Soft Sensors

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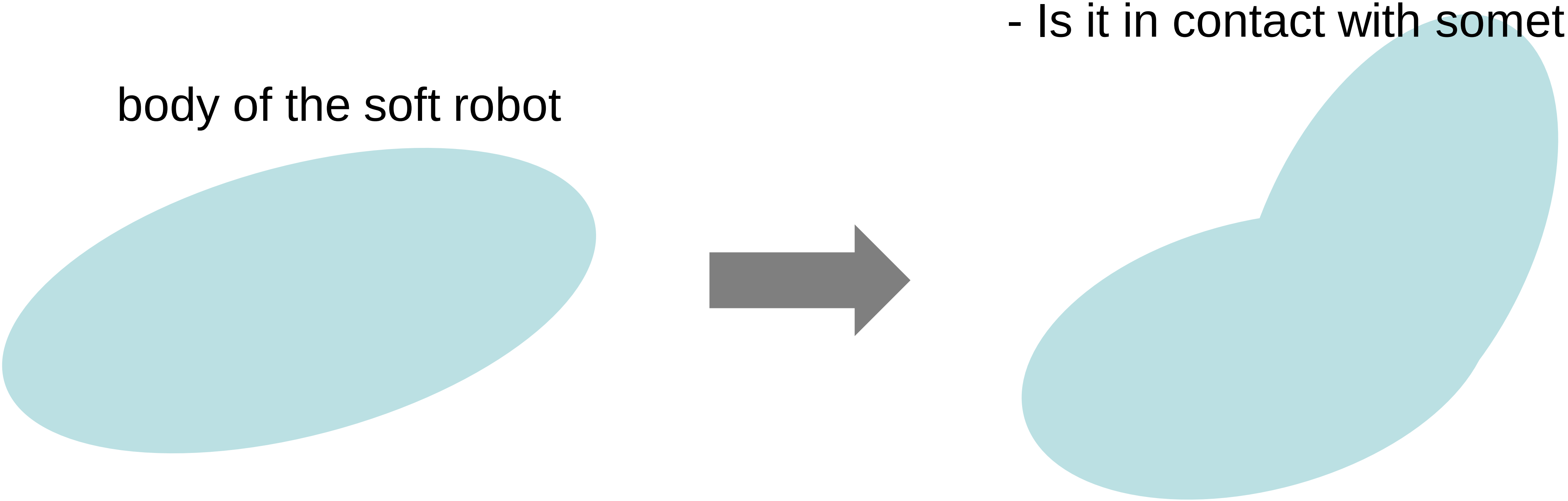
Sensor for soft robot



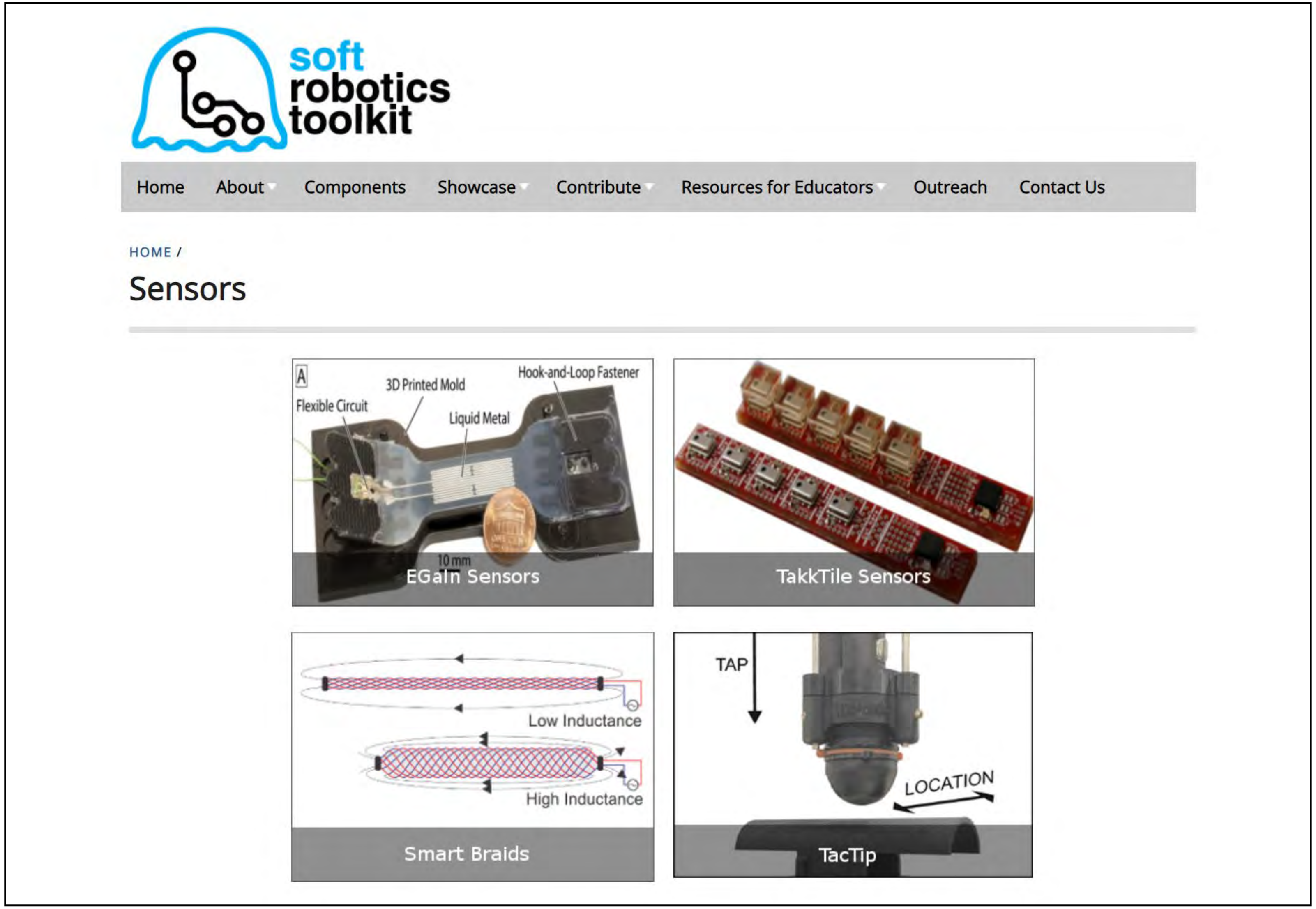
- How much bended?
- Are there external force?
- Is it in contact with something?

