64-424
Intelligent Robotics

https://tams.informatik.uni-hamburg.de/
lectures/2019ws/vorlesung/ir

Marc Bestmann / Michael Görner / Jianwei Zhang

University of Hamburg
Faculty of Mathematics, Informatics and Natural Sciences
Department of Informatics
Technical Aspects of Multimodal Systems

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Outline

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1. Force and Tactile Sensors
    - Motivation
    - Strain gauge
    - Force/Torque Sensors
    - Human Tactile Sensing
    - Tactile Sensors
    - Advanced Sensors
    - Robot Skin
    - Application Example

Today's agenda

- recall some physics: force, torque, stiffness
- pure position control vs. manipulation

- strain-gauges
- six-axis force/torque sensor

- tactile sensors
- advanced sensors and robot skin
- application example

Force

Application of force to a point of an object accelerates the object in the direction of the applied force

Newton's second law defines acceleration of an object as proportional to the applied force (F) and inversely proportional to the mass (m) of the object, hence:

$$a = \frac{F}{m}$$

- The unit of force is the Newton (N):
- One Newton of applied force accelerates an object with a mass of 1 kg with 1 m/s^2

Torque

When a force F is applied to a rigid object and the axis of rotation is known (e.g. a robot joint axis), the corresponding torque is given by the vector cross product

$$\tau = r \times F$$

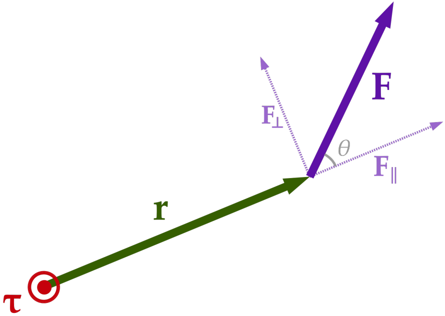
where r is the vector from the axis to the point of action of the force.

- The unit of torque is the Newtonmeter (Nm)

The angular acceleration α of an object is proportional to the torque τ and inversely proportional to the moment of inertia I of the object, hence:

$$\tau = I \cdot \alpha \qquad \Longleftrightarrow \qquad F = m \cdot a$$

Torque



Show animation with linear/angular momentum

Measuring forces

Force cannot be measured directly, only by its effects:

- acceleration of a rigid object
- deformation of an elastic object

Hooke's Law:

- the force F needed to extend or compress a spring by some distance x is proportional to that distance,
- $F = k \cdot x$ with stiffness k
- most solid materials obey this law when the elongation x is small
- calculate F from known stiffness k and observed x

Manipulation tasks and position control...

typical industrial manipulator (example PA-10 robot):

- 10 kg payload, 1 m reach, lower arm weight $\approx$ 10 kg
- position accuracy better than 0.2 mm (total load 10+10 kg)
- calculate corresponding stiffness: $k = F/x \geq 9.81 \cdot 10^5 \,\mathrm{Nm}^{-1}$

accidentally moving into an obstacle ($k = 10^6$):

- 0.2 mm: contact force > 200 N (20 kg)
- 1.0 mm: contact force > 1000 N
- 1.0 cm: contact force > 10000 N

- even minor position errors can be catastrophic
- need sensors to measure the interaction forces
- need fast control to limit contact forces

Manipulation tasks and position control (cont'd)

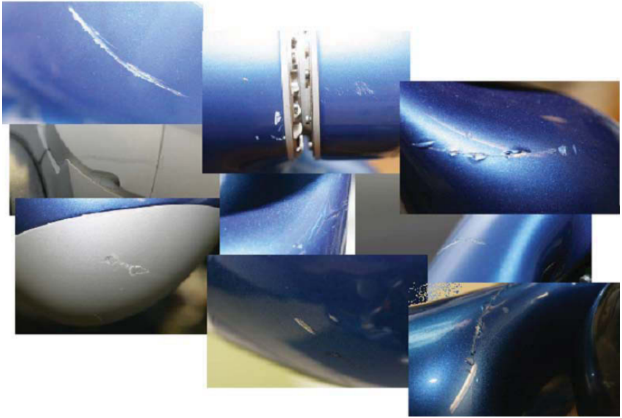
moving a stiff robot into an obstacle...

- no force readings until the robot touches the object
- need to stop the robot very quickly once we hit the object

- motion with constant acceleration a: $v = a \cdot t$, $s = \frac{1}{2}at^2$
- most robots use a fixed control cycle, e.g. 100 Hz (PA-10)
- want to brake in one control cycle, $t = 0.01\,\mathrm{s}$, so $a = 2s/t^2$
- assuming maximum interpenetration distance $s = 0.2\,\mathrm{mm}$

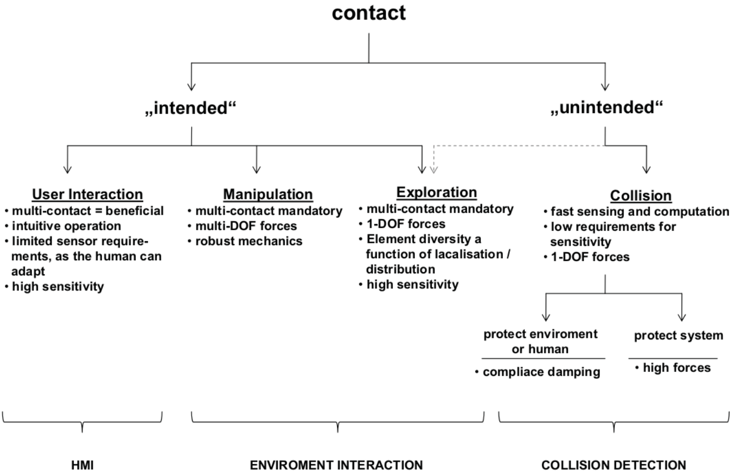
- maximum allowed velocity: $v = 2s/t \leq 0.04 m/s$
- the motion has to be very slow!
- (or braking accelerations become really large)

