TOWARDS ARTIFICIALLY RESTORING THE SENSE OF TOUCH

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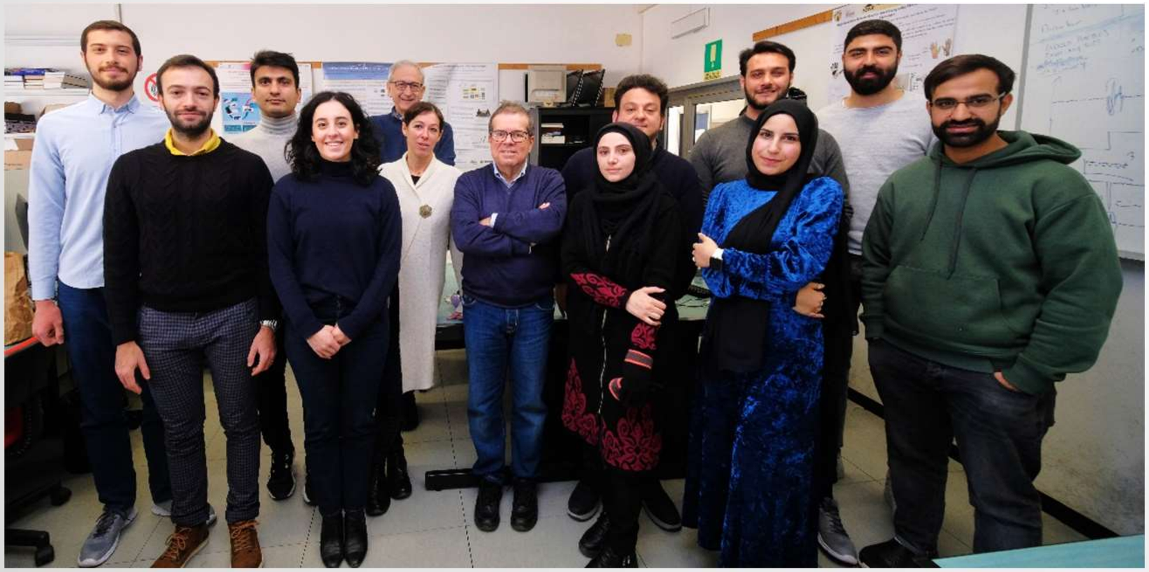
Where we are



Who we are

COSMIC lab
CONNECTED OBJECTS
SENSING MATERIALS
INTEGRATED CIRCUITS

- **MOTIVATION**
- **HUMAN SENSE OF TOUCH**
- **ARTIFICIAL SENSE OF TOUCH**
  - ***Our system***: distributing sensing, electronics, cutaneous electrostimulation
  - Clinical applications and *WORK IN PROGRESS*

- **MOTIVATION**
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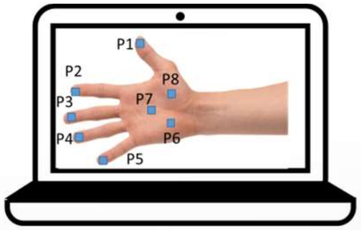
PROSTHETICS

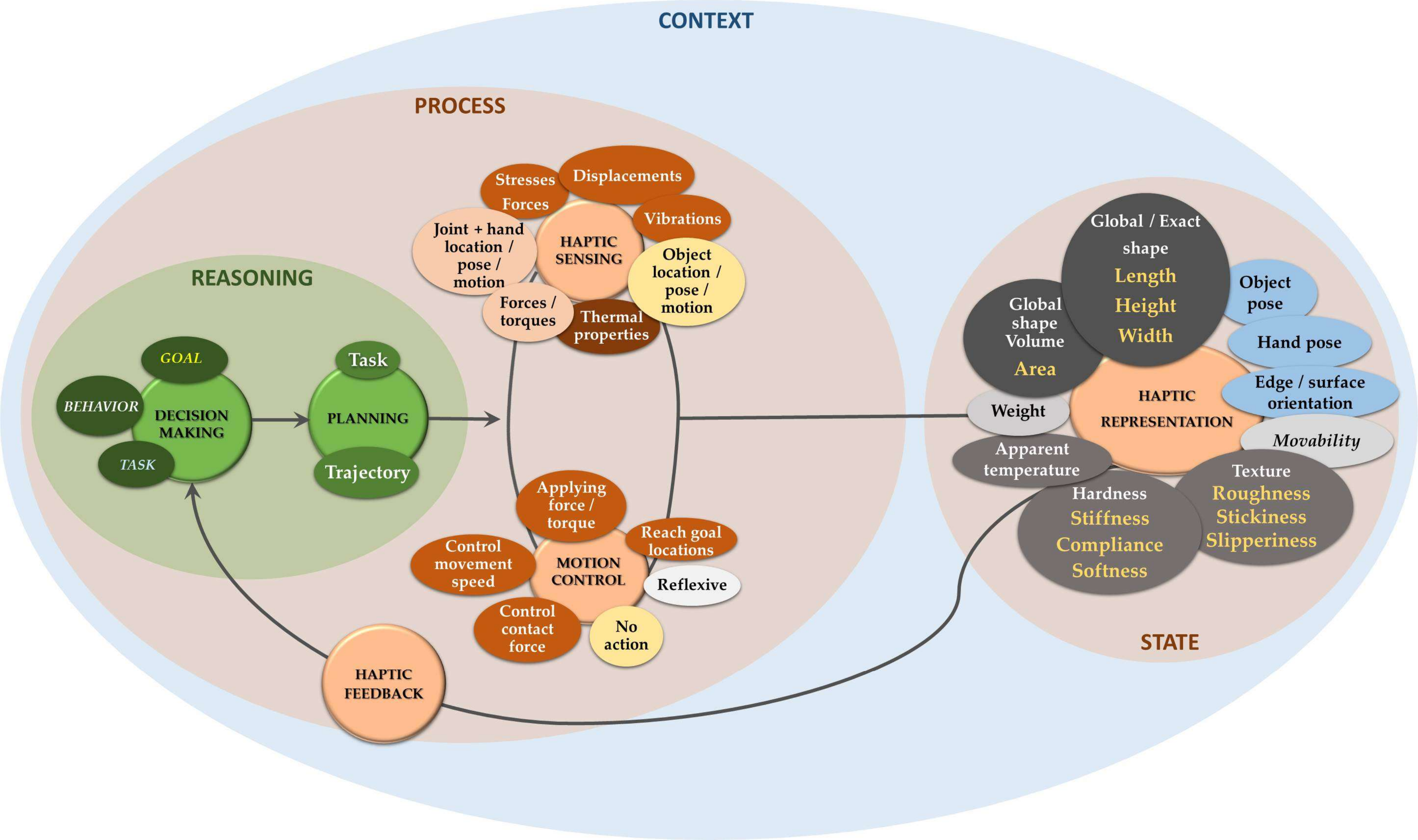
OttoBock ® HAND



POST-STROKE REHABILITATION

Nataletti, S., Leo, F., Seminara, L., Trompetto, C., Valle, M., Dosen, S., & Brayda, L. (2020). Temporal asynchrony but not total energy nor duration improves the judgment of numerosity in electrotactile stimulation. Frontiers in Bioengineering and Biotechnology, 8, 555.

A complex picture



CONTEXT

PROCESS

REASONING

GOAL

BEHAVIOR

TASK

DECISION MAKING

Task

PLANNING

Trajectory

Stresses

Displacements

Forces

Vibrations

Joint + hand location / pose / motion

HAPTIC SENSING

Object location / pose / motion

Forces / torques

Thermal properties

Applying force / torque

Reach goal locations

Control movement speed

MOTION CONTROL

Reflexive

Control contact force

No action

HAPTIC FEEDBACK

Global / Exact shape

Length

Height

Width

Object pose

Global shape

Volume

Area

Hand pose

Weight

HAPTIC REPRESENTATION

Edge / surface orientation

Movability

Apparent temperature

Texture

Roughness

Stickiness

Slipperiness

Hardness

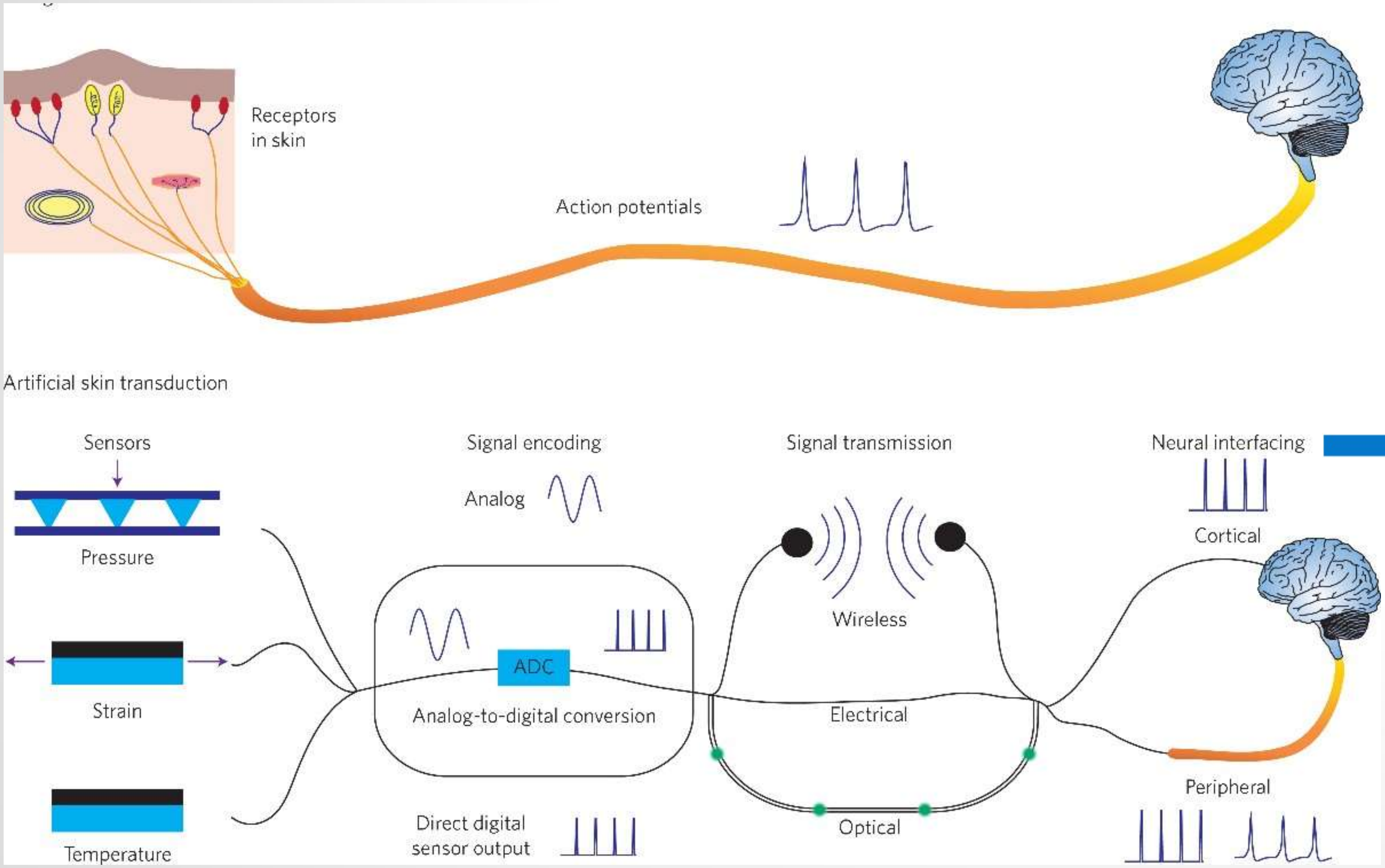
Stiffness

Compliance

Softness

STATE

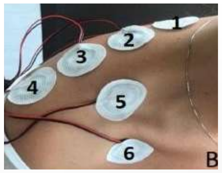
Seminara, L., Gastaldo, P., Watt, S. J., Valyear, K. F., Zuher, F., & Mastrogiovanni, F. (2019). Active haptic perception in robots: a review. Frontiers in neurorobotics, 13, 53.



