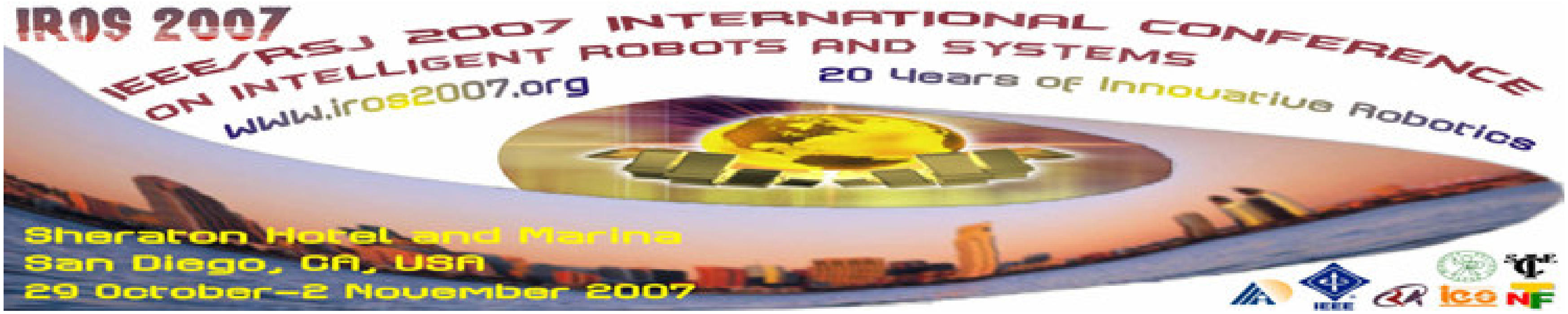
Assistive Technologies:
Rehabilitation and Assistive Robotics



Neuro-robot for functional support of the human body

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Introduction

- The primary goal of bionics is "to extend man's physical and intellectual capabilities by prosthetic devices in the most general sense" (Von Gierke et al. 1970; Dario et al. 1993)
- Hybrid Bionic Systems (HBSs) can be defined generically as systems that contain both technical (artificial) and biological components, or biological systems with artificial elements or subsystems
- The basic assumption for designing new HBSs is to bring together neuroscience knowledge on sensory-motor control with robotic and interfacing technologies, while keeping the human person at the centre of the design approach
- This is the ultimate goal of the NEUROBOTICS project: the fusion of NEUROscience and roBOTICS), an "Integrated Project" funded by the European Commission (IST-FET-contract no. 001917-2003) and aimed at encouraging neuroscientists and roboticists to work together for jointly developing new, high performance HBSs

Two case studies of Hybrid Bionic Systems

- The NEUROEXOS platform: an upper limb exoskeleton to investigate functional support of human arm
- The CYBERNETIC HAND: an hand prosthesis to investigate functional replacement of upper limb

EXOSKELETON

"A hard outer structure, such as the shell of an insect or crustacean, that provides protection or support for an organism"

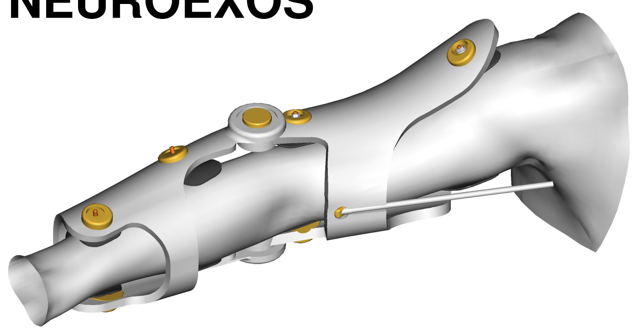
Source: *The American Heritage® Dictionary of the English Language, Fourth Edition*

Design Methodology

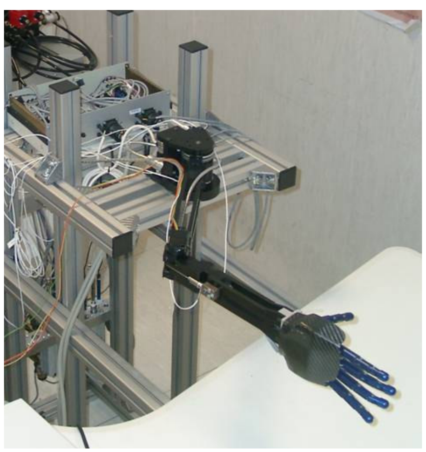
- Functional Requirements were obtained from analytical and biomechanical models
- The models were evaluated experimentally in a catching platform designed for that purpose
- The models were exploited for designing a robotic arm with biomechanical properties similar to the human arm
- The robotic arm has been used as a test-bed for assessing design criteria and technologies for the NEUROEXOS

NEUROEXOS

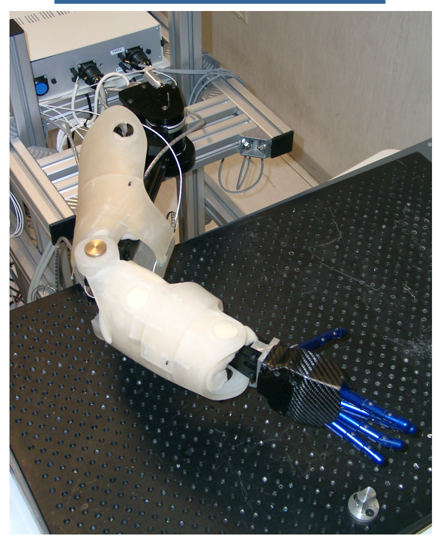
NEUROEXOS



NEURARM – safe testbed



Integration and testing

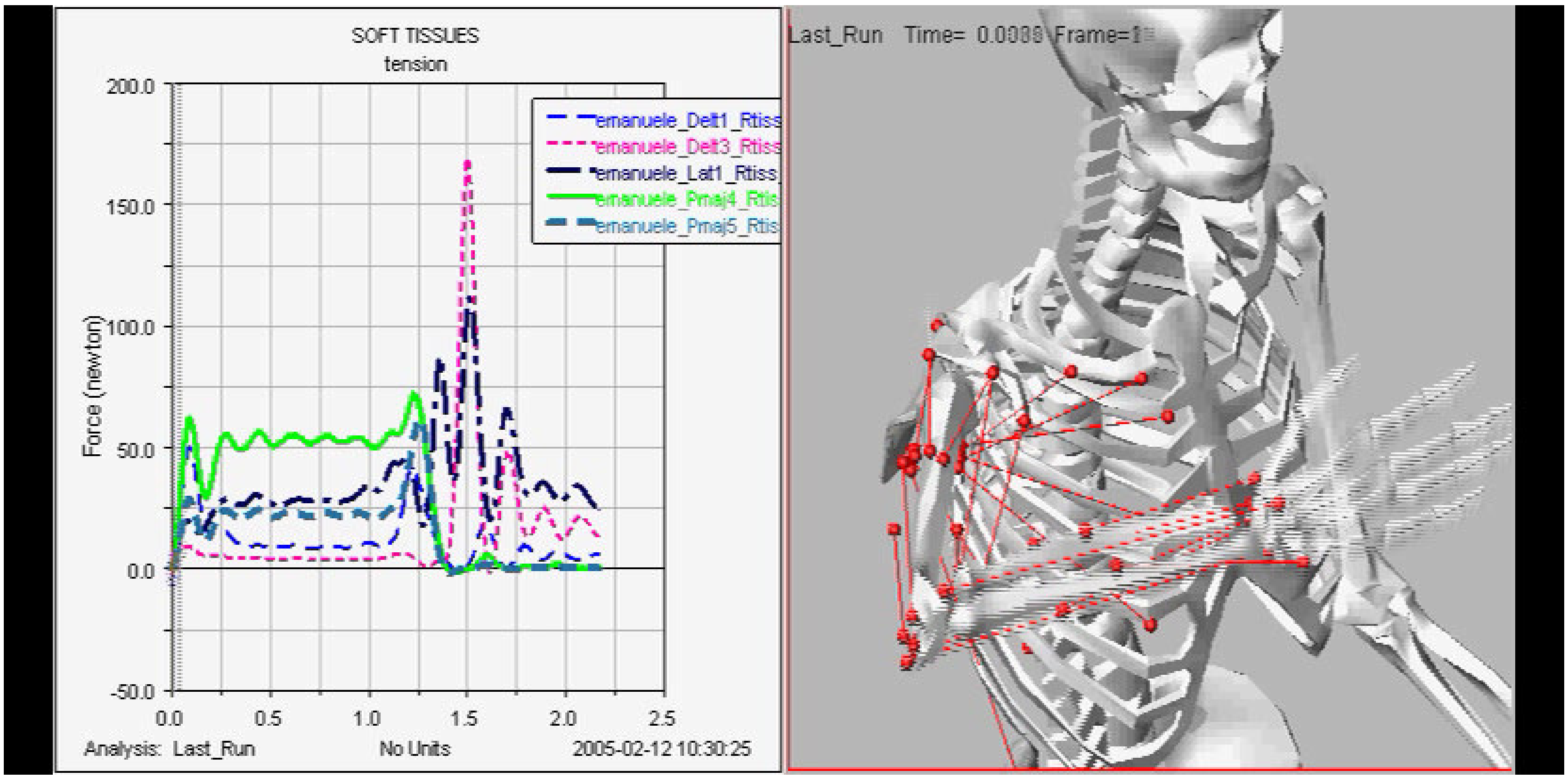


Final objective:
An exoskeleton safely used by humans

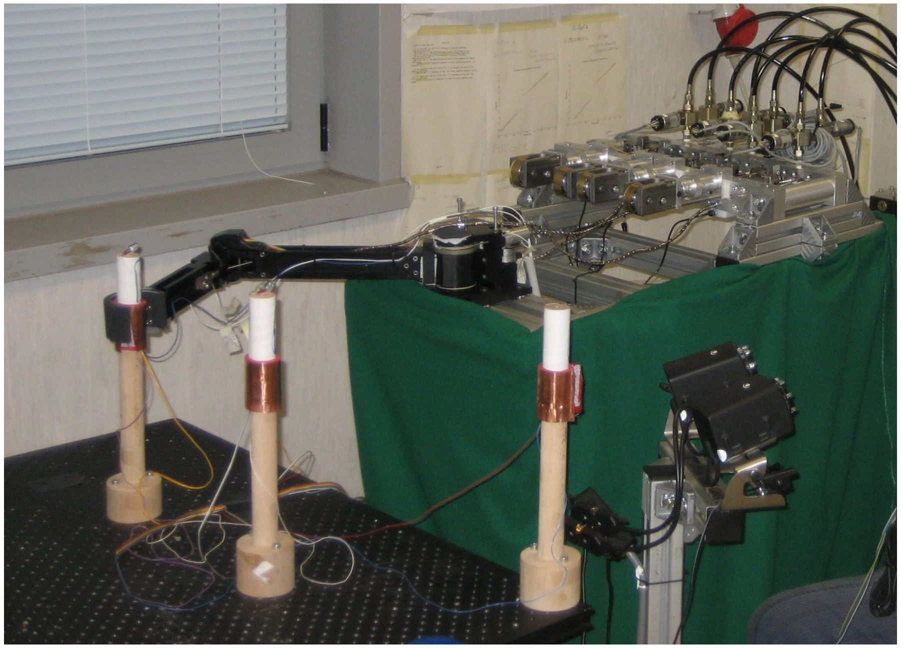
The catching task as a prototypical task

