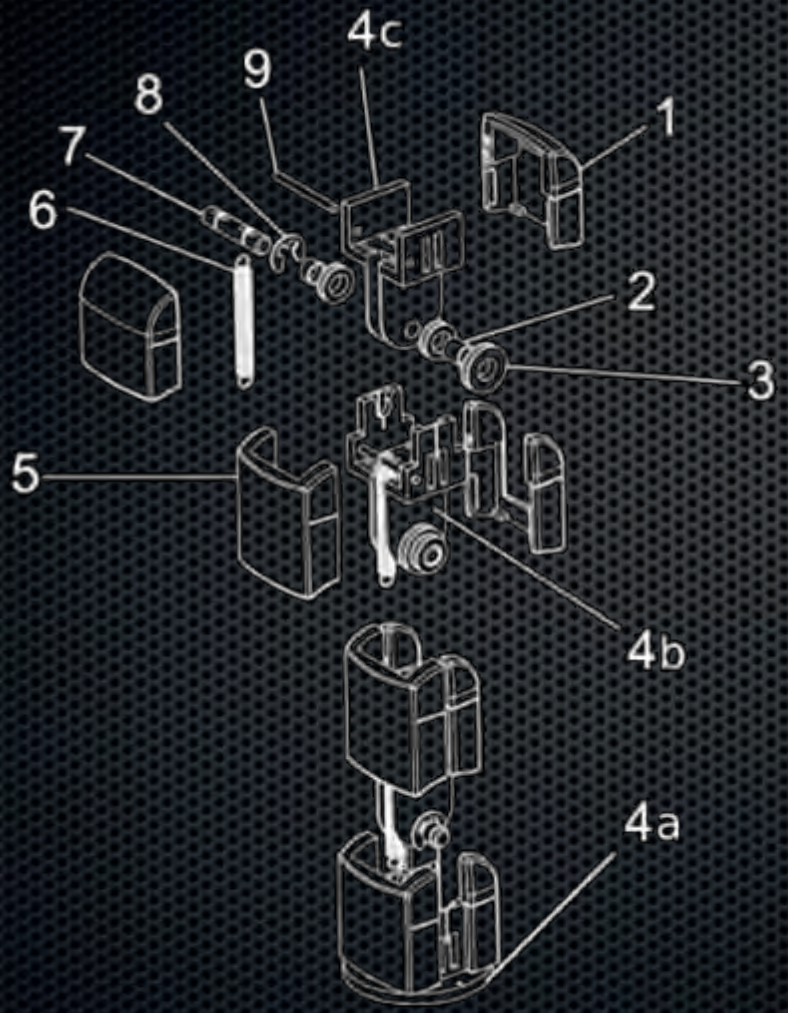
$\mathbf{p}_a = (\mathbf{I} - \mathbf{G}_K^R\mathbf{G})\mathbf{KJS}\Delta\sigma$

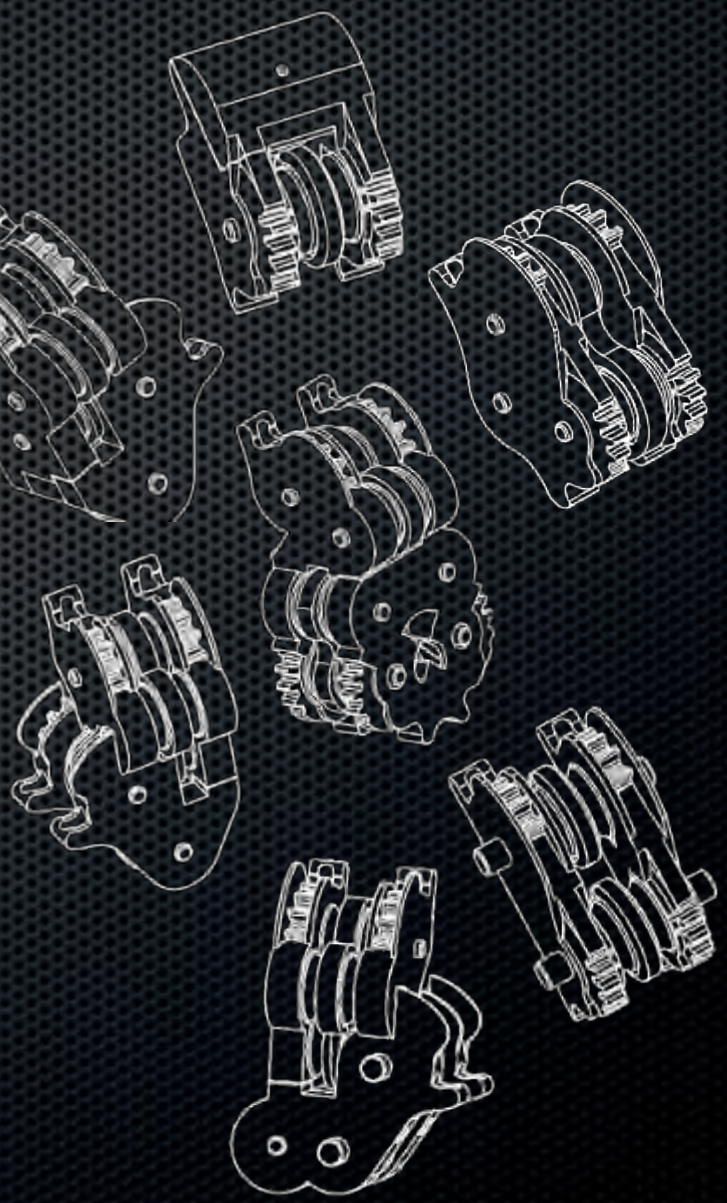
or $\mathbf{p}_a = \mathbf{E}_\sigma \mathbf{y}$

Regulates the *equilibrium hand* configuration (λ)

