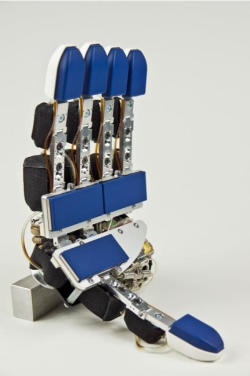
Karlsruher Institut für Technologie

Hochperformante Humanoide Technologien

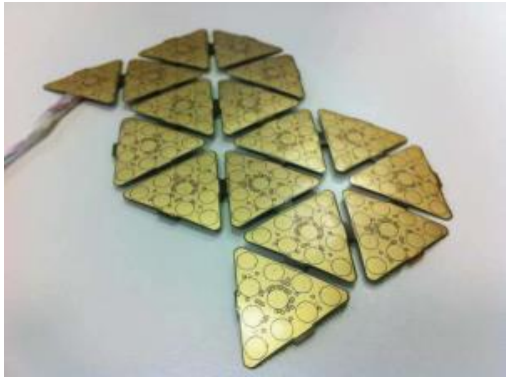
Robotics III: Sensors and Perception in Robotics
Chapter 04: Tactile Sensing

Tamim Asfour

http://www.humanoids.kit.edu



BioTac, © SynTouch Inc. (2020)



iCub tactile Skin

External (Exteroceptive) Sensors

External sensors

Proximity sensors

- Capacitive Sensors
- Optical Sensors
- Acoustic Sensors

© ST Microelectronics (2020)

Depth sensors

- Time-of-Flight based
- Triangulation based

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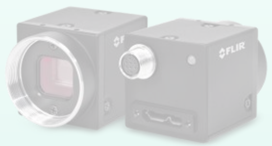
Visual sensors

- Photodiodes
- CCD/CMOS
- Stereo



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Position sensors

- GPS
- Natural/artificial Landmarks

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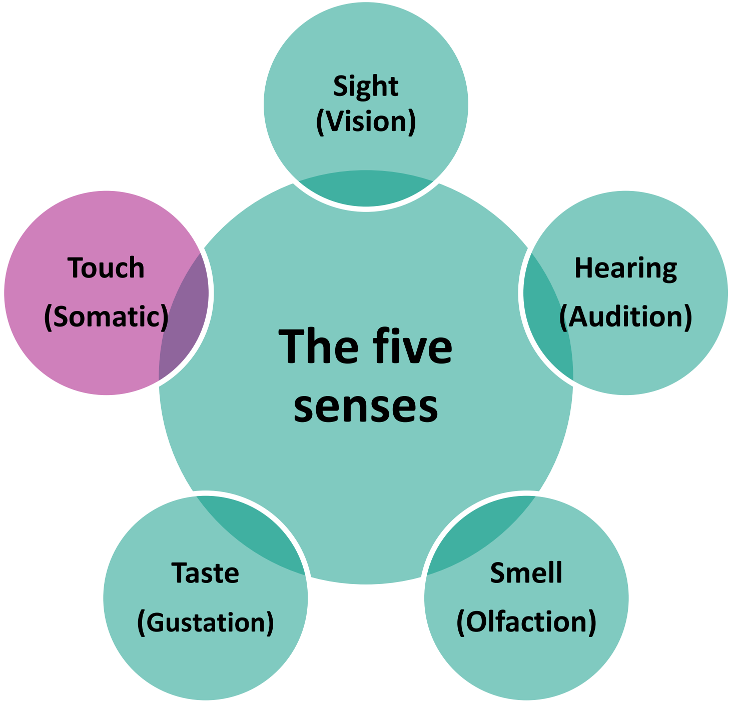
Tactile sensors

- Touch & Slip Sensors
- Force/Torque Sensors

Human senses



What is Haptics?

- The sense of touch

- Any form of nonverbal communication involving touch

- The sense of touch is natural for humans to feel surface roughness, object softness, lightness or heaviness, etc.

- Loss of the sense of touch is a catastrophic deficit that can impair skilled actions such as holding objects or using tools and walking

Haptic Perception

- **Tactile / Cutaneous:**
  - Temperature, pressure, vibration, slip, pain
  - Sensation arising from stimulus to the skin

- **Proprioception / Kinesthesia:**
  - Limb position/location, motion, force
  - End organs located in muscles, tendons and joints
  - Stimulated by body movement

Haptics = Tactile + Proprioception

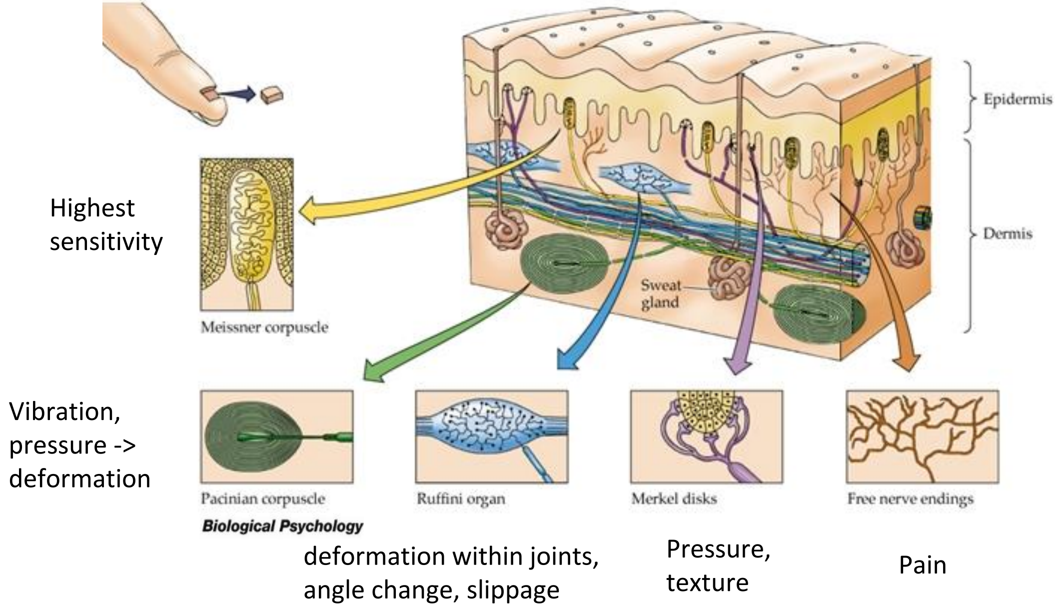
Sensory Receptors - Example: Human Skin (I)

- **Haptic:** The process of recognizing objects by touch
- It involves a combination of **somatosensory** perception of patterns on the skin surface (e.g. edges, curvature and texture) and **proprioception** of hand position and conformation
- The **somatosensory system** is a complex sensory system. It is made up of a number of different receptors, including **thermoreceptors**, **nociceptors**, **mechanoreceptors** and **chemoreceptors**
- It also comprises essential processing centers, or sensory modalities, such as **proprioception**, **touch**, **temperature**, and **nociception**. The sensory receptors cover the skin and epithelia, skeletal muscles, bones and joints, internal organs, and the cardiovascular system

Sensory Receptors - Example: Human Skin

- A **mechanoreceptor** is a sensory receptor that responds to mechanical pressure or distortion

- **Four main types in skin**: Pacinian corpuscles, Meissner's corpuscles, Merkel's discs, and Ruffini endings



Breedlove, S. M., Watson, N. V., & Rosenzweig, M. R. (2010). Biological psychology

Outline Tactile Sensing and Perception

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Tactile Sensors

- At fingertips
- Normal force
- Shear forces
- Vibration
- Temperature
- Texture
- Surface orientation

Robotic skin

- Large scale
- On robot body
- Self-Calibration
- Contact sensing
- Cobots

Tactile Exploration

- Use of tactile sensors
- Exploration procedure
- Surface estimation
- Object softness
- Classification

Tactile Sensors

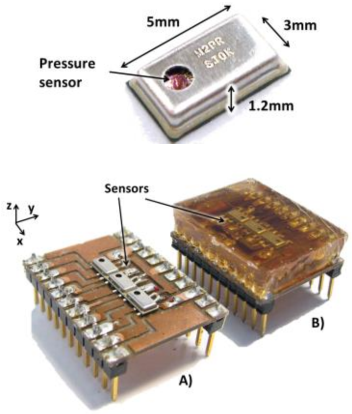
Tactile Sensors – Why is it hard?

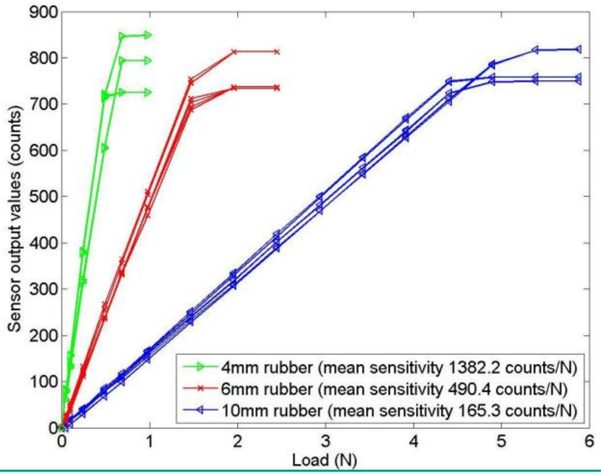
- Unlike other sensor modalities (forces/torques, position, vision, etc.) **tactile sensing is not broadly used in industry**
  → Only very few tactile sensors are commercially available for application to robotic skin/hands

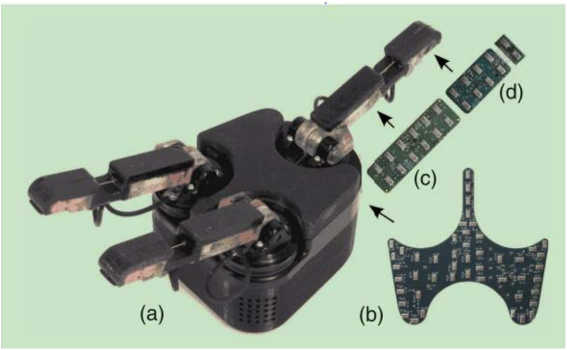
- There exists a broad community in robotics research working on **tactile sensors based on very different measurement principles**
  - Resistive, capacitive, vision-based, Hall-effect based, Piezo-effect based, etc.
  - There is no common ground yet on the best sensor design
  - Different sensor designs suitable for different applications

TakkStrip Tactile Pressure Sensor

- **MEMS barometer** covered with **rubber material**
- Pressure applied to the rubber surface is transferred to the pressure sensor
- Sensor sensitivity is dependent on the thickness of the rubber







i-HY hand with 108 sensors

Images taken from referenced paper

Tenzer, Yaroslav, Leif P. Jentoft, and Robert D. Howe. "Inexpensive and easily customized tactile array sensors using MEMS barometers chips." *IEEE R&A Magazine* 21.c (2012): 2013.

Hall-Effect based Tactile Sensor

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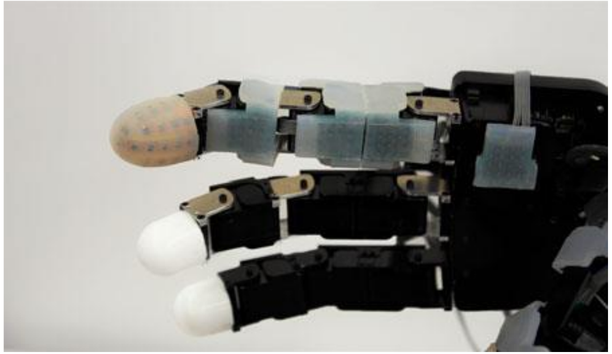
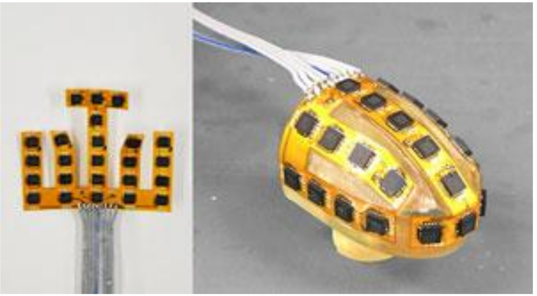
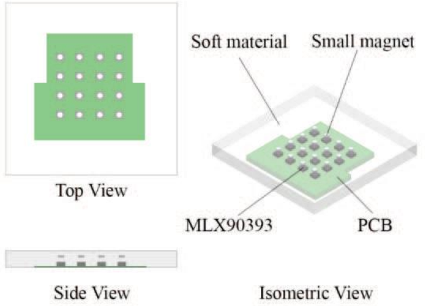
- **Small magnets** are embedded in a **soft material**
- Applied force deforms the soft material
- Magnets move with the soft material
- **Hall-effect sensor** measures change in magnetic field
- Matrix structure
- 3D force measurement F_x, F_y, F_z
- Resolution: 0.5 N







Images taken from referenced paper

- Tomo, Tito Pradhono, et al. "Design and characterization of a three-axis hall effect-based soft skin sensor." *Sensors* 16.4 (2016): 491.
- Tomo, Tito Pradhono, et al. "Covering a robot fingertip with uSkin: A soft electronic skin with distributed 3-axis force sensitive elements for robot hands." *IEEE Robotics and Automation Letters* 3.1 (2017): 124-131.

