Minimality and Under-Sensing: A human-inspired Approach

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with

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Centro E. Piaggio
bioengineering and robotics research center

iit ADVR Advanced Robotics

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ROBOTICS SCIENCE AND SYSTEMS
June 18-22, 2016 University of Michigan

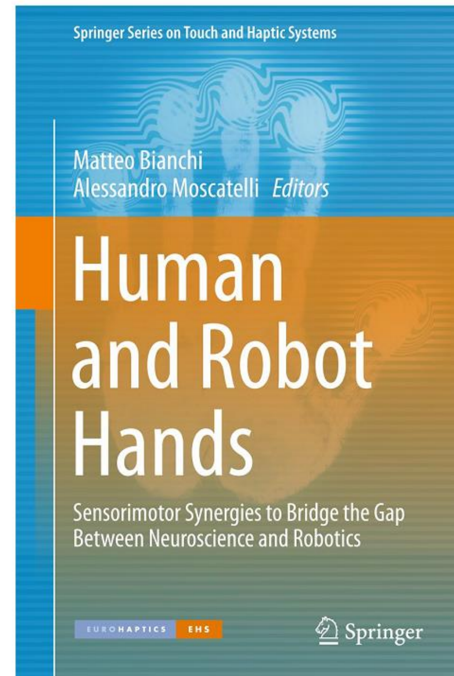
WORKSHOP

Human Hands and Robot Hands

http://www.centropiaggio.unipi.it/~bianchi

Haptics

Sensing



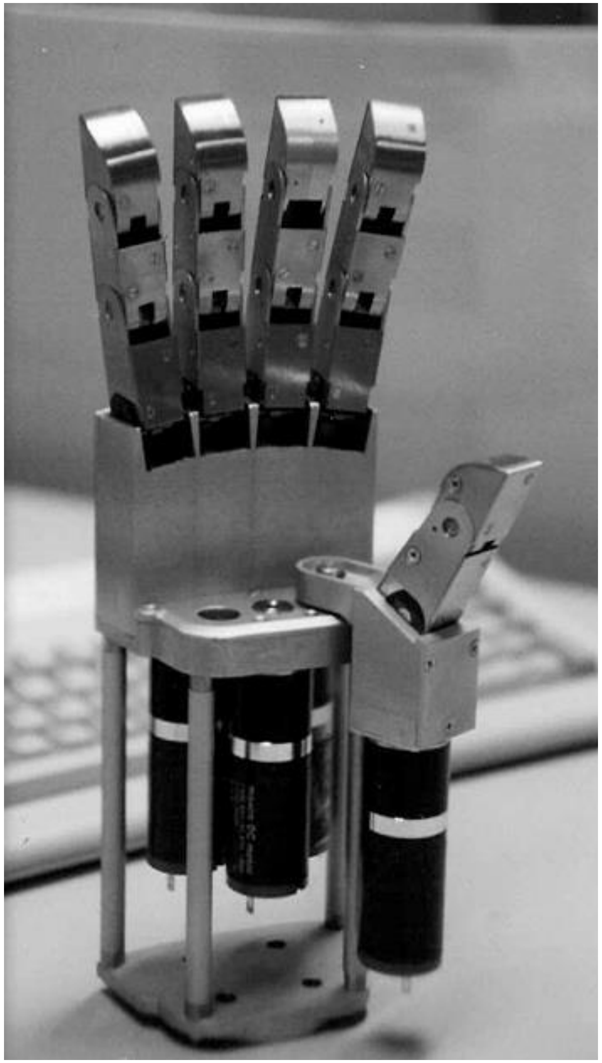
SoftPro

softpro.eu

Under-Actuation and Robot Hands

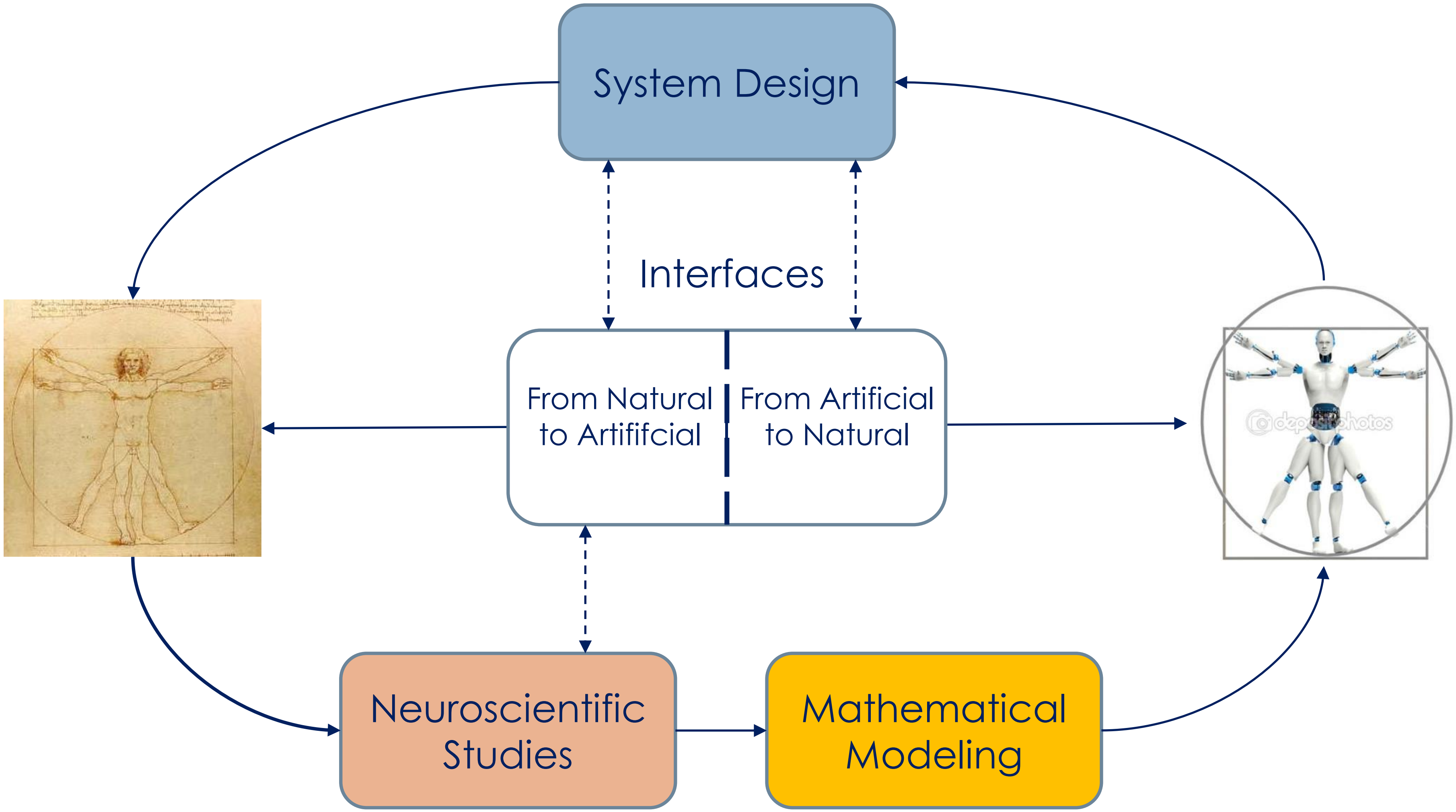
- Pros:
  - Small size, weight, low cost
  - Adaptable, enveloping grasps
- Cons:
  - Theoretical underpinnings not clearly spelled out

Not quite a new idea....