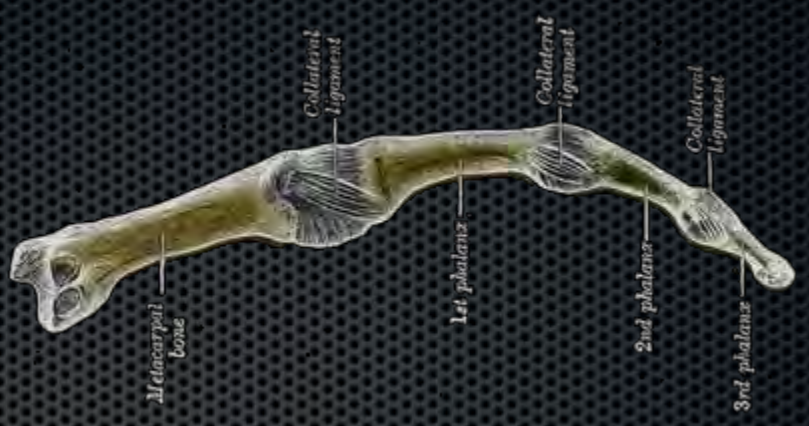
From theory to practice

Module design optimization



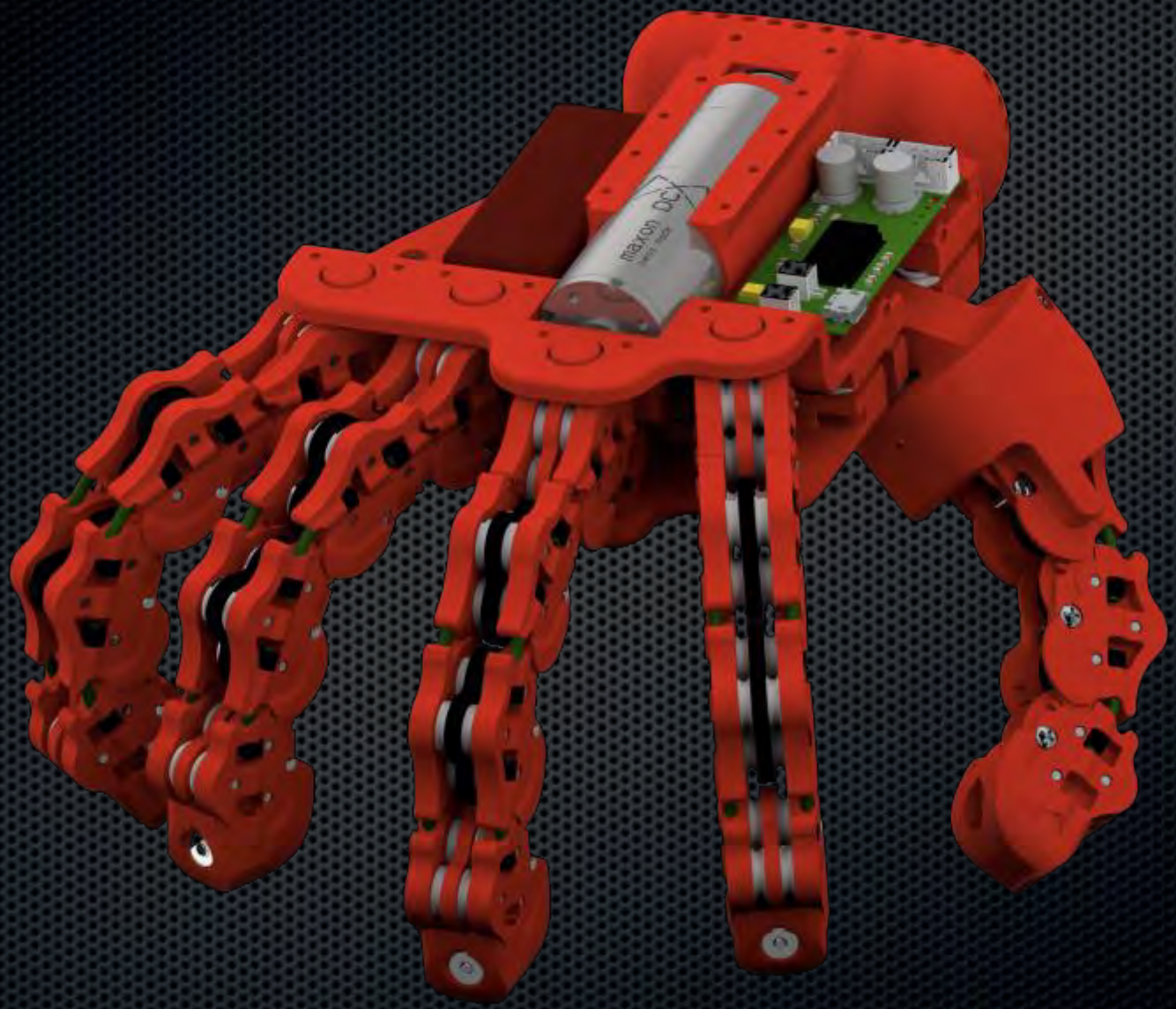


Innovative Design

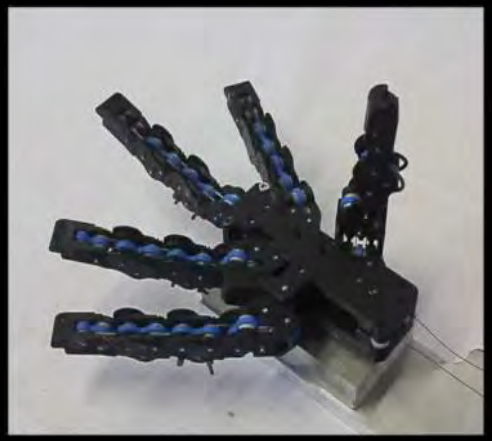


Articular Joints
and Soft Ligaments
for Robustness & Safety

The PISA/IIT Soft Hand

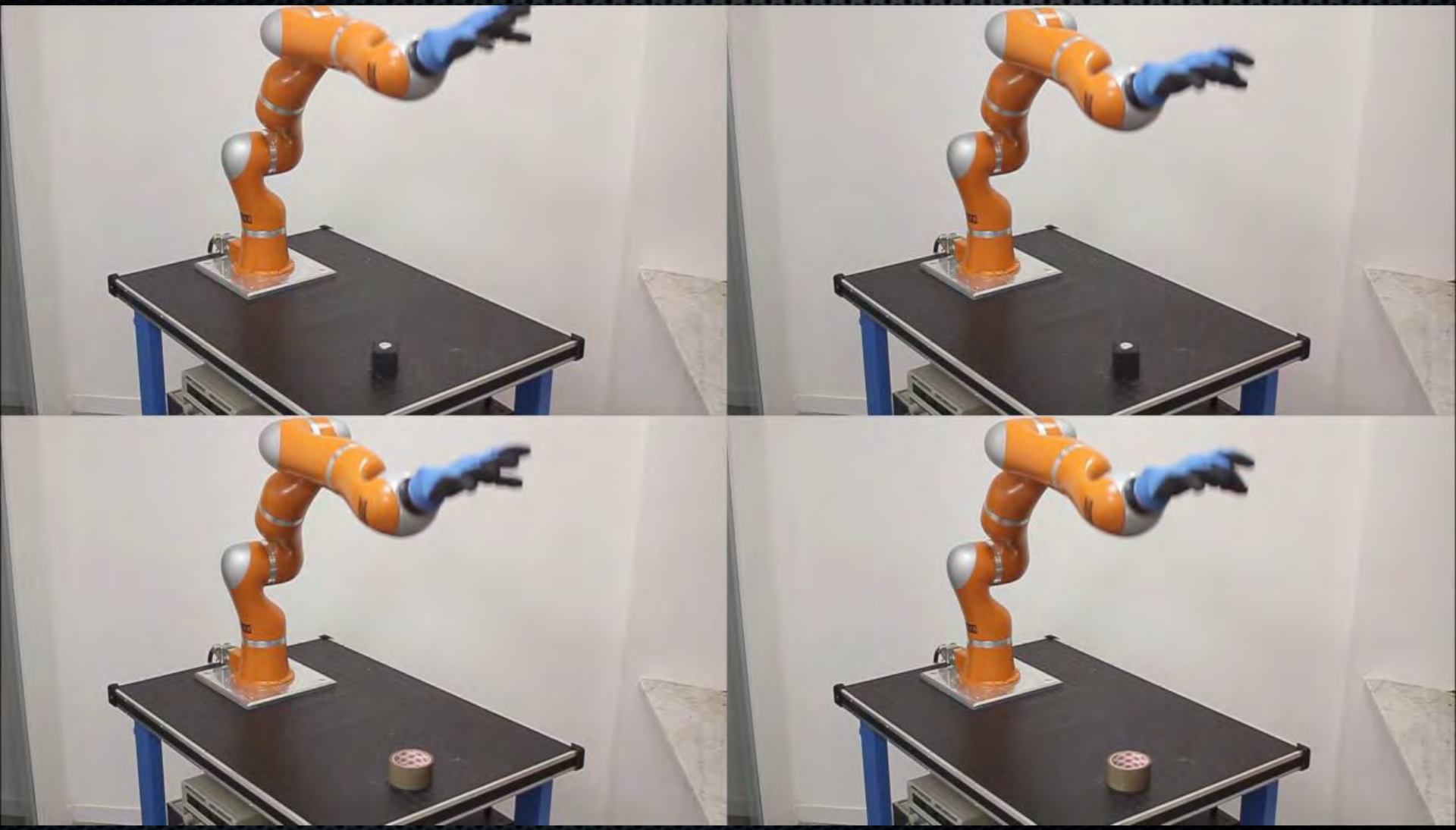


The Pisa-IIT Soft Hand

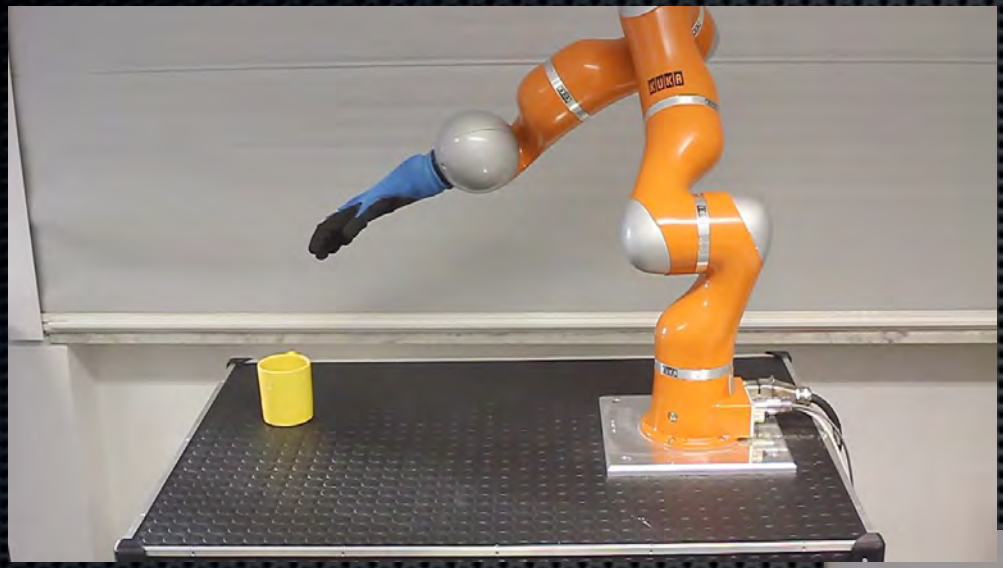


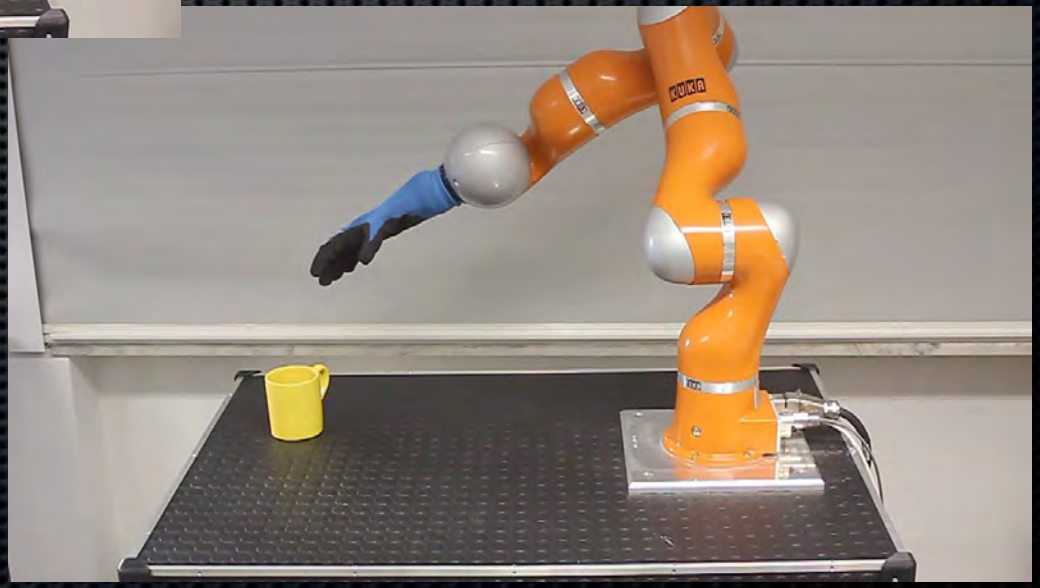
- 18 anthropomorphic joints
- One soft synergy
- One motor