BioTac Sensor I

- Multimodal tactile sensor
- Sensor as a complete fingertip
- Conductive fluid inside the finger
  - Fluid movement is measured by impedance sensing electrodes
    → Force sensing
  - Fluid transports vibrations
    → Slip detection
    → Texture recognition
- Thermistor
  → Measure temperature flux

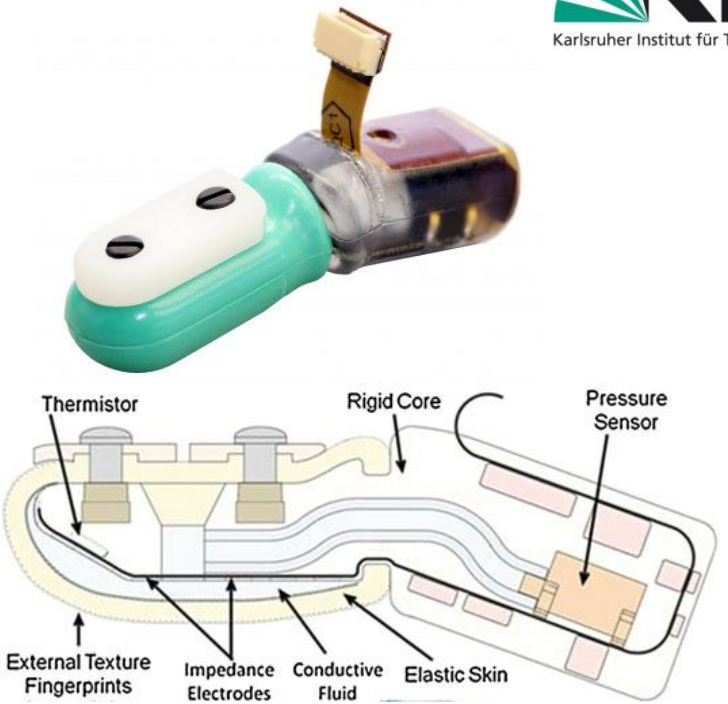


Image taken from referenced paper

https://www.syntouchinc.com/sensor-technology

Wettels, Nicholas, Jeremy A. Fishel, and Gerald E. Loeb. "Multimodal tactile sensor." *The Human Hand as an Inspiration for Robot Hand Development*. Springer, Cham, 2014. 405-429.

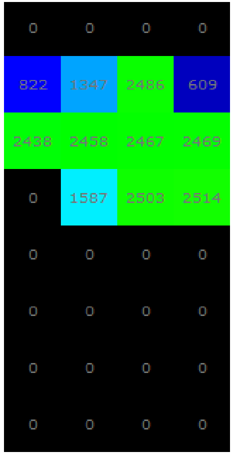
BioTac Sensor II

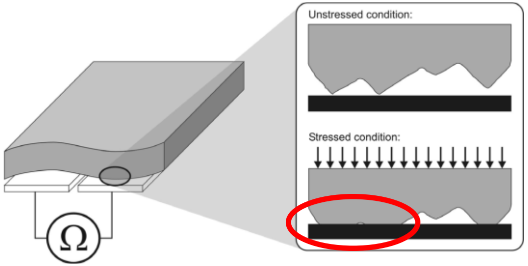
https://www.youtube.com/watch?v=W_O-u9PNUMU

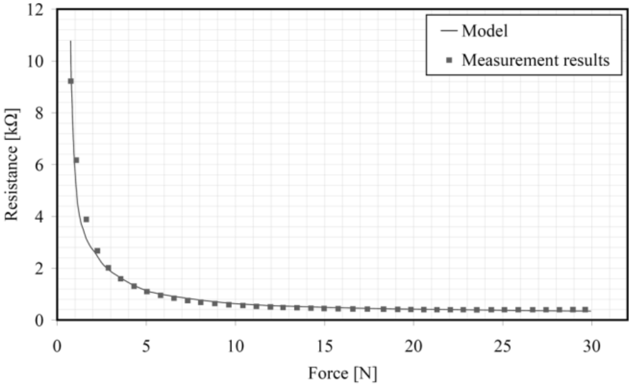
Resistive Haptic Sensor

- Sensor changes resistance when force is applied
- Resistance is high when force is low
- Resistance is low when force is high
- Matrix structure possible
  ➔ Tactile "image"
- Developed at KIT, IPR

$$R \sim \frac{1}{F}$$





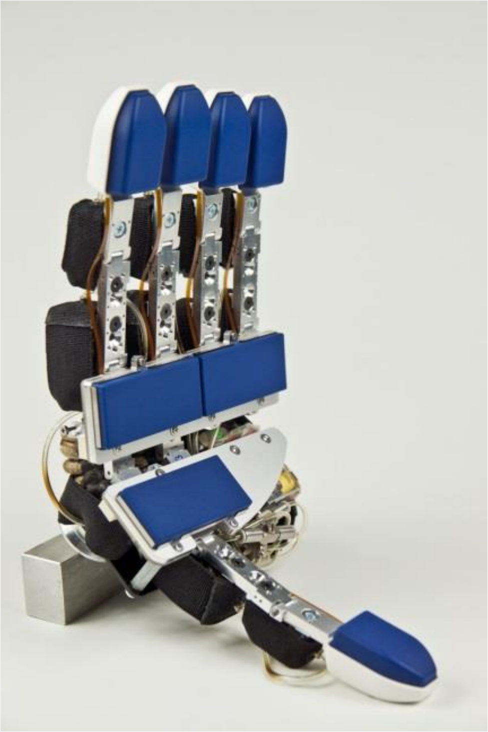


Images taken from referenced paper

Weiß, Karsten, and Heinz Wörn. "The working principle of resistive tactile sensor cells." *IEEE International Conference Mechatronics and Automation, 2005*. Vol. 1. IEEE, 2005.

Weiss Robotics Tactile Sensors

- High sensitivity
- 12 bit resolution
- Integrated signal processor
- USB Interface
- Sensors in the palm
  - 6x14 taxel
- Sensor in the finger tips
  - 4x8 taxel
  - Curved surface



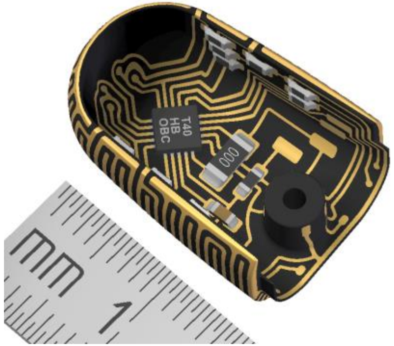
ARMAR-III hand

Weiss Robotics artificial skin (no longer available)

3D Shaped Tactile Sensor

- Based on resistive haptic sensor principle
- Applied to fingertip
- Can measure normal force in all directions
- 3D printed fingertip
- Circuit board and structure are combined
- Integrated electronics
- Mechatronic Integrated Device (MID)
- Helge Ritter’s group: https://ni.www.techfak.uni-bielefeld.de/tactile

$$R \sim \frac{1}{F}$$



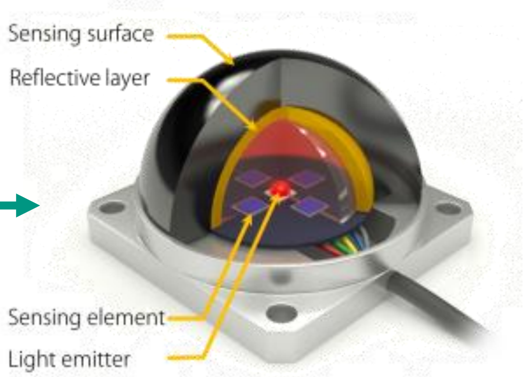
Images taken from referenced paper

Koiva, Risto, et al. "A highly sensitive 3D-shaped tactile sensor." *2013 IEEE/ASME International Conference on Advanced Intelligent Mechatronics*. IEEE, 2013.

OptoForce Sensors (no Longer Available)

- Optical sensing principle
- Infrared LED in the center
- Hollow dome
  - Elastic
  - Reflects light
- Photodiodes measure light
- Force ➔ deformation
- Measures F_x, F_y, F_z

Tactile Sensor
OMD-10-SE-10N
Nominal Capacity: 10N
Resolution: 2.5 mN



optoforce.com

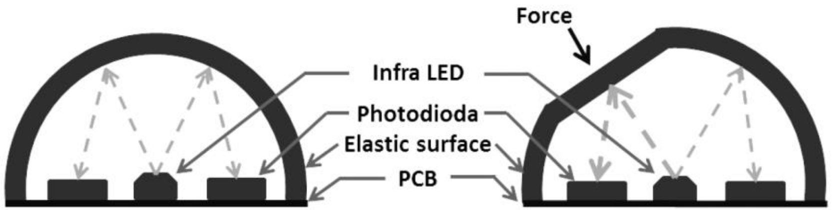


Image taken from referenced paper

Tar, Akos, and Gyùrgy Cserey. "Development of a low cost 3d optical compliant tactile force sensor." *2011 IEEE/ASME International Conference on Advanced Intelligent Mechatronics (AIM)*. IEEE, 2011.

OptoForce Sensors

Tactile Sensors are not used – Objects are crushed

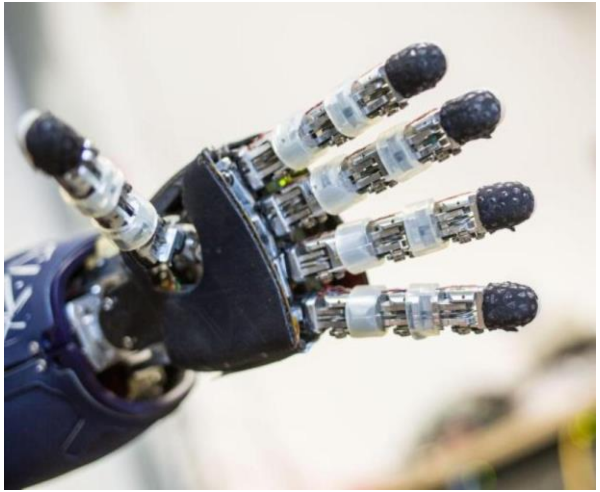
https://www.youtube.com/watch?v=ekMBor5LvVg

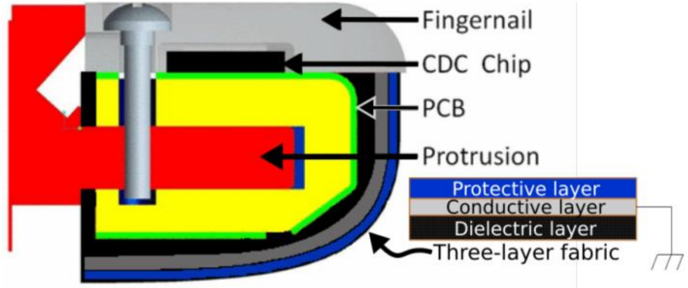
Tactile Sensors are used

https://www.youtube.com/watch?v=ekMBor5LvVg

iCub Fingertip Sensor

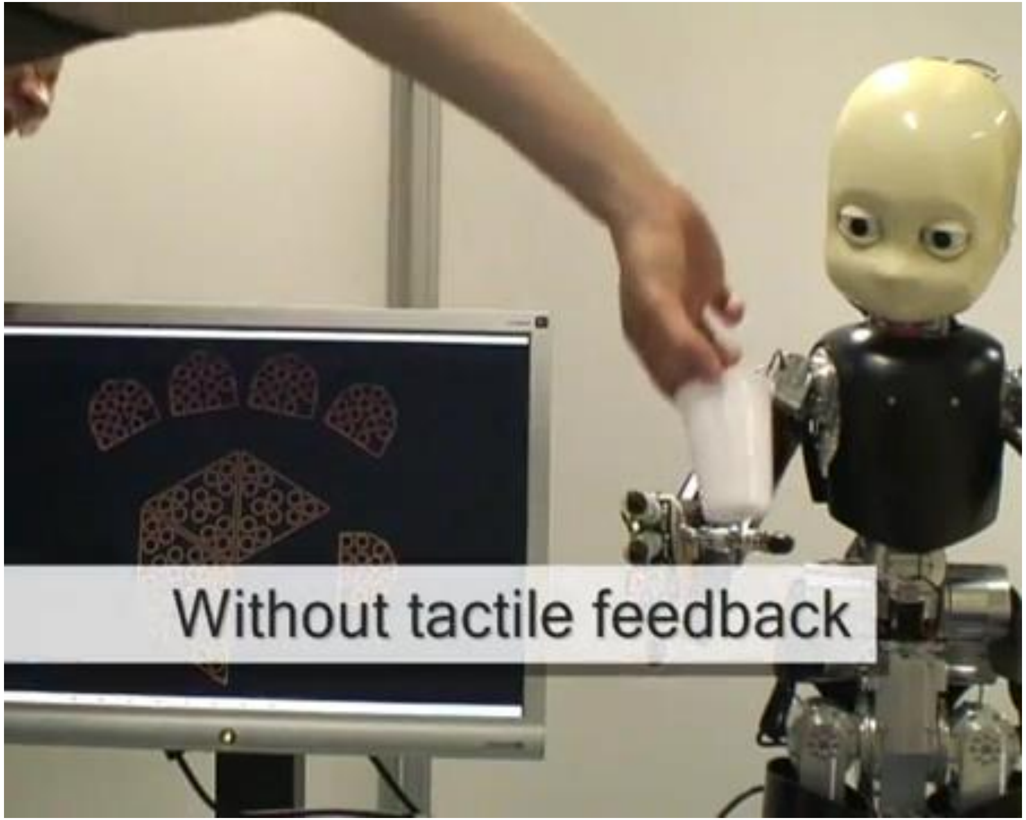
- iCub Skin measuring principle
- Miniaturized in 3D structure
- Applied to all fingers of iCub
- Sensitivity: 0.05 N