Biomechanical model

Shoulder agonistic/antagonistic muscles activations



The NEURArm platform

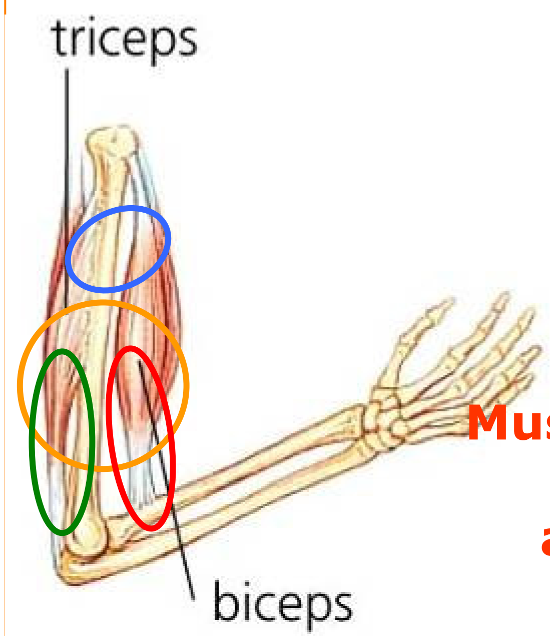


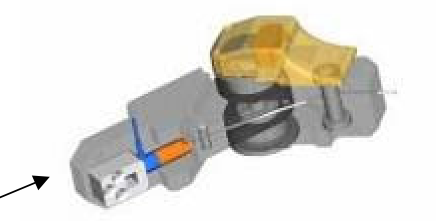
- NEURARM is a 2 DoF planar robot actuated in agonistic-antagonistic modality:
  - Link masses and inertias similar to those of the European standard man
  - Remote hydraulic actuation
  - Transmission by Bowden Cable and hydraulic piston stroke amplifiers
  - High Sensorization:
    - joint angle
    - cable force
    - hydraulic piston stroke
    - hydraulic circuit pressures

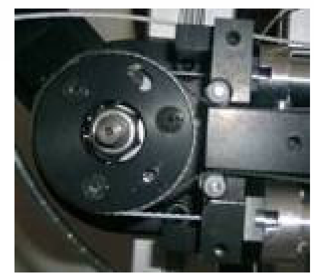
E.Cattin, S.Roccella, N.Vitiello, I.Sardellitti, P.K.Artemiadis, P.Vacalebri, F.Vecchi, M.C.Carrozza, K.J.Kyriakopoulos, P.Dario, Design and Development of a Novel Robotic Platform for Neuro-Robotics applications: the NEURobotics ARM (NEURARM), *Int.Journal Advanced Robotics, Special Issue on Robotics Platforms for Neuroscience* (in press)

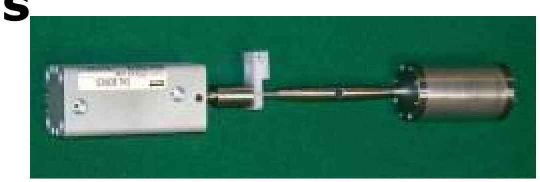
Human arm vs NEURArm (mehanisms /actuators)

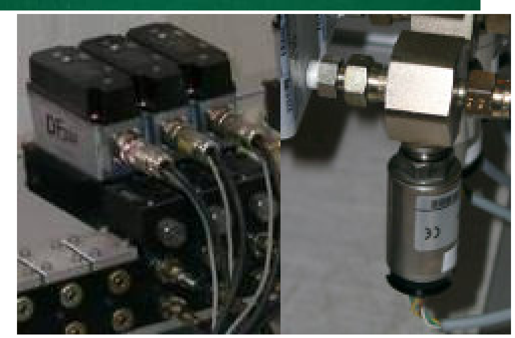
Human arm	NEURArm
Agonist-antagonist tendon driven	Agonist-antagonist cable driven
Tendons fixed on the bones	Cables fixed on the link (forearm) and on the joint (shoulder)
Muscles (non linear actuators)	Hydraulic pistons in series with non-linear springs
Tunable contraction force	DC - proportional electrovalves and force low level controller





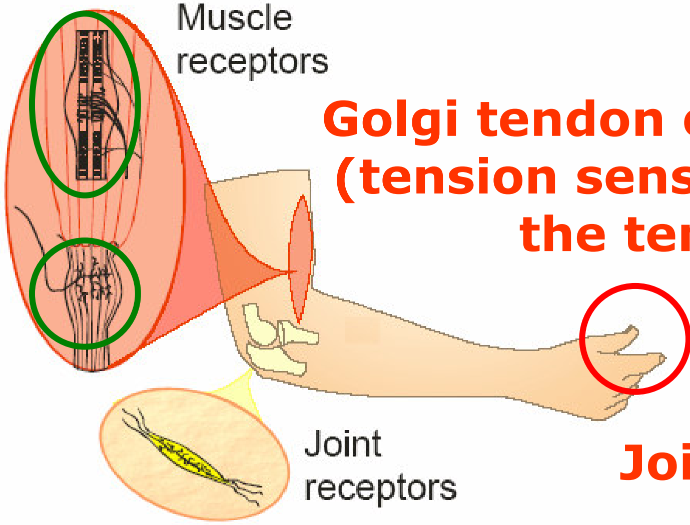






Human arm vs NEURArm (sensory system)

Muscle spindles (stretching sensors)



Golgi tendon organs (tension sensors on the tendons)

**Joint/Ski
n
receptors**

Sensory system in the hand

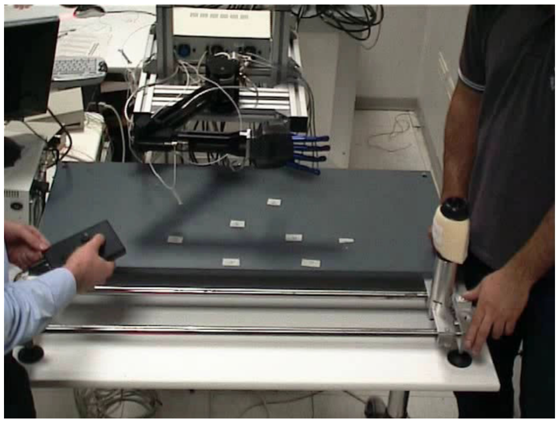
Linear potentiometers in series with the actuators

Force sensors on cables

**Joints
Angle sensors**

Force sensors in end effector and artificial hand with sensors

NEURARM is exploited in 4 experiments

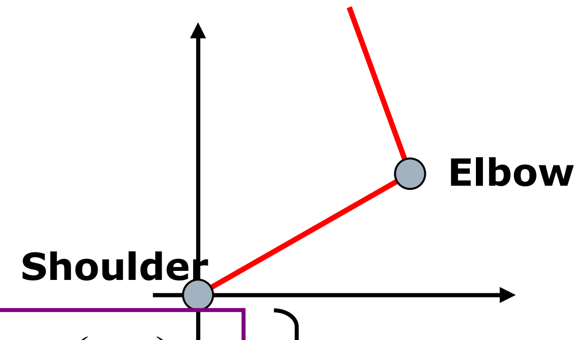


1. to verify the NEURARM ability to mimic the kinematics performances of the human arm: the catching task was proposed (concluded)
2. to investigate learning and sensory feedback for developing a new highly intuitive and efficient Human Machine Interface (ongoing)
3. to evaluate a controller based on Feldman's equilibrium point hypothesis based on non-linear springs (ongoing)
4. to assess NEUROEXOS prototype (planning)

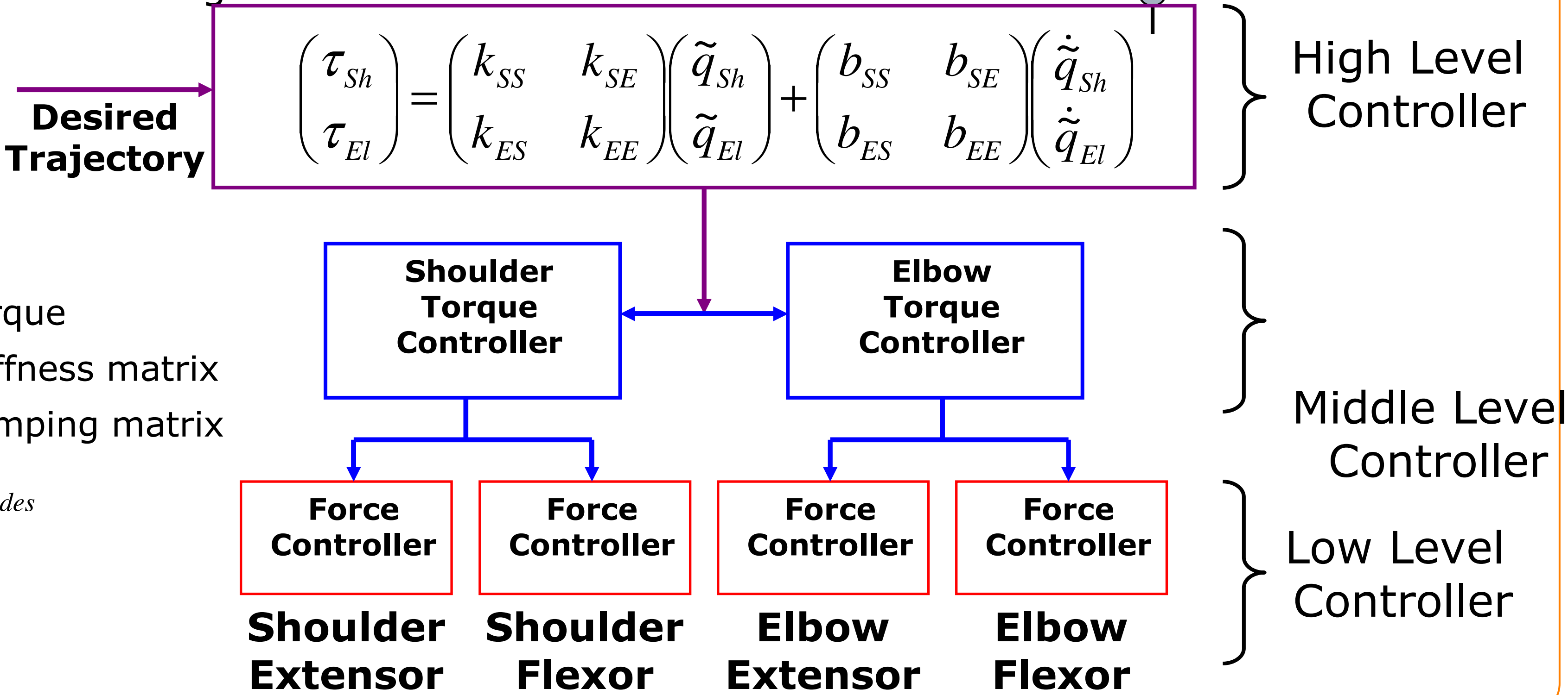
1. Catching Task – Controller

Characteristics of control system:

- Hierarchical structure
- Based on the Equilibrium point hypothesis (*software implementation*)
- Model free high level control law



$$\begin{pmatrix}\tau_{Sh}\\ \tau_{El}\end{pmatrix} = \begin{pmatrix}k_{SS} & k_{SE}\\ k_{ES} & k_{EE}\end{pmatrix}\begin{pmatrix}\tilde{q}_{Sh}\\ \tilde{q}_{El}\end{pmatrix} + \begin{pmatrix}b_{SS} & b_{SE}\\ b_{ES} & b_{EE}\end{pmatrix}\begin{pmatrix}\dot{\tilde{q}}_{Sh}\\ \dot{\tilde{q}}_{El}\end{pmatrix}$$



τ = Torque

K = Stiffness matrix

B = Dumping matrix

$\tilde{q} = q - q_{des}$

1. Catching Task – Controller (II)

The middle level controller is based on simple balance equations:

$$\tau_{Sh} = \Delta F \cdot R_{Sh} = \left(F_{Sh-Flex} - F_{Sh-Ext}\right) \cdot R_{Sh}$$

$$\begin{cases} F_{Sh-Flex} = F_{\Pr e-load} + \left|\Delta F\right| \\ F_{Sh-Ex} = F_{\Pr e-load} \end{cases} \quad if \quad \tau_{Sh} \geq 0$$

$$\begin{cases} F_{Sh-Flex} = F_{\Pr e-load} \\ F_{Sh-Ex} = F_{\Pr e-load} + \left|\Delta F\right| \end{cases} \quad if \quad \tau_{Sh} < 0$$

$F_{Sh-Flex}$ = shoulder flexor force

F_{Sh-Ext} = shoulder extensor force

R_{Sh} = shoulder moment arm

The same algorithm is used for the elbow torque

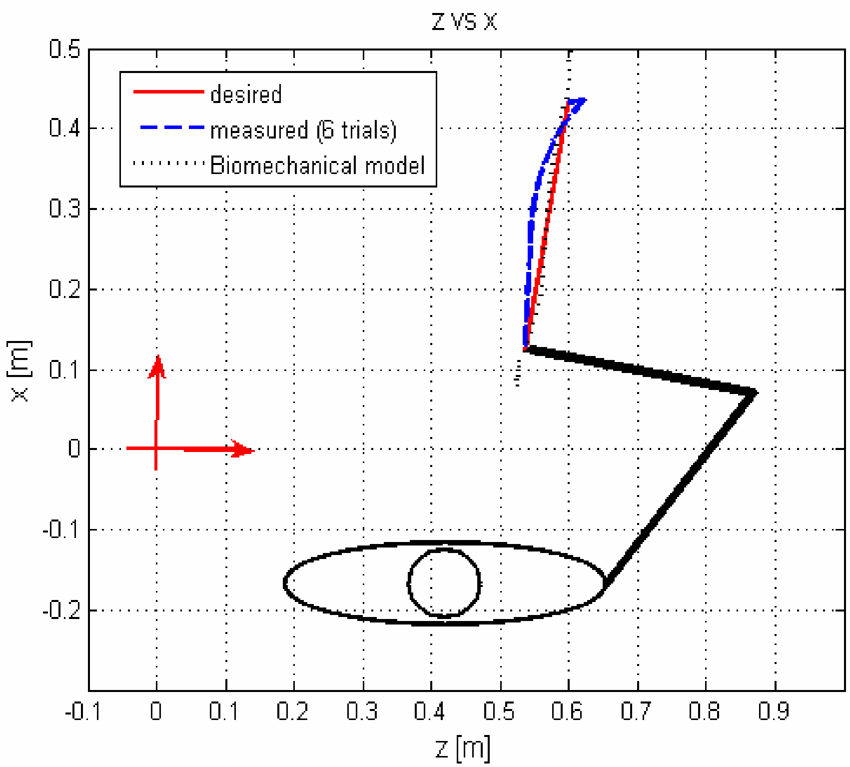
In order to perform the catching task the following parameters were used:

$$K = \begin{pmatrix} -28 & 4 \\ -4 & -12 \end{pmatrix} \text{[Nm/rad]} \quad B = \begin{pmatrix} -0.8 & 0 \\ 0 & -1.5 \end{pmatrix} \text{[Nms/rad]}$$

1. Catching Task – Experimental Results (I)

The desired trajectory was modelled from the output of the biomechanical analysis: a point-to-point straight line in the Cartesian Space, with a bell shape speed profile.

- 6 trials were performed to test repeatability
- According to experimental results the NEURArm is able to mimic the kinematic performance of the human arm that are relevant for NEUROEXOS and for experiments

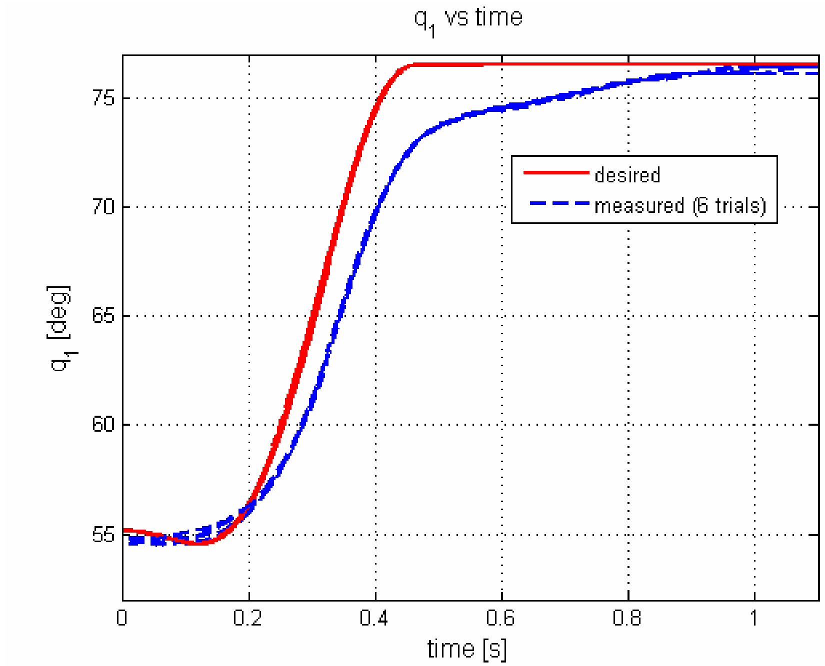


Variable	Mean	STD	% variation
Max ($\lvert\dot{q}_{Sh}\rvert$) [deg/s]	88.29	1.78	2.01 %
Max ($\lvert\dot{q}_{El}\rvert$) [deg/s]	323.14	2.56	0.79 %
Max ($\lvert\dot{z}\rvert$) [m/s]	0.54	1.18e-2	2.17 %
Max ($\lvert\dot{x}\rvert$) [m/s]	1.19	1.08e-2	0.89 %
RMSE($\tilde{q}_{Sh}$) [deg]	1.44	1.68e-2	1.16 %
RMSE($\tilde{q}_{El}$) [deg]	5.67	0.13	2.28 %

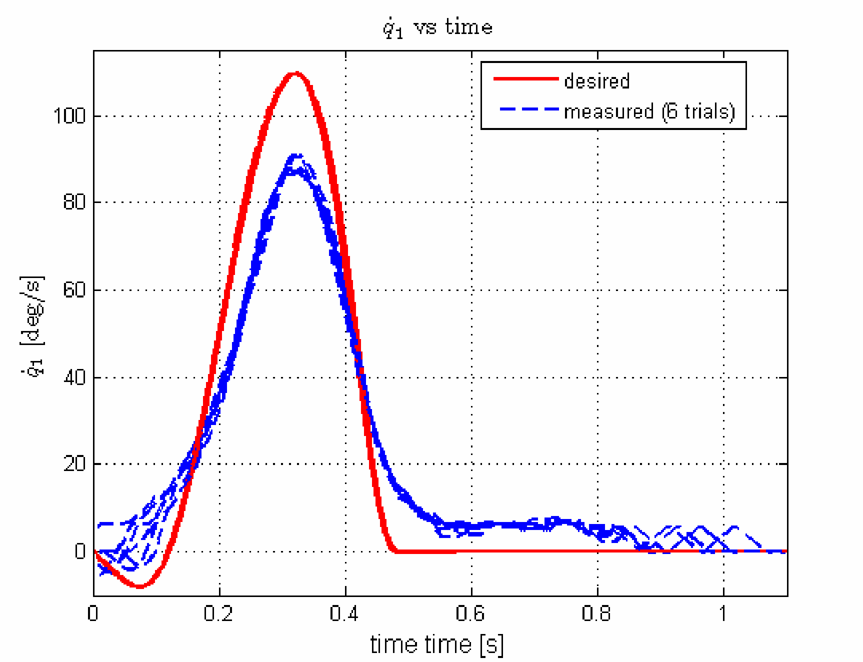
TABLE – Some parameters to show the platform repeatability and the kinematics performances during the catching task