Grasping round and cubic objects



Grasping mugs & embodied intelligence

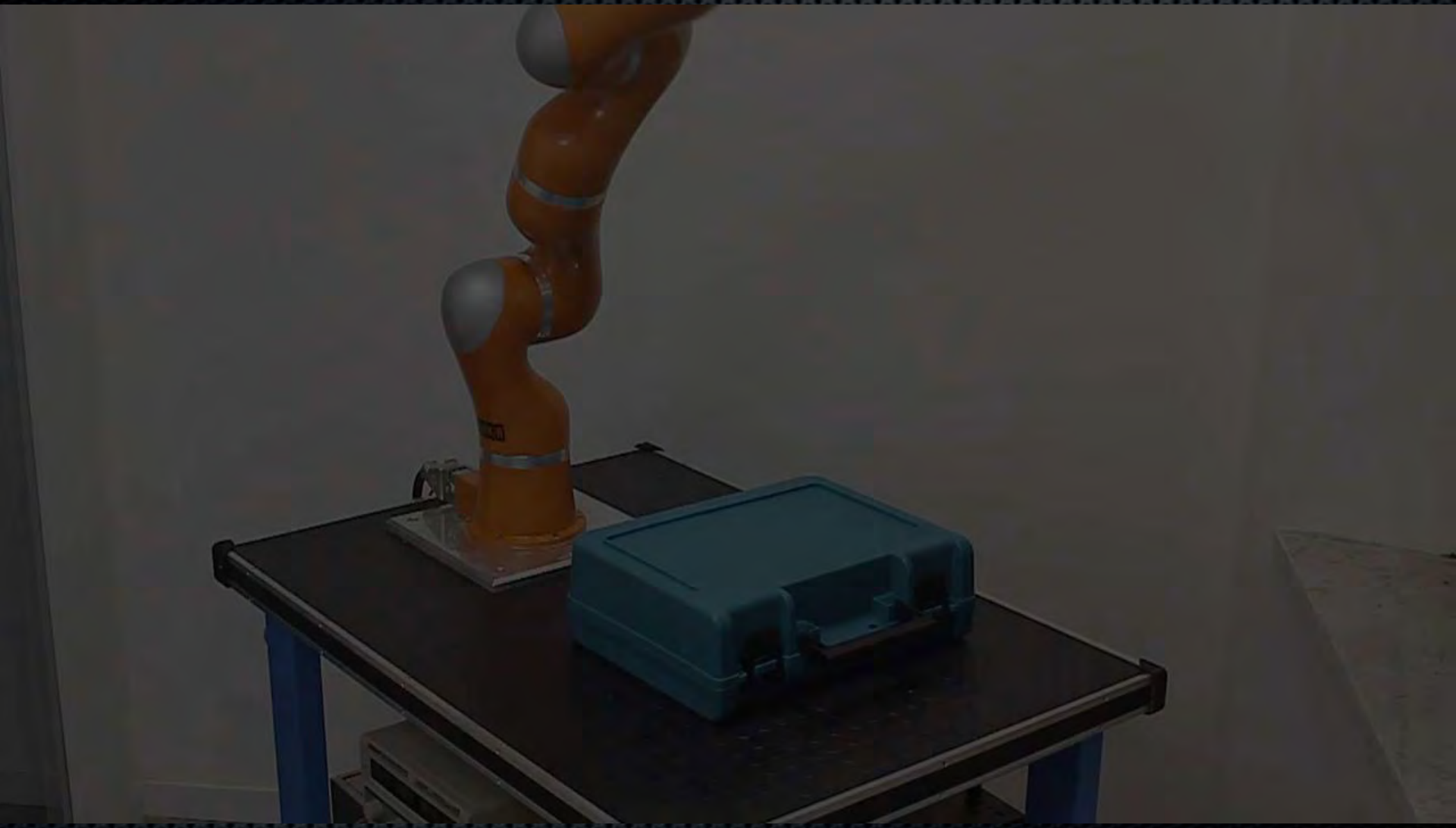




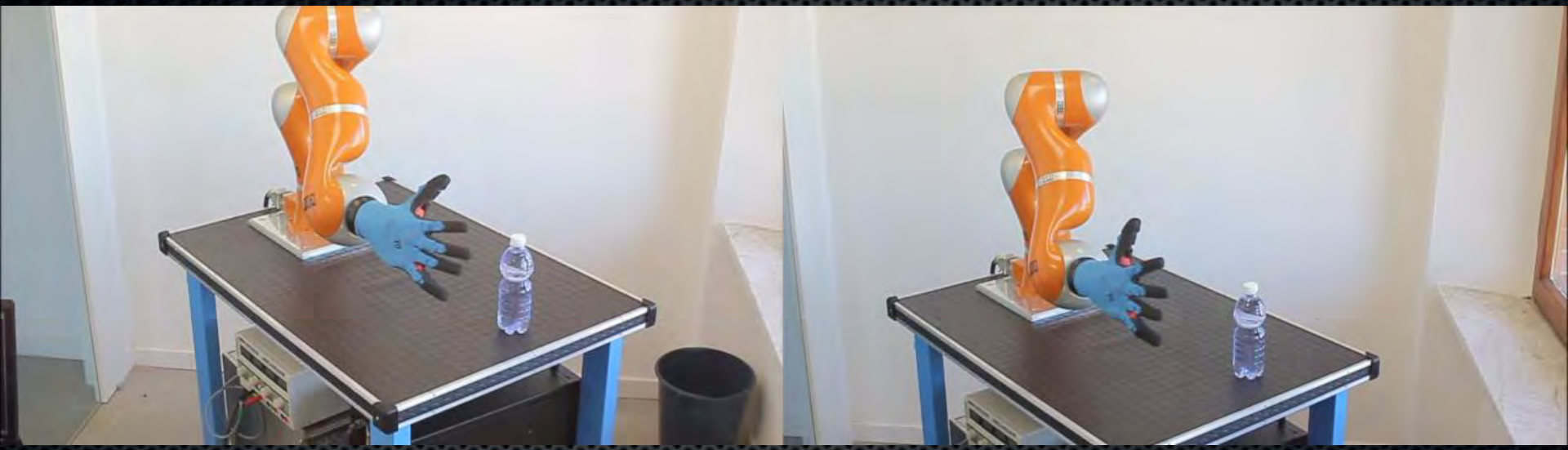
- Same hand
- Same object
- Same on/off control

- Two different grasps depending on affordance

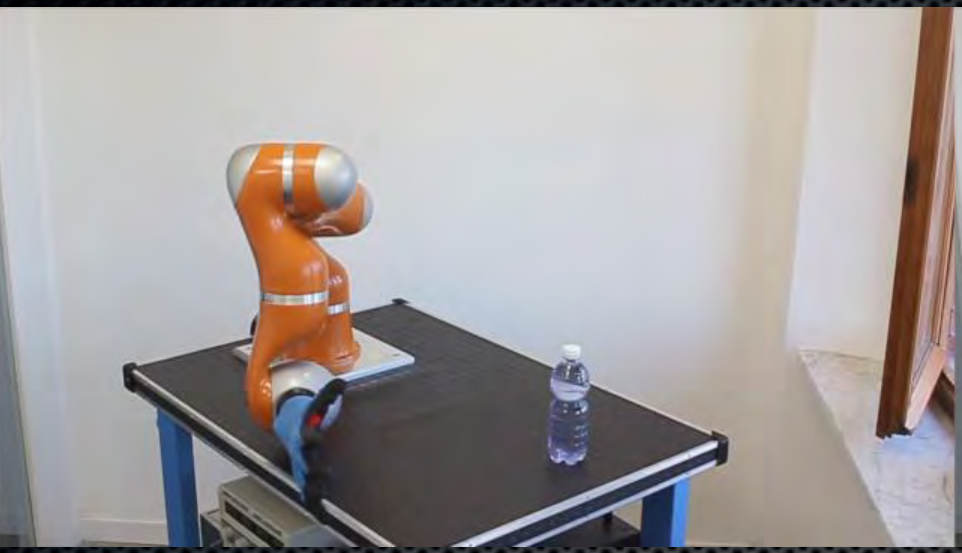
Grasping Handles



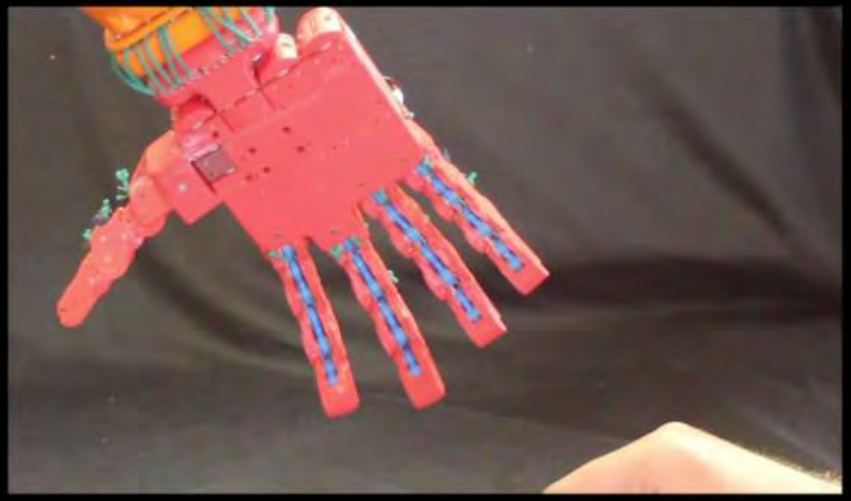
Grabbing Bottles

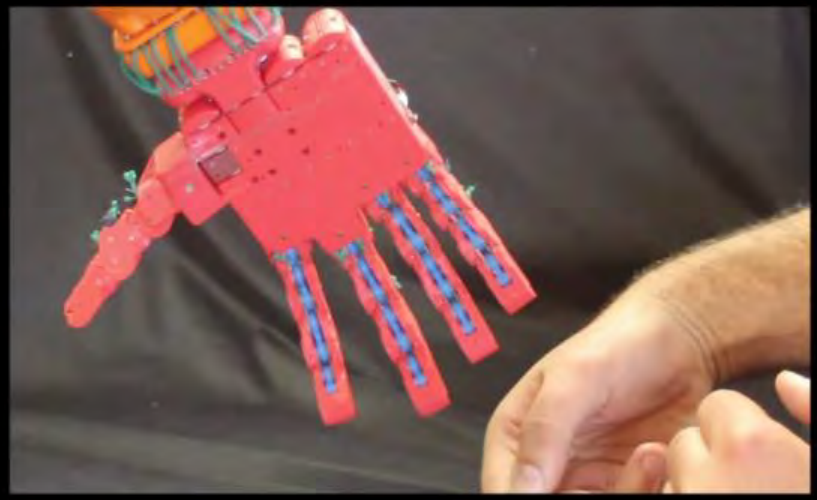


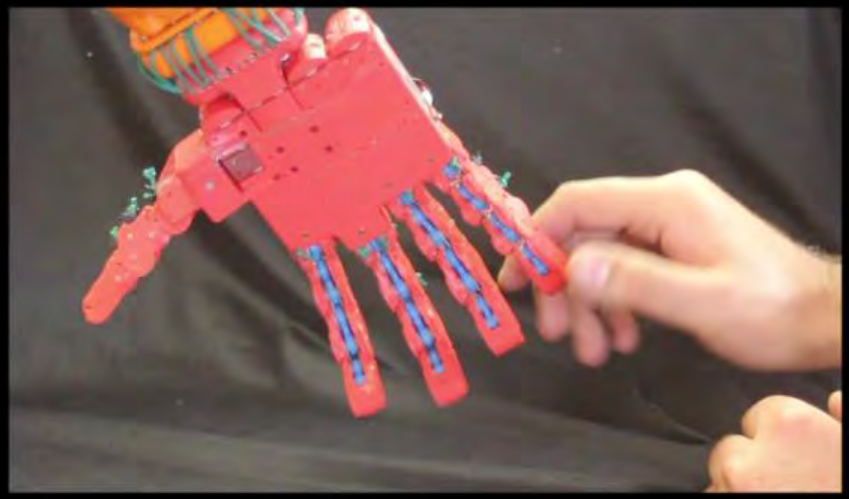
Grabbing Bottles – quick!



