Touch and tactile perception for robots

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Human sense of touch

Lateral motion
Texture

Pressure
Hardness/softness

Static contact
Temperature

Unsupported holding
Weight

Enclosure
Global shape, volume

Rim following
More precise shape

Related human vocabulary

- **Tactile**
  - Perceptible to the sense of touch.
  - *From Latin tactilis ("that may be touched, tangible").*
  - *From French tactile.*
- **Touch**
  - Make physical contact with.
  - *From e.g. French toucher.*

Source: Wiktionary

- **Haptic**
  - Of or relating to the sense of touch; tactile.
  - *From Ancient Greek ἁπτικός (haptikos, "able to come in contact with"), ἅπτω (haptō, "I touch").*
- **Haptics**
  - (in medicine) The study of the sense of touch.
  - (in computing) The study of user interfaces that use the sense of touch.

A greater picture, a somatosensory system

Cutaneous
(in the skin)

- Temperature
- Texture
- Slip
- Vibration
- Force

Kinesthesia

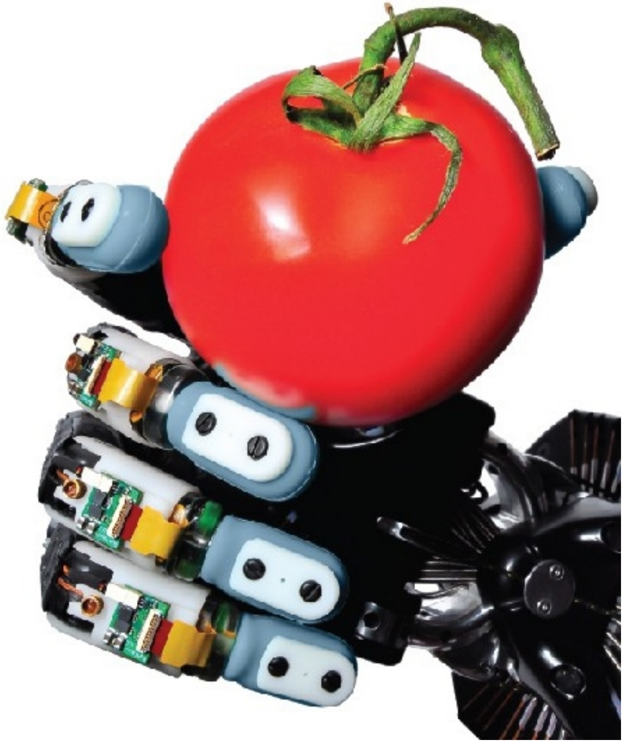
- Location
- Configuration
- Motion
- Force
- Compliance

Somatosensory system

- The touch impression uses several modalities.
- Somatosensory system comprising the receptors and processing centers to perceive touch, temperature, proprioception (body position from stimuli inside the body), and nociception (pain).
- Cutaneous sensations obtains inputs from the receptors embedded in the skin *(examples: temperature, pressure, pain)*.
- Kinesthetic sensations gets inputs from the receptors within muscles, tendons and joints *(examples: body position, movement, weight, equilibrium)*.

Towards robot tactile sensors

- Receptors in humans cover the skin and epithelia, skeletal muscles, bones and joints, internal organs, and the cardiovascular system.
- Tactile sensors in robotics ≈ cutaneous sensory receptors in humans.

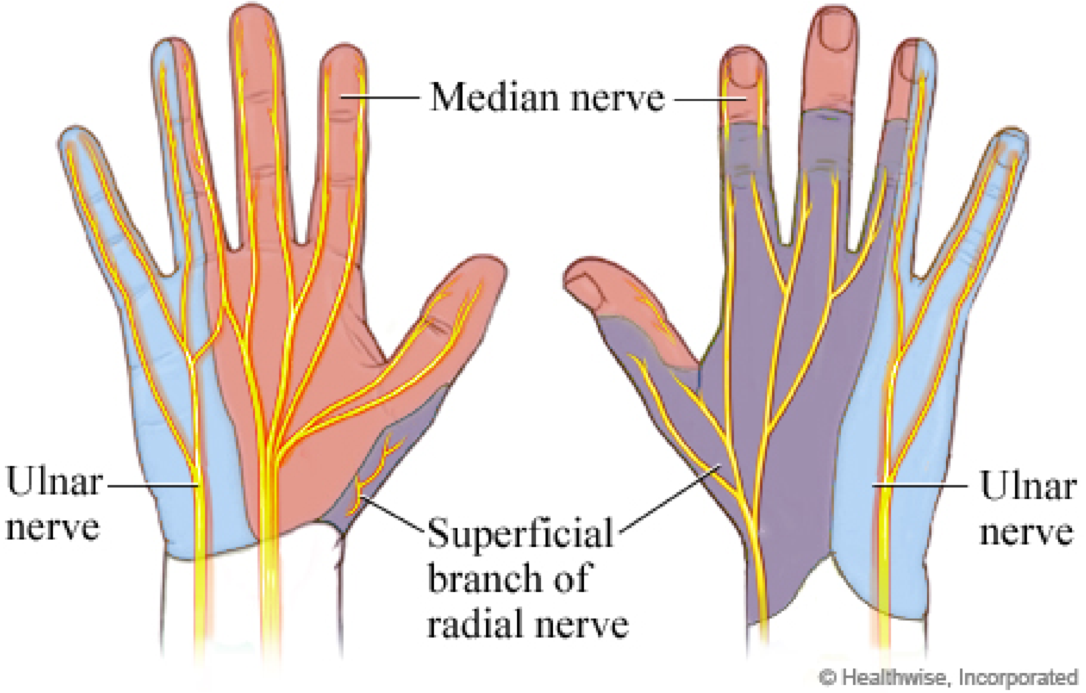


Human sensory physiology

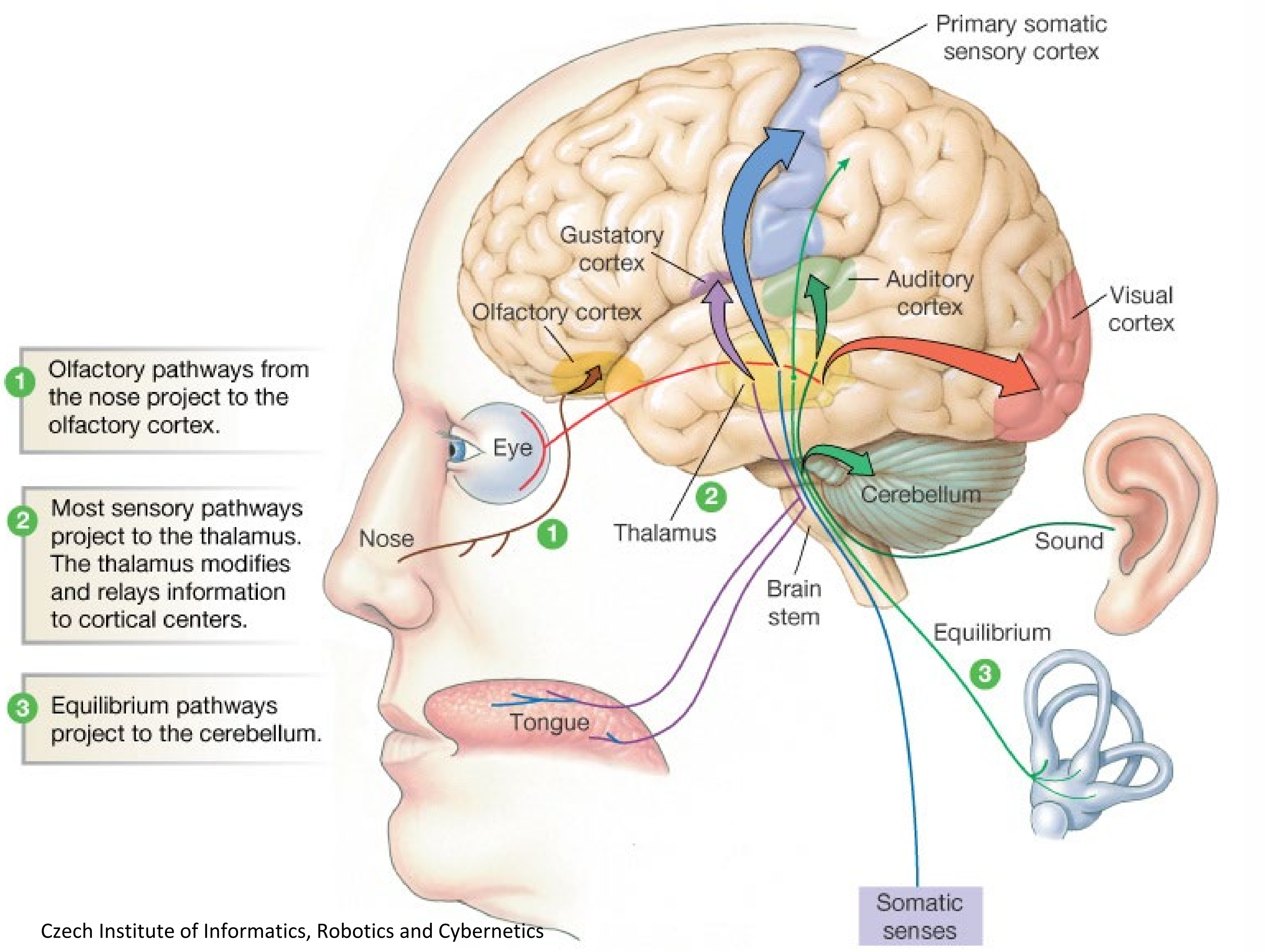
Stimulus → Receptors → Afferent pathway → CNS integration

Stimulus
- Internal
- External
- Energy source

Receptors
- Sense organs
- Transducers



External stimuli, special senses



Neurophysiological view

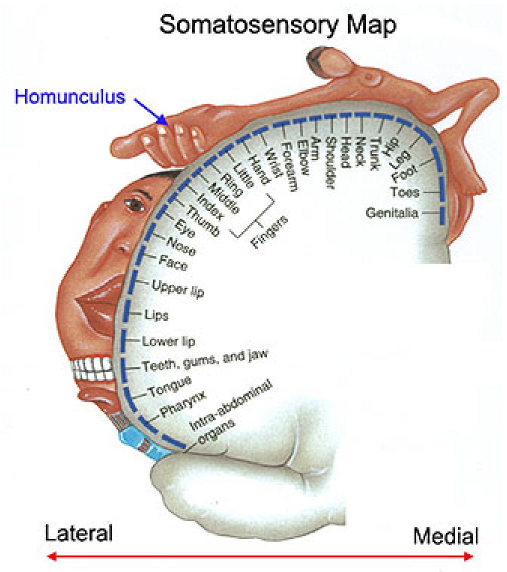
Somatosensory system

comprises of 3 parts:

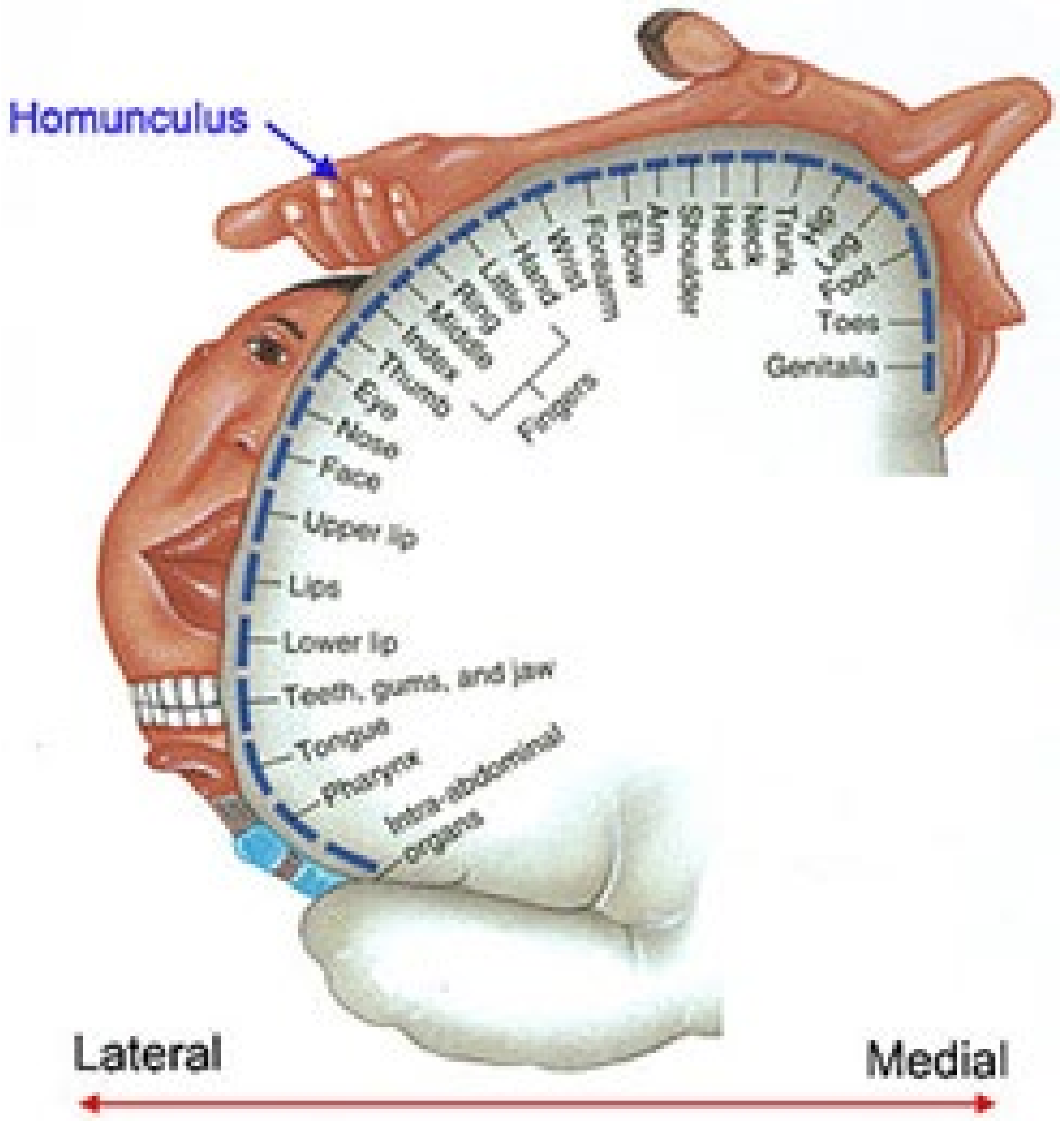
- Exteroceptive cutaneous system.
- Proprioception system (monitors body position).
- Interoceptive system (monitors conditions within the body as blood pressure).

Cortical homunculus

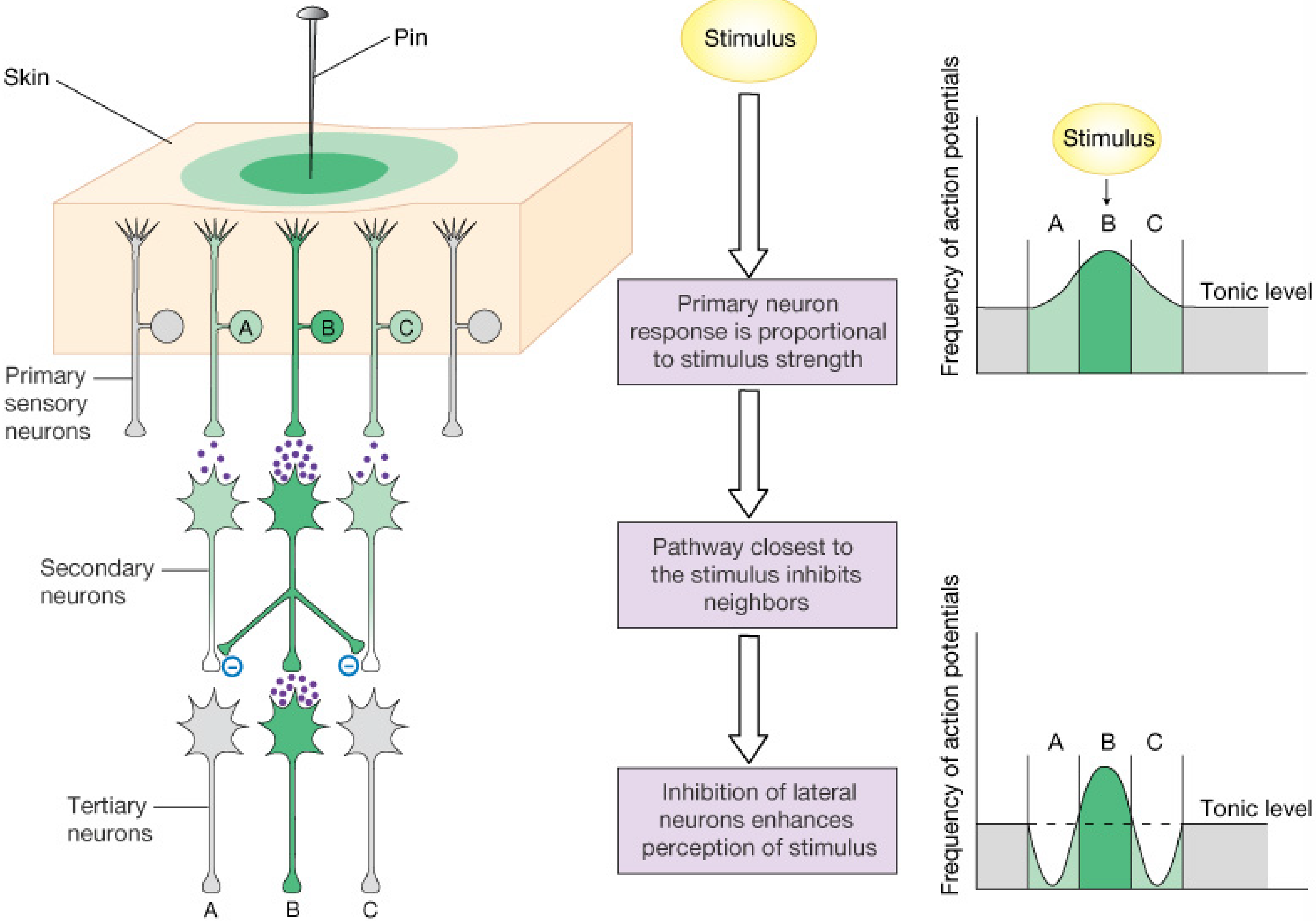
- Visualization of the point-to-point mapping between body surfaces (and function) to the brain surface.