Problem with stiff robots



Results of unintended contacts. . . Strohmayr, Dissertation, 2012

Functional taxonomy of contact types



contact

„intended“

„unintended“

User Interaction
- multi-contact = beneficial
- intuitive operation
- limited sensor requirements, as the human can adapt
- high sensitivity

Manipulation
- multi-contact mandatory
- multi-DOF forces
- robust mechanics

Exploration
- multi-contact mandatory
- 1-DOF forces
- Element diversity a function of lacalisation / distribution
- high sensitivity

Collision
- fast sensing and computation
- low requirements for sensitivity
- 1-DOF forces

protect enviroment or human
- compliace damping

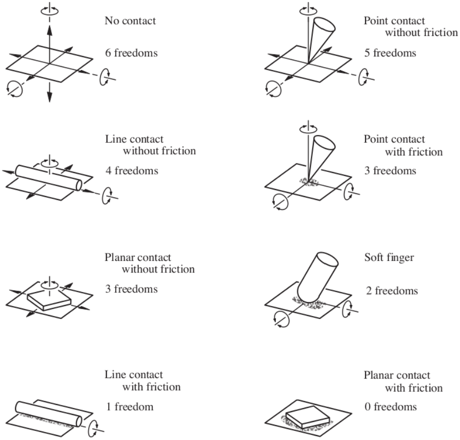
protect system
- high forces

HMI

ENVIROMENT INTERACTION

COLLISION DETECTION

Geometric taxonomy of contact types



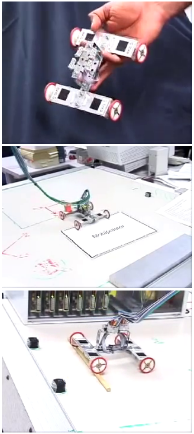
Salisbury, PhD thesis, 1982

Fun example: Mobipulator

- 4-wheel skid-steering platform
- simple DC-motors, rubber wheels

- tracking with fixed overhead camera
- compare: dead-reckoning navigation and odometry (last lecture)

- exploits wheel and object friction
- surprising (2D-) manipulation skills
- tasks would be quite difficult with a robot arm and hand…



Matt Mason and students, in Experimental Robotics VI 1999

Mobipulator

Video
www.youtube.com/watch?v=kUkxhM4W7Jg

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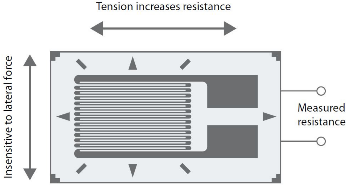
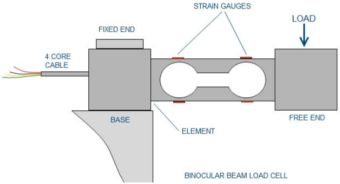
Strain gauge

Most modern sensors use the approach of measuring the deformation of an elastic material

- a strain gauge is composed of conducting paths laminated onto an elastic carrier material
- mechanical strain affects the path resistance
- the resistance change is very small → special measurement circuitry is required
- Specific application of strain gauges allows to measure:
  - the magnitude and direction of mechanical strain
  - force and pressure
  - associated quantities like acceleration, distance, etc.

Strain gauge and load-cell





- resistance of a wire increases with length
- put thin long wire on carrier material

- foil type: conducting wire layered onto elastic carrier material
- semiconductor: typically polisilizium
- wire type: thin wire on paper

Foil strain gauge

Typical characteristics of foil strain gauges

- resistance values: 120 - 600 Ω
- tolerance of the resistance usually less than $\pm 0,5\,\%$
- operating voltages: $1\,V \;-\; 10\,V$

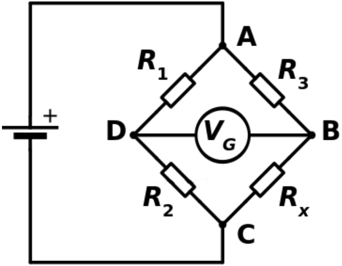
- length variation of the strain gauge up to $\pm 3\,\%$
- typical length variation: $0.1 \;-\; 10\,\mu m$
- achievable accuracy at 20° C $\approx$ 1 % - 5 %

Wheatstone bridge

How to measure the resistance change of a strain-gauge?

- measure voltage drop over R
- length change small, $\Delta L \ll L$
- $\Delta R \approx 10^{-3}\,\Omega$, $\Delta R / R \approx 10^{-5}$

- difficult to measure tiny changes of large voltage; easier to measure tiny change of near-zero voltage
- Wheatstone bridge uses four resistors,
- tuned so that $R_1/R_2 \approx R_3/R_x$
- useful voltage between D and B



Strain Gauge Demo

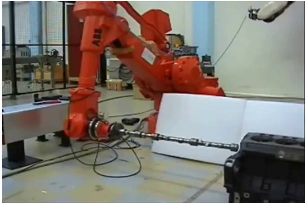
Live Demo

Six-axis force/torque sensor

- common tool for industrial robots
- mounted between wrist and tool

- sensor measures total force, including weight of sensor and tool
- calibration step to estimate tool size, weight, COG
- subtract tool/sensor from total forces
- gives environment interaction forces
- use for robot control

- note: no force measurements for any contacts between robot base and wrist



ATi/ABB automation video, youtube

Six-axis force/torque sensor

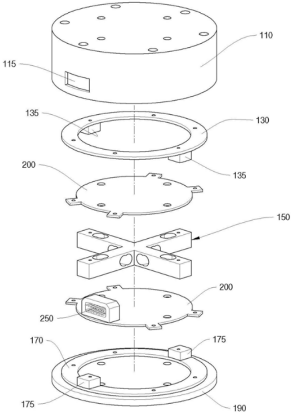
Video
https://www.youtube.com/watch?v=4Ro6rQbePqE
Video2
https://www.youtube.com/watch?v=b4nz_hAh7qs (0:55-1:50)

Six-axis F/T sensor: Construction

- stiff upper housing (110) with screw threads (tool connection)
- connector ring from (110) to (150)
- elastic member (150) with strain-gauges
- stiff bottom plate (190)
- amplifier circuit boards (200)