Images taken from referenced papers

iCub Fingertip Sensor

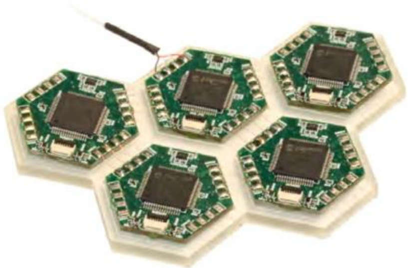


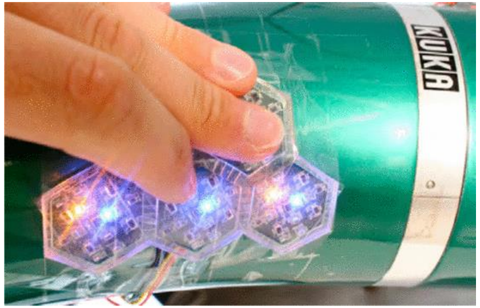
Images taken from referenced papers

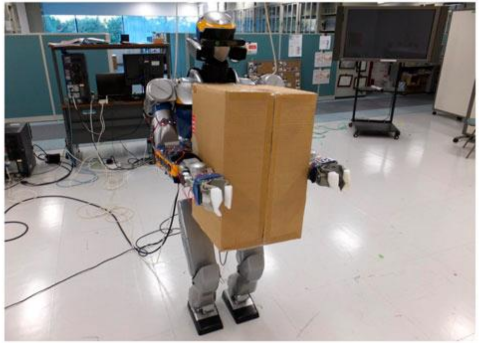
Robotic Skin

Tactile Skin HEX-O-SKIN I

- Multimodal
  - Optical proximity sensor
  - 3-axis accelerometer
  - Temperature sensing
  - Capacitive normal force sensor
  - Weight of one module: 5g
- Self-organizing structure through network redundancy
- Gordon Cheng's group: https://www.ics.ei.tum.de







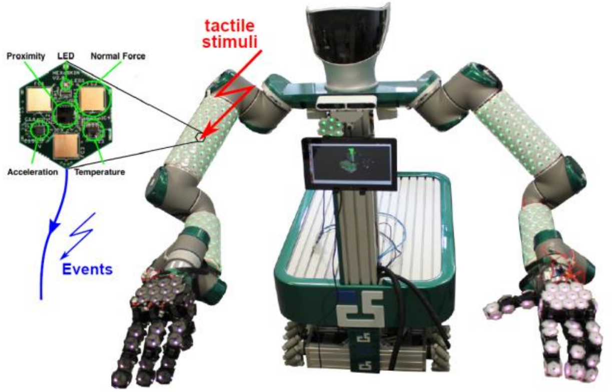
Images taken from referenced papers

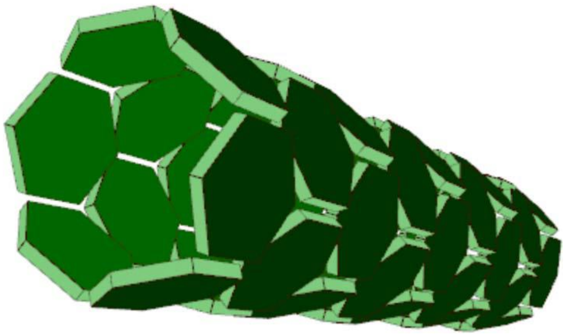
- Mittendorfer, Philipp, and Gordon Cheng. "Humanoid multimodal tactile-sensing modules." *IEEE Transactions on robotics* 27.3 (2011): 401-410.
- Mittendorfer, Philipp, and Gordon Cheng. "3D surface reconstruction for robotic body parts with artificial skins." *2012 IEEE/RSJ International Conference on Intelligent Robots and Systems*. IEEE, 2012.
- Bergner, Florian, et al. "Event-based signaling for reducing required data rates and processing power in a large-scale artificial robotic skin." *2015 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*. IEEE, 2015.

Tactile Skin HEX-O-SKIN II

- Mechanical structure (body schema) of the robot can be inferred by the skin
  - All modules are connected
  - The topology of the skin can be derived from the network routing
  - Relative orientation of the modules can be derived from the accelerometer values

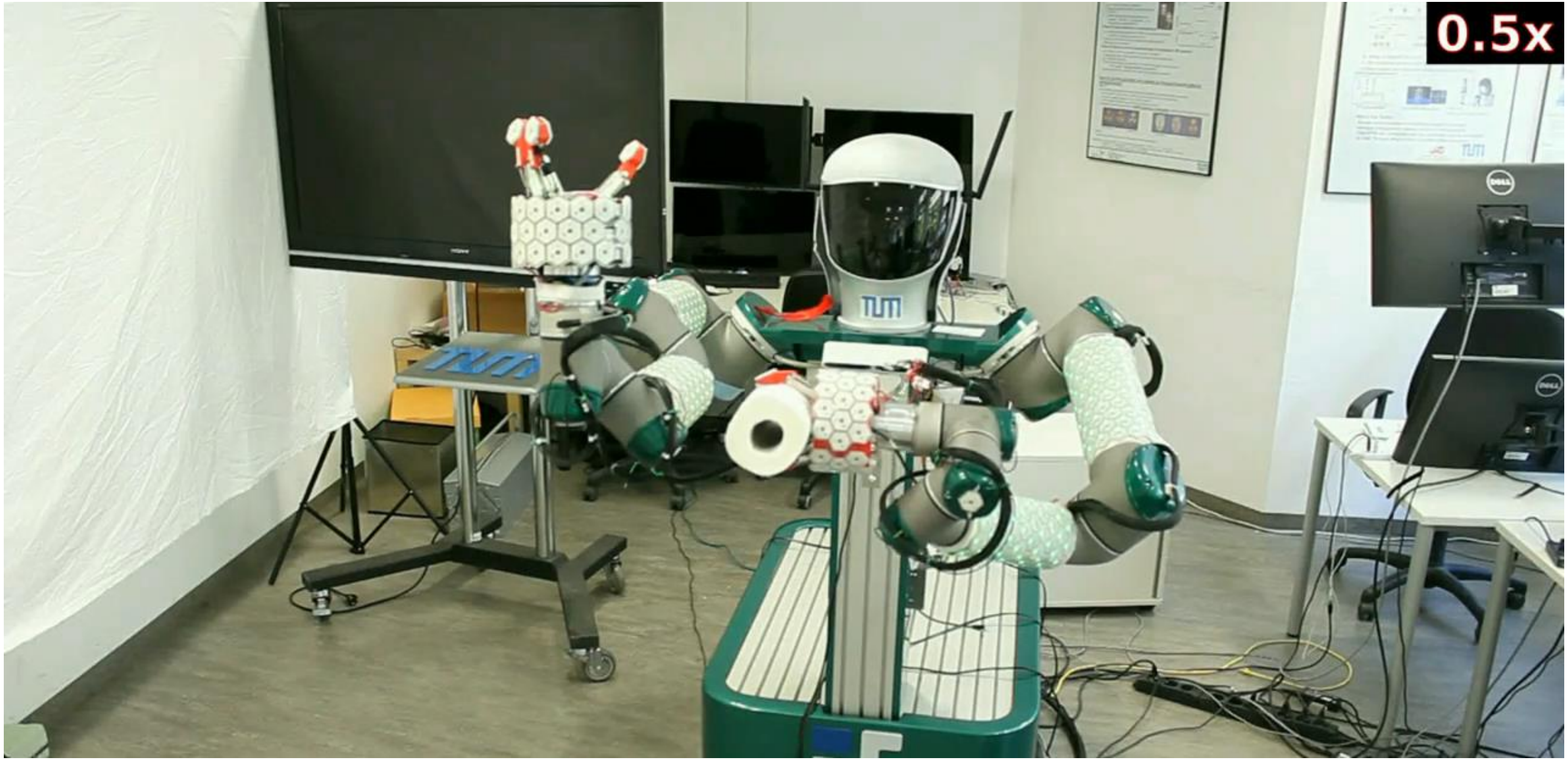
➔ Complete shape of the skin can be derived without additional input





Images taken from referenced papers

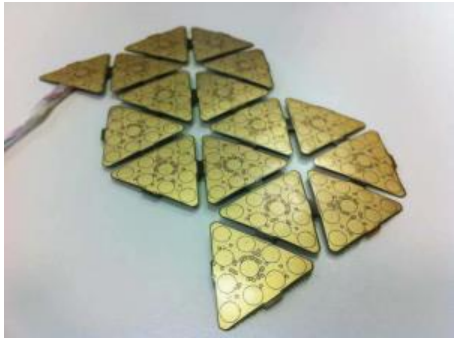
Tactile Skin HEX-O-SKIN III



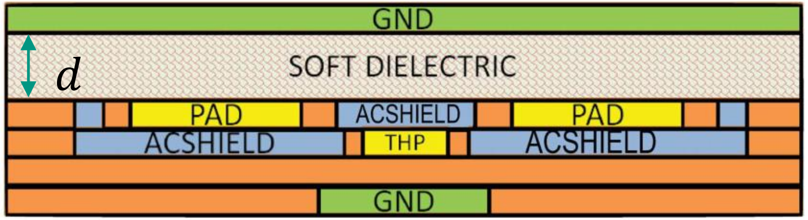
Images taken from referenced papers

iCub Skin I

- Triangular modular structure
- Capacitive sensing
  - When force is applied a soft dielectric is compressed
- Cells are interconnected -> Sensing network transports contact information



$$C \sim \frac{1}{d}$$

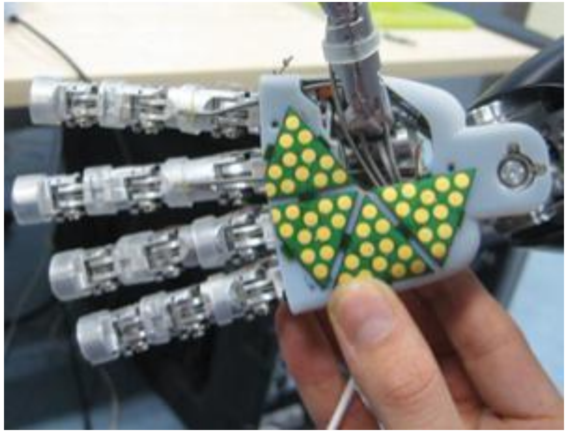


Images taken from referenced papers

- Jamali, Nawid, et al. "A new design of a fingertip for the iCub hand." *2015 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*. IEEE, 2015.
- Maiolino, Perla, et al. "A flexible and robust large scale capacitive tactile system for robots." *IEEE Sensors Journal* 13.10 (2013): 3910-3917.
- Schmitz, Alexander, et al. "Methods and technologies for the implementation of large-scale robot tactile sensors." *IEEE Transactions on Robotics* 27.3 (2011): 389-400.

iCub Skin II

- Large parts of the humanoid robot iCub are covered with the tactile skin
  - Torso, Arms, Legs, Palms, Fingers
- Tactile skills
  - Collision detection
  - Self-Calibration
  - Tactile based guidance



Images taken from referenced papers

iCub Skin III

- Tactile based guidance:

Images taken from referenced papers

iCub Skin – Robotics homunculus

- Sensory map:

Robotic homunculus: Learning of artificial skin representation in a humanoid robot motivated by primary somatosensory cortex

Matěj Hoffmann[1,2*], Zdeněk Straka[2],
Igor Farkaš[3], Michal Vavrečka[4], Giorgio Metta[1]

1 iCub Facility, Istituto Italiano di Tecnologia, Genova, Italy
2 Department of Cybernetics, Faculty of Electrical Engineering, Czech Technical University in Prague, Czech Republic
3 Centre for Cognitive Science, Department of Applied Informatics, Faculty of Mathematics, Physics and Informatics, Comenius University in Bratislava, Slovak Republic
4 Faculty of Electrical Engineering, Czech Technical University in Prague, Czech Republic