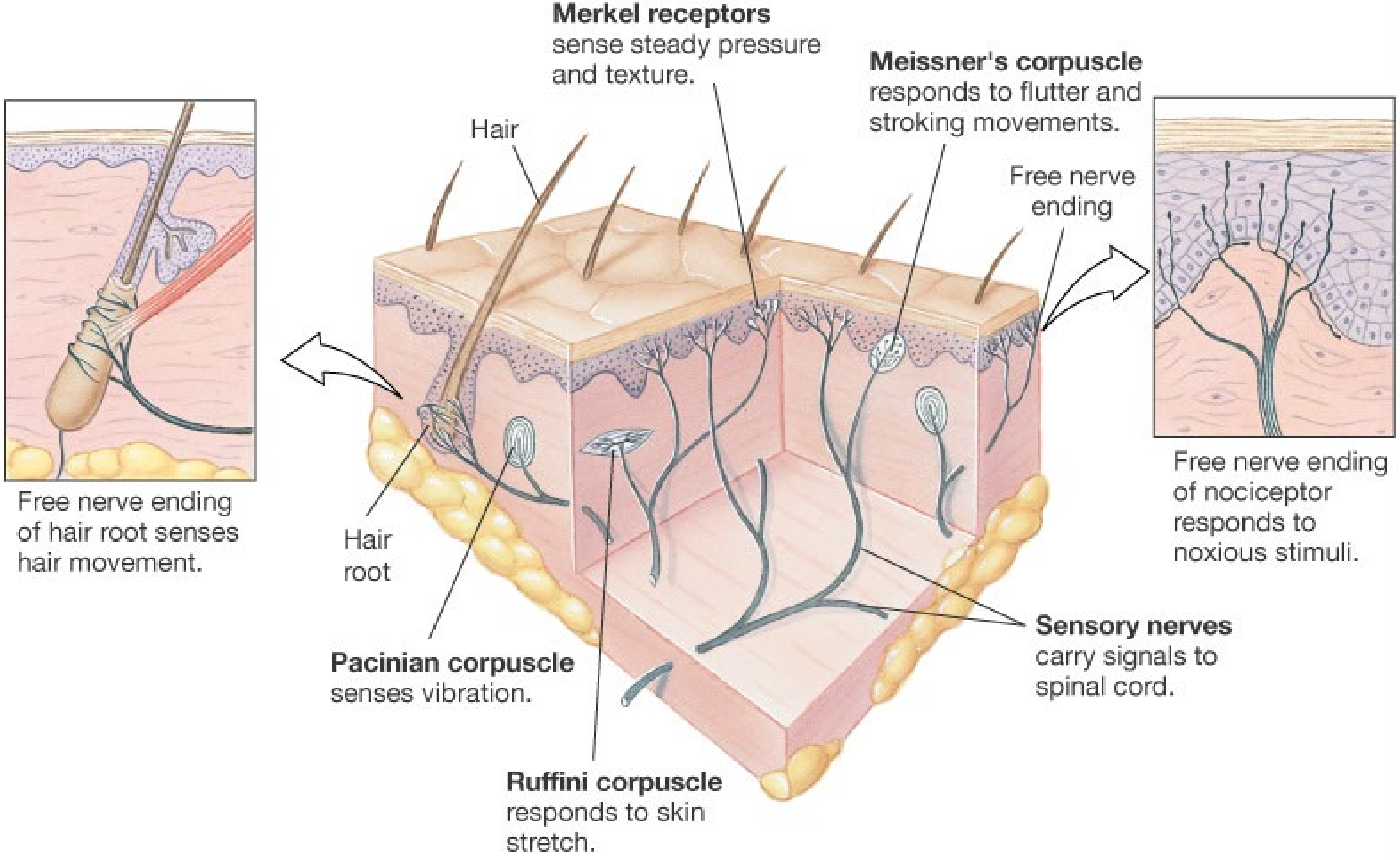
Somatosensory map



Sensory modality



Various receptors in the skin



Human touch signals

RECEPTOR TYPE	FIELD DIAMETER	FREQUENCY RANGE	POSTULATED SENSED PARAMETER
FAI	3—4 mm	10—60 Hz	Skin stretch
SAI	3—4 mm	DC—30 Hz	Compressive stress (curvature)
FAII	>20 mm	50—1000 Hz	Vibration
SAII	>10 mm	DC—15 Hz	Directional skin stretch

- FAI; Meissner corpuscules; Fast Adapting type I; Respond to skin deformation only.
- SAI; Merkel disc; Slow Adapting type I; dynamically sensitive and exhibit a response linked to the strength of maintained skin deformation.
- FAII; Pacini corpuscules; Fast Adapting type I; Respond to changes in skin deformation and vibrations.
- SAII; Ruffini receptors; Slow Adapting type II; Dynamically sensitive and exhibit a response linked to the strength of maintained skin deformation.

Touch reception in animals

- Touch reception (called also tangoreception) is a perception in an animal when in contact with a (solid) object.
- Two types of receptors are common:
  - Tactile hairs (in many animals from worms, birds to mammals). Some can be very specialized as, e.g., cat whiskers.
  - Subcutaneous receptors, which lie in "the skin".

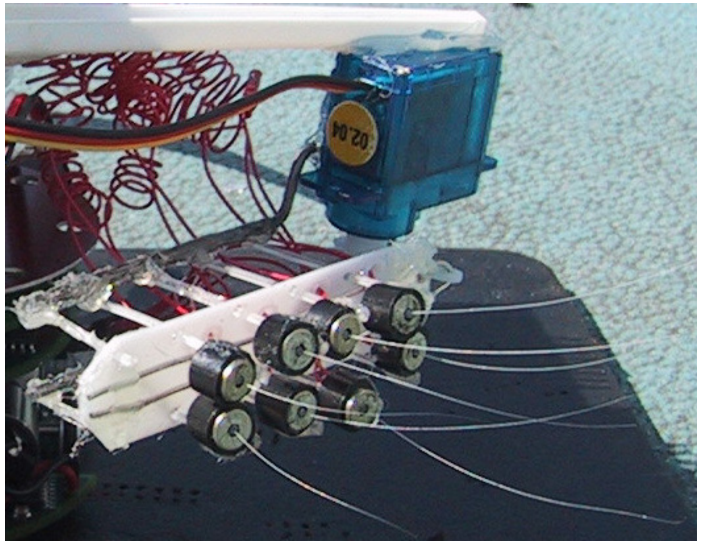
Whiskers

In the nature:

- comparable to finger tips
- motion detection of distant objects
- navigation in the dark
- rich shape and texture information
- neural processing model system for somatosensory processing

In robotics, so far:

- limited (binary, strain sensors, bending angles)



Tactile sensing vs. haptics *in robotics and/or computing*

Tactile sensing

- What is sensed?
  Deformation of bodies (strain).
- Through deformation measure change of parameters, and find:
  - Static texture, local compliance, or local shape.
  - Force (normal and/or shear) (*indirect*).
  - Pressure.
  - Slippage.

Haptics

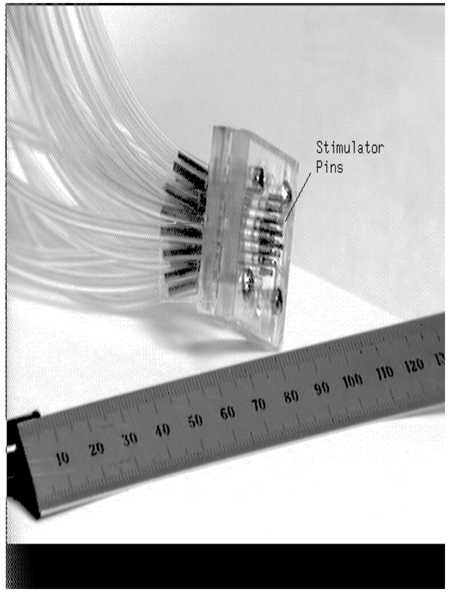
- Haptics explores human touch sense as a channel.
- The counterforce and its dynamics stimulates touch, compliance, vibrations, etc.
- ≈ 1 kHz loop needed.
- Two main devices:
  - Force feedback devices.
  - Haptic displays and rendering algorithms.

Haptics, ideas

- Haptics provides a human an additional communication channel to sight and sound in (computer) applications.
- Traditionally, the bidirectional communication is often secured by a keyboard and a mouse only.
- Haptics expands the bidirectional communi-cation by providing sensory feedback that simulates physical properties and force.
- Machine part of the haptic interface exerts forces to simulate contact with a virtual object.

Haptic devices

- Virtual reality / telerobotics:
  - Exoskeletons.
  - Gloves.
- Feedback devices:
  - Force feedback devices.
  - Tactile display devices.

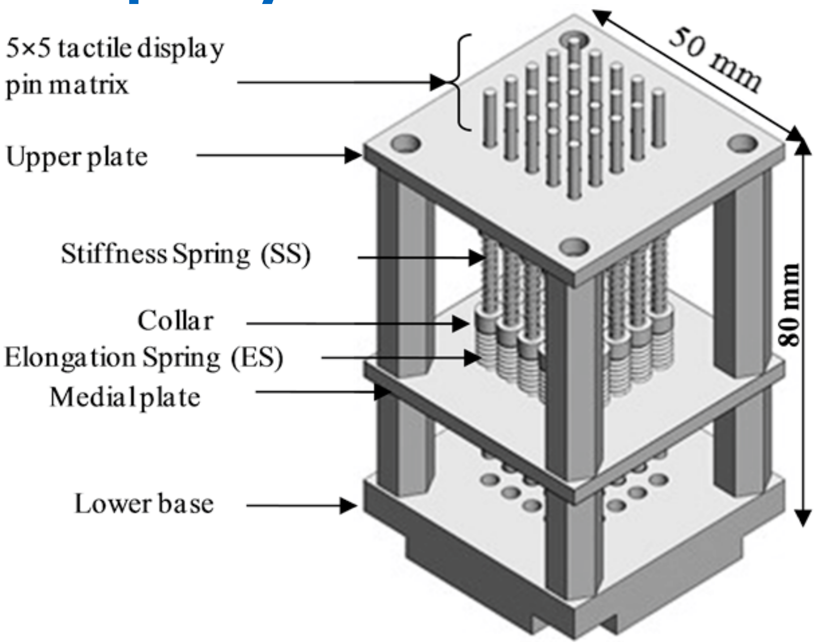


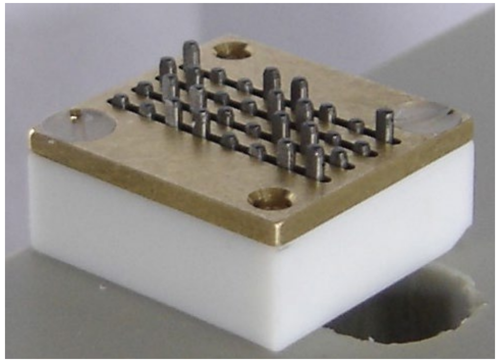
Haptics has many applications

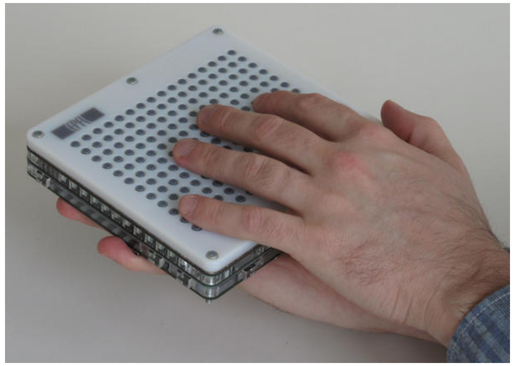
- Blind Persons
  - Programmable Braille
  - Access to GUIs
- Training
  - Medical Procedures
  - Astronauts
- Education
- Computer-Aided Design
  - Assembly-Disassembly
  - Human Factors
- Art / Animation / Modeling
- Entertainment
  - Arcade (steering wheels)
  - Home (game controllers)
- Automotive
  - BMW “iDrive”
  - Haptic Touchscreens
- Mobile Phones
  - Immersion “Vibetonz”
- Material Handling
  - Virtual Surfaces

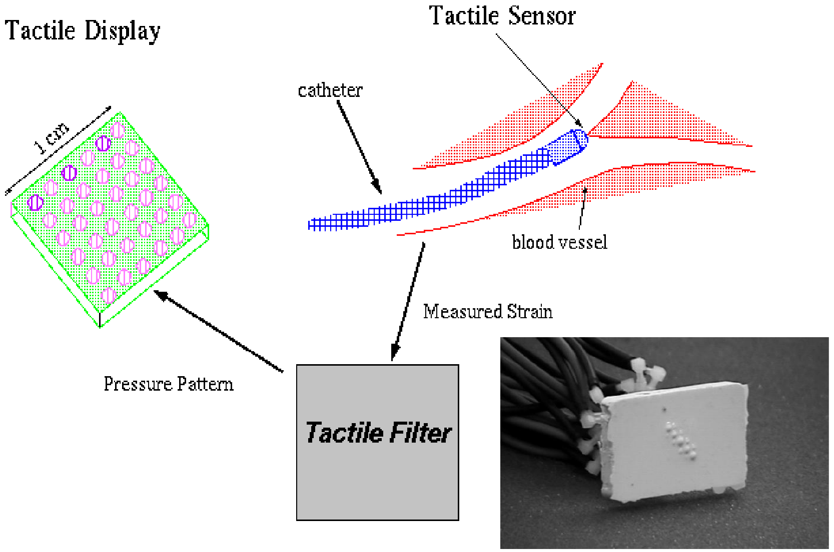
Pneumatic / magnetic tactile display

- The inverse problem:
  When the collected data is to be presented directly to human as touch, force feedback…
- UC Berkeley’s tactile display:
  - 5 x 5 array of pneumatic pins
  - 0.3 N per element, 3 dB point of 8 Hz, and 3 bits of force resolution



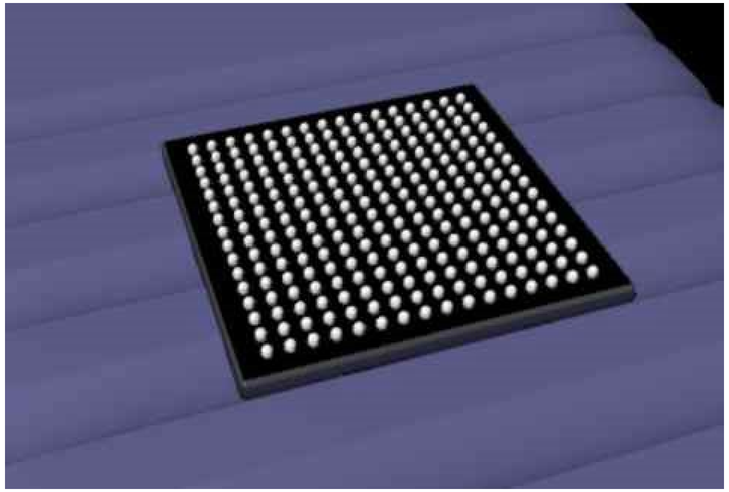


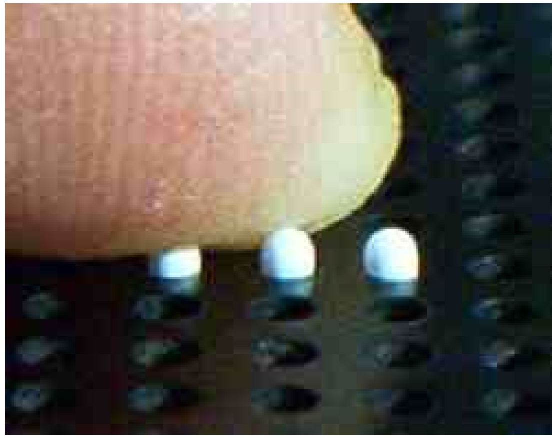




Piezoelectric display for the blind

- Display with 256 tactile dots on an area
  of 4 x 4 cm.
- Displays characters instead of Braille cells.
- Piezoelectric actuators.



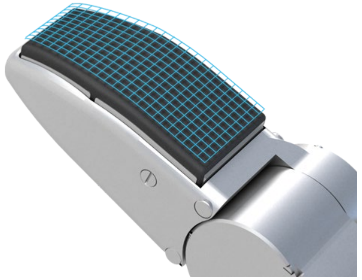


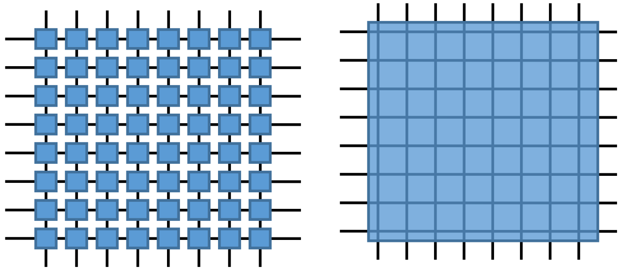
http://www.abtim.com/home__e_/home__e_.html

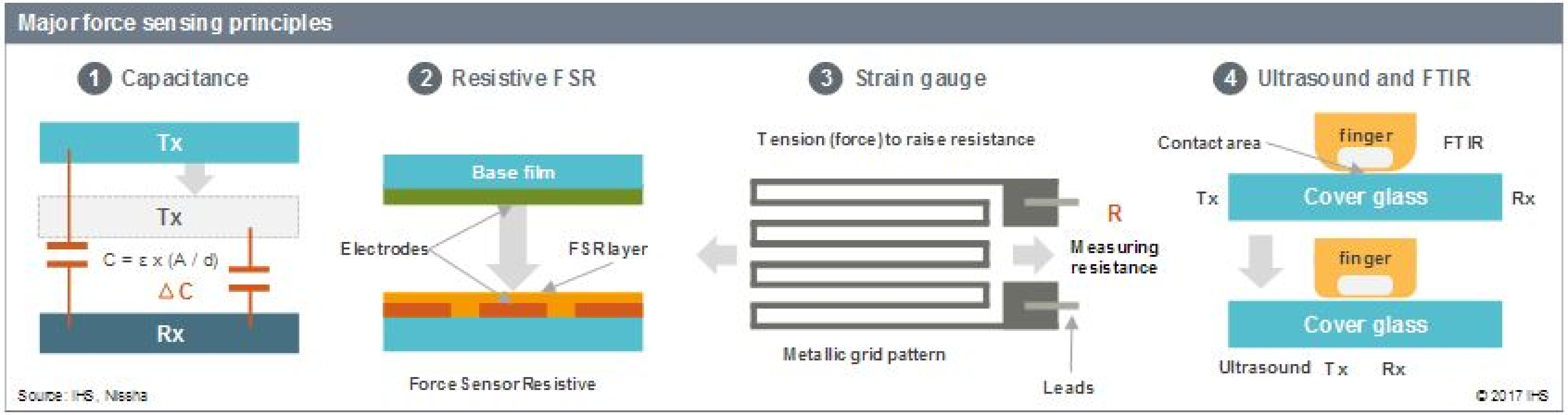
Principles of tactile sensors

- Mechanical – micro switch.
- Resistive – elastomer or foam.
- Capacitive.
- Magnetic (Hall effect).
- Piezoresistive, etc.