1. Catching Task – Experimental Results (II)

Shoulder – Angle vs. time

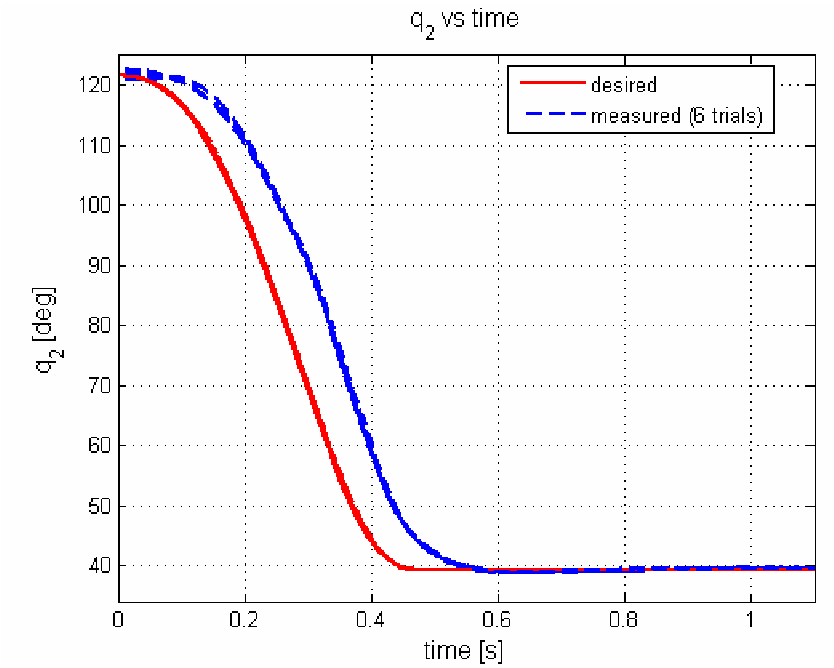


Shoulder – Angular Speed vs. time

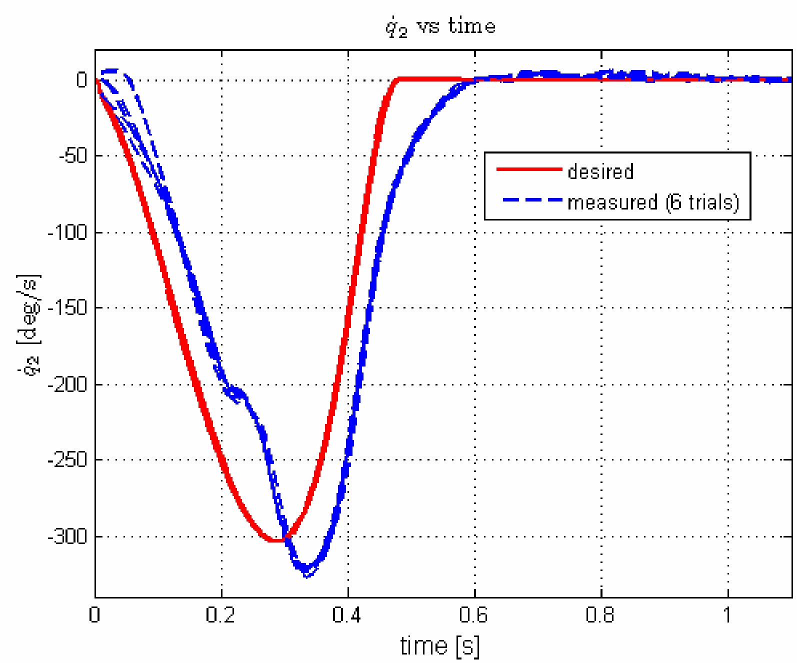


1. Catching Task – Experimental Results (III)

Elbow – Angle vs. time

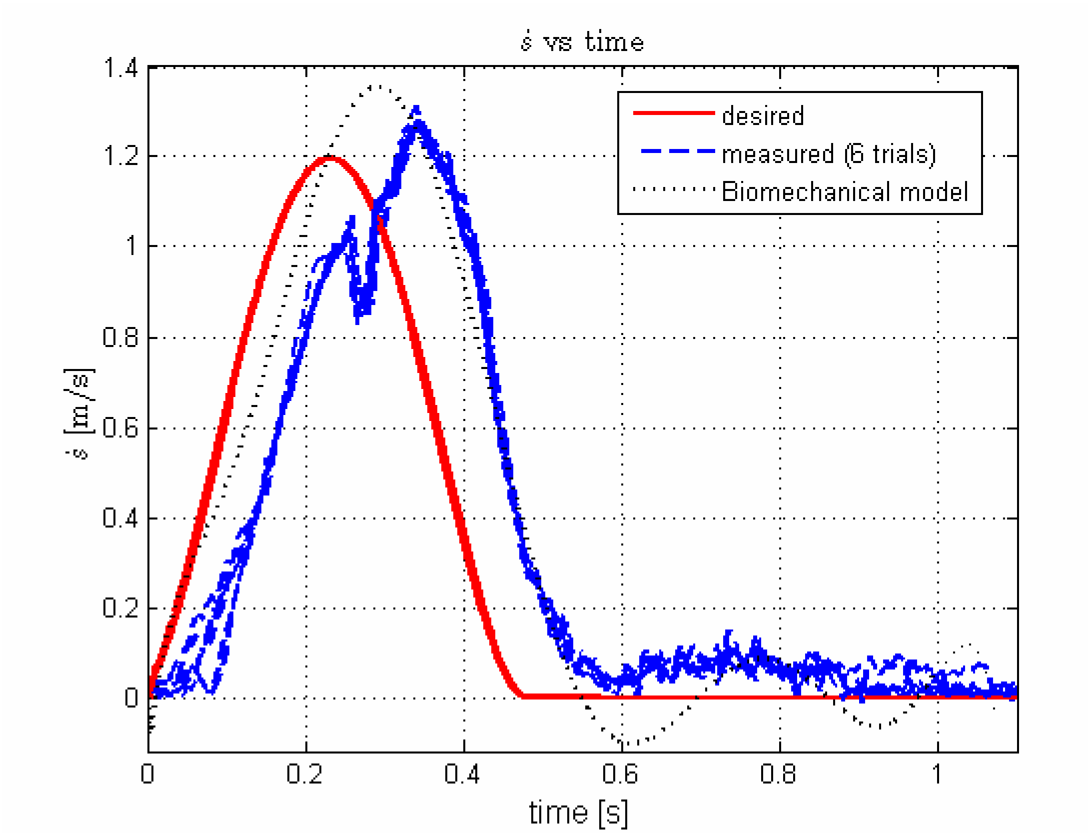


Elbow – Angular Speed vs. time

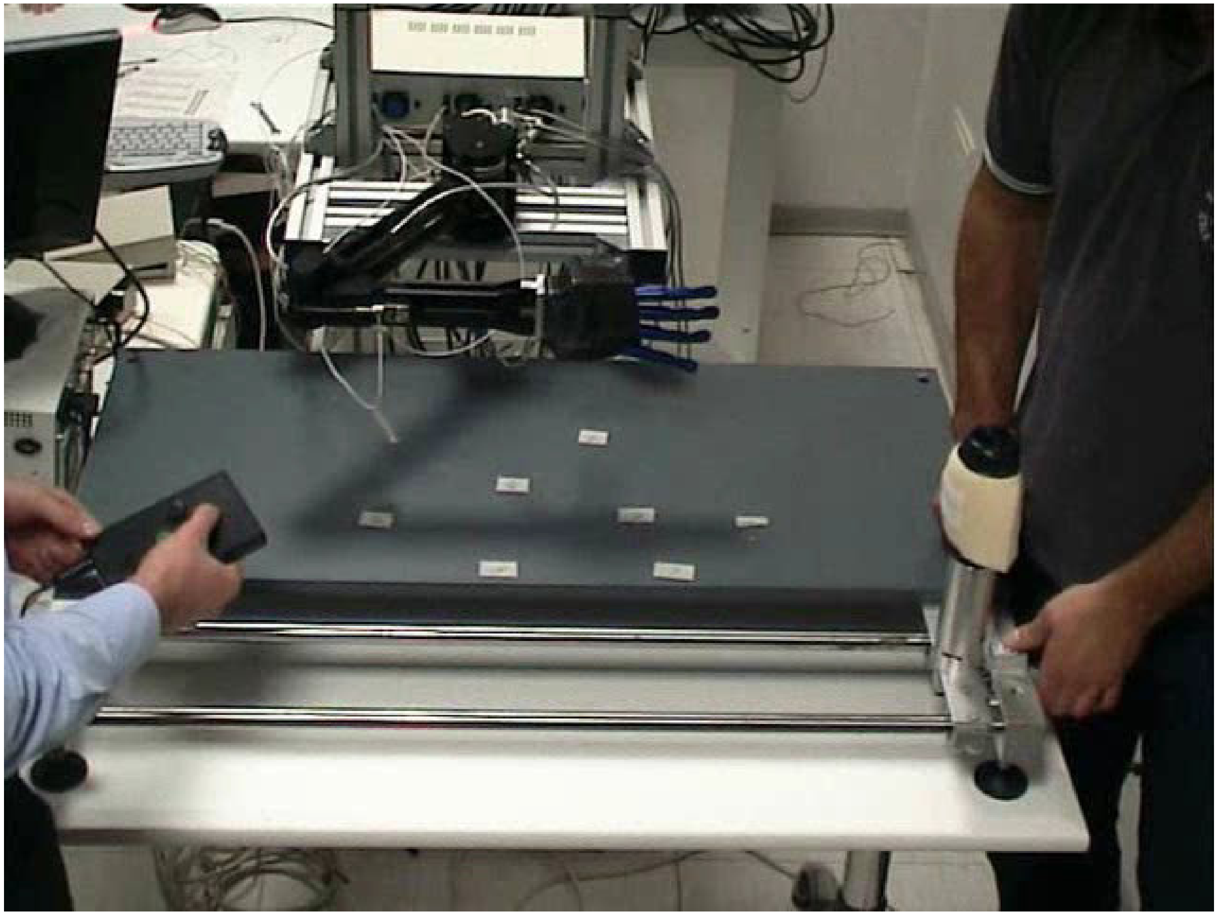


1. Catching Task – Experimental Results (IV)

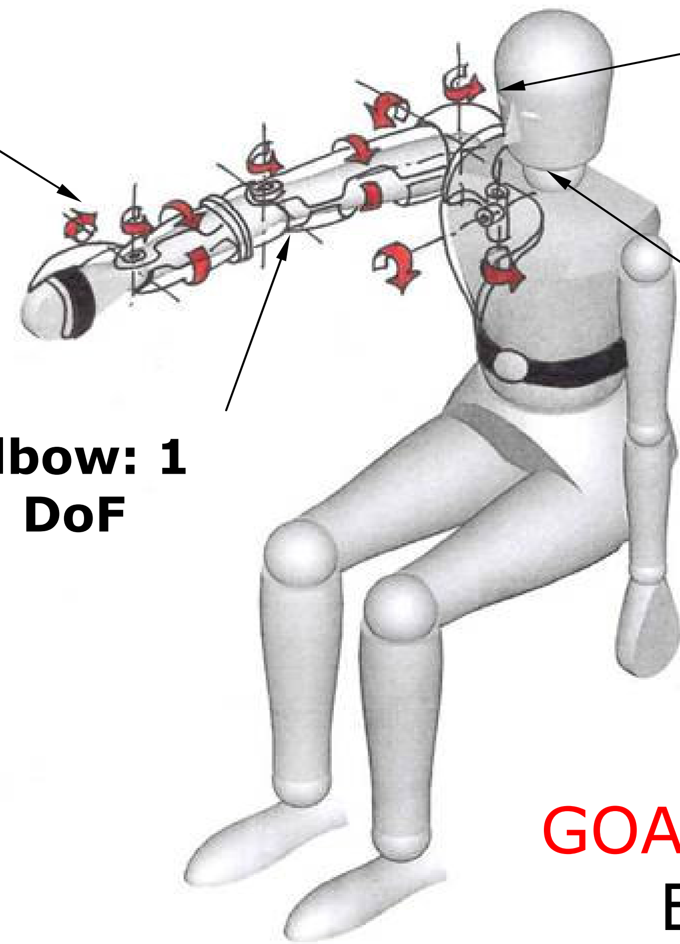
|Tangential Speed| vs. time



1. Catching Task – video

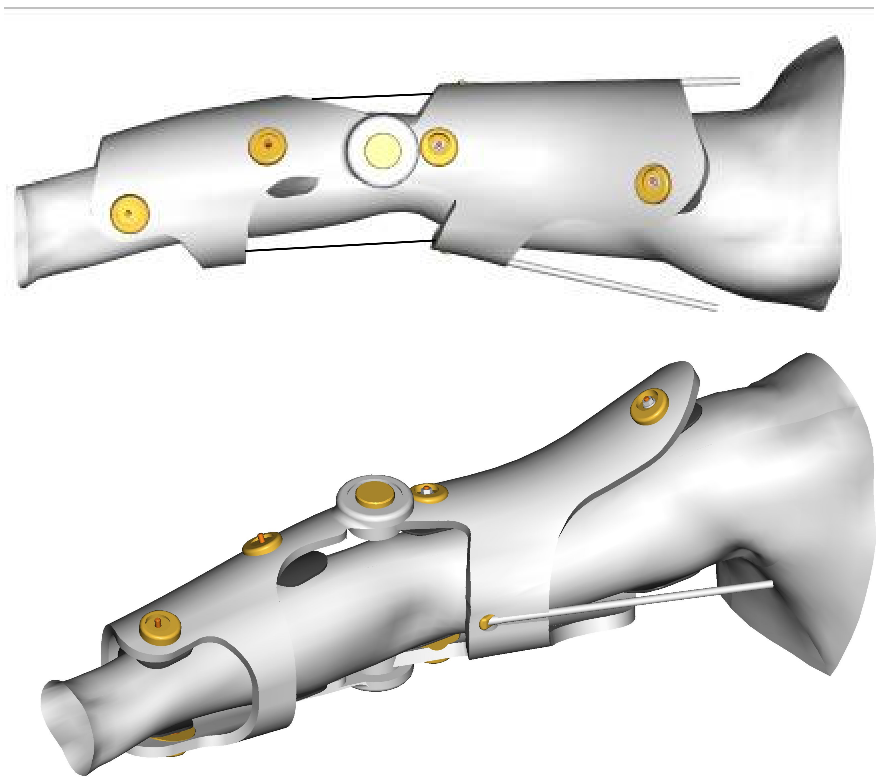


On the NeuroEXOS development :KINEMATICS



