Neuro-IT Workshop - July 8, 2003
Alicante, Spain

The CYBERHAND Project
IST-2001-35094

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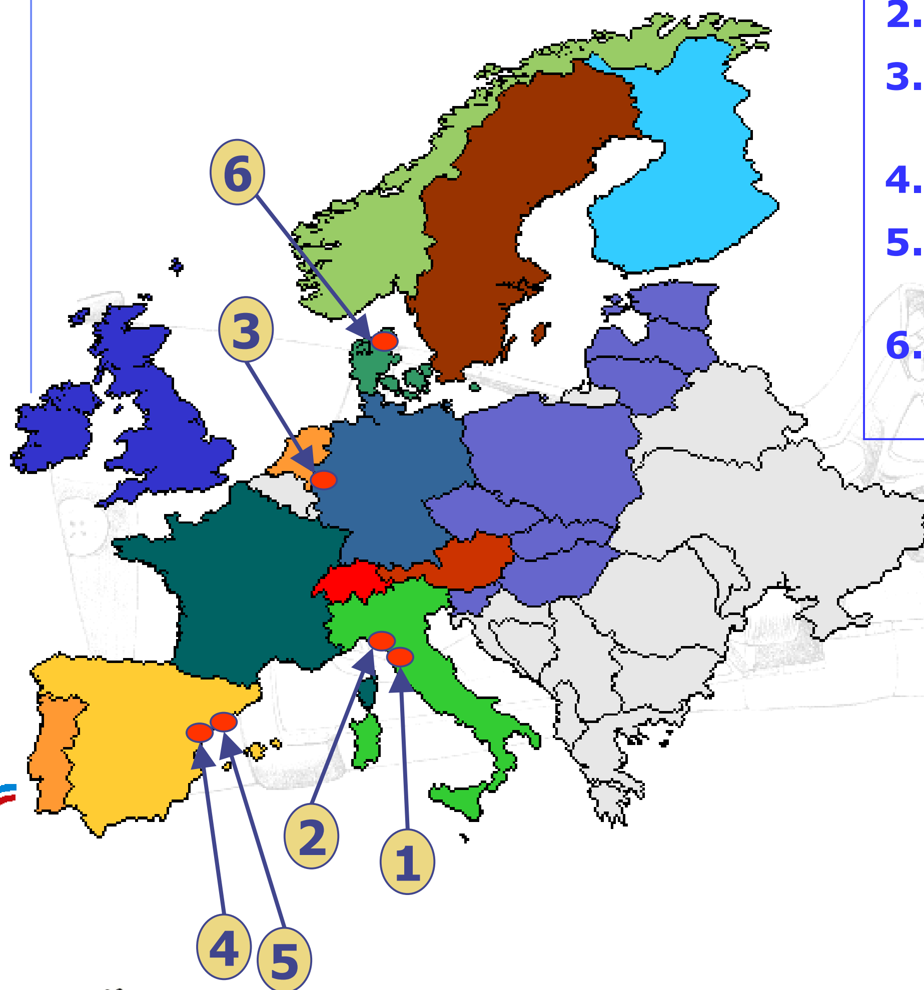
The Consortium



1. **Scuola Superiore Sant'Anna**
2. **INAIL RTR Center**
3. **Fraunhofer Institut für Biomedizinische Technik**
4. **Centro Nacional de Microelectronica**
5. **Universidad Autonoma de Barcelona**
6. **Center for Sensory-Motor Interaction**

List of Principal Investigators of CYBERHAND

Project Co-ordinator Prof. Paolo Dario

Technical Team Co-ordinators

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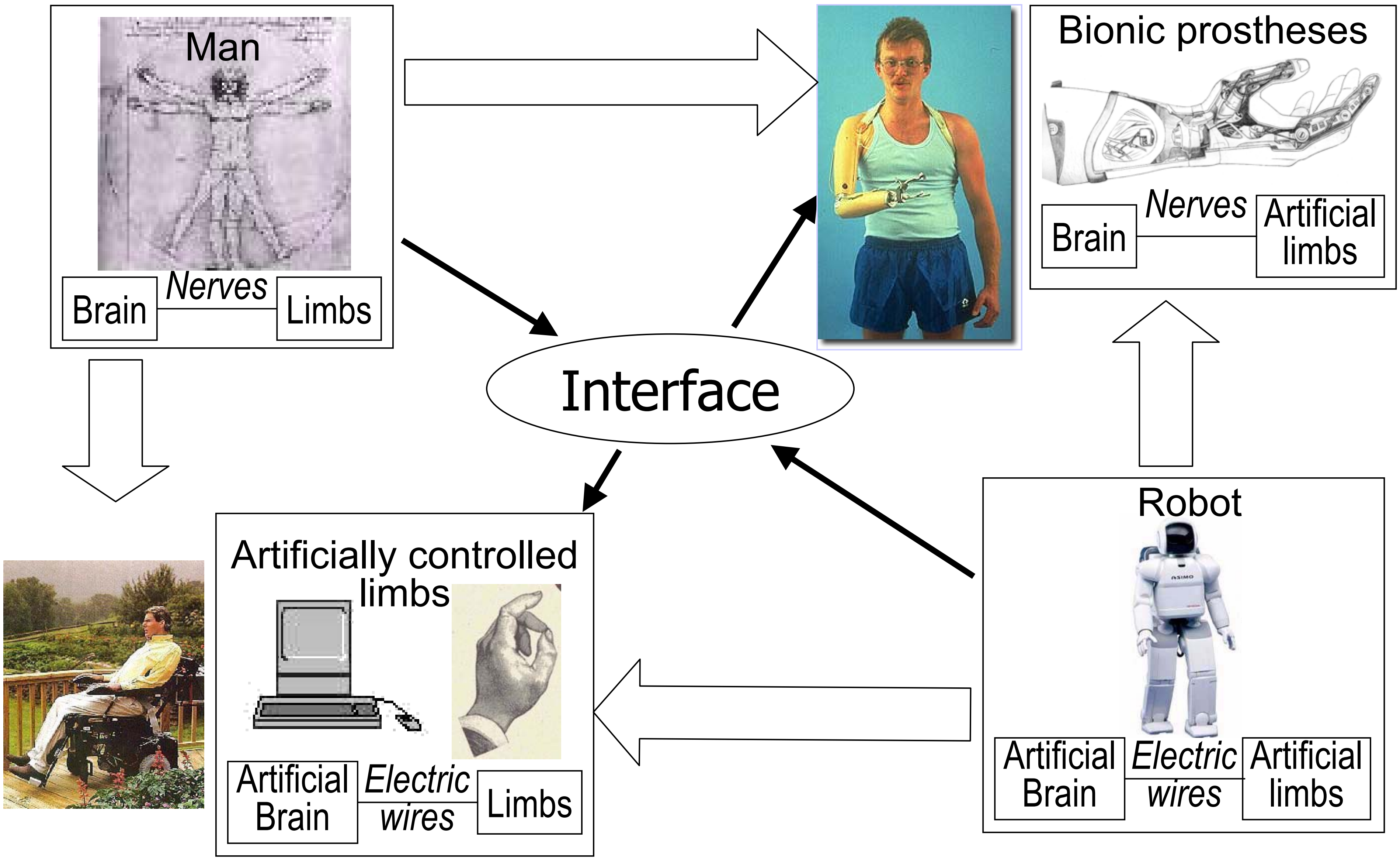
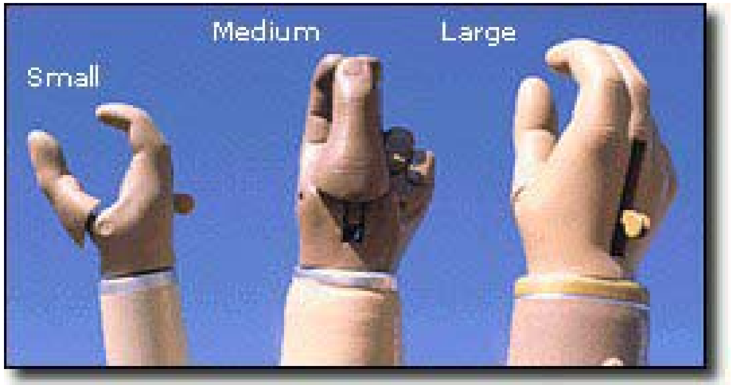
CP-RTR	Prof. M. Chiara Carrozza
FhG-IBMT	Dr. Thomas Stieglitz
CSIC-CNM	Dr. M. Teresa Oses
UAB	Prof. Xavier Navarro
AAU-SMI	Prof. Ronald R. Riso

"Connecting" Man and Robot



The problem: the technology of current prosthetic hands (and fingers) is clearly inadequate

- Low dexterity (only 1 active DOF)
- No (or limited) sensorisation
- The prosthesis is not perceived as own body part



….as a consequence

Surveys on the use of such artificial hands revealed that 30 to 50% of amputees do not use their prosthetic hand regularly

*LaPlante M.P., Carlson D., Disability in the U.S.; Prevalence and Causes, 1992. Report No.7, Disability Statistics Center, University of California, San Francisco

The Options for Hand Substitution in Amputees

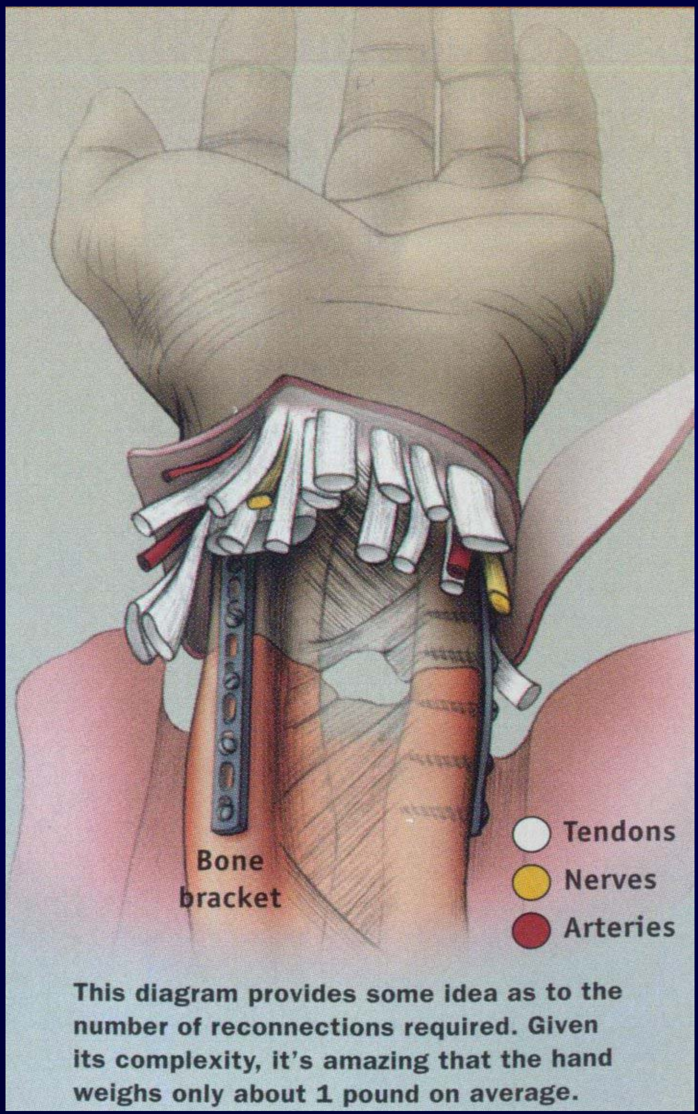
TODAY:

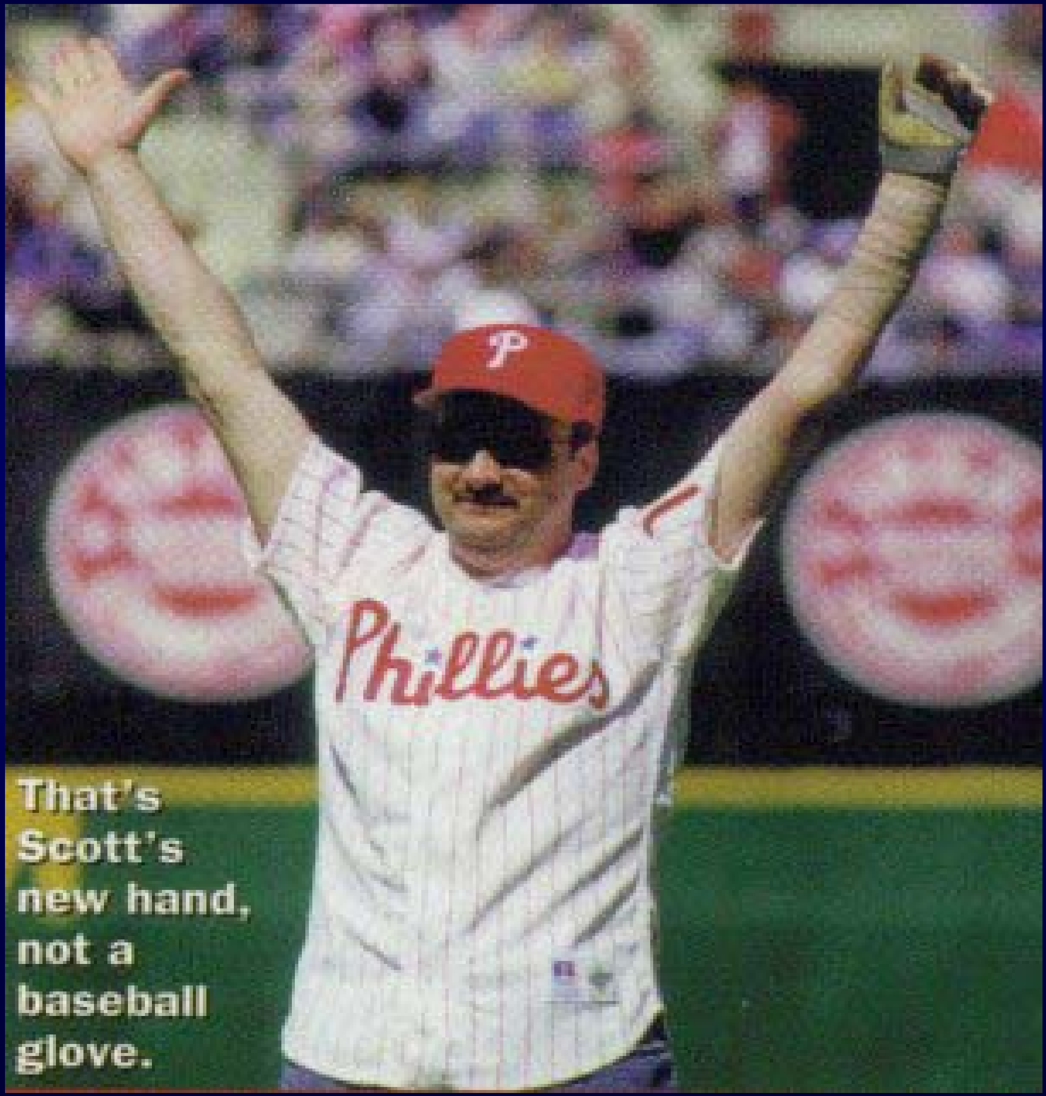
- myoelectric prostheses
- hand transplantation

TOMORROW:

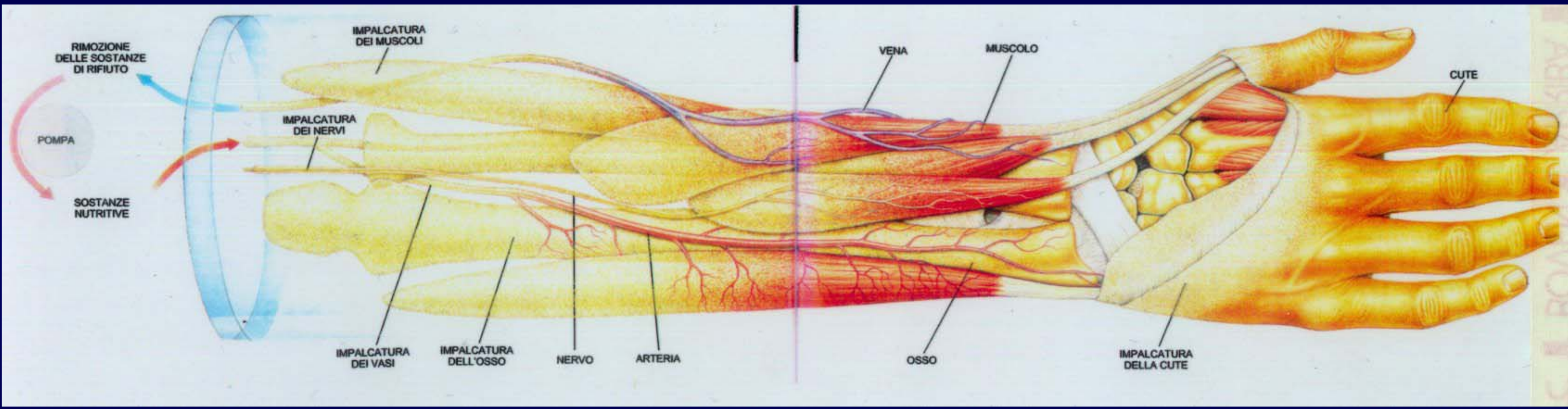
- cybernetic (or “biomechatronic”) hands
- ...and even hand regeneration

Hand Transplantation





Towards hand regeneration



Objectives of the CyberHand project

- **Long-Term Objective**:

  to increase the basic knowledge of neural regeneration, and sensory-motor control of the hand in humans

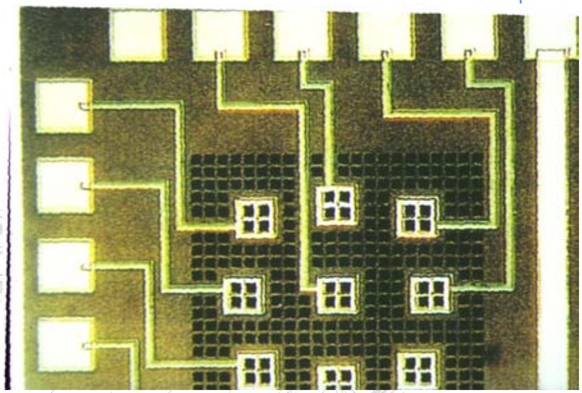
- **Intermediate Objective**:

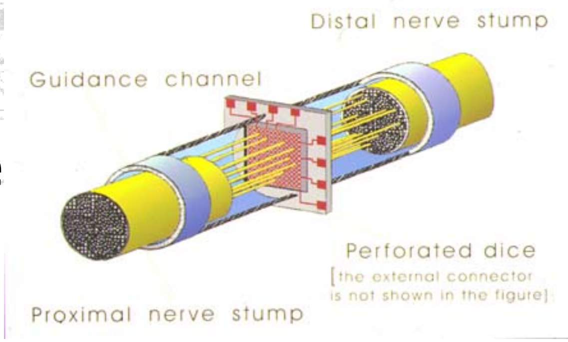
  to exploit this knowledge to develop a new kind of hand prosthesis which will overcome some of the drawbacks of current hand prostheses. This new prosthesis will:

  - be felt by an amputee as the lost natural limb delivering her/him a natural sensory feedback by means of the stimulation of some specific afferent nerves;
  - be controlled in a very natural way by processing the efferent neural signals coming from the central nervous system (reducing the discomfort of the current EMG-based control prostheses)

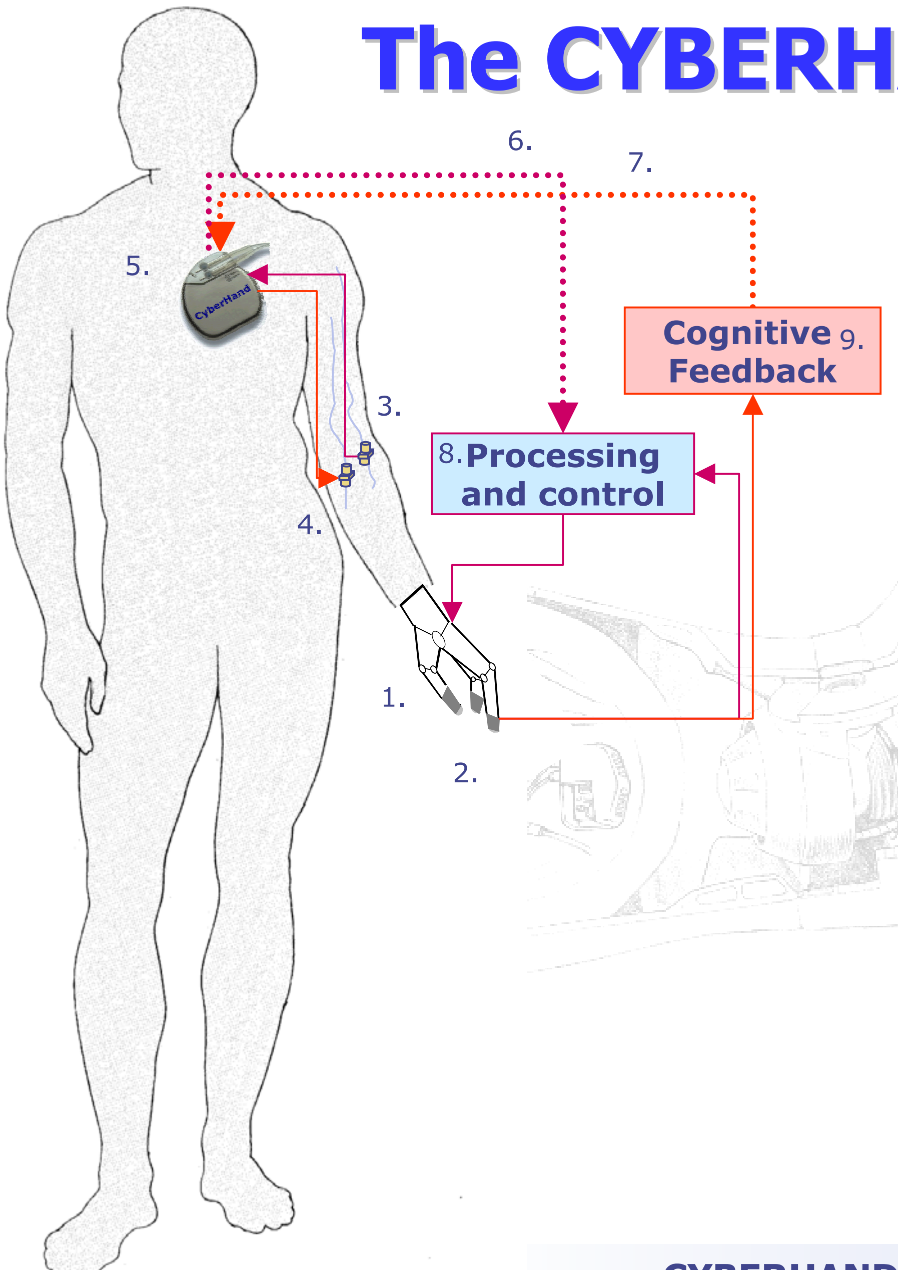
From the key component…

- The peripheral nervous system has a relatively good capacity to regenerate compared to the central nervous system
- The exploitation of the characteristics can allow the creation of a selective and intimate contact between the regenerating fascicles and the (sieve) electrodes
- This contact can allow the creation of a real bi-directional link between the nervous system and the artefact
- It is necessary to understand what degree of regeneration is obtainable not only from an histological point of view, but addressing in detail the issues related to the extraction/delivery of the information from/to the nervous system (the “bandwidth” of the sieve electrodes)
- **This is the key issue which is addressed during the project**





…to the final system: The CYBERHAND Demonstrator



1. Biomechatronic Hand
2. Biomimetic sensors
3. Regeneration-type electrode (efferent nerve)
4. Regeneration-type electrode (afferent nerve)
5. Implantable system for neural stimulation and recording
6. Efferent telemetric link
7. Afferent telemetric link
8. External unit for decoding patient's intentions and for prosthesis control
9. Cognitive feedback

The Final Demonstrator

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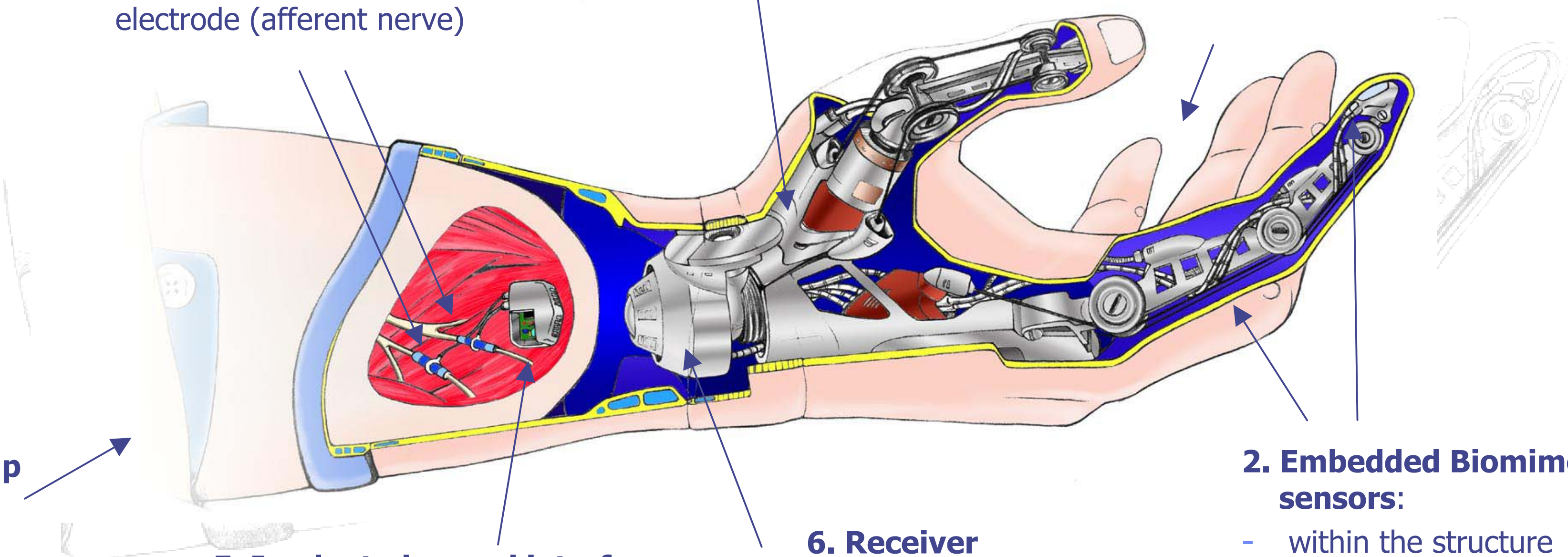
Regeneration-type electrodes:

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

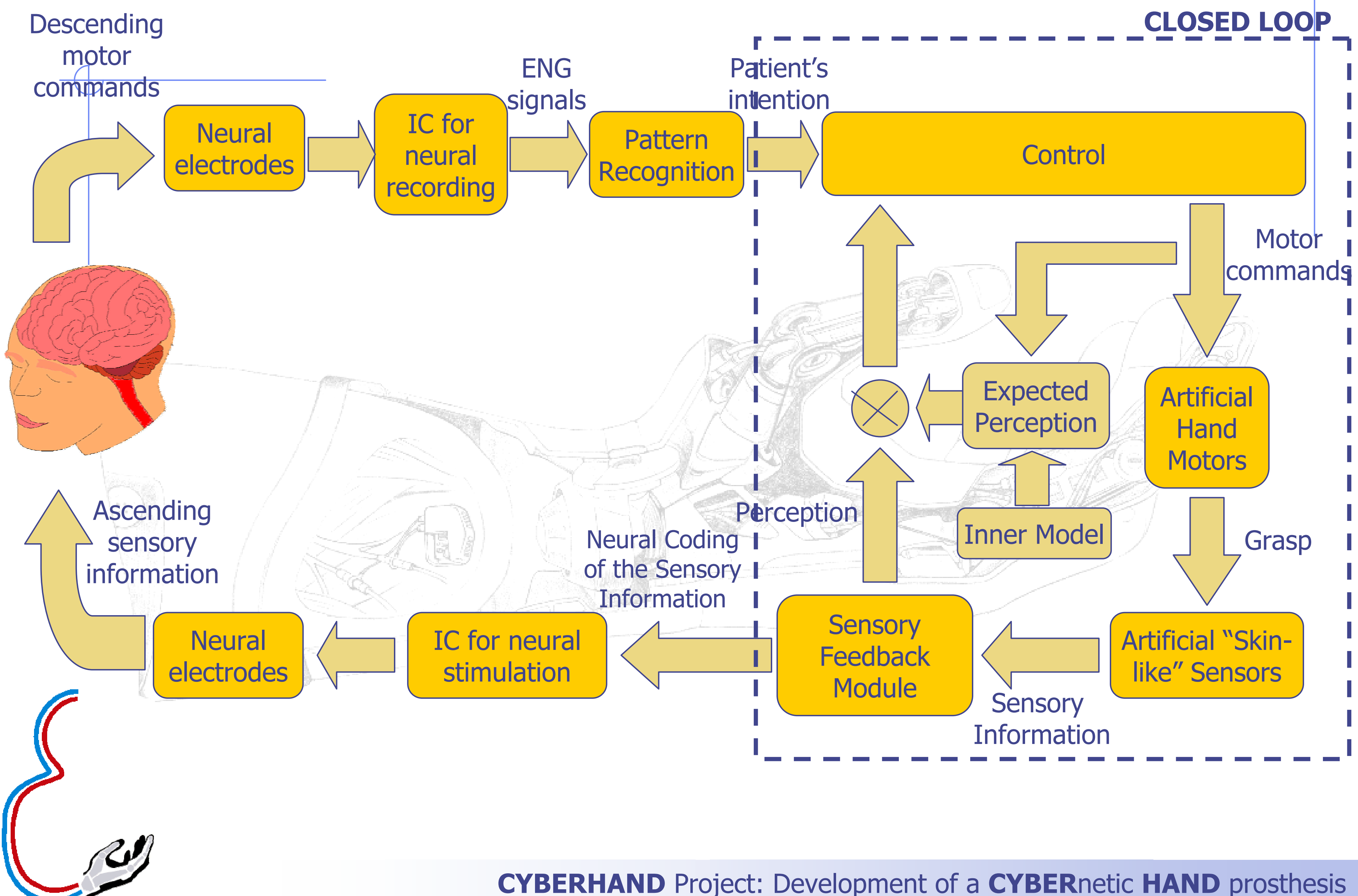
5. Implanted neural interface:

- 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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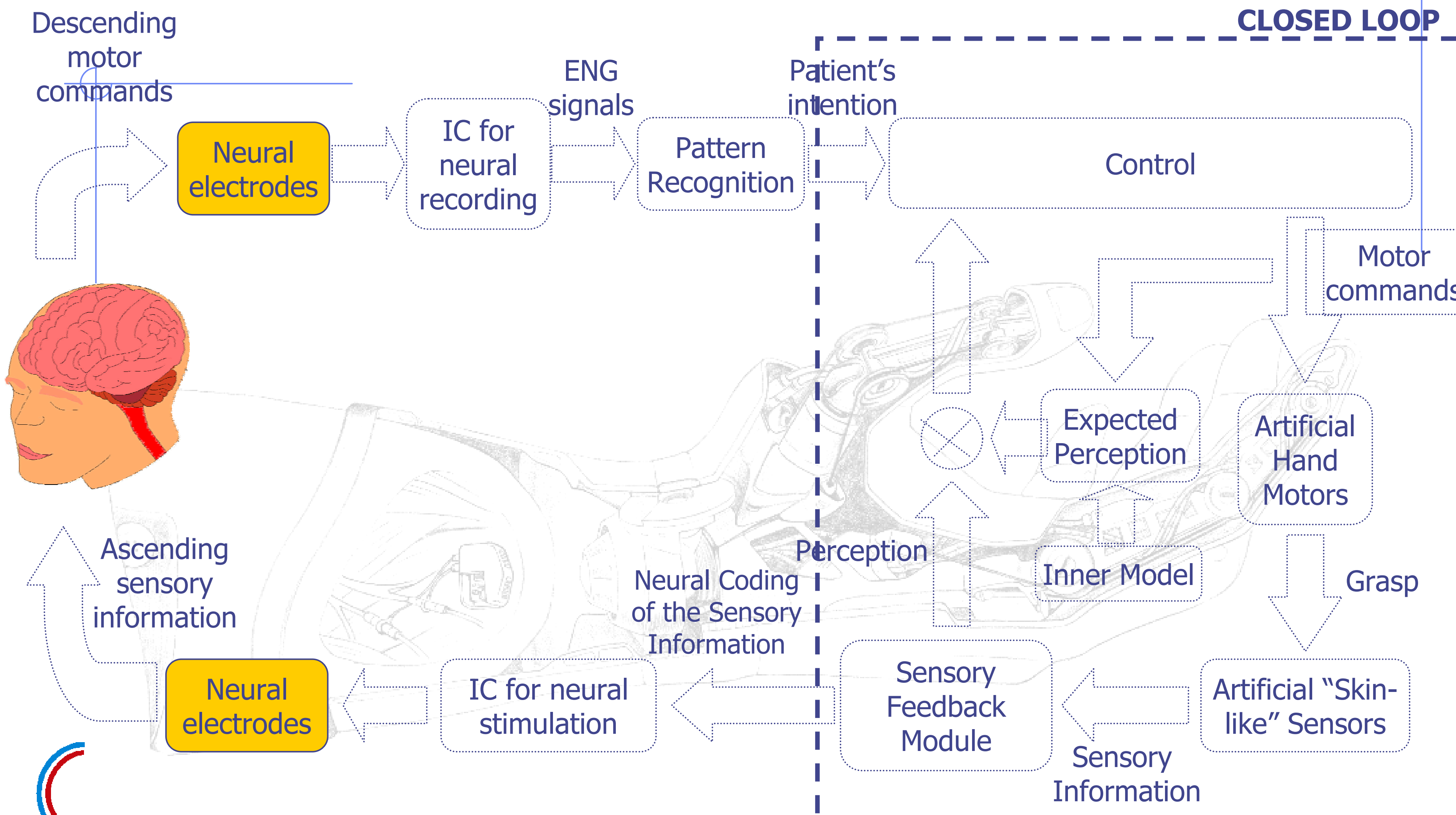