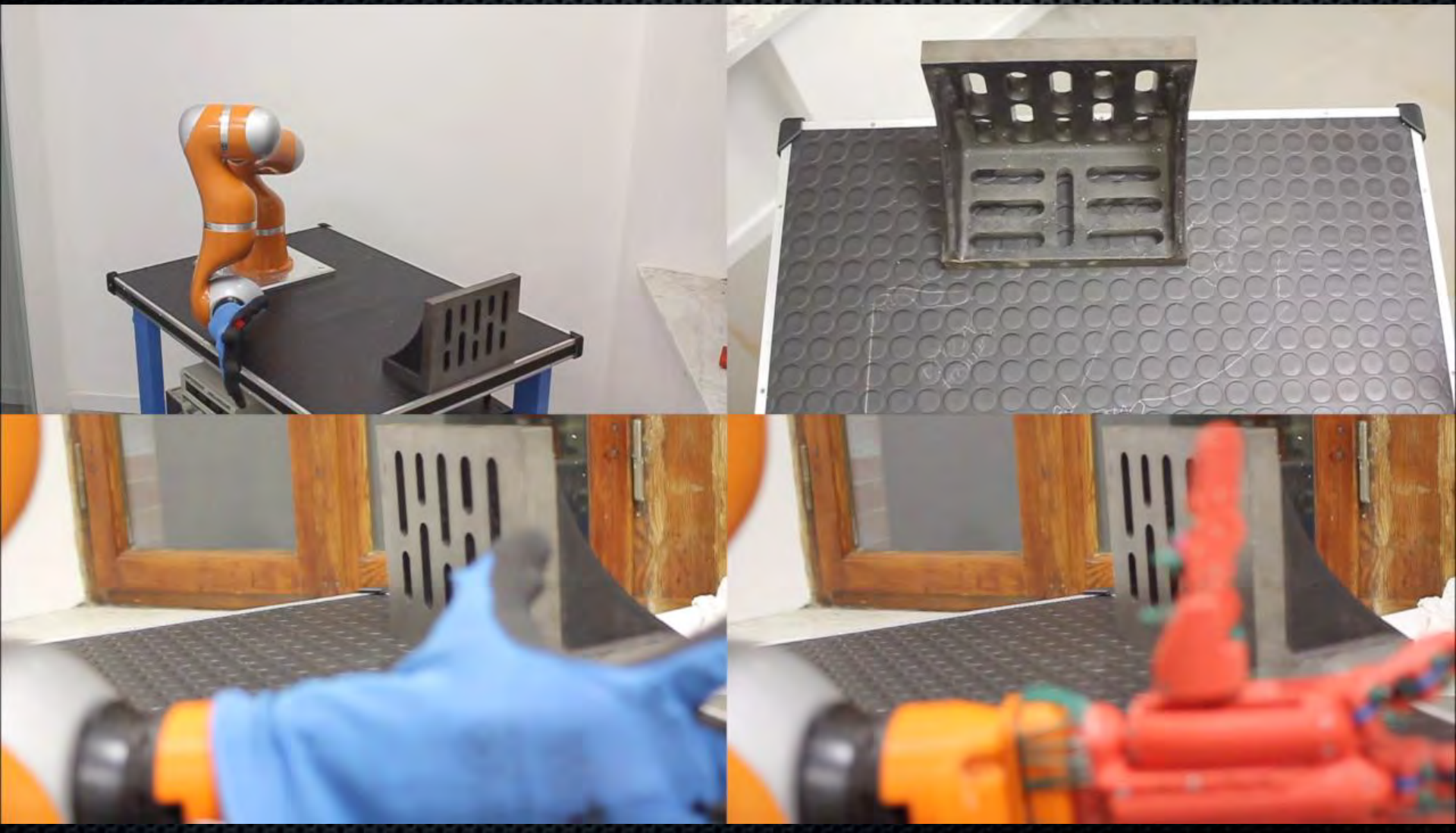
Safety & Robustness By Design





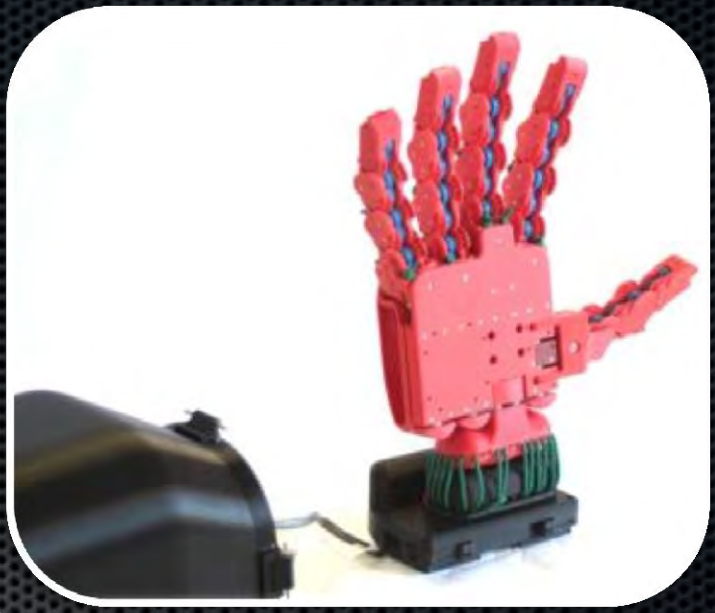


Grebenstein's Robustness Test



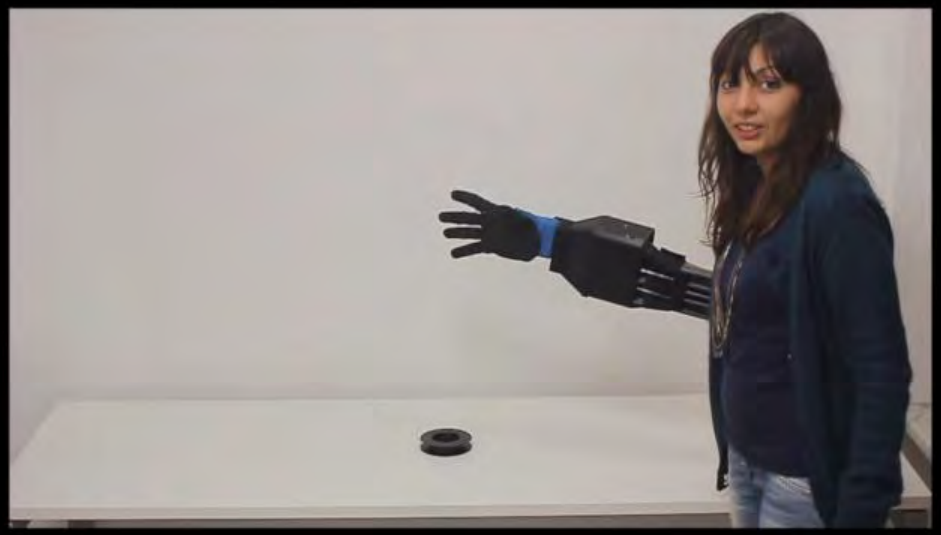
What does human use of a robot hand teach us?