body of the soft robot

A sensor for soft robot should measure aspects of the robot itself or external input to the robot **without** interfering with its movement and deformation, **without** compromising softness of the robot.

Examples of soft sensors

https://softroboticstoolkit.com/sensors

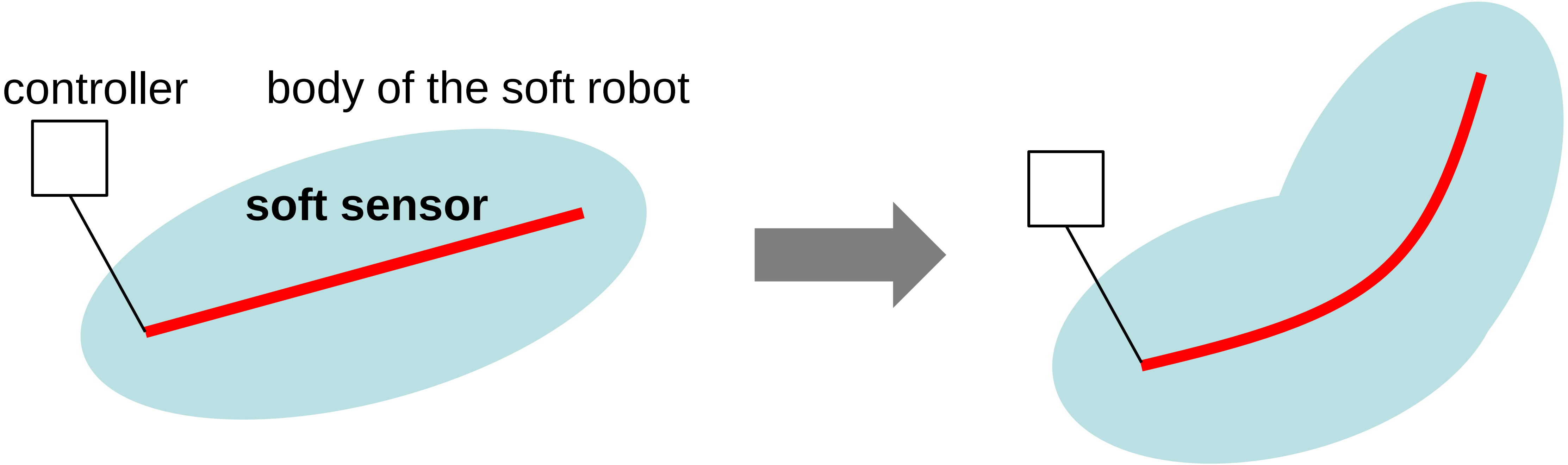


Agenda

1. Soft sensors classification
2. Resistive sensors
3. Capacitive sensors
4. Piezoelectric sensors
5. Magnetic sensors
6. Optical sensors
7. Distributed sensors for large area sensing
8. Camera based sensors