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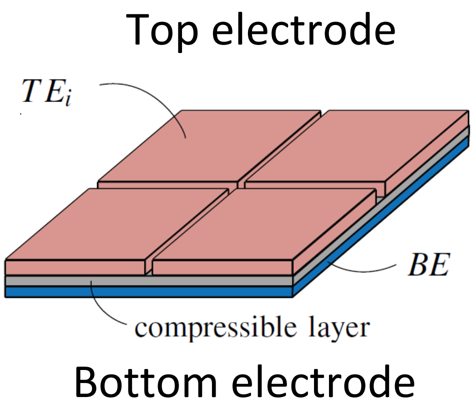
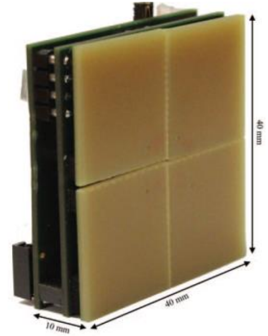
Appears in: IEEE Transactions on Cognitive and Developmental Systems, 2017
DOI: 10.1109/TCDS.2017.2649225

Images taken from referenced papers

Tactile Proximity Sensor I

- Developed at IPR, KIT
- Combined proximity and tactile sensor
- Integrated signal processing
- Two modes
  - **Proximity mode:** Signal is transmitted and response of environment is measured
  - **Tactile mode:** Deformation of the compressible layer is measured



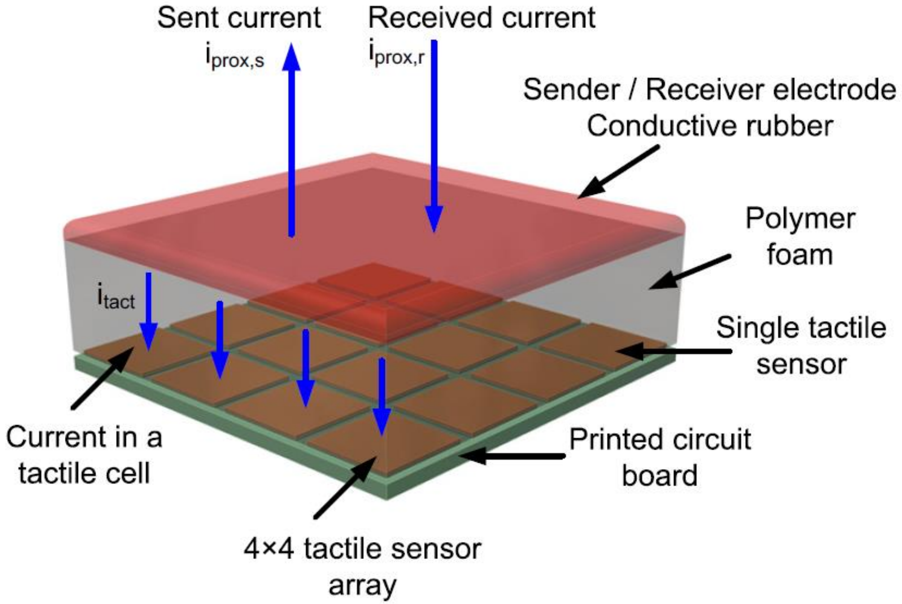


Images taken from referenced papers

- Alagi, Hosam, et al. "A versatile and modular capacitive tactile proximity sensor." *2016 IEEE Haptics Symposium (HAPTICS)*, 2016
- Escaida Navarro, Stefan, et al. "Flexible Spatial Resolution for Preshaping with a Modular Capacitive Tactile Proximity Sensor." *IEEE/RSJ International Conference on Intelligent Robots and Systems, 2016*

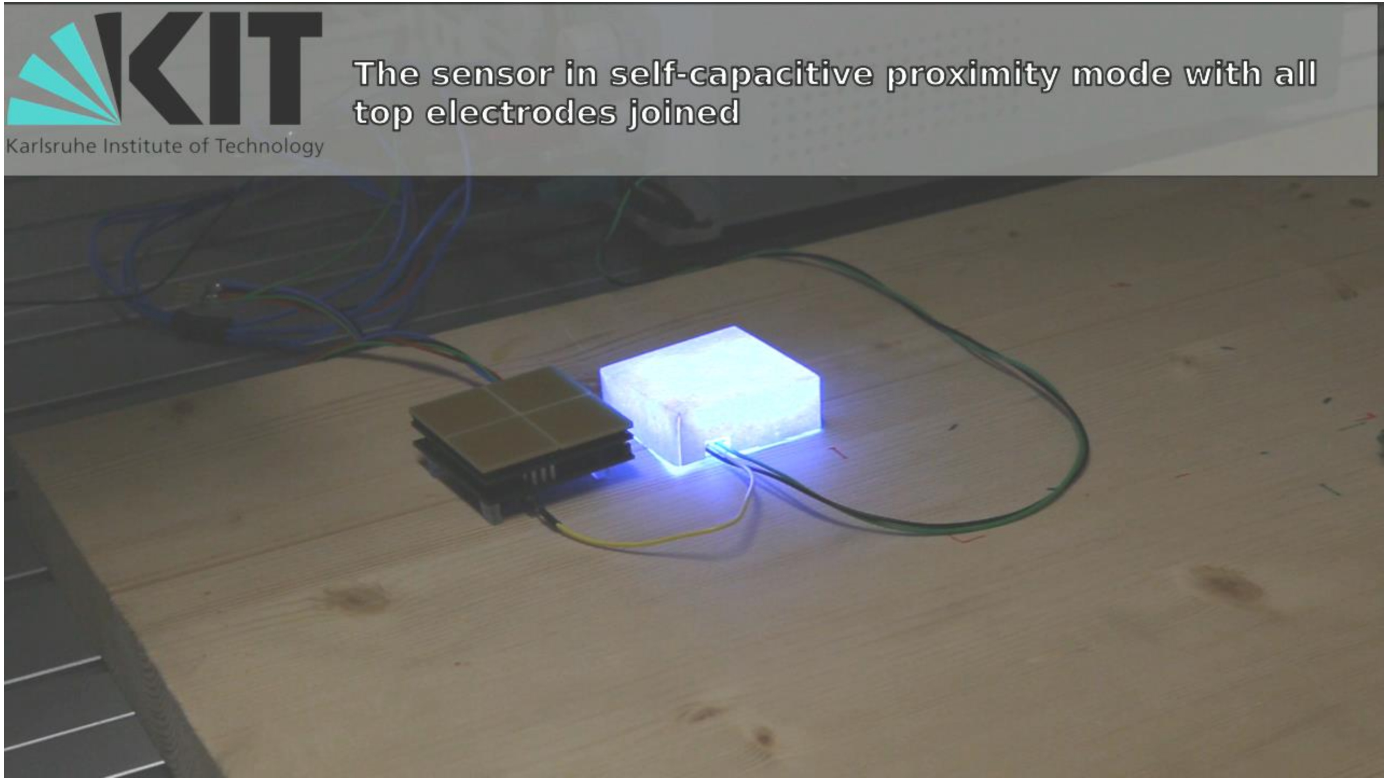
Tactile Proximity Sensor II

- Tactile skin for collaborative robots (Cobots)
- Proximity sensing
  - Sensor measures distance to humans and environment
  - Robot avoids collisions before they occur
- Tactile sensing
  - Sensor measures contact forces
  - Robot can be guided or taught by human



Images taken from referenced papers

Tactile Proximity Sensor III

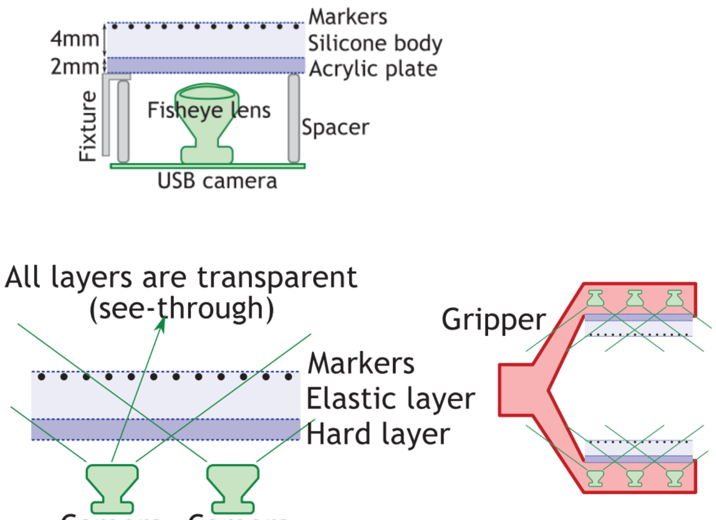


Images taken from referenced papers

Camera-based Tactile Sensors

FingerVision I

- Transparent skin
  - Two layers: hard and soft
  - Markers on soft layer
- Camera behind the skin
  - See through skin
  - Track markers
- Force/Torque measurement
  - 3-axis force measurement at each marker position
  - Estimate torque based on multiple markers



(a) Skin structure
(b) Installation on gripper

Images taken from referenced paper

Yamaguchi, Akihiko, and Christopher G. Atkeson. "Combining finger vision and optical tactile sensing: Reducing and handling errors while cutting vegetables." *2016 IEEE-RAS 16th International Conference on Humanoid Robots (Humanoids)*. IEEE, 2016.

FingerVision II

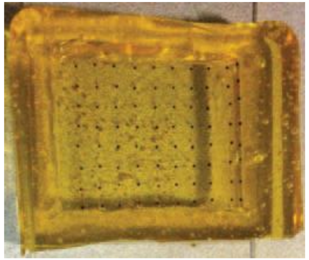
Force estimation

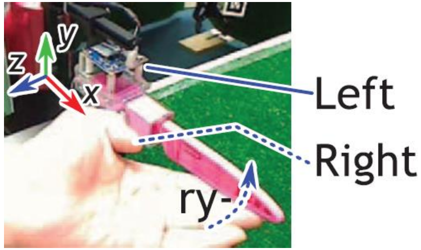
- Blob detection with OpenCV
- Store initial marker positions:
  $p_{i,0} = [p_{i,0,x}, p_{i,0,y}, p_{i,0,z}]$
- Capture current maker positions
  $p_{i,c} = [p_{i,c,x}, p_{i,c,y}, p_{i,c,z}]$
- Calculate delta
  $d_i = [d_{i,x}, d_{i,y}, d_{i,z}] = p_{i,c} - p_{i,0}$
- Estimate force (with $d_{i,z} \approx \sqrt{d_{i,x}^2 + d_{i,y}^2}$)

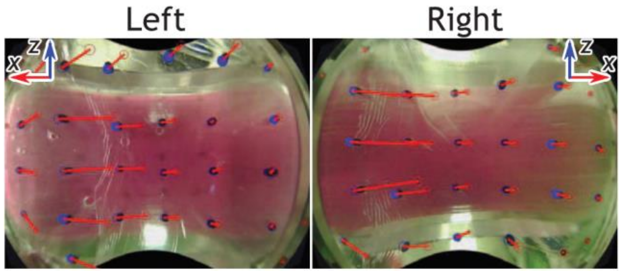
$$f_i \approx [c_x d_{i,x}, \quad c_y\sqrt{d_{i,x}^2 + d_{i,y}^2}, \quad c_z d_{i,y}]$$

(c_x, c_y, c_z … scaling factors)

Initial markers (no load)







→ **Average force**: $F = \frac{1}{N}\sum_{i=1}^{N} f_i$

Images taken from referenced paper

FingerVision III

Torque estimation

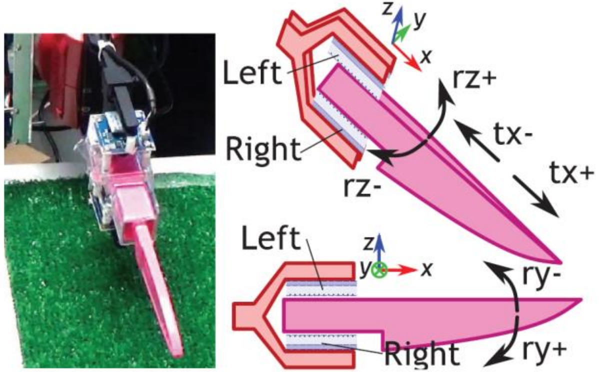
- Calculate center c of initial marker positions and relative positions r_i

$$c = \frac{1}{N}\sum_{i=1}^{N} p_{i,0} \qquad\qquad r_i = p_{i,0} - c$$

- Estimate torque for each marker

$$\tau_i = c_\tau r_i \times f_i \qquad (c_\tau \ldots \text{scaling factor})$$

→ **Average torque**: $\mathrm{T} = \frac{1}{N}\sum_{i=1}^{N} \tau_i$



Images taken from referenced paper

GelSight I

Working principle

- Object is pressed against the skin of an elastomer block
- Skin is distorted
- Measure shape using photometric stereo