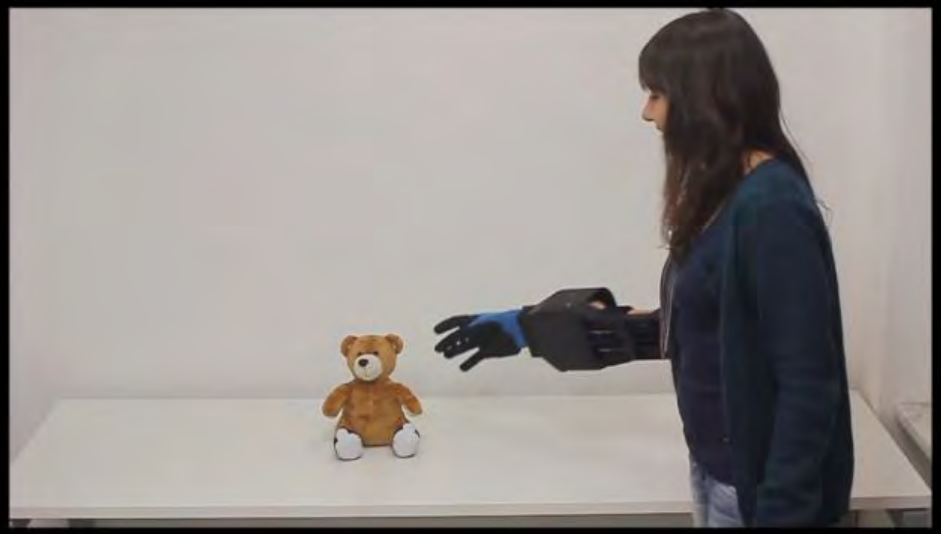
The Pisa-IIT SoftHand Human Interface

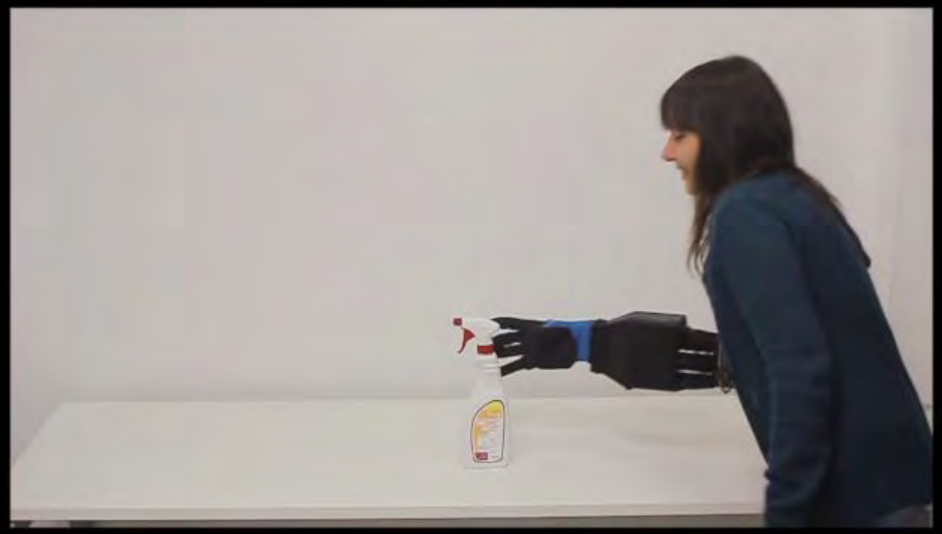


Humans can use the hand in a natural way

possibly because the hand befits our *body schema*



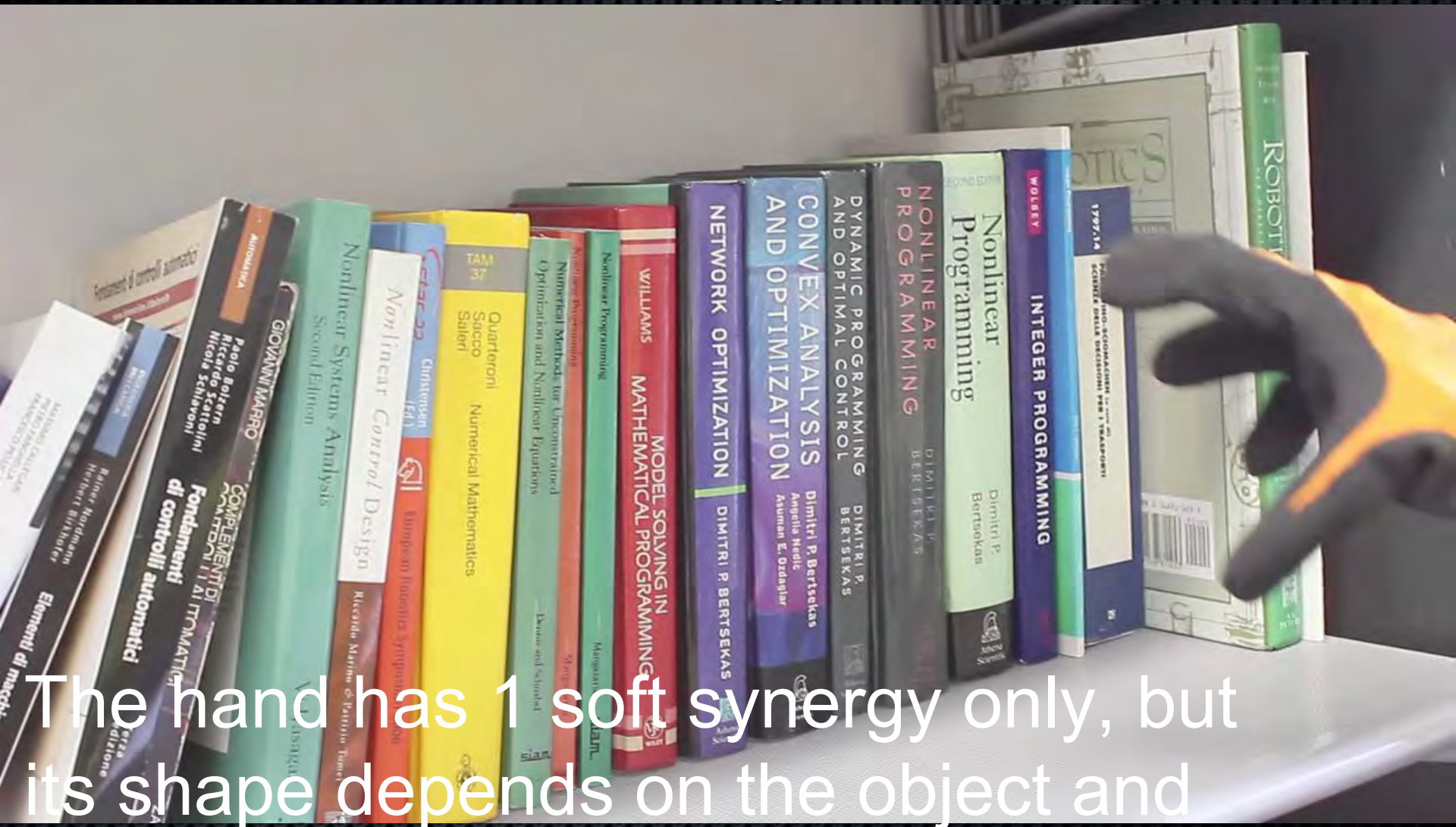




Wonders kids can do

look at this! →

Inspired by the creative manipulation of kids, use the hand as if your own…

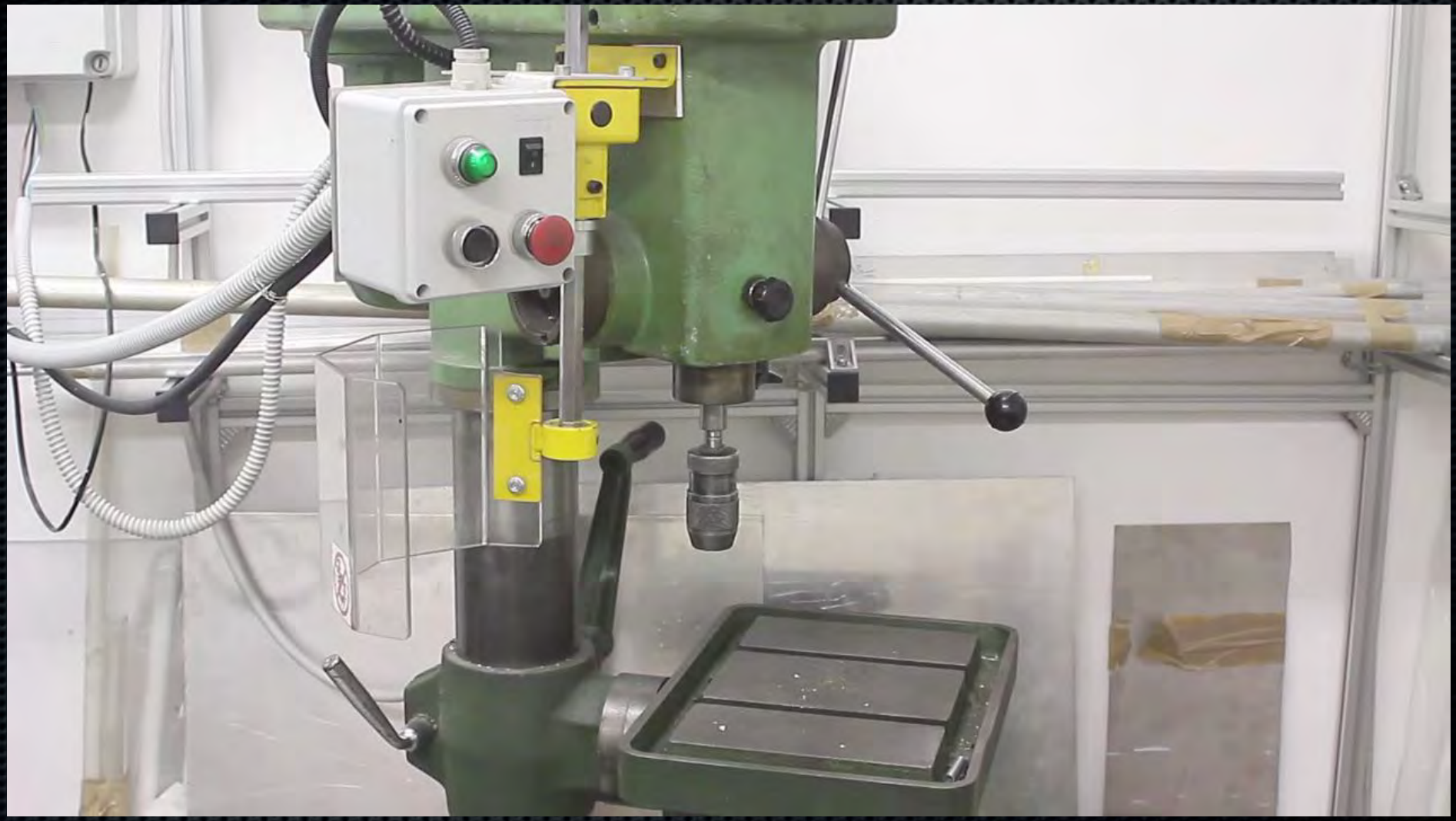


The hand has 1 soft synergy only, but its shape depends on the object and how it is approached

Push the hand against the environment to shape it - strongly

but also softly (from the same ream…)

A Workshop for Robotic Hands



my preferred clip…

Flicking, Throwing, Catching

Soft, not weak

questions

- Can we program a robot to use a soft, simple robot hand as effectively as humans?
- Using simple, soft hands changes grasp planning deeply:
  - thinking where to place fingertips for maximizing grasp measures might be less important
  - thinking on how to approach the environment to shape the hand properly for a grasp is more relevant
- Reasoning about robot-environment interaction is key!

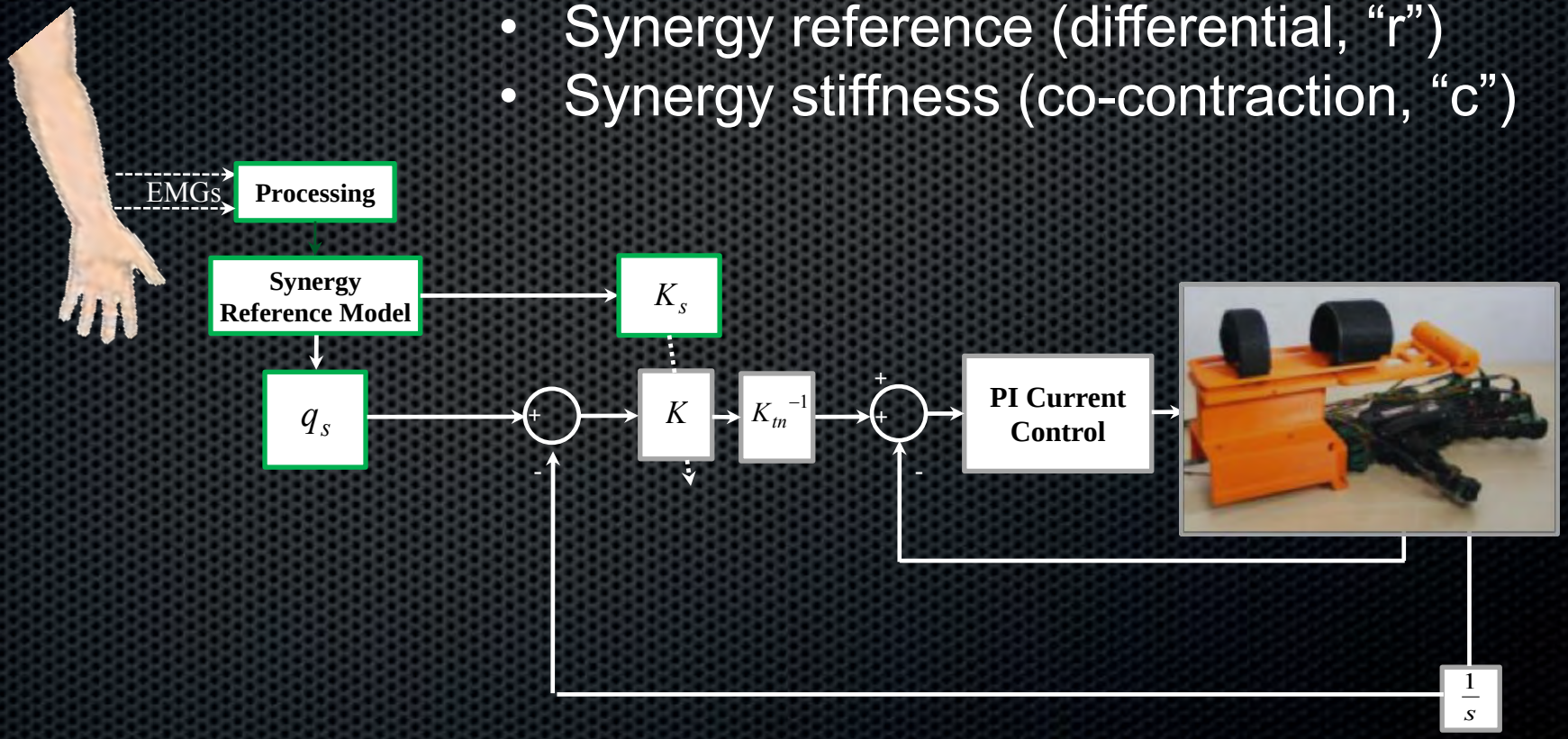
Body-Robot Interfaces

Toward Prosthetic Applications

Teleimpedance control

sEMG of FDS and EDC used for

- Synergy reference (differential, “r”)
- Synergy stiffness (co-contraction, “c”)



SoftHand Synergy References

$$\tau = a_\tau \delta$$

$$a_\tau \delta = I\ddot{q} + c\dot{q} + K_s(q - q_o)$$

$$q_{k+1} = (1 - \frac{K_s T}{c})q_k + \frac{T a_\tau}{c}\delta + \frac{K_s T}{c} q_o$$

$$\delta = \frac{a_q(1 - e^{-b_q(FDS-EDC)})}{(1 + e^{-b_q(FDS-EDC)})} \qquad K_s = \frac{a_k(1 - e^{-b_k(FDS+EDC)})}{(1 + e^{-b_k(FDS+EDC)})}$$

$\delta(FDS - EDC)$

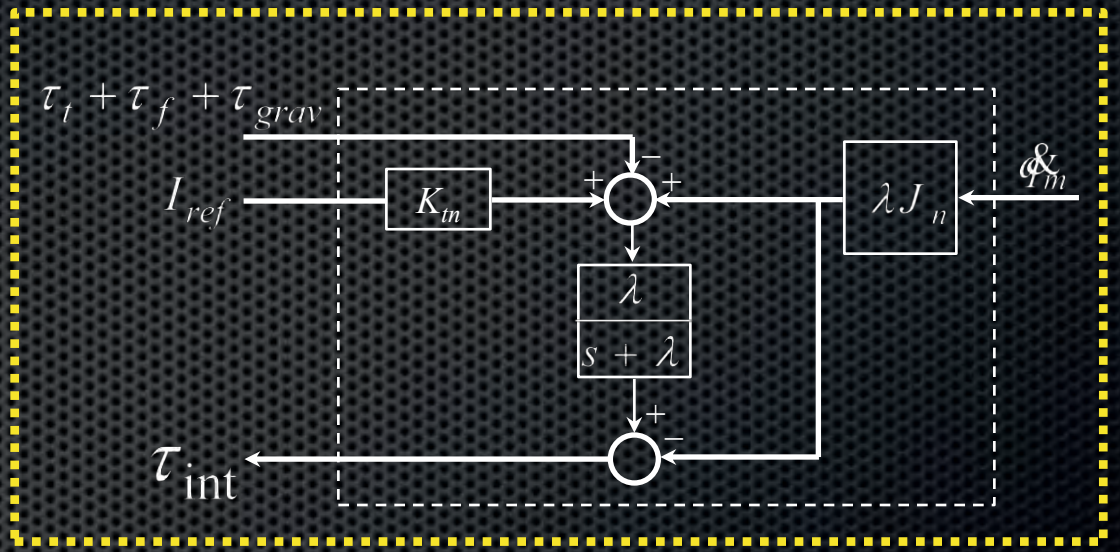
$K_s(FDS + EDC)$

Identification led to average 14% error across five subjects using the two main antagonistic flexor/extensor of the fingers

Interaction torque observer

$$J_n\ddot{q} = K_{tn}I - (\underbrace{\tau_{te} + \tau_f + \tau_{grav}}_{\tau_{model}} + \tau_{inte})$$

$$\tau_{model} = \begin{cases} D_1\dot{q} + n_{s1}K_{te}(q - q_0) & \dot{q} > 0 \\ D_2\dot{q} + n_{s2}K_{te}(q - q_0) & \dot{q} < 0 \end{cases}$$



$$\tau_{model} = K_{tn}I - J_n\ddot{q}$$

$$\hat{\tau}_{model}(s) = \frac{\lambda}{\lambda + s}(K_{tn}I - J_n s\dot{q})$$

$$= \frac{\lambda}{\lambda + s}(K_{tn}I + \lambda J_n\dot{q}) - \lambda J_n\dot{q}$$

$$\hat{\tau}_{int}(s) = \frac{\lambda}{\lambda + s}(K_{tn}I + \lambda J_n\dot{q} - \hat{\tau}_{model}) - \lambda J_n\dot{q}$$