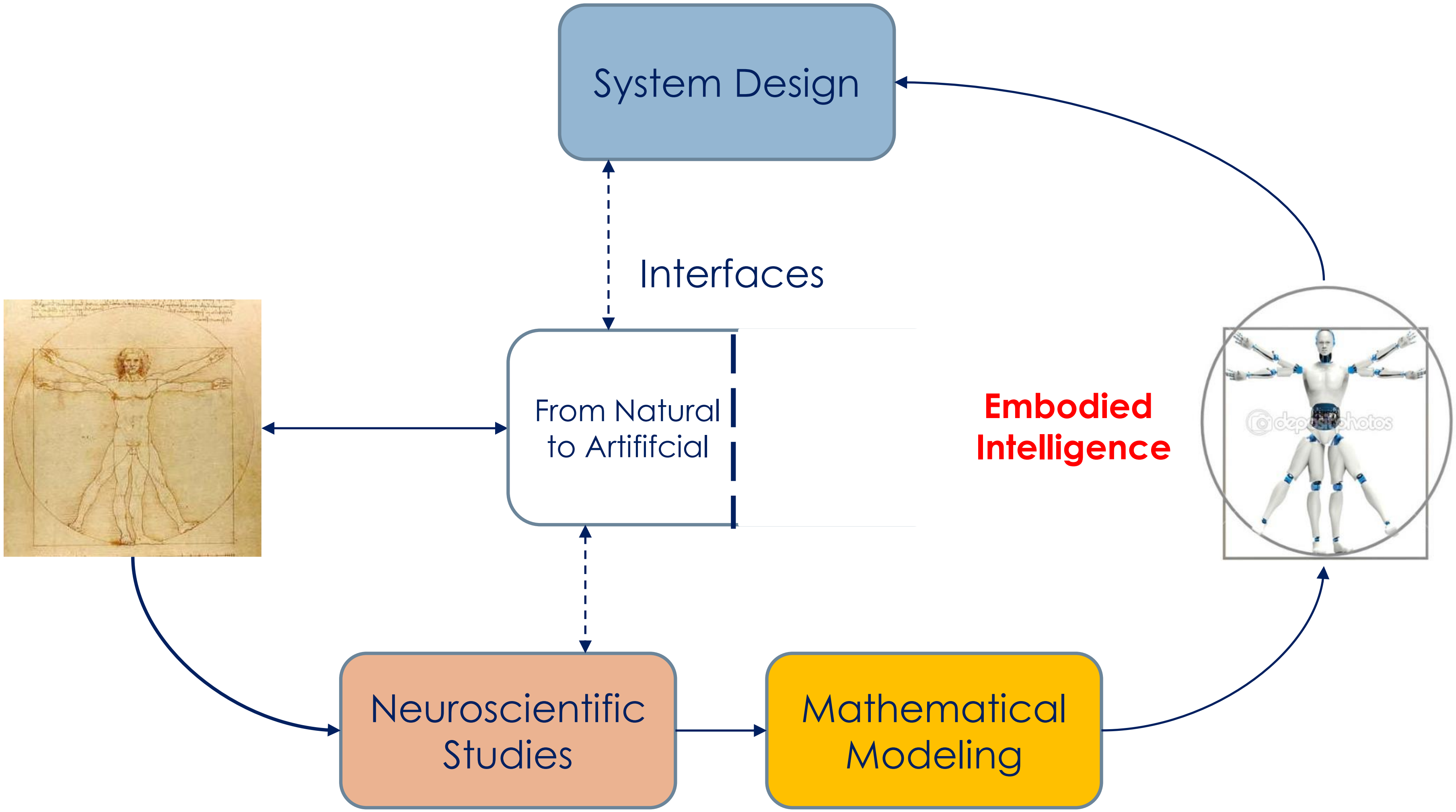


USC - Belgrade Hand [ca. 1962]

From Humans to Robots and Back Again



From humans to robots…



Artificial, Our Mirror…

- Human behavior is an **extraordinary source of inspiration**
- **Bio-Aware Robotics** - knowing Biology and Ergonomics concepts is good for doing Robotics – *copycatting* is not
- Translating neuroscientific observations into a **mathematical language**, which can be understood by artificial systems and used to inform a more **simple** and **effective** device design

Mathematical/Geometrical System Description

Human Hand/Haptics

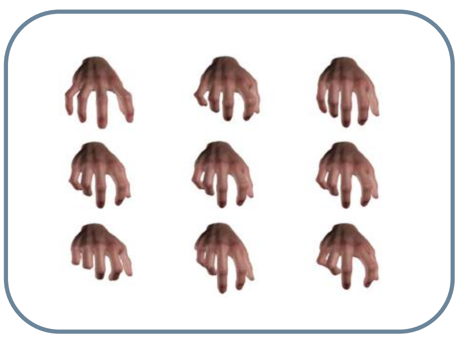
Robot Hand/ Sensing Systems

Synergy-based Approach

Extensive neuroscientific studies have demonstrated that human central nervous system controls movements in a **synergistic manner** (Babinski (1914!), Bernstein, Latash, Bizzi, Soechting, D'Avella…)

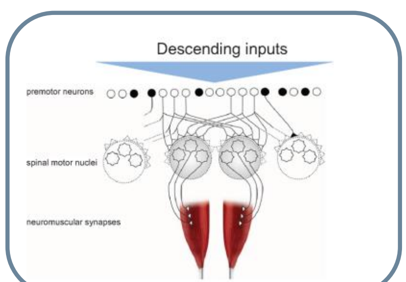
- **Synergies** can be defined as *''a collection of relatively independent degrees of freedom that behave as a single functional unit''* [Turvey et al. 2007]
- With special focus on **human hand**, synergies denote *patterns of voluntary muscular activity and multi joints activation*, and can be defined at different levels [Santello et al. 2013]

Kinematic



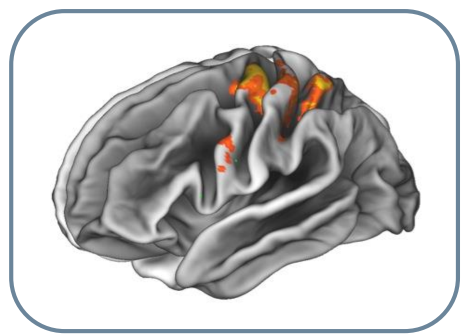
[Santello et al. 1998]

Muscular



[Ting and McKay 2007]

Neural



[Leo et al. 2016]

Implication for Robotics: A Road Towards Simplification

SoftHand Pro

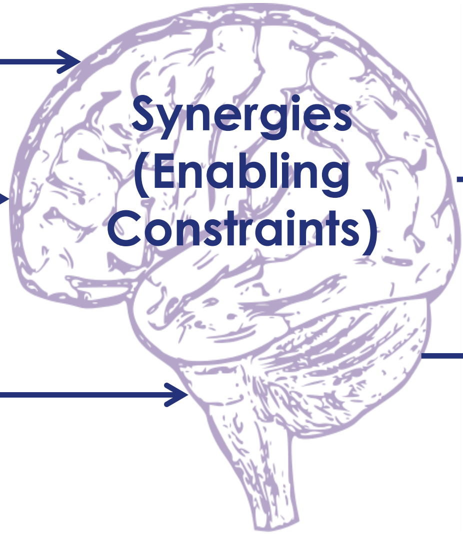
El_1

El_2

•

•

El_n



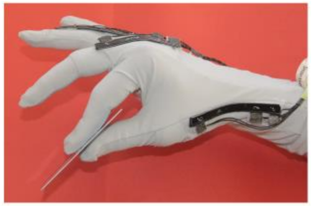
In_1

•

In_m

Elements (n):
e.g. joints…

Control Inputs (m < n)