Classification by sensor form and installation

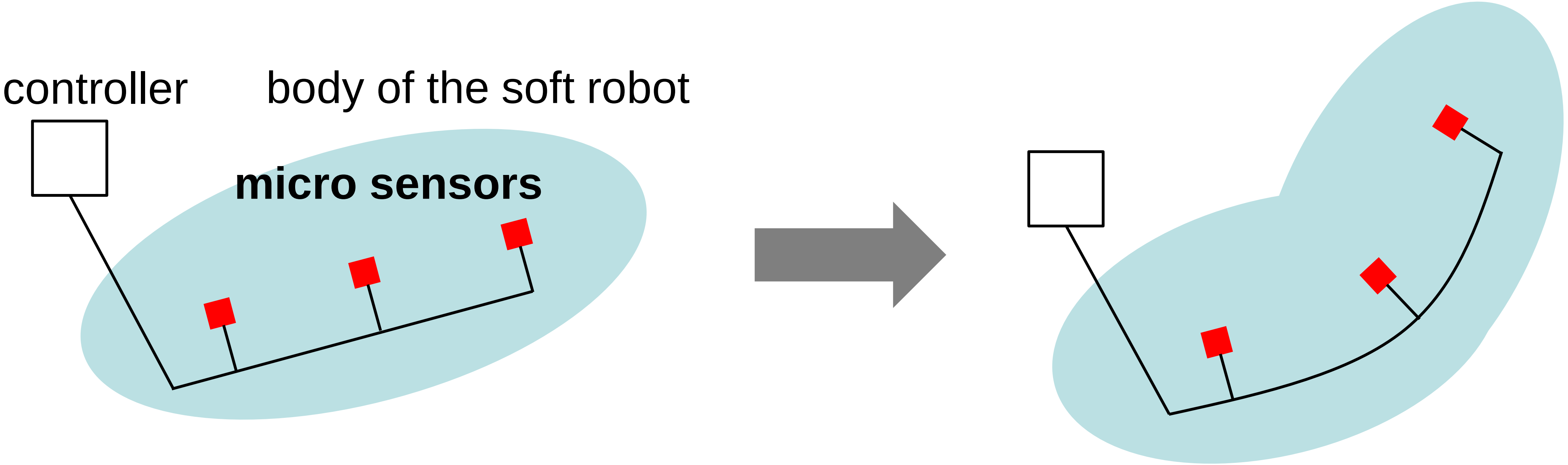
1) Embed soft and deformable sensors inside the body of the soft robot



- The sensor can measure deformation of the body such as stretching and bending.
- The sensor should be soft enough not to affect the deformation of the soft robot.

Classification by sensor form and installation

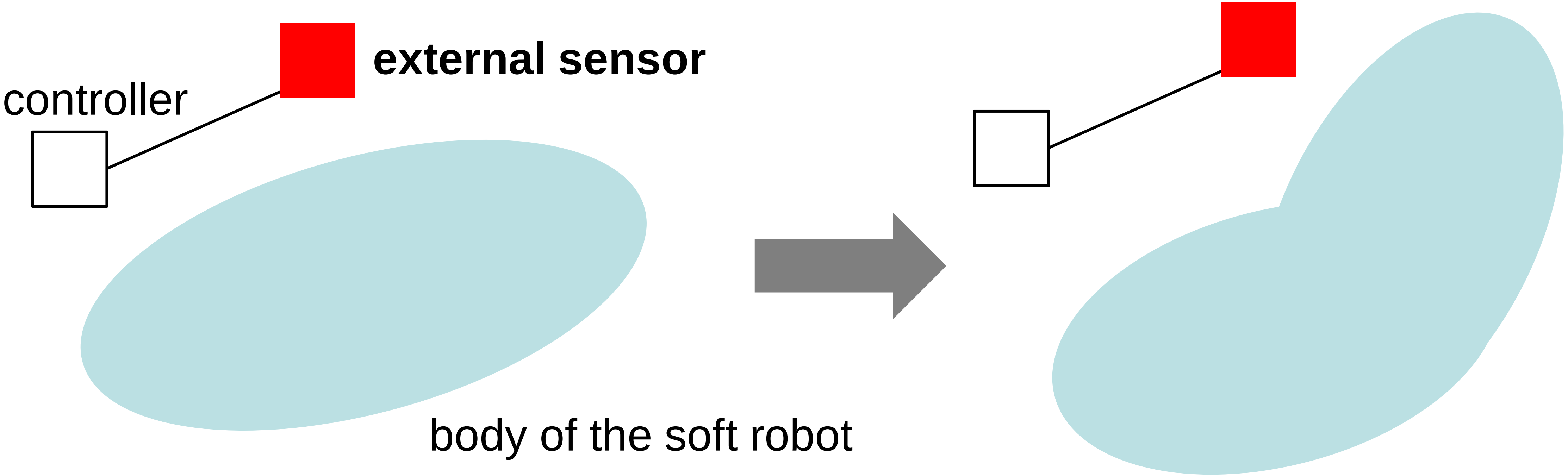
2) Embed micro-scaled sensors inside the body of the soft robot