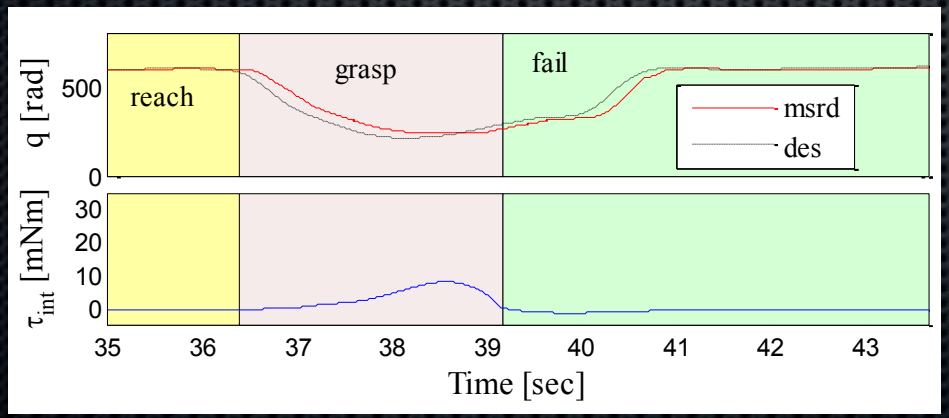
Pisa-IIT SoftHand

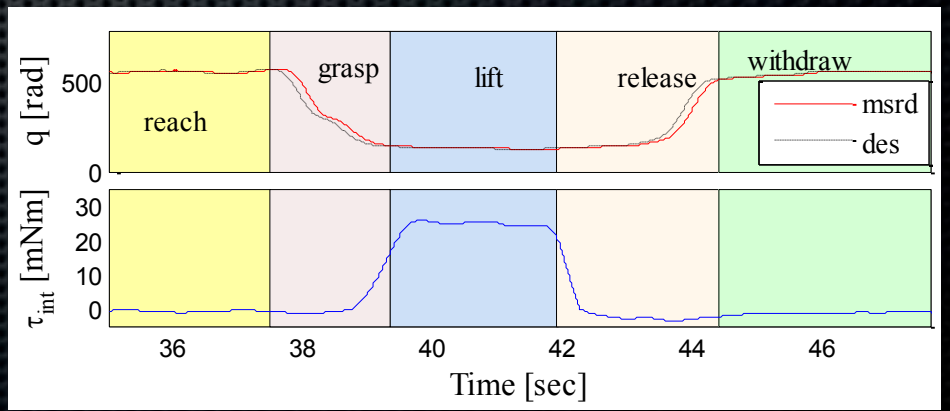
Classical controller

Too Compliant

Too Rigid

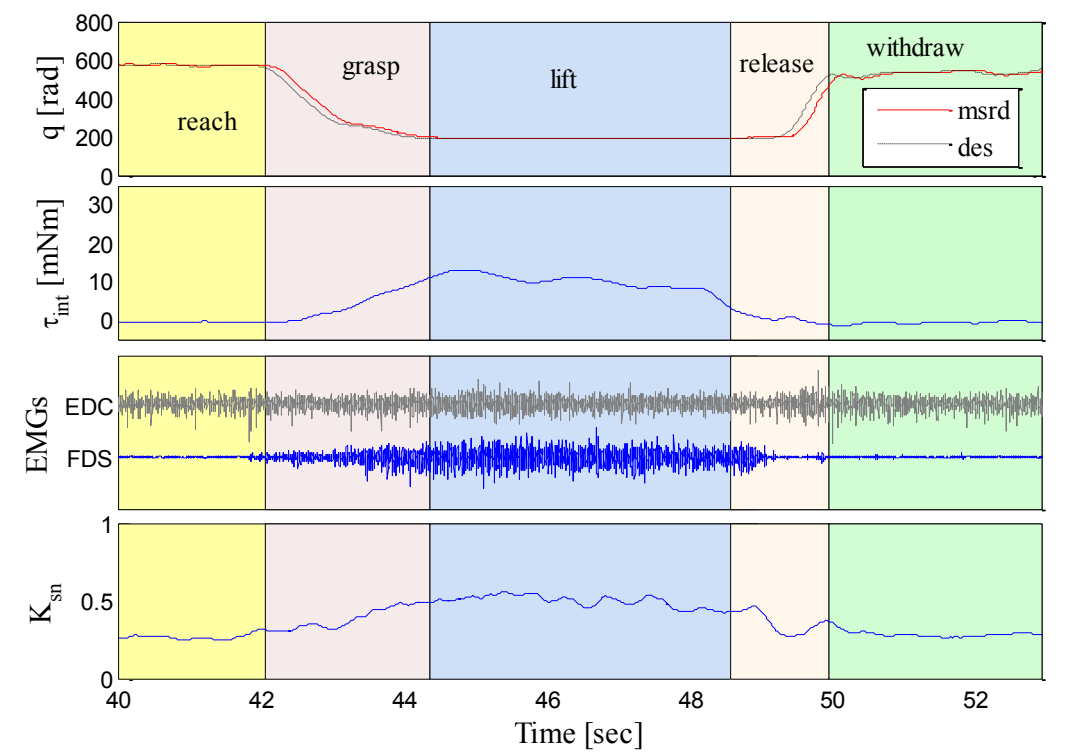
A fragile object might break



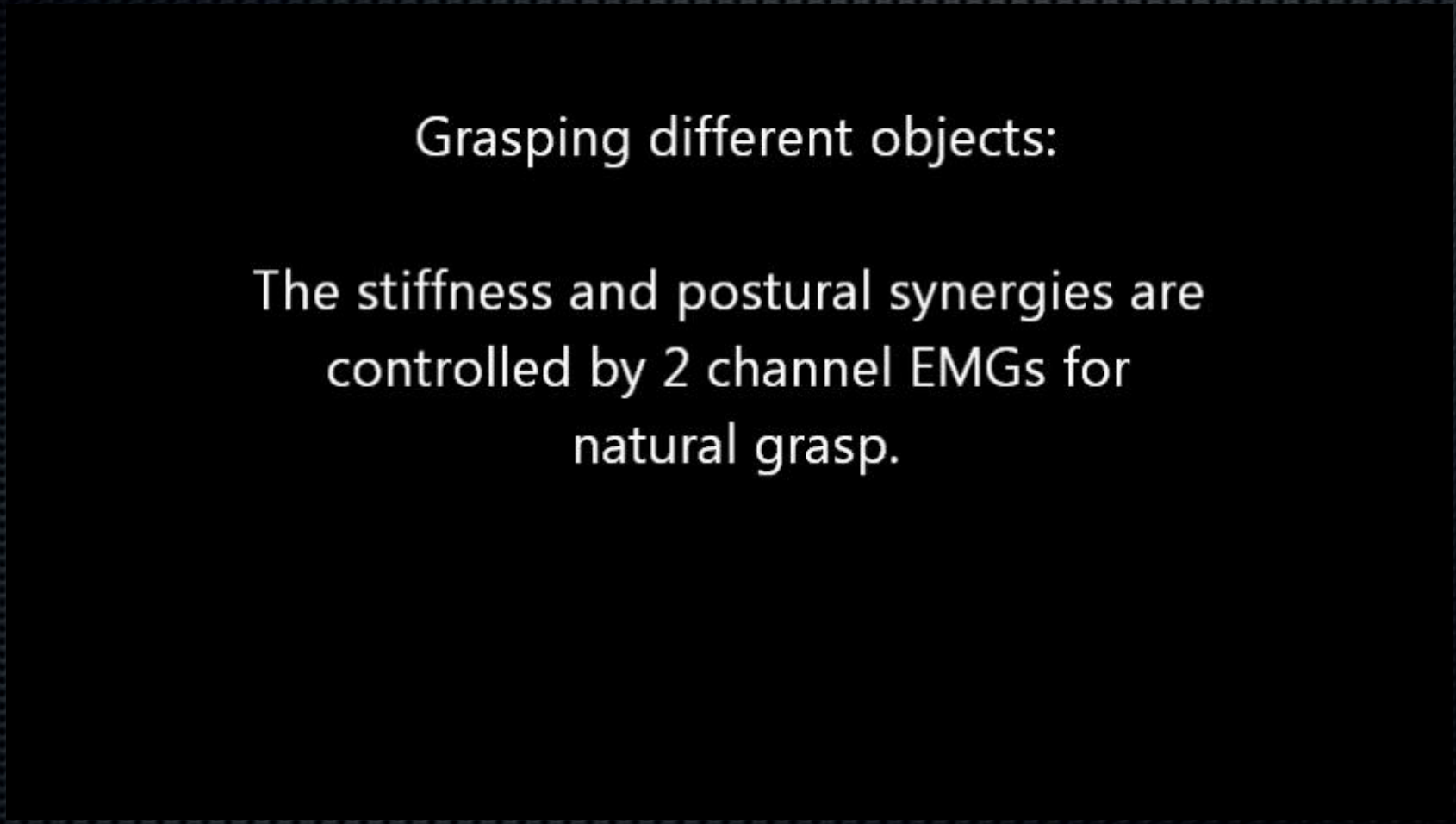


Teleimpedance Control

SoftHand executed under Teleimpedance controller



Teleimpedance control of the Pisa/IIT SoftHand



Feedback

Feedback to user would be great – but introducing complexity is just too easy.

What is the optimal tradeoff between functionality and complexity?

Feedback most useful to:

- Provide sense of grasp force to user to enable more secure grasp and allow grasp without visual feedback
- Provide sense of touch – contact acquisition, texture, slippage

Needs:

- Sense Grasping Force → Torque Observer (SW)
- Display Grasping Force → Cuff display