GOAL: 9 ACTIVE DoFs EXOSKELETON

The NeuroEXOS elbow module

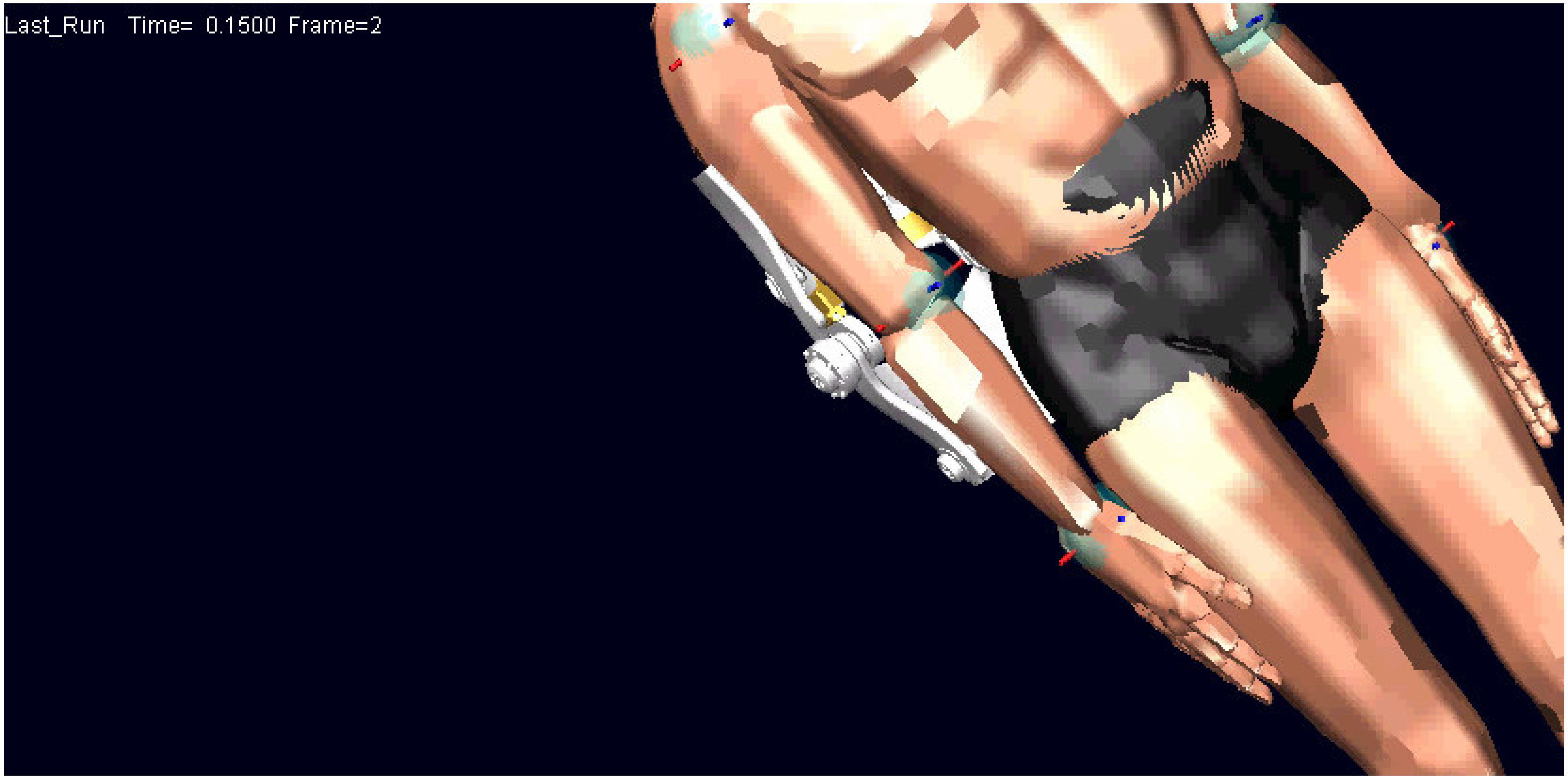


NeuroExos Elbow Design

Preliminary Prototype

- Full kinematics compatibility by means 5 passive DoF: perfect matching between the robotics and human elbow joint axis
- The system is under patenting

The concept of the whole NEUROEXOS

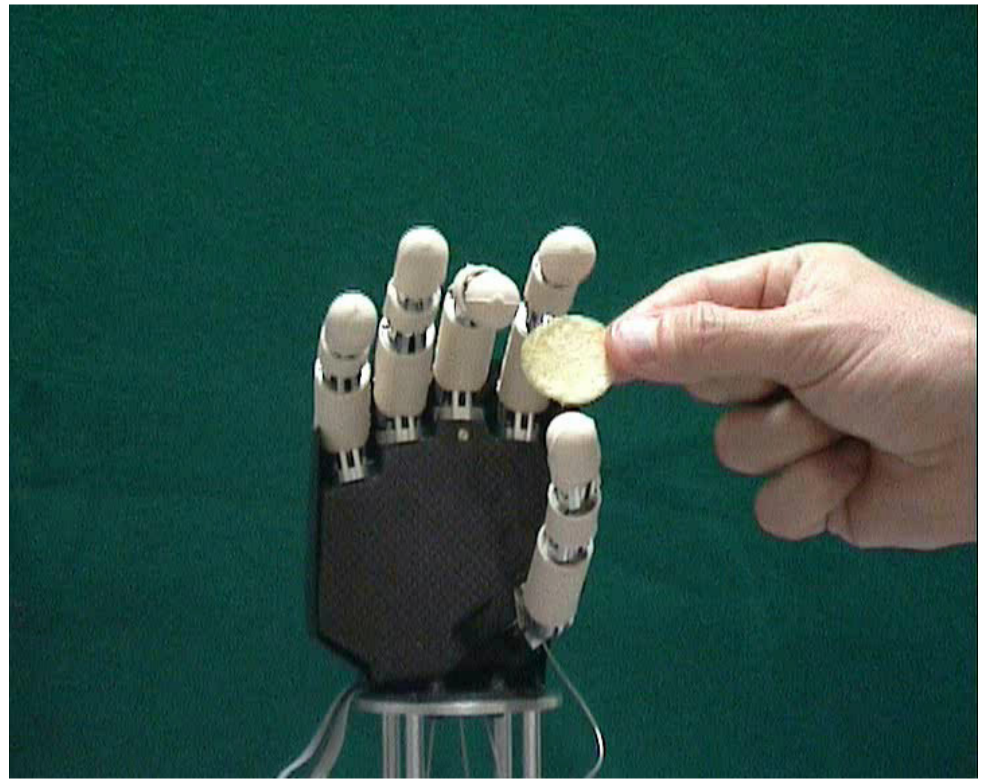


Two case studies of Hybrid Bionic Systems

- The NEUROEXOS platform to investigate functional support of upper limb
- The CYBERNETIC HAND prosthesis to investigate functional replacement of upper limb