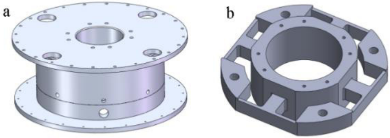
- two strain-gauges on each cross arm

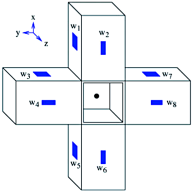
- triangular setup with three elastic arms (at 120°) another popular arrangement

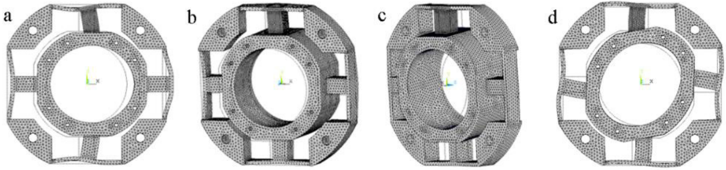


C.G. Kang, Int. Journal of Control, Automation, and Systems, vol. 3, no. 3, 469–476, 2005

Six-axis F/T sensor: Deformation under load





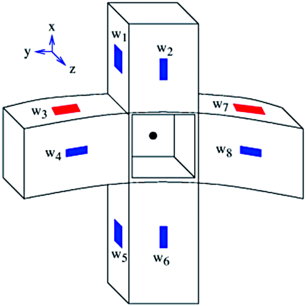


(a) $F_x = 10000\text{N}$, (b) $F_z = 12000\,\text{N}$, (c) $M_x = 2000\,\text{Nm}$, (d) $M_z = 3000\,\text{Nm}$

D. Cheng et.al., APISAT 2014, doi:10.1016/j.proeng.2014.12.699

Six-axis F/T sensor: Coupling matrix

- deformation of the elastic part affects different strain gauges
- specific for each sensor design



F/T DOF	**Strain gauges**
F_x	W_3, W_7
F_y	W_1, W_5
F_z	W_2, W_4, W_6, W_8
M_x	W_4, W_8
M_y	W_2, W_6
M_z	W_1, W_3, W_5, W_7

Six-axis F/T sensor: Coupling matrix

- resistance change of stain-gauges is linear for small deformation
- therefore, the transformation from stain-gauge values to forces and torques can be written as matrix multiplication
- this is called the coupling matrix K

$$\begin{bmatrix} F_x \\ F_y \\ F_z \\ M_x \\ M_y \\ M_z \end{bmatrix} = K \cdot \begin{bmatrix} W_1 \\ W_2 \\ W_3 \\ W_4 \\ W_5 \\ W_6 \\ W_7 \\ W_8 \end{bmatrix}$$

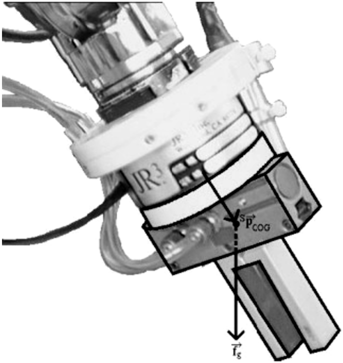
- coupling matrices are very device specific
- in ideal case, many coefficients zero
- datasheet usually includes detailed K values from factory calibration

Six-axis F/T sensor: Calibration

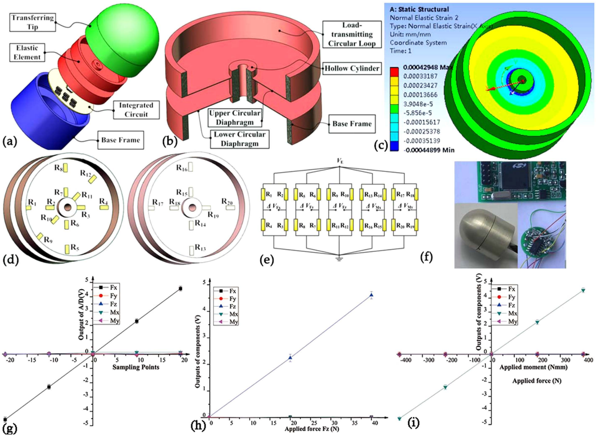
- mass of the attached tool $\vec{F}_{tool}$
- tool's center of gravity $\vec{p}_{COG}$
- also, mass and COG of the moving part (tool side) of the F/T sensor

- once tool COG and weight are known, software can subtract those values from the measured data
- this allows estimation of external forces

- calibration is only valid in the configuration it was carried out
- still temperature-dependent



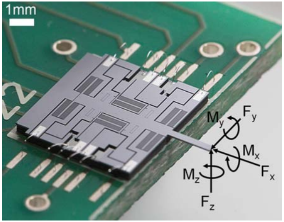
Miniaturization: Five-axis fingertip F/T sensor

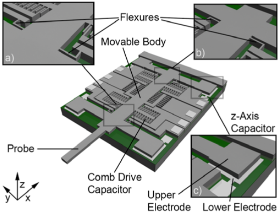


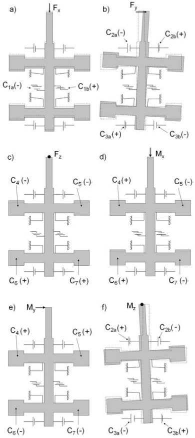
- measures F_x, F_y, F_z, M_x, M_y
- thin diaphragm as flexible element
- FEM analysis
- 20 strain-gauges
- five Wheatstone bridges

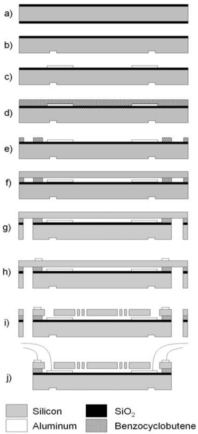
Q.-K. Liang et.al., Scientific Reports 6:24689 2016, DOI: 10.1038/srep24689