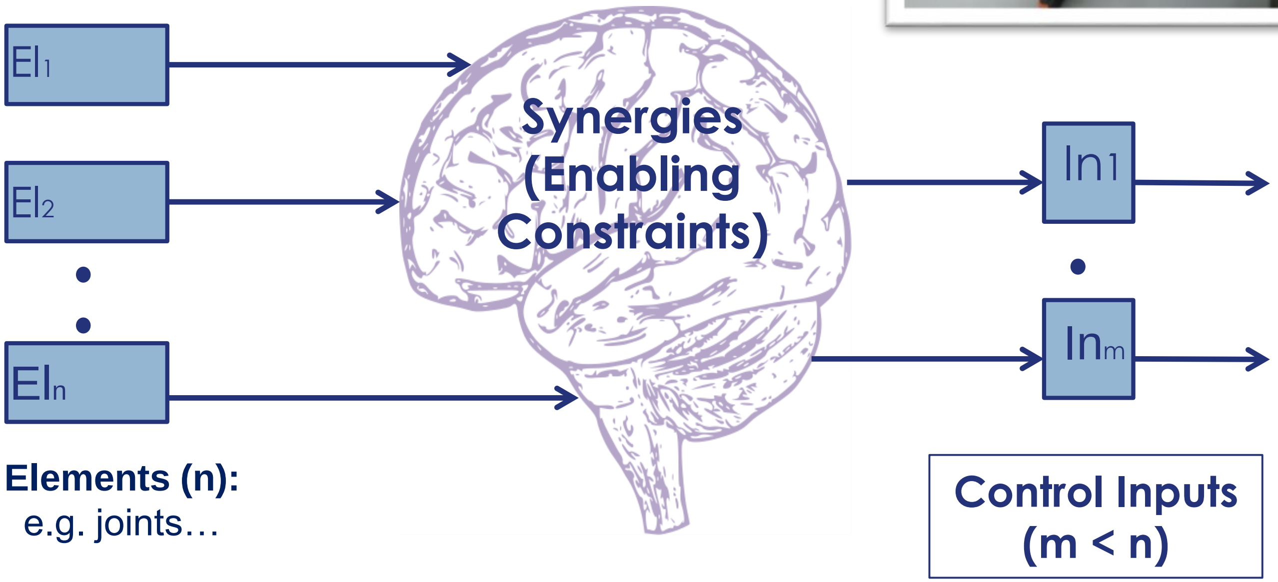


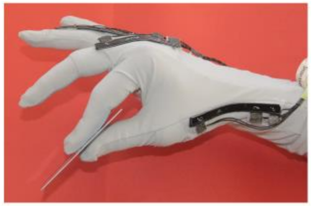
- 29 major joints
- ≥ 29 major and minor bones
- ≥ 123 named ligaments
- 34 muscles
- 48 named nerves
- 30 named arteries

[Catalano et al. 2014]
[Brown and Asada, 2007]
[Bianchi et al, 2013]

Implication for Robotics: A Road Towards Simplification

SoftHand Pro





Elements (n):
e.g. joints…

Enabling Constraints

To design robotic devices with a reduced number of control inputs and actuators

[Catalano et al. 2014]
[Brown and Asada, 2007]
[Bianchi et al, 2013]

The Shape of Synergies

Glossary: "Postural Synergies" = Principal Components of Grasp A Priori Covariance Matrix $S_i = u_i(Po)$

(1-st synergy)

Few linear combinations of hand DoFs explain most of the variance

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

First synergy alone more than 50%

[Santello et al.,1998]

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[Santello et al.,1998]

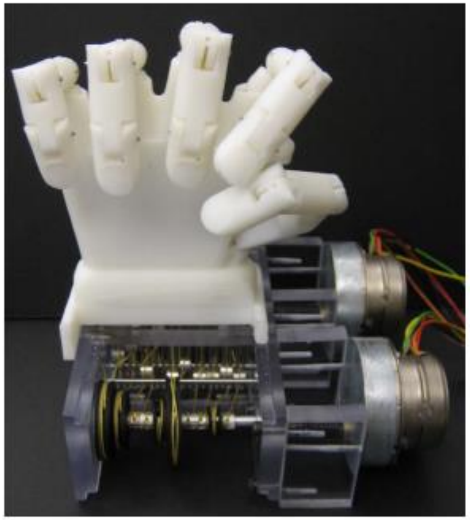
Direct Mechanical Synergies

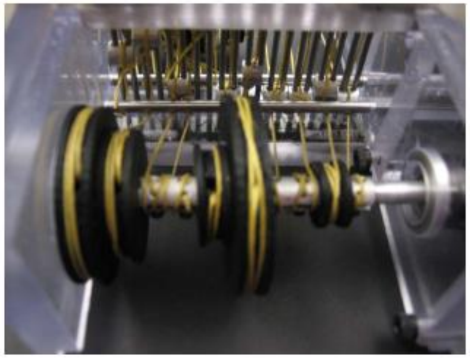
- Implement the first k synergies with pulley trains

$$\sigma^{(k)} \in \Re^{k}$$

$$\dot{q} = S[\sigma_1 \,|\, \sigma_2 \,|\, \ldots \,|\, \sigma_k \,|\, 0 \,|\, \ldots \,|\, 0] = S^{(k)} \dot{\sigma}^{(k)}$$

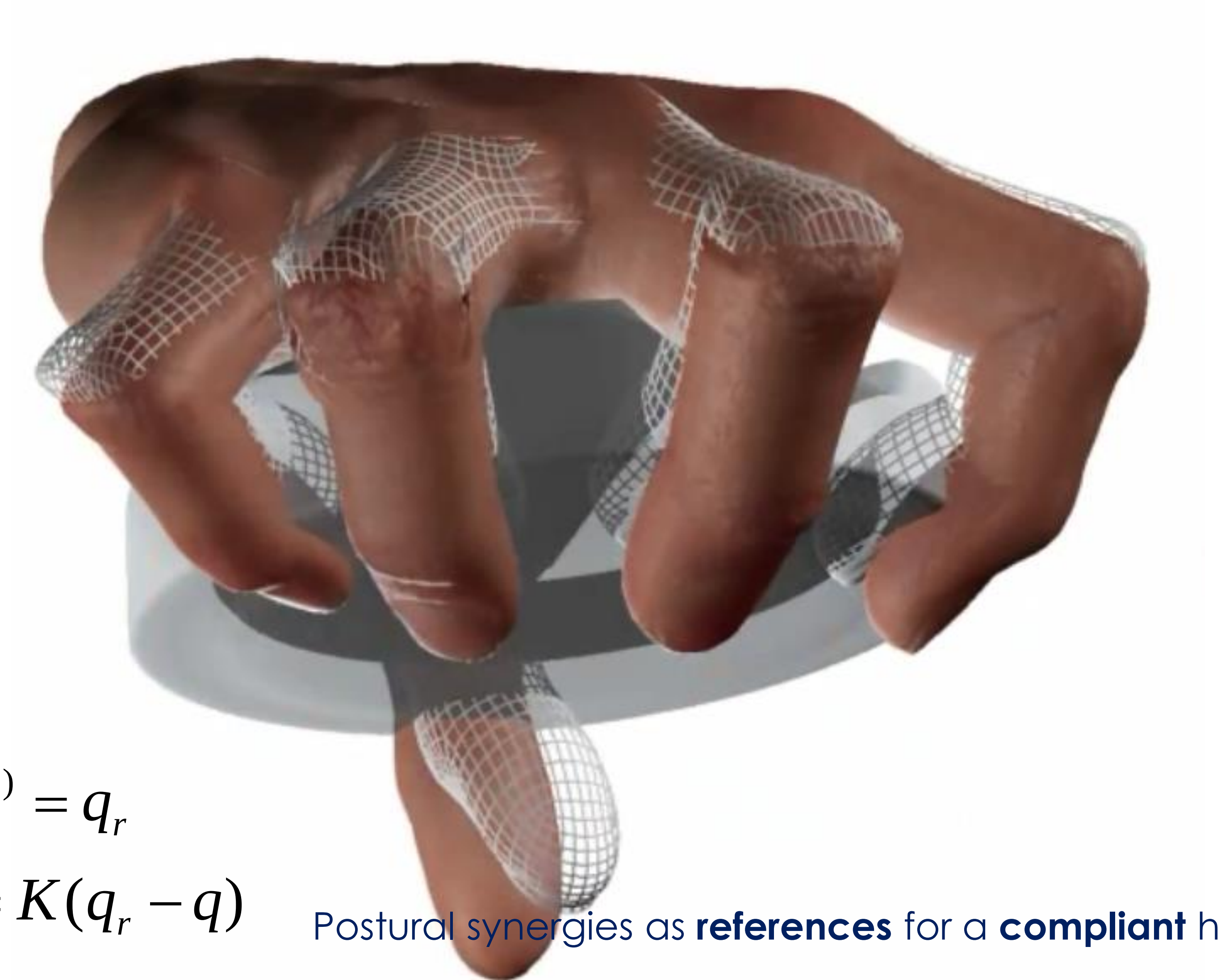
- Pros:
  - Natural (synergy space) control
  - Less motors
- Cons:
  - No adaptation
  - Few contact points
  - No grasp force control