Toward Prosthetic Applications

Teleimpedance control +
Grasp force feedback

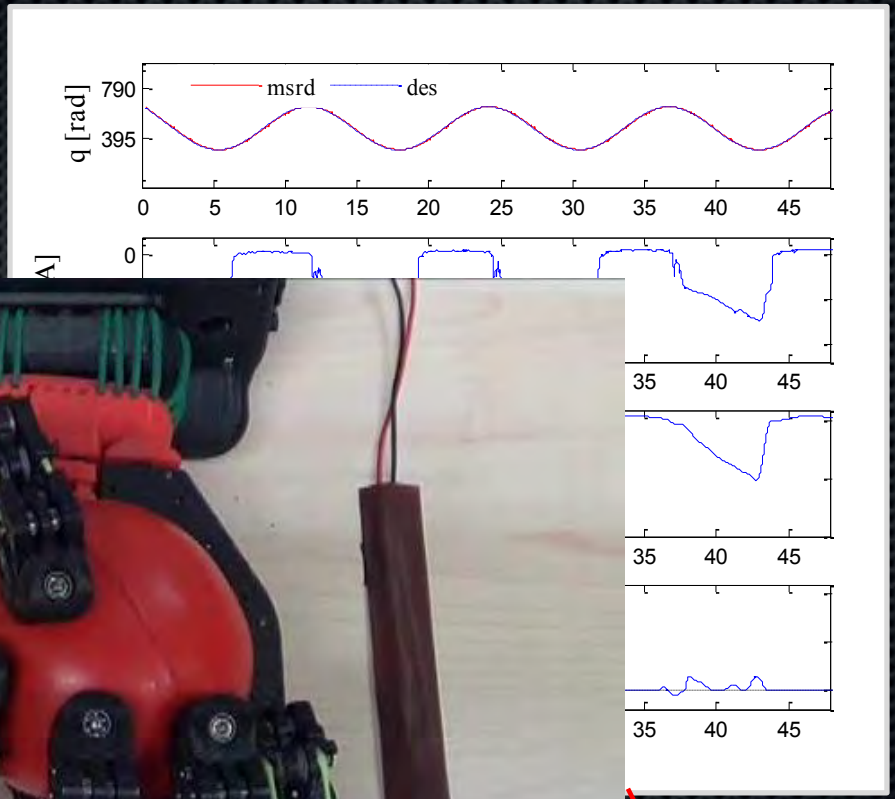
Torque observer

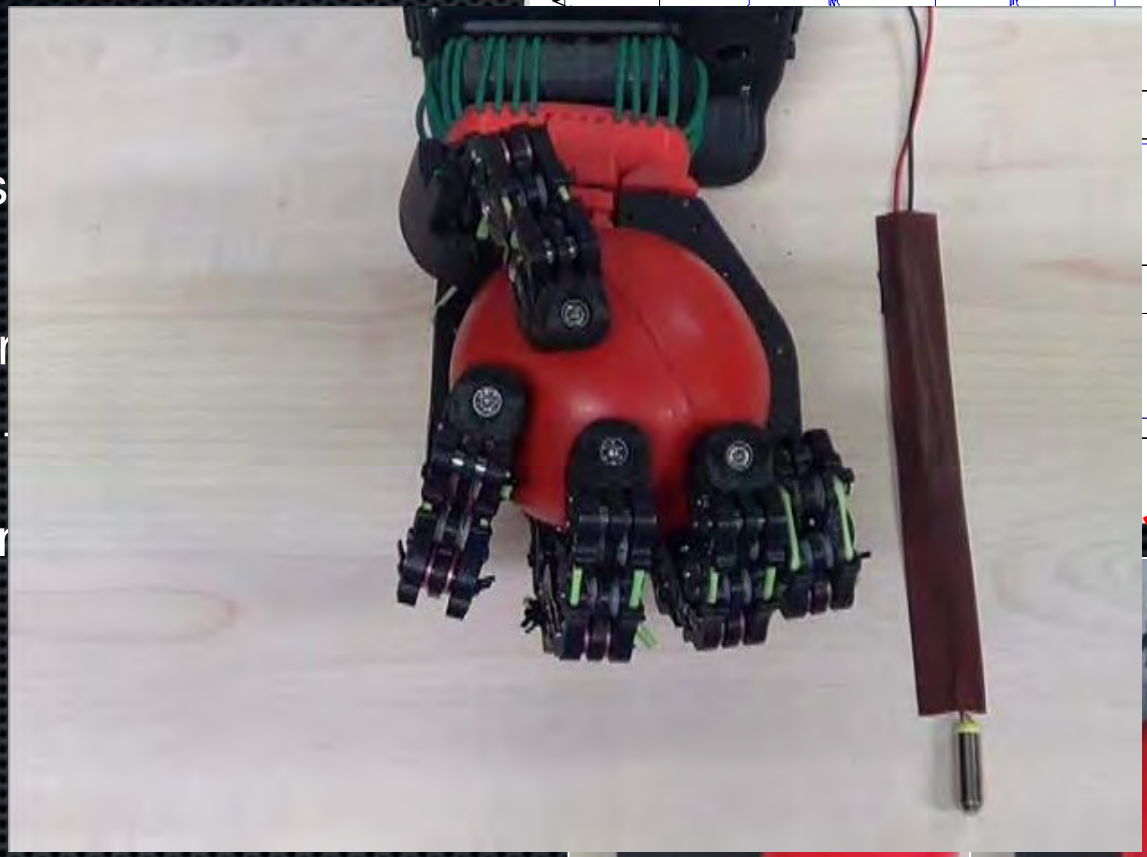
q : motor des
measured

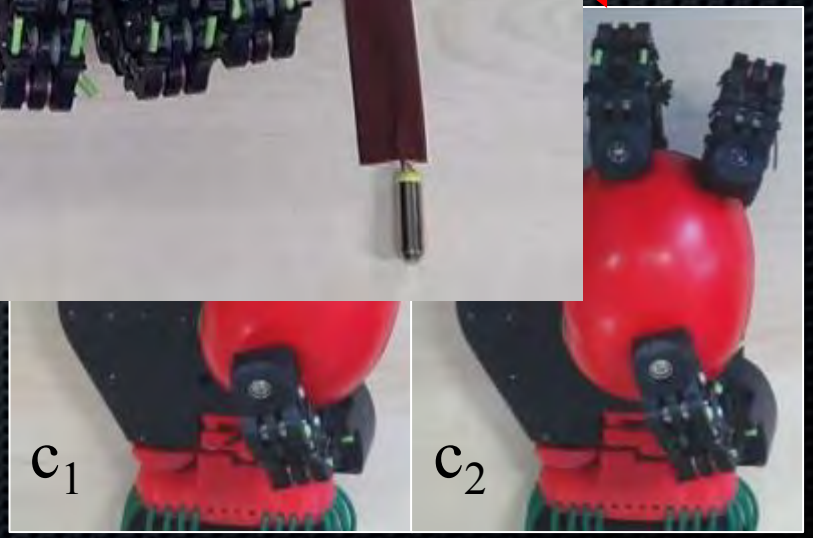
I_m : motor curr

V_m : motor Vol

τ_{int} : Interactior







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Needs:

- Sense Grasping Force → Torque Observer (SW)
- Display Grasping Force → Cuff display
- Tactile Sensors → Accelerometers
- Haptic Displays → Voice coils

Tactile Feedback

Touch sense mostly a dynamic sense: high frequency dominate contact detection, relative motion, texture recognition, slippage detection

→ Good Old Vinyl HiFi

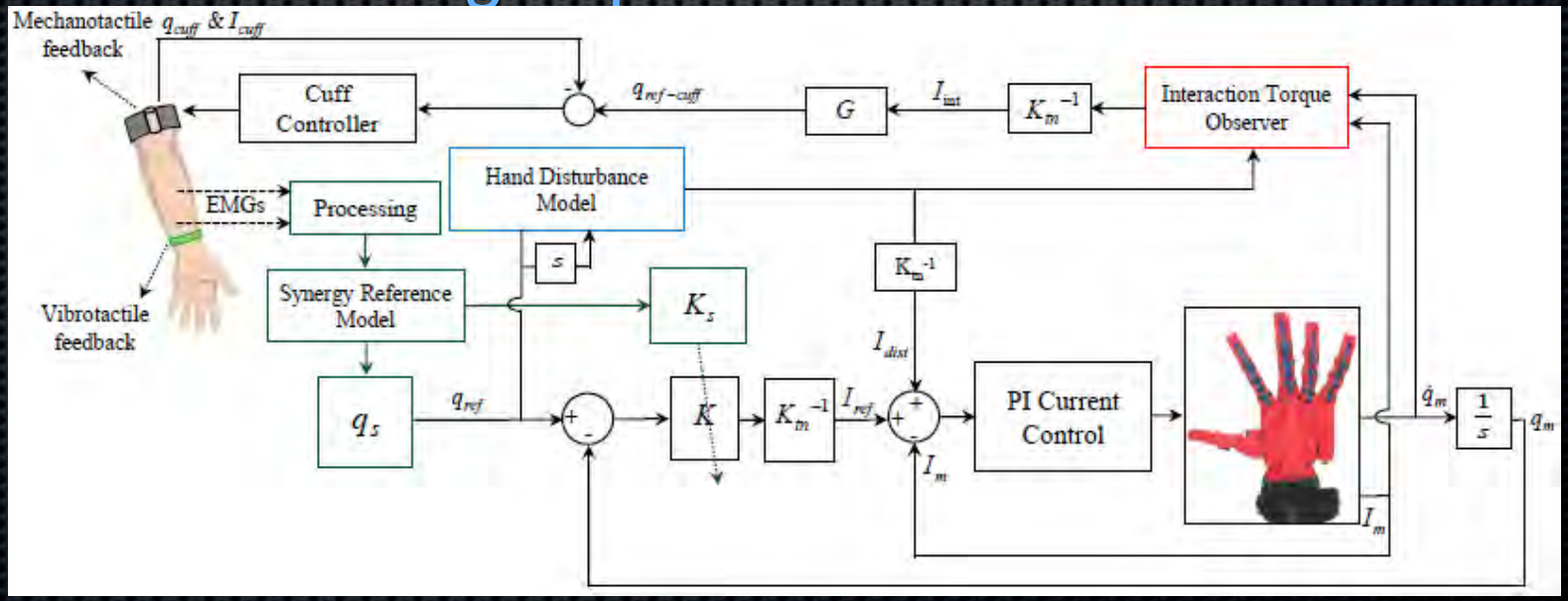
Needle: accelerometers (range ± 2g) on the dorsal part of the SoftHand phalanges pick up contact vibrations from environment

Amplifier: Hi-Fi amplifier minimizing signal distortion

Loudspeaker: voice coil (or vibratory eccentric motors) worn on the dorsal side of the forearm

EMG Control of the SoftHand

- sEMG of FDS and EDC used for
  - –Synergy reference (differential, “r”)
  - –Synergy stiffness (cocontraction, “c”)
- Additionally, use an interaction torque observer to determine grasp force and feed back to user



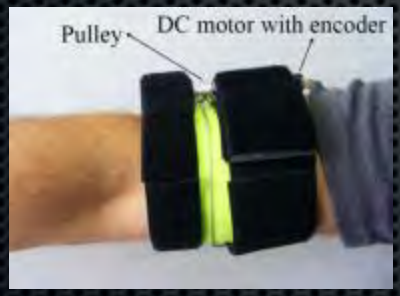
Feedback Types

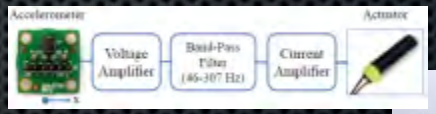
Mechanotactile Force Feedback

- Goal: provide sense of grasp force to user to enable more secure grasp and allow grasp without visual feedback
- Method: The interaction torque observer is used to determine the grasp force. This force is then experimentally scaled and delivered to:
  - Small DC motor attached to a band encircling the arm; as the motor turns, the band gets tighter, resulting in modality matching force feedback

Vibrotactile Surface Texture Feedback

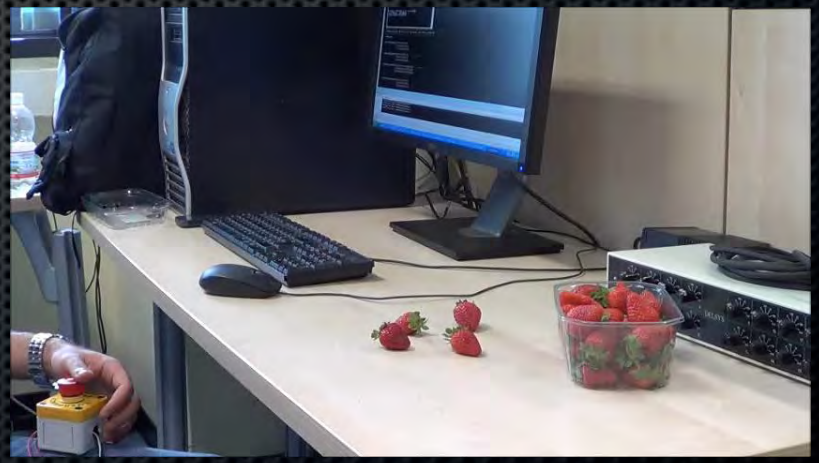
- Goal: provide knowledge of surface texture to aid in exploration and grasping without visual feedback [1]
- Method: Accelerometers (range ± 2g) on the dorsal part of the SoftHand phalanges registered variations in surface texture. Data from the x-axis was then replicated on the user side with small eccentric mass motors worn on the dorsal side of the forearm





[1] K. Kuchenbecker, J. Gewirtz, W. McMahan, D. Standish, P. Martin, J. Bohren, P. Mendoza, and D. Lee, "Verrotouch: High-frequency acceleration feedback for telerobotic surgery," in Haptics: Generating and Perceiving Tangible Sensations, ser. Lecture Notes in Computer Science, A. Kappers, J. Erp, W. Bergmann Tiest, and F. Helm, Eds. Springer Berlin Heidelberg, 2010, vol. 6191, pp. 189–196.