Miniaturization: MEMS F/T sensor



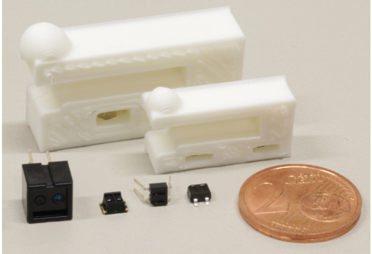


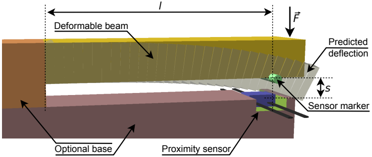




Beyeler et.al., Microfabricated 6-Axis Force-Torque Sensor, ICRA 2009, 520–525

3D Printed Alternative





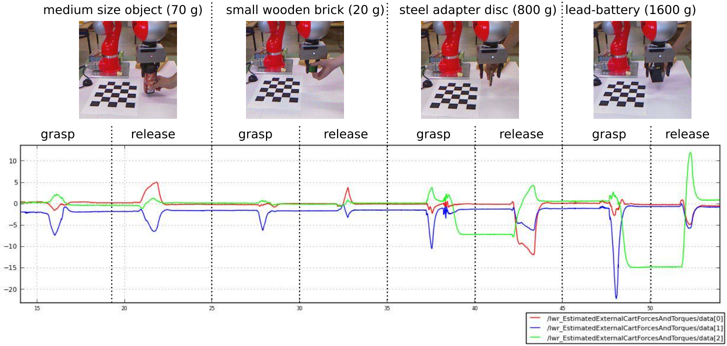
- Other materials and other sensors possible
- Measuring deformation with proximity sensor
- Easier integration into an object

Florens Wasserfall, Norman Hendrich, Fabian Fiedler, Jianwei Zhang, 3D-Printed Low-Cost Modular Force Sensors, 20th Intl. Conference on Climbing and Walking Robots (CLAWAR-2017)

F/T sensor applications

- guarded motions: check motion execution and stop when preset force thresholds are exceeded
- compliant motions
  - peg-in-hole insertion tasks
  - surface following and measurements
  - polishing and grinding tasks, constant normal forces
  - human-guided motion/trajectory teaching
- direct or hybrid force control
  - torque control of individual motors (joints)
  - force / torque control of tool center point
  - mixture of position and force control schemes
  - requires precise dynamics model of the robot
- note: forces behind the F/T sensor are not measured!

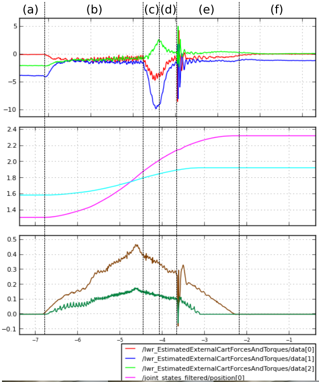
Application example: Force-guided object handover



- measured tool forces F_x, F_y, F_z over time, KuKA LWR4+
- grasped object weight plus human interaction forces
- gripper grasp and release triggered by interaction forces

Liebrecht, Bistry, Hendrich, Zhang, IROS-WS 2014

Application Example: In-motion object handover



- top: estimated external forces F_x, F_y, F_z
- middle: robot joint angles ϕ_1, ϕ_6
- bottom: joint velocities ω_1, ω_6

- estimated forces quite noisy while the robot moves (despite good sensors and exzellent LWR4+ robot model)
- reliable force threshold too high for user acceptance
- gripper tactile sensor used as additional sensor
- grasp release triggered by robot force sensing and gripper tactile sensor

Liebrecht, Bistry, Hendrich, Zhang, IROS-WS 2014

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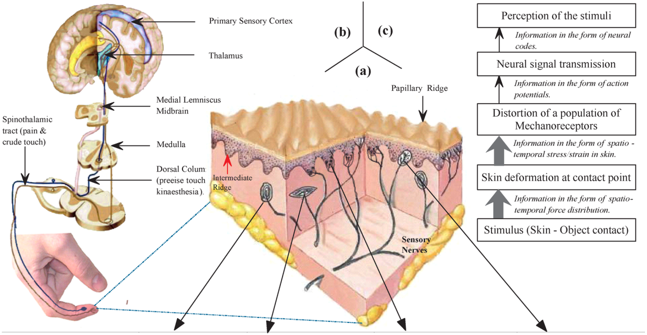
Human tactile sensing

- amazing grasping and manipulation capabilities of humans
- human hand tactile sensing provides a reference system

- three layers: subcutaneous (fatty) tissue, dermis, epidermis
- four different receptor types
  - FA-I: Meissner's corpuscles: vibration and motion detection
  - SA-I: Merkel's disks: sustained pressure, texture perception
  - FA-II: Pacinian corpuscles: skin deformation, vibration, tool use
  - SA:II: Ruffini endings: skin stretch, slip, tangential forces
  - fast and slow adaptation to stimulus
- cold/anaesthesized fingertips: dramatic loss of manipulation capabilities, especially for small objects

Human tactile sensing



Perception of the stimuli

Information in the form of neural codes.

Neural signal transmission

Information in the form of action potentials.

Distortion of a population of Mechanoreceptors

Information in the form of spatio - temporal stress/strain in skin.

Skin deformation at contact point

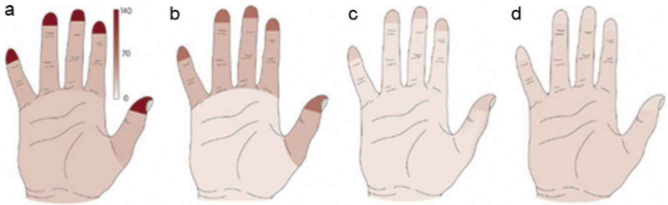
Information in the form of spatio-temporal force distribution.

Stimulus (Skin - Object contact)

Classification Basis		**Pacinian Corpuscle**	**Ruffini Corpuscle**	**Merkel Cells**	**Meissner's Corpuscle**
Type		FA II	SA II	SA I	FA I
Adaptation Rate		Fast	Slow	Slow	Fast
Spatial Acuity (mm)		10+	7+	0.5	3-4
Vibration/rapid indent. threshold	Best(μm)	0.01	40	8	2
	Mean(μm)	0.08	300	30	6
Stimuli Frequency (Hz)		40-500+	100-500+	0.4-3	3-40
Conduction Velocity (m/s)		35-70	35-70	40-65	35-70
Effective Stimuli		Temporal changes in the skin deformation	Sustained downward Pressure; Lateral skin stretch; Skin slip.	Spatial deformation; Sustained pressure; Curvature, edge, corners.	Temporal changes in skin deformation
Sensory Function		High frequency vibration detection; Tool use.	Finger position; Stable grasp; Tangential Force; Motion direction	Pattern/form detection; texture perception; Tactile flow perception.	Low frequency vibration & motion detection; Grip control; Tactile flow perception.