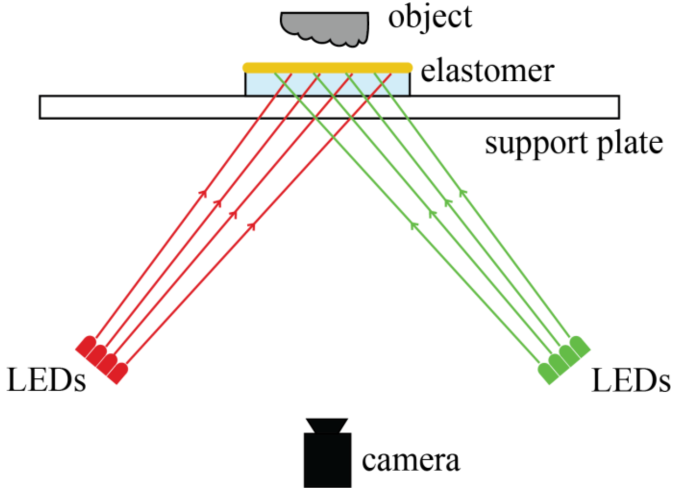
Images taken from referenced papers

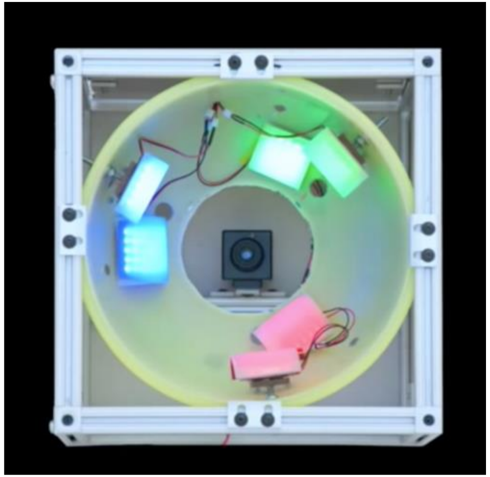
- Johnson, Micah K., and Edward H. Adelson. "Retrographic sensing for the measurement of surface texture and shape." *2009 IEEE Conference on Computer Vision and Pattern Recognition*. IEEE, 2009.
- Yuan, Wenzhen, et al. "Measurement of shear and slip with a GelSight tactile sensor." *2015 IEEE International Conference on Robotics and Automation (ICRA)*. IEEE, 2015.
- Yuan, Wenzhen, Siyuan Dong, and Edward H. Adelson. "Gelsight: High-resolution robot tactile sensors for estimating geometry and force." *Sensors* 17.12 (2017): 2762.

GelSight II

Gel deformation measurement (object surface)

- Gel is illuminated from below with RGB LEDs (LEDs for each color)
- Camera captures RGB image of the gel from below
  ➔ Calculate deformations from reflected RGB light



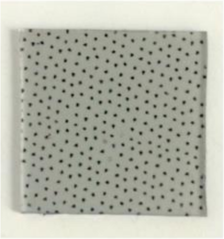


Images taken from referenced paper

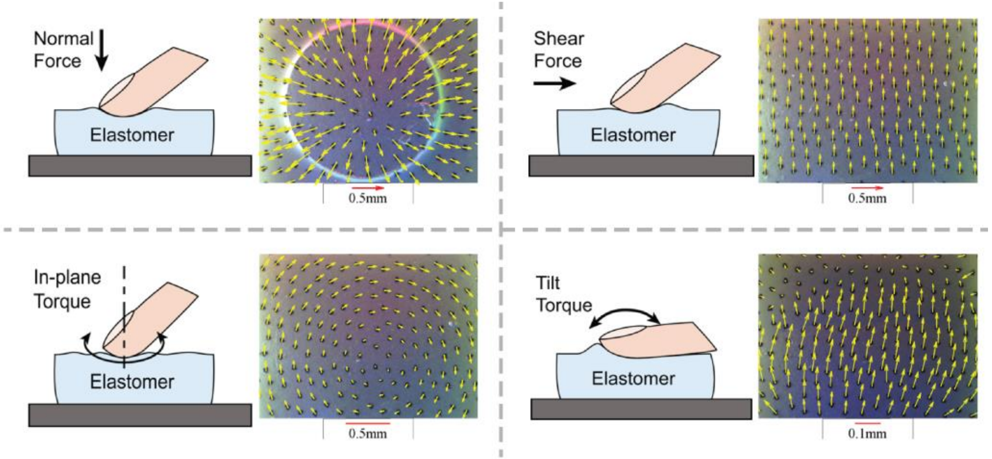
GelSight III

Normal and shear force detection

- Similar to FingerVision sensor
- Track dots on gel using the camera
- Calculate displacement



(a)



(b)

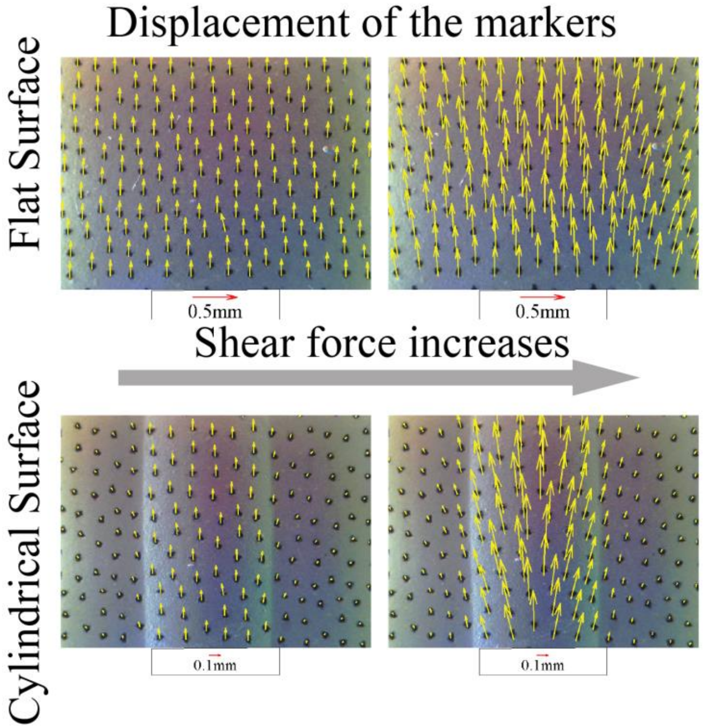
Images taken from referenced papers

GelSight IV

Shear detection

- Flat surface
  ➔ all markers are displaced
- Cylinder
  ➔ some markers are displaced

- Displacement magnitude correlates with shear force

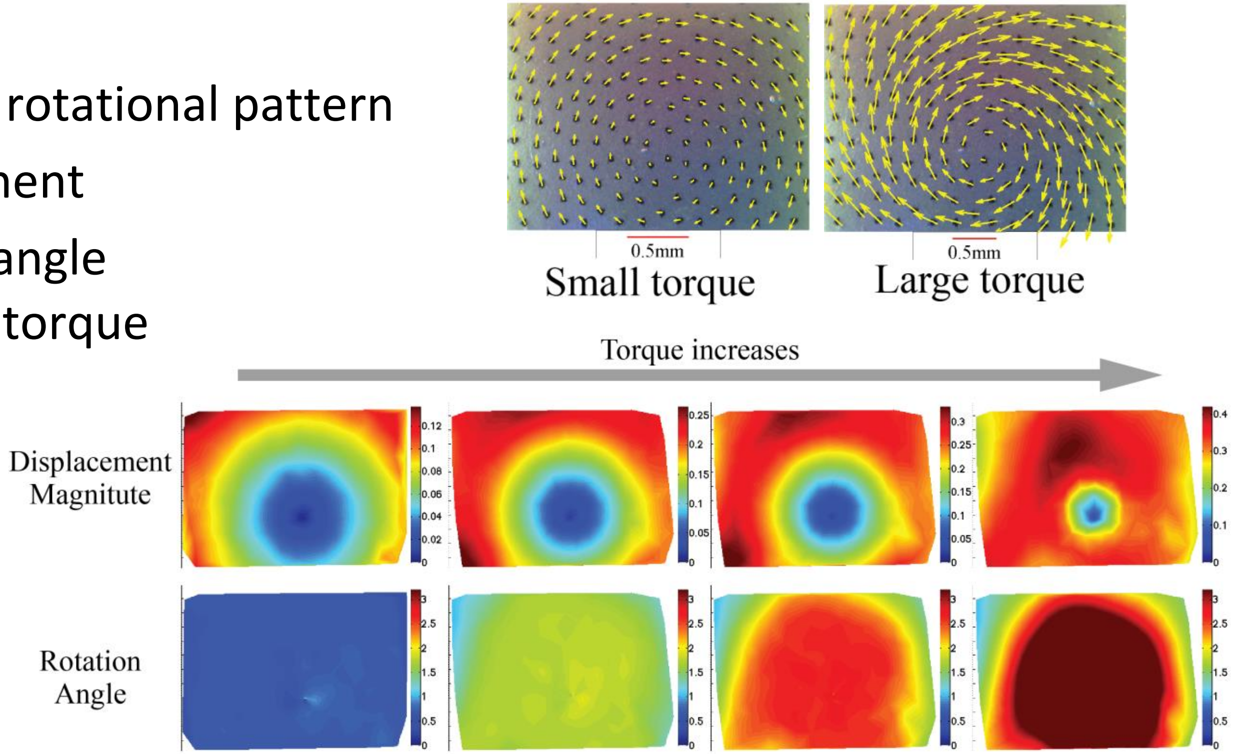


Images taken from referenced papers

GelSight V

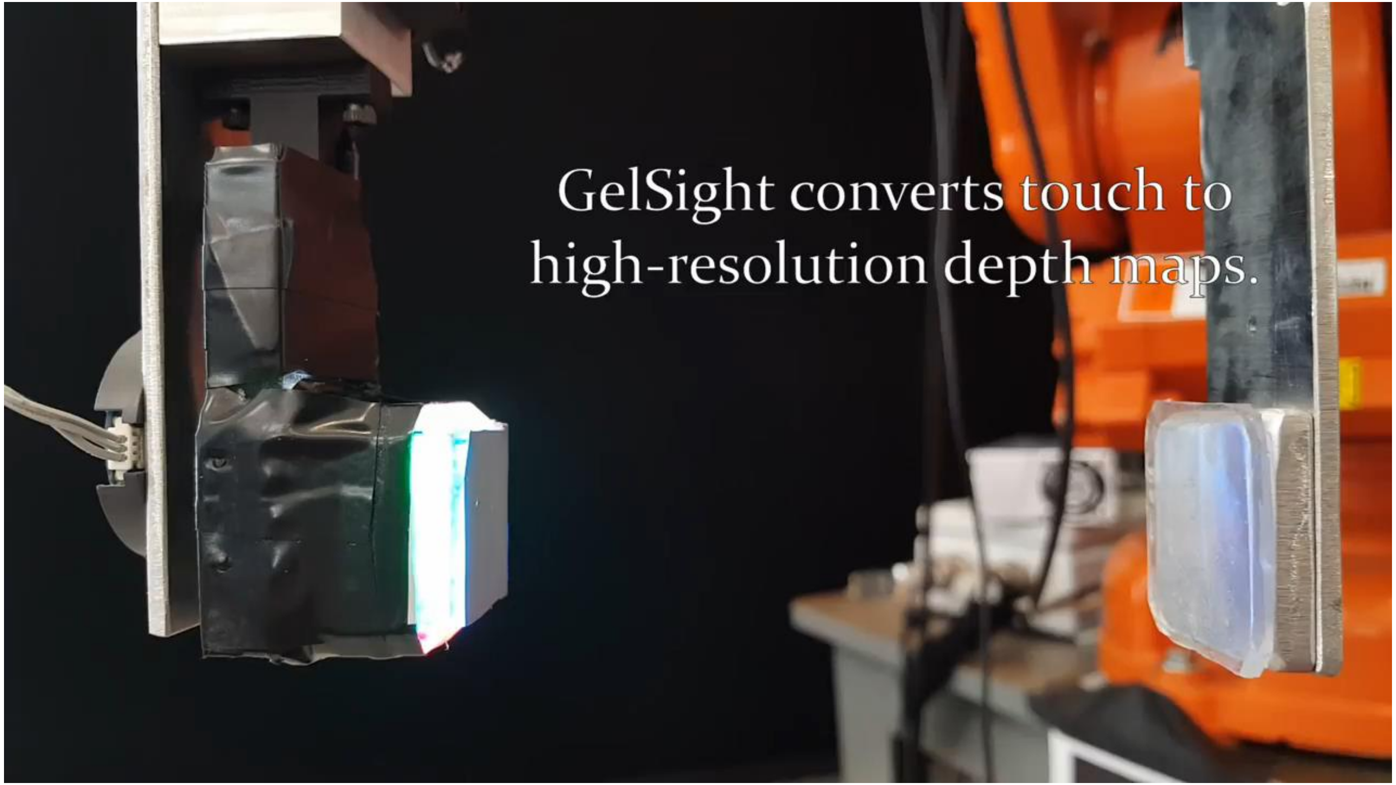
Torque detection

- Markers move in a rotational pattern
- Measure displacement
- Calculate rotation angle
  ➔ proportional to torque