- Tactile element (tactel)
- A grid of tactels (tactile elements)

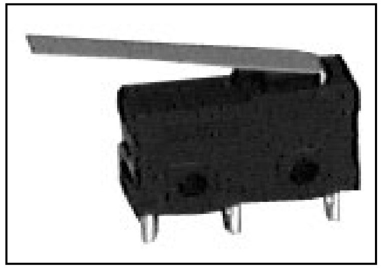


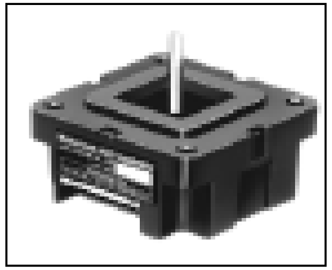


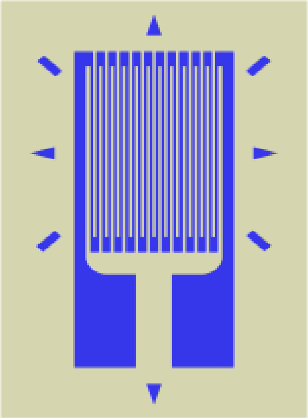


Mechanical sensor

- One-directional reed switch
- Omni-directional reed switch
- Roller contact switch
- Strain gauge (tensometer)
- Etc.

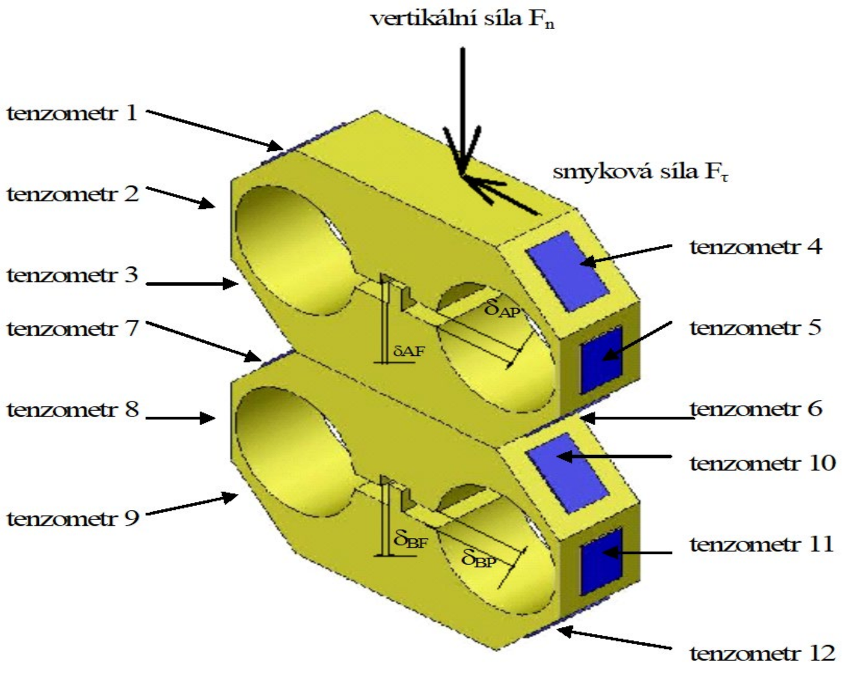


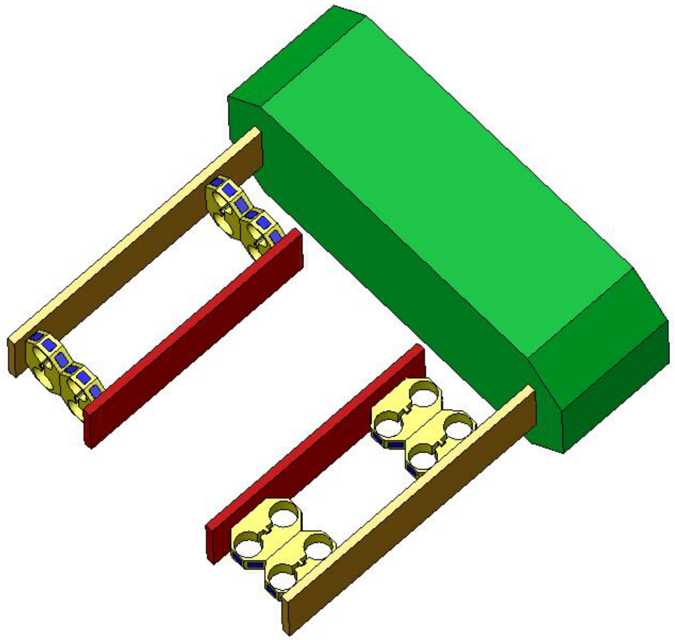




Strain gauge tactile sensor

- Measures also the shear force F_τ.
- Double Octagon Tactile Sensor (DOTS)

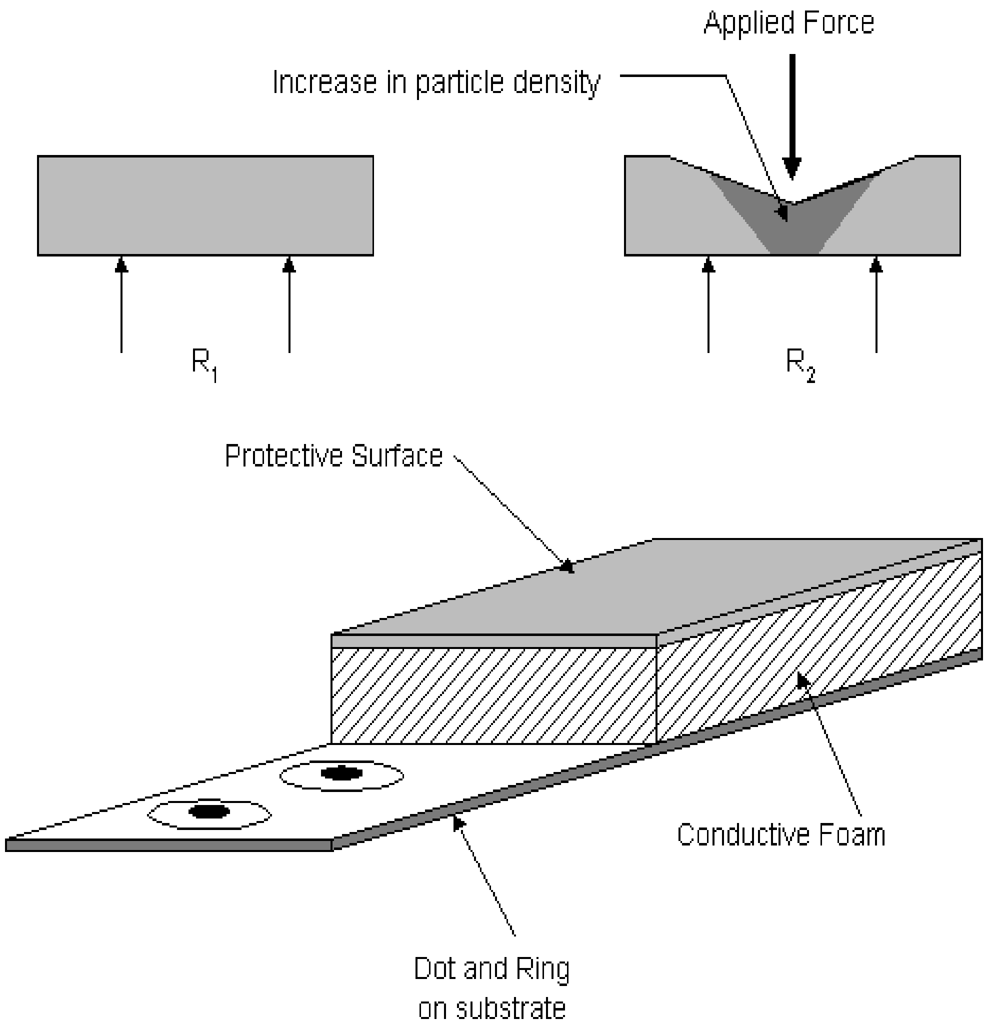




Application in a gripper

Resistive sensor

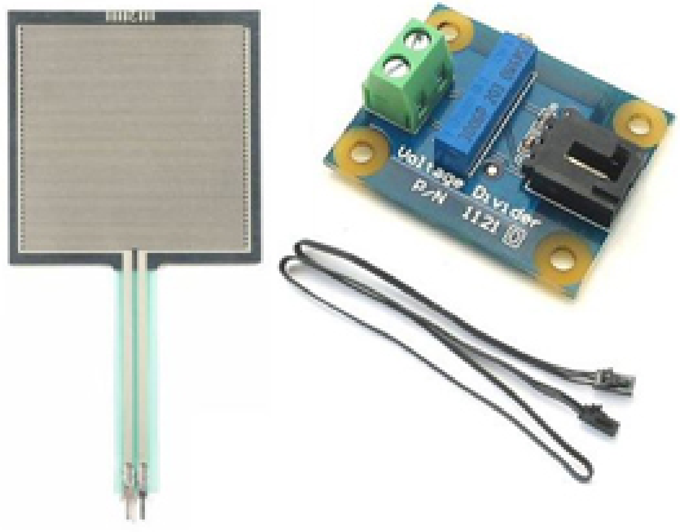
- The basic principle is the measurement of the resistance of a conductive elastomer or foam between two points.
- The majority of the sensors use an elastomer that consists of a carbon doped rubber.

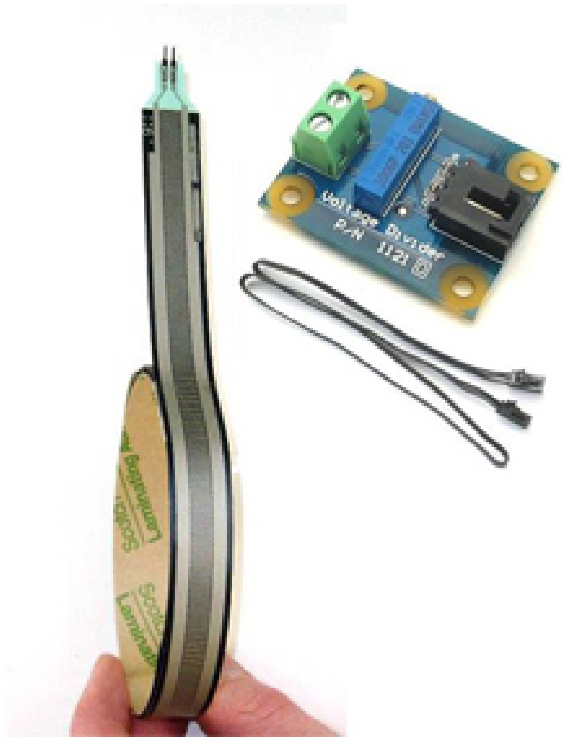


Disadvantages, resistive sensors

- An elastomer has a long nonlinear time constant, different for applying and releasing force.
- Highly nonlinear transfer function.
- Cyclic application of forces causes resistive medium migration within the elastomer in time.
- If the elastomer becomes permanently deformed then a fatigue leading to sensor malfunction.
- This will give the sensor a poor long-term stability and will require its replacement after an extended period of use.

Common package and pricing

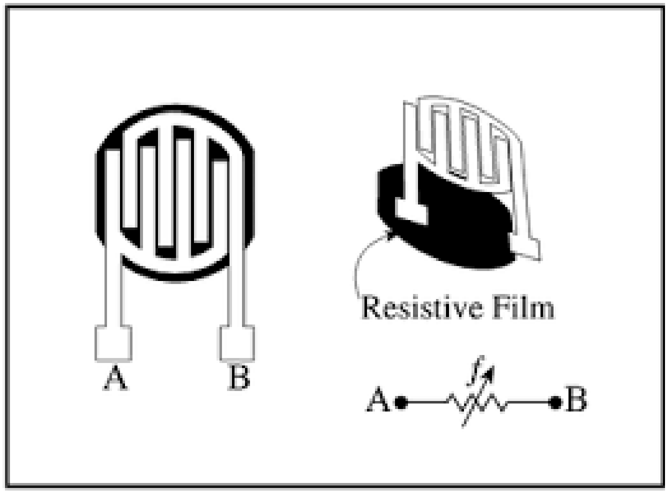


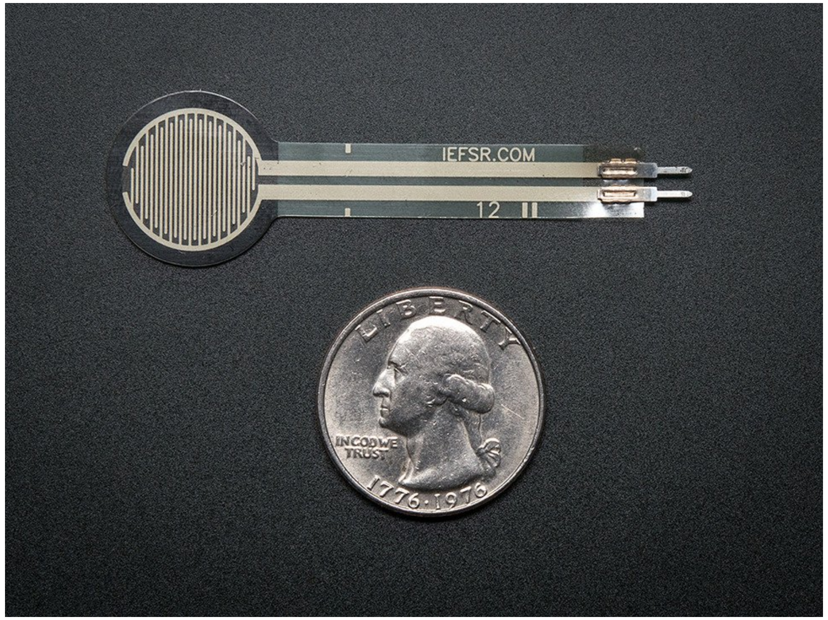


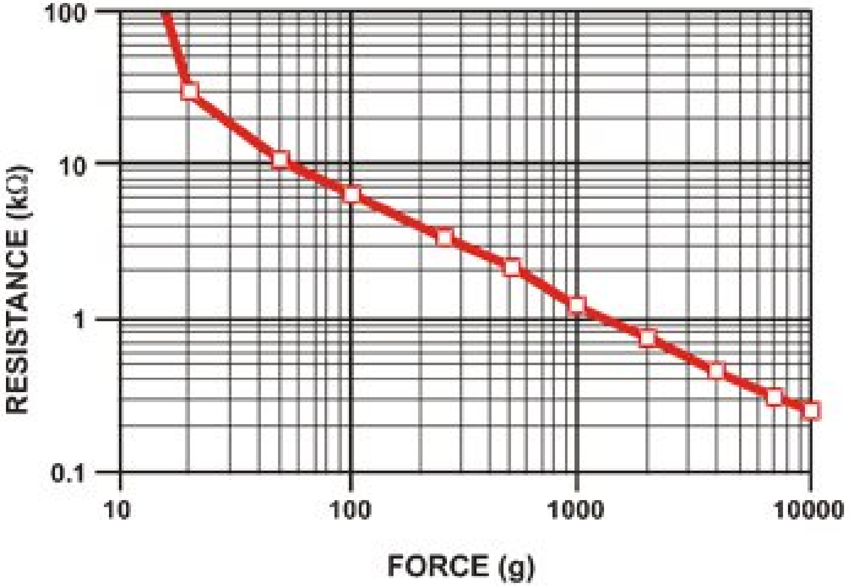
Price ranges from a few dollars to a few tens of dollars.

Force-Sensitive-Resistor sensor

- FSR = Force-Sensitive-Resistor
- Used also for touch keyboards.