[Brown and Asada, 2007]

Soft-Synergy Model
[Bicchi et al. 2011]



$$\begin{cases} S^{(k)}\sigma_r^{(k)} = q_r \\ J^T f_c = K(q_r - q) \end{cases}$$

Postural synergies as **references** for a **compliant** hand

Under-Actuation and Adaptive Synergies

- Self (adaptive) motions

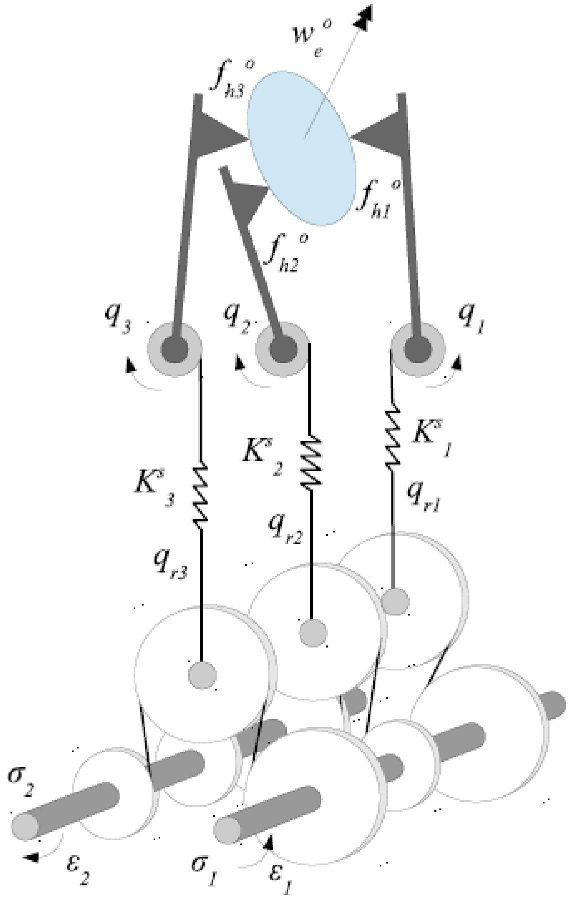
$$q = S^{(k)}\sigma^{(k)} + N^{(k)}\lambda$$

- Balance of actuator, recoil springs and contact forces

$$J^T f = R^T f - Eq$$

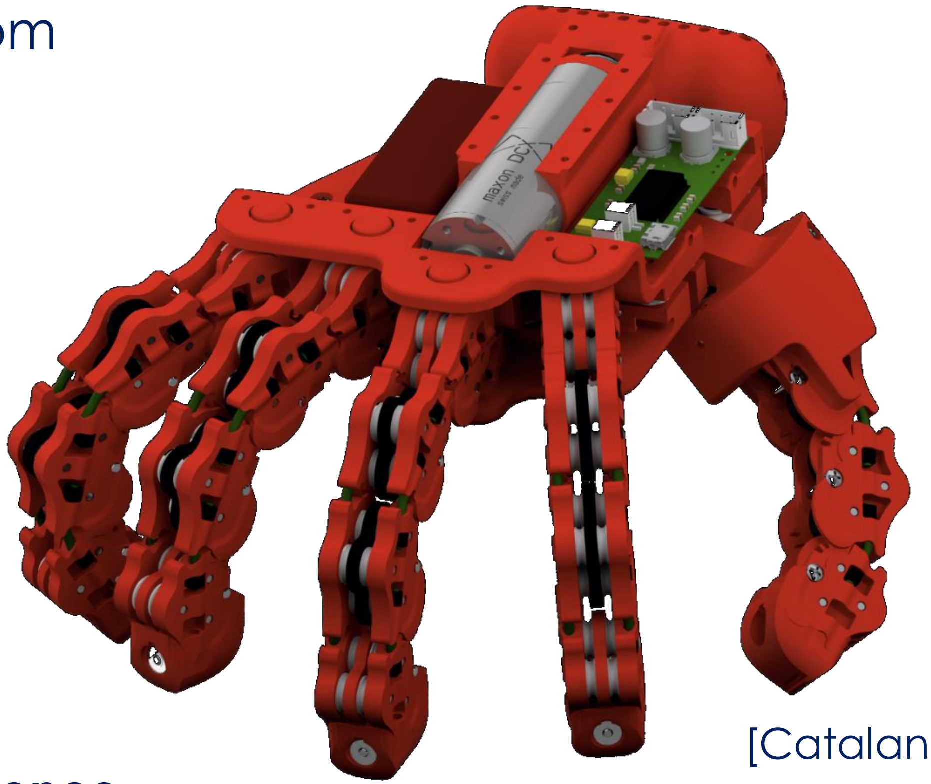
- Design **springs** (E) and **pulley trains** (R) to achieve desired behavior

$$S^{(k)} = E^{-1}R^T(RE^{-1}R^T)^{-1}$$



The PISA/IIT Soft Hand

19 degrees of freedom
1 Motor to move



[Catalano et al. 2014]