Images taken from referenced papers

GelSight VI

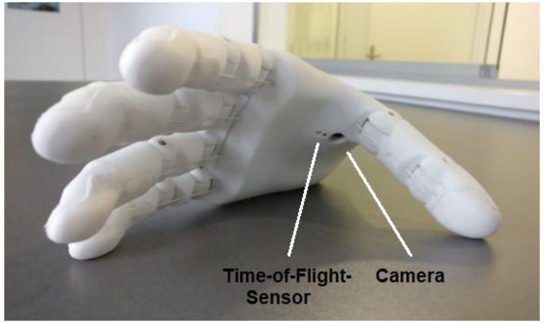


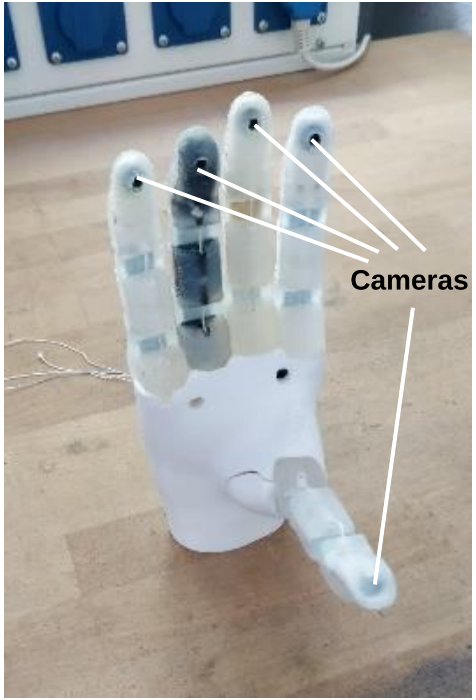
https://www.youtube.com/watch?v=BIW_jq3dOEE

In-Hand Vision @ H^2T

In-Hand Vision

- **Goal:** Obtain visual feedback from the hand to improve the grasping success
- **Applications:**
  - **Prosthetics:** Support user by semi-autonomous hand functions based on visual feedback
  - **Robotics:** Supplement external vision with local object information





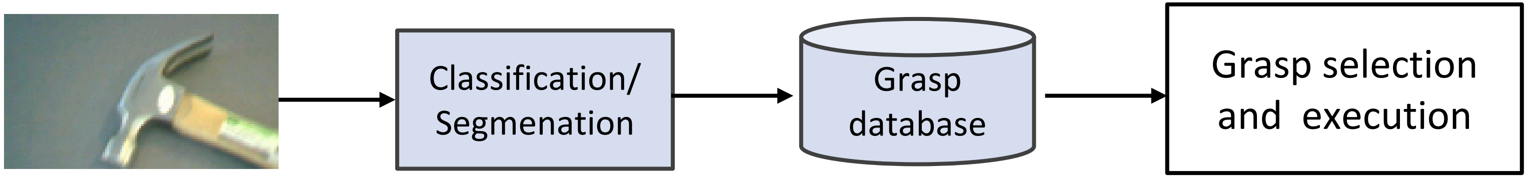
In-Hand Vision: Semi-autonomous Prosthetic Hand I

- Typically prosthetic hands controlled by 2-channel EMG-interface
  - \+ Robust
  - \+ not expensive
  - \- only primitive commands can be transmitted
  - \- user has to focus on prosthesis control

- Approach: Use methods from robotics

  → **Intelligent hand prosthesis**

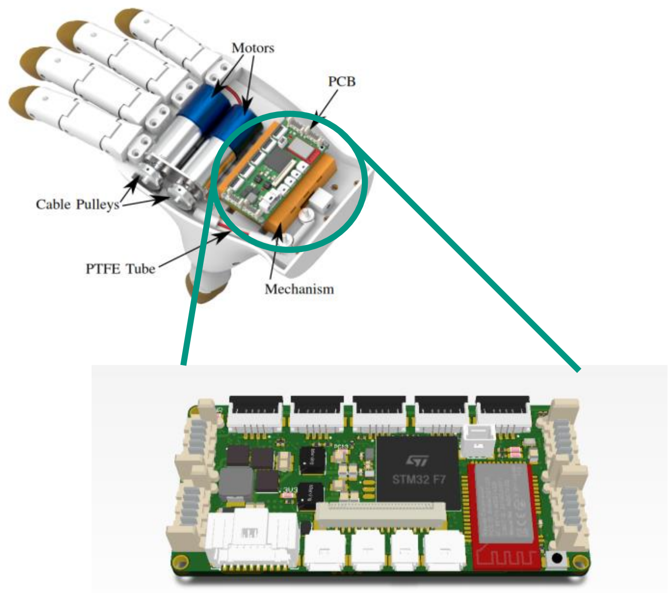
  - Realize semi-autonomous control: Object classification + segmentation



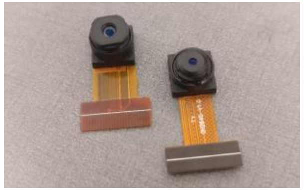
Camera Image

In-Hand Vision: Semi-autonomous Prosthetic Hand II

- Hand-internal camera and data processing hardware:



- Camera: 2M Pixel miniature camera

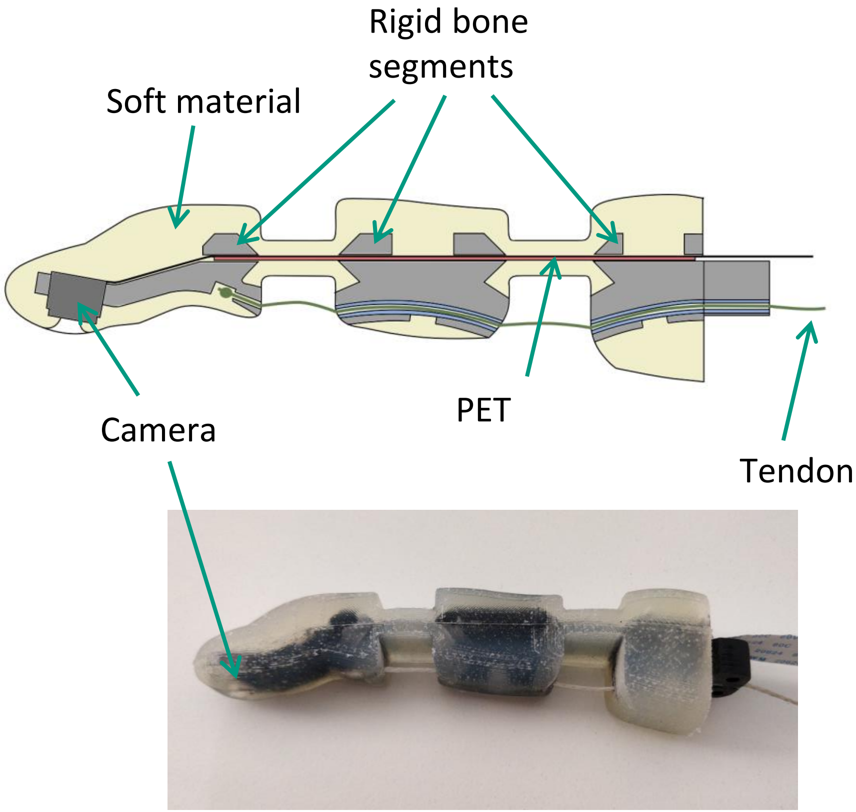


- Embedded data processing hardware:
  - ARM Cortex H7
  - 400MHz
  - 2 MB Flash, 1MB RAM
- optimization of CNN architecture for resource-aware operation and real-time inference

Hundhausen, Felix, et al. "Resource-Aware Object Classification and Segmentation for Semi-Autonomous Grasping with Prosthetic Hands" Humanoids (2019)

In-Hand Vision: In-Finger-Vision

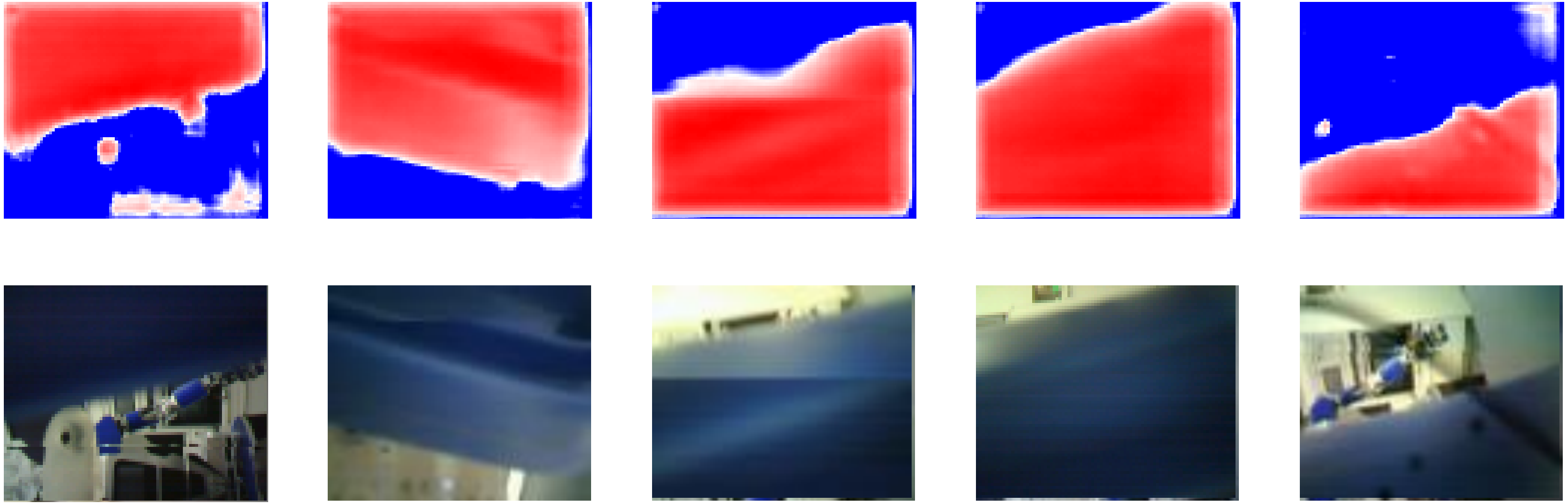
- Integration of cameras inside of fingertips:
  - Tendon actuated soft-finger
  - Flat-flex cable follows a non tensile, bendable pet strip
  - Hand internal programmable logic (FPGA) provides 5 parallel camera interfaces
  - Objects can be located during grasping



Hundhausen, Felix, et al. "A Soft Humanoid Hand with In-Finger Visual Perception"; submitted

In-Hand Vision: In-Finger-Vision

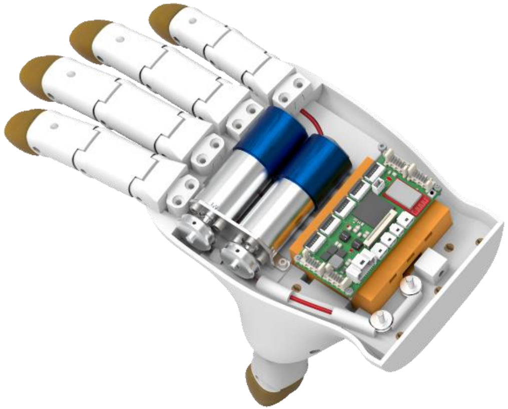
- In-finger perception
  - Object segmentation with Encoder-Decoder CNN:



Tactile Sensing @ H^2T

Tactile Sensing for Prosthetic and Robotic Hands - Challenges

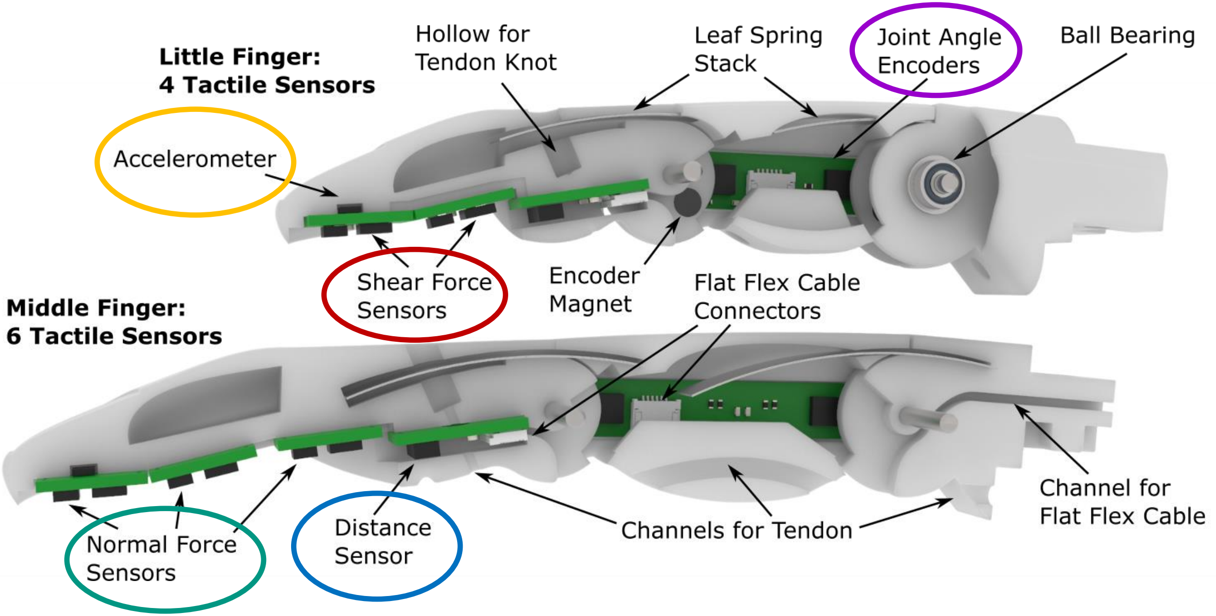
- Integrate a multimodal sensor system/embedded system into an anthropomorphic hand to support grasping
  - Space is very limited
  - Electrical contacts need to be embedded into narrow fingers/joints
  - The hand should be personalizable for different persons and sizes



Sensorized Robotic Fingers – Modalities I

- Joint Angle encoders
- Distance Sensors
- Accelerometers

- **Tactile sensors**
  - Normal force sensors (MEMS barometers)
  - Shear forces sensors (Hall-effect sensors)



Weiner, Pascal, et al. "An Embedded, Multi-Modal Sensor System for Scalable Robotic and Prosthetic Hand Fingers." *Sensors* 20.1 (2020): 101.