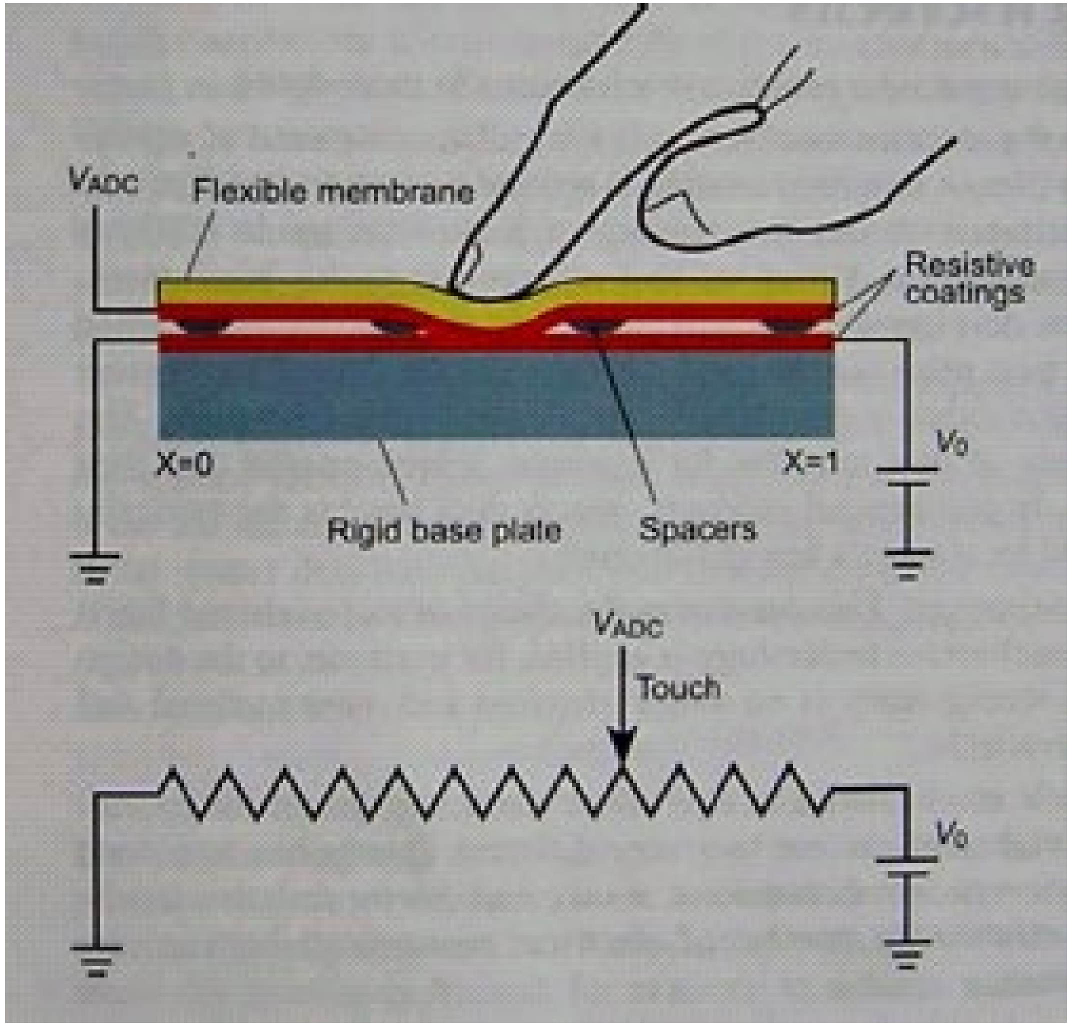






Resistive touchscreen

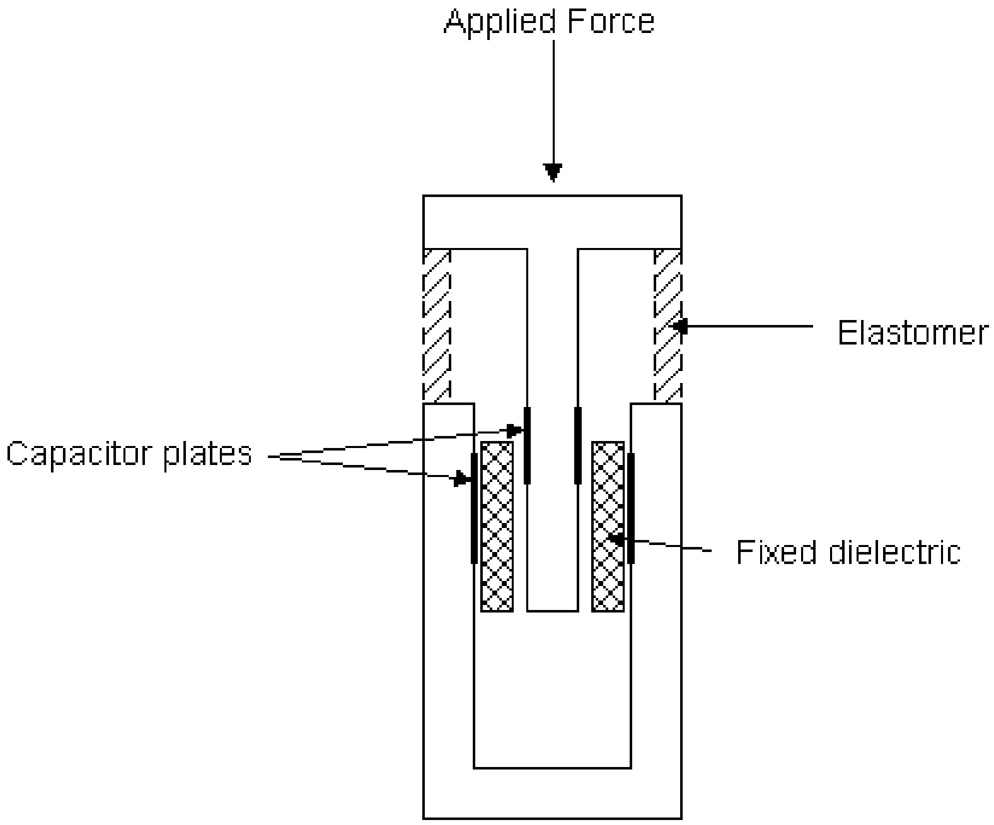
- Two flexible resistive layers are separated by a grid of spacers.
- When the two layers are pressed together the resistance can be measured between several points.
- This determines where the two resistive layers contacted.



Capacitive force sensor (1)

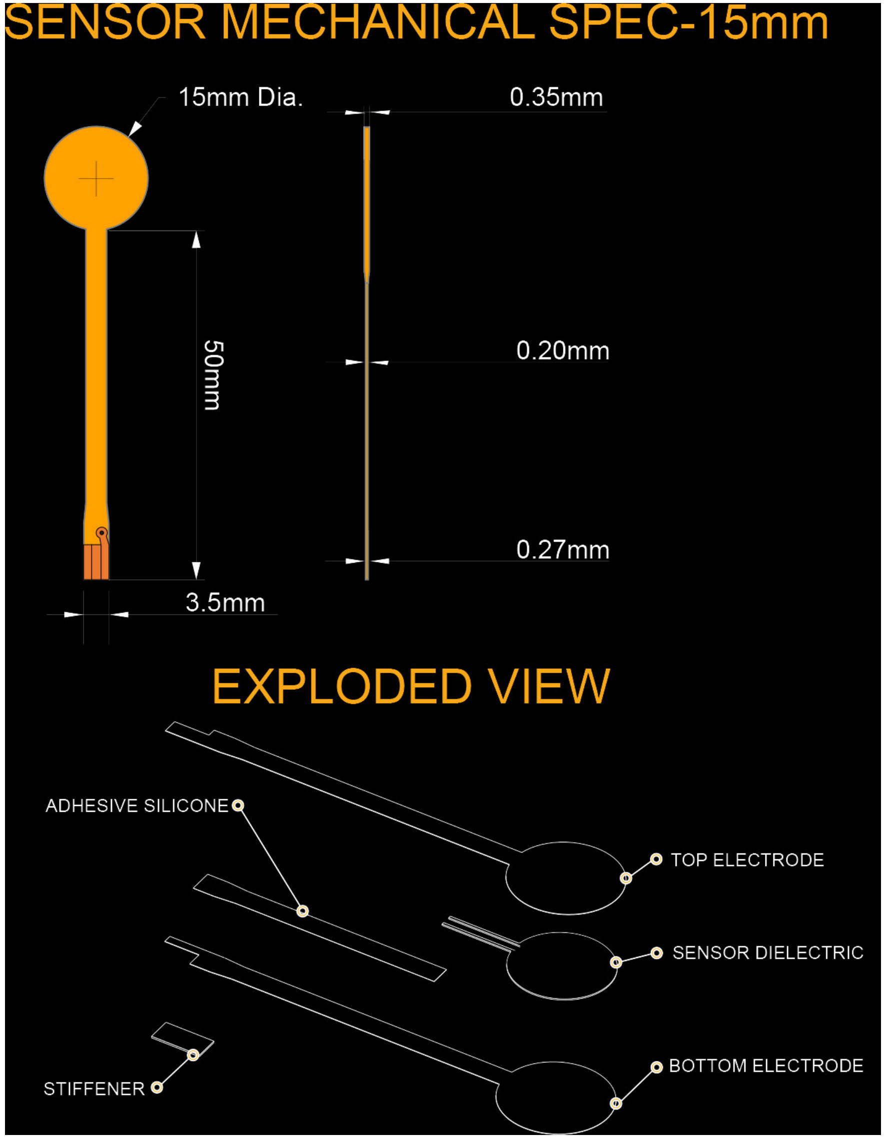
Capacitance between two parallel plates $C = \frac{\varepsilon\, A}{d}$, where

- ε is the permittivity of the dielectric medium,
- A is the plate area,
- d is the distance between plates,
- The elastomer gives force-to-capacitance characteristic.



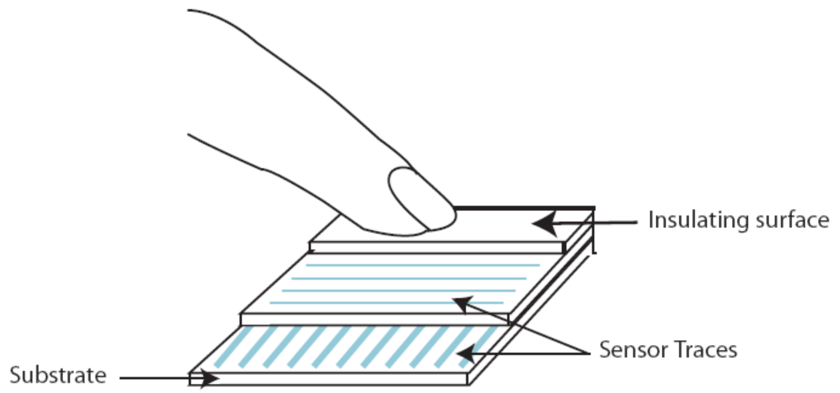
Capacitive force sensor (2)

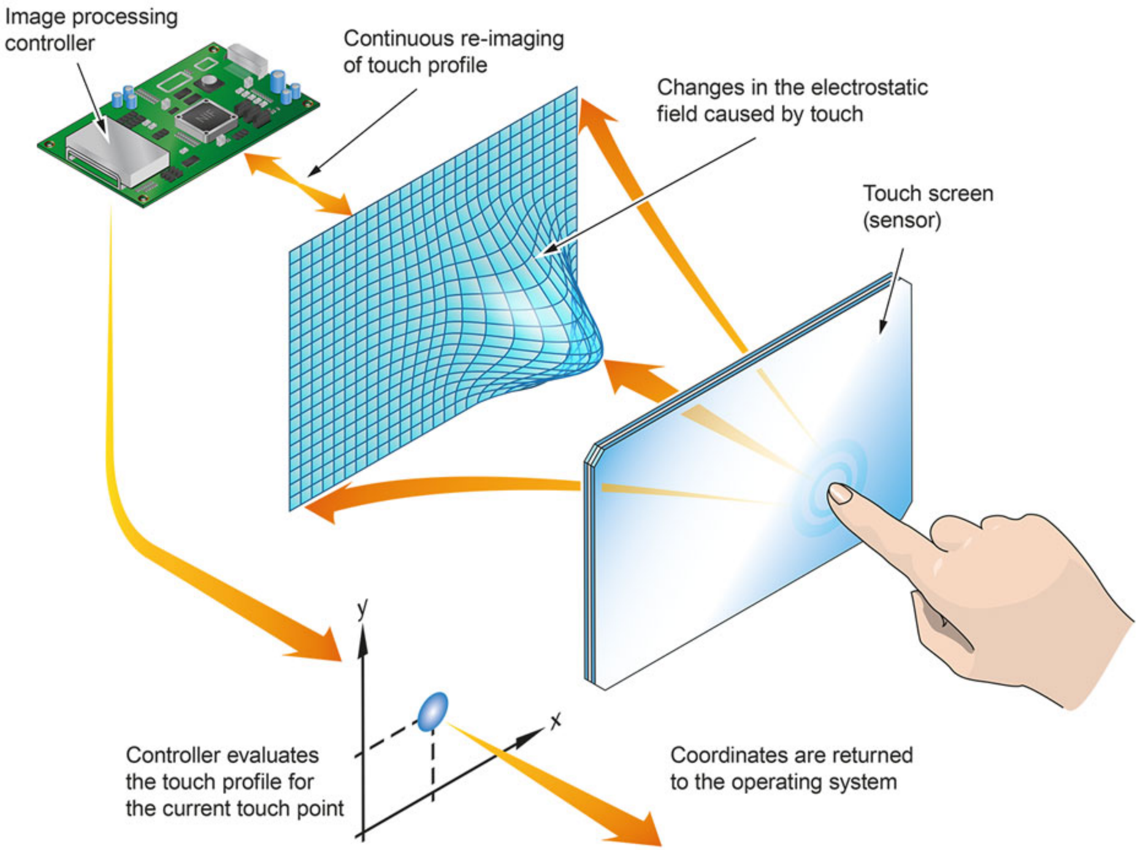
- As the size is reduced to increase the spatial resolution, the sensor's absolute capacitance will decrease.
- To maximize the change in capacitance as force is applied, it is preferable to use a high permittivity, dielectric in a coaxial capacitor design.
- The use of a highly dielectric polymer such as poly vinylidene fluoride maximizes the change capacitance.



Capacitive touchscreen

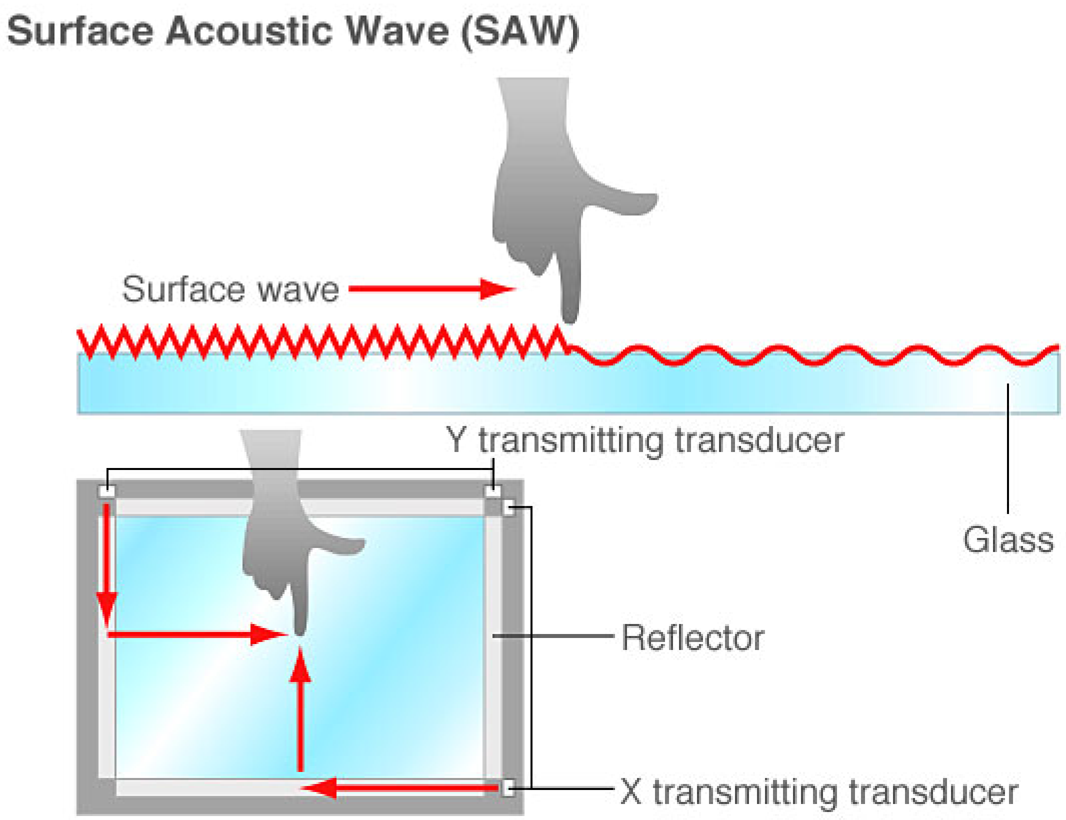
- A conductive layer is covered with a dielectric layer.
- The finger = the other plate of the capacitor.
- A few kHz signal is transmitted through the conductive plate, the dielectric, and the finger to ground.
- The current from each corner is measured to determine the touch location.





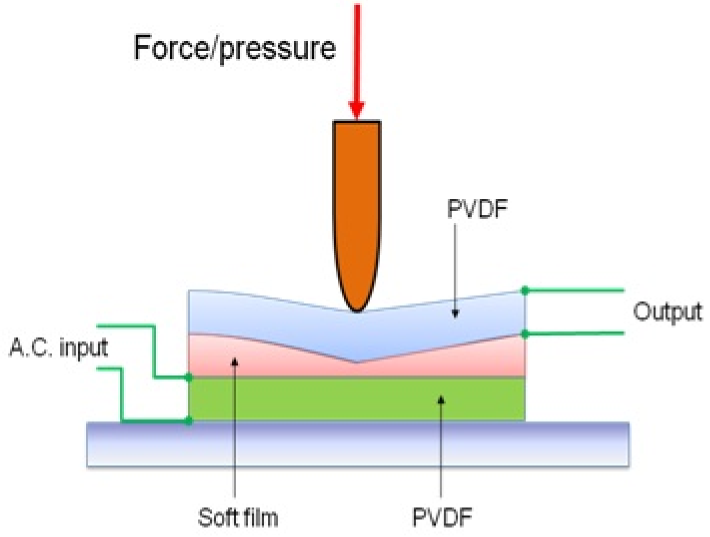
Ultrasound touch panel/screen

- Ultrasonic sound waves (>40 kHz) are transmitted in both the horizontal and vertical directions.
- When a finger touches the screen, the waves are damped.
- Receivers on the other side detect, where the sound was damped.
- Multiple touch locations are possible.



Piezoelectric sensor

- Principle: measures voltage created due to polarization under stress.
- Polymeric materials that exhibit piezoelectric properties such as polyvinylidene fluoride (PVDF) are used. A thin layer of metallization is applied to both sides of the sheet to collect the charge and permit electrical connections to be made.