- each sensor can measure something information at each location.
- fabricated by MEMS (micro electro-mechanical system) technology

Classification by sensor form and installation

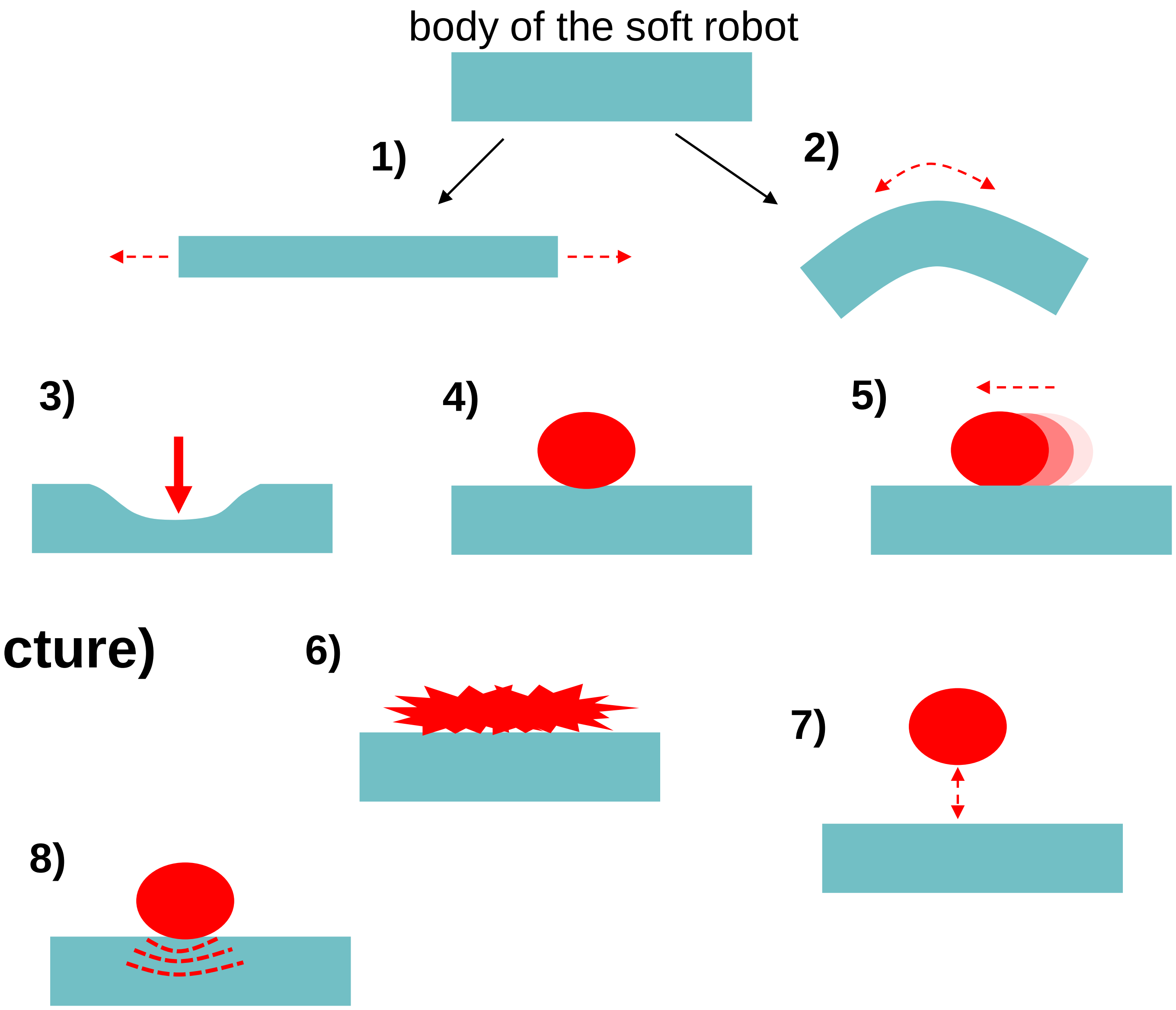
3) Put external sensor outside the body of the soft robot



- Typical external sensor is 2D/3D camera
- can measure the state of surface, shape, position and motion

Classification by physical quantities to be measured

- **1) stretching**
- **2) bending**
- **3) force**
- **4) contact**
- **5) slip**
- **6) Texture (surface microstructure)**
- **7) Proximity**
- **8) Temperature**