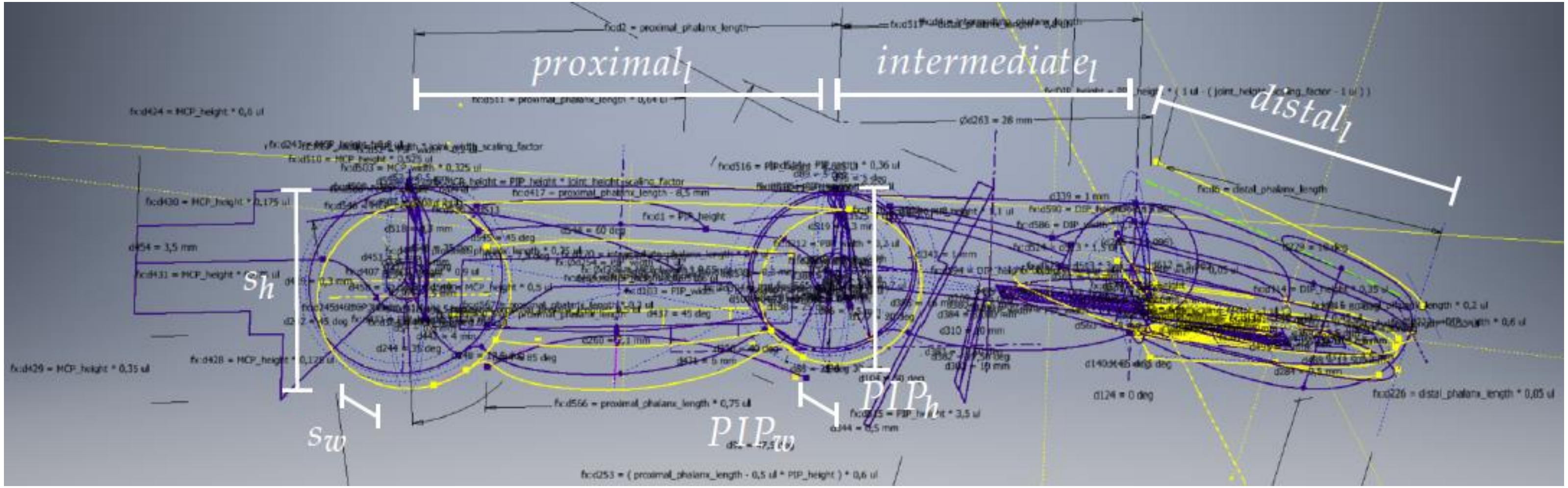
Sensorized Robotic Fingers – Modalities II

Rationale for the inclusion of the sensor modalities:

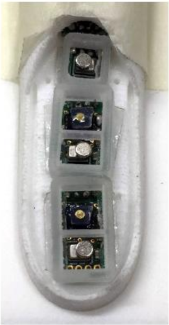
- Joint angle sensors: Finger positions in underactuated hands can not be inferred by motor relative encoders
- Distance sensing: Measure distance to the object when approaching it
- Accelerometer: Used to detect vibrations induced by slip
- Normal and shear force sensors: Needed to control the grasping force for fragile objects

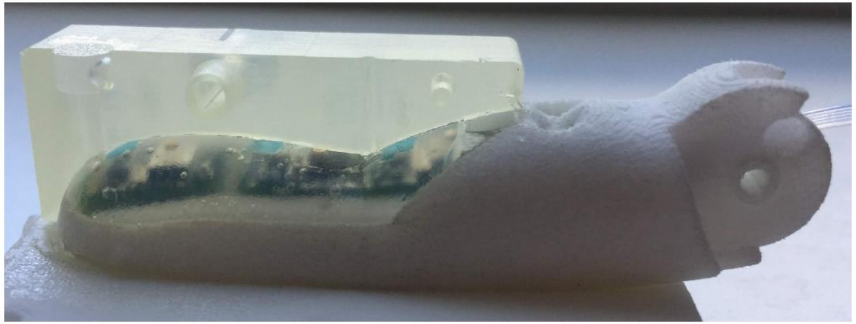
Sensorized Fingers - Scalability

- **Scalability** is very important for **prosthetic applications**
- Individual sizes are realized using a **parametric CAD-model** and **3D-printing**
  - A few high level parameters control every dimension through formulas
  - **Electronics** is made out of **small modules** (longer finger → more modules)



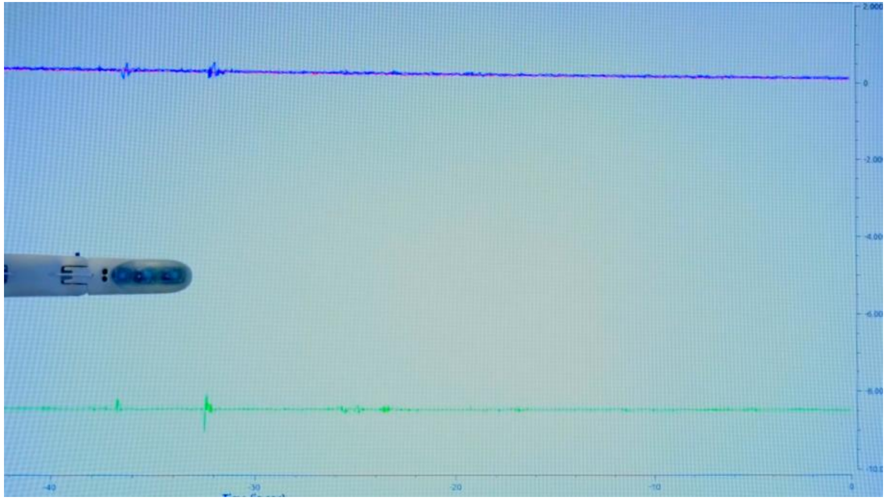
Sensorized Fingers - Demonstrators





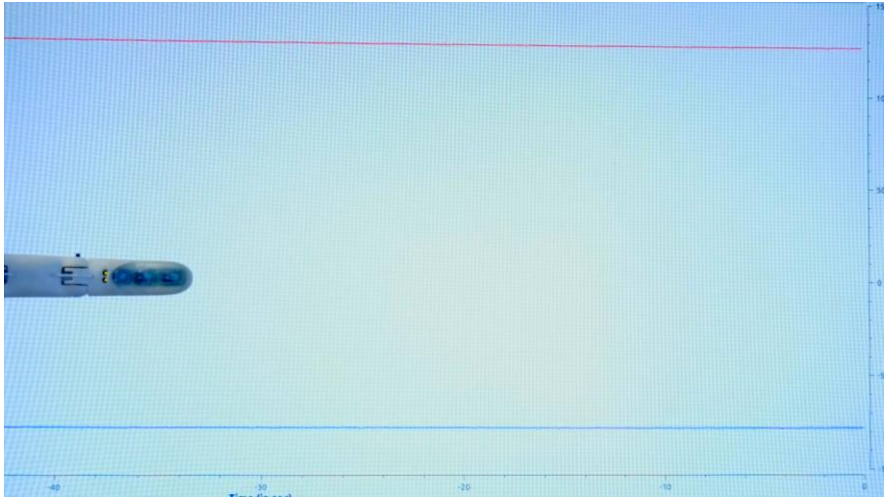
Sensorized Fingers – Measurements I

Accelerometer



Slip and dynamic contact events
Are detected trough 3-axis vibration sensing

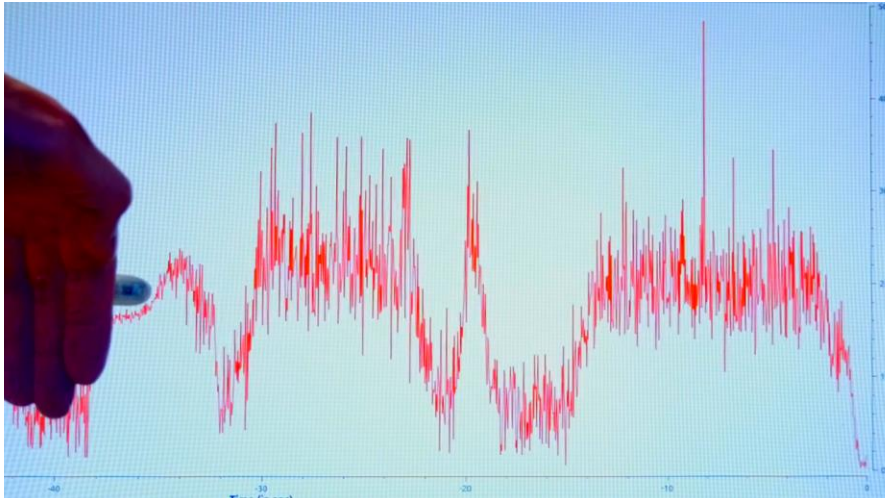
Joint Angles



The joint angle encoders are able to measure externally induced motions

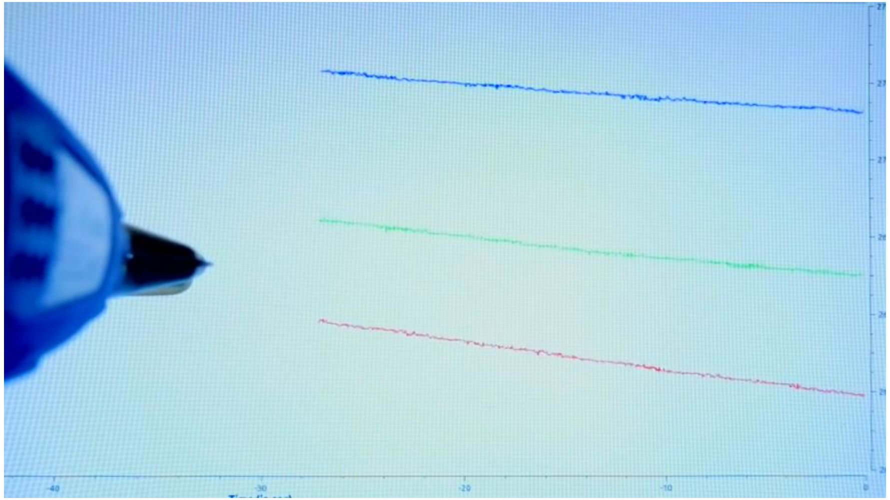
Sensorized Fingers – Measurements II

Distance



Dynamic sensing of distance (in this case to the human hand)

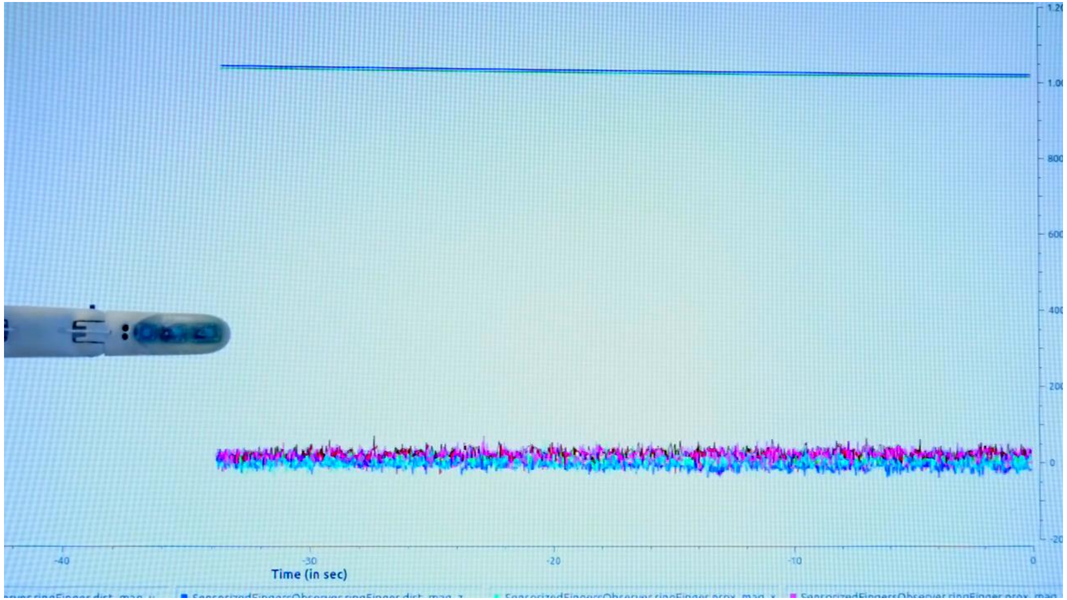
Temperature



Temperature of grasped objects (for example hot tea) can be measured (visualized with heatgun)