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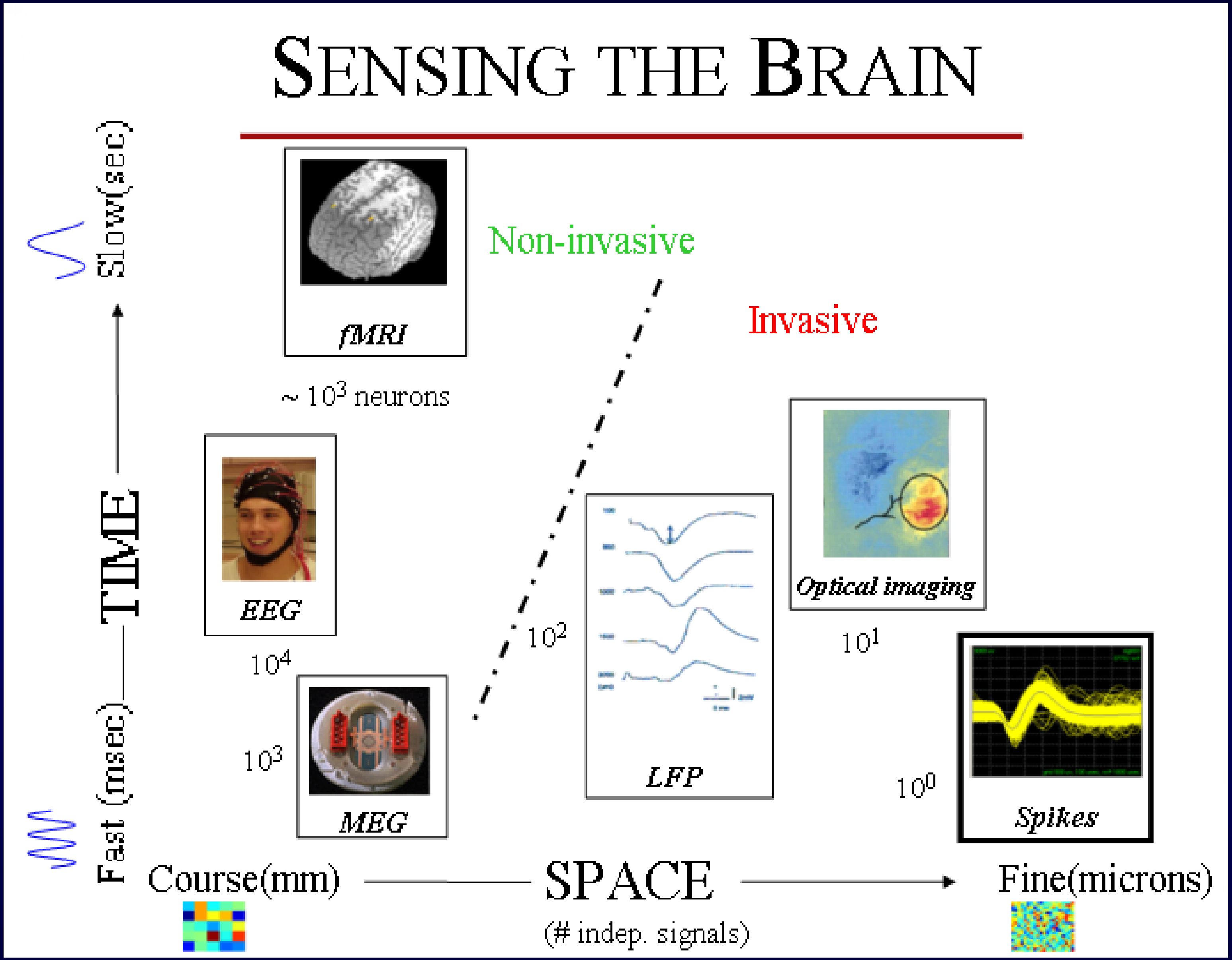
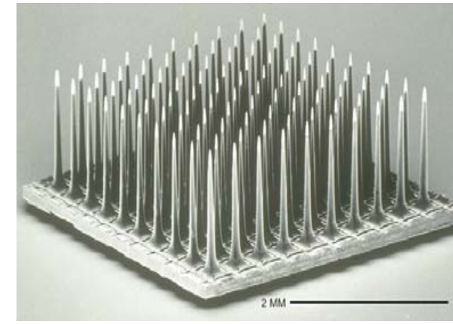
"Brain to Computer Interface is one of the 10 Emerging Technologies that will change the world"

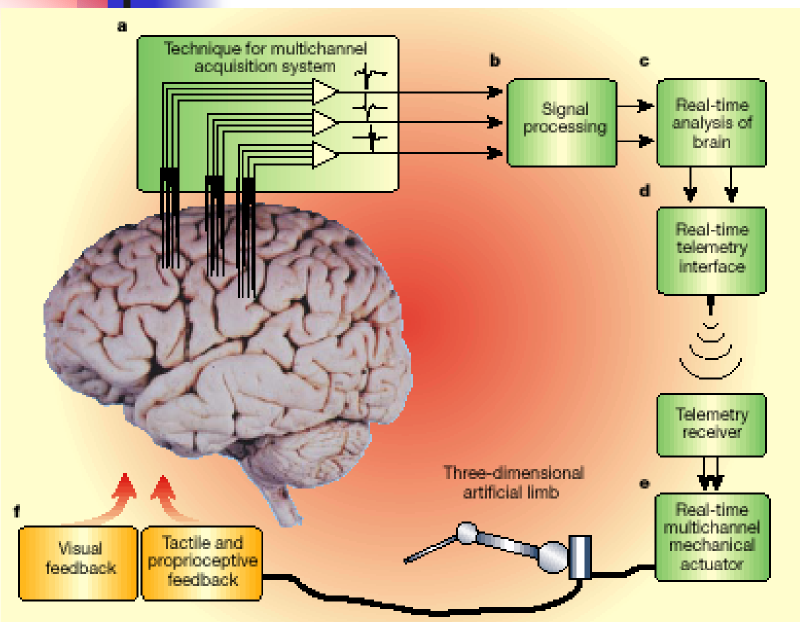
***Technology Review*, January/February, 2001**

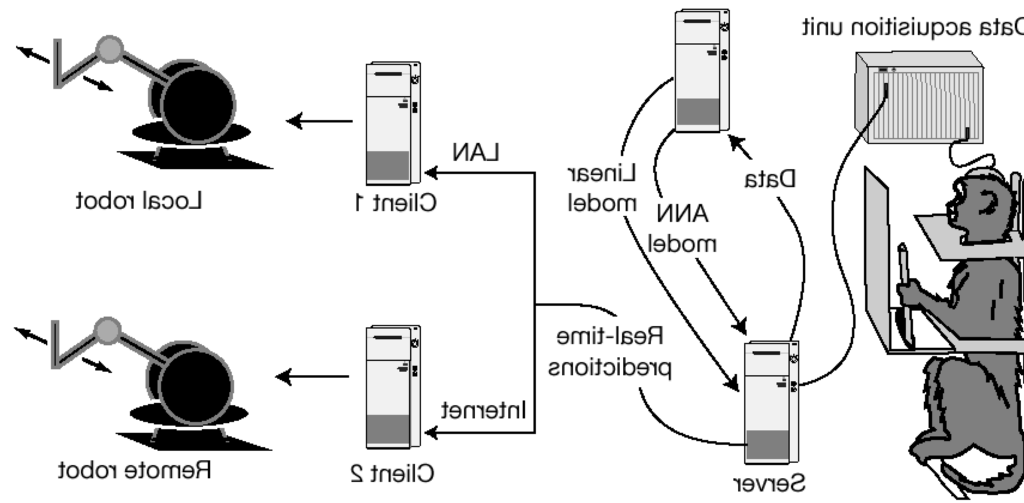


Sensing technologies that can be used to observe neural activity, divided by non-invasive vs. invasive, spatial and temporal resolution.

INVASIVE CORTICAL INTERFACES



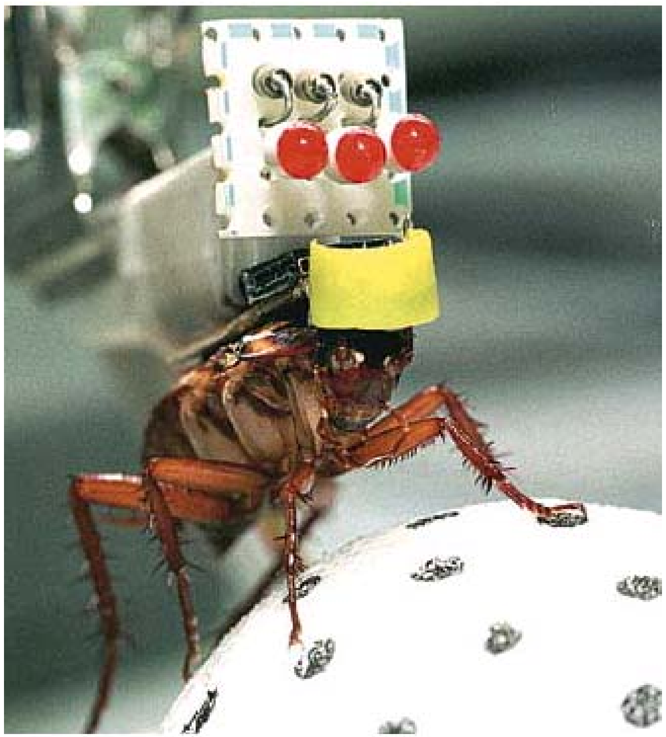




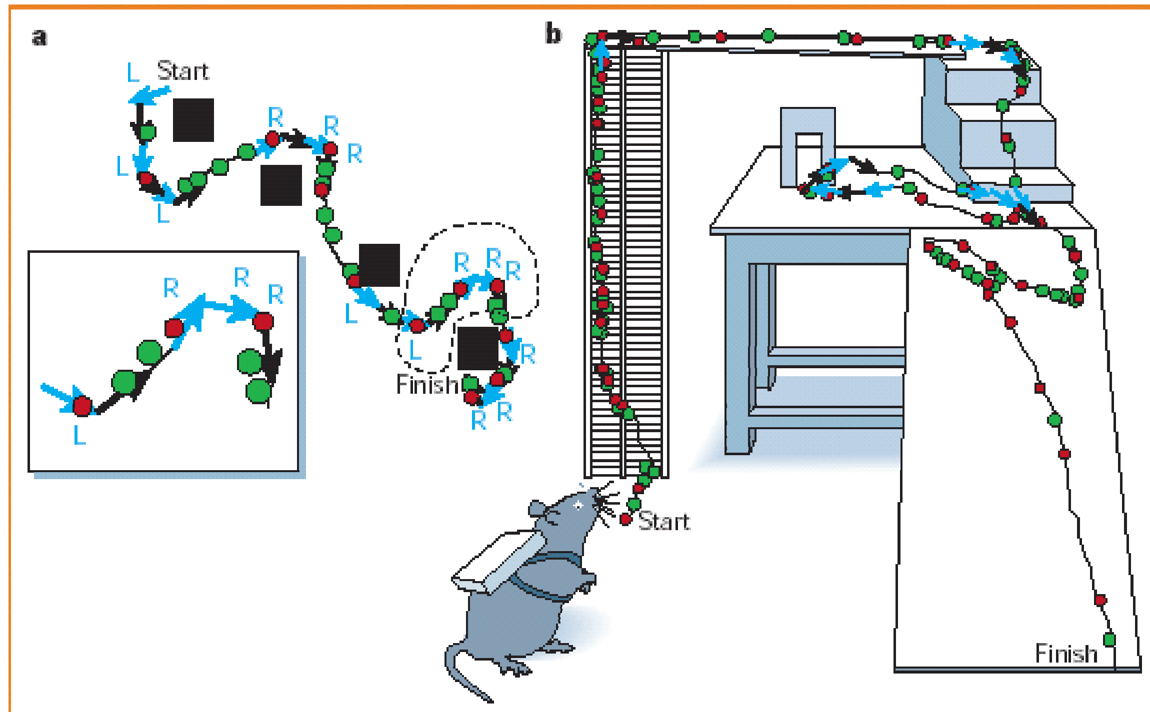
M. Nicolelis, Duke University, USA, Nature, January 2001

Cortically derived signals were successfully used for real-time control of robotic devices, both locally and through the Internet

Controlling biological systems by artificial stimulation



Raphael Holzer, Isao Shimoyama, "Bio-robotics Systems Based on Insect Fixed Behavior by Artificial Stimulation," Robotics Research, The Eighth International Symposium, pp. 401-407, Springer, 1998

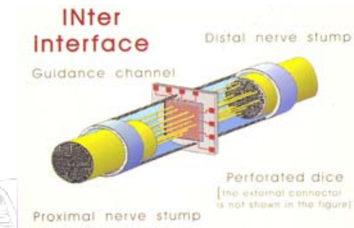


S. K. Talwar, S. Xu, E.S. Hawley, S. A. Weiss, K. A. Moxon, J. K. Chapin, “Behavioural neuroscience: Rat navigation guided by remote control” Nature 417, 37 - 38 (2002)

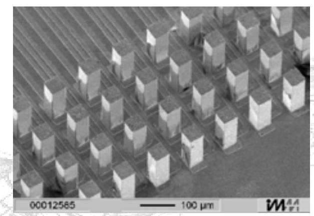
Interfaces with the PNS

Selectivity

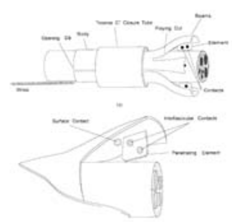
Sieve



Multi-needle



Intraneural



Cuff

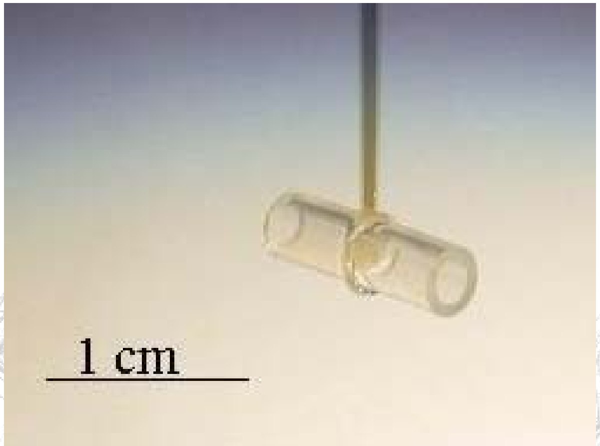
In order to control many DoFs and to deliver a sensory feedback a good selectivity is crucial

Invasivity

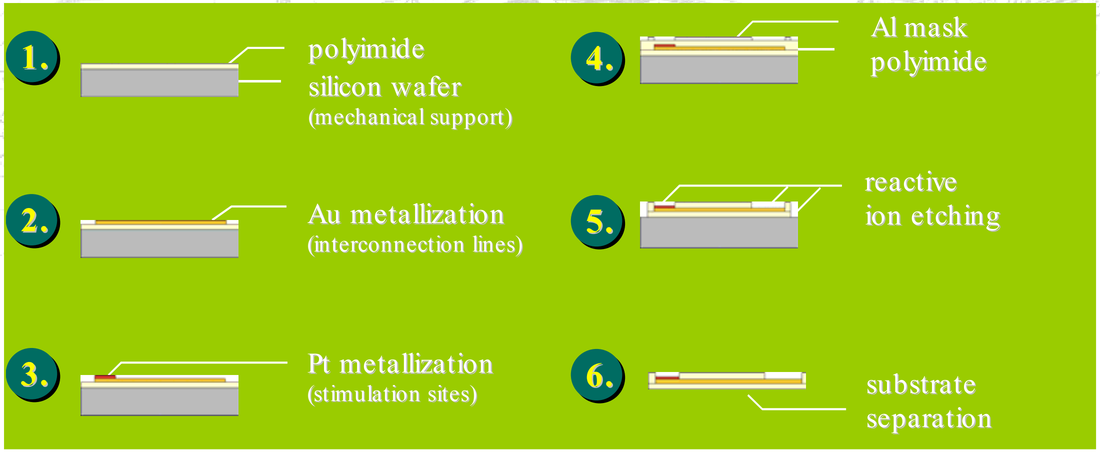
Regeneration-type electrodes - First design

Technology and characteristics

- Micromachining of the electrodes
- Thin-film electrodes with platinum electrodes
- Tubes as channels for nerve
- Ground electrodes near the regeneration area
- 9 ring electrodes



Sieve electrode with silicone tube

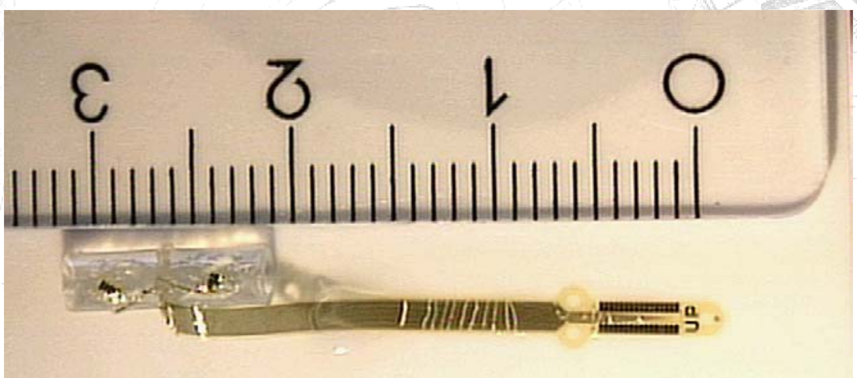


Technology process for the sieve electrodes implementation

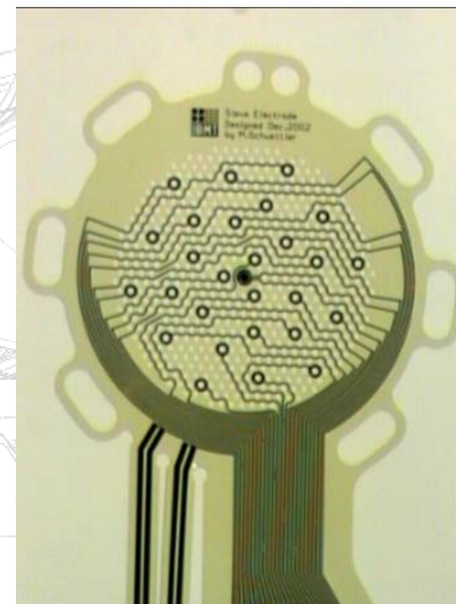
Regeneration-type electrodes - Second design

Technology and characteristics

- 27 ring electrodes for recording and stimulation
- Separate recording reference electrode
- Distal and proximal stimulation counter electrode
- Improved fixation of the silicone tubes