R.S. Dahiya et.al., Tactile Sensing From Humans to Humanoids, IEEE T-RO Vol.26,No.1, 2010

Human tactile sensing: Receptor distribution



- density (afferents per cm^2) of receptor cells in the human hand
- (a) and (b): fast and slow adapting type I
- (c) and (d): fast and slow adapting type II

- the special role of the fingertips is obvious
- “two point resolution” at fingertip ca. 1.6 mm, palm 7.7 mm

Yousef et.al., Tactile sensing - A Review, 2011. doi:10.1016/j.sna.2011.02.038

Tactile sensors: Requirements

Tactile sensors → special category of force sensors

- usually very thin
- robot skin, palm and finger tip sensors
- other applications: medical measurements, touch screens, etc.

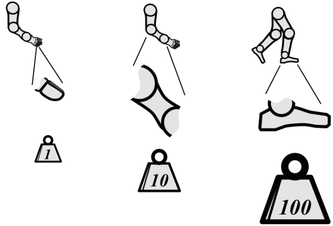
Typical requirements:

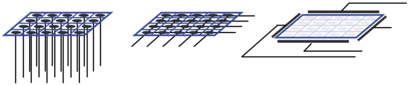
- spatial resolution ca. $1 \ldots 2\,\mathrm{mm}^2$
- force sensitivity in range $0.4 \ldots 10\,\mathrm{N}$
- minimum sampling frequency of 100 Hz
- linear transfer function and low hysteresis
- low crosstalk between neighboring sensors

Tactile sensors: Taxonomy and classification

- sensor technology:
  - switch sensors
  - resistive materials
  - capacitive sensors
  - MEMS (silicon) sensors
  - optical sensors
  - . . .
- sensor layout:
  - single sensors
  - 1D- and 2D matrix sensors
  - flat and curved shape
  - layer structure

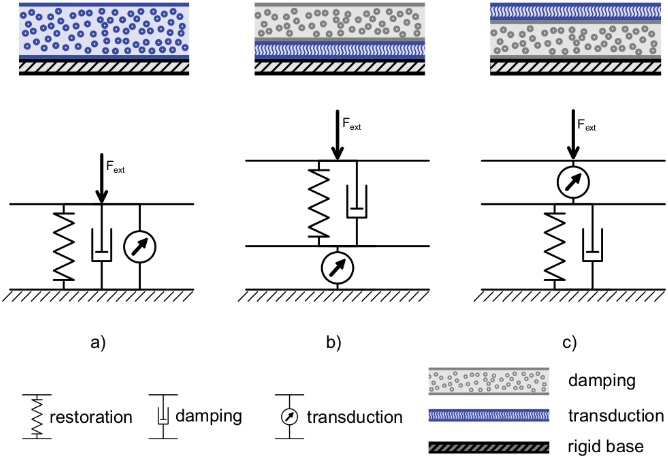
- load scale:





$N_w = N_{tx} \cdot N_{ty}$ $N_w = N_{tx} + N_{ty}$ $N_w = 4$

Tactile sensors: Layers

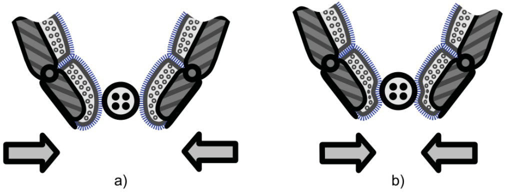


Strohmayr, Dissertation, 2012

Tactile skin: Layers

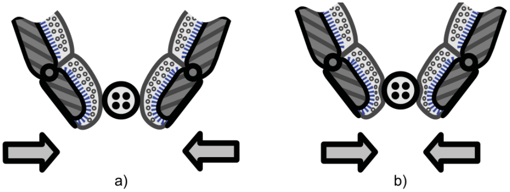
Sensing layer on top:

- high sensitivity
- good spatial resolution
- sensor exposed
- fragile, not robust

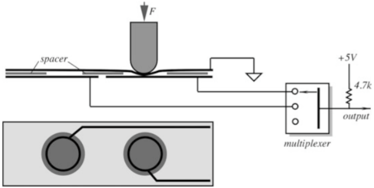


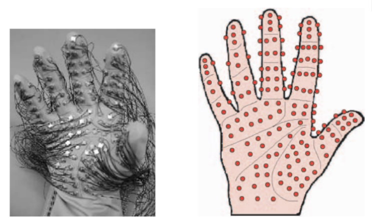
Sensing layer inside:

- force "smeared out":
- low sensitivity
- low spatial resolution
- sensor protected
- robust



Switch-type sensor





- mechanical or membrane type switches
- binary on/off decision, no force measurement
- usually, low spatial resolution, no shearing forces

K. Matsuo et.al., Placement of Tactile Sensors for Manipulation Task Recognition, ICRA 2008, 1641–1646

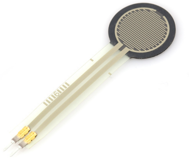
Force-sensitive resistors

Materials whose electrical resistance is a function of strain

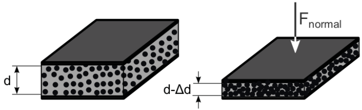
- a force-sensitive resistor (FSR) changes its resistance depending on the applied pressure
- use of conductive elastomeres or pressure-sensitive ink
- integration of the elastomer between two conductive plates

\+ very simple functional principle
\+ low manufacturing costs

– drift of resistance during prolonged pressure
– more useful for qualitative measurements



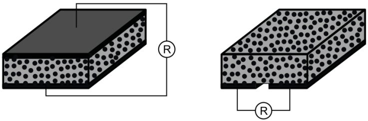
Force-sensistive resistor: Conductive elastomere