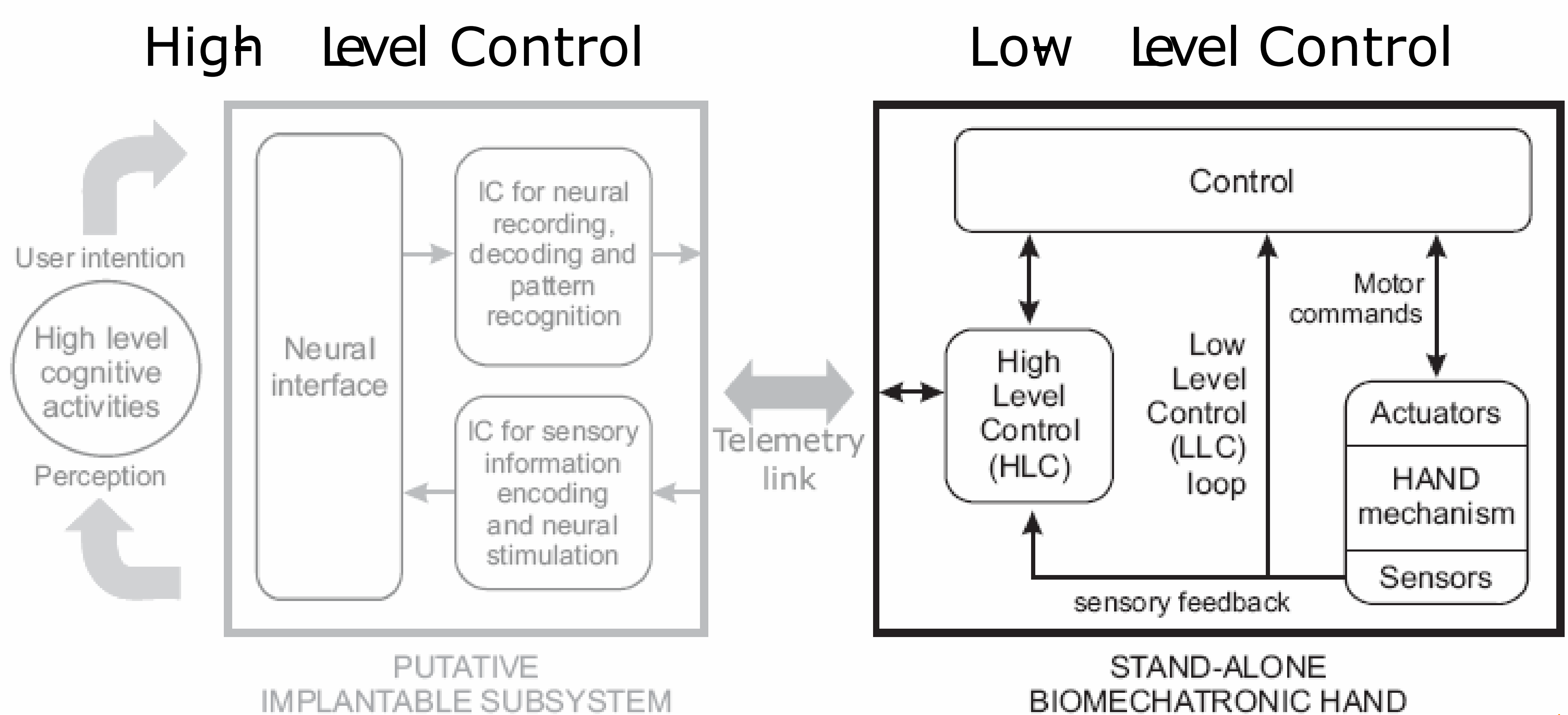
The CyberHand

Hand mechanical specifications



- 16 d.o.f. total – 6 d.o.m. total
- Underactuated fingers, each driven by a single cable actuated by a motor
- 6 d.o.m. : one for each finger (flexion/extension) + one for thumb positioning (adduction/abduction) 6 DC 6V motors
- trapezo-metacarpal thumb joint abduction/adduction range: 0°-120°
- finger joints flexion range: 0-90°
- Weight: Palm+fingers about 400 gr., Socket interface (actuation and transmission system) about 1400 gr.
- Grasping force: 35 N.
- Tip to tip force: 15 N.
- Anthropomorphic size, and kinematics.

Shared Control



Carrozza et al, *Biological Cybernetics*, 2006, 95:629–664
Edin et al, *Brain Research Bulletin*, in press

Properties of a Cybernetic Hand

- Must be perceived by the user as the natural hand by encoding sensory feedback and stimulating afferent nerves (*Perceptual Illusion*)

- Must be controlled directly by the user brain by means of real time decoding of efferent signals (*Natural Motor Control*)

S. Micera, M.C. Carrozza, L. Beccai, F. Vecchi, P. Dario,
Hybrid bionic systems for the replacement of hand function, Proc IEEE, (2006)

CyberHand Architecture

(01/05/2002 – 30/04/2005) IST-FET Project #2001-35094

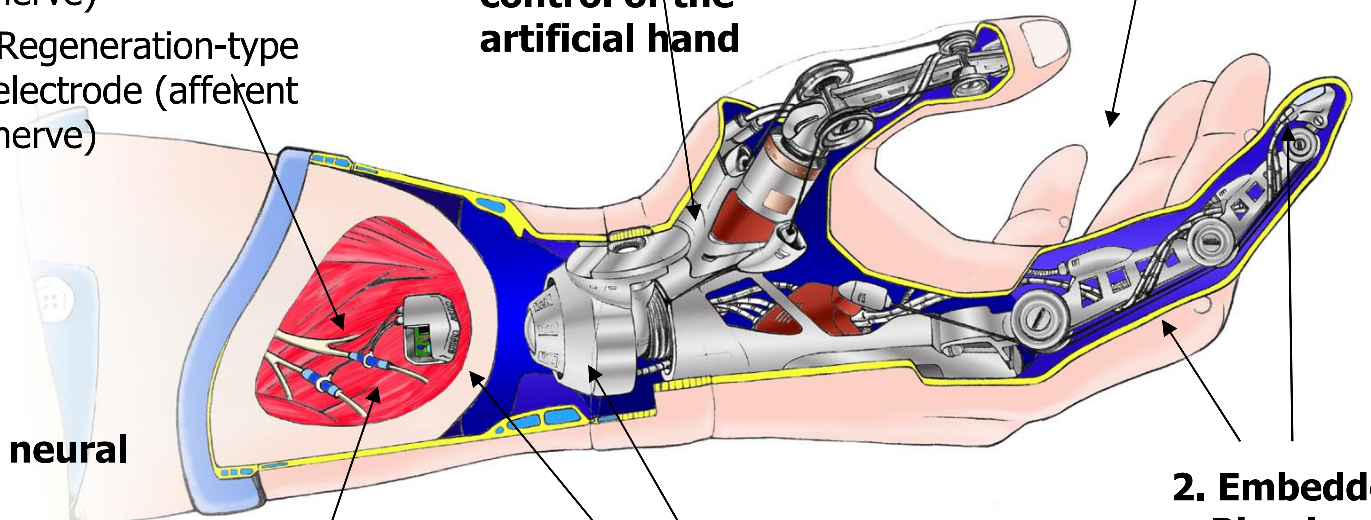
Regeneration-type electrodes:

3. Regeneration-type electrode (efferent nerve)
4. Regeneration-type electrode (afferent nerve)

8. Decoding patient's intentions and **Embedded closed-loop control of the artificial hand**

1. Biomechatronic Hand

Stump



5. Implanted neural interface:

- ENG efferent signals recording (patient's intention detection)
- Afferent nerves stimulation (to provide sensory feedback to the patient)

6. Receiver

7. Transmitter

2. Embedded Biomimetic sensors:

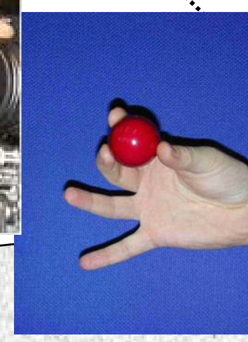
- within the structure
- within the glove

Basic functionalities of the human hand

The challenge is to identify the appropriate grasp primitives and relative minimum set of sensors for each hand function

Reaching & pre-shaping

Grasping



Manipulation with a stable grasp

Exploration

(sensory-motor coordination)

Gesture

CYBERHAND sensory system from components (mechanosensors) to function

PROPRIOCEPTIVE system

- 5 tension sensors on the cables
- 15 Hall effect sensors embedded in all the joints of each finger
- an incremental magnetic encoder and 2 stroke end Hall effect sensors on each of the 6 motors

↓

PROPRIOCEPTION
the ability to sense hand position and movement

EXTEROCEPTIVE system

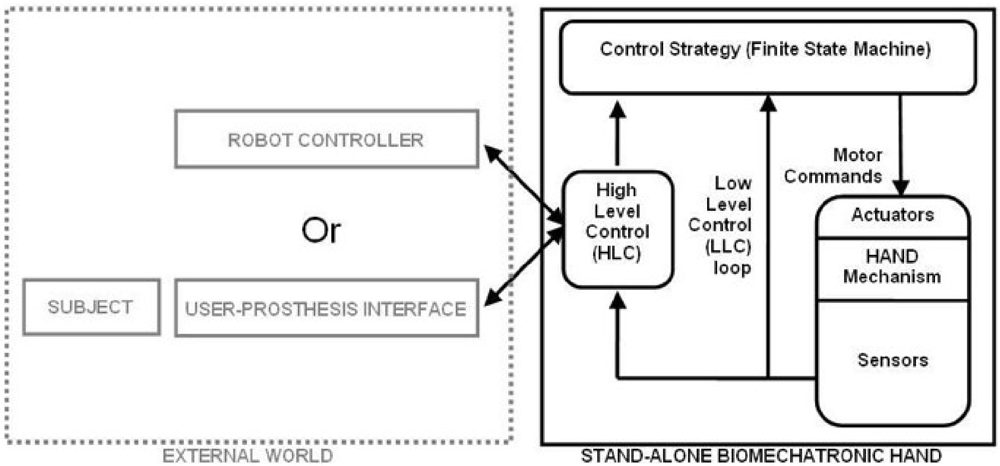
- contact sensors
- three-axial strain gauge force sensors