Chortos, A. L. J. and Bao, Z., «Pursuing prosthetic electronic skin«, Nature materials, 2016

NON-INVASIVE INVASIVE

cortical neural interfaces that record / stimulate neurons directly in the **brain**

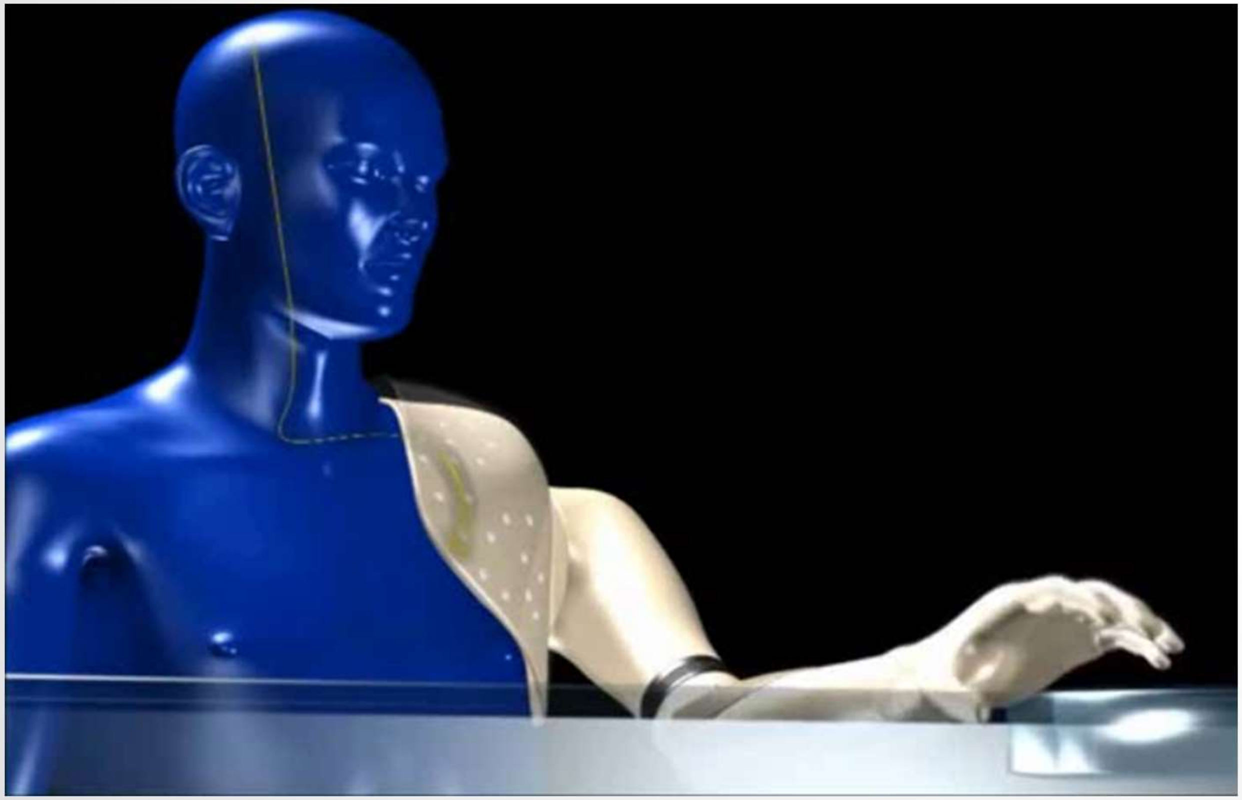


NON-INVASIVE

INVASIVE

interface with the **peripheral nervous system**

Sensory feedback to the user



UTILITY

EMBODIMENT

Focusing on the SKIN

The human haptic perceptual system can be conceptualized as a **continuum** organized as a **tensegrity structure*** modeling the conjunction of muscular, connective tissue, and skeletal structures. In biological systems, **touch receptors are intimately connected to this continuum, and the surrounding tissue with its surface properties** (e.g., ridges) **becomes an extension of the sensor system itself.**

→ To artificially reconstruct the sense of touch, a reliable and robust *biomimetic* **artificial system** integrating **high-density networks of sensing units** is needed

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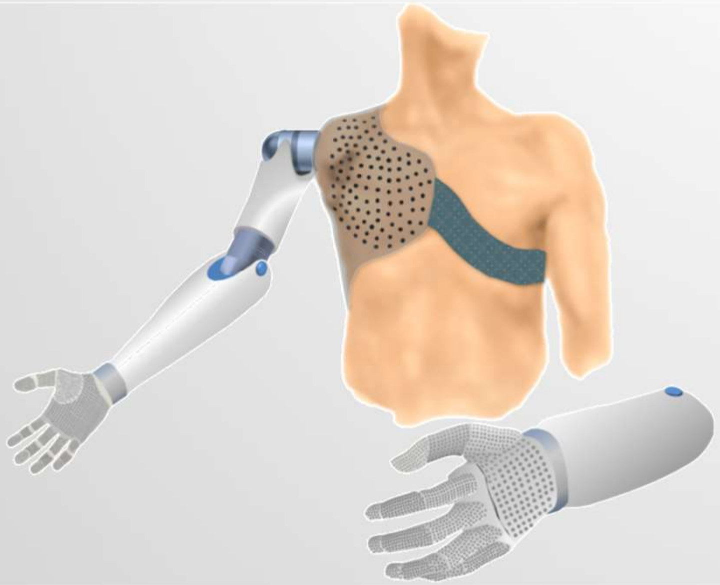
* **M. T. Turvey, S. T. Fonseca, The medium of haptic perception: a tensegrity hypothesis. *J. Mot. Behav.* 46, 143–187 (2014).**

Non invasive approach - Concept

High-density haptic feedback system
(Distributed Stimulation)

Embedded system
(Tactile data acquisition and processing)

High-density sensor array
(Distributed Tactile Sensing)



SYSTEM FEATURES

Wearable: Small size, not heavy

Real-time sensing-stimulation

Low power consumption

Self-powered device

Long-life (daily) device

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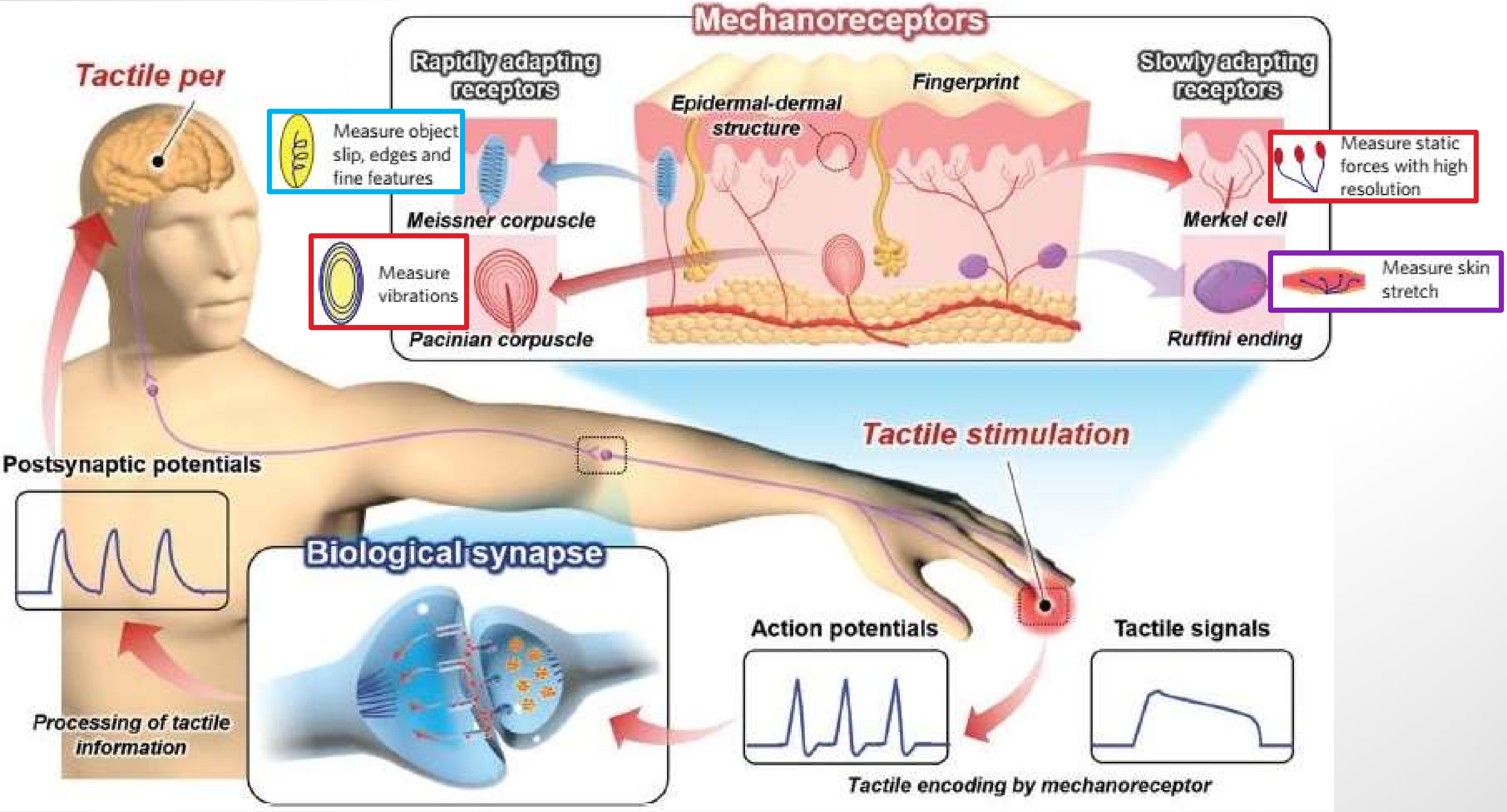
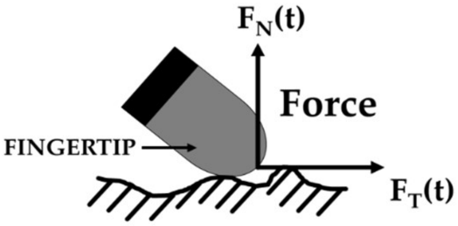
The whole process of tactile perception in humans



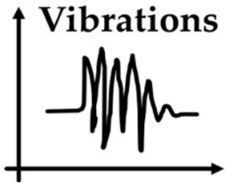
Y. Lee, J. Park, A. Choe, S. Cho, J. Kim, and H. Ko, "Mimicking Human and Biological Skins for Multifunctional Skin Electronics," Adv. Funct. Mater., 2020.

!

The **sensory function**
DOES NOT ONLY depend
on the ***mechanoreceptor type,***
but also on **how** it is integrated
into the ***whole mechanical***
structure.



DISPLACEMENT
(Strain, curvature, stretch)



MECHANICAL and SURFACE PROPERTIES of the HUMAN SKIN (under the spotlight):
- Soft and compliant
- Hyperelastic + viscoelastic behaviour
- Ridges

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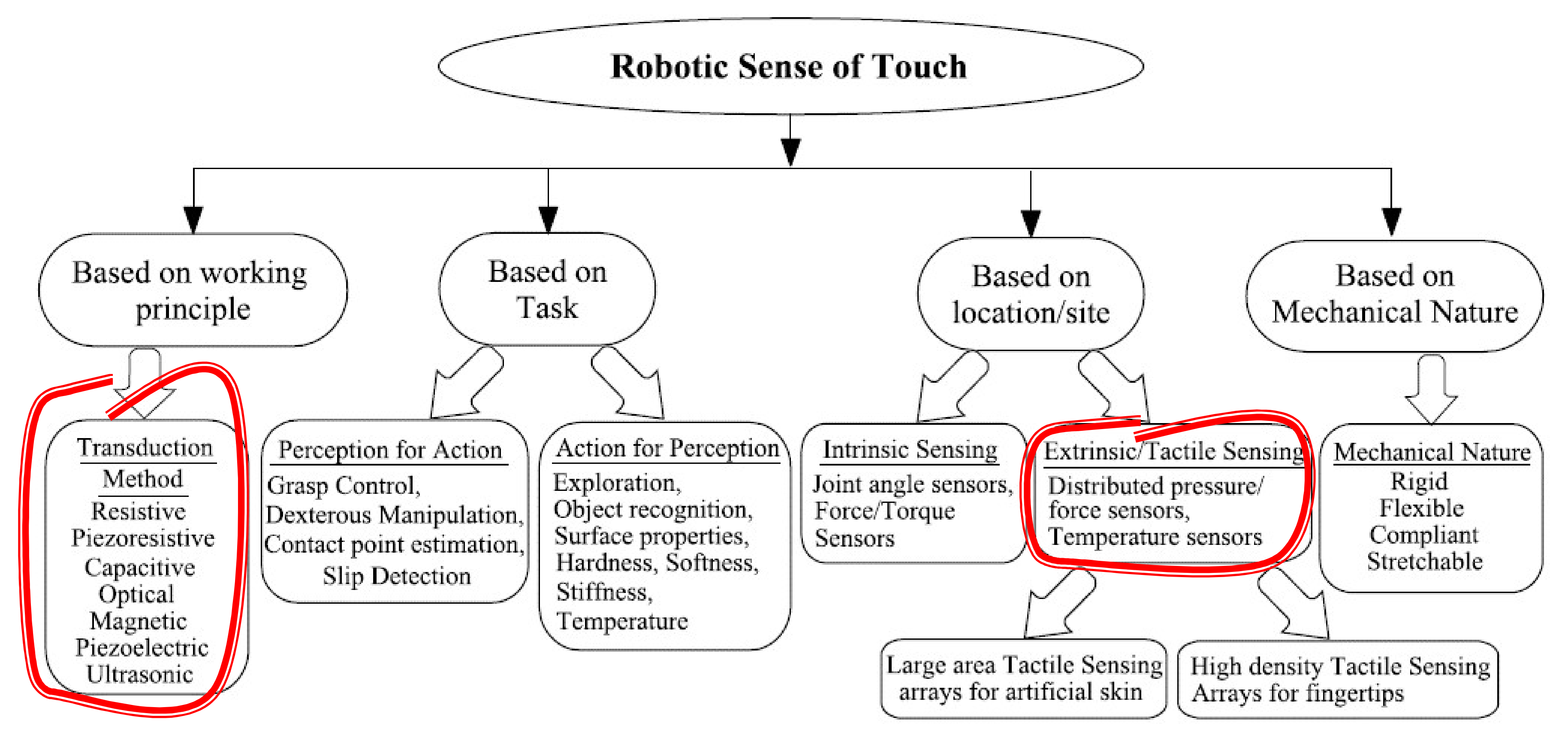
Artificial sense of Touch

If we want to understand and, to some extent, replicate human intelligence **we need to understand the technological solutions supporting the biological functions** and **discover the technologies** which allow such functions to be implemented artificially.