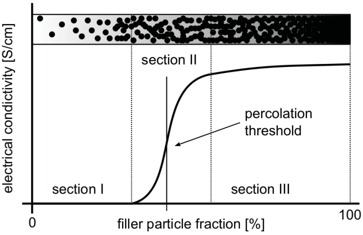


- foam with embedded conductive particles
- e.g. metal, coal
- low cost

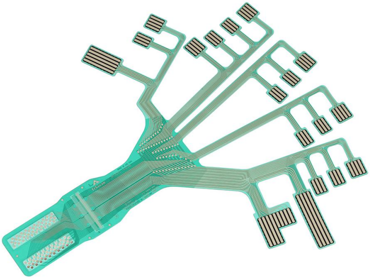
- top and bottom electrodes
- pair of bottom electodes

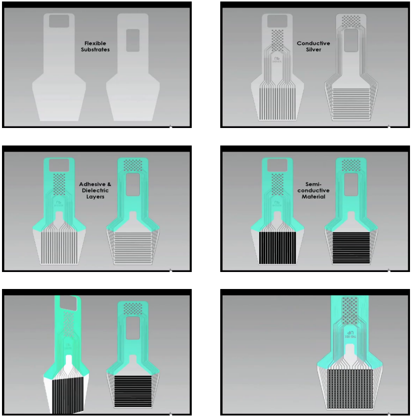
- nonlinear resistance curves





Forse-sensitive resistor: Matrix-type sensor



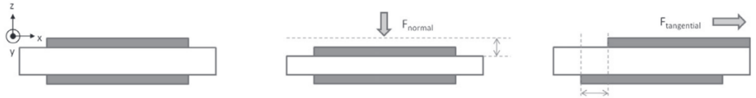


TekScan Inc., How the Tekscan Pressure Sensor is made, www.youtube.com/watch?v=q6_iZwuK3cU

Forse-sensitive resistor: Matrix-type sensor

Video
www.youtube.com/watch?v=q6_iZwuK3cU

Capacitive sensors

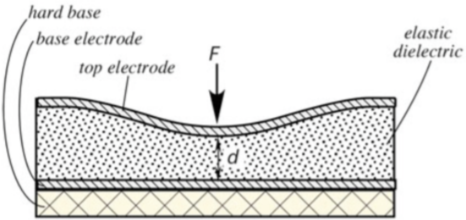


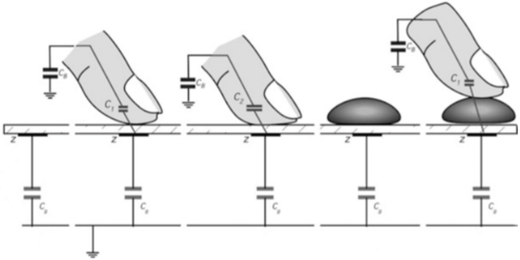
- capacitors made from flexible materials
- plate capacitor

$$C = \frac{dQ}{dV} = \epsilon \frac{A}{d}$$

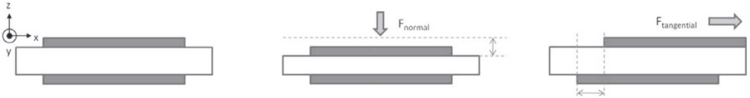
- an applied force either changes
  - the distance d between the plates (normal forces)
  - the surface area A (shearing forces)
- capacitance measured using frequency response of an oscillating R-C circuit
- also used for contactless proximity sensing (human tissue near the top electrode also changes capacitance)

Capacitive sensors





Capacitive sensors: Shearing forces



- plate capacitor: $C = \frac{dQ}{dV} = \epsilon \frac{A}{d}$
- typically, $A \gg d$
- good sensitivity to normal forces
- but less sensitivity to shearing forces
- use finger electrode layout to increase sensitivity to shearing forces
  - top-right electrode: z direction
  - top-left: $z + y$ direction
  - bottom-right: $z + x$ direction
  - decouple to get F_x, F_y, F_z

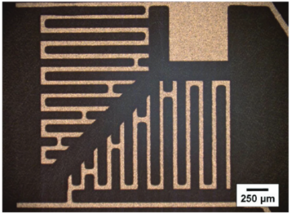
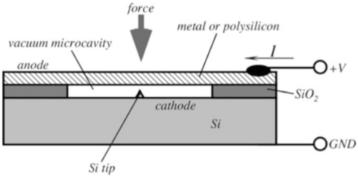


Fig. 2 Top view of one set of the sensor capacitor plates. Each of the capacitors is sensitive to applied forces in a specific direction (top right in the z-direction, top left in the z&y directions and bottom in the z&x-directions).

H. Yousef et al. / Procedia Engineering 25 (2011) 128 – 131

MEMS sensors



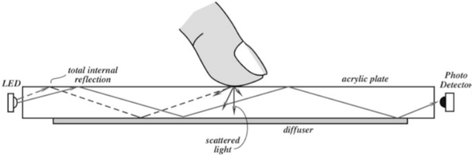
- integrated (micro-) electronics and mechanical structures
- exploit existing microelectronics fabrication processes
- e.g. polysilicon structures on top of base silicon material
- typical structure has membranes or thin moving parts

\+ small sensor size, good spatial resolution

\+ often high sensitivity, high dynamic range

− fragile, sensors too small to cover large areas

Optical sensors



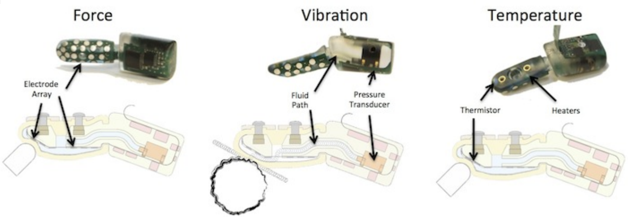
- combination of light emitters and detectors
- many different sensor principles
  - touching object changes refractive properties of surface
  - membrane deflection changes reflection
  - optical proximity/distance sensors
  - bending optical fibers
  - ...
- usually robust
- unreliable performance in bright ambient light