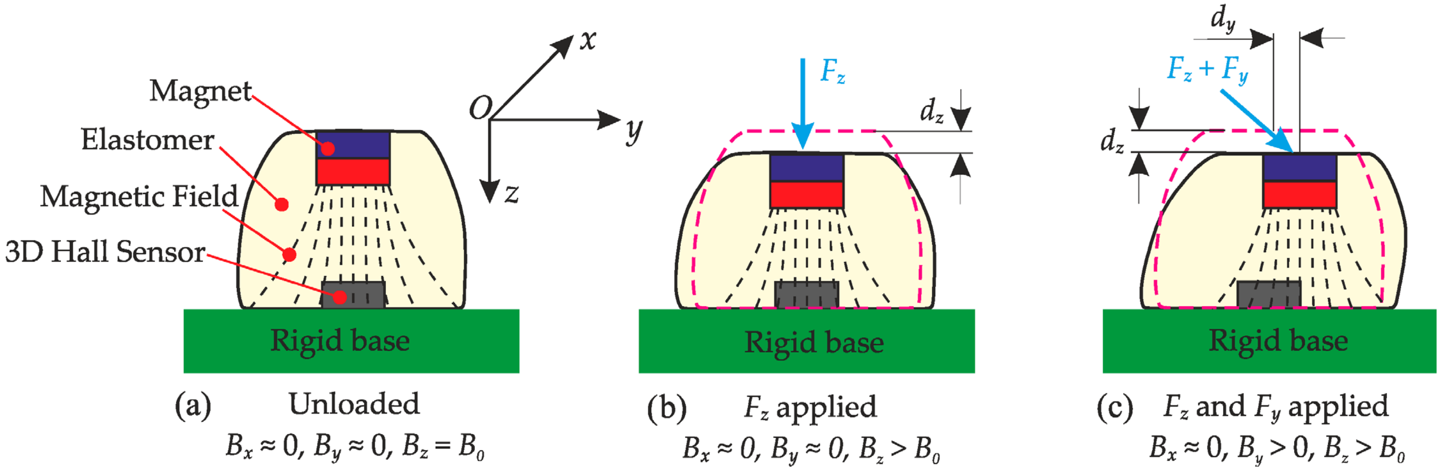
- Alternating current applied do lower PVDF layer (green) generates vibrations due to reverse piezoelectric effect. Soft film (pink) transmits vibrations. Force changes the output voltage.

Magnetic sensor

Two approaches:

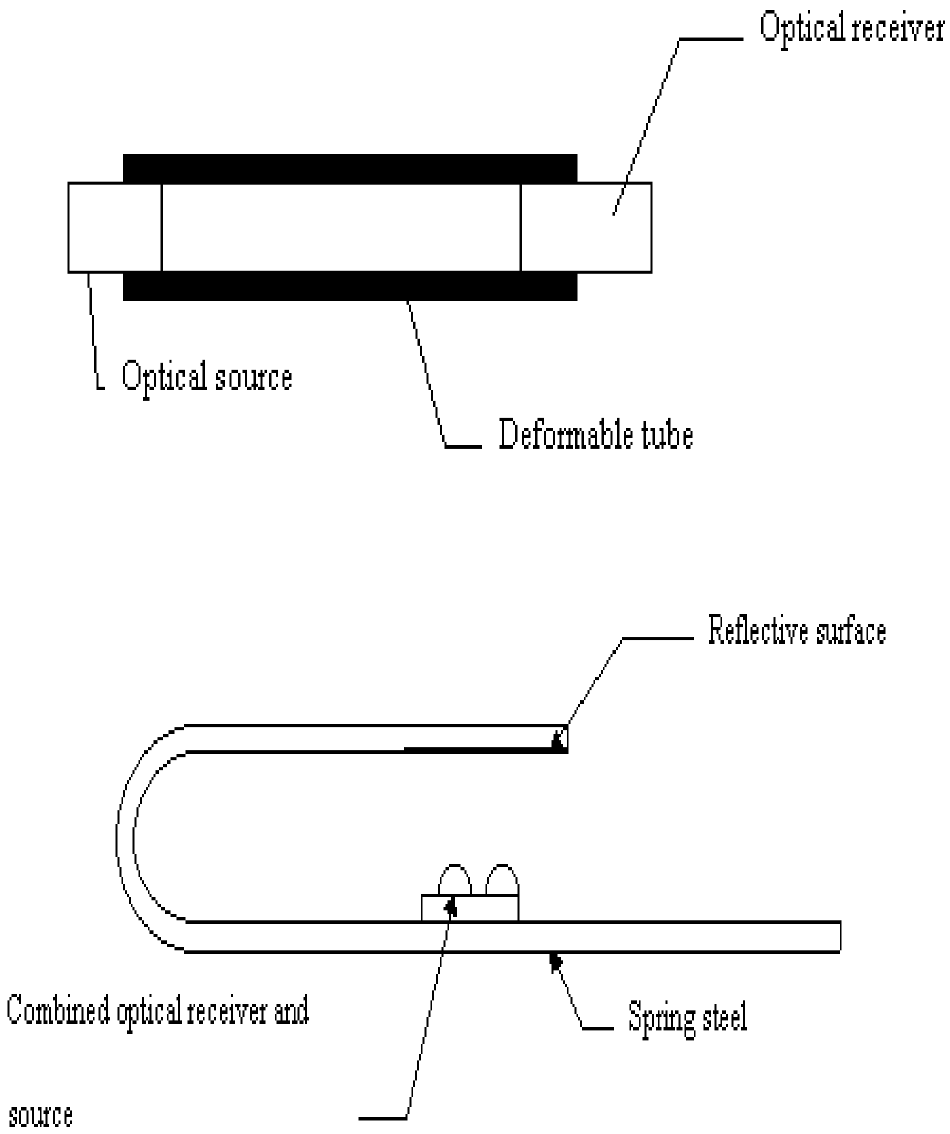
1. Movement of as small magnet due to applied force. Magnetic flux change is detected by Hall effect probe or a magnetoresistive probe.
2. Core of a coil (or transformer) from magnetoelastic material. Under pressure, the inductance change.

Reminder:
***Hall effect** is the development of a transverse electric field in a solid material when it carries an electric current and is placed in a magnetic field that is perpendicular to the current.*



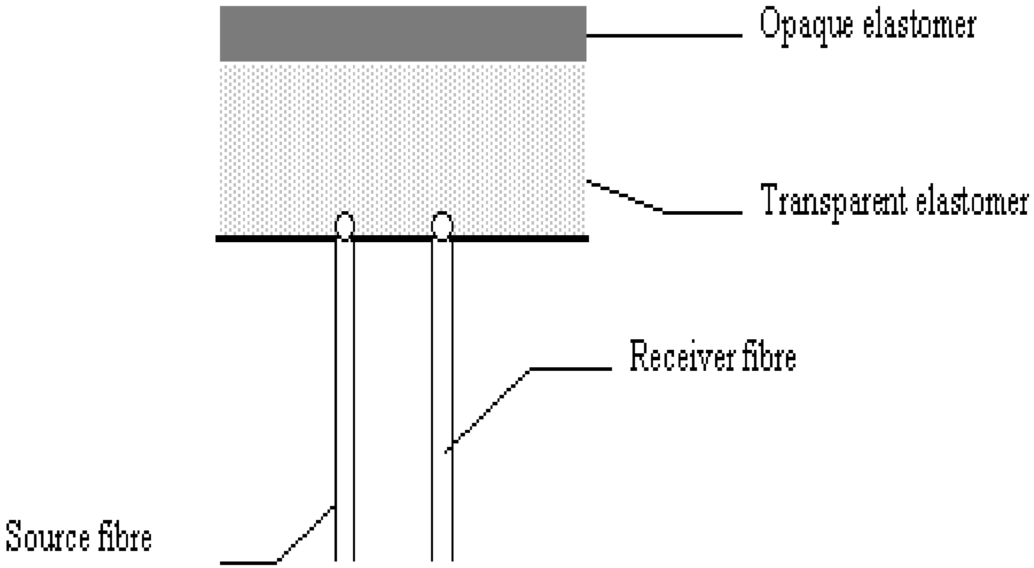
Optical sensor (1)

- The transmission or reflection is damped by the deformation due to applied force, which obstructs the light path.
- Top: deformable tube from elastomer.
- Bottom: U shaped steel spring.



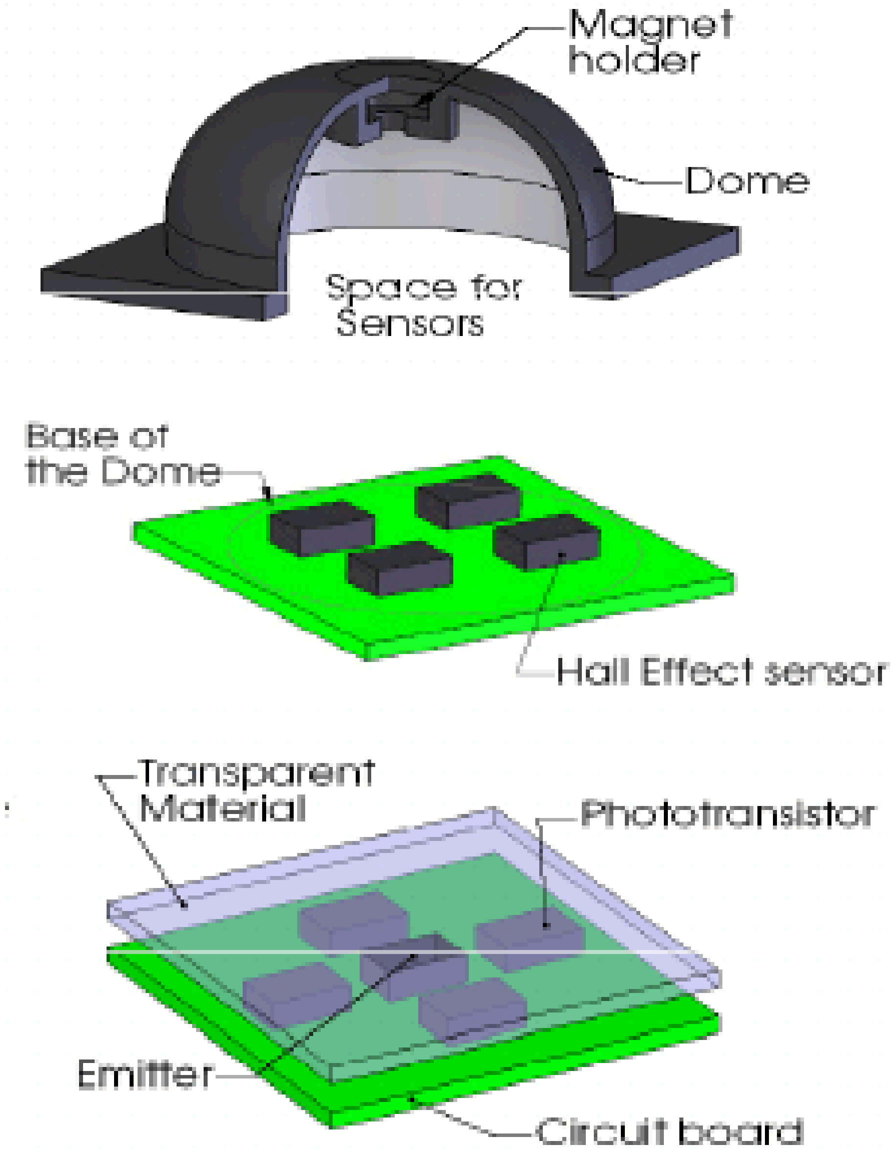
Optical sensor (2)

- A reflective sensors can be constructed with source-receiver fiber pairs embedded in an solid elastomer structure.
- The amount of light reflected to the receiver is determined by applied force, that changes the thickness of the clear elastomer.



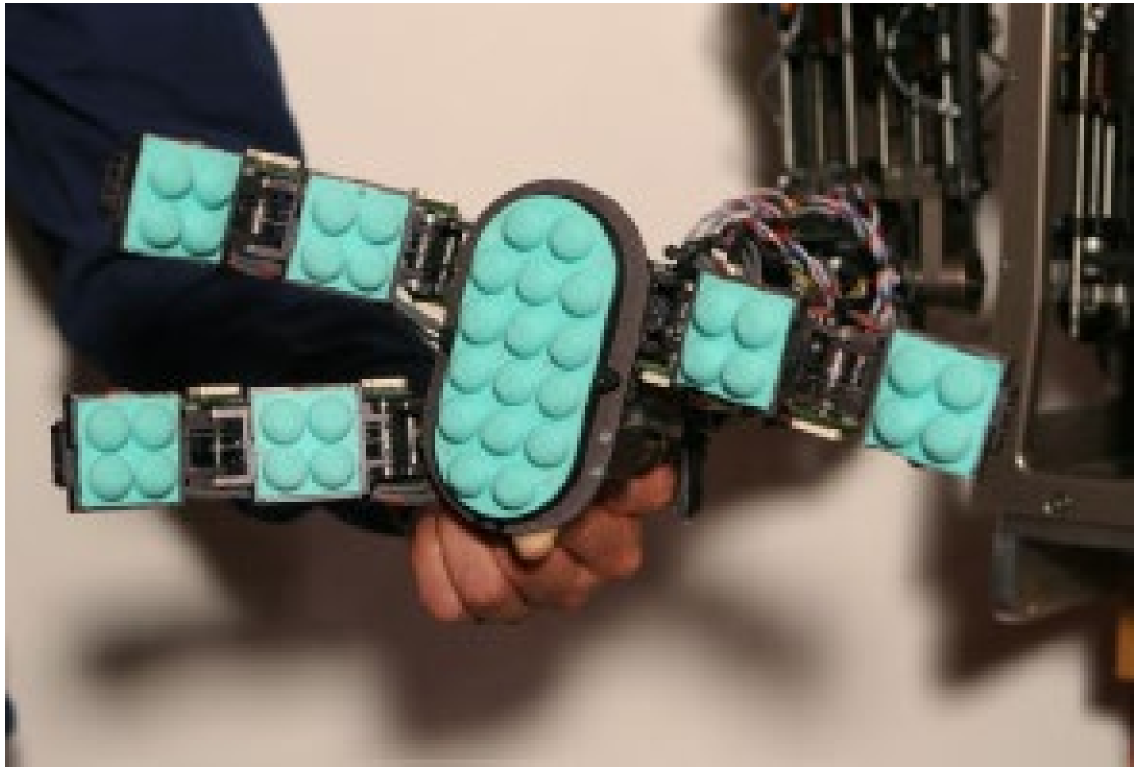
Skin sensor, magnetic or optical

- Position of the top of the sensor gives an estimation of the force applied.
- Magnetic version: magnet on the dome, four Hall effect sensors on the base.
- Optical version: A LED and four photo receptors on the base.



Skin sensor in the gripper

- Six tactile sensors on the fingers and thumb.
- A tactile sensor has four domes with four hall effect sensors in each dome.
- Palm: 16 domes, each with four hall effect sensors.



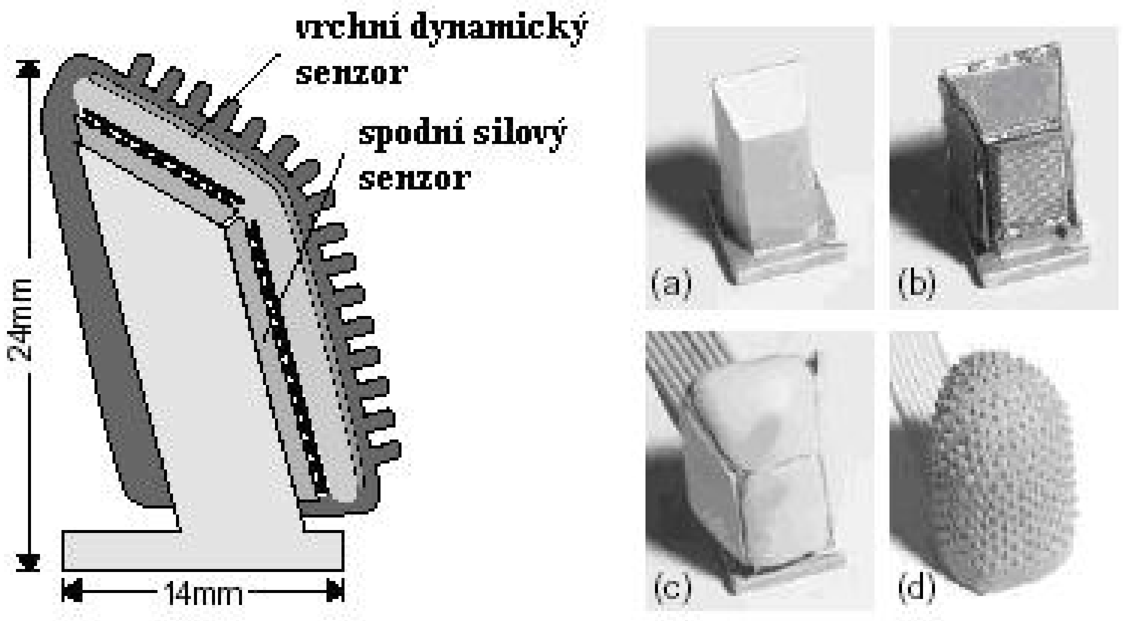
Tactile sensors, a comparison (1)