Giulio Sandini, **I**talian **I**nstitute of **T**echnology
Robotics, Brain and Cognitive Sciences



Robotic Sense of Touch

- Based on working principle
  - Transduction Method
    - Resistive
    - Piezoresistive
    - Capacitive
    - Optical
    - Magnetic
    - Piezoelectric
    - Ultrasonic
- Based on Task
  - Perception for Action
    - Grasp Control, Dexterous Manipulation, Contact point estimation, Slip Detection
  - Action for Perception
    - Exploration, Object recognition, Surface properties, Hardness, Softness, Stiffness, Temperature
- Based on location/site
  - Intrinsic Sensing
    - Joint angle sensors, Force/Torque Sensors
  - Extrinsic/Tactile Sensing
    - Distributed pressure/ force sensors, Temperature sensors
    - Large area Tactile Sensing arrays for artificial skin
    - High density Tactile Sensing Arrays for fingertips
- Based on Mechanical Nature
  - Mechanical Nature
    - Rigid
    - Flexible
    - Compliant
    - Stretchable

R. S. Dahiya, G. Metta, M. Valle and G. Sandini, "**Tactile Sensing—From Humans to Humanoids**", IEEE Transactions on Robotics, Vol. 26, No. 1, 2010

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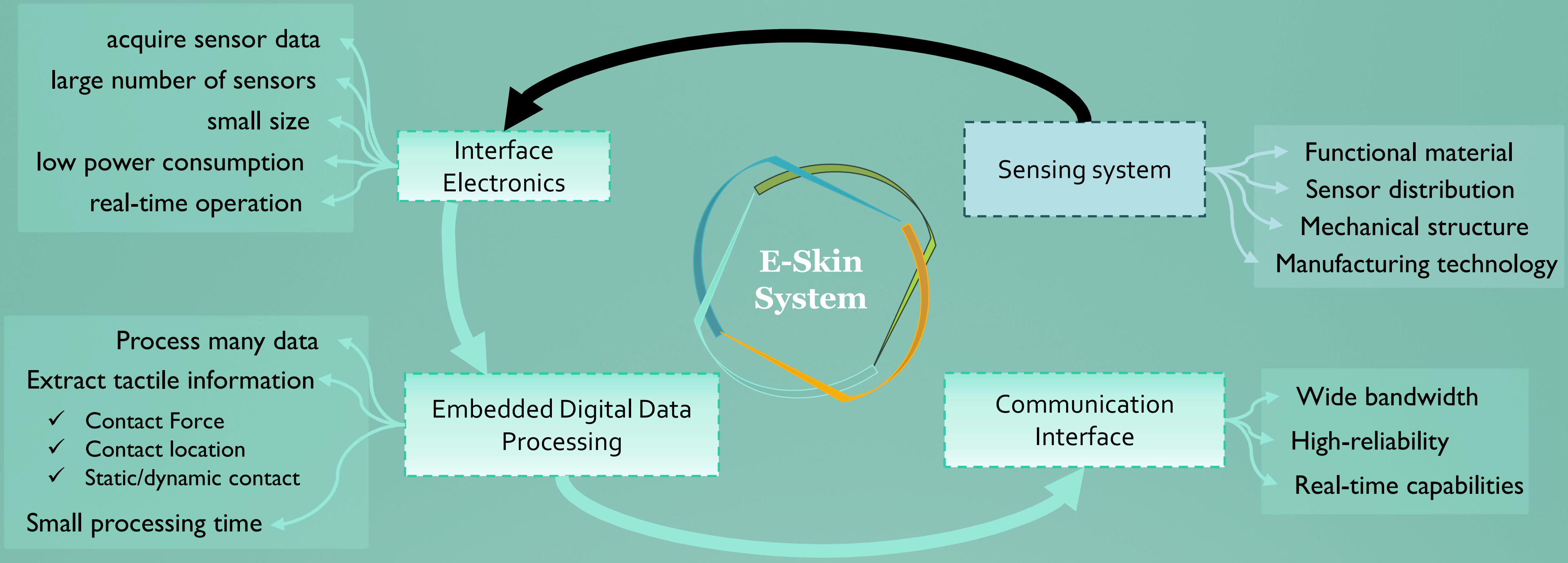
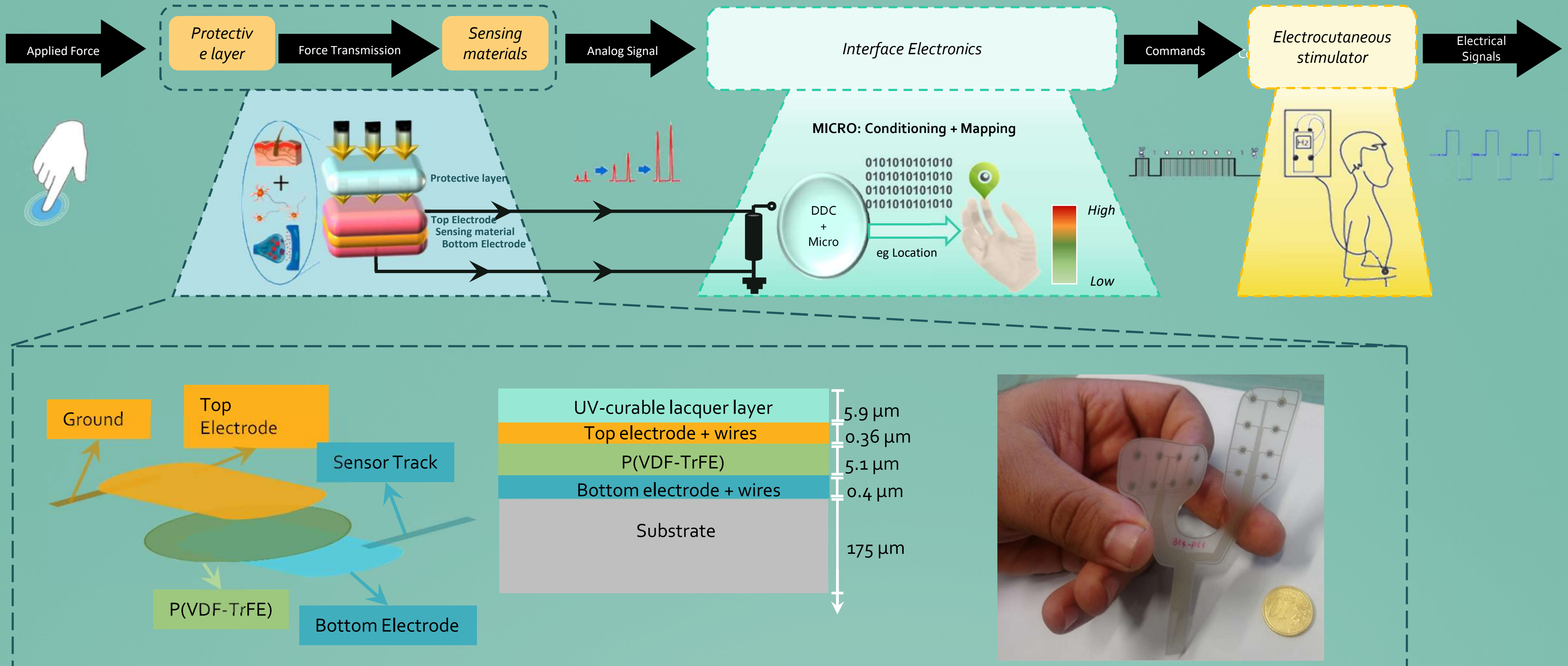
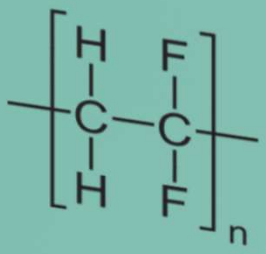

acquire sensor data
large number of sensors
small size
low power consumption
real-time operation
Interface Electronics
Sensing system
Functional material
Sensor distribution
Mechanical structure
Manufacturing technology
E-Skin System
Process many data
Extract tactile information
✓ Contact Force
✓ Contact location
✓ Static/dynamic contact
Small processing time
Embedded Digital Data Processing
Communication Interface
Wide bandwidth
High-reliability
Real-time capabilities



Single sensor Structure

FUNCTIONAL MATERIAL: PVDF PIEZOELECTRIC POLYMER

Poly**V**inili**D**ene
Fluoride



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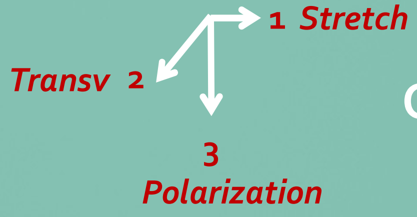
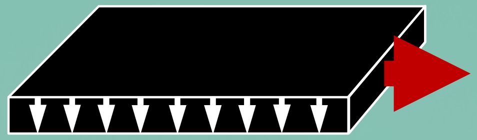


ORTHOTROPIC SYSTEM

Polarized PVDF film



Oriented
molecules

Oriented dipoles

« Flexible
« Frequency: <1Hz -1kHz
« Wide dynamics

PACINIAN + RUFFINI + MERKEL + MEISSNER

ALL HUMAN SKIN MECHANORECEPTORS

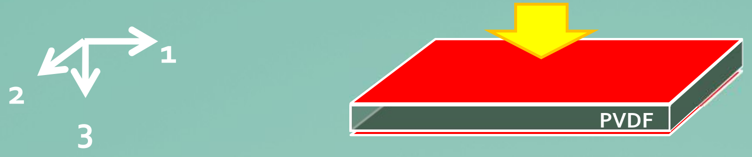
DYNAMIC
&
TRANSIENT
STIMULATION

THICKNESS MODE

$$\underset{\text{OUTPUT}}{\overset{\textit{ELECTRICAL DISPLACEMENT}}{\begin{bmatrix} D_1 \\ D_2 \\ \boxed{D_3} \end{bmatrix}}} = \overset{\textit{PIEZOELECTRIC MATRIX}}{\begin{bmatrix} 0 & 0 & 0 & 0 & d_{15} & 0 \\ 0 & 0 & 0 & d_{24} & 0 & 0 \\ d_{31} & d_{32} & \boxed{d_{33}} & 0 & 0 & 0 \end{bmatrix}} \underset{\text{INPUT}}{\overset{\textit{STRESS}}{\begin{bmatrix} \cancel{T_{11}} \\ \cancel{T_{22}} \\ \boxed{T_{33}} \\ T_{23} \\ T_{13} \\ T_{12} \end{bmatrix}}} + \overset{\textit{PERMITTIVITY}}{\begin{bmatrix} \varepsilon_{11} & 0 & 0 \\ 0 & \varepsilon_{22} & 0 \\ 0 & 0 & \varepsilon_{33} \end{bmatrix}} \overset{\textit{ELECTRIC FIELD}}{\begin{bmatrix} E_{ext1} \\ E_{ext2} \\ \cancel{E_{ext3}} \end{bmatrix}}$$

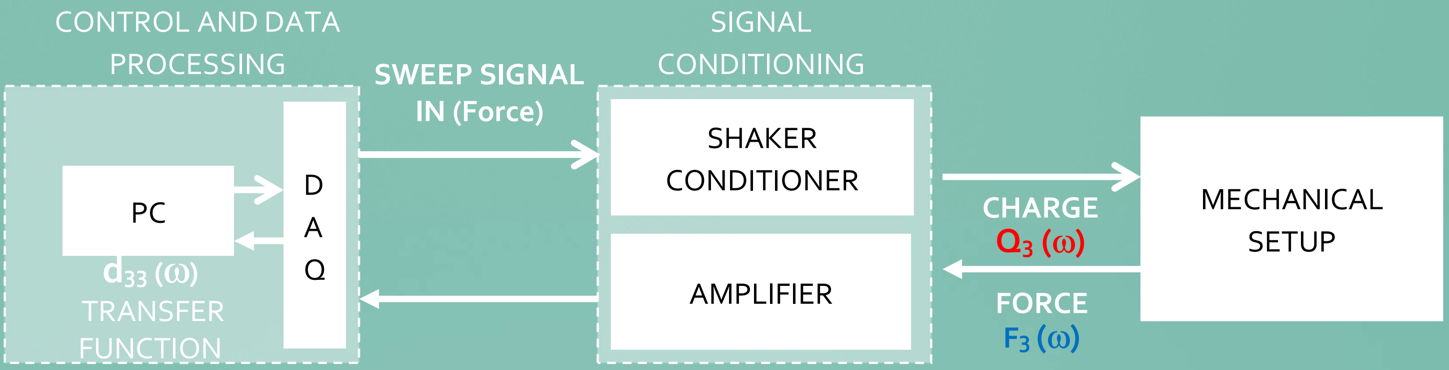
(Normal stress)

T_{33}



RIGID SUBSTRATE

EXPERIMENTAL SETUP: THICKNESS MODE



CONTROL AND DATA PROCESSING

PC

DAQ

$d_{33}(\omega)$ TRANSFER FUNCTION

SWEEP SIGNAL IN (Force)

SIGNAL CONDITIONING

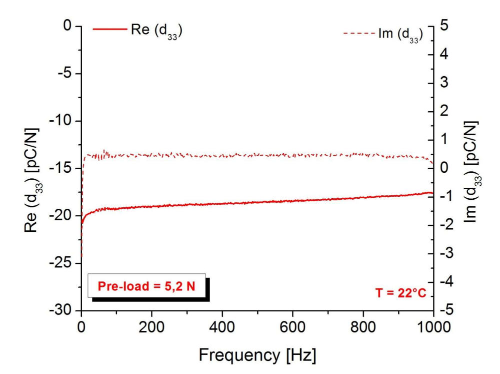
SHAKER CONDITIONER

AMPLIFIER

CHARGE $Q_3(\omega)$

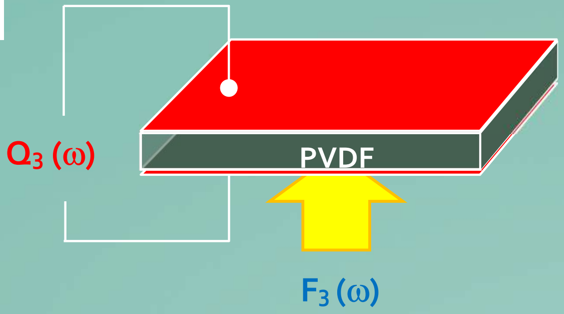
FORCE $F_3(\omega)$

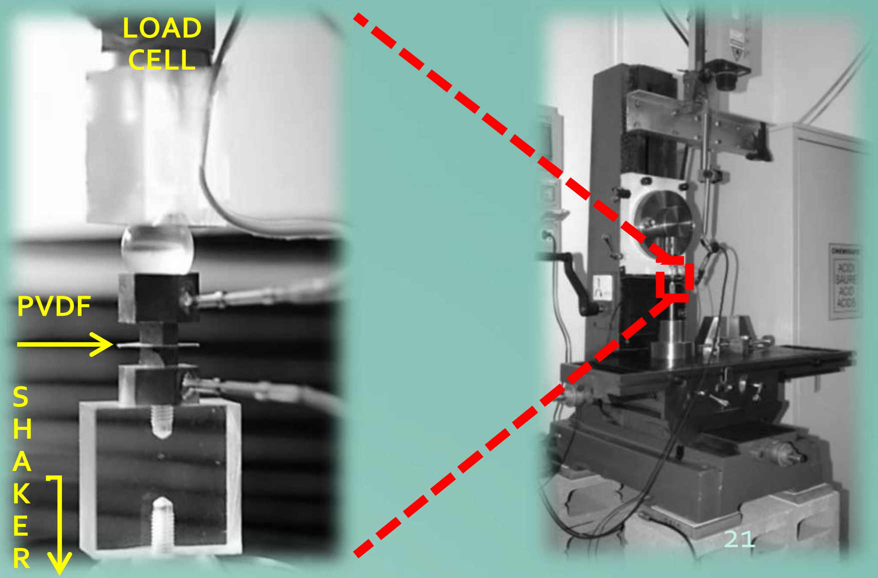
MECHANICAL SETUP



***Thickness* mode**

$$D_3(\omega) = d_{33}(\omega) * T_{33}(\omega)$$





Seminara, L., Capurro, M., Cirillo, P., Cannata, G., & Valle, M. (2011). Electromechanical characterization of piezoelectric PVDF polymer films for tactile sensors in robotics applications. Sensors and Actuators A: Physical, 169(1), 49-58.