Pisa-IIT SoftHand with EMG Teleimpedance: Strong but Delicate



Pisa-IIT SoftEspresso

Applications to Prosthetics

INAIL
ISTITUTO NAZIONALE PER L'ASSICURAZIONE CONTRO GLI INFORTUNI SUL LAVORO

MAYO CLINIC

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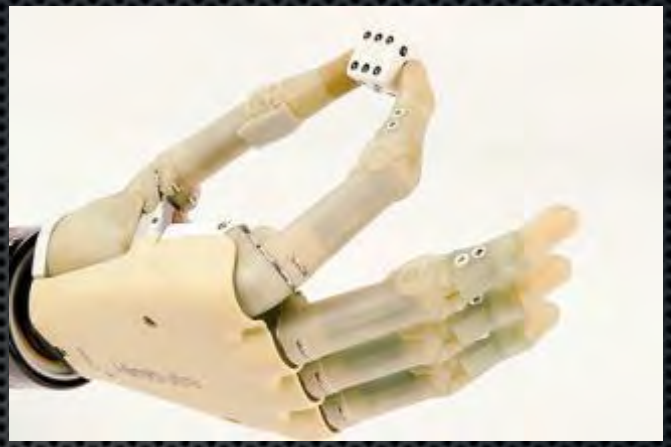
ISTITUTO ITALIANO DI TECNOLOGIA

ASU ARIZONA STATE UNIVERSITY

Commercial Upper-Limb Prostheses

Mioelectric Hands
(Otto Bock)

Standard Hook (Hosmer)



Touch Bionics *i-Limb Ultra*

Otto Bock *Michelangelo*

RSL Steeper *BeBionic 3*

Softhand Pro

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NATIONAL INSTITUTES OF HEALTH

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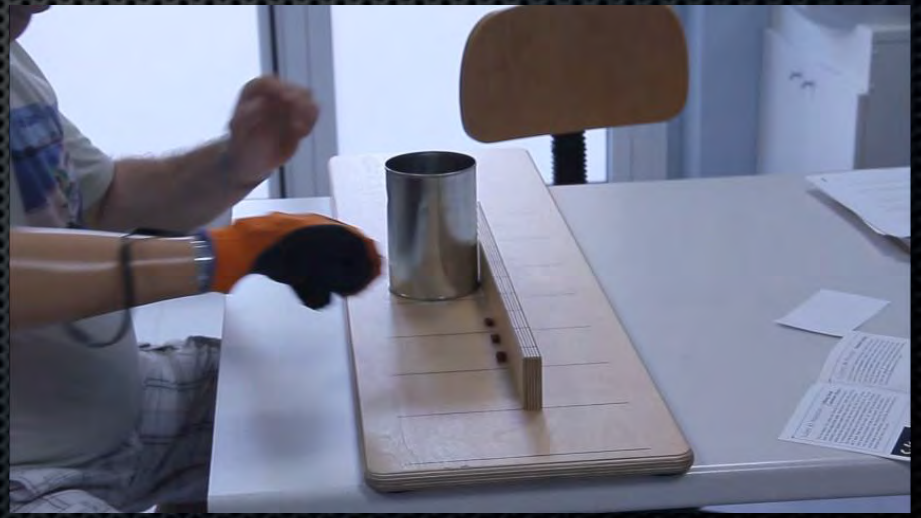


CANOTTIERI
AERONAVALE

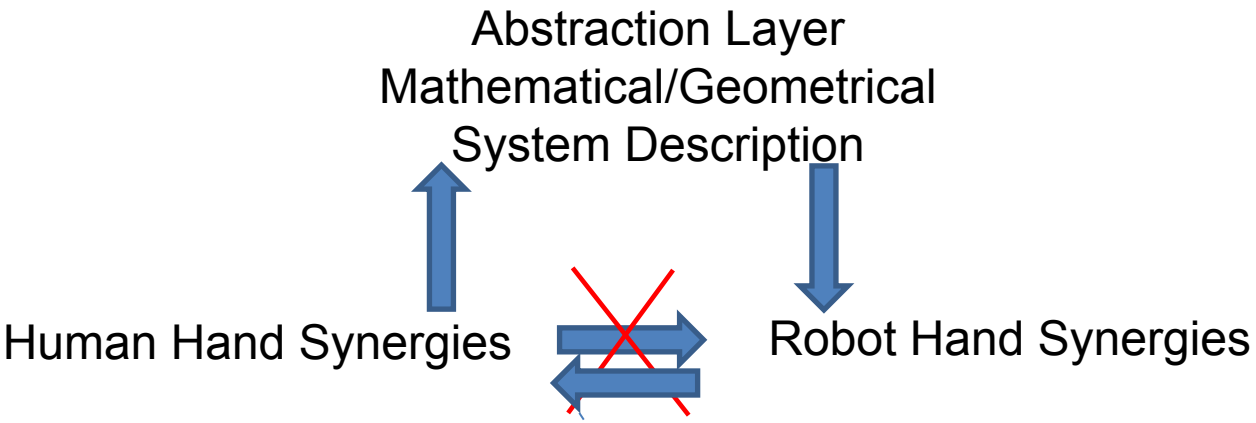
AERONAVALE

Discussion

- Bio Awareness means knowing Biology concepts and applying to Robotics – *not copycatting*, though…
- There is also something Robotics can contribute towards the understanding of human synergies:

  – A study of the role of synergies in grasp force distribution and force closure

  – A mathematical description of the geometry of sensorimotor synergies

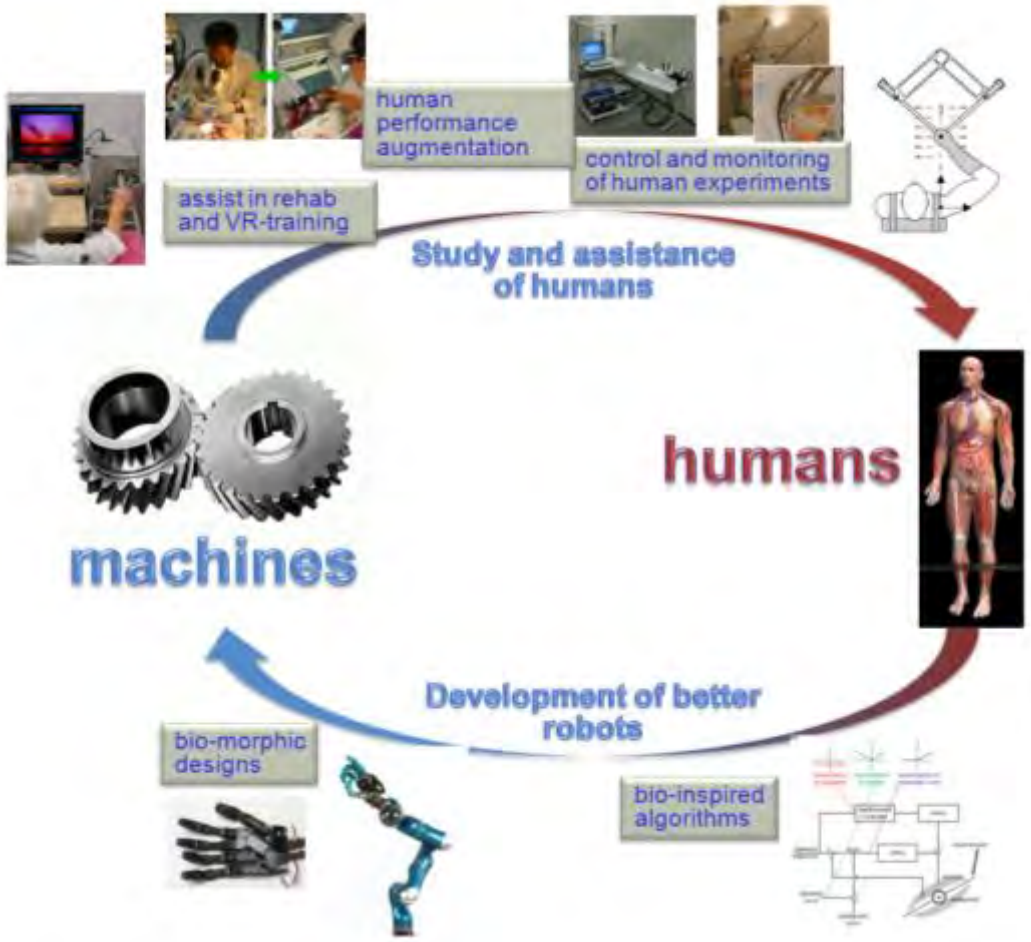


Embodied Intelligence

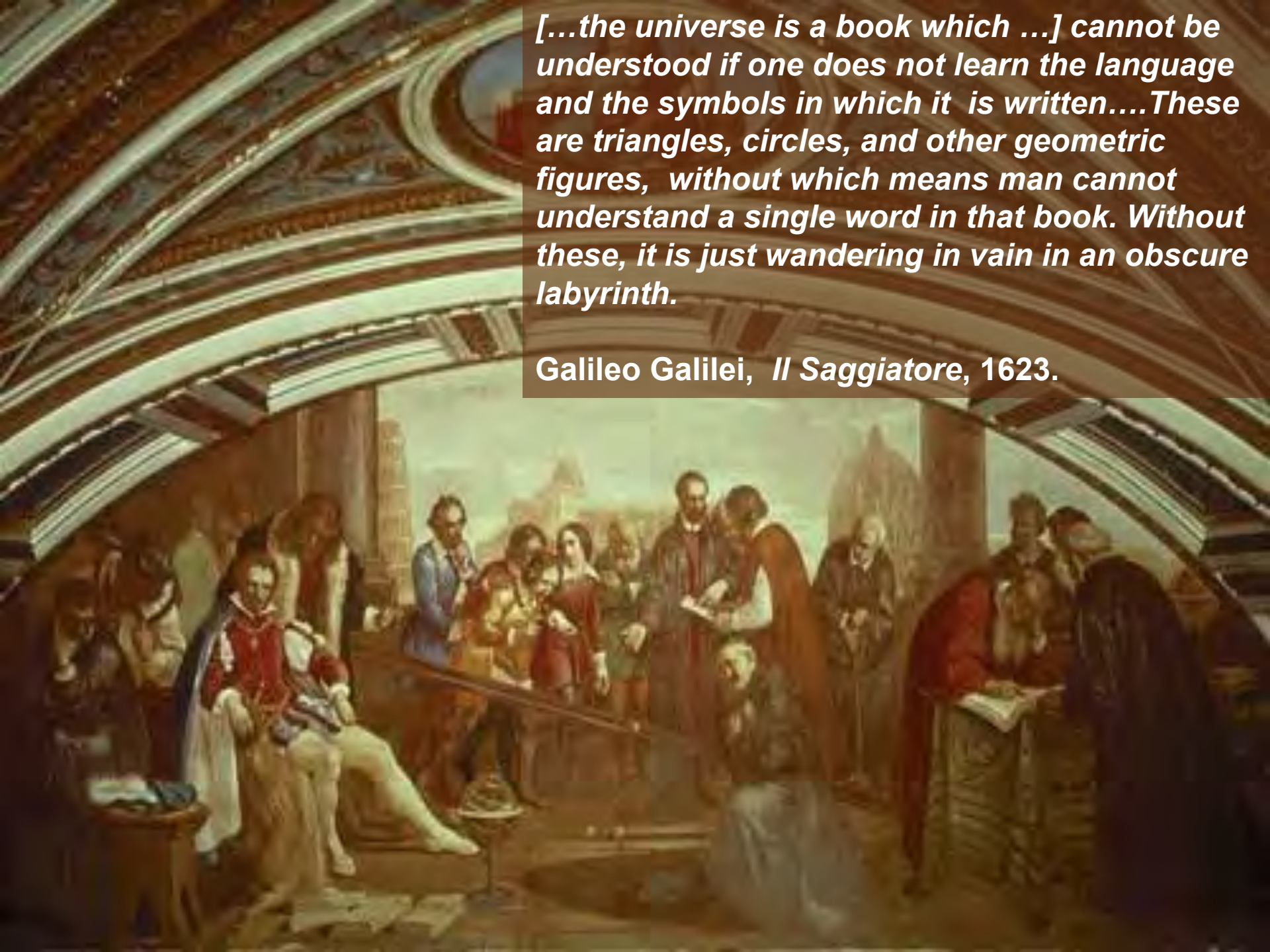
- There can't be a Mind without a Body
- Anatomy of the Body does not tell much about the Mind – nor would a mere "Xerox" approach to artificial life do

[…the universe is a book which …] cannot be understood if one does not learn the language and the symbols in which it is written….These are triangles, circles, and other geometric figures, without which means man cannot understand a single word in that book. Without these, it is just wandering in vain in an obscure labyrinth.

Galileo Galilei, Il Saggiatore, 1623



- **Build a Science** of Embodied Intelligence
- **Abstract** the insight from nature in terms of mathematical models
- **Apply** the new theory to achieve the technology our society is asking for



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PROGRAMME
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Thanks!