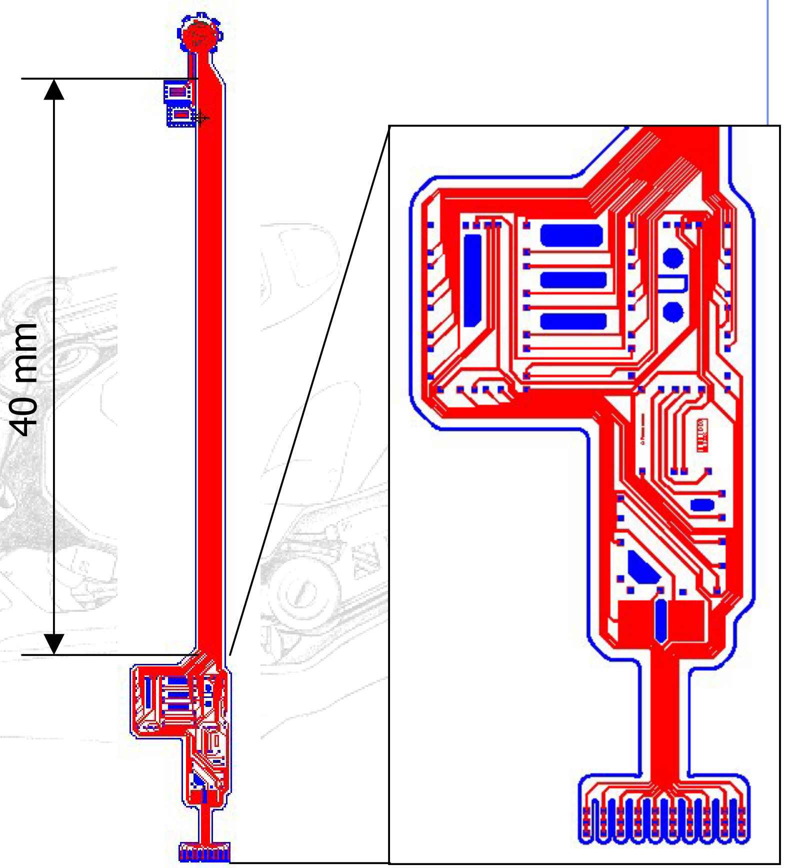
Sieve like electrode with tube and connector



Head of a sieve like electrode

Intelligent electrode with integrated miniaturised multiplexer

- Two simultaneous recording or stimulation channels
- Mixed distribution of the electrodes related to the channel on the electrode
- Channel controlling by Reset, Count and Enable
- Additional recording reference contact
- Totally nine cables for the control
- Improved fixation of the silicone tubes
- 40 mm polyimide lead
- Chips on flexible PCB
- Foldable design to reduce the size
- Holes under the chips for better distribution of encapsulation material
- Line loop to change the reference electrode concept



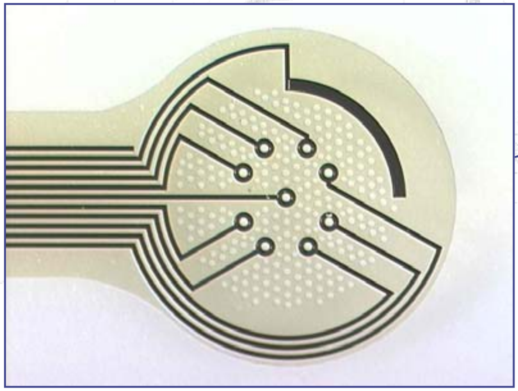
Evaluation of long-term nerve regeneration through regeneration type electrodes

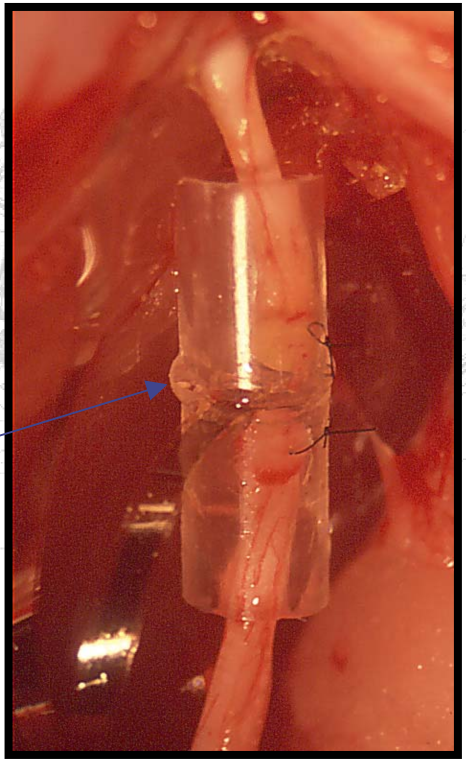
Implantation of regenerative electrodes in the sciatic nerve of rats (n = 30)

– up to 2 mo (n = 14)

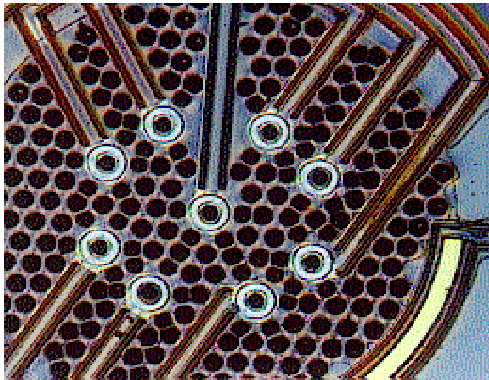
– up to 6 mo (n = 8)

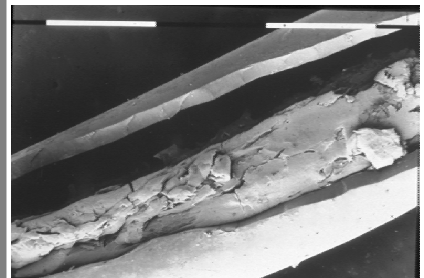
– up to 12 mo (n = 8)

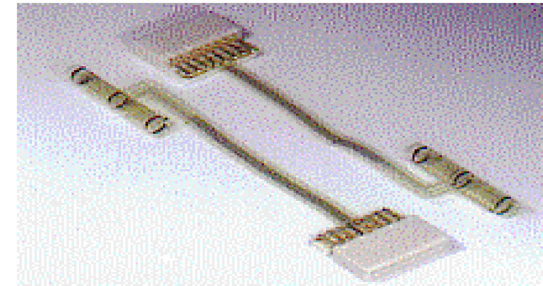


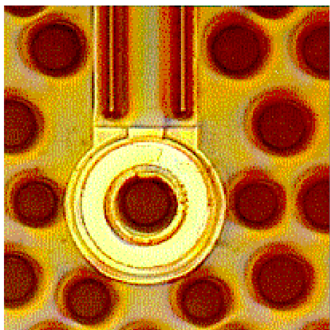


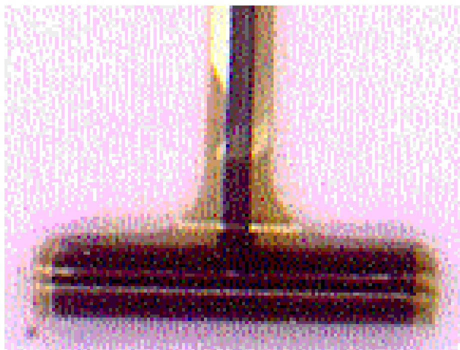
Neural interfaces for PNS

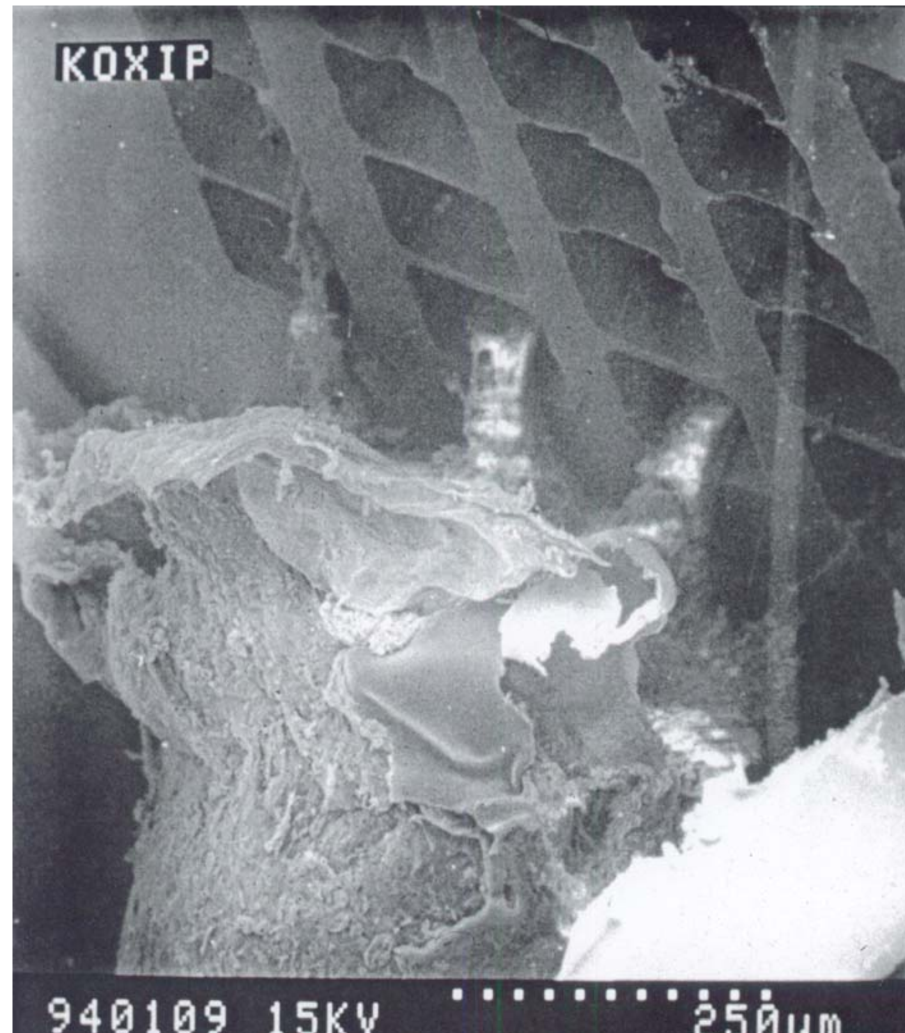










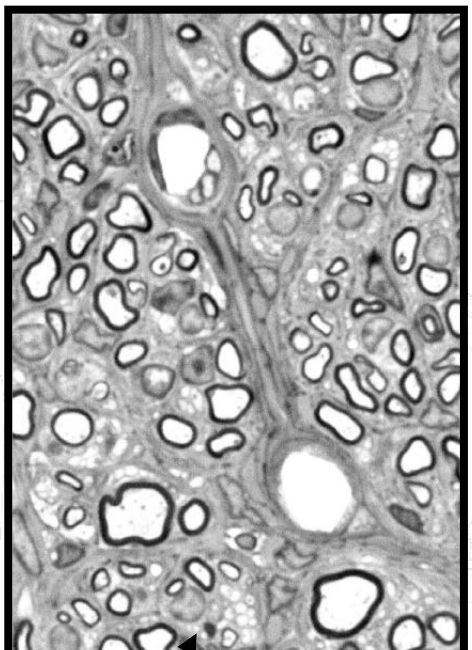


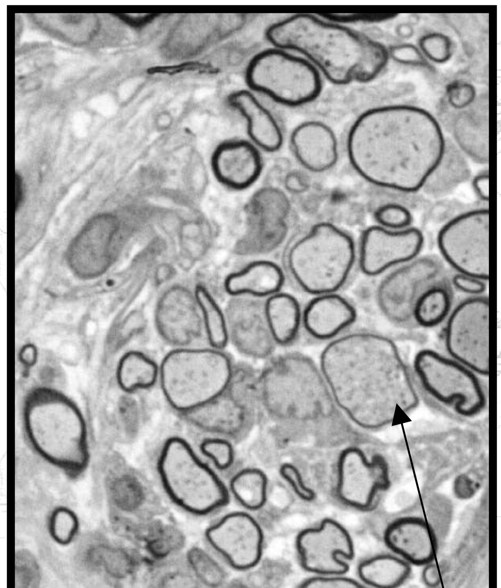
Evaluation of long-term nerve regeneration through regeneration type electrodes

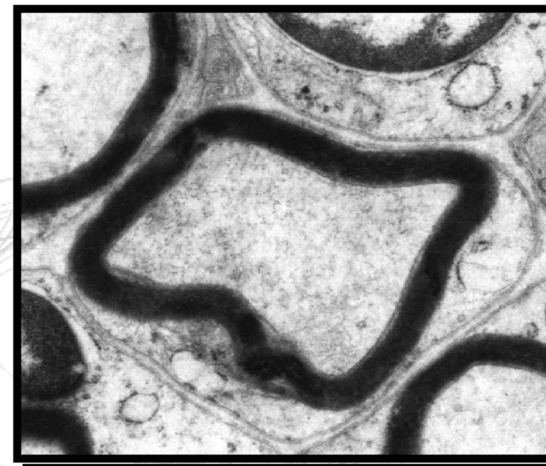
Morphological evaluation of regeneration

- LM and EM of regenerated nerve near the sieve

Transverse sections at 1 mm from the sieve electrode







Most axons have normal regenerative appearance.

A low proportion of axons suffer from compressive axonopathy at the electrode level.

Thinner myelin sheath than more distally.

Evaluation of long-term nerve regeneration through regeneration type electrodes

Functional evaluation of regeneration and reinnervation

- motor and sensory nerve conduction
- walking track
- pain sensibility

0, 2, 3, 4, 6, 9, 12 mo

	2 months	3 months	4 months	6 months	9 months
(n)	(30)	(30)	(19)	(19)	(9)
Gastrocnem. CMAP (mV)	9 ± 1	18 ± 2	25 ± 1	26 ± 1	23 ± 2
Plantar CMAP (mV)	0.1 ± 0.0	0.4 ± 0.1	1.3 ± 0.2	1.7 ± 0.4	1.5 ± 0.4
Tibial CNAP (µV)	24 ± 3	49 ± 11	95 ± 14	93 ± 11	73 ± 14
Digital CNAP (µV)	1.7 ± 0.4	3.4 ± 0.9	5.3 ± 0.7	12.2 ± 1.8	8.0 ± 2.4

Regeneration increased during the months in all the rats implanted

Evaluation of long-term nerve regeneration through regeneration type electrodes

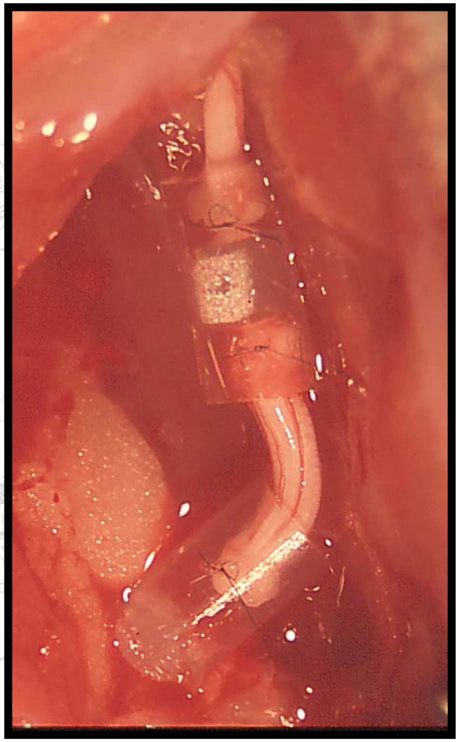
Design of a nerve amputee model in rats

- evaluated at 2.5 mo (n = 6)
- evaluated at 6 mo (n = 6)

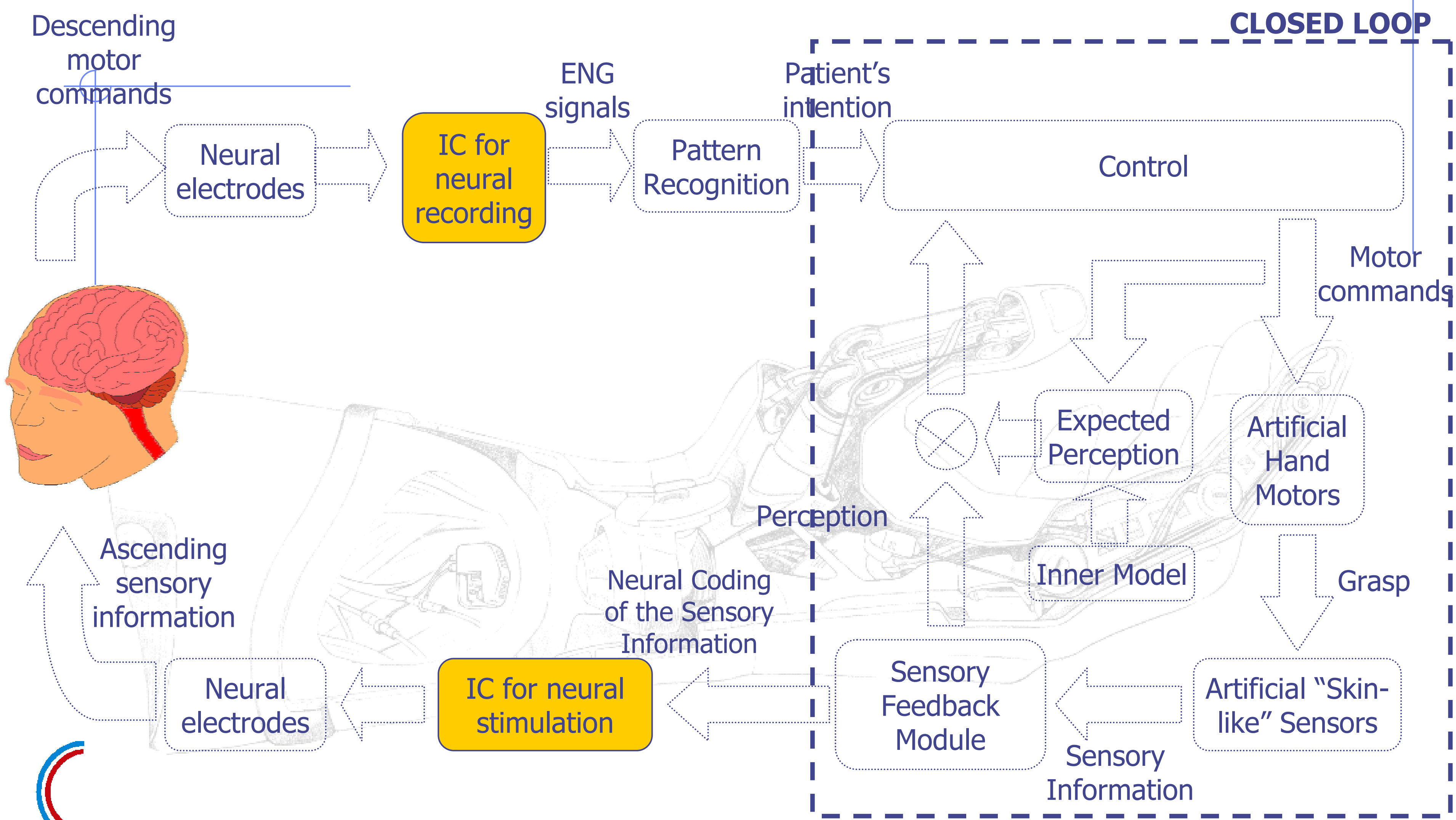
Under follow-up and analysis

Ongoing strategies to promote axonal regeneration and survival:

- transplant of Schwann cells in the capped tube
- immortalization of the transplanted Schwann cells
- overexpression of growth factors (selective for motor or sensory neurons)



Distal stump within a capped silicone tube



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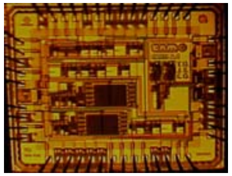
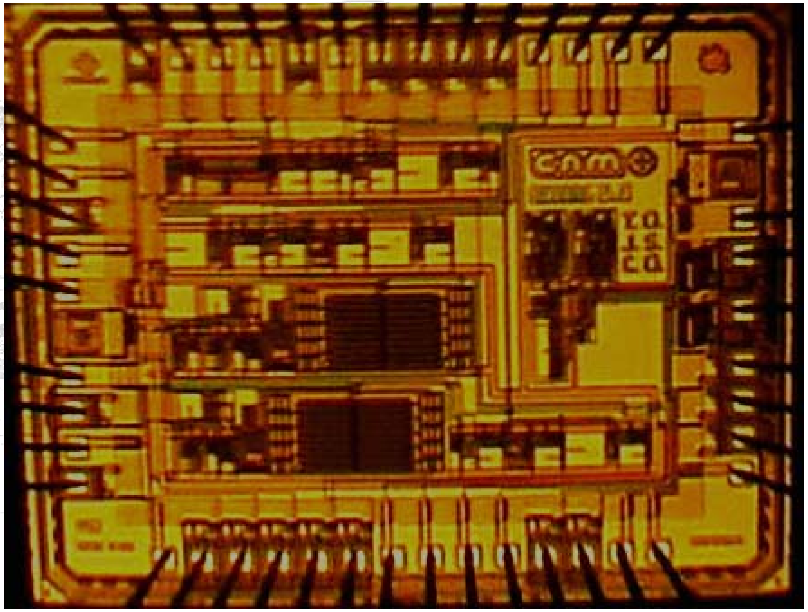
Recording circuitry, 1st prototype



Functional blocks included:

- One full channel and individual test modules
- Two DC-DC voltage regulators 5 and 28 Volts

Parameter	*Value*
Input range	V_{min} 4 µV V_{max} 400 µV
Noise	350 nV rms @ 100 Hz to 5KHz
Offset	+/- 100 mV
CMRR	-90 dB
Band width	100 - 5000 Hz
Gain	100 dB



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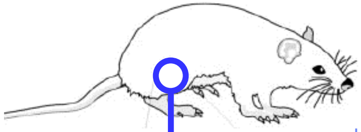
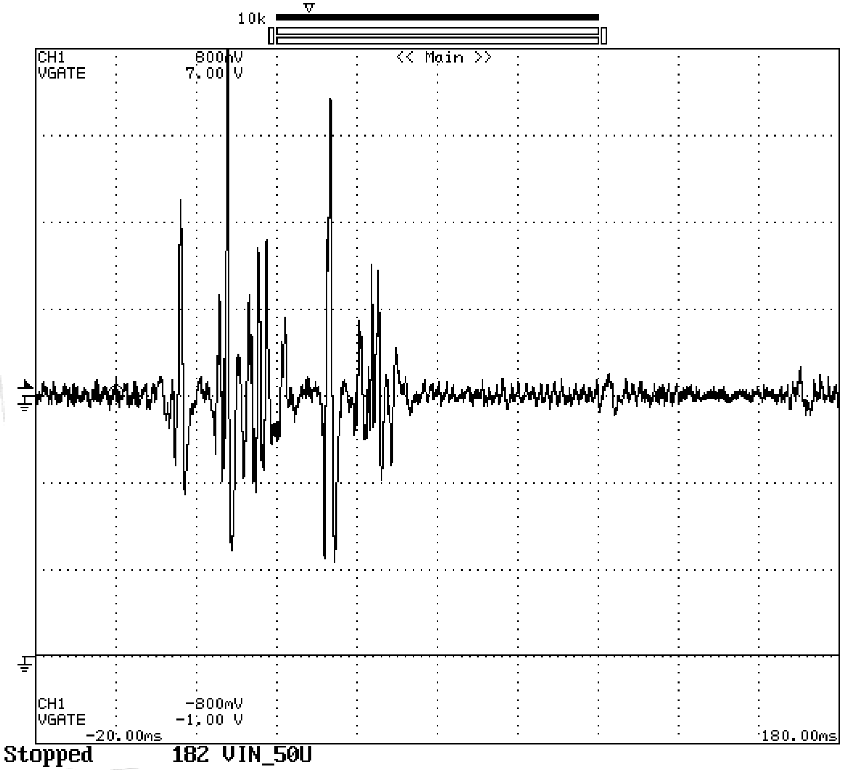
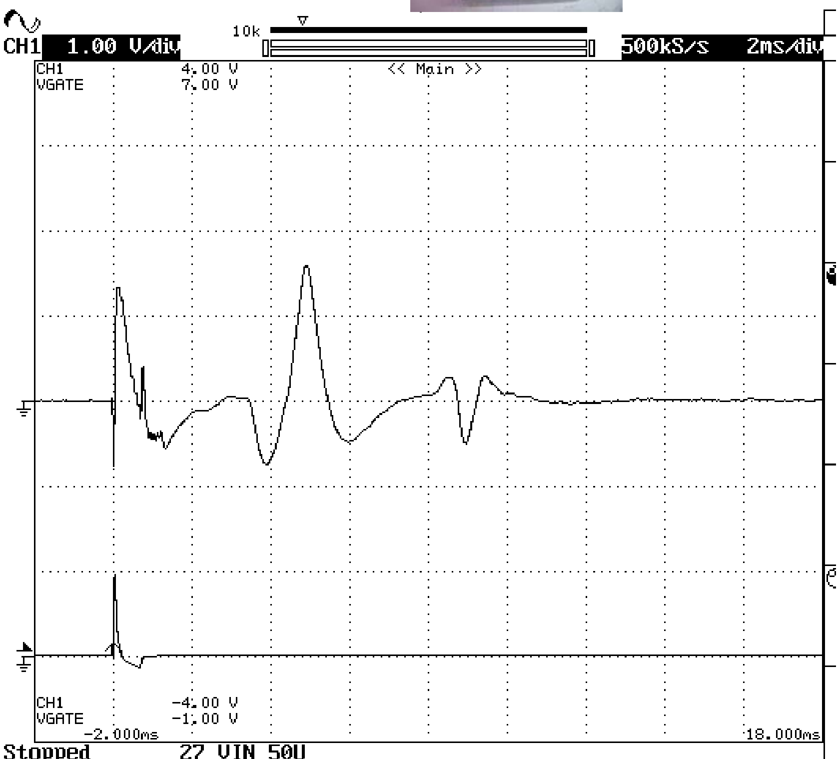


- Registered neural signals in a rat using needles

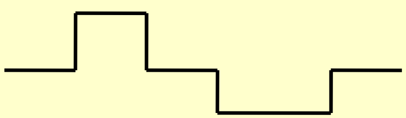


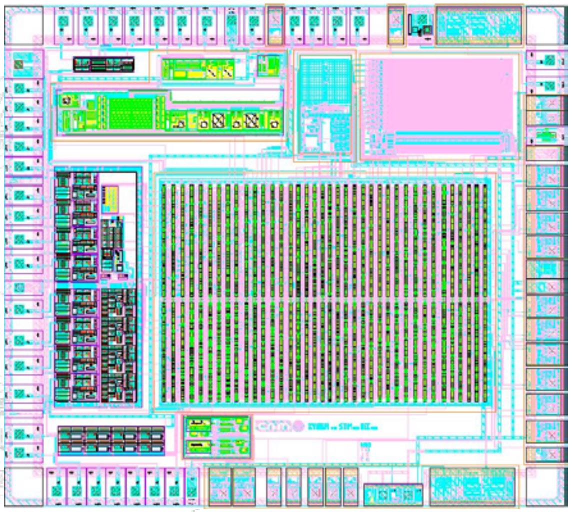
Motor units' activation in response to pain



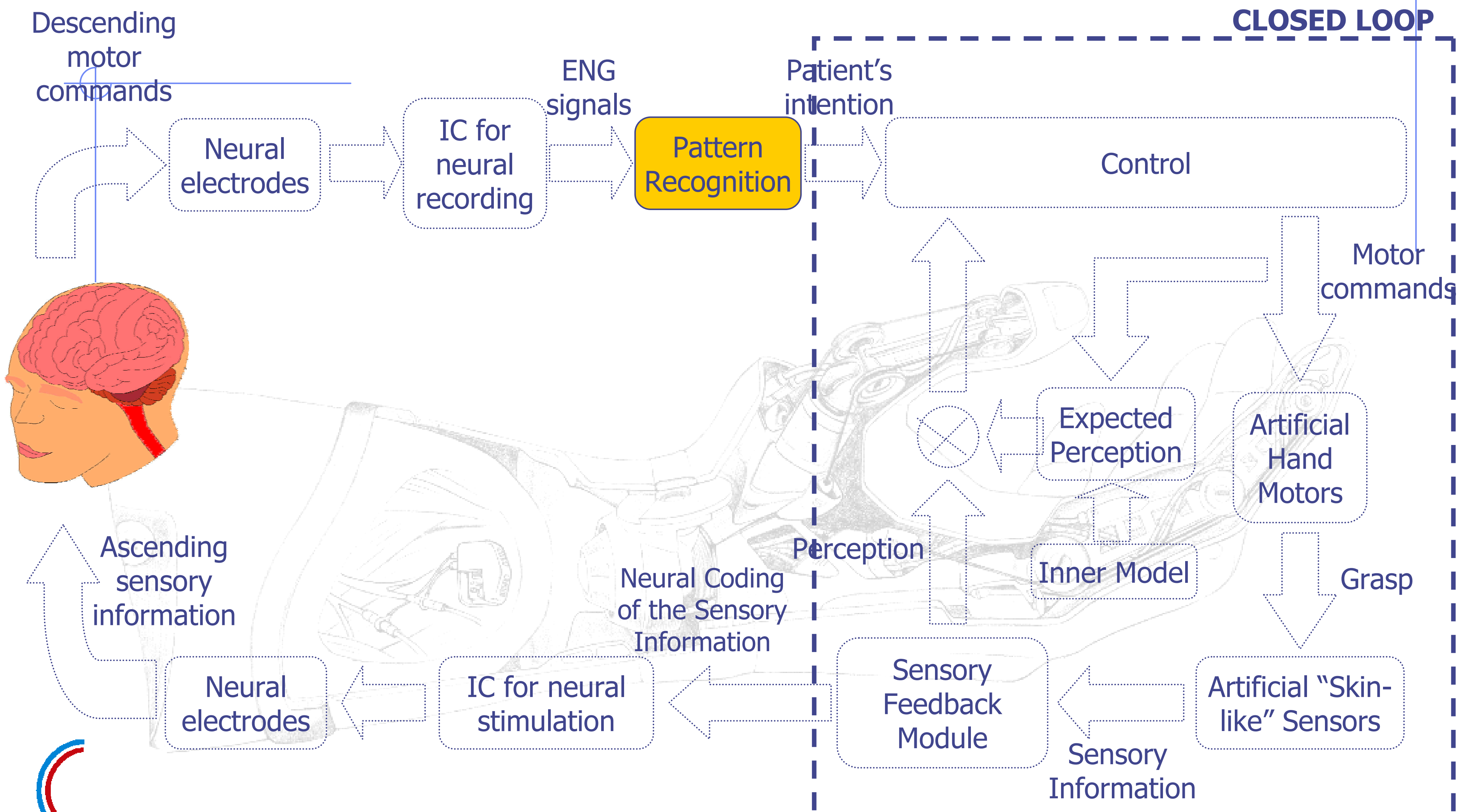
CAP in muscle plantar in response to electrical stimuli in sciatic nerve

Stimulation circuitry, 1st prototype

Stimulation specifications	
# channels	8. This is the number of electrodes that the stimulator can control once programmed without any external interaction.
Amplitude	2 - 126 μA resolution 2 μA 20 - 1260 μA resolution 20 μA
Pulse duration and Inter-delay	4 μs to 255 μs resolution 1 μs
Recovery phase	4 times the stimulation time
Waveform (with or without Pre-pulse option)	
Charge recovery	Exponential programmable extra charge recovery added to the stimuli and/or before neural signal recording.
Stimulation frequency	7 - 300 Hz resolution 1 Hz for low frequencies 3 Hz for high frequencies 8 different frequencies
Impedance measurement	The resistive component of the electrode will be provided for electrode verification purposes.



Layout of the stimulator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The pattern recognition problem for the control of hand prosthesis by using ENG signals from sieve electrodes

Pattern recognition (PR) is performed through several steps: pre-processing, feature selection and extraction, classification.

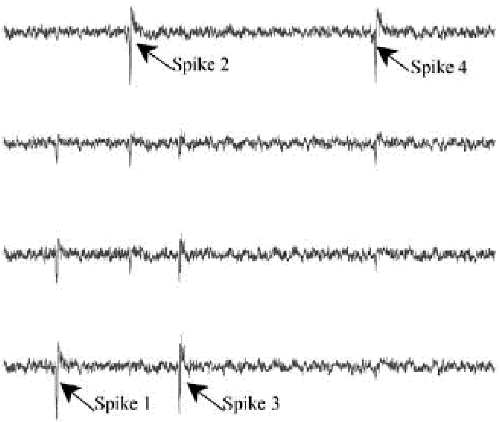
Ideally, the pattern recognition algorithm has to be:

-Fast (real-time operating)

-Accurate (minimum error)

-Unsupervised (minimal intervention of human)

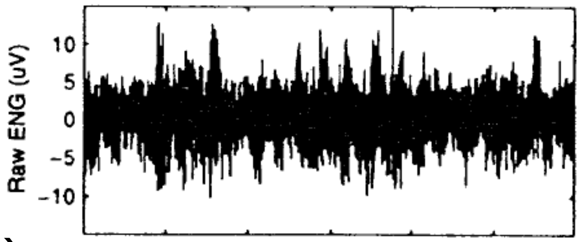
-Adaptive (dynamically adapt patterns to track changes in the characteristics of the signal)



Needle Signals (composed of spikes, PR is related to the detection of the different spikes)

Sieve signals characteristics are somewhere between cuff and needle signal properties. These characteristics depend on many factors.

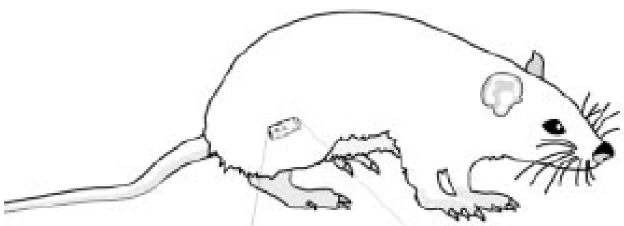
Cuff signals (the spike are no more detectable, PR is related to the identification of functions)



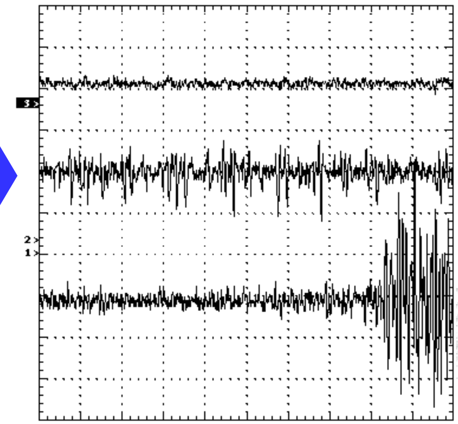
Experiments for the recording of efferent neural signals

- The experiments on the animal models (rats) are useful for:
  - Verifying what degree of regeneration is obtainable with the new electrodes, not only from an histological point of view, but addressing in detail the issues related to the extraction of the information carried in the recorded signals, specifically:
    - which is the degree of similarity of the recorded signals to cuff signals and to needle signals
    - which is the influence of the afferent signals on the efferent signals and what kind of countermeasures can be envisaged in order to reduce the interference
  - Testing the multiplexing strategies (for selecting the four best channels among the available) and the implantable RF system
  - Testing the signal processing algorithms