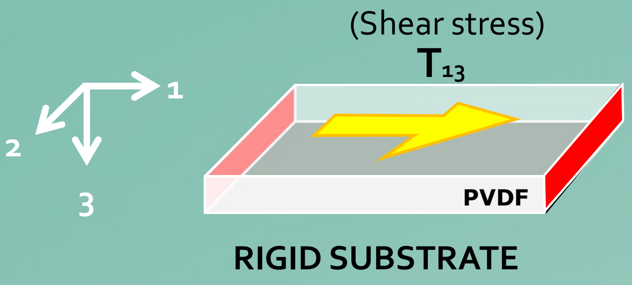
SHEAR MODES

ELECTRICAL DISPLACEMENT *PIEZOELECTRIC MATRIX* *STRESS* *PERMITTIVITY* *ELECTRIC FIELD*

$$\begin{bmatrix}\boxed{D_1}\\D_2\\D_3\end{bmatrix} = \begin{bmatrix}0&0&0&0&d_{15}&0\\0&0&0&d_{24}&0&0\\d_{31}&d_{32}&d_{33}&0&0&0\end{bmatrix}\begin{bmatrix}T_{11}\\T_{22}\\T_{33}\\T_{23}\\\boxed{T_{13}}\\T_{12}\end{bmatrix} + \begin{bmatrix}\varepsilon_{11}&0&0\\0&\varepsilon_{22}&0\\0&0&\varepsilon_{33}\end{bmatrix}\begin{bmatrix}\xcancel{E_{ext1}}\\E_{ext2}\\E_{ext3}\end{bmatrix}$$

OUTPUT

INPUT



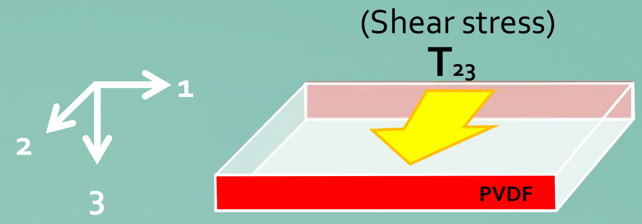
SHEAR MODES

ELECTRICAL DISPLACEMENT · *PIEZOELECTRIC MATRIX* · *STRESS* · *PERMITTIVITY* · *ELECTRIC FIELD*

$$\begin{bmatrix} D_1 \\ \boxed{D_2} \\ D_3 \end{bmatrix} = \begin{bmatrix} 0 & 0 & 0 & 0 & d_{15} & 0 \\ 0 & 0 & 0 & d_{24} & 0 & 0 \\ d_{31} & d_{32} & d_{33} & 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} T_{11} \\ T_{22} \\ T_{33} \\ \boxed{T_{23}} \\ T_{13} \\ T_{12} \end{bmatrix} + \begin{bmatrix} \varepsilon_{11} & 0 & 0 \\ 0 & \varepsilon_{22} & 0 \\ 0 & 0 & \varepsilon_{33} \end{bmatrix} \begin{bmatrix} E_{ext\,1} \\ \cancel{E_{ext\,2}} \\ E_{ext\,3} \end{bmatrix}$$

OUTPUT

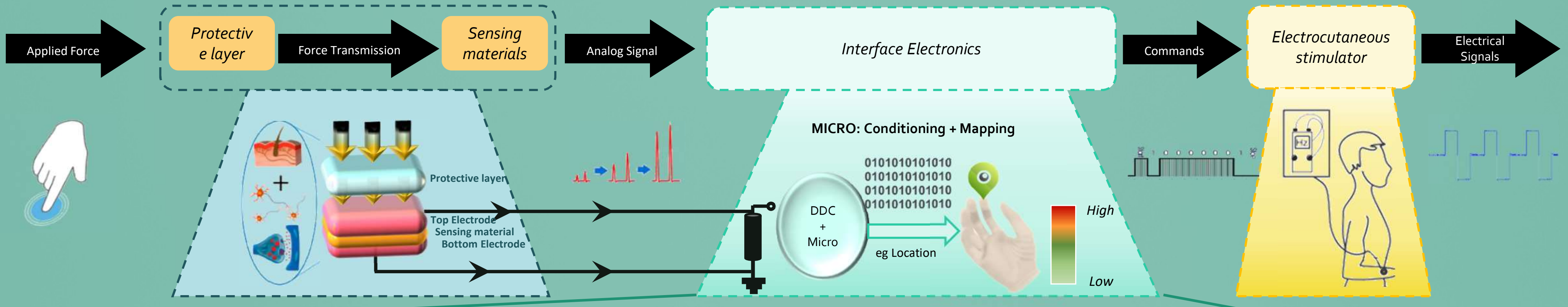
INPUT

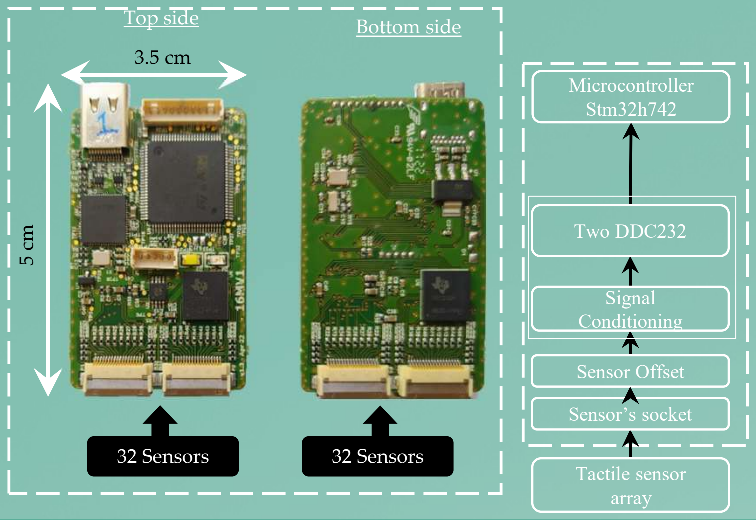


RIGID SUBSTRATE

E-SKIN REQUIREMENTS

Detectable Force Range	0.01N-10N
Sensor Frequency Bandwidth	< 1 Hz - 1kHz
Spatial Resolution	≤ 1mm for fingertips 10 – 20 mm for palm
Mechanical Sensor system characteristics	Flexible & conformable Robust & durable
Electrical Sensor system characteristics	Low power Low *latency* (real-time) Minimal wiring and cross talk





Based on:* *1- Two *Analog-to-digital converters (DDC232)*
2- Stm32h742 (single core M7)

Sampling rate : 2 KSamples/ second

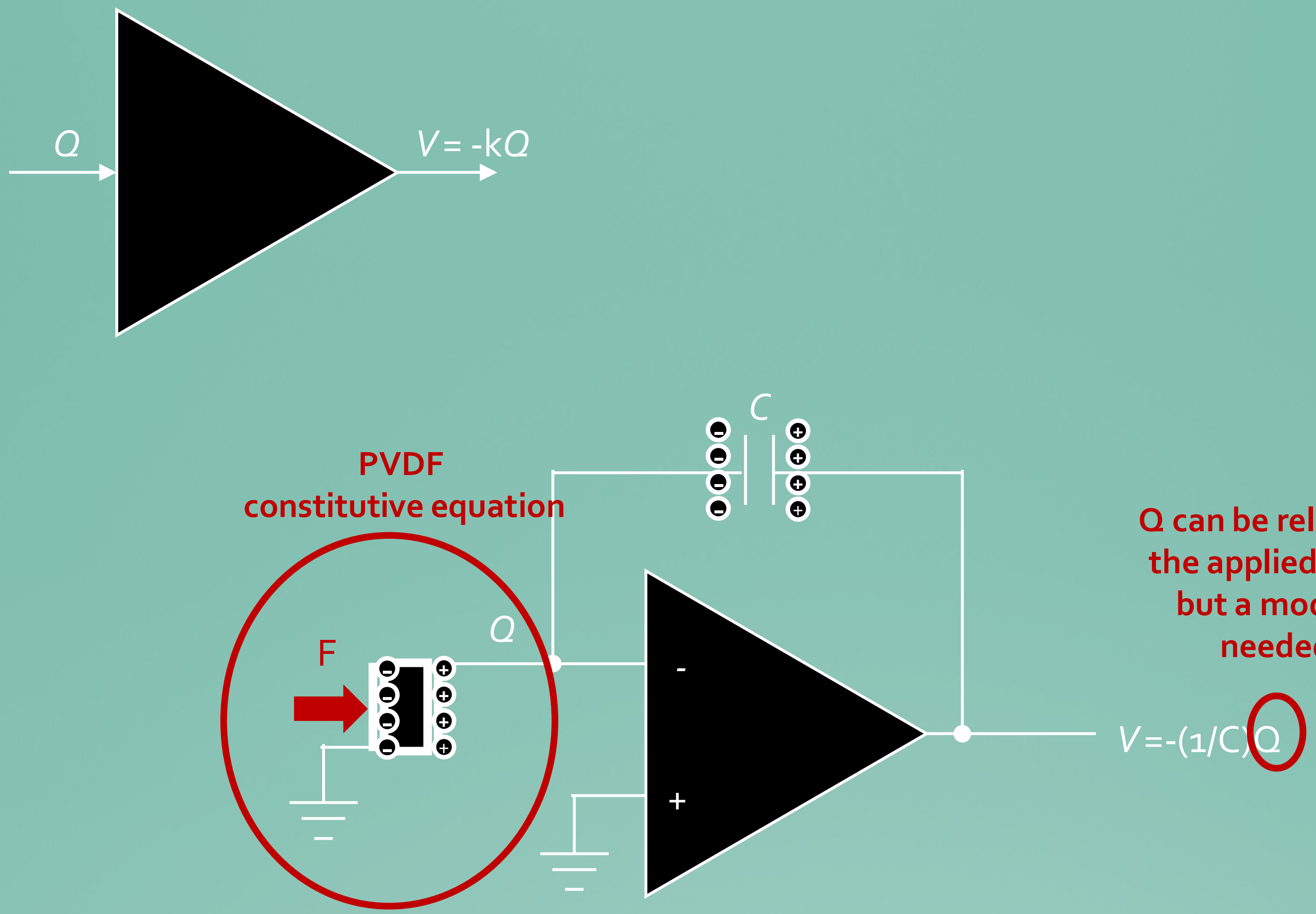
Power consumption: 250mW

Number of Channels: 64 input channels

Abbass, Y., Saleh, M., Dosen, S., and Valle, M., Embedded Electrotactile Feedback System for Hand Prostheses Using Matrix Electrode and Electronic Skin; TBCAS Oct. 2021 912-925

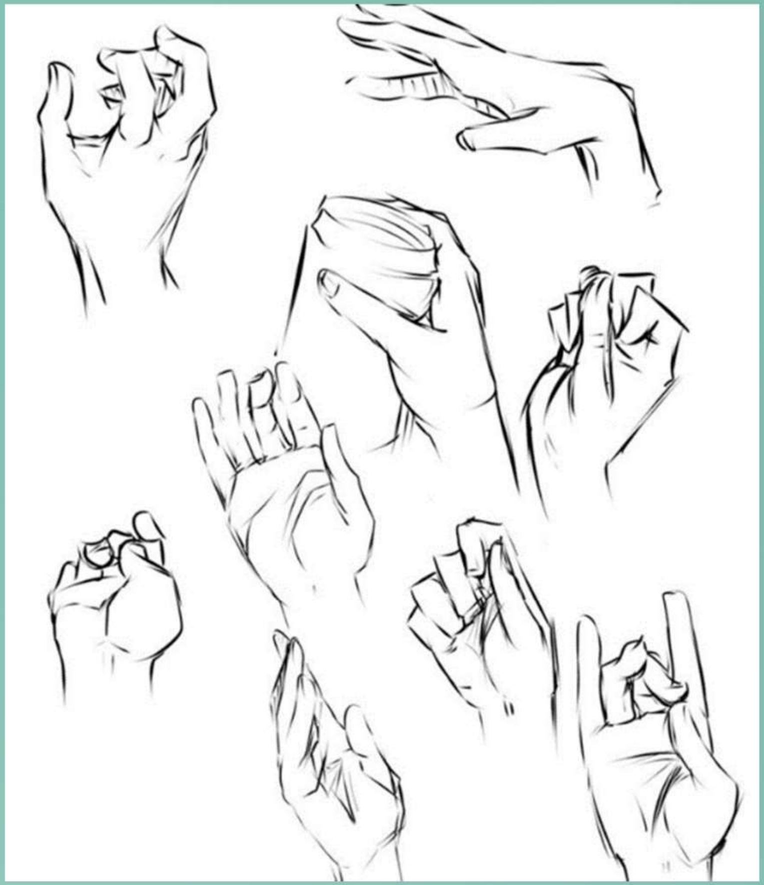
Abbass, Y., Dosen, S., Seminara, L., & Valle, M. (2022). Full-hand electrotactile feedback using electronic skin and matrix electrodes for high-bandwidth human–machine interfacing. Philosophical Transactions of the Royal Society A, 380(2228), 20210017.