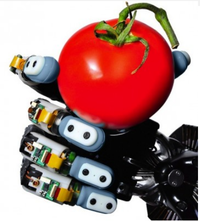
FingerVision

- Sens deformation with camera
- Position of dots change with force

Yamaguchi et al. "Implementing tactile behaviors using FingerVision." 2017 IEEE-RAS Humanoids

Syntouch BioTAC sensor





Bio-inspired robot fingertip sensor:

- combines pressure sensor, conductive liquid, thermistor
- static pressure relates to applied normal force
- pressure vibration for surface identification and slip detection
- electrodes provide spatial information, reconstruct force location and shearing forces
- temperature gradient for material identification

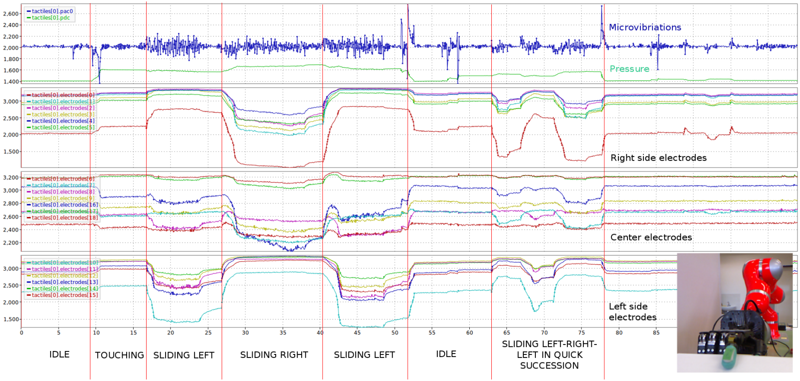
Syntouch LLC., 2012,

Syntouch BioTAC sensor

Video
www.youtube.com/watch?v=W_O-u9PNUMU

BioTAC sensor: sliding finger

normal and shearing forces, slippage detection



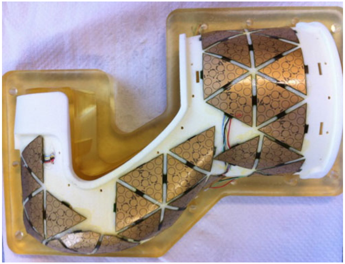
- sensor pre-processing pipeline: on-line calibration, low-pass filter, normal-force estimation

Ciobanu, Hendrich, Zhang, ICSTCC 2013

Robot skin

The full body of a robot covered by tactile skin?!

- a lot of new problems of scale
- connecting all those sensors?
- calibration of 1000's sensors?
- mapping sensor positions?
- how to combine sensor readings?



EU RoboSKIN project (2010–2012):

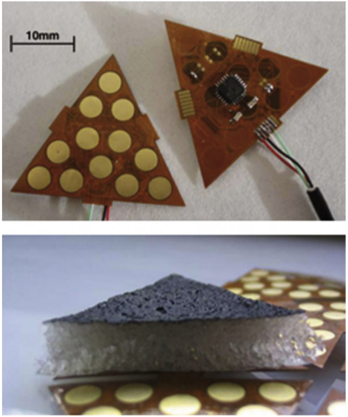
- modular sensor modules
- tactile middleware to manage the sensors
- available for the iCub robot

RoboSkin: sensor module

“triangle module”:

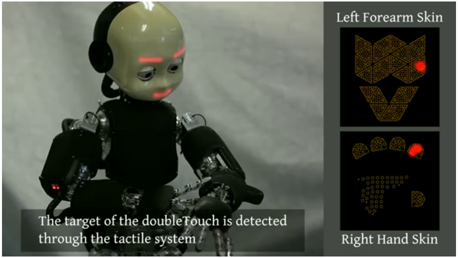
- triangles can tile curved surfaces
- 12 taxels on each module
- integrated electronics, amplifier and communication
- three ports to neighboring modules
- supports automatic topology detection

- silicone rubber foam that covers the sensors;
- conductive layer used as ground plane sprayed on top of the module



EU project FP7-RoboSKIN, 2011 (website roboskin.eu not active anymore)

iCub: Self-calibration and body schema learning



- skin consists of many sensor modules, different addresses, etc.
- arms and hands have curved and irregular surfaces
- manual calibration of all modules difficult (a lot of work)
- let the robot learn its kinematics and sensor layout
- robot touches itself, correlates arm/hand position and sensor response

Roncone et.al., Learning Peripersonal Space on the iCub, www.youtube.com/watch?v=pfse424t5mQ

iCub: Self-calibration and body schema learning

Video
https://www.youtube.com/watch?v=pfse424t5mQ
Video2
https://www.youtube.com/watch?v=jQfX2SyxxXo
Video3
https://www.youtube.com/watch?v=3IaXxNwC_7E

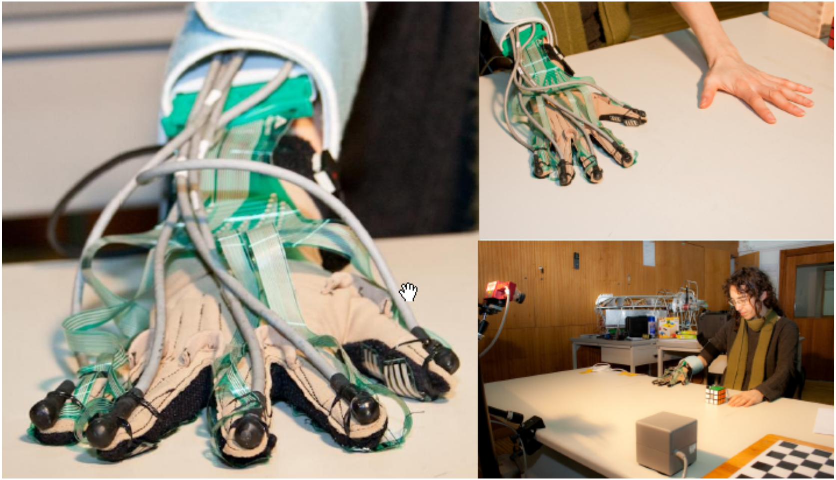
Application example: Recording human manipulation