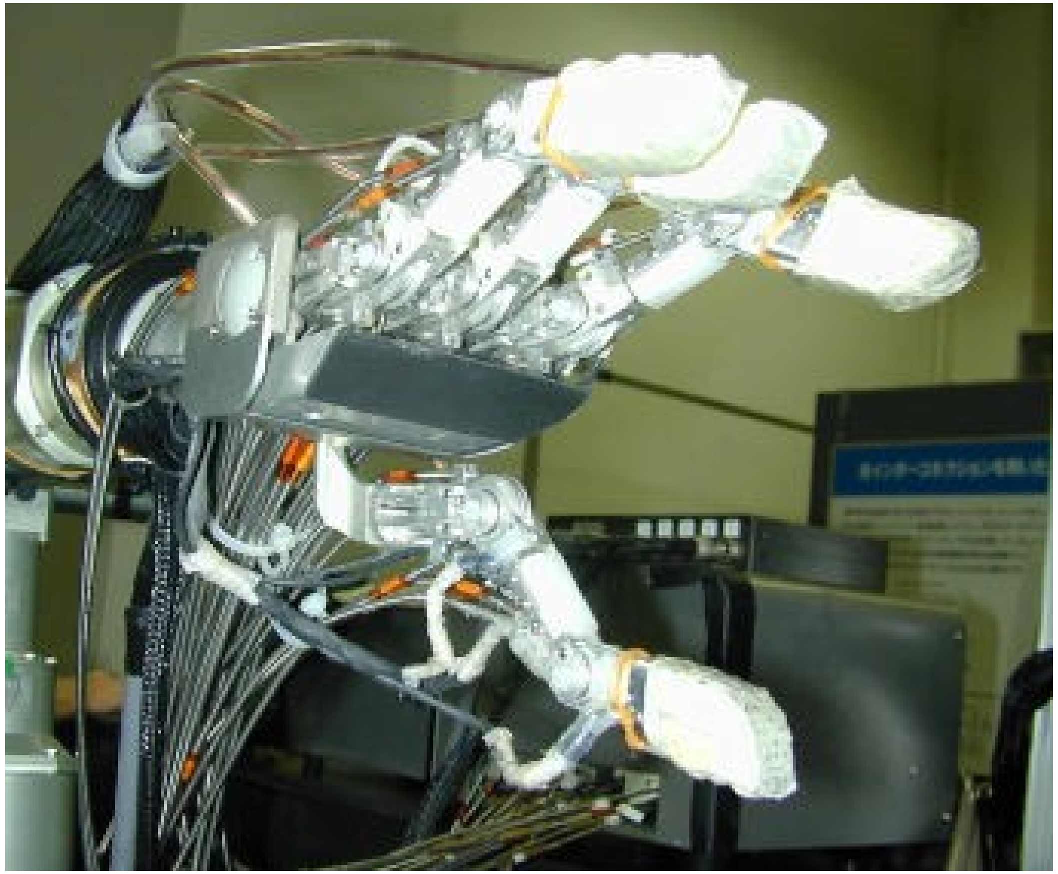
Type	Pros	Cons
Resistive	Sensitive; low cost	High power consumption; single detect contact point; does not measure a contact force
Conductive rubber	Mechanically flexible	Hysteresis, non-linear response
Piezoresistive	Low cost; good sensitivity; low noise; simple electronics	Stiff and frail; non-linear response; hysteresis; temperature sensitive; signal drift
Tunnel effect	Sensitive; mechanically flexible;	Non-linear response
Capacitive	Sensitive; low cost; available commercial A/D chips	Cross talk; hysteresis; complex electronics

Tactile sensors, a comparison (2)

Type	Pros	Cons
Optical	Immune to electromagnetic interference; sensitive; fast; mechanically flexible	Bulky; loss of light by microbending; chirping; complex computation; high power consumption
Magnetic	High sensitivity; good dynamic range; no hysteresis; mechanical robustness;	Suffer from magnetic interference; bulky; complex computation; high power consumption
Piezoelectric	Dynamic response; high bandwidth	Temperature sensitive; not so robust electrical connection
Ultrasonic	Fast dynamic response; good force resolution	Temperature sensitive; limited utility at low frequencies; complex electronics

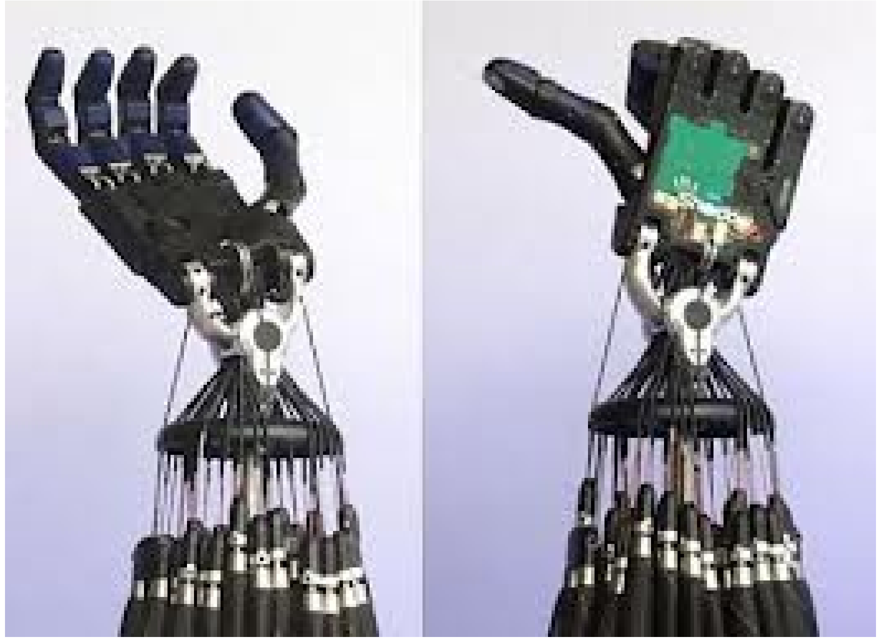
Two layers sensor

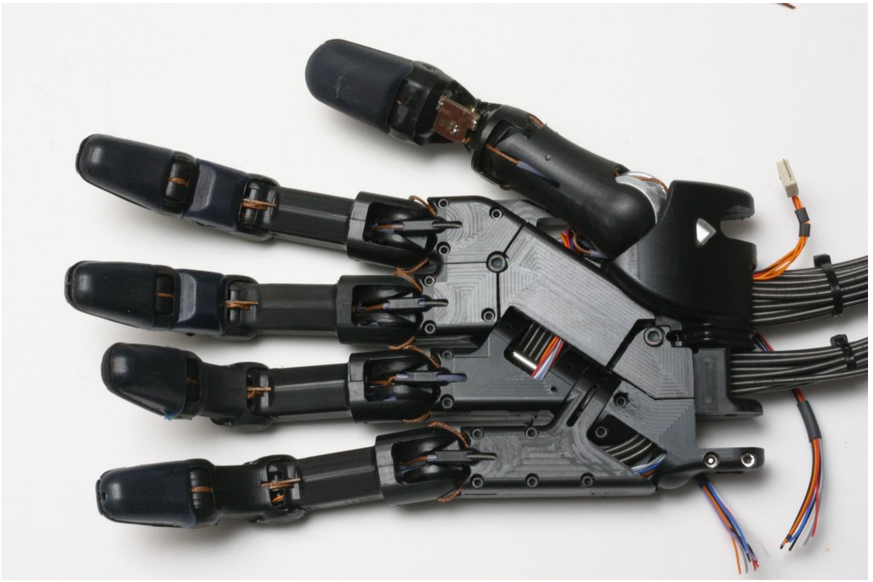




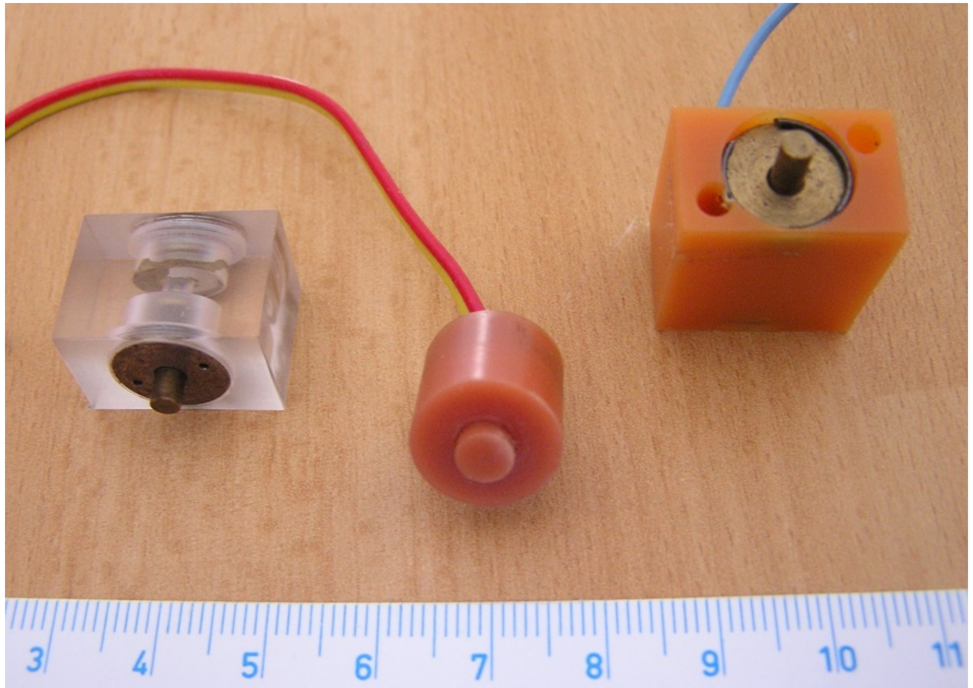
Shadow hand, a top level model

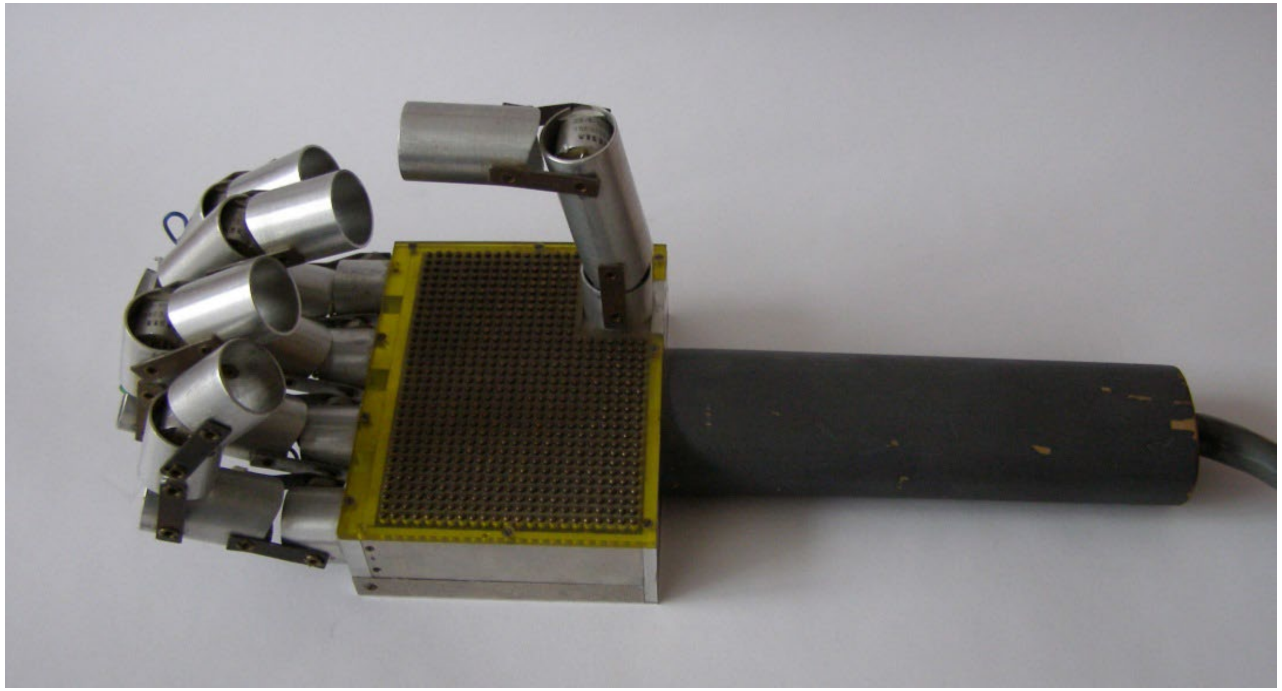
- Shadow Dexterous Hand
- Shadow Robot Company, London, http://www.shadowrobot.com
- Actuation:
  - Pressurized air muscle
  - or Electric motor driven
- Hall effect sensors from Syntouch LLC
- ROS compatible
- Price ≈ USD 100k





Resistive sensors, Jaromír Volf

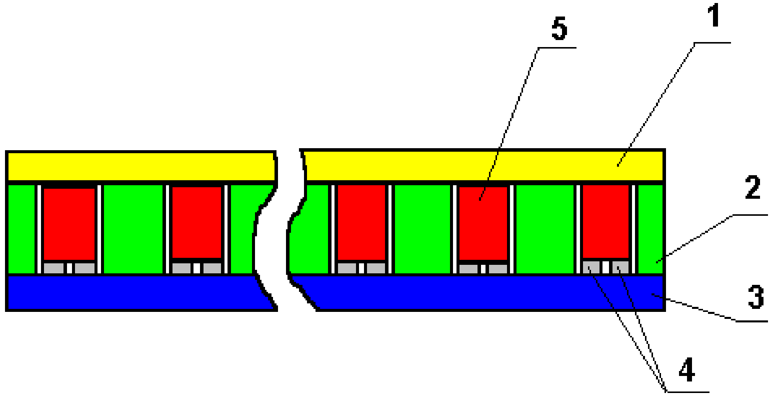




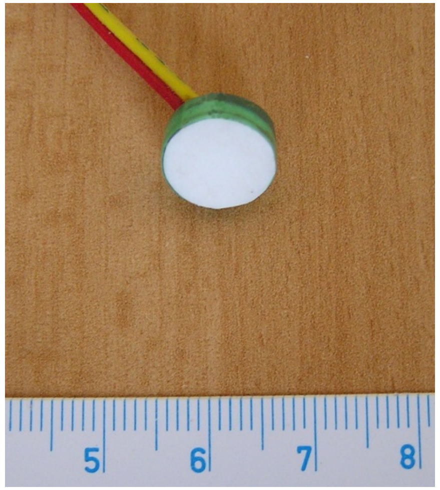
≈ 1981

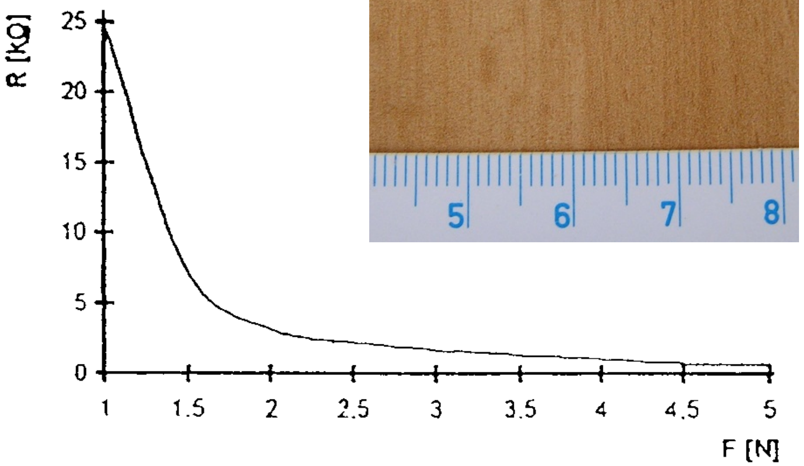
Resistive sensor PTM 1.3

- Jaromír Volf, Faculty of Mechanical Engineering CTU in Prague.
- Layout
    1. Cover layer.
    2. Distance insert.
    3. Base plate.
    4. Electrodes.
    5. Conductive elastomer.



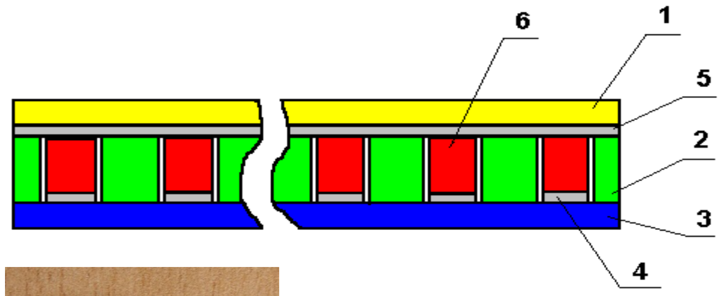
Tactile sensor PTM 1.3

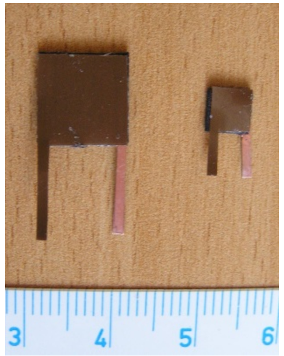


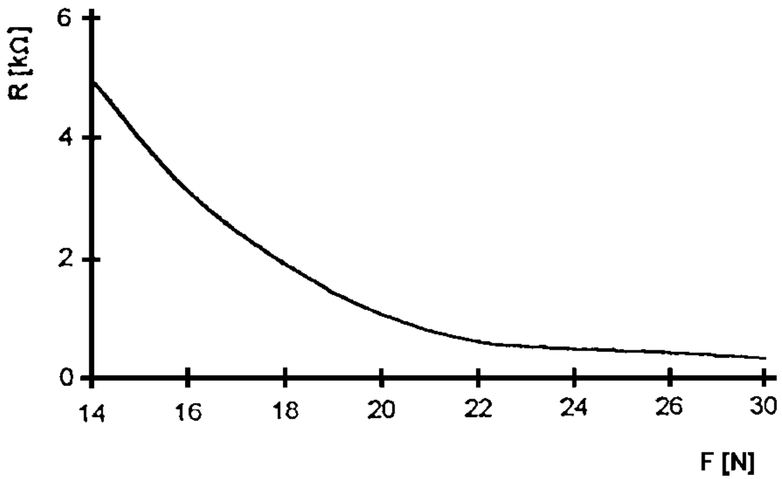


Resistive sensor PTM 1.4

- Jaromír Volf, Faculty of Mechanical Engineering CTU in Prague.
- Layout
  1. Cover layer.
  2. Distance insert.
  3. Base plate.
  4. Electrodes.
  5. Electrode.
  6. Conductive elastomer.