Classification by sensing principle

- Resistive sensor

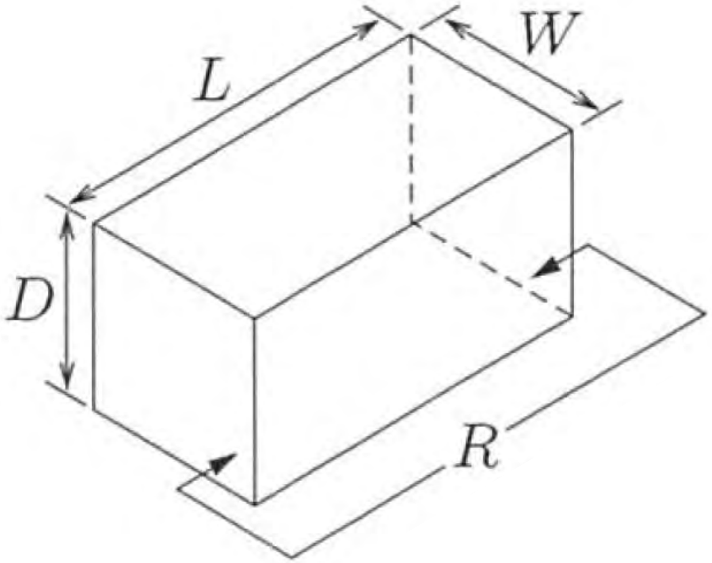
- Capacitive sensor

- Piezoelectric sensor

- Magnetic sensor

- Optical sensor

Resistive sensor



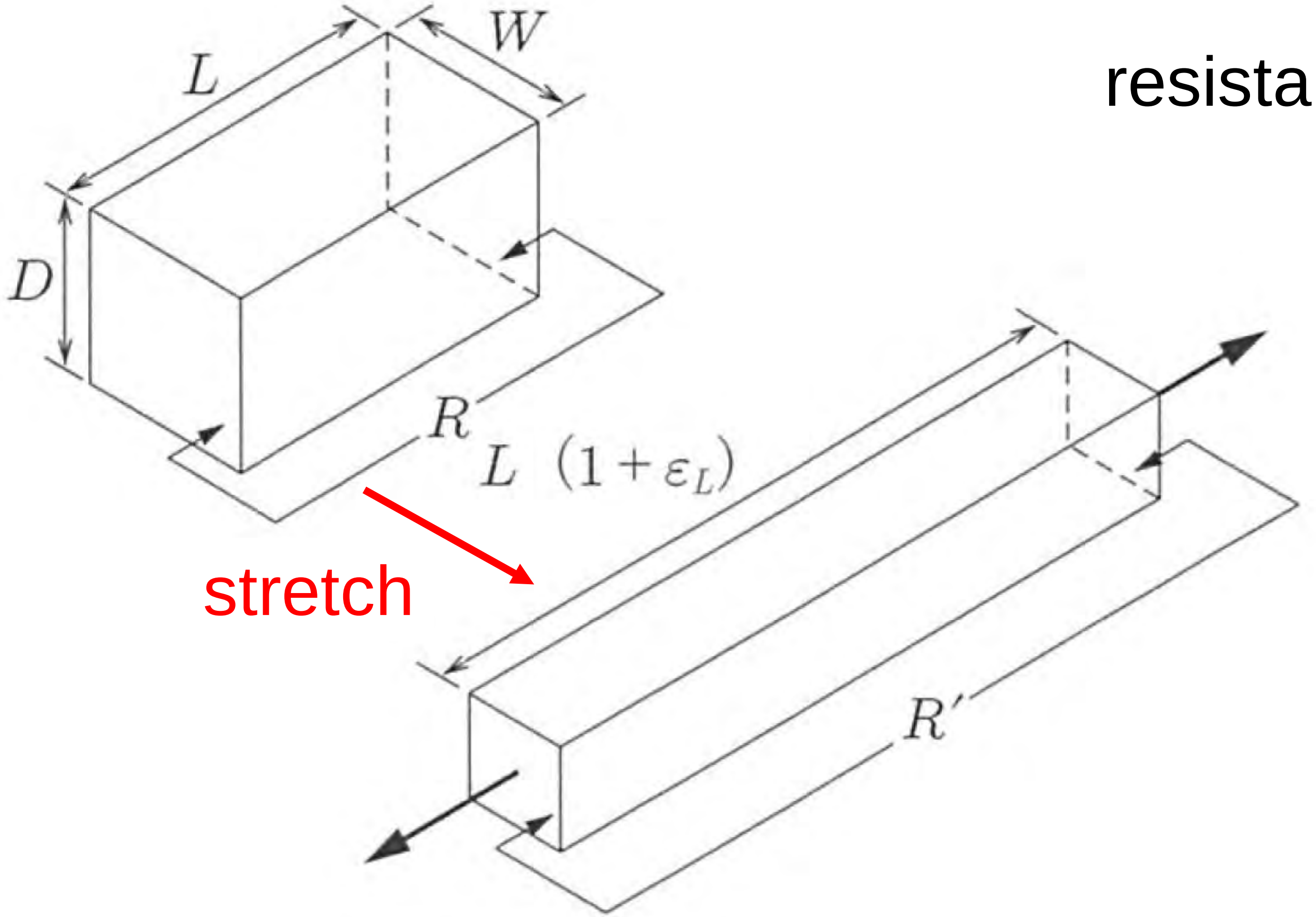
resistance $R = \rho \dfrac{L}{WD}$

ρ [Ωm] : volume resistivity, or electrical resistivity
（体積抵抗率，電気抵抗率）

insulators	glass :	$10^{10} \sim 10^{14}$
	rubber :	10^{13}
conductors	iron :	1.00×10^{-7}
	aluminum :	2.65×10^{-8}

(from Wikipedia)