CHARGE AMPLIFIER



PVDF constitutive equation

Q can be related to the applied force, but a model is needed!

FROM CONTACT TO PERCEPTION

ROBOTICS

TACTILE SENSING = detection and measurement of contact parameters in a predetermined contact area + **subsequent processing of the signals at the taxel level**, i.e., before sending tactile data to higher levels for perceptual interpretation.

PROSTHETICS

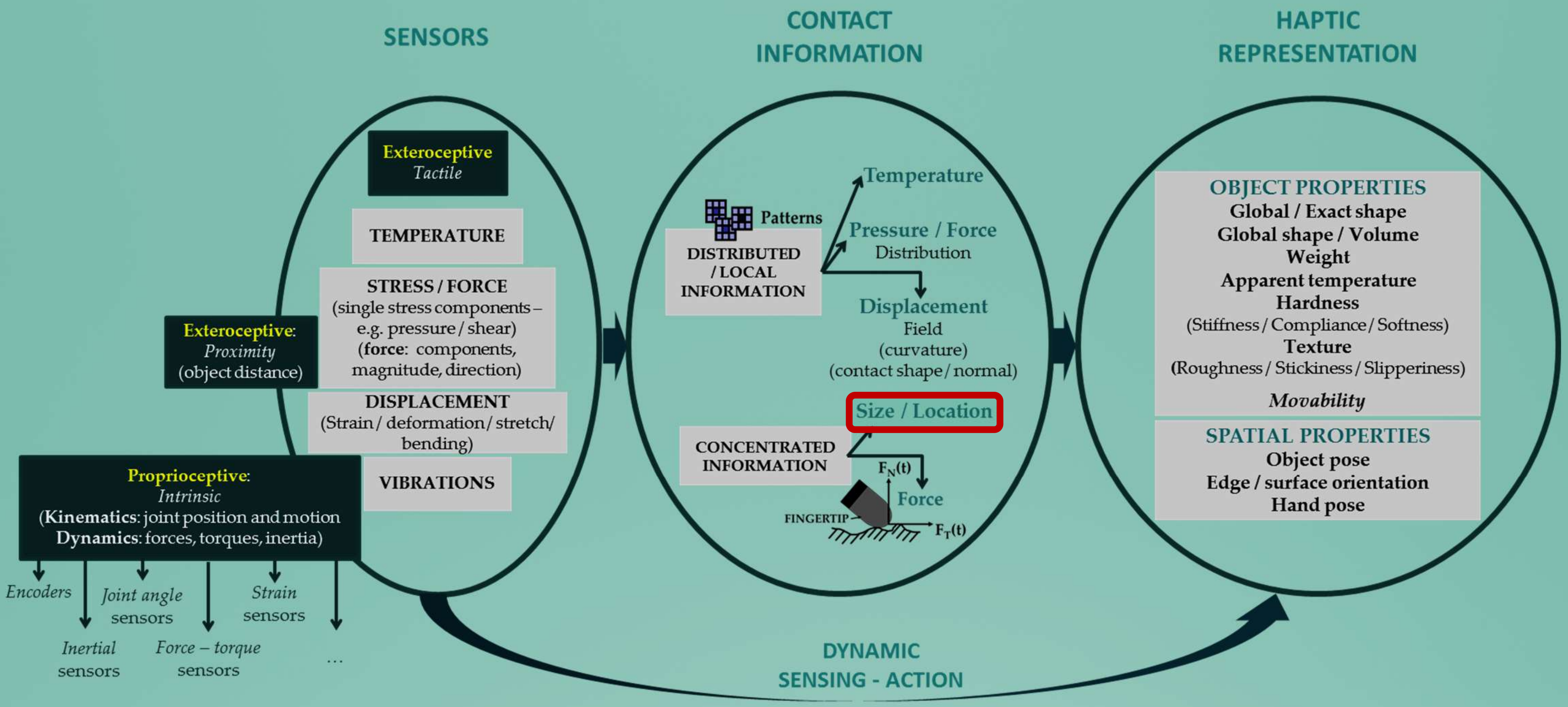
TACTILE SENSING = detection and measurement of contact parameters in a predetermined contact area

Signal processing at the taxel level?

OR

Rough signals?

?



SENSORS

Exteroceptive
Tactile

TEMPERATURE

STRESS / FORCE
(single stress components – e.g. pressure / shear)
(**force**: components, magnitude, direction)

DISPLACEMENT
(Strain / deformation / stretch/ bending)

VIBRATIONS

Exteroceptive:
Proximity
(object distance)

Proprioceptive:
Intrinsic
(**Kinematics**: joint position and motion
Dynamics: forces, torques, inertia)

Encoders
Inertial sensors
Joint angle sensors
Force – torque sensors
Strain sensors
…

CONTACT INFORMATION

DISTRIBUTED / LOCAL INFORMATION

Patterns

Temperature

Pressure / Force
Distribution

Displacement
Field
(curvature)
(contact shape / normal)

CONCENTRATED INFORMATION

Size / Location

Force

HAPTIC REPRESENTATION

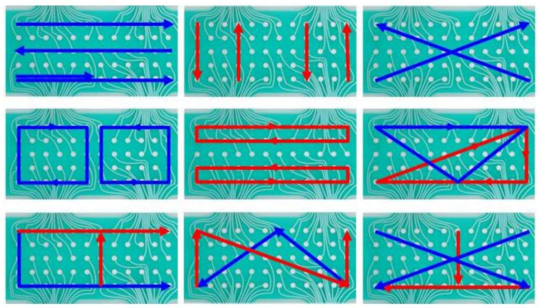
OBJECT PROPERTIES
Global / Exact shape
Global shape / Volume
Weight
Apparent temperature
Hardness
(Stiffness / Compliance / Softness)
Texture
(Roughness / Stickiness / Slipperiness)
Movability

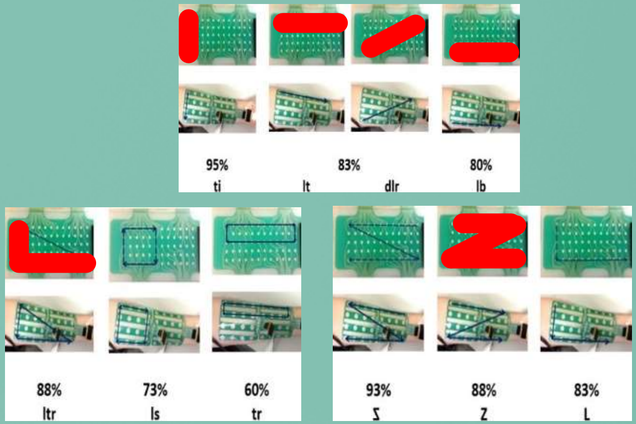
SPATIAL PROPERTIES
Object pose
Edge / surface orientation
Hand pose

DYNAMIC SENSING - ACTION

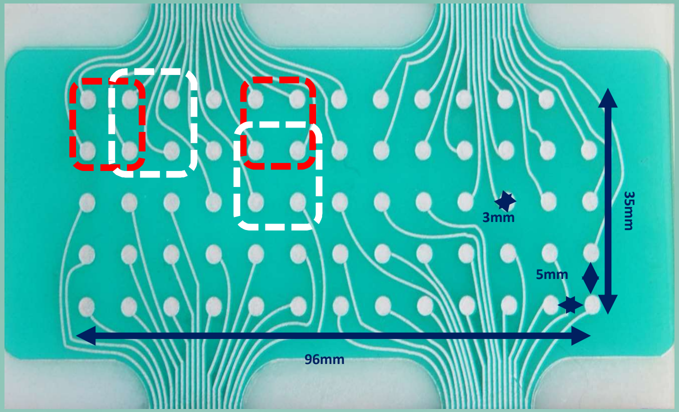
Seminara, L., Gastaldo, P., Watt, S. J., Valyear, K. F., Zuher, F., & Mastrogiovanni, F. (2019). Active haptic perception in robots: a review. Frontiers in neurorobotics, 13, 53.

__Data processing__ (1): contact size, position and movement

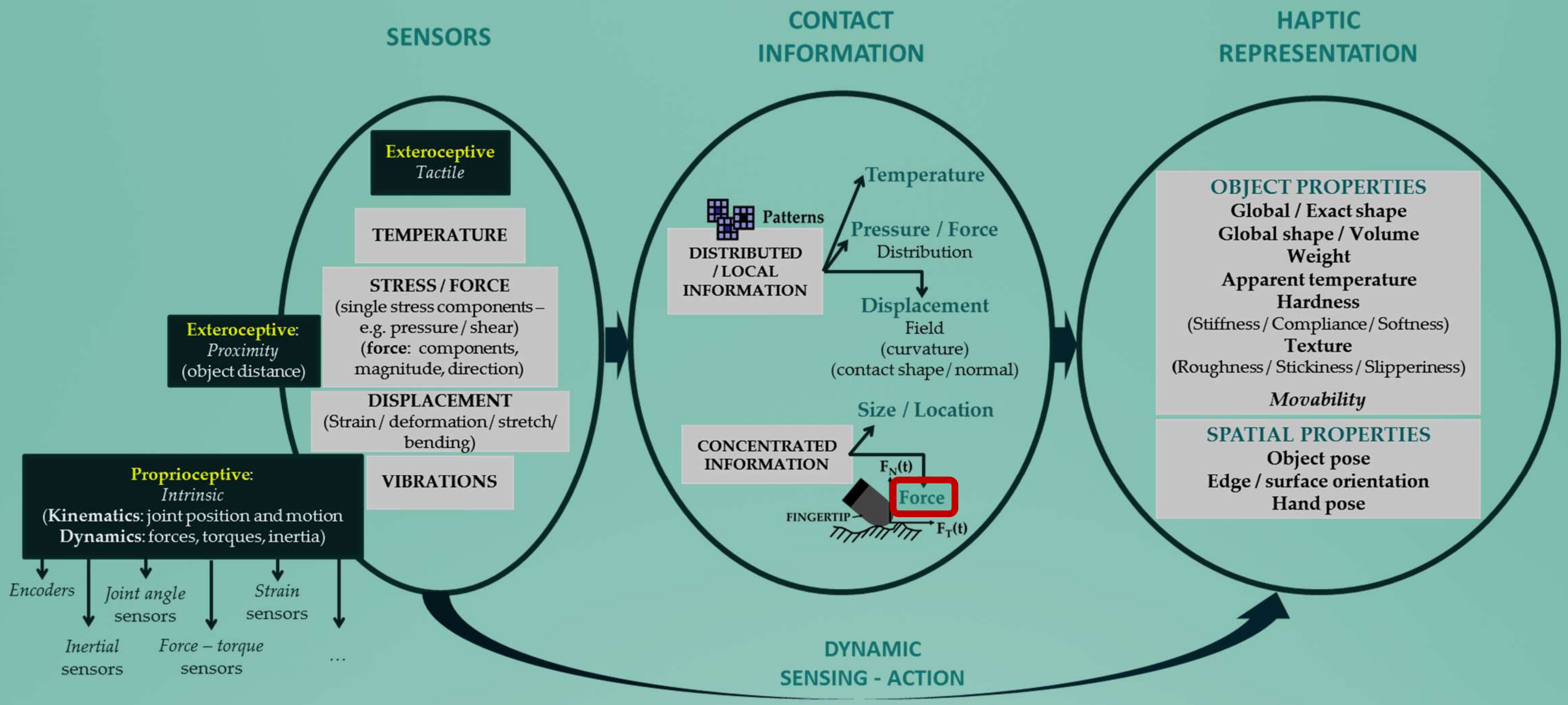




Space: Sensor fusion



M. Franceschi, L. Seminara, S. Dosen, M. Strbac, M. Valle and D. Farina, "A System for Electrotactile Feedback Using Electronic Skin and Flexible Matrix Electrodes: Experimental Evaluation," in IEEE Transactions on Haptics, vol. 10, no. 2, pp. 162-172, 1 April-June 2017, doi: 10.1109/TOH.2016.2618377.