ENG-based extraction of motor information

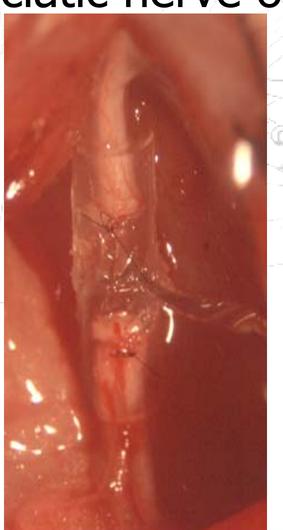


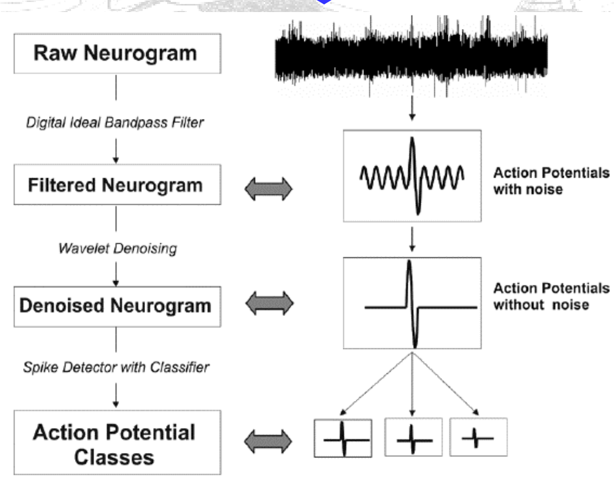
Implant in the sciatic nerve



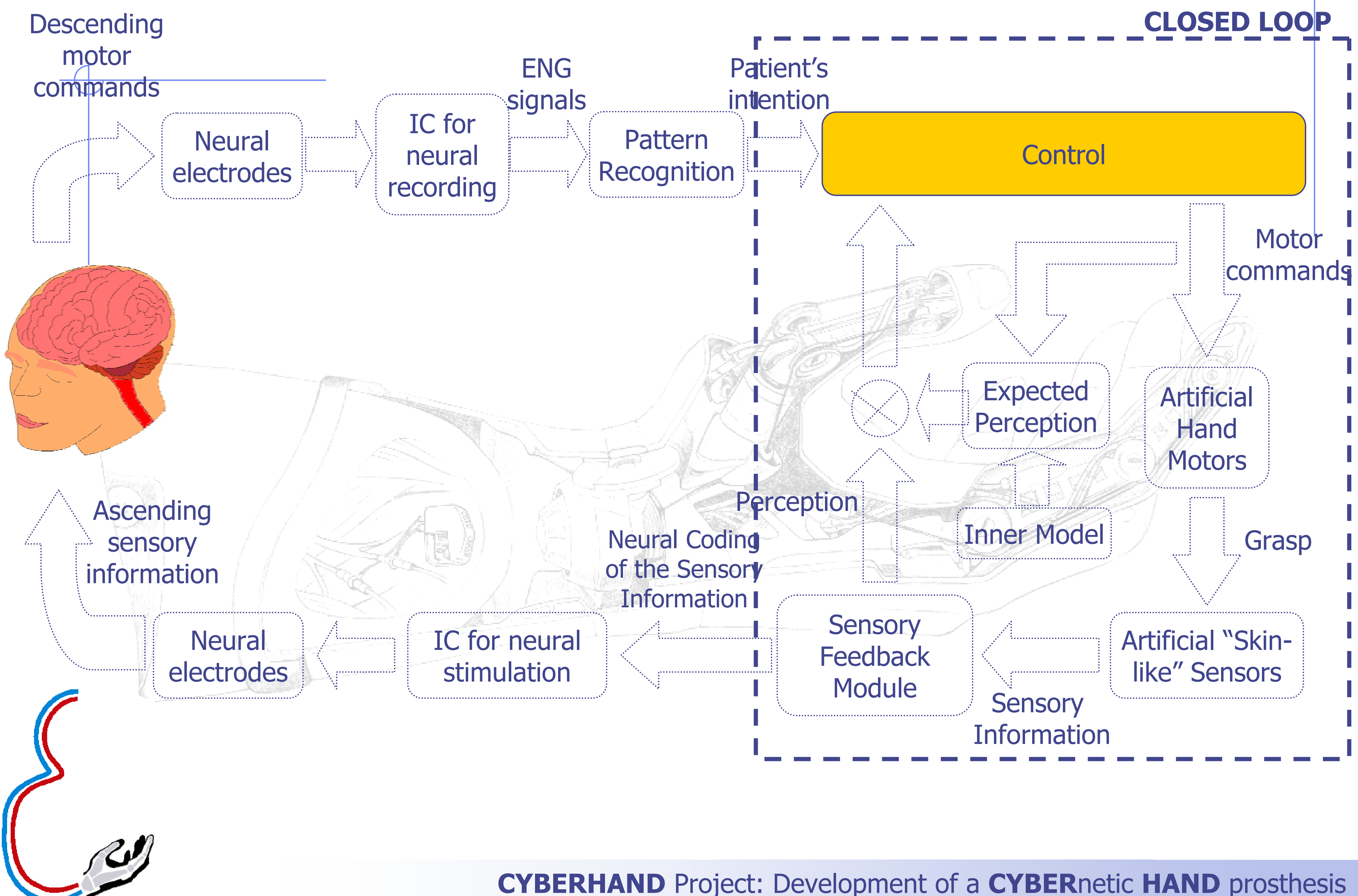
The paw of the rat is stimulated in order to obtain different voluntary movements (for example by means of laser assisted stimuli). The neural signals recorded are used to test an algorithm for pattern recognition

Sieve electrodes are implanted in the sciatic nerve of the rat





A pattern recognition algorithm is used to discriminate among the different movements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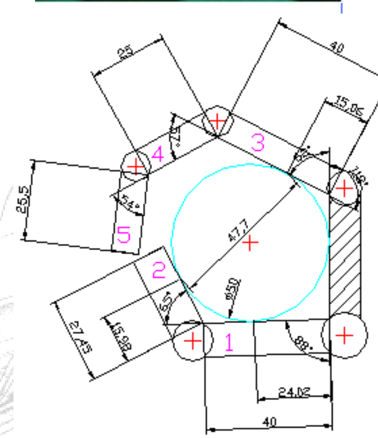
The Closed Loop Control module

Control approches for grasping tasks

To realize a grasping task requires to study three basic mechanisms:

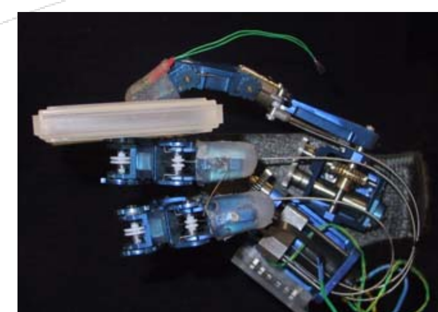
1) The approach to the object and the shape adaptation (low values of torque are required)
2) The grasp of the object with thumb opposition (a suitable level of power is needed to manage critical situations)
3) The grasp regulation according to the sensory information



Two different approches:

1) a "traditional" parallel position/force control

2) a neural controller

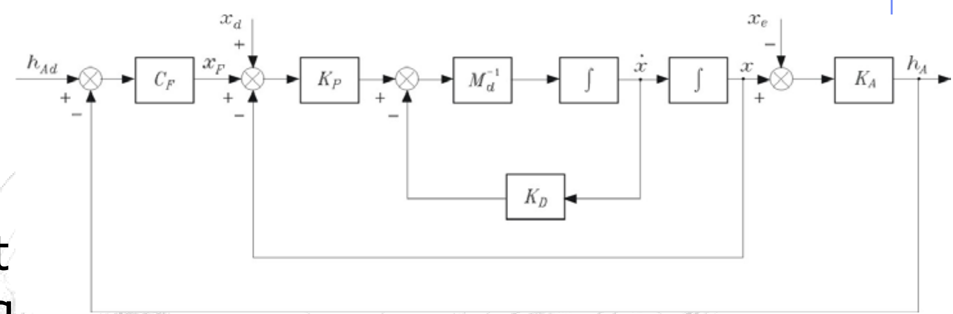


The Closed Loop Control module

Approach 1: Parallel Position/Force Control

The **parallel position/force control** allows grasping the object and regulating fingers positions (through the position control loop) and it ensures grasp stability (through the force control loop).

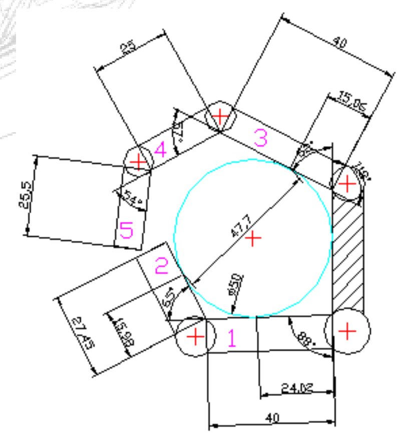
- The force control loop ensures the force regulation at the contact point
- The position control loop is aimed at tracking the reference position along the unbound directions



The generic parallel position/force control law is

$$y = J_{Ac}^{-1}(q) M_d^{-1}\left(-K_D \dot{x} + K_P (x_F - x + x_d) - M_d \dot{J}_{Ac}(q,\dot{q})\dot{q}\right)$$

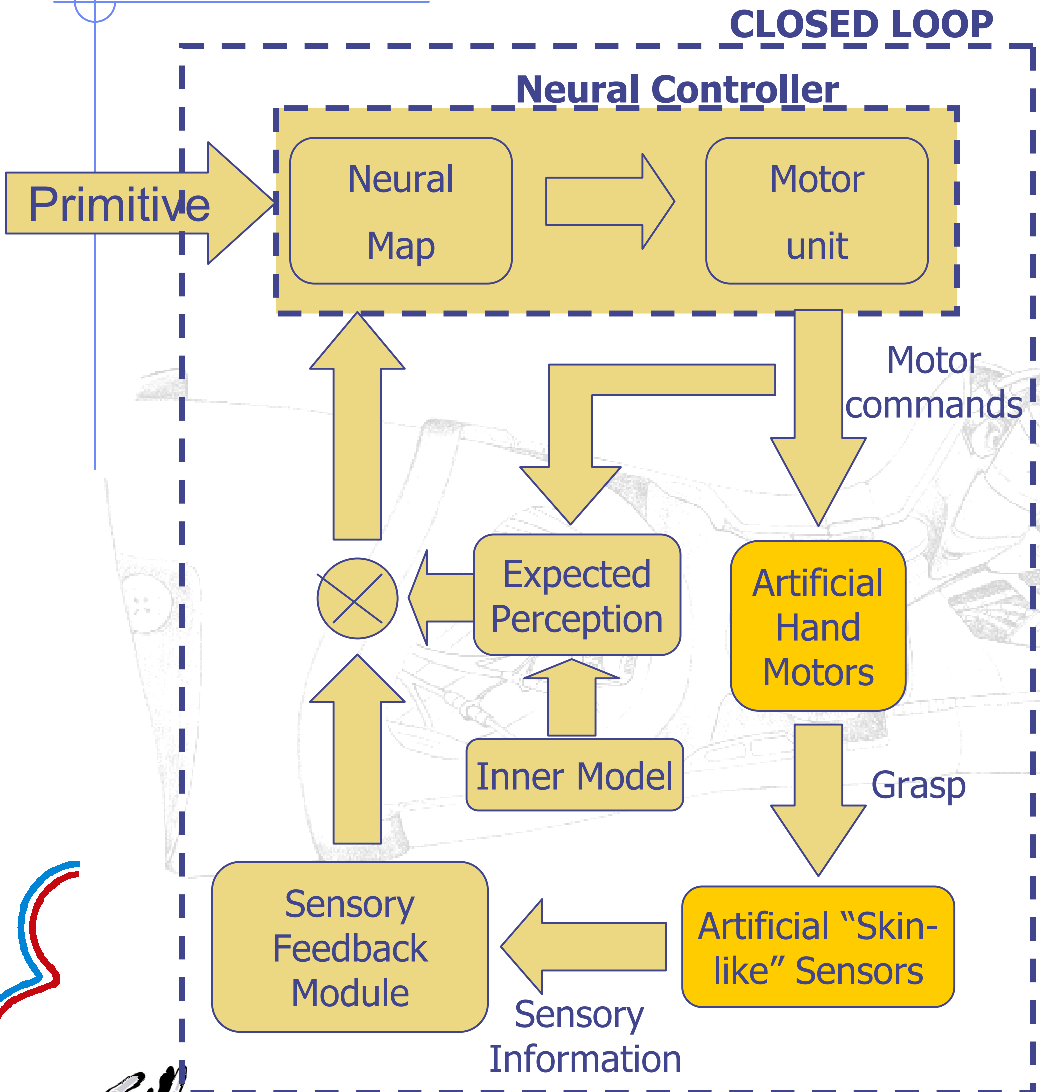
It can be applied to the thumb as well as to the index and middle finger, under the assumption that each finger can be regarded as a manipulator



P. Scherillo, E. Guglielmelli, P. Dario, et al. "Parallel force/position control of a novel biomechatronic hand prosthesis" accepted for *AIM 2003, IEEE/ASME International Conference on Advanced Intelligent Mechatronics*, Kobe, Japan, July 20 - 24, 2003

The Closed Loop Control module

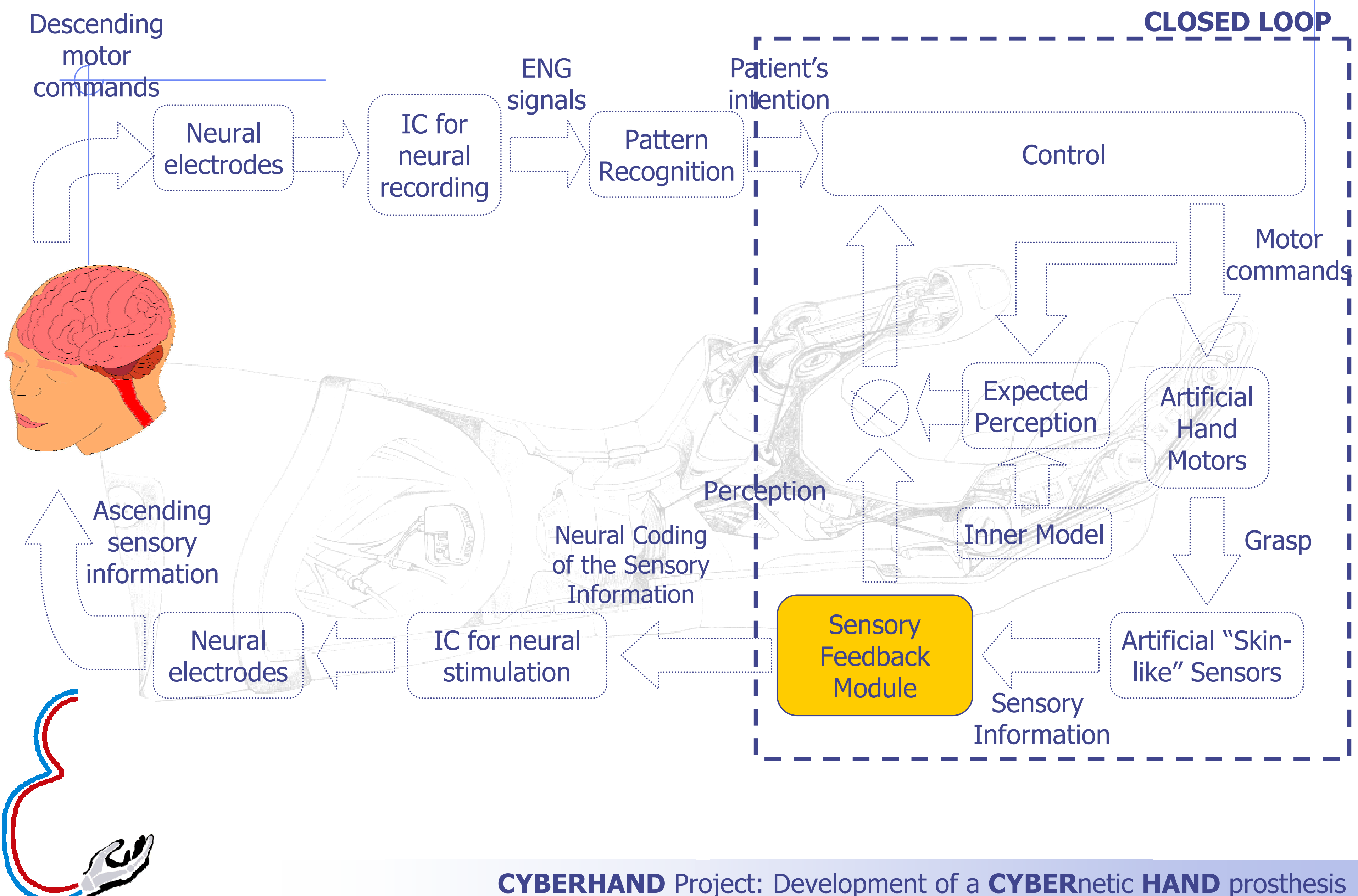
Approach 2: Neural controller



- A neural controller creates the **relations** between the primitives, the sensory data and the motor commands
- Such relations are established by a continuous **learning**
- The learning strategy is aimed at **stable grasps**

neural map: integrates the information coming from the sensory module and the desired primitive

motor unit: provides the motor command (supervised learning)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Experiments for the delivery of sensory feedback via neural stimulation

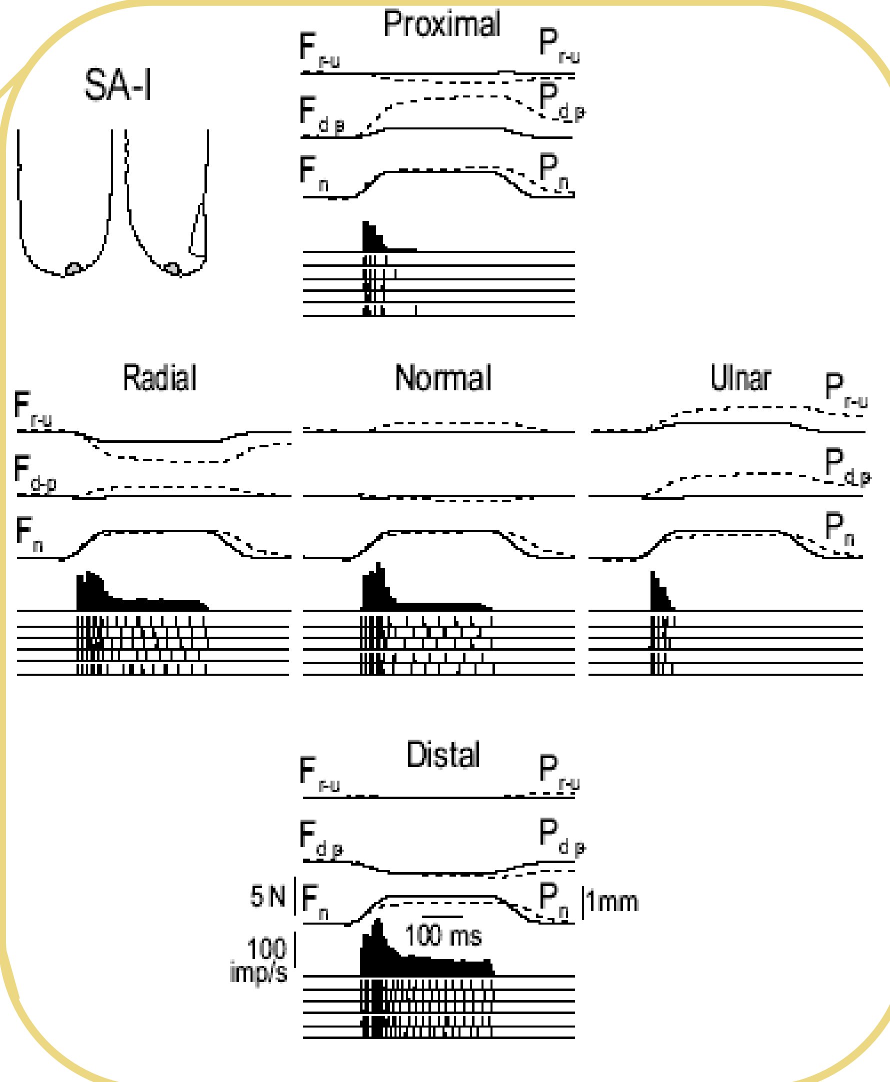
- The experiments on sensory feedback will be carried out in three different phases:
  - Phase #1: Development of a model to correlate the sensory stimuli delivered to the hindpaw of the rat to the signals recorded from the holes of the sieve electrodes
  - Phase #2: Update of the model developed during Phase #1 by comparing the cortical signals obtained during sensory and electrically-induced stimulation
  - Phase #3: Deliver the sensory feedback by using the signals recorded from the artificial sensors developed in the framework of the project