Resistive sensor



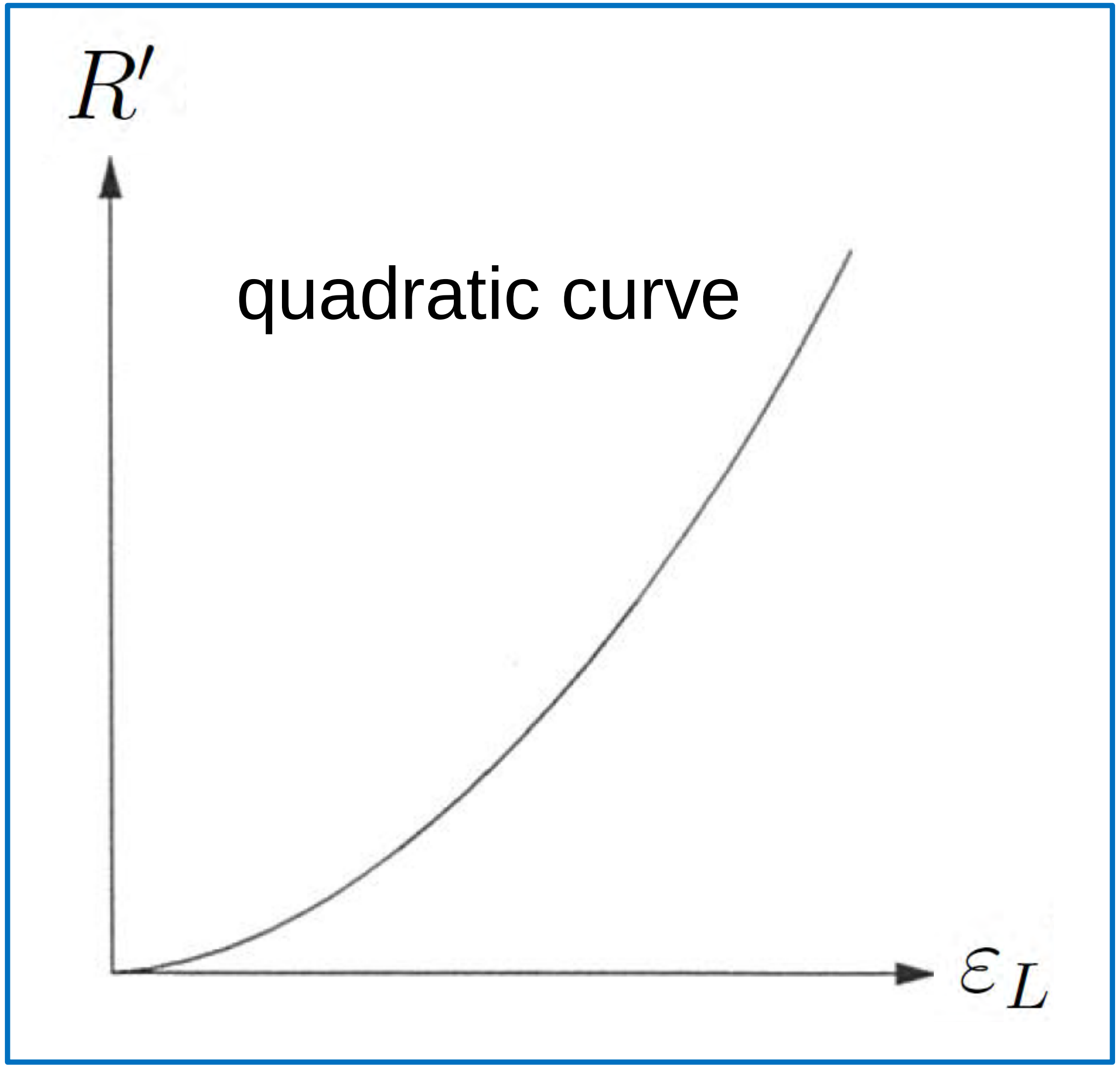
resistance $R = \rho \dfrac{L}{WD}$

ε_L : strain

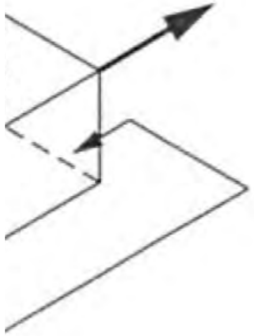
Assuming that the volume is constant,

$$R' = \rho \frac{L(1+\varepsilon_L)^2}{WD}$$