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CONTACT INFORMATION

DISTRIBUTED / LOCAL INFORMATION

Patterns

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Pressure / Force
Distribution

Displacement
Field
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(contact shape / normal)

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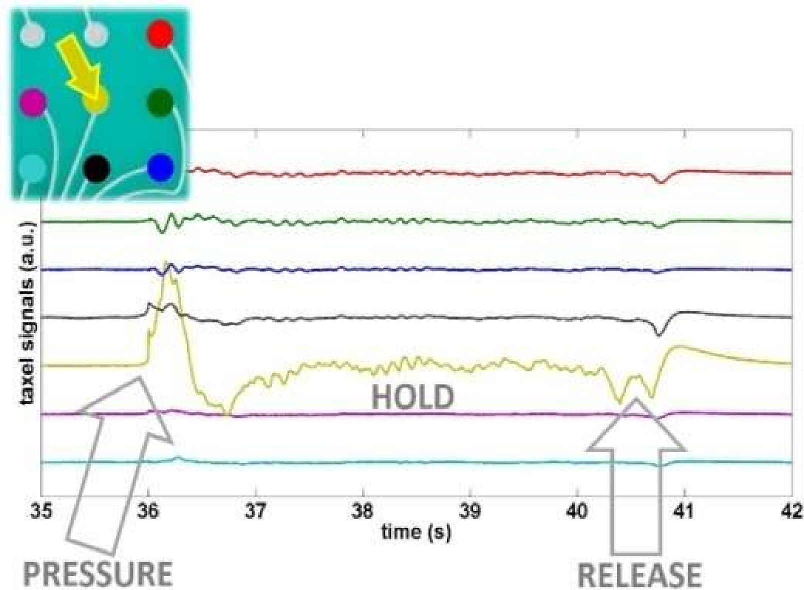
(Stiffness / Compliance / Softness)
Texture
(Roughness / Stickiness / Slipperiness)
Movability

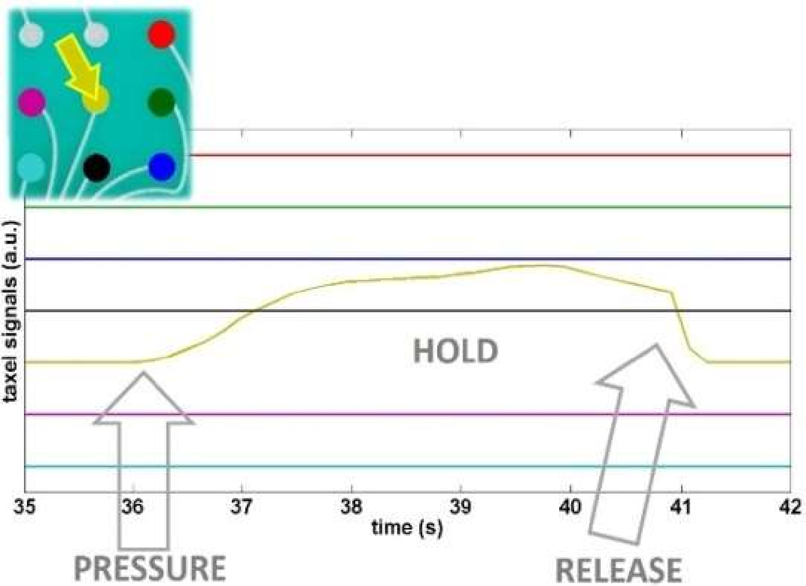
SPATIAL PROPERTIES
Object pose
Edge / surface orientation
Hand pose

DYNAMIC SENSING - ACTION

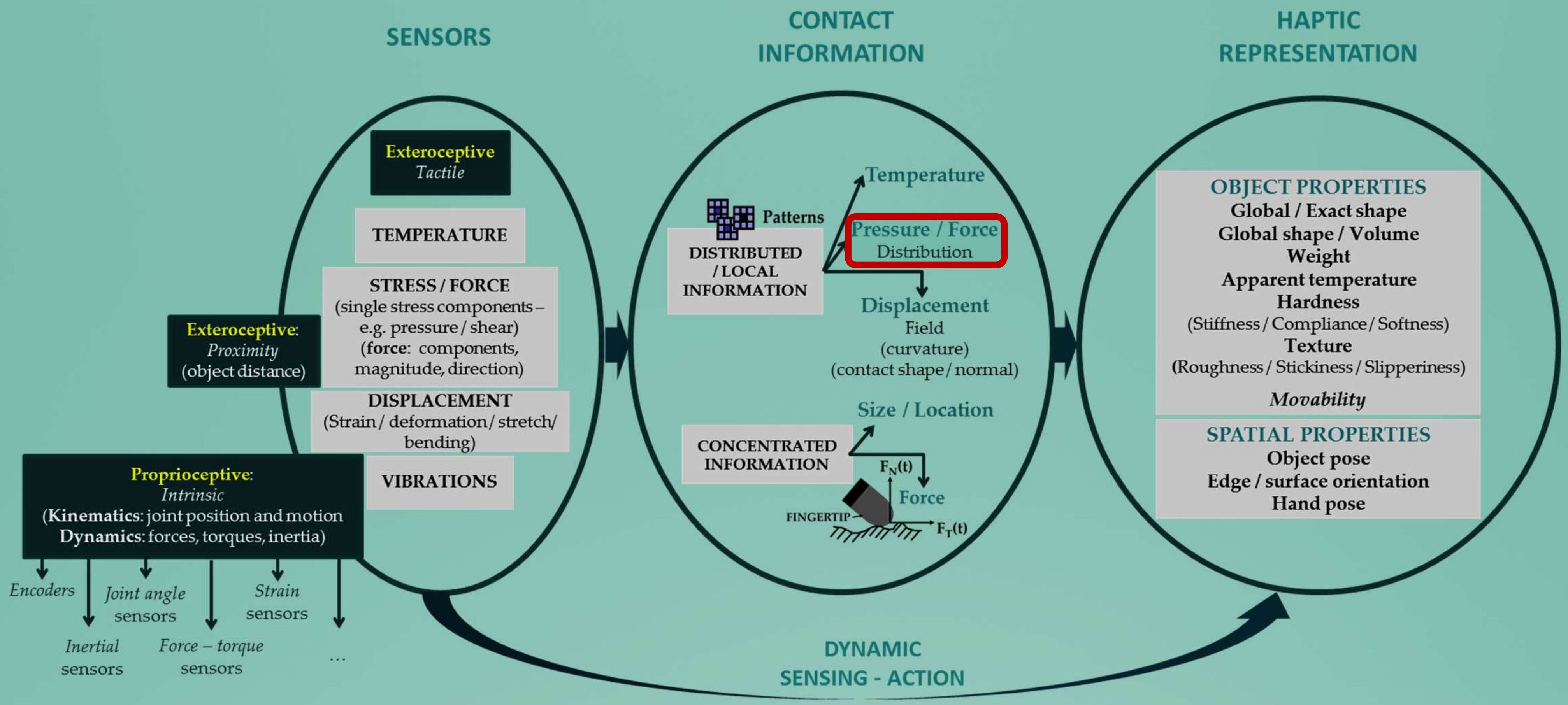
Data processing (2): contact energy

Time: Integrative method





M. Franceschi, L. Seminara, S. Dosen, M. Strbac, M. Valle and D. Farina, "A System for Electrotactile Feedback Using Electronic Skin and Flexible Matrix Electrodes: Experimental Evaluation," in IEEE Transactions on Haptics, vol. 10, no. 2, pp. 162-172, 1 April-June 2017, doi: 10.1109/TOH.2016.2618377.



SENSORS

Exteroceptive
Tactile

TEMPERATURE

STRESS / FORCE
(single stress components – e.g. pressure / shear)
(**force**: components, magnitude, direction)

DISPLACEMENT
(Strain / deformation / stretch/ bending)

VIBRATIONS

Exteroceptive:
Proximity
(object distance)

Proprioceptive:
Intrinsic
(**Kinematics**: joint position and motion
Dynamics: forces, torques, inertia)

Encoders
Joint angle sensors
Strain sensors
Inertial sensors
Force – torque sensors
…

CONTACT INFORMATION

DISTRIBUTED / LOCAL INFORMATION

Temperature

Pressure / Force
Distribution

Displacement
Field
(curvature)
(contact shape / normal)

CONCENTRATED INFORMATION

Size / Location

HAPTIC REPRESENTATION

OBJECT PROPERTIES
Global / Exact shape
Global shape / Volume
Weight
Apparent temperature
Hardness
(Stiffness / Compliance / Softness)
Texture
(Roughness / Stickiness / Slipperiness)
Movability

SPATIAL PROPERTIES
Object pose
Edge / surface orientation
Hand pose

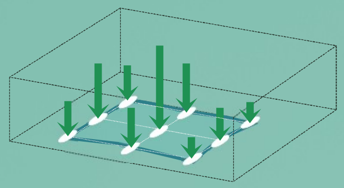
DYNAMIC SENSING - ACTION

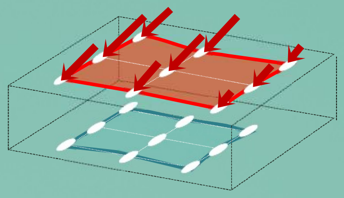
Data processing **(3): reconstruction of the contact force distribution**

Array structure:

Normal stress component in the sensors: ***MEASURED***

Surface force distribution + contact shape: ***RECONSTRUCTED***





- Goal: from the **measured normal stress component** in the sensors, the goal is to reconstruct **complete contact force vectors at discrete points** on the upper surface layer**.**

Proposed approach

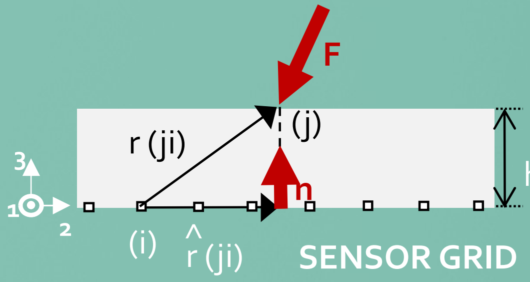
- Discretize external forces
- Derive parameterized solutions *compatible with physical constraints*
- Parameters found to maximize an "efficiency" functional

Assumptions

- Elastic half-space bounded by a plane
- Elastomer layer Poisson ratio ν ~ 0.5
- Small deflections

BOUSSINESQ'S EQUATION

$$\mathbf{n}\cdot\mathbf{T}(i) = \frac{3}{2\pi}\sum_j \frac{\mathbf{F}(j)\cdot\mathbf{r}(ji)h}{(\hat{r}^2(ji)+h^2)^{5/2}}\mathbf{r}(ji)$$

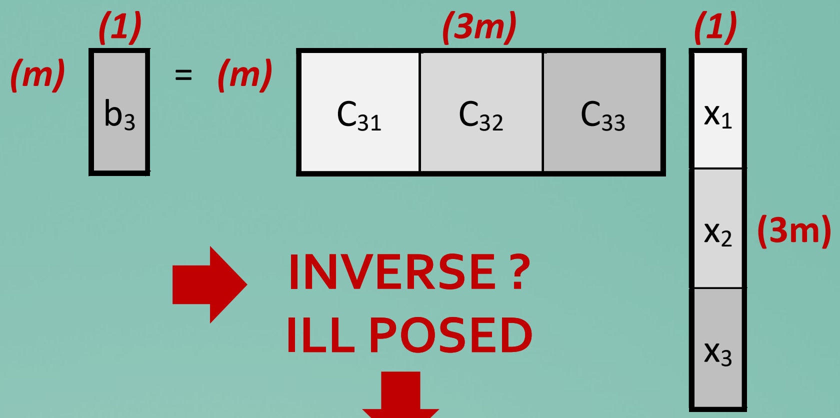


DIRECT PROBLEM: $b = C\,x$

Sensors only give information about the normal T_{33} component

BOUSSINESQ'S EQUATION

$$T_{33}(i) = \frac{3}{2\pi}\sum_j \frac{\left(\hat{\mathbf{F}}(j)\cdot\hat{\mathbf{r}}(ji)+F_n h\right)h^2}{(\hat{r}^2(ji)+h^2)^{5/2}}$$



INVERSE ?
ILL POSED

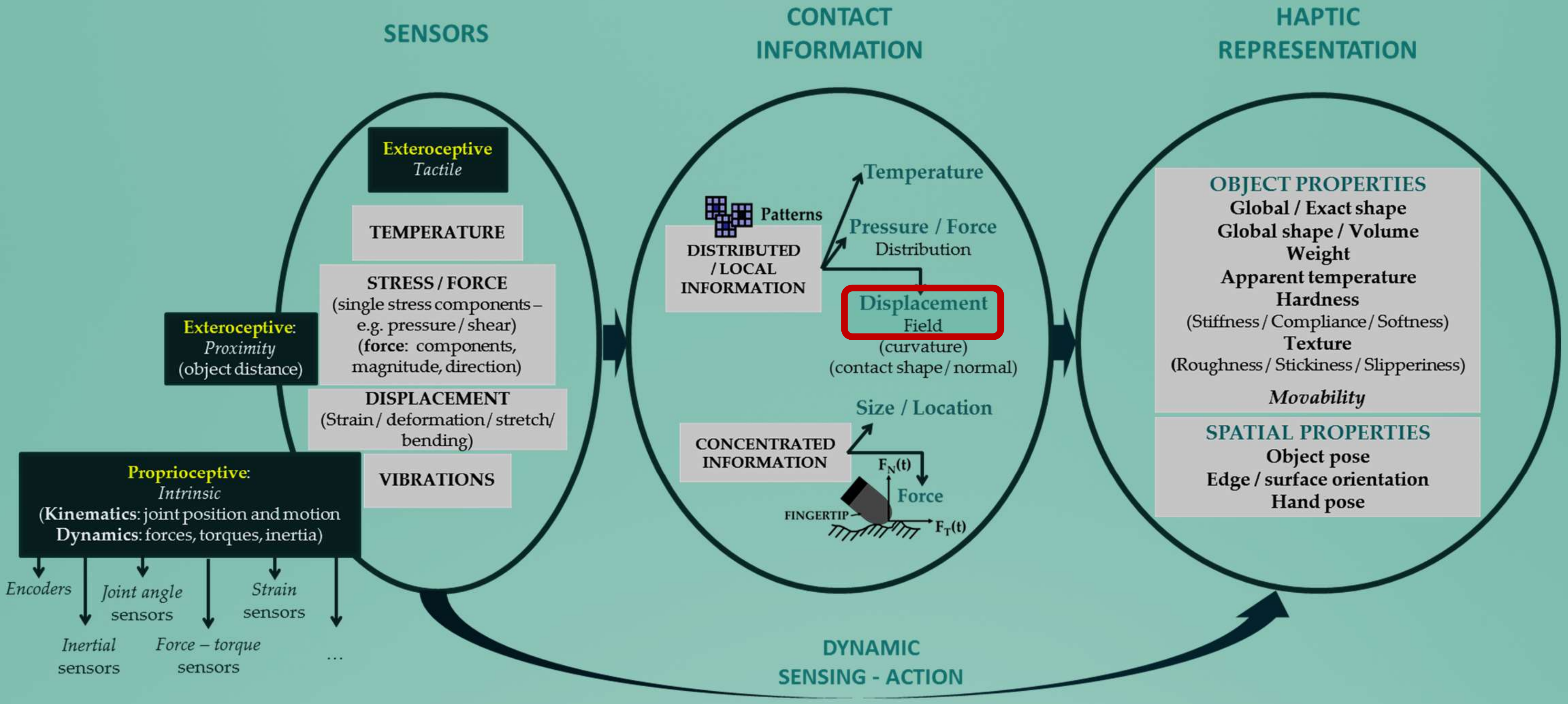
SET OF SOLUTIONS

$$\mathbf{x = C^{\dagger}\,b + (I - C^{\dagger}C)\,w}$$

[$C^{\dagger} = C^T(CC^T)^{-1}$ MOORE-PENROSE PSEUDOINVERSE]

Choice of the solution: The x solution which is best complying with the physical conditions of the problem = **x vector contains the best** (most "efficient") **3-component force distribution**.