Experiments for the delivery of sensory feedback via neural stimulation

- Electrophysiological experiments will be performed on a statically significant number of rats (>10) six months after the implantation of a sieve electrode in the sciatic nerve
- Hindpaws will be stimulated with a series of “von Frey” monofilaments in ascending order, constant pressures, arrays of embossed dots, and different range of thermal and pain stimuli
- The signals extracted from all the sieve hole contacts will be related to a single (ideal, but not realistic, case) or a group of axons growth in a hole, developing a mathematical model of the relationship between the stimuli and the afferent neural signals
- This model will provide the parameters usable in order to stimulate the rat sciatic nerve to provide a sensory feedback similar to the natural stimuli

The simulation of the tactile sensation
The use of a neural network

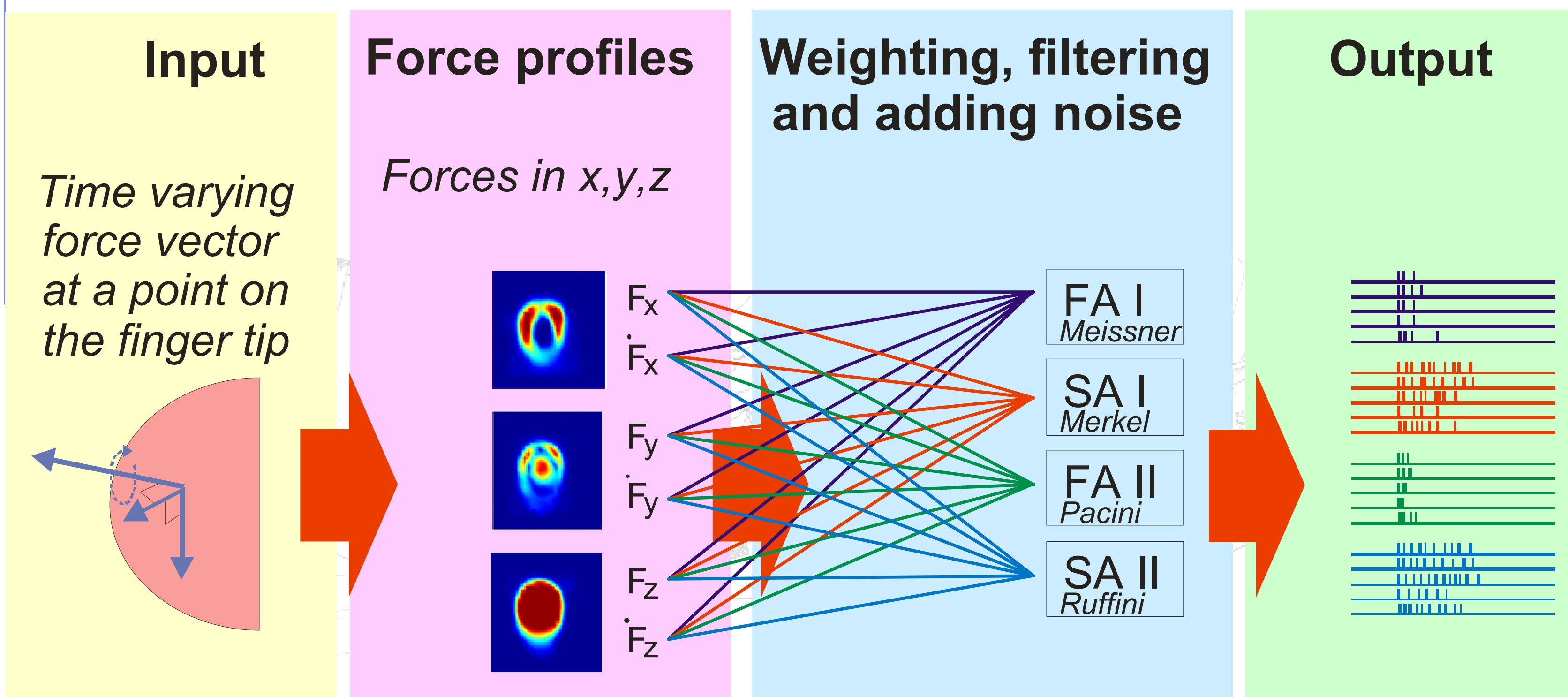
A neural network model to fit human data and able to generate human like mechano receptors responses during grasping and manipulation



Edin et al., 2002

The simulation of the tactile information

The model



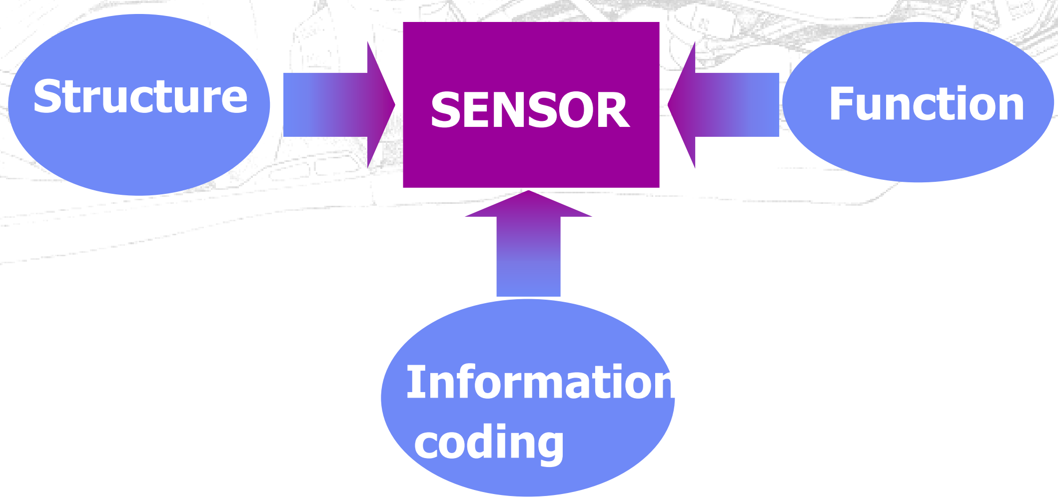
Edin et al., 2002

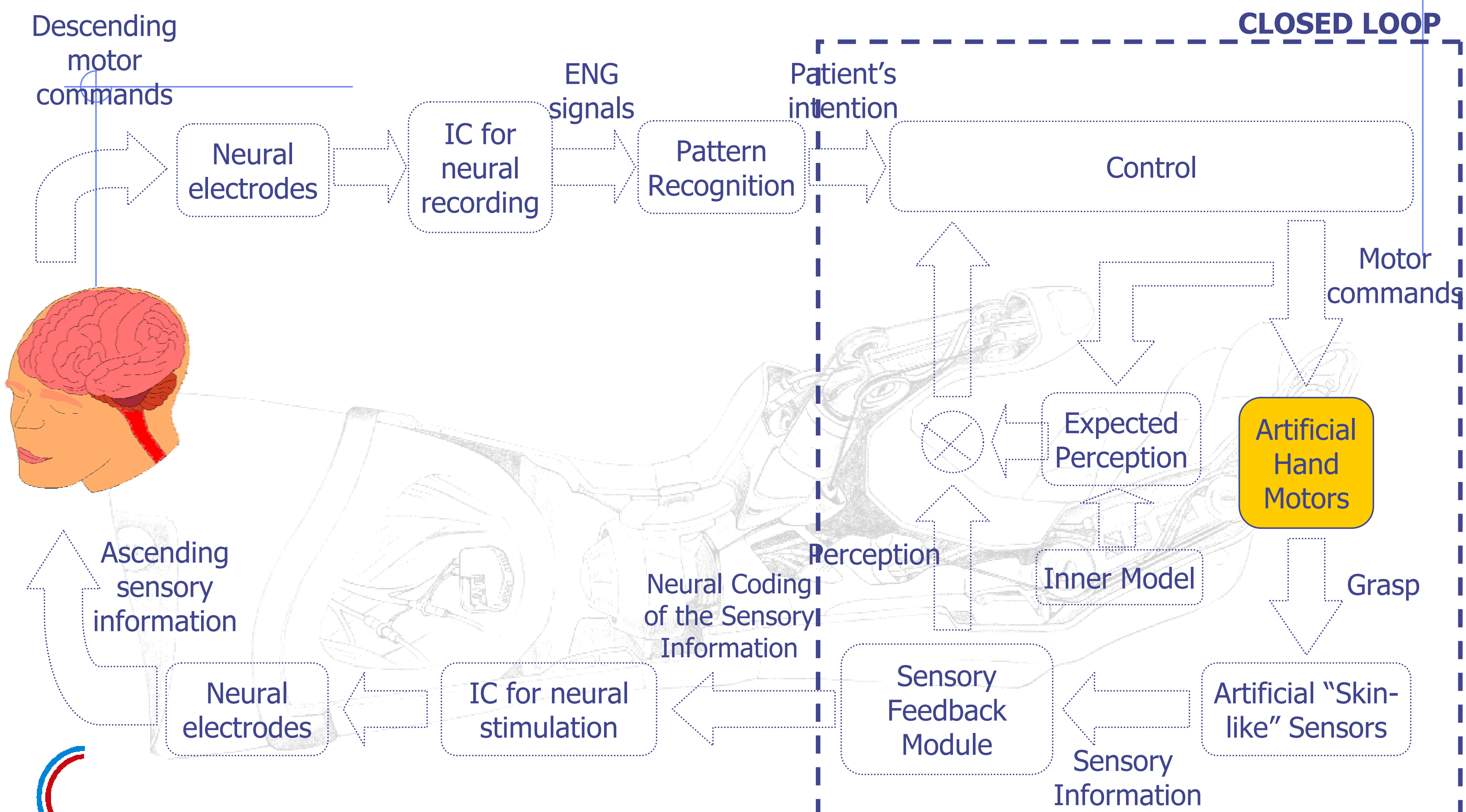
Experiments for the delivery of sensory feedback via neural stimulation

- In a second phase, experiments will be carried out to record and compare the cortical signals during sensory and electrically induced stimulation
- This phase will allow us to evaluate the accuracy of evoked sensation delivered through sieve electrodes and, if necessary, to carry out a re-tuning of the feedback cognitive algorithms

Experiments for the delivery of sensory feedback via neural stimulation

- During the final phase the signals recorded from the biomimetic sensors will be used to deliver sensory feedback
- During this phase, the differences between the structure, function, and information coding of the natural and the artificial sensors will be investigated.

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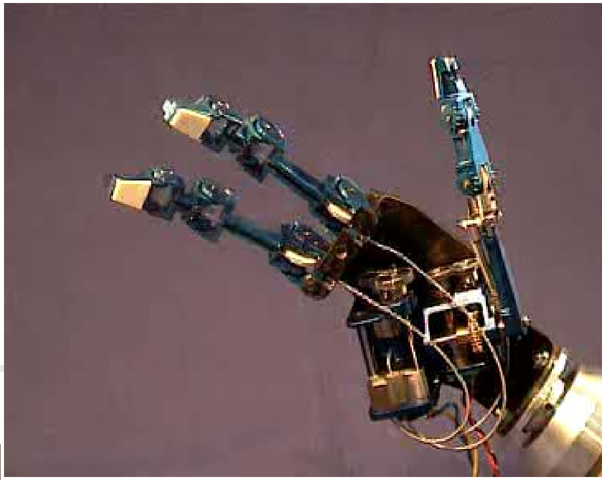
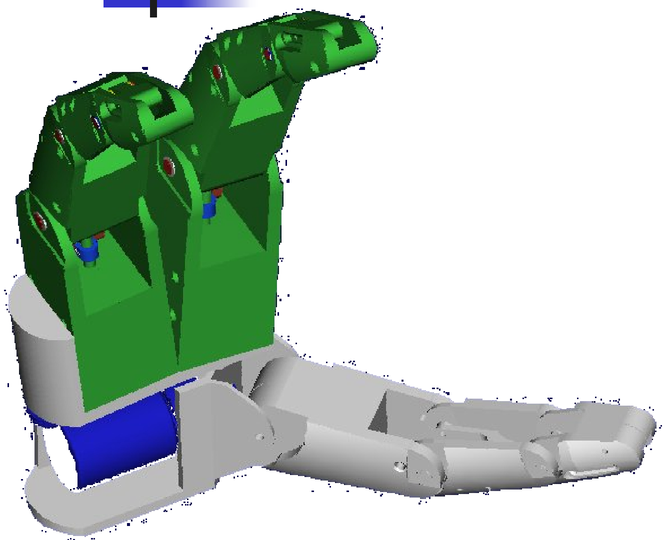
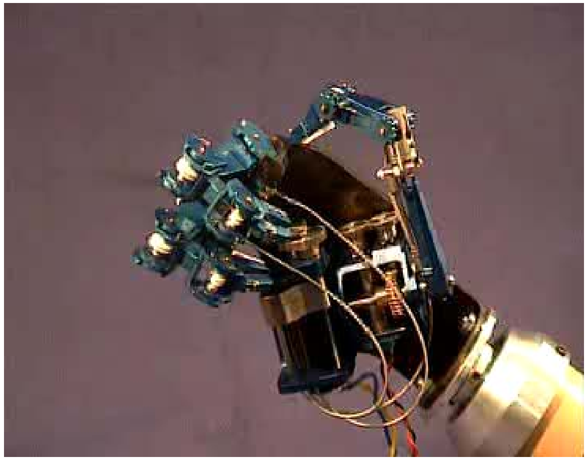
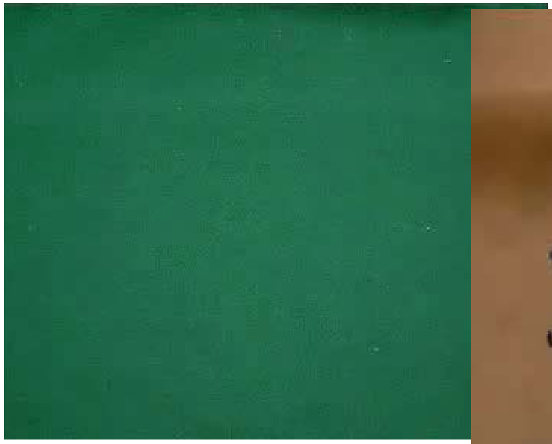
Prosthetic hand prototype

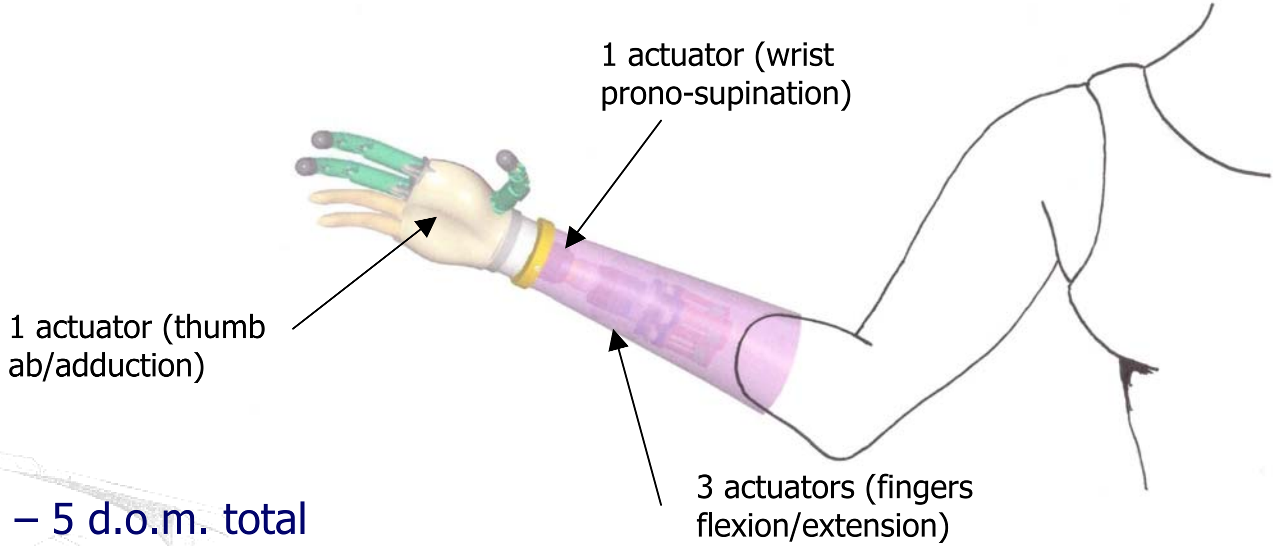








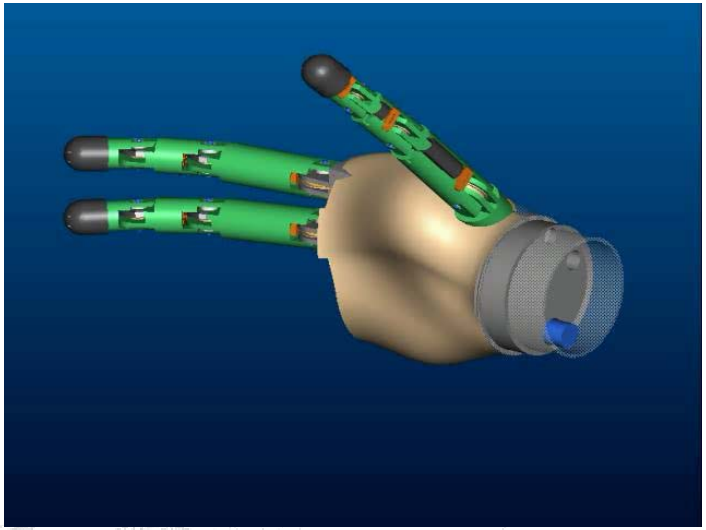
The new “CYBERHAND” prosthesis



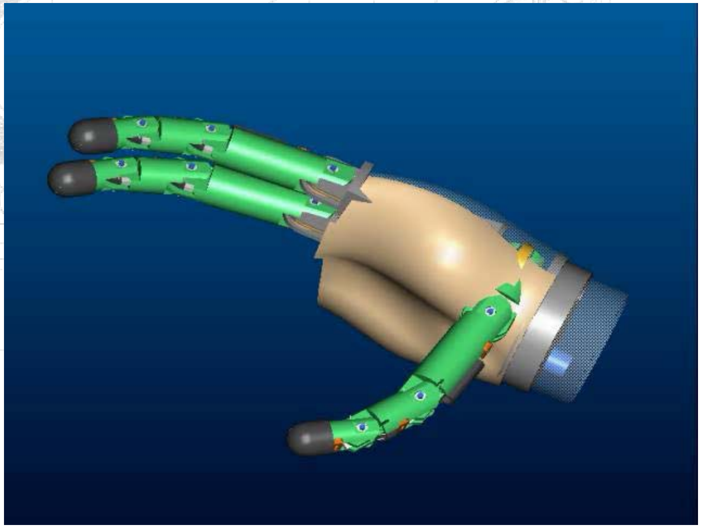
- 13 d.o.f. total – 5 d.o.m. total
- Underactuated fingers, each driven by a single cable actuated by a motor.
- 5 d.o.m. one for each finger (flexion/extension) + one for thumb positioning (adduction/abduction) + one for the prono-supination of the wrist
- 9 Hall effect sensors, one for each finger joint
- 5 DC 6V motors
- Weight: Palm+fingers: about 400 gr., Socket interface (actuation and transmission systems): about 700gr.
- Anthropomorphic size, weight and kinematics