↓

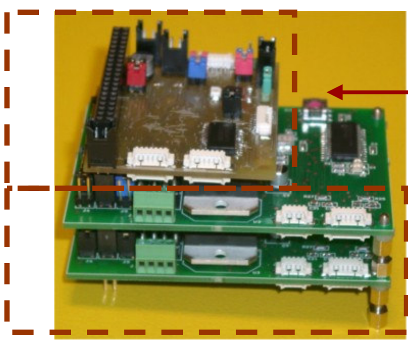
EXTEROCEPTION
sensing hand-object-environment interactions and exploring object-environment characteristics

The model for the sensory system is the Physiology of the Hand (Natural Perception, Action and Sensory-Motor Coordination)

"Stand-Alone" Mechatronic Hand



Integration of the Control System

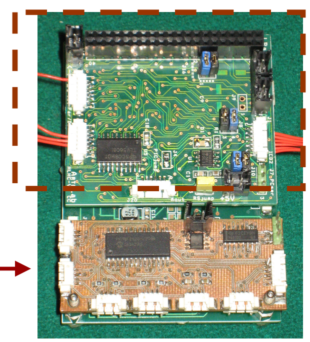


Lateral view

HLC

LLCs

EMG Classifier

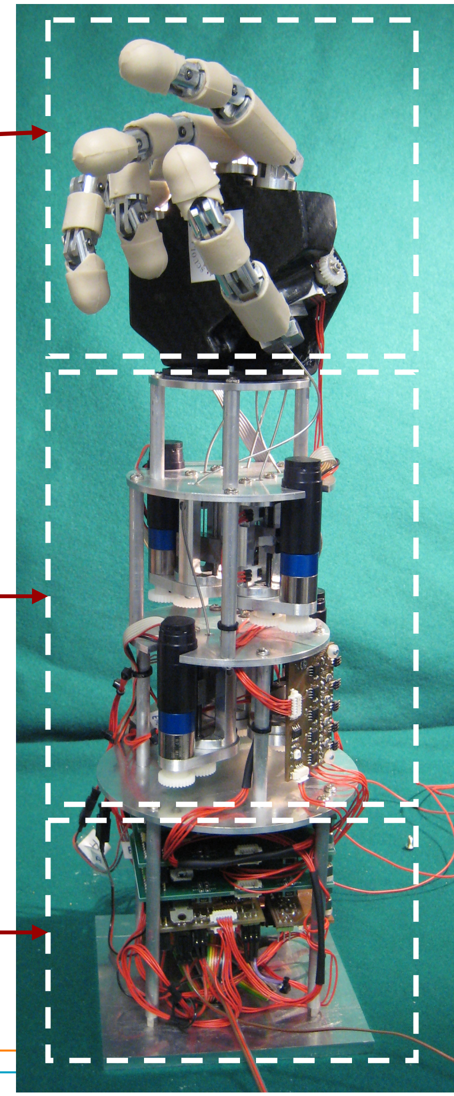


Top view

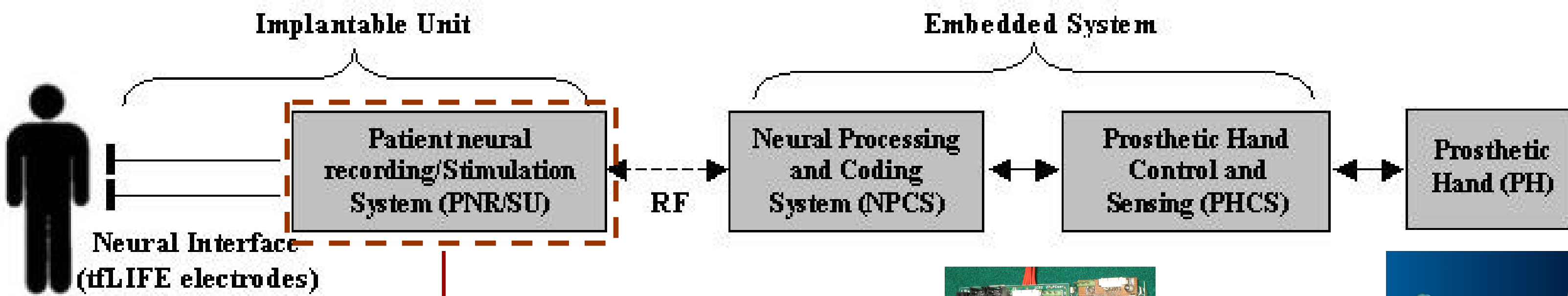
Underactuated Hand with intrinsic thumb opposition motor

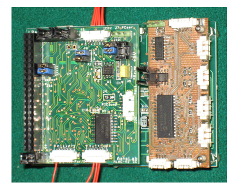
DC Motor Actuation Units

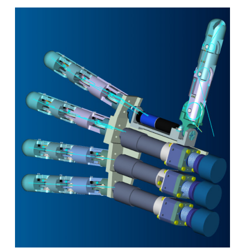
Dedicated Hierarchical Control Architecture