- learn grasping from human demonstration
  1. record human manipulation experiments
  2. annotate and classify the phases of the manipulation
  3. learn human strategies
  4. transfer to robot system

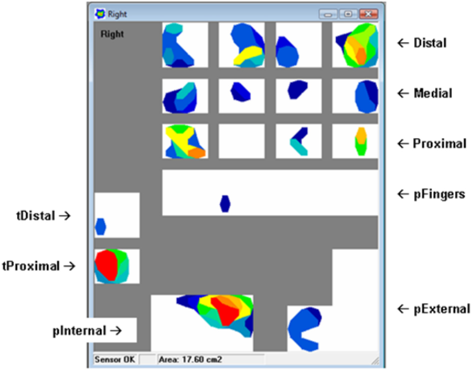
- complex multi-sensor system
  - Camera(s): video of the overall scene
  - Stereo-Camera: 3D-scene reconstruction, hand position
  - Cyberglove: hand shape
  - Polhemus: 3D fingertip positions (magnetic tracker)
  - TekScan Grip: fingertip and hand palm forces
  - Instrumented Rubik: forces on grasped object

EU project FP7-HANDLE, 2009-2013

Multisensor: Polhemus and Tekscan on Cyberglove

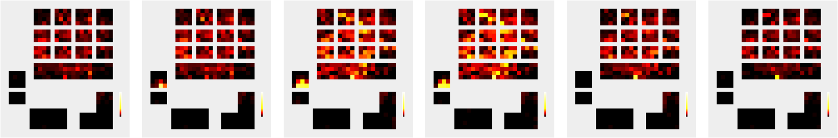


Tekscan Grip (on Cyberglove)



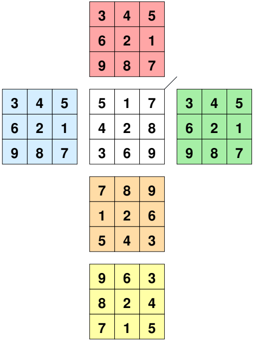
TekScan Inc., EU project FP7-HANDLE, 2012

Using a ball-point pen: clicking the pen



- heatmap of sensor TekScan grip activation
- back-view of the right hand: thumb, fingers, palm sensors
- pen is held in a power-grasp, thumb operates the button:
  (a) idle state, grasp forces are low, distributed evenly
  (b) thumb touches the button
  (c-d) clicking, grasp forces increase to stabilize the pen
  (e-f) idle state, grasp forces are low again.

Force-Sensing Rubik cube



3	4	5
6	2	1
9	8	7

3	4	5
6	2	1
9	8	7

5	1	7
4	2	8
3	6	9

3	4	5
6	2	1
9	8	7

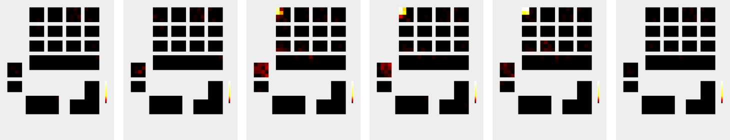
7	8	9
1	2	6
5	4	3

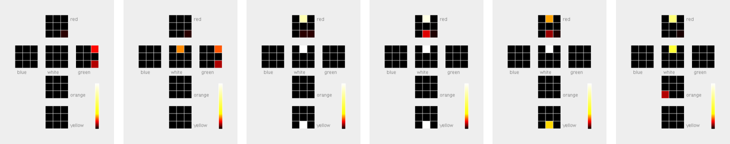
9	6	3
8	2	4
7	1	5

- record grasp forces during manipulation experiments
- 6 × 3 × 3 FSR sensors, 6×3-axis accelerometers

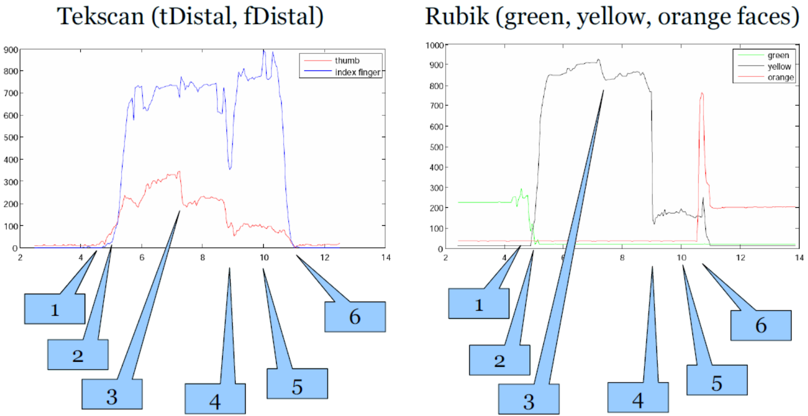
Shadow Robot Ltd., EU project FP7-HANDLE, 2011

Grasping the Rubik cube





Grasping the Rubik-cube: segmentation



Tekscan (tDistal, fDistal)

Rubik (green, yellow, orange faces)

1 first contact 2 lift-off 3 holding 4 letting slip 5 holding 6 setting down

Take home message

- pure robot position control is dangerous
- many robot tasks require force-sensing and -control
  - collision detection and human safety
  - manipulation and grasping
  - interaction in unknown environments
  - (physical) human-robot interaction

- forces measured by object deformation
- strain-gauges, elastic polymers, optical, . . .
- six-axis force/torque sensor

- tactile sensors and robot skin
- need for self-calibration and multisensor fusion

References

- R.S. Dahiya et.al., Tactile Sensing From Humans to Humanoids, IEEE Transactions on Robotics, Vol.26,No.1, 2010
- M. Cutkosky, Force and Tactile Sensing, in: Bruno Siciliano, Ed., Handbook of Robotics, Springer, 2011.
- Hanna Yousef, Mehdi Boukallel, Kaspar Althoefer, Tactile sensing for dexterous in-hand manipulation in robots — A review, Sensors and Actuators A: Physical, 2011. doi:10.1016/j.sna.2011.02.038
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- several papers (see slides)