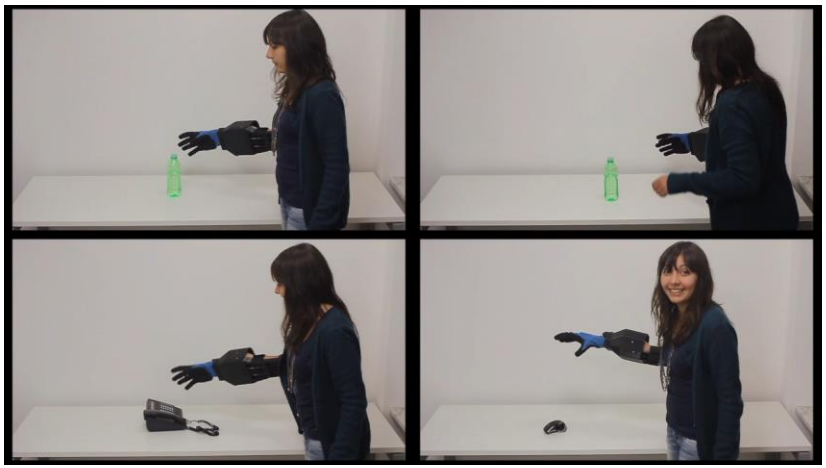
Embodied Intelligence

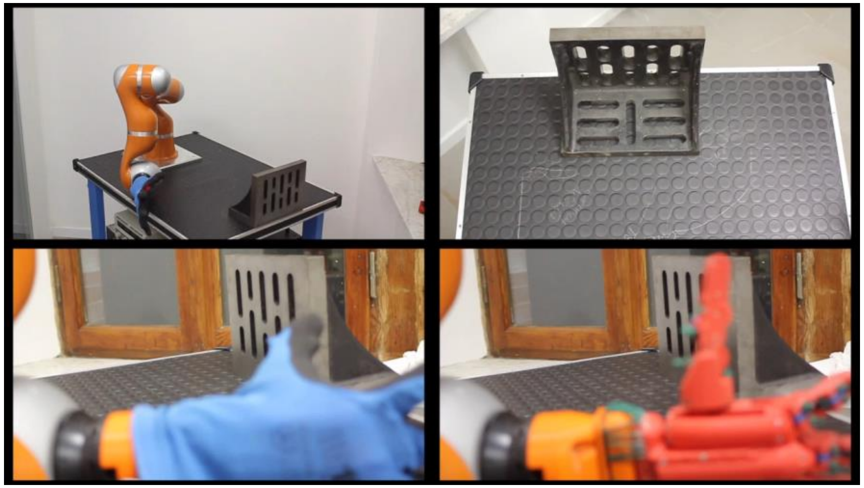
Simple mechanics
Easy to control

Robust
Adaptive

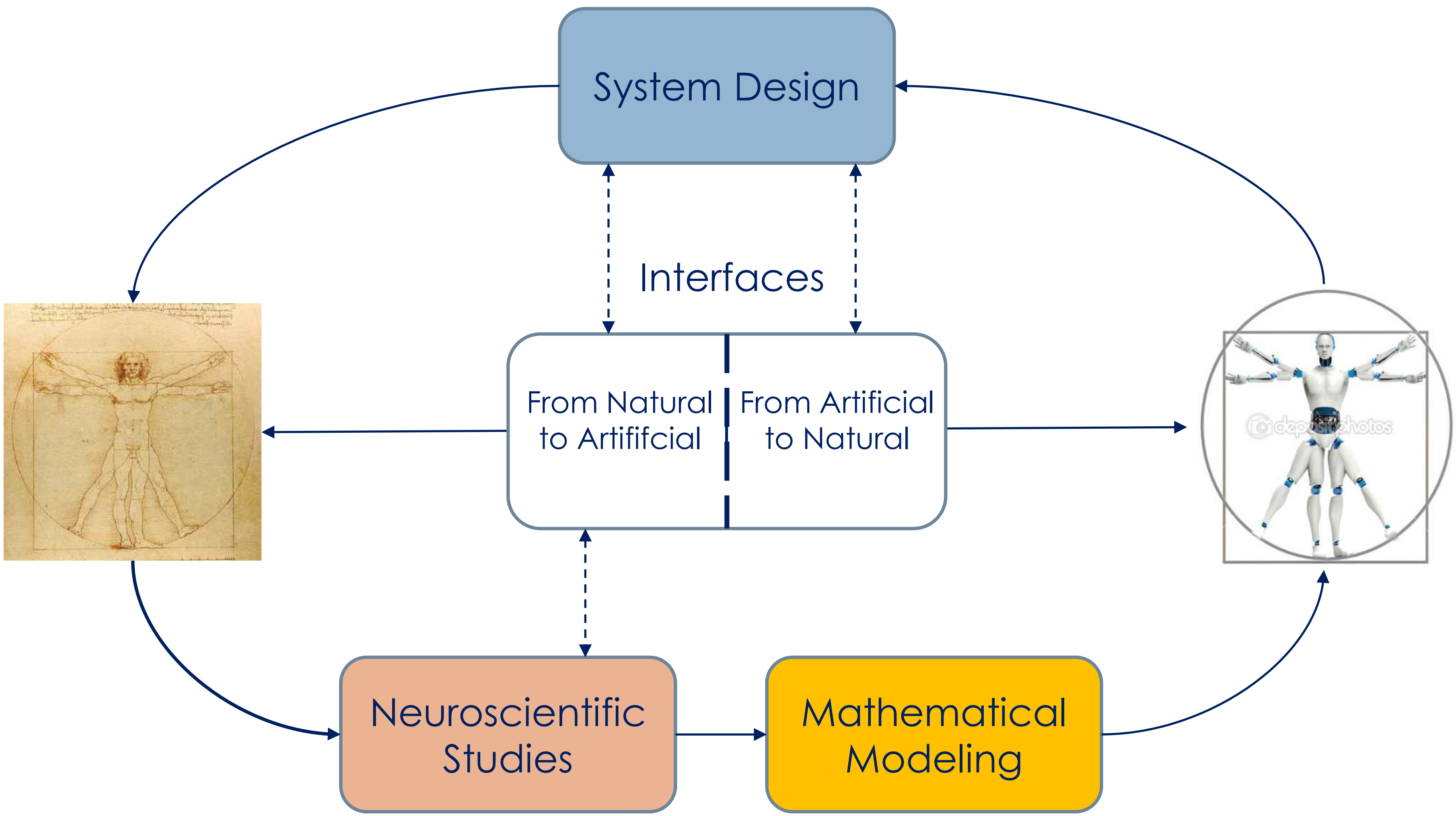
Affordable
Modular

Gentle, Robust, Adaptable





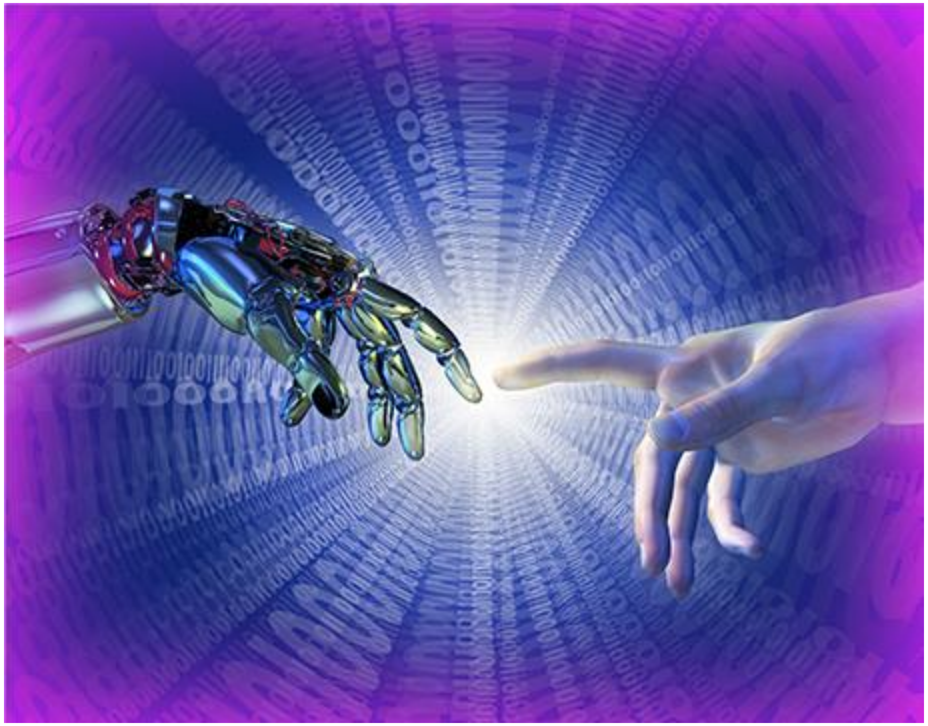
…and Back Again



SoftHand Pro

MAYO CLINIC

What About Sensing?



From Humans to Robots: Hand Pose Reconstruction (HPR) Systems

Glove-based HPR Systems

5DT Data Glove - www.5dt.com

[Dipietro et al.,2008]

The problem of correct hand pose estimation:

- ❑ many non-idealities (e.g. the complexity of human hand biomechanics, measurement inaccuracies)
- ❑ widespread use of glove-based HPR systems

Glove-based HPR Systems

Didjiglove by Didjiglove Pty. Ltd (AUS)

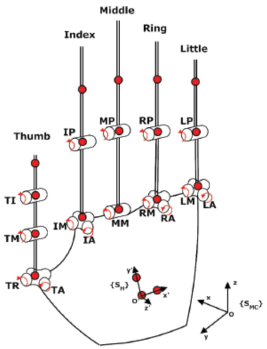
HPR system output: a set of (noisy) measurements of quantities that are related to the configuration of (some of) the hand DoFs via an imperfectly known relationship

Limitations on Intrinsic Accuracy

- ❑ Ergonomics » To discourage the use of accurate/cumbersome sensors
- ❑ Economic Considerations » Technology and Number of sensors
  - **CyberGlove** by Cyberglove System LLC, US-CA: 18/22 sensors » 12,297/17,795 USD (2010 quote)

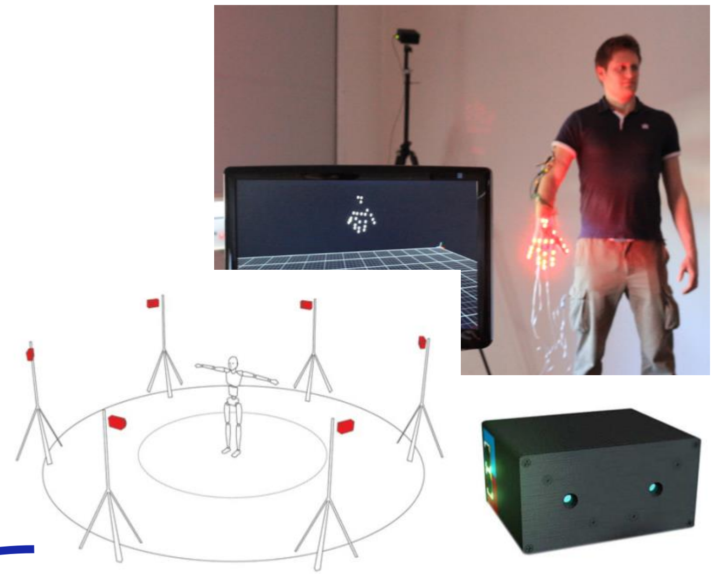
How to use/realize economic HPR systems and still guarantee a good accuracy ?