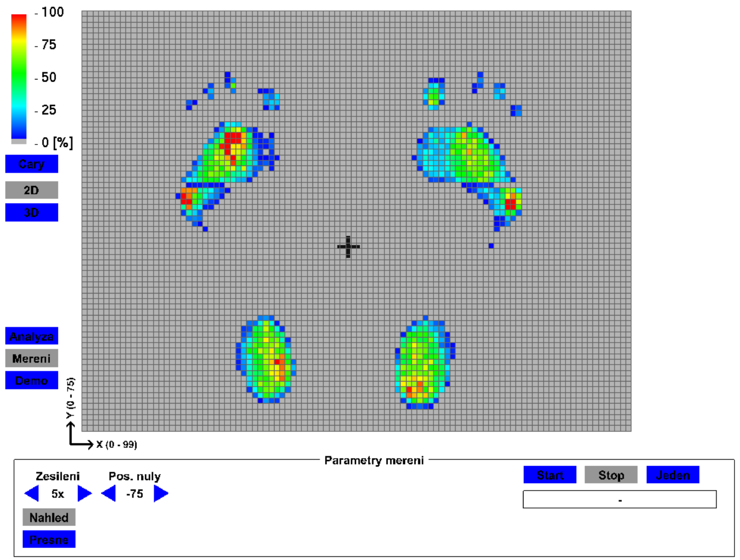


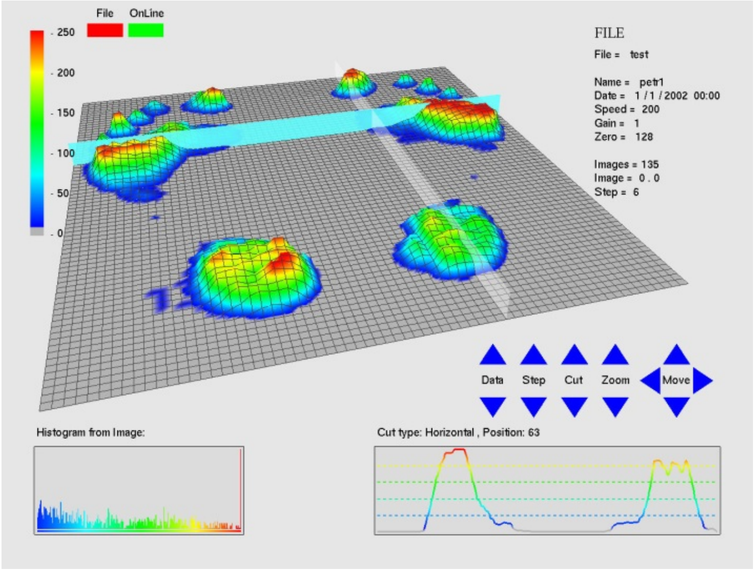
Plantograph V05, J. Volf

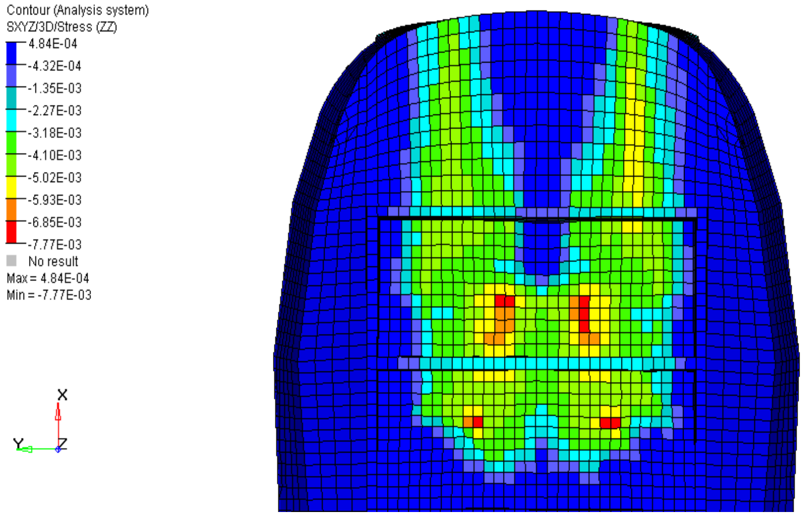
Plantograph, specifications

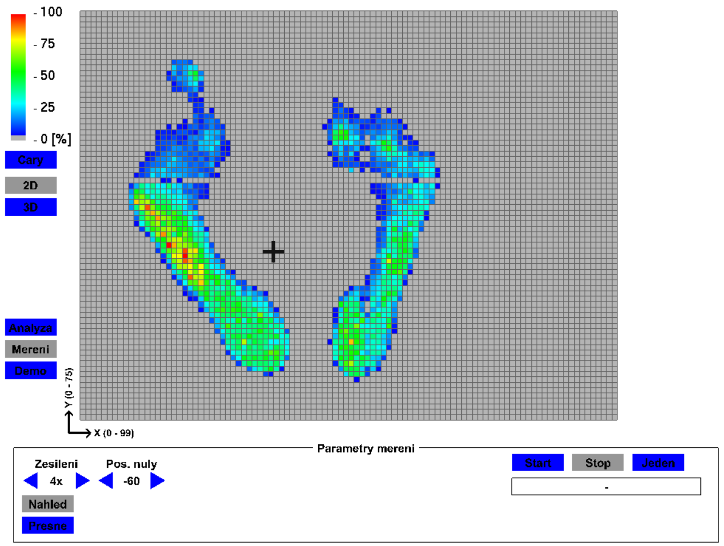
Active area of the sensor	300 x 400 mm
Number of sensors	7 500
Resolution	4 x 4 mm
Area of the singe sensor	2 x 2 mm
Measured pressure range	0 - 414 kPa
Allowed permanent overloading	1.4 MPa
Impact overloading	10 MPa
Frame frequency	300 Hz
Line frequency	25 kHz
Sampling frequency	300 kHz
Digital output range	256 pressure levels (8 bits)

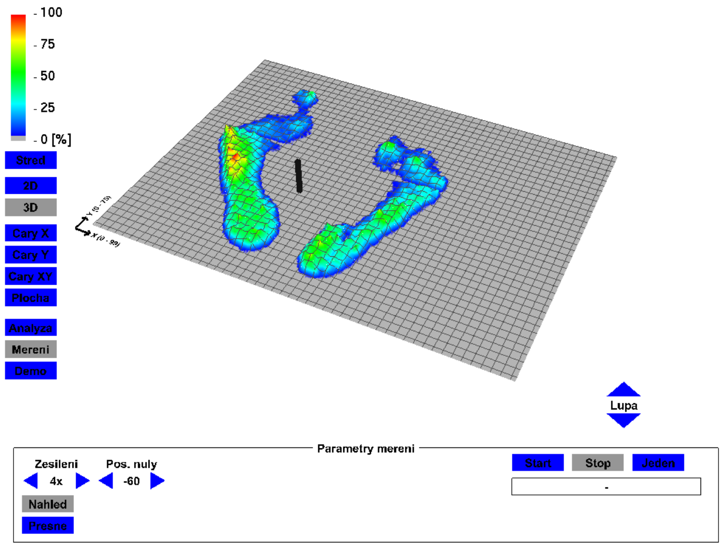
Plantograph, results

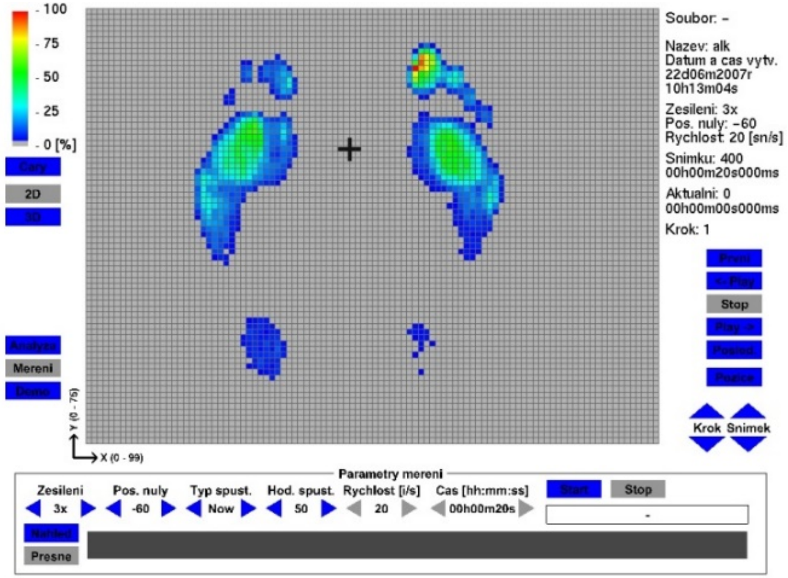




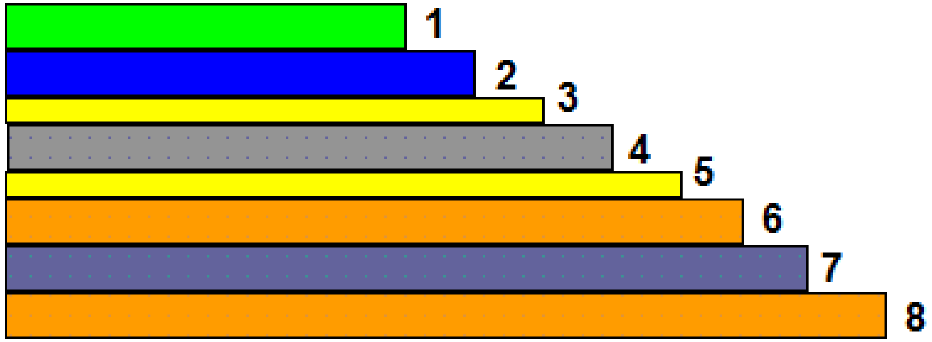


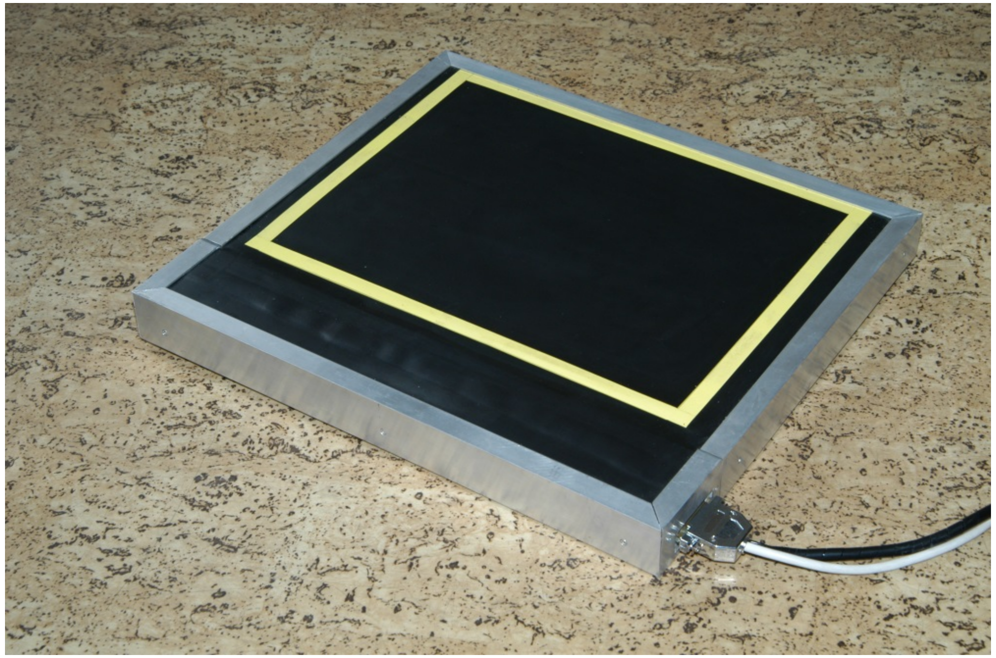






Plantograph construction





1 – cover layer
2 – shear force layer
3 – top electrode CUFLEX
4 – conductive elastomer CS 57-7 RSC
5 – bottom electrode CUFLEX
6 – antistatic layer
7 – duralumin plate
8 – antistatic layer

Project RadioRoSo, tactile sensor

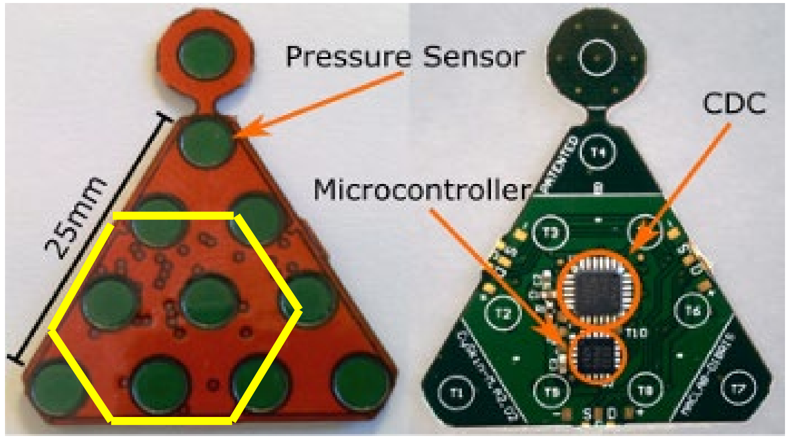
- RadioRoSo = Radioactive Waste Robotic Sorting; EC funded project September 2016 to February 2018
- Grippers and tactile sensor created at the University of Genova, Matteo Zoppi, Giorgio Cannata, Michal Jilich

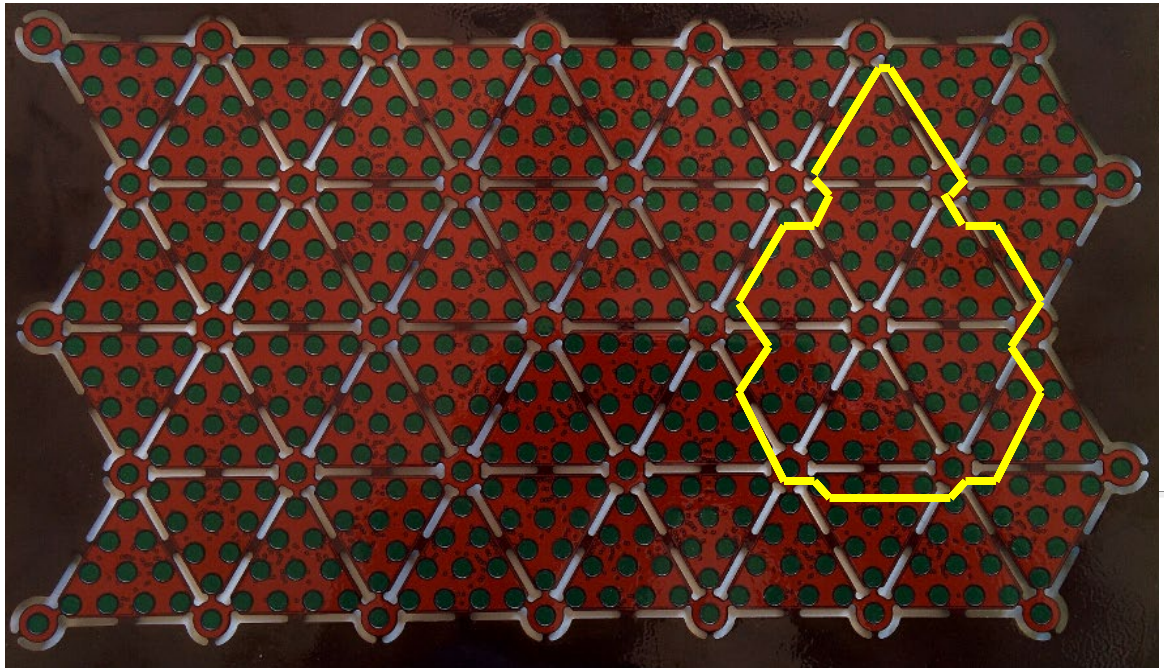
Tactile sensor hardware 1

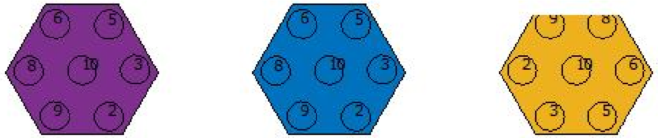
- Capacitive based transducers
- Modular and scalable

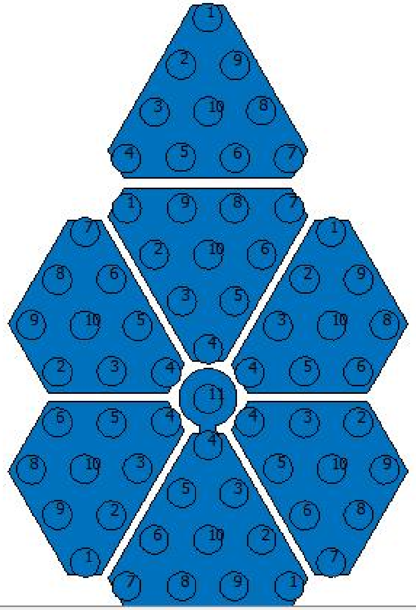
- Taxels:
  - ~3.5 mm dia.
  - ~8 mm pitch
- 48 modules&sheet (467 tactels)
- 16 bits capacitance to digital converters