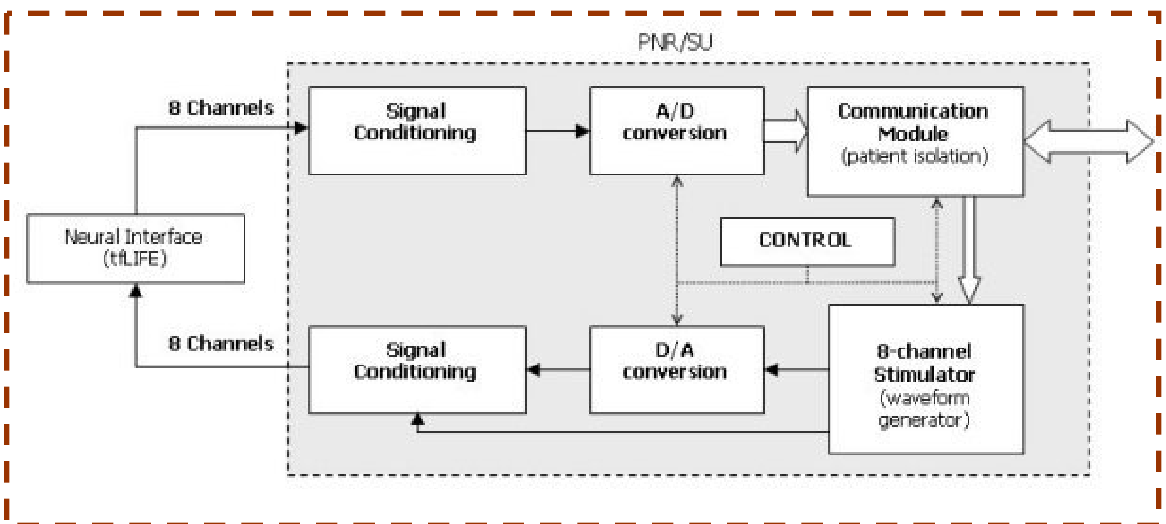


Recording and Stimulating Implantable System



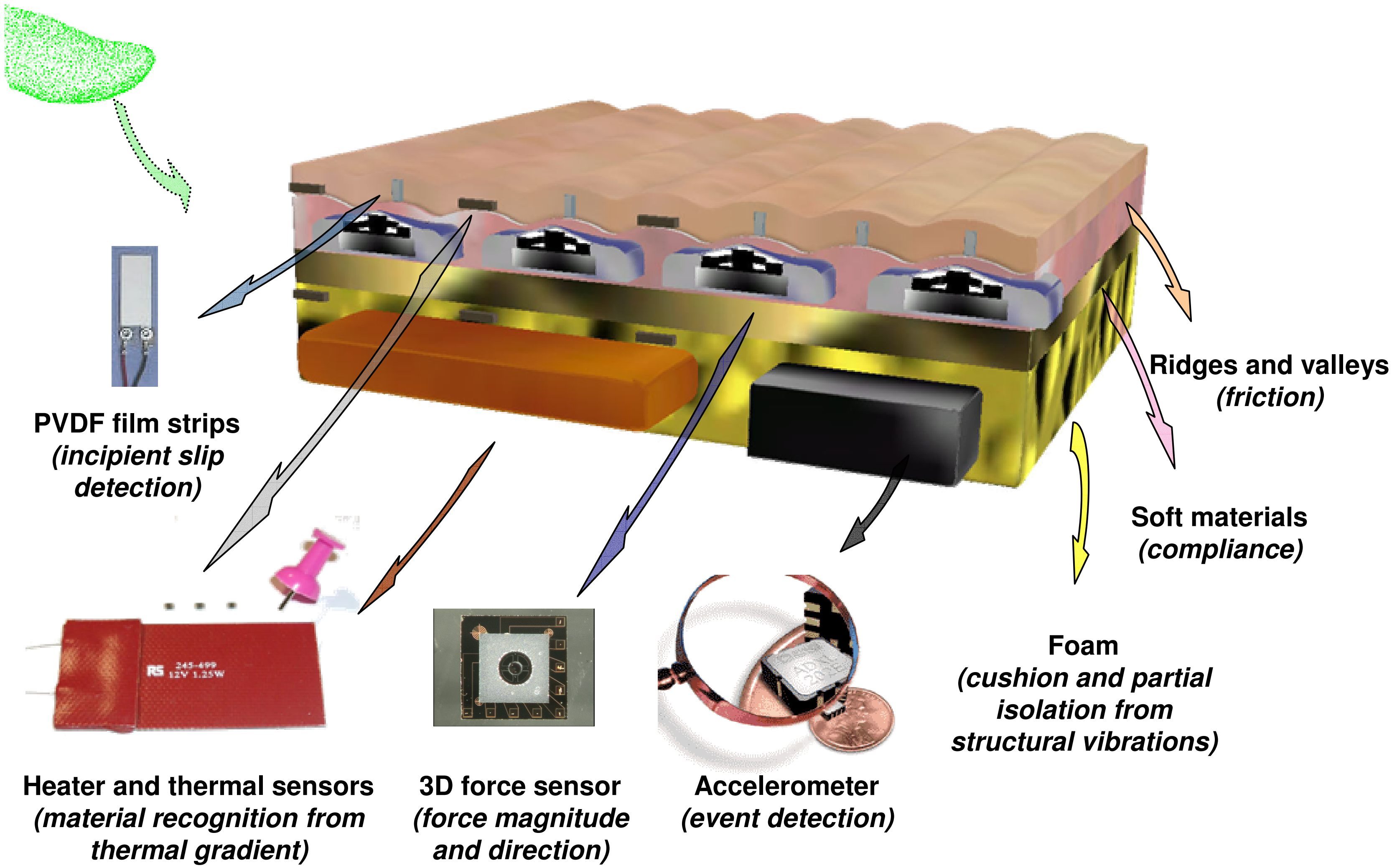




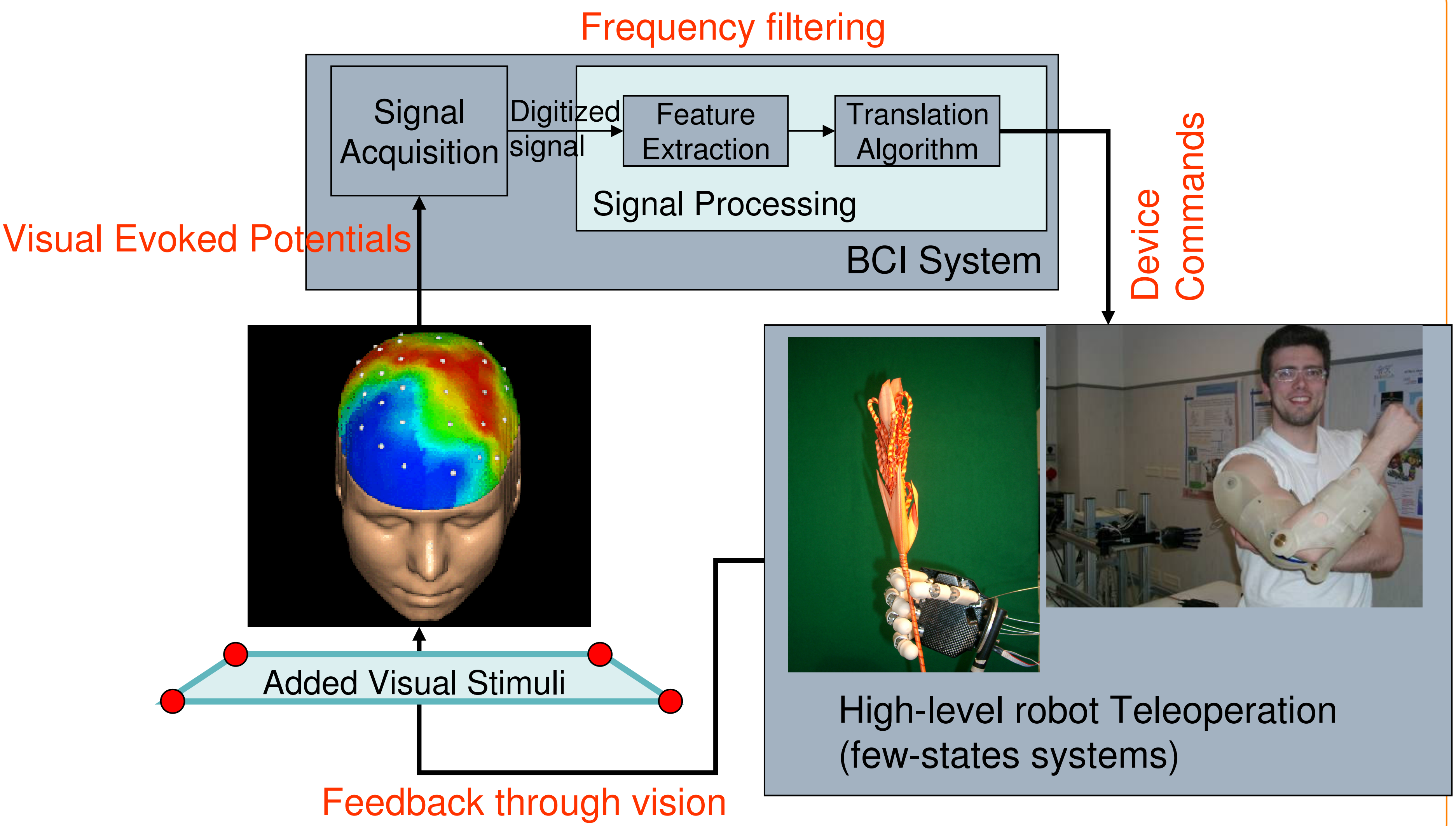


SafeHand Project
PRIN 2006

The artificial skin



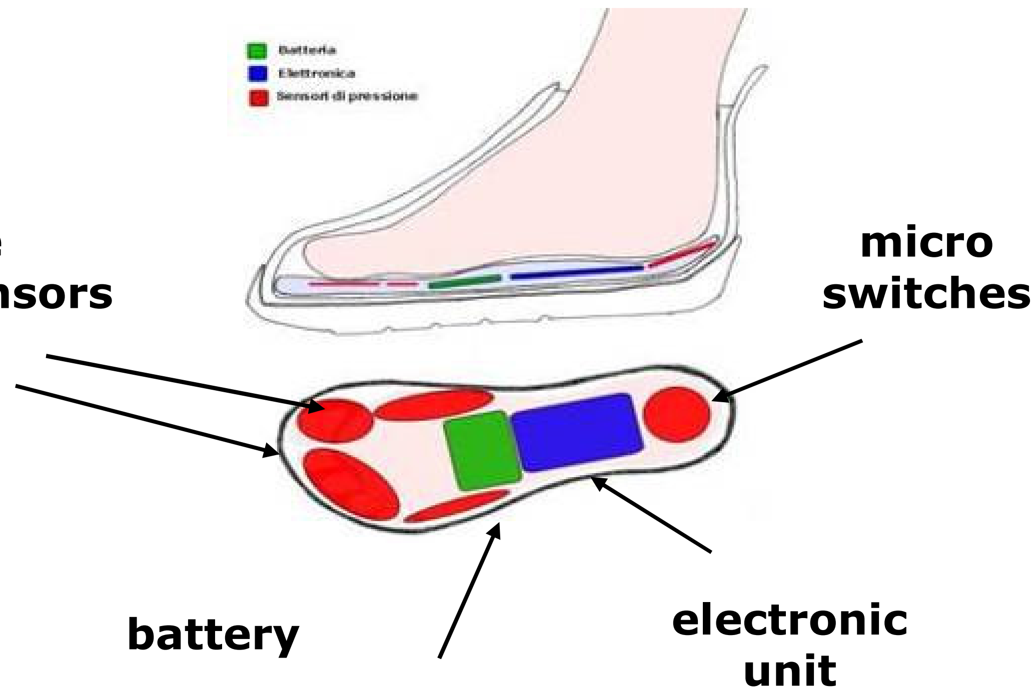
Brain-Robot Interfaces



Achille: **A**dvan**C**ed **HI**gh **L**evel contro**L** interfac**E**
A wearable interface to control external devices

ACHILLE is an intelligent human/machine interface for the wireless control of robotic artefact or external devices

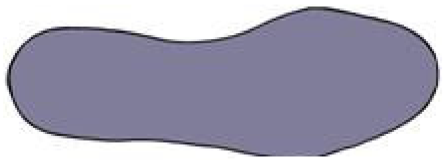
M. C. Carrozza et al, A Wearable Biomechatronic Interface for Controlling Robots with Voluntary Foot Movements, accepted for publication in IEEE/ASME Transactions on Mechatronics, (March 2007)



The main modules of the system are:

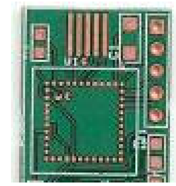
- **MicroSensors**
- **Signal Processing and Telemetry Unit**
- **Battery**

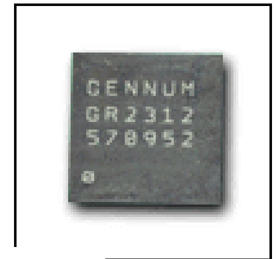
The ACHILLE prototype (Carrozza et al, IEEE TMECH, 2007)

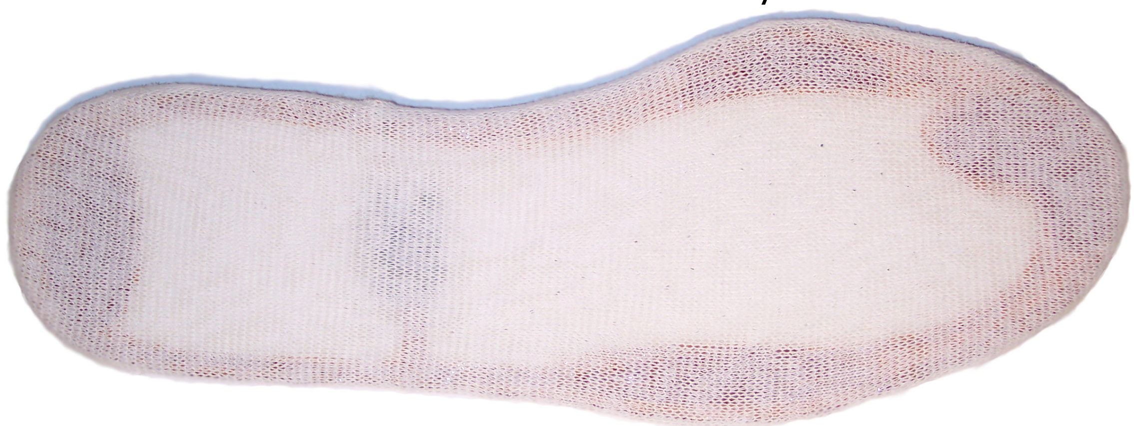


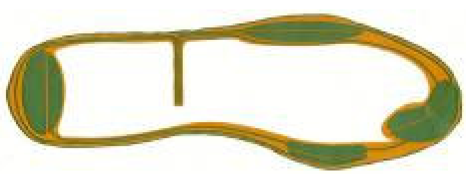
Commercia

Signal processing, telemetry unit (bluetooth based), and accelerometer for switching on/off the system









Four switches on flexible circuit

Battery

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Scuola Superiore Sant'Anna

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The NEUROBOTICS Project
FP6-IST-FET-2003 num.1917