A Priori Information



DoFs	Description
TA	Thumb Abduction
TR	Thumb Rotation
TM	Thumb Metacarpal
TI	Thumb Interphalangeal
IA	Index Abduction
IM	Index Metacarpal
IP	Index Proximal
MM	Middle Metacarpal
MP	Middle Proximal
RA	Ring Abduction
RM	Ring Metacarpal
RP	Ring Proximal
LA	Little abduction
LM	Little Metacarpal
LP	Little Proximal

Kinematic Hand Model



Phase Space System ©

A Priori Grasp Set
N=114

$$X \in \mathbb{R}^{n\times N}$$

$P_o \in \mathbb{R}^{n\times n}$

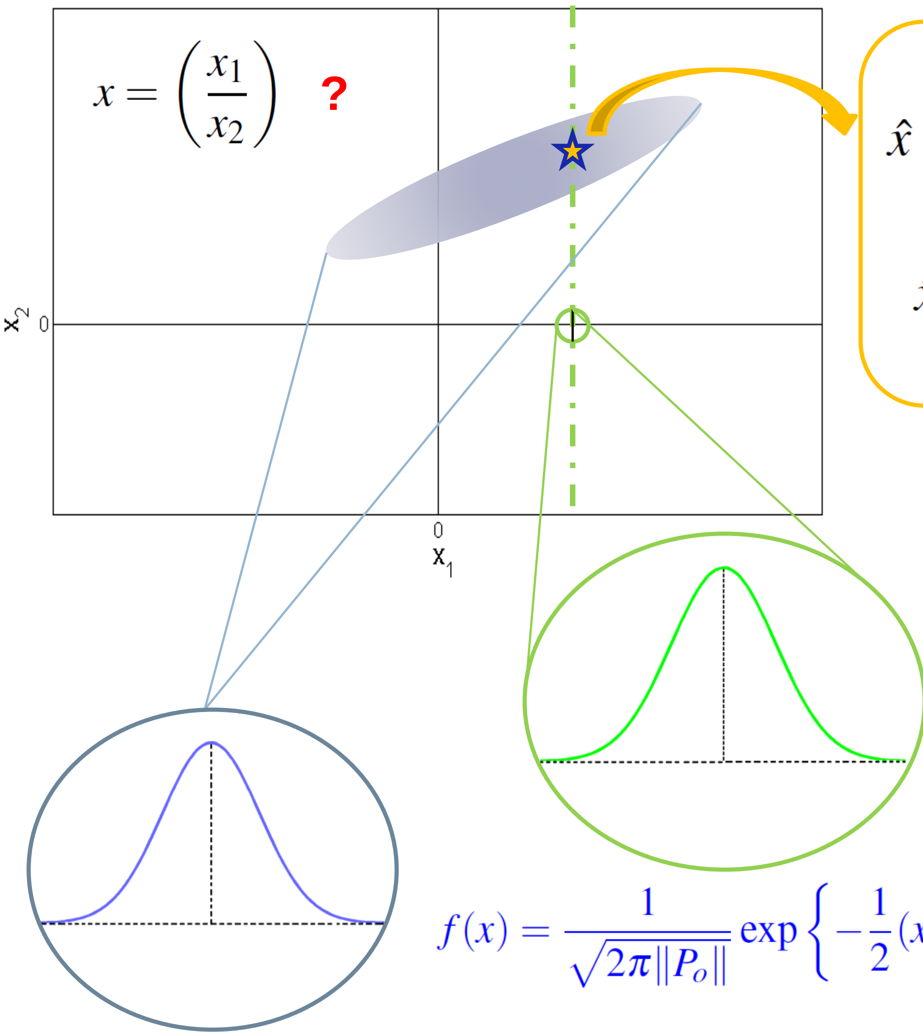
***A priori* Covariance**

$\mu_o \in \mathbb{R}^{n}$

Mean

How Such Information Can Be Fused with Measures?

Minimum Variance Estimation (MVE)



A priori

$$\hat{x} = (P_o^{-1} + H^T R^{-1} H)^{-1} (H^T R^{-1} y + P_o^{-1} \mu_o)$$

$$\hat{x} = \mu_o - P_o H^T (H P_o H^T + R)^{-1} (H \mu_o - y)$$

$$y = Hx + \nu \Longrightarrow x = H^{\dagger} y + N_h \xi$$

- H: measurement matrix
- y : output from the glove
- x : hand DoFs (usually dim(x)>dim(y))
- v : measurement noise
- R : noise covariance matrix

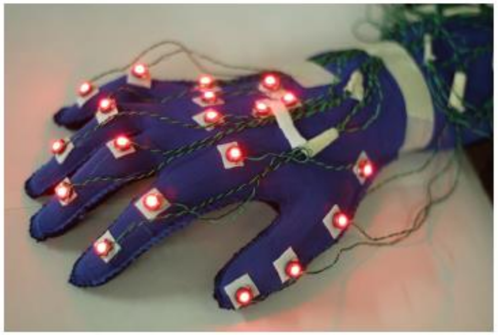
$$f(x) = \frac{1}{\sqrt{2\pi \|P_o\|}} \exp\left\{ -\frac{1}{2} (x - \mu_o)^T P_o^{-1} (x - \mu_o) \right\}$$

[Bianchi, Salaris and Bicchi. IJRR 2013a]

Experiments: Low Cost Glove (m = 5, n= 15)

- ❑ Conductive Elastomer (CE) Sensors into Elastic Fabric
- ❑ Hysteresis and Non Linearities
- ❑ Linear Relation : Electrical Changes/Hand Aperture

[Tognetti et al.,2006]



Experiments: Results

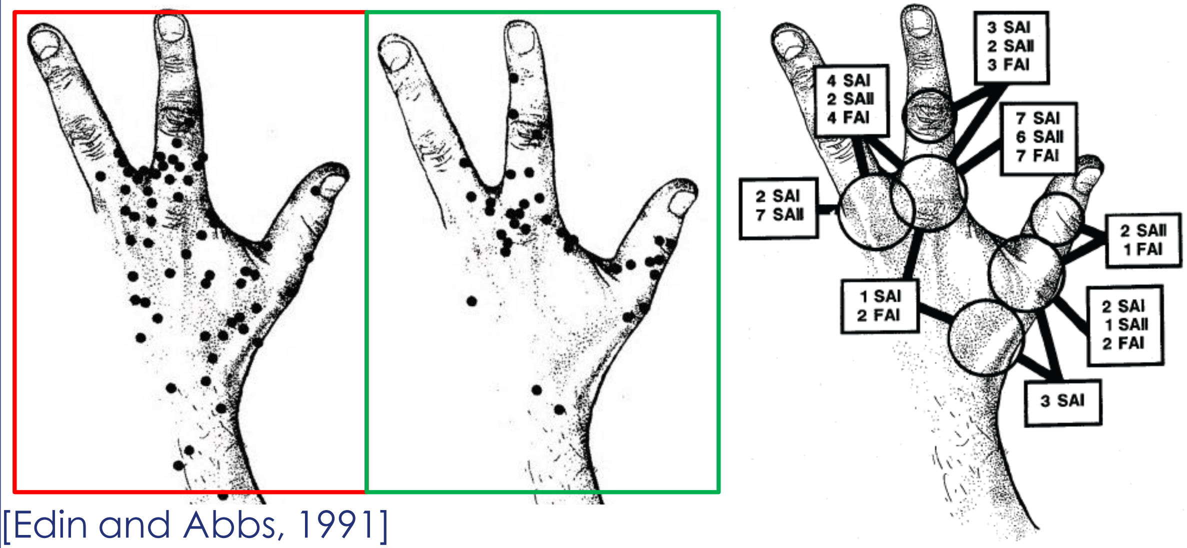
Pinv

$\hat{x} = H^{\dagger} y$

MVE

Average absolute pose estimation error: **MVE** 10.92 vs. **PINV** 19.00° (p<.0001)

If you were the designer: Biological Inspiration



[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

The Problem

- Sensor density needs not be uniform
- There are better and worse distributions of sensors
- **Is there a preferential distribution and density of different sensors, which optimizes the overall accuracy of a glove?**

How to design an optimal glove with a given technology/budget?