Tactile sensor hardware 2

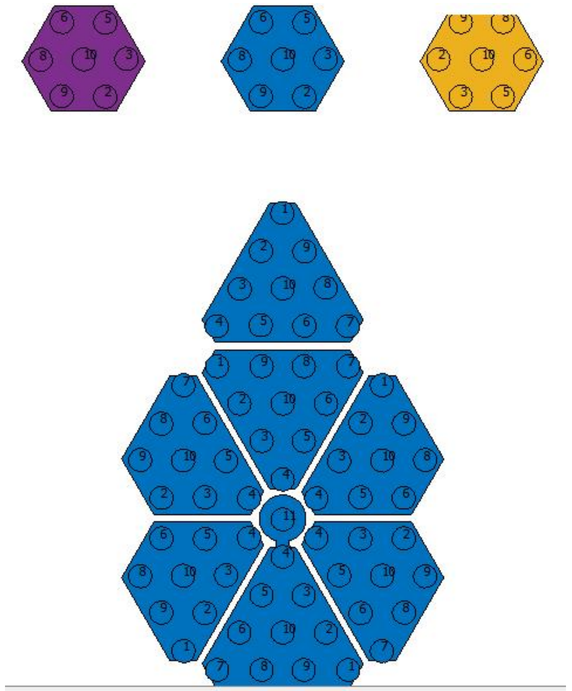


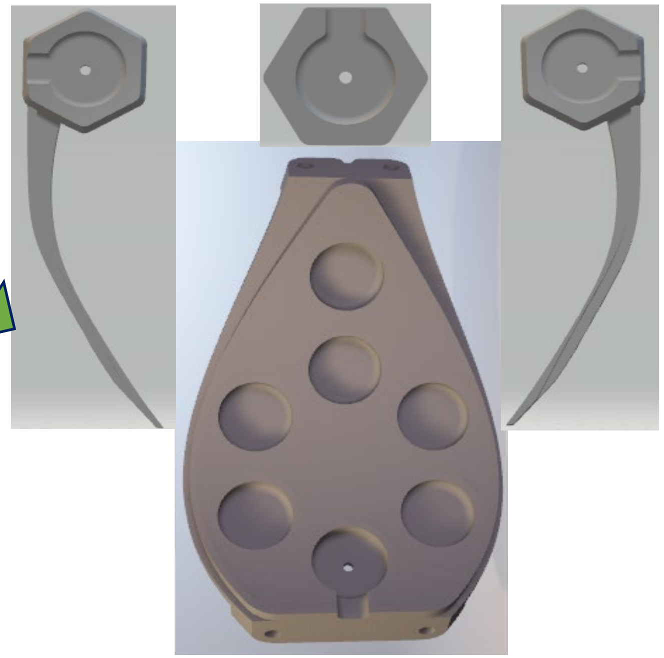


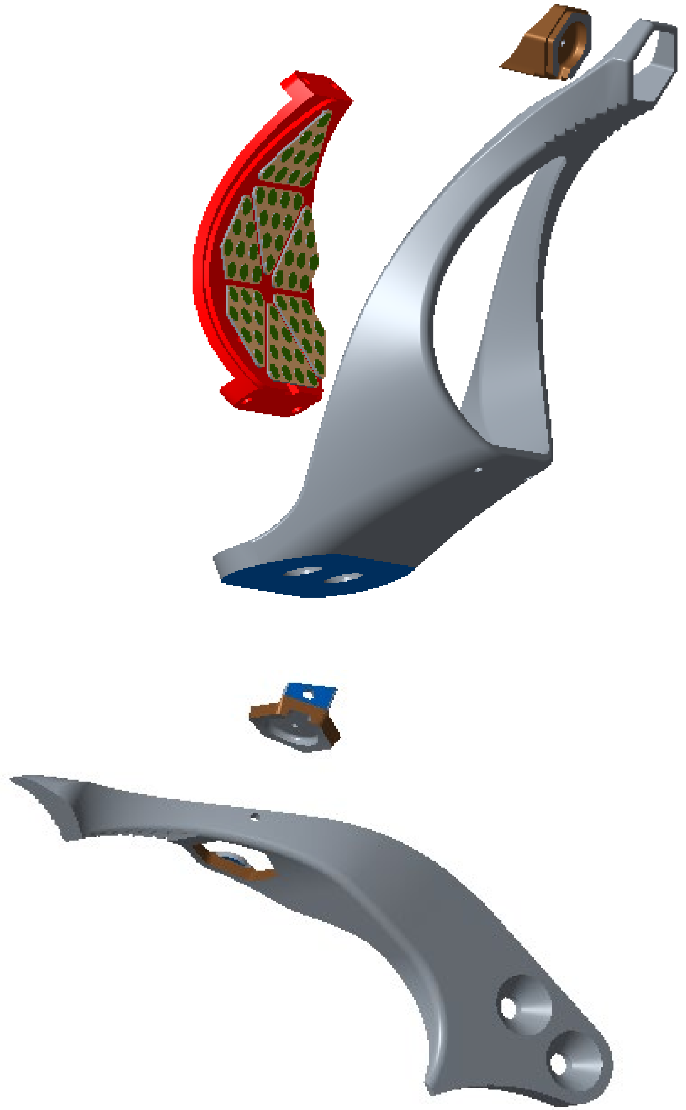




Tactile sensors integration

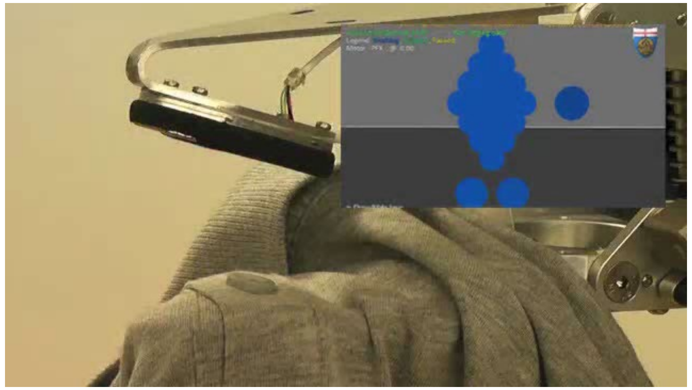


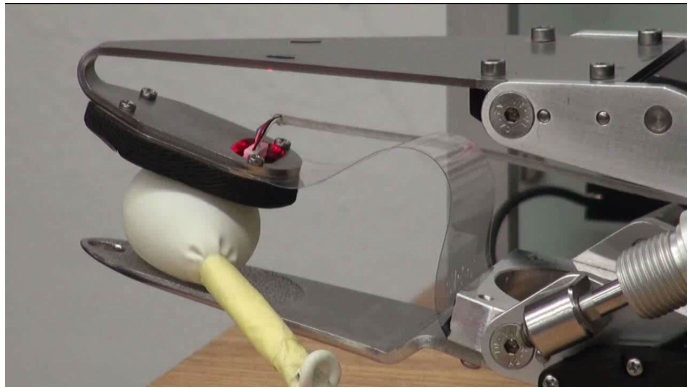




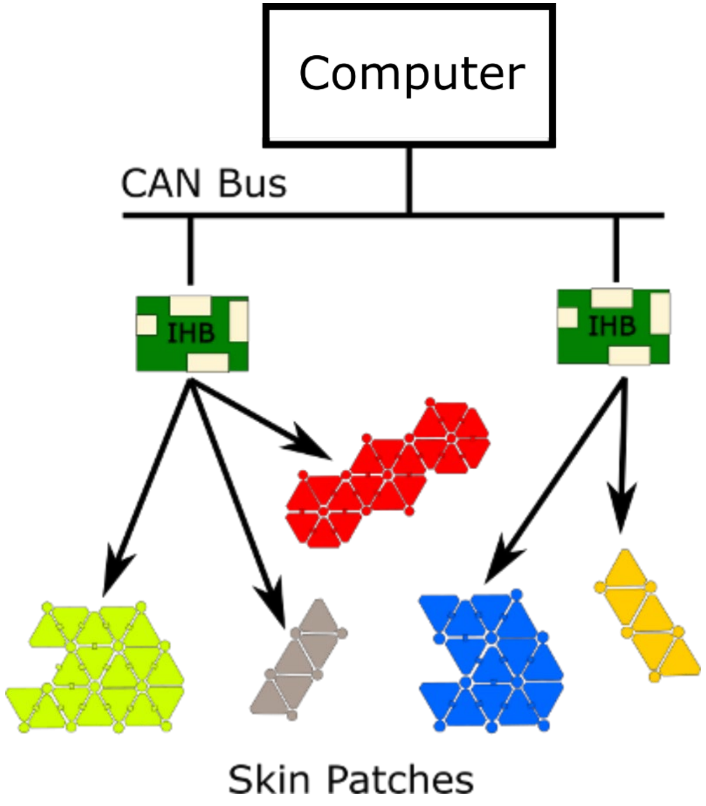
Tactile sensing applications

10K+ tactels



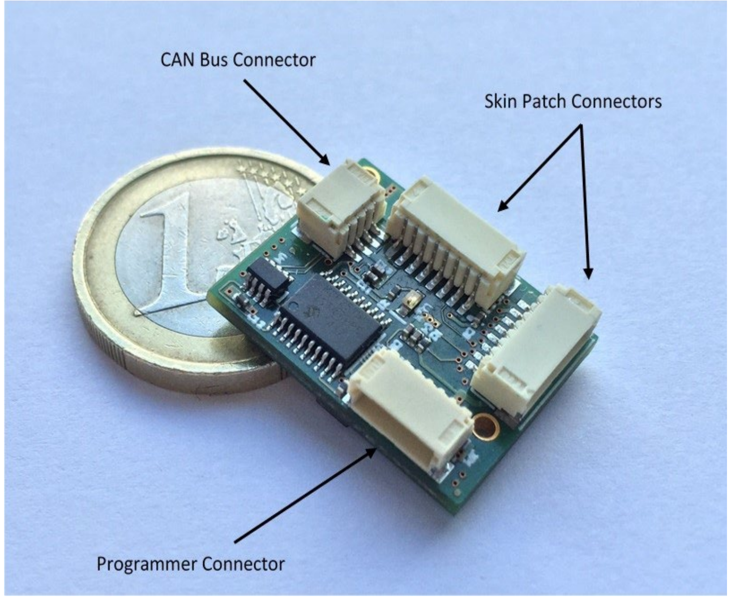


Tactile sensing architecture

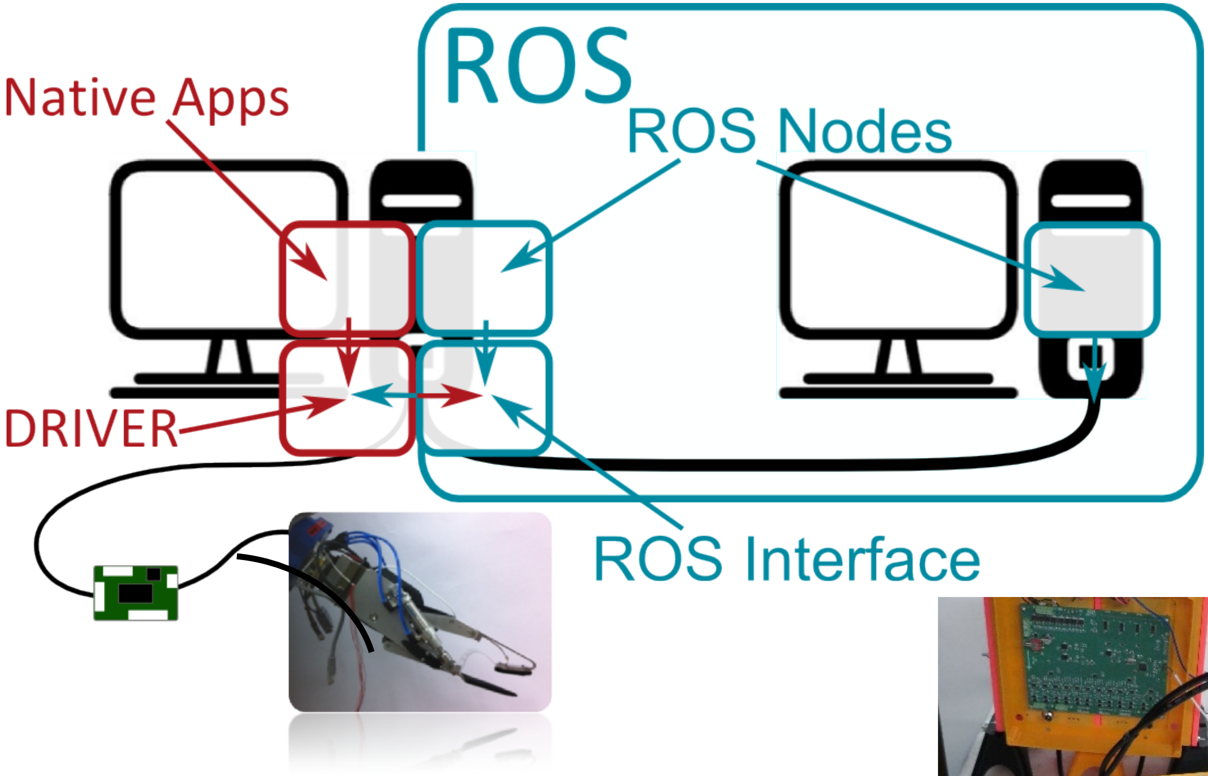


- Data communications (sensor to host)

- Remote programming of embedded electronics (host to sensor)



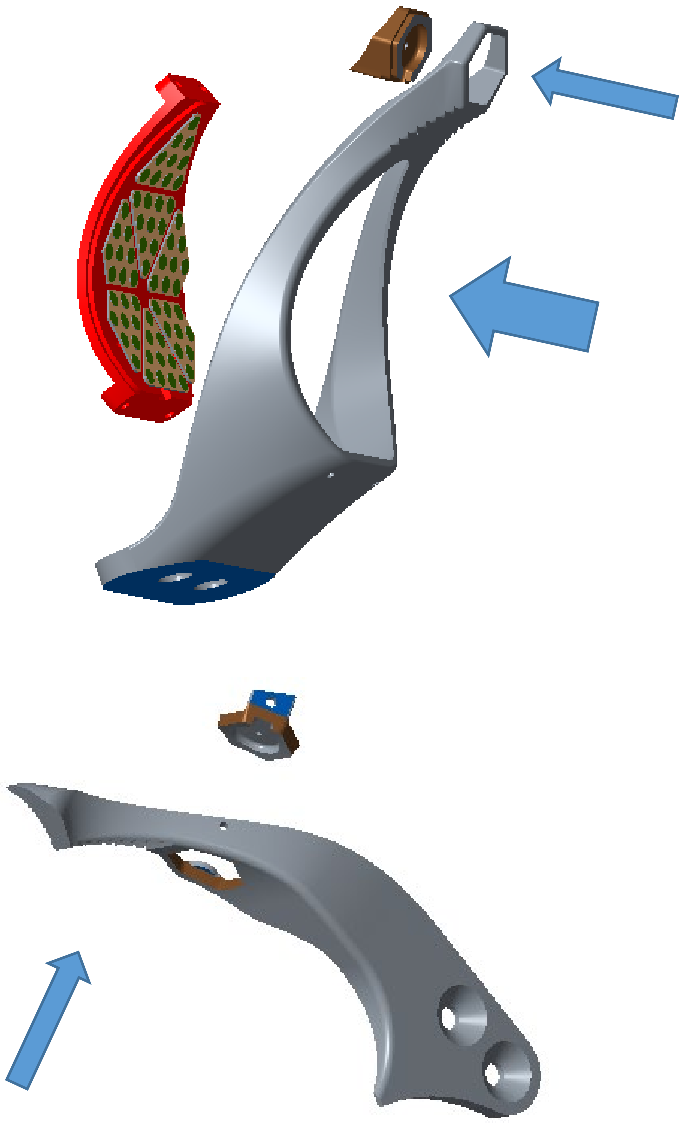
ROS hand module



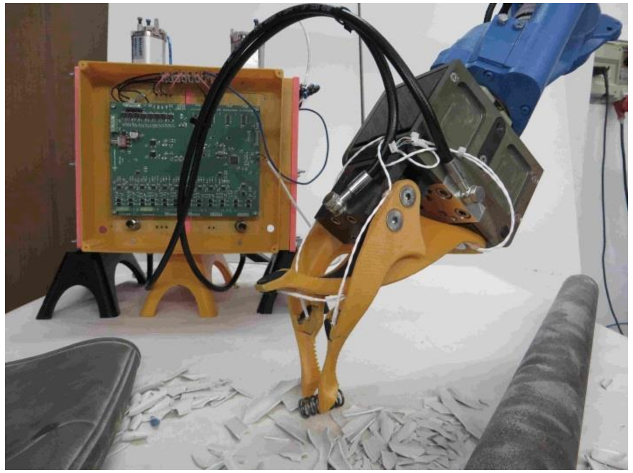
- Software has been designed to work in ROS or independently.
- The ROS interfaces allow to acquire sensor feedback and to send gripper control commands

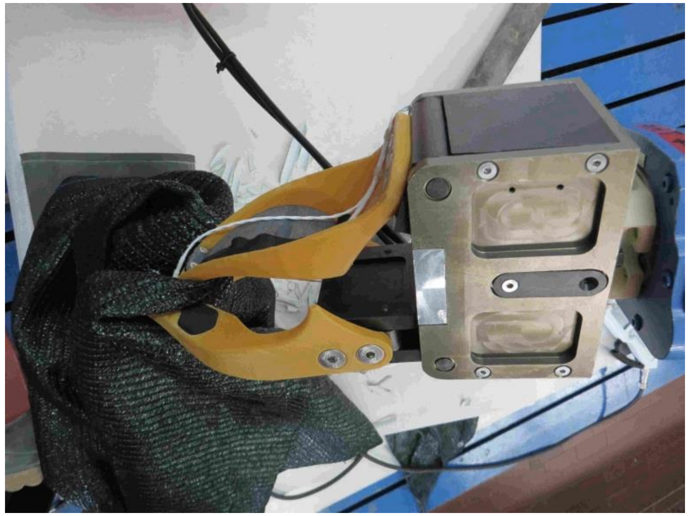
Incorporation of tactile sensors

- Three blocks of sensitive tactels covering relevant areas of the fingers
  - Palm pad and finger tip pad on the single finger
  - Mid body pads on the paired fingers
- Enough information to confirm presence and successful grasp of all categories of items
- Can be used to close a control loop on contact pressure
- Do not affect grasp schemes and their geometrical foundations



Grasp examples





Where to buy?

http://www.tekscan.com/

http://www.pressureprofile.com

https://contactile.com/

http://www.xsensor.com/

https://solarbotics.com/

http://www.takktile.com/

http://www.sensorprod.com/

http://www.syntouchllc.com/

TakkTile Kit for Robotiq Three-Fingered Gripper

Conclusions

- Tactile sensing in robotics have not left research labs yet.
- Tactile sensing reliability and industrial proliferation is much smaller as compared to, e.g. robot vision.
- There are prospective teams, ideas, materials, companies (see previous slide), ongoing research projects, which might change the picture soon.