Seminara, L., Capurro, M., & Valle, M. (2015). Tactile data processing method for the reconstruction of contact force distributions. Mechatronics, 27, 28-37.



SENSORS

Exteroceptive
Tactile

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(single stress components – e.g. pressure / shear)
(**force**: components, magnitude, direction)

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Intrinsic
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Encoders
Joint angle sensors
Strain sensors
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Force – torque sensors
…

CONTACT INFORMATION

Patterns

DISTRIBUTED / LOCAL INFORMATION

Temperature

Pressure / Force
Distribution

Displacement
Field
(curvature)
(contact shape / normal)

CONCENTRATED INFORMATION

Size / Location

Force

$F_N(t)$

$F_T(t)$

FINGERTIP

HAPTIC REPRESENTATION

OBJECT PROPERTIES
Global / Exact shape
Global shape / Volume
Weight
Apparent temperature
Hardness
(Stiffness / Compliance / Softness)
Texture
(Roughness / Stickiness / Slipperiness)
Movability

SPATIAL PROPERTIES
Object pose
Edge / surface orientation
Hand pose

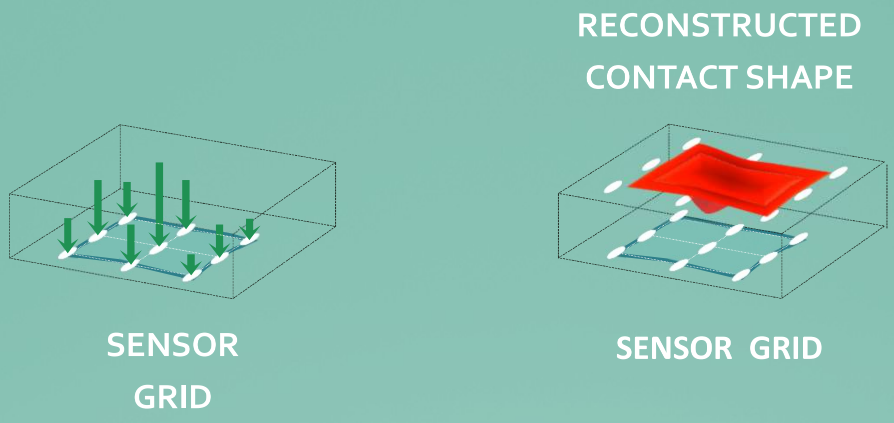
DYNAMIC
SENSING - ACTION

Data processing (4): reconstruction of the displacement distribution (contact shape)

Array structure:

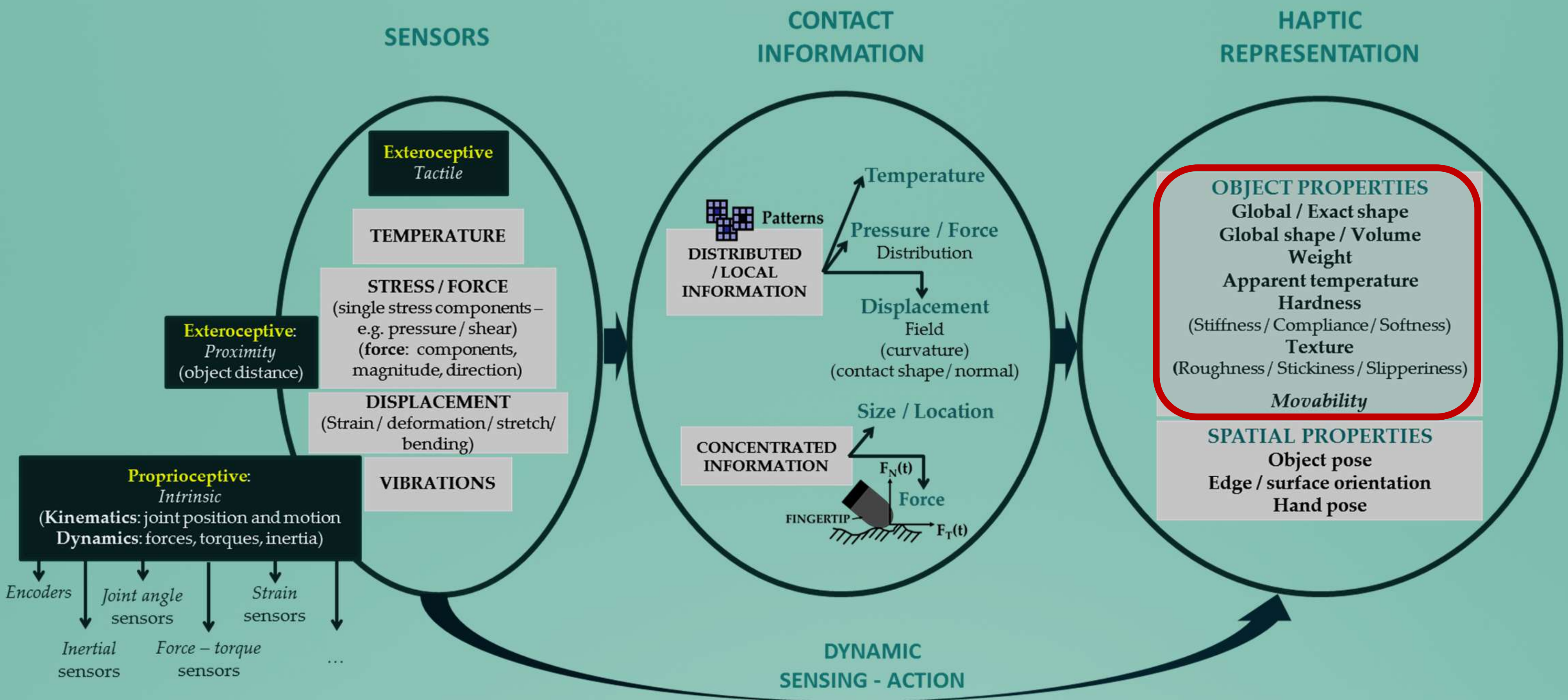
Normal stress component in the sensors: ***MEASURED***

Surface force distribution + contact shape: ***RECONSTRUCTED***



- Goal: from the **reconstructed contact force vectors calculate displacements at discrete points** on the upper surface layer**.**

Muscari, L., Seminara, L., Mastrogiovanni, F., Valle, M., Capurro, M., & Cannata, G. (2013, May). Real-time reconstruction of contact shapes for large area robot skin. In 2013 IEEE International Conference on Robotics and Automation (pp. 2360-2366). IEEE.



SENSORS

Exteroceptive
Tactile

TEMPERATURE

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(single stress components – e.g. pressure / shear)
(**force**: components, magnitude, direction)

DISPLACEMENT
(Strain / deformation / stretch/ bending)

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…

CONTACT INFORMATION

DISTRIBUTED / LOCAL INFORMATION

Patterns

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Distribution

Displacement
Field
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CONCENTRATED INFORMATION

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Force

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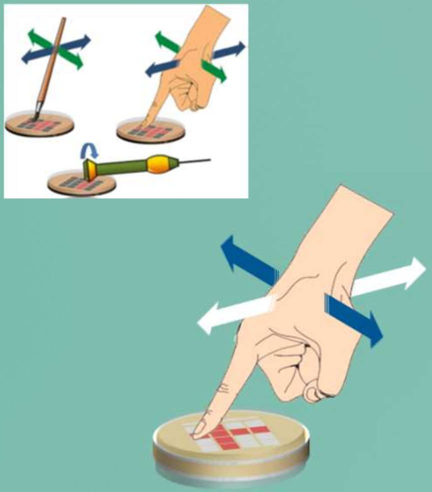
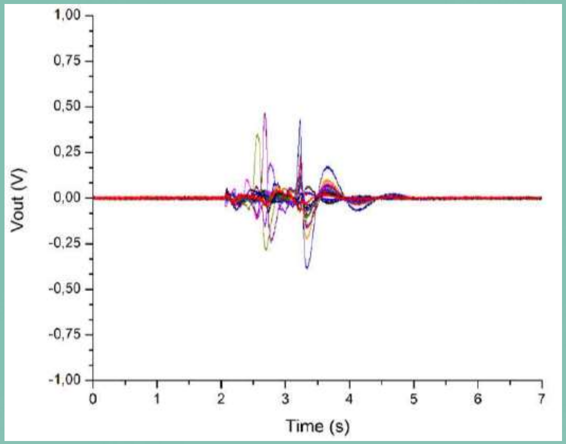
Texture
(Roughness / Stickiness / Slipperiness)
Movability

SPATIAL PROPERTIES
Object pose
Edge / surface orientation
Hand pose

DYNAMIC SENSING - ACTION

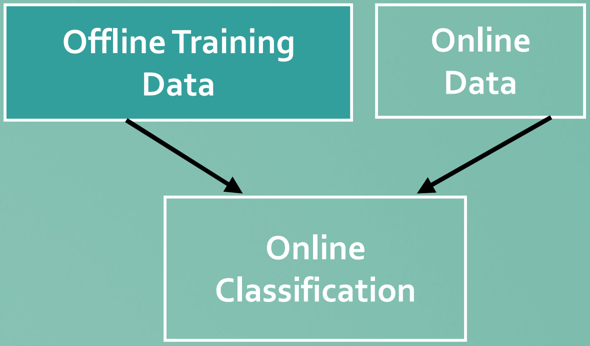
Data processing (5): classifying the touch modality





MACHINE LEARNING

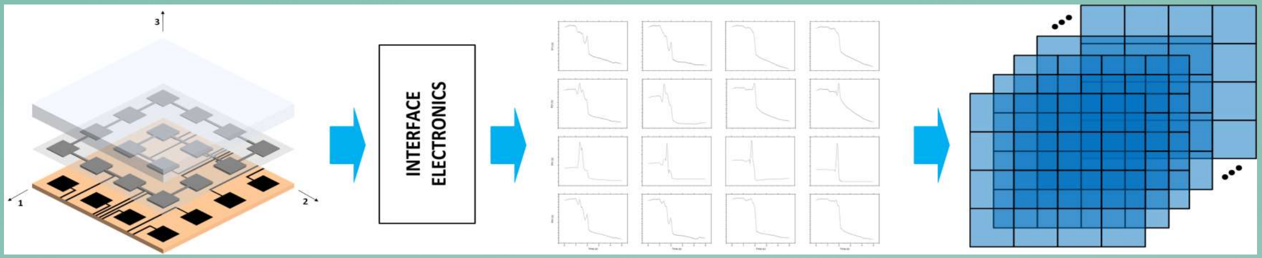
Learning by examples



Offline Training Data

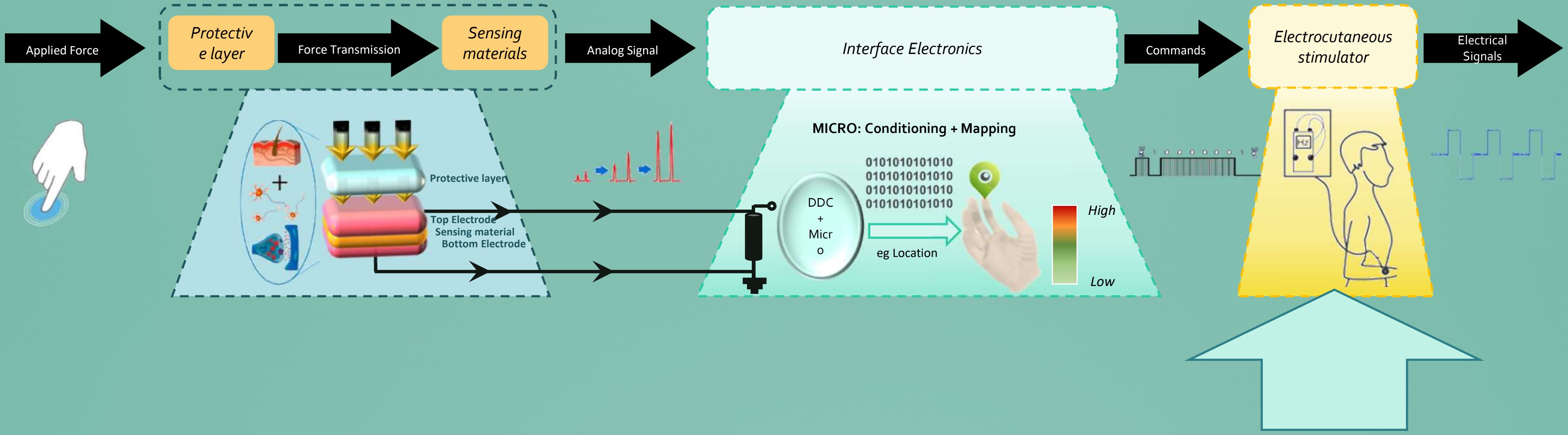
Online Data

Online Classification



Touch modality classification

Gastaldo, P., Pinna, L., Seminara, L., Valle, M., & Zunino, R. (2015). A tensor-based approach to touch modality classification by using machine learning. Robotics and Autonomous Systems, 63, 268-278.