Problem Definition

$$\boxed{y = Hx + v}$$

$$\boxed{\hat{x} = \mu_o - P_o H^T (H P_o H^T + R)^{-1} (H \mu_o - y)}$$

$$\boxed{(P_o^{-1} + H^T R^{-1} H)^{-1} = P_o - P_o H^T (H P_o H^T + R)^{-1} H P_o}$$

***A posteriori* Covariance Matrix**

$$\boxed{P_p = P_o - P_o H^T (H P_o H^T + R)^{-1} H P_o}$$

Measurement of the amount of information that
the observable variables carry about unknown parameters

[Bianchi, Salaris and Bicchi, IROS 2012 – **JTCF Novel Technology Paper Award**]
[Bianchi, Salaris and Bicchi, IJRR 2013b]

Problem Definition

Objective:

to determine the measurement matrix **H** - and hence sensor distribution – which minimizes the a posteriori covariance matrix $\mathbf{P_p}$, thus increasing the information on the actual posture

The role of measurement matrix H for the optimal design

***A posteriori* Covariance Matrix**

$$P_p = P_o - P_o H^T \left(H P_o H^T + R \right)^{-1} H P_o$$

Measurement of the amount of information that the observable variables carry about unknown parameters

[Bianchi, Salaris and Bicchi, IROS 2012 – **JTCF Novel Technology Paper Award**]
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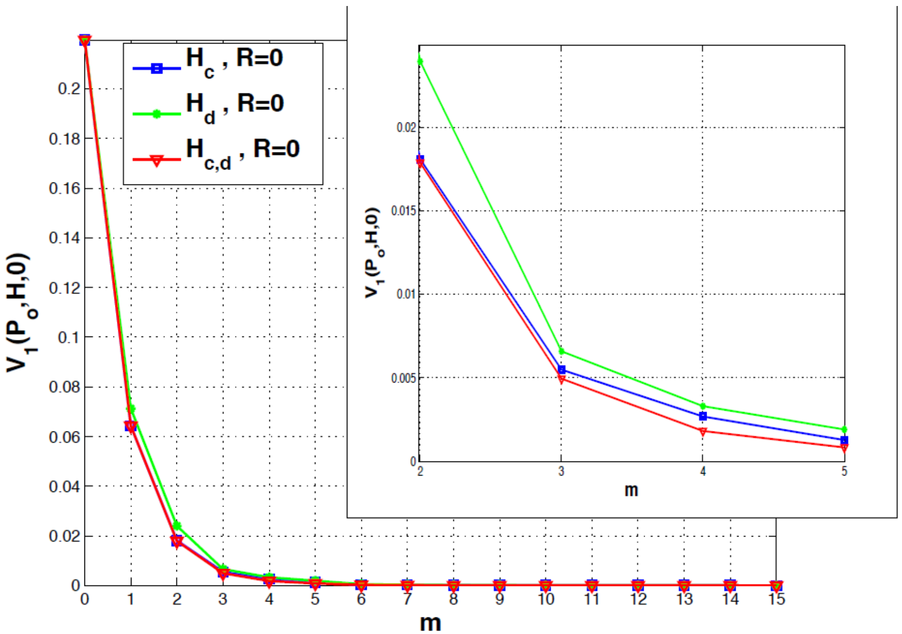
Estimation Performance Comparison for Optimal Sensor Designs



Hc = 0.2 0.5 0.1

$$Hd = \begin{pmatrix} 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

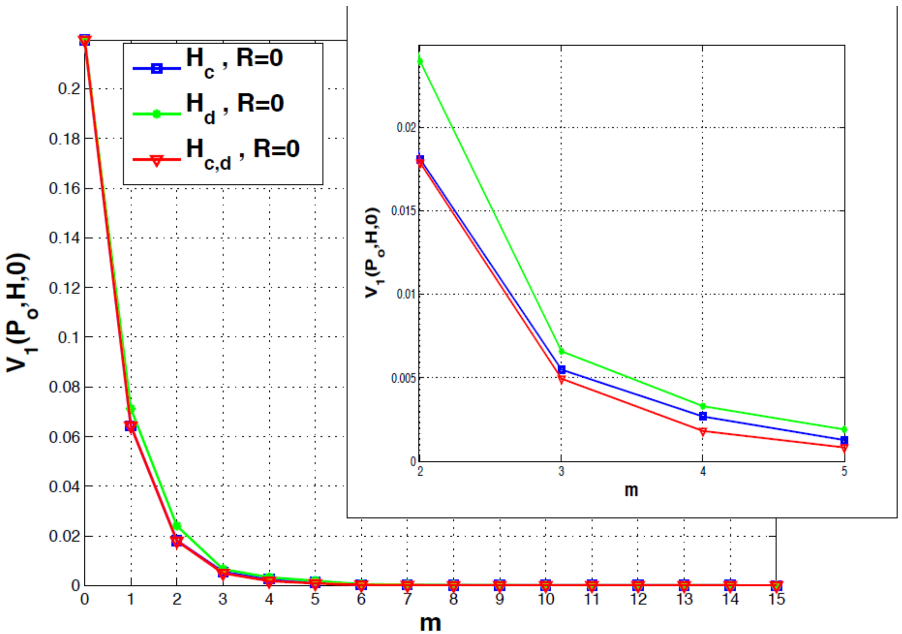
$$Hc,d = \begin{pmatrix} 0.2 & 0.7 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Problem 1. *Let H be an $m \times n$ full row rank matrix with $m < n$ and $V_1(P_o, H, R) : \mathbb{R}^{m\times n} \to \mathbb{R}$ be defined as $V_1(P_o, H, R) = \|P_o - P_o H^T (H P_o H^T + R)^{-1} H P_o\|_F^2$, find*

$$H^* = \arg\min_H V_1(P_o, H, R)$$

where $\|\cdot\|_F$ denotes the Frobenius norm defined as $\|A\|_F = \sqrt{\mathrm{tr}(AA^T)}$, for $A \in \mathbb{R}^{n\times n}$.