3D Hand model

- Hand kinematics and dynamics have been evaluated using ProMechanica Motion software
- The performance of the hand has been assessed during open loop movements
- The dimensions have been optimised according to the results
- Each finger can move independently by the others, the hand is able to perform 4 functional grasping movements:
  - Cylindrical movement
  - Lateral movement
  - Tip to tip thumb-middle opposition
  - Tip to tip thumb-index opposition



Lateral movement

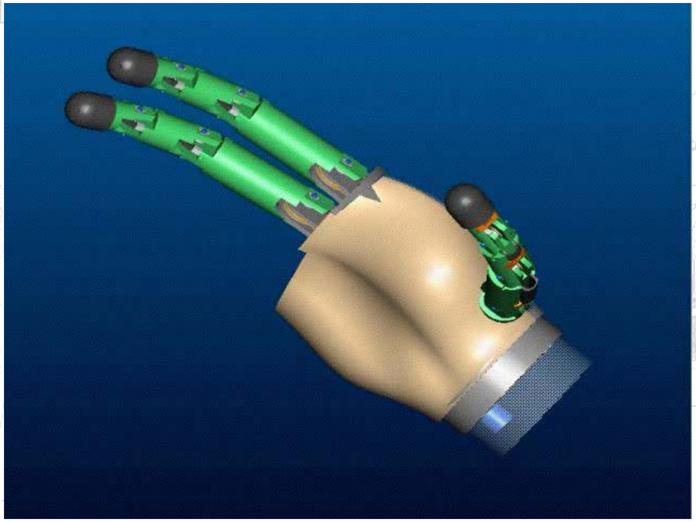


Cylindrical movement

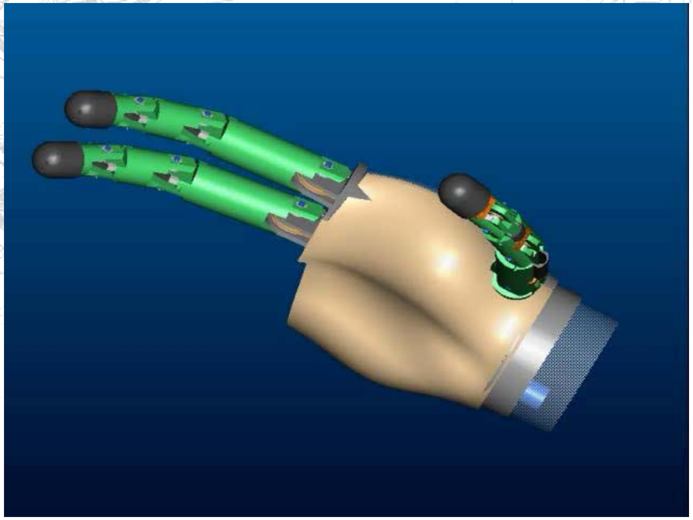
Simulated Hand Tasks

Analysis of the kinematics and its optimisation

Analysis of range of movements of the fingers



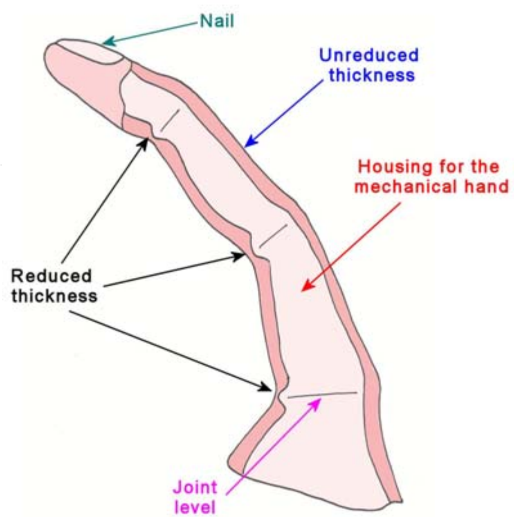
Tip to tip thumb-index opposition



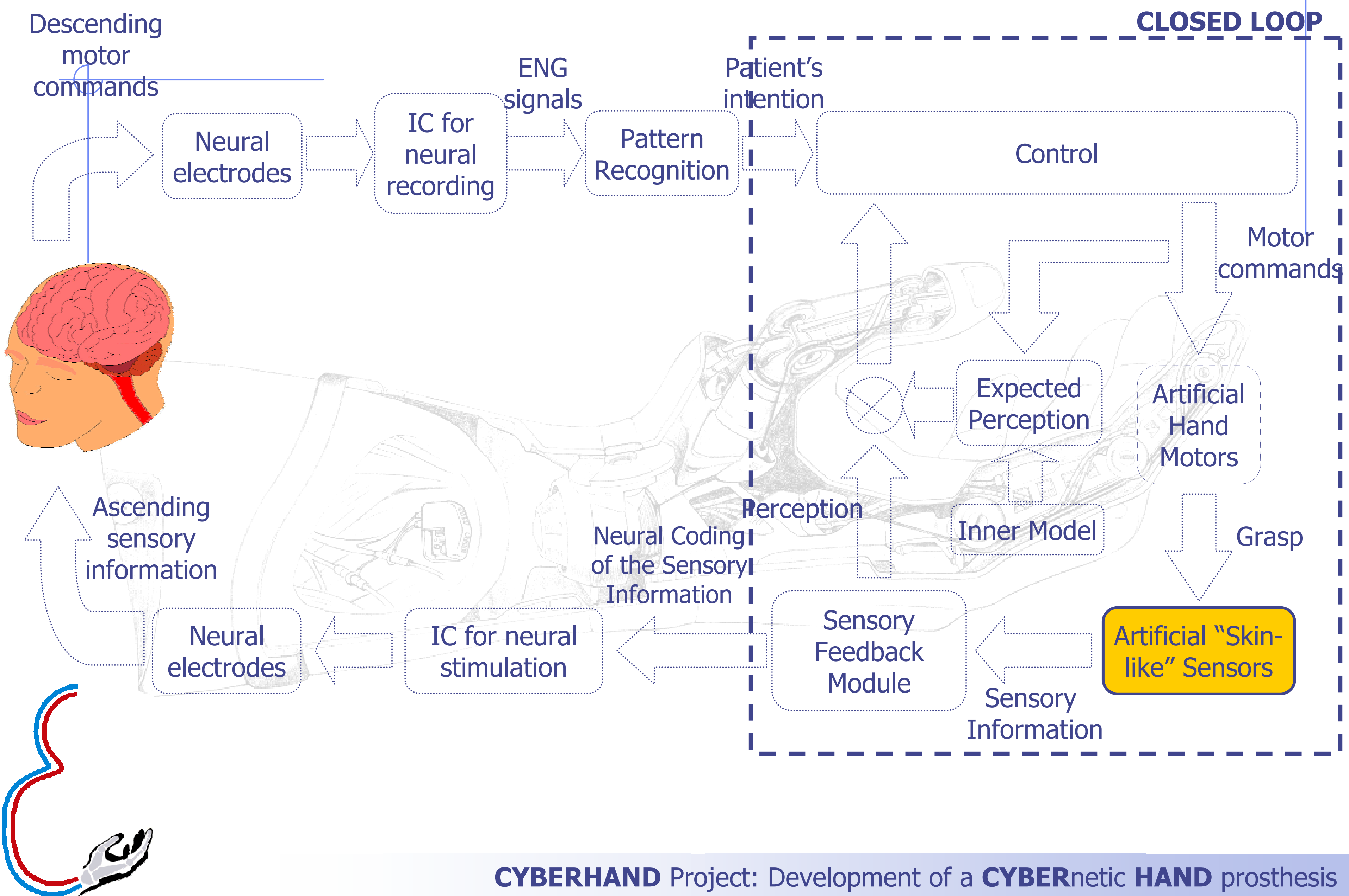
Tip to tip thumb-middle opposition

Cosmetic glove

To reduce the energy absorption caused by the articulated flexion of the cosmetic glove, a new type of silicone glove (with reduced thickness at the joint level) has been ideated



The first prototype of the cosmetic glove has been already fabricated and preliminary tested. The colour and other aesthetic details like nails, hairs, etc. have been not yet added.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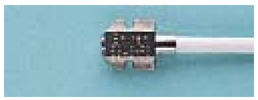
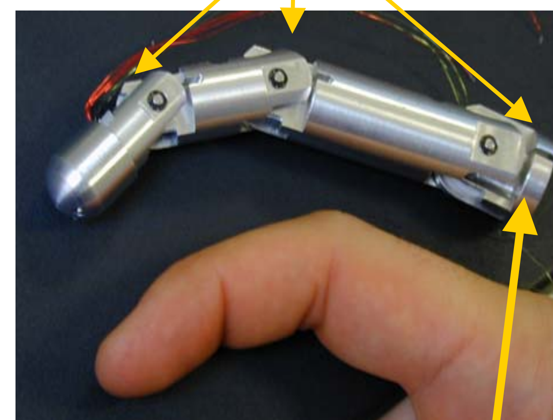
The strategy for the development of biomimetic sensors

- Phase #1: Adaptation of existing sensors
  - Proprioceptive sensors
  - Exteroceptive sensors
    - Distributed on/off contact sensors
    - 3 Components Force Sensor (integrated in the fingertips)
    - Silicon-based three-axial force sensor (distributed on the fingertips)
- Phase #2: Design of novel biomimetic sensors

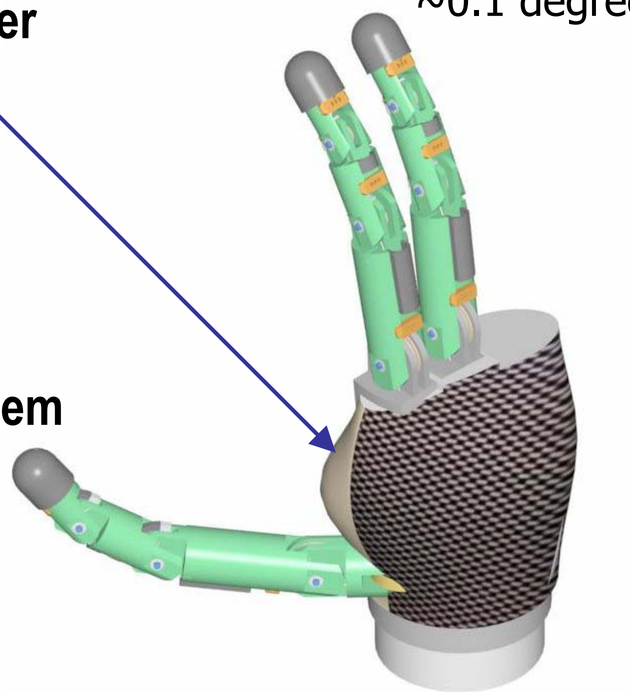
Proprioceptive sensory system



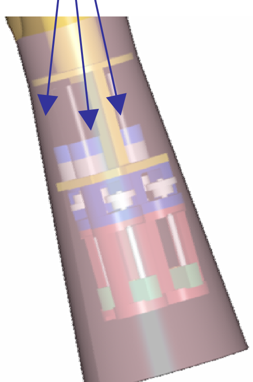
1 accelerometer in the palm



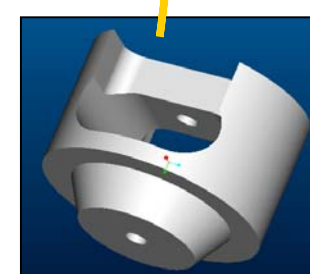
9 Embedded Joint Angle Sensors (Hall effect)
(Operational range: 0 – 90 degrees, Resolution: ~0.1 degrees).



4 Encoders in the Actuators System

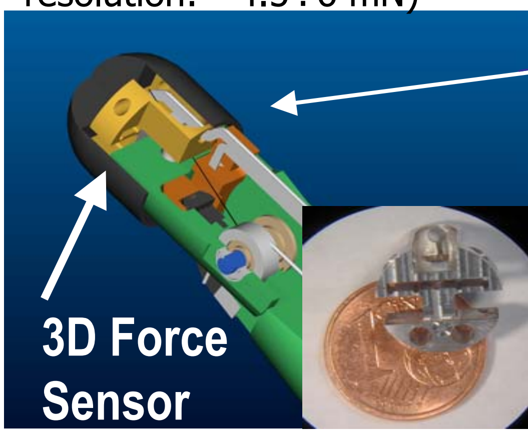


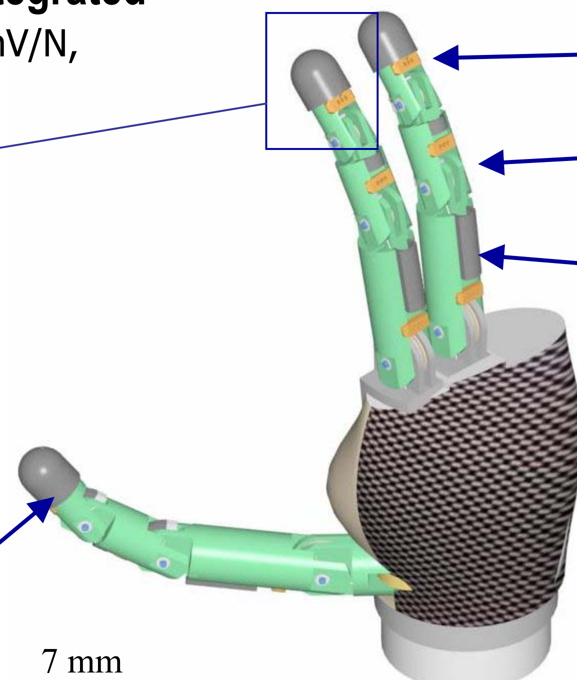
3 cable/tendon tension sensors
(Operational range: 0 – 20 N, output characteristic: linear, resolution: ~20 mN)



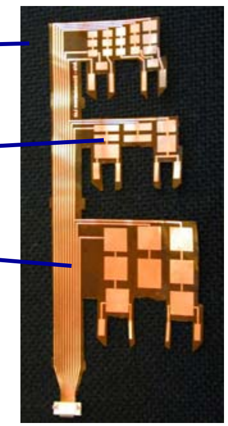
Exteroceptive sensory system

3 components force sensors integrated in the fingertips (sensitivity: ~1 mV/N, resolution: ~4.5÷6 mN)



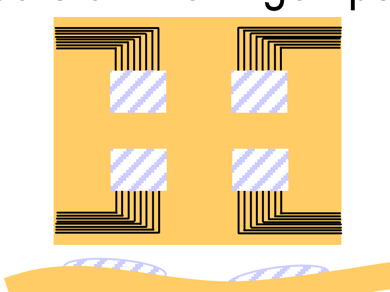


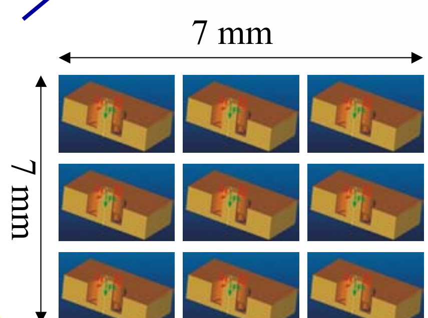
Distributed on/off contact sensors

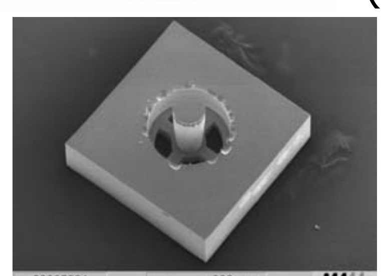


Contact sensors on fingertips, palm and dorsum: high sensitivity on the dorsum (threshold less than 1N) resolution decreasing from palm/dorsum to fingertips

Array of 3x3 3D micro force sensors on the fingertips







The EU-FET "CYBERHAND" Project: developing a cybernetic prosthesis controlled by the brain