Applied Force

Protectiv e layer

Force Transmission

Sensing materials

Analog Signal

Interface Electronics

Commands

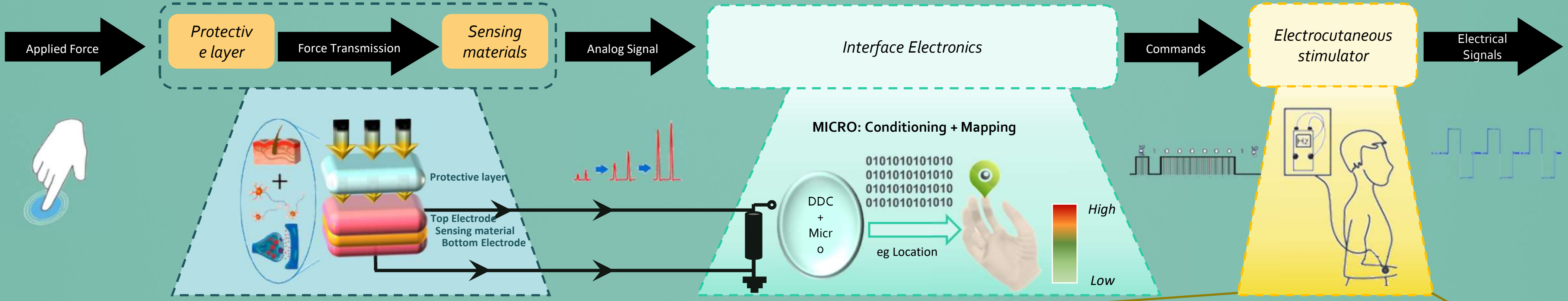
Electrocutaneous stimulator

Electrical Signals

HIGH-DENSITY STIMULATION

FEEDBACK TO THE USER

The **ability of perceiving movements** on the skin
and
the **spatial-temporal resolving capacity** of the skin have an important role.



Applied Force

Protectiv
e layer

Force Transmission

Sensing
materials

Analog Signal

Interface Electronics

Commands

*Electrocutaneous
stimulator*

Electrical
Signals

Protective layer

Top Electrode
Sensing material
Bottom Electrode

MICRO: Conditioning + Mapping

0101010101010
0101010101010
0101010101010
0101010101010

DDC
+
Micr
o

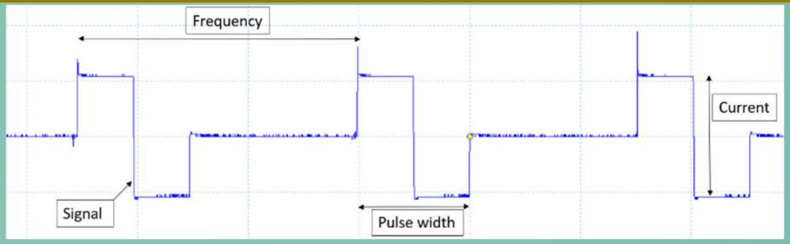
eg Location

High

Low

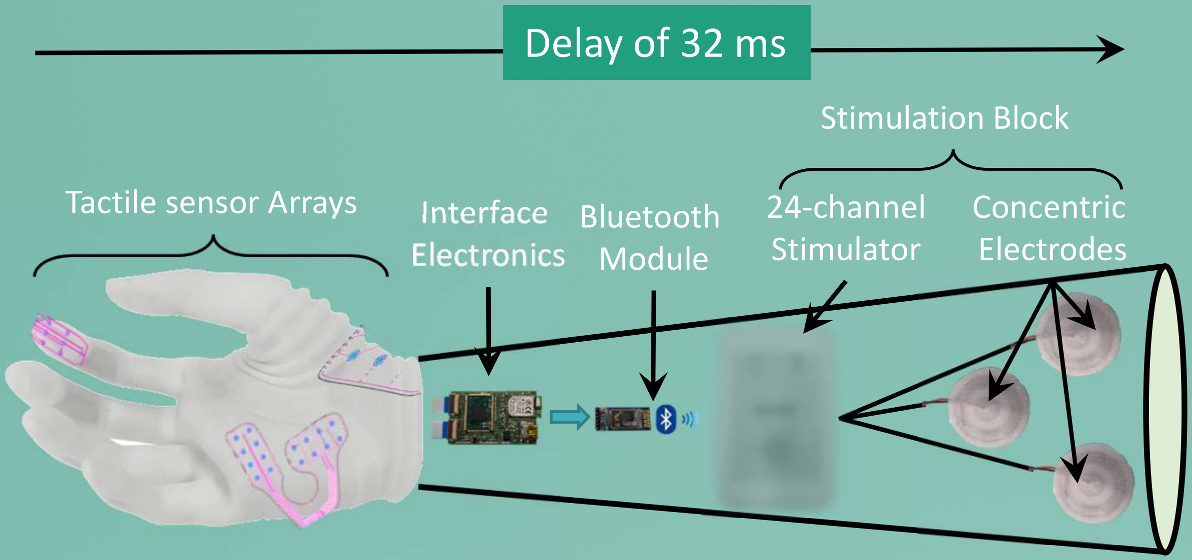
Electrocutaneous stimulator

Concentric electrodes



- ☐ 24-channel programmable battery-powered stimulator
- ☐ charge-balanced biphasic continuous electrostimulation pulses
  - *Current: 0-10mA with 0.1mA step.*
  - *Frequency: 1 to 400 Hz.*
  - *Pulse width: 50 to 500 µs.*
- ☐ self-adhesive concentric electrodes

THE OVERALL SENSORY FEEDBACK SYSTEM



Delay of 32 ms

Stimulation Block

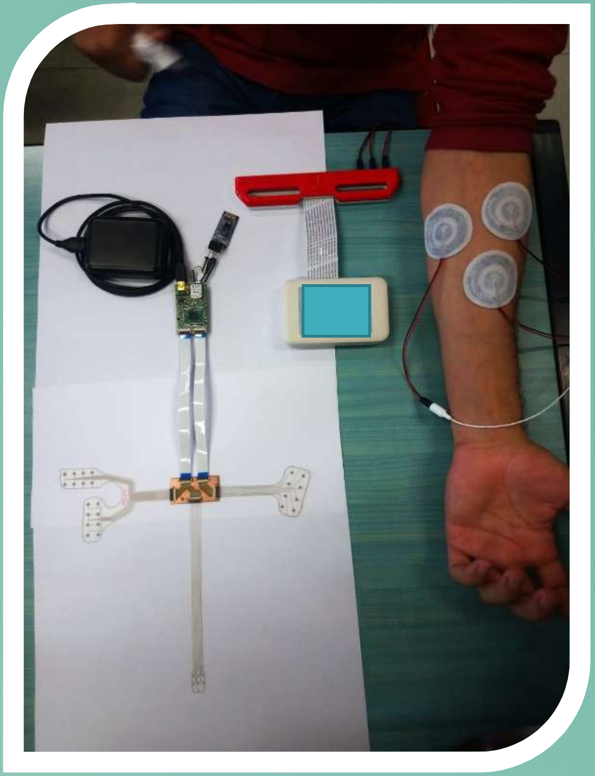
Tactile sensor Arrays

Interface Electronics

Bluetooth Module

24-channel Stimulator

Concentric Electrodes



- MOTIVATION
- HUMAN SENSE OF TOUCH
- ARTIFICIAL SENSE OF TOUCH
  - *Our system*: distributing sensing, electronics, cutaneous electrostimulation
  - Clinical applications and *WORK IN PROGRESS*

INTELLIGENCE ON THE PROSTHESIS

Autonomous management of
vital – safety issues
(*reflexive* behavior)

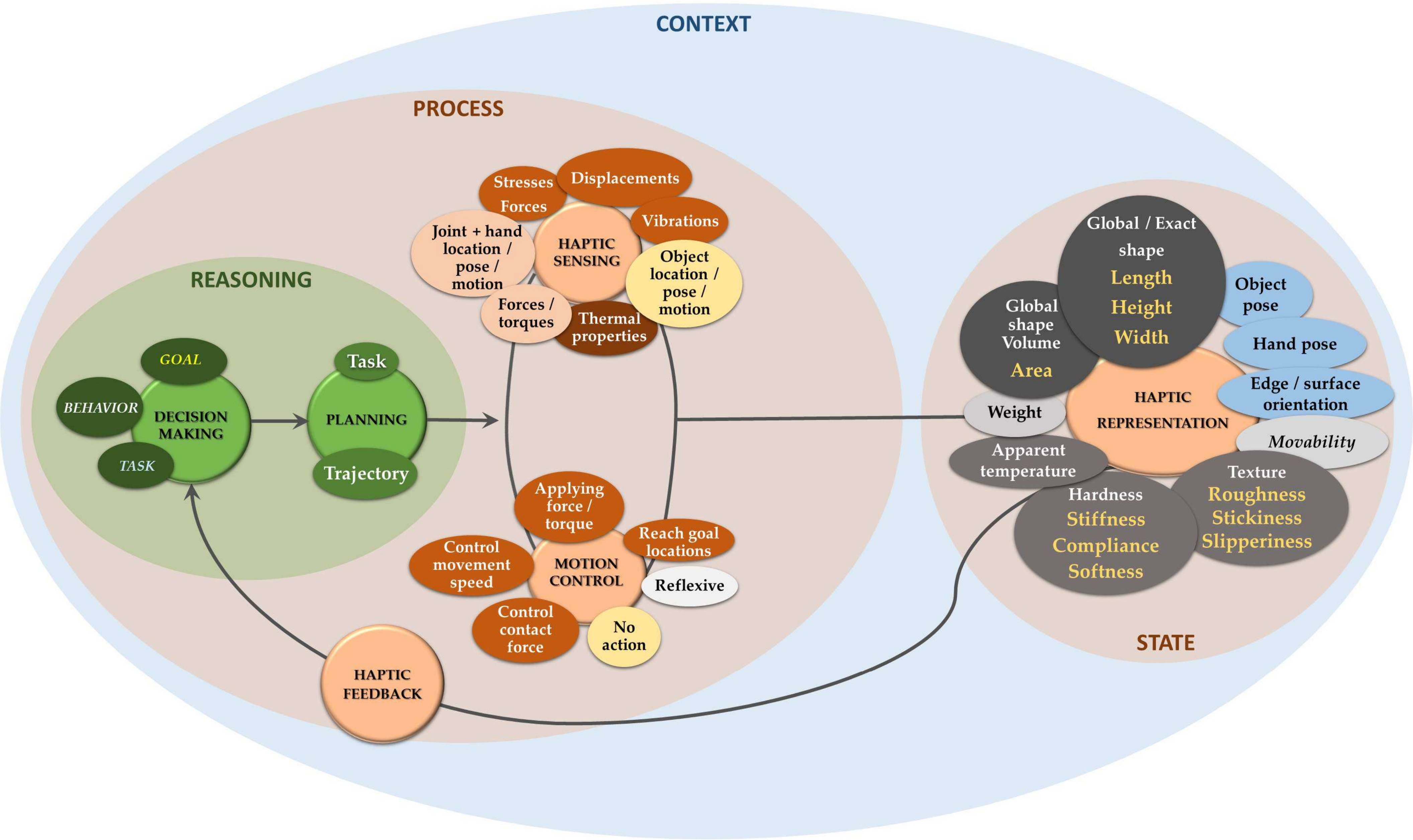
Feedback? What type?
Autonomous when?
EMBODIMENT

L. Seminara, S. Dosen, F. Mastrogiovanni, M. Bianchi, S. Watt, P. Beckerle, T. Nanayakkara, K. Drewing, A. Moscatelli, R. L. Klatzky and G. E. Loeb, (2023) A touch of humanity for human-in-the-loop artificial hands. Accepted for publication in SCIENCE ROBOTICS.

- Which kind of information about a touched object do we **send back to the user**? Only **low level or processed or "depending on user intention"**?
- How to convey this information back to the user? **What kind of feedback promotes embodiment**?
  - Where do we place electrodes?
  - Is that placing optimized on the specific task?
  - Which encoding? Frequency, power, amplitude…?

TRAINING COUNTS!

THE BOTTLENECK IS STILL THE FEEDBACK INTERFACE



CONTEXT

PROCESS

REASONING

GOAL

BEHAVIOR

DECISION MAKING

TASK

Task

PLANNING

Trajectory

Stresses

Forces

Displacements

Vibrations

Joint + hand location / pose / motion

HAPTIC SENSING

Object location / pose / motion

Forces / torques

Thermal properties

Applying force / torque

Reach goal locations

Control movement speed

MOTION CONTROL

Reflexive

Control contact force

No action

HAPTIC FEEDBACK

Global / Exact shape

Length

Height

Width

Object pose

Global shape Volume

Area

Hand pose

Edge / surface orientation

Weight

HAPTIC REPRESENTATION

Movability

Apparent temperature

Texture

Roughness

Stickiness

Slipperiness

Hardness

Stiffness

Compliance

Softness

STATE

COLLABORATIONS & ACKNOWLEDGEMENTS

Modeling mechanical behavior (Multiphysics / CAE simulations, analytical models)

collab. Prof. Berselli, University of Genoa, Italy

Prosthetic application

collab. Prof. Farina, Imperial College, UK
collab. Prof. Dosen, Aalborg University, Denmark

From FPGA to ASIC
Emerging techniques to reduce power consumption
e.g. «Approximate Computing»
Memory management («approximate memory»):
collab. Prof. Olivieri Univ. Roma 1
Implementation on **Parallel Ultra Low Power (PULP) processors**
collab Prof. Benini, ETH
Reducing Power Consumption of arithmetic blocks e.g.
Tunable Floting Point multipliers: *collab. Prof. Nannarelli DTU*

Embedded implementation

Art-science research center for studies related to touch

www.tacta.it

Spin-off activities related to Applications other than prosthetics: e.g. robotics, tele-operation, virtual reality
collab. Prof. Dosen, Aalborg University, Denmark

Other applications

Other Applications in neurorehabilitation (rehabilitation of post-stroke patients)
collab. Prof. Trompetto, Ospedale San Martino, Genova

Feedback side

Intuitive communication with the brain:
multisensory integration as a framework
collab. Prof. Watt, Bangor University, Wales

Skin Integration

collab. SMARTEX s.r.l., Prato, Italy

Hannes Hand

Collab. De Michieli, Laffranchi, Boccardo, IIT, Genoca, Italy

ANY QUESTIONS ?