Estimation Performance Comparison for Optimal Sensor Designs



$Hc = 0.2\ 0.5\ 0.1$

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$Hc,d = \begin{pmatrix} 0.2 & 0.7 & 0 \\ 0 & 0 & 1 \end{pmatrix}$

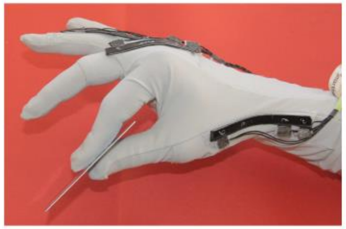
- ❑ The first three Postural Synergies explain for ~90% of pose variability [Santello et al., 1998]
- ❑ Here, the first three synergies achieve ~97% HPR posteriori covariance (V_1) reduction
- ❑ The first few synergies are crucial under both the <u>controllability</u> and <u>observability</u> point of view

Optimal Glove

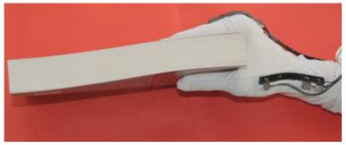
- Two identical conductive layers coupled through one insulating layer (**double layer**)
  - Knitted **piezoresistive** fabrics
  - **Resistance difference** (ΔR) between layers **depends** on the **angle** between the tangents on the sensor endings
  - ΔR **does not depend** on sensor **elongation** and **bending profile**

[Ciotti, Battaglia, Carbonaro, Bicchi, Tognetti and Bianchi, 2016 - Sensors]

Optimal Glove




From **ONLY 5 sensors** optimally placed according to synergy information to **kinematic posture reconstruction in R^{19}**


[Ciotti, Battaglia, Carbonaro, Bicchi, Tognetti and Bianchi, 2016 - Sensors]

Conclusions

- Optimal design and estimation technique based on **hand synergy definition** provide a complete procedure for performance enhancement of HPR gloves

- To enable an **effective** and **economic development** and use of **sensorization schemes** for robotic hands, active touch sensing systems and human-machine interfaces

- Wide range of applications: **VR**, **Tele-Robotics**, Entertainment, Rehabilitation

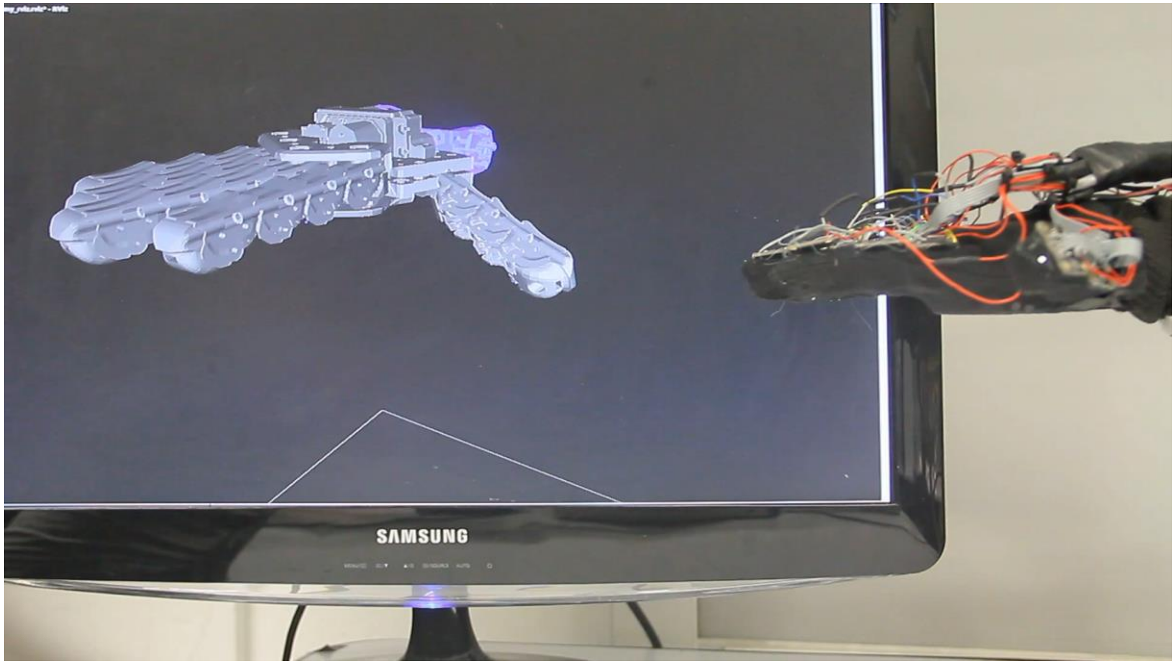
- Patent

Conclusions and Future Works

To leverage upon **a priori** (***model*** and/or **synergy**) **information** to shape the design of **new under-sensing apparatuses** (retrieving other types of information, e.g. force, from posture; reduced number of sensors) for **human** and **robotic hands**

Bio-aware robotics

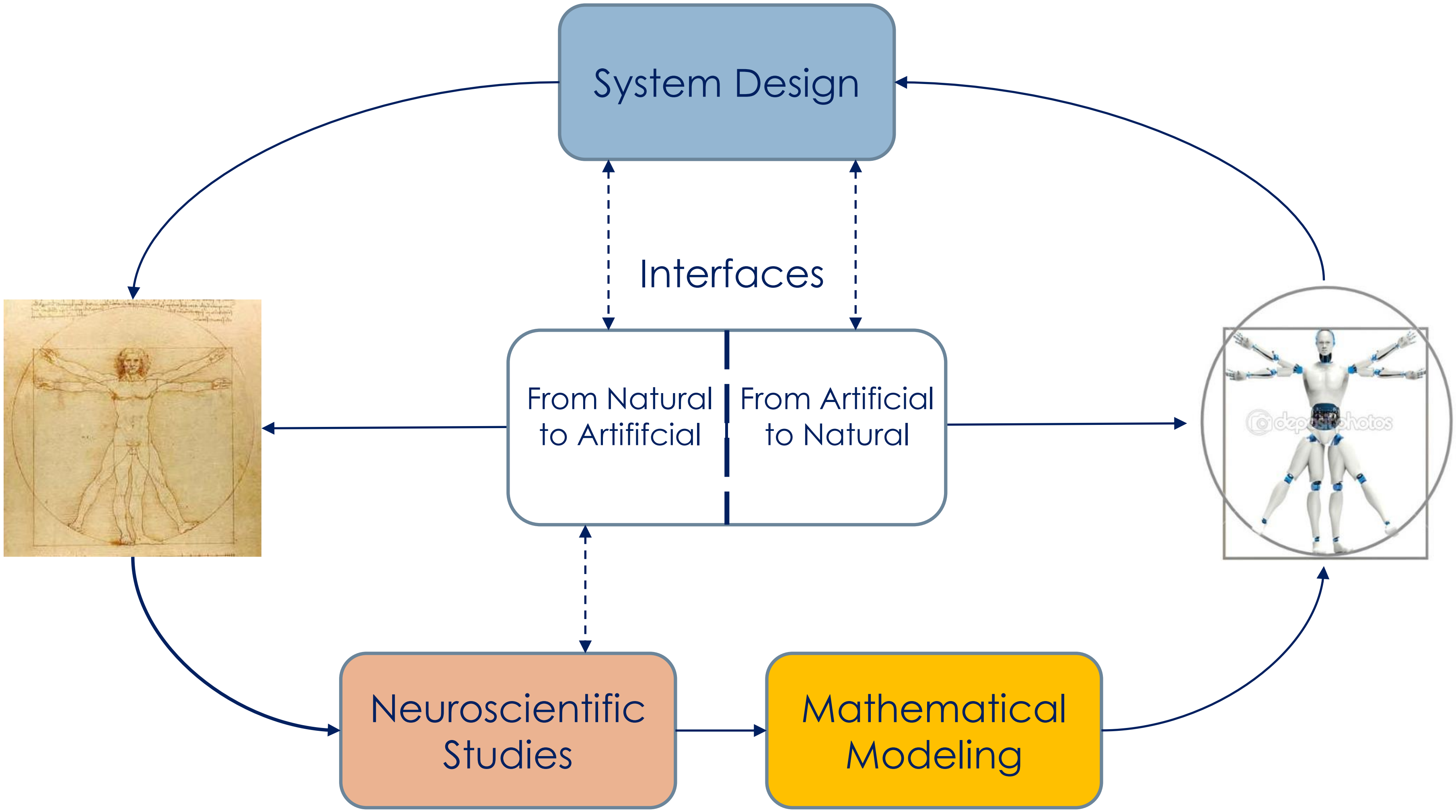
Posture Reconstruction
[Santaera et al. 2015]



Pisa/IIT SoftHand – 17 IMUs

Passive Complementary Filter provides an estimation of the orientation between two frames in space knowing the gravity and the magnetic field values in the frames and the relative angular velocity between these ones

From Humans to Robots and Back Again



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Thank you!

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