Sensorized Fingers – Measurements III

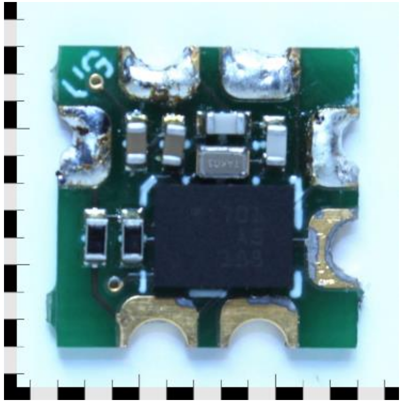
Tactile Sensors



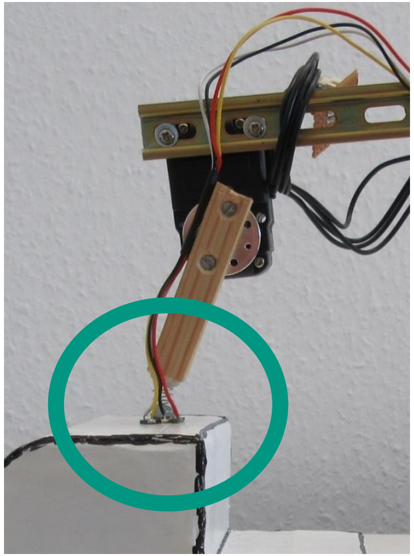
Normal and shear forces measured during a
contact event along the fingertip

Surface Normal Sensing (I)

- A state-of-the-art MEMS **inertial orientation sensor** mounted onto a robotic end-effector with a **flexible coil spring**
- The spring ensures **automatic alignment** with the contact surface
- Local surface orientation can be **measured directly**



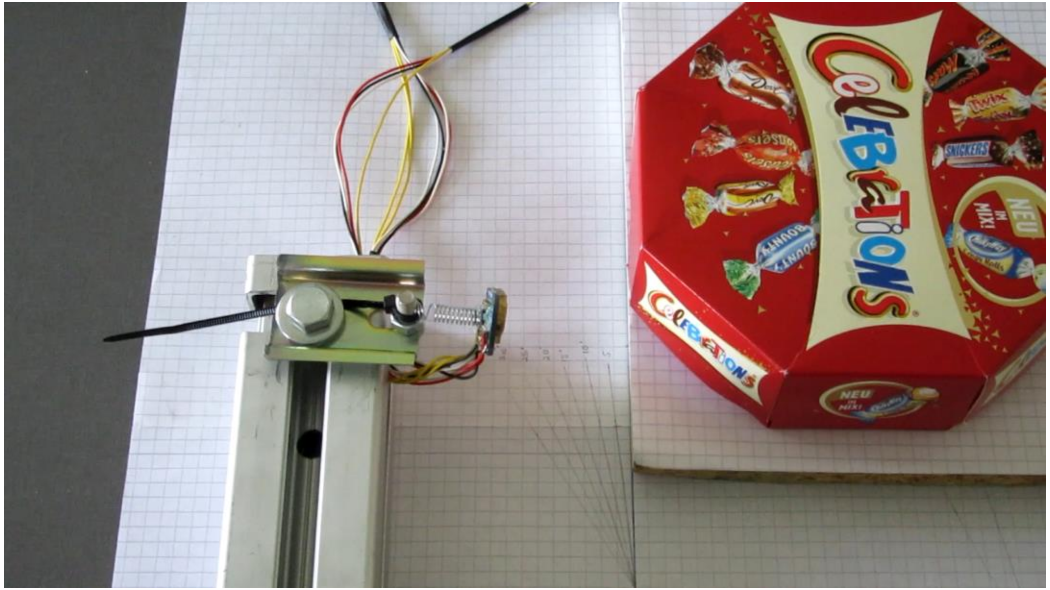
Bosch Sensortec BNO055 integrated orientation sensor on custom breakout board (scale in mm)

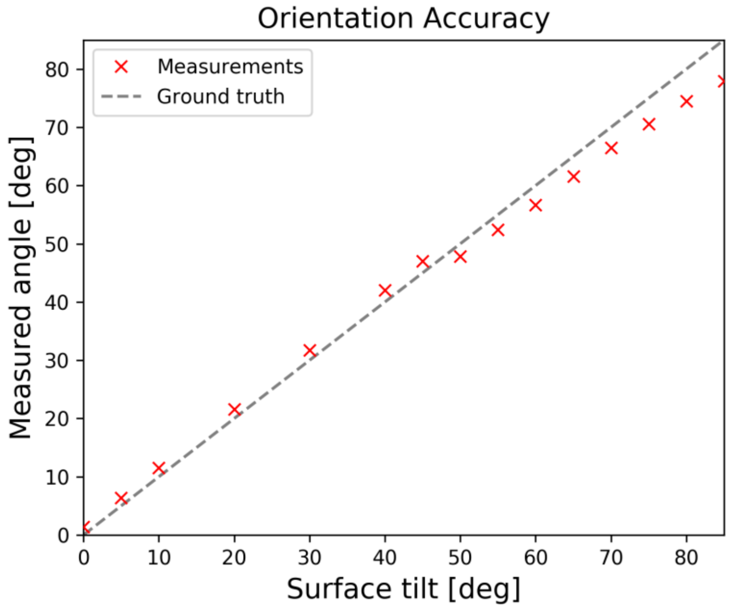


Kaul, L., Ottenhaus, S., Weiner, P. and Asfour, T., *The Sense of Surface Orientation - A New Sensor Modality for Humanoid Robots*, IEEE/RAS International Conference on Humanoid Robots (Humanoids), pp. 820-825, 2016

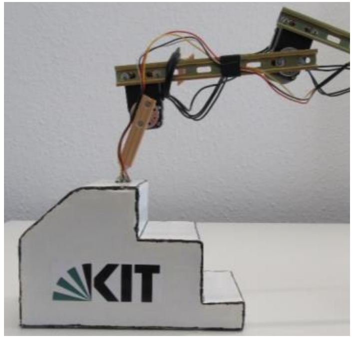
Surface Normal Sensing (II)

- The sensor **self-aligns with the local surface** due to the flexible mount
- High orientation accuracy

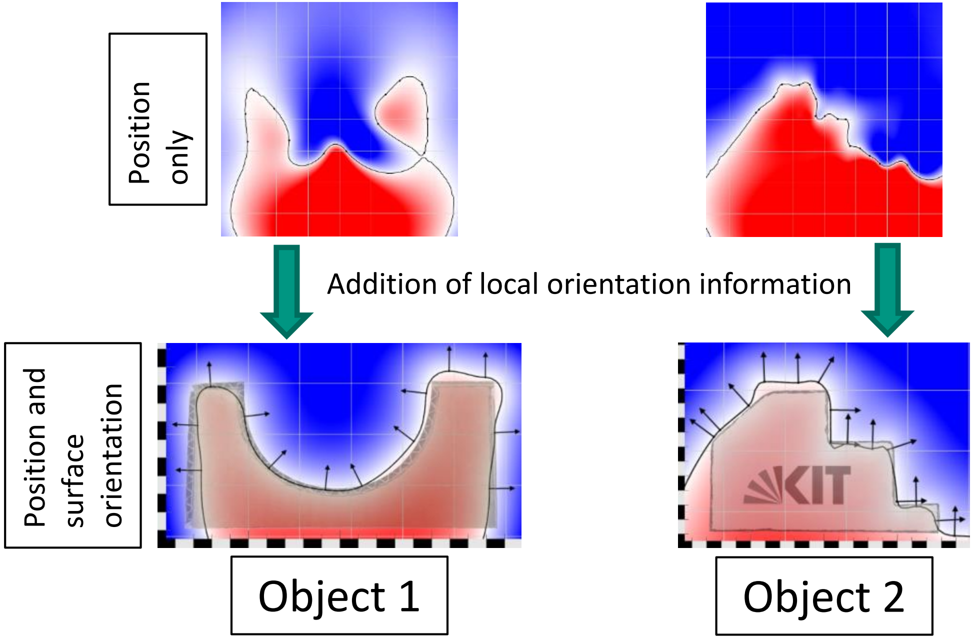




Surface Normal Sensing (III)

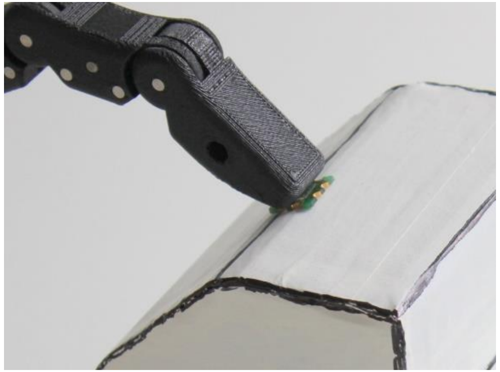


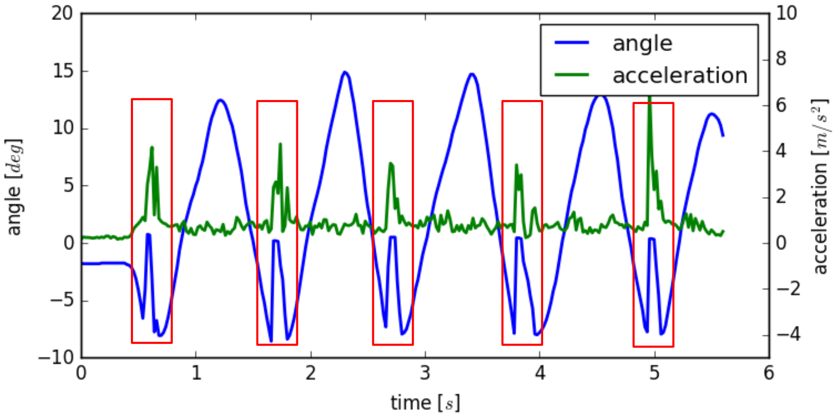
- **Two objects** explored with a 4 DOF robot arm
- Incorporation of measured local surface orientation **significantly improves shape reconstruction**



Gaussian Processes Implicit Surfaces (GPIS) for shape reconstruction

Surface Normal Sensing (IV)





- Contact with an object causes significant, almost instant changes in the **acceleration** signal, and due to the self-alignment also in the **orientation** signal
- The graph shows both, for consecutively making and breaking contact five times
- Difficult for slow or static contacts

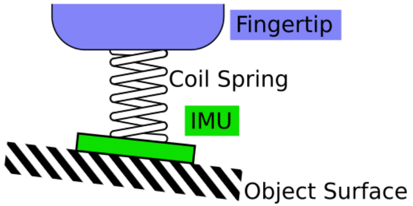
Surface Normal Sensing (V)

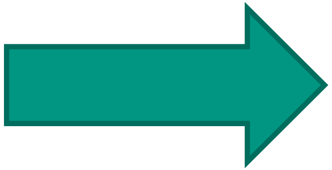
How to determine contact?

- Add MEMS barometer based normal force sensor
  - ➔ Static force sensing modality

Sensor modalities

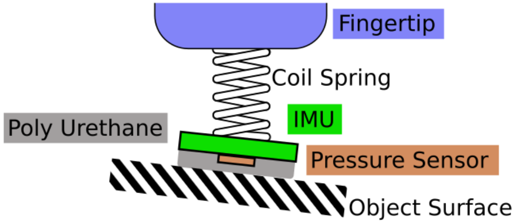
- 3D Orientation (IMU)
- 3D Linear Acceleration (IMU)





New Sensor modalities

- 3D Orientation (IMU)
- 3D Linear Acceleration (IMU)
- Static force (MEMS barometer)



Tactile Sensing and Perception

- Exciting and challenging research topic
- Mature tactile sensor technology would have huge impact on robotics and automation
  - Object exploration and reliable grasping
  - Safe human robot interaction and collaboration
- A tactile sensor system similar to human skin is a dream for robotics
- New material science driven developments: Soft (printed) tactile sensors