Resistive sensor



resistance $R = \rho \dfrac{L}{WD}$

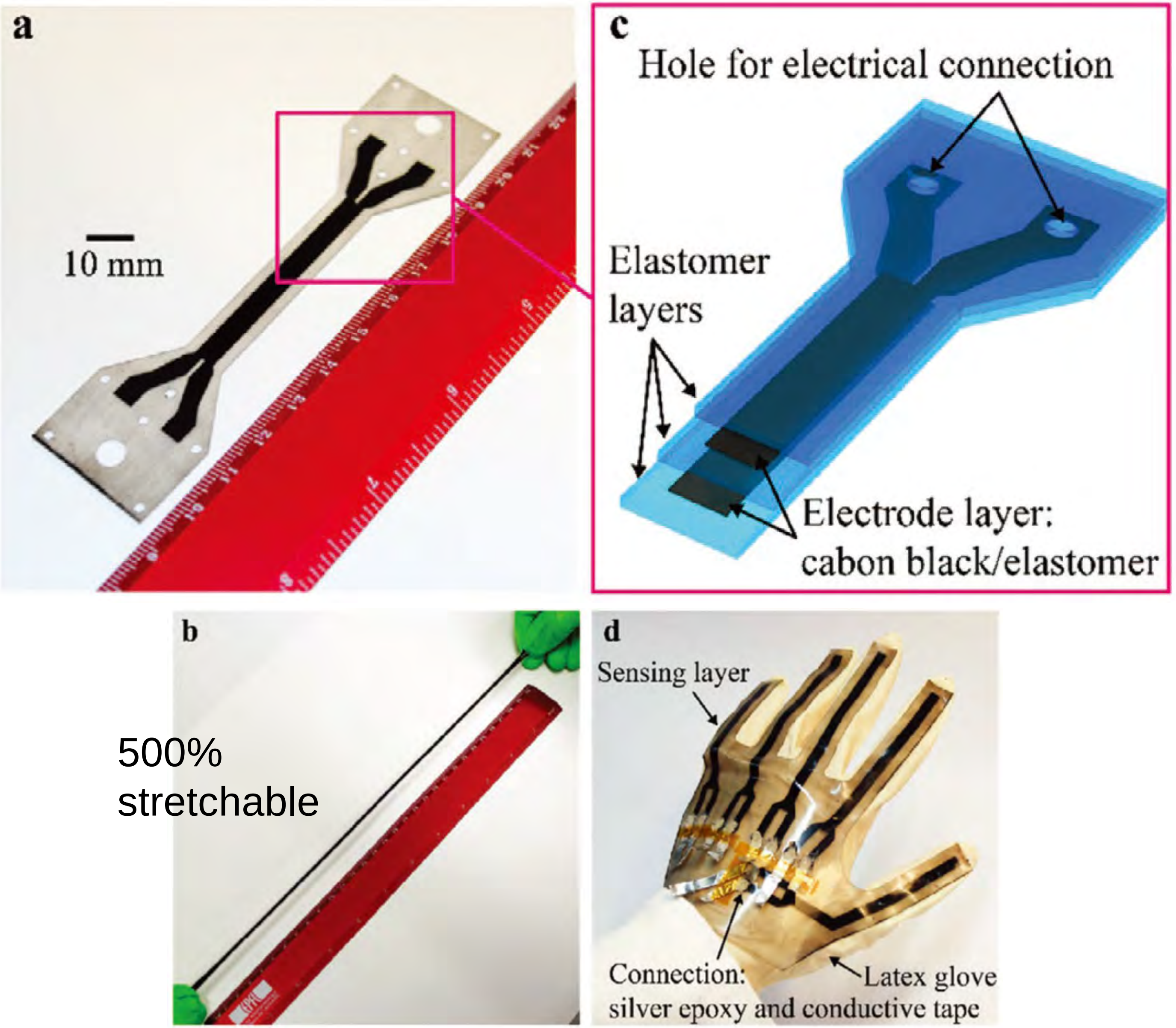


ε_L : strain

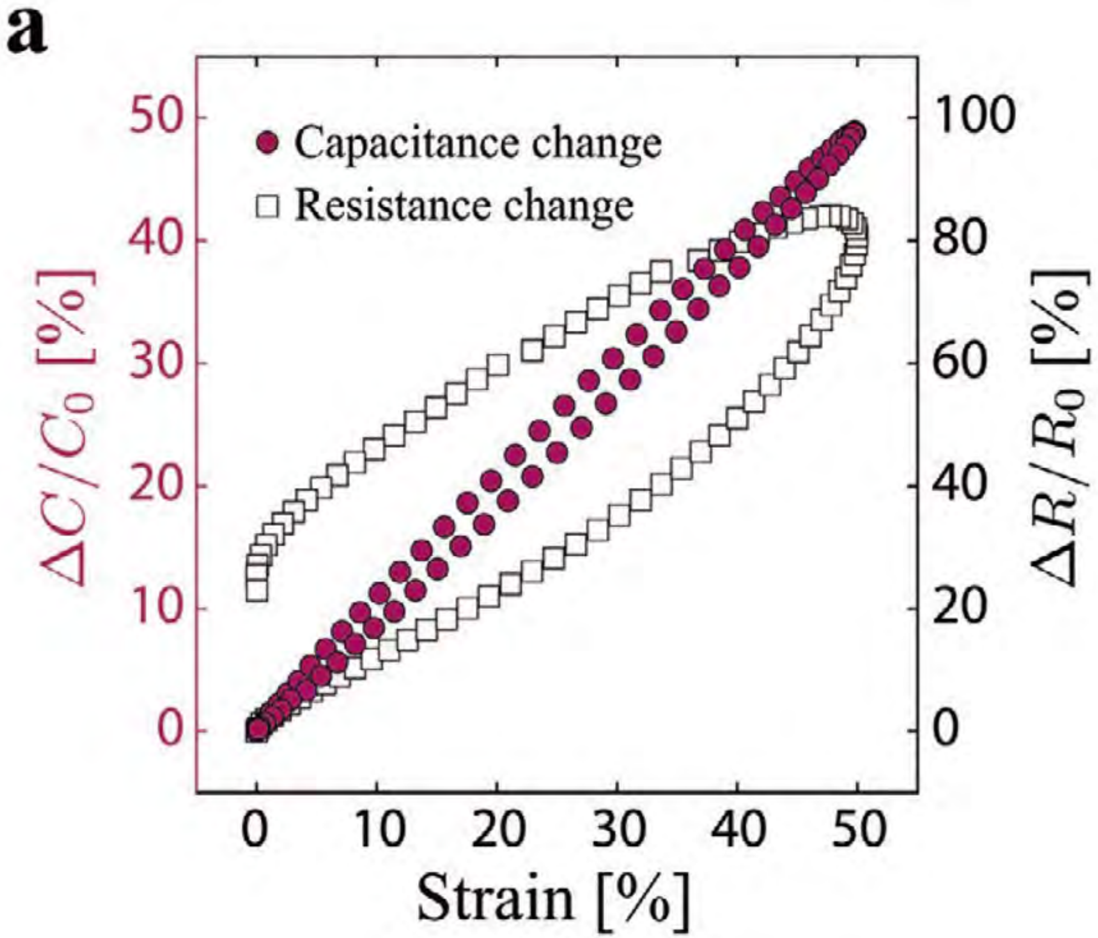
Assuming that the volume is constant,

$$R' = \rho \frac{L(1+\varepsilon_L)^2}{WD}$$

Ultrastretchable Strain Sensors Using Carbon Black-Filled Elastomer Composites and Comparison of Capacitive Versus Resistive Sensors



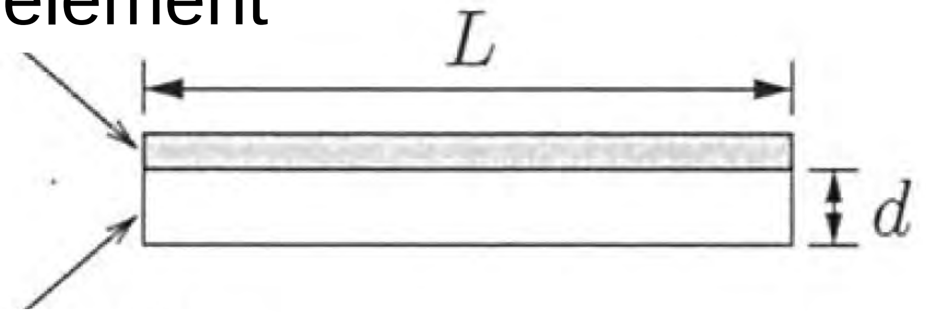
500% stretchable



Shintake et al., Advanced Materials Technologies, 3, 1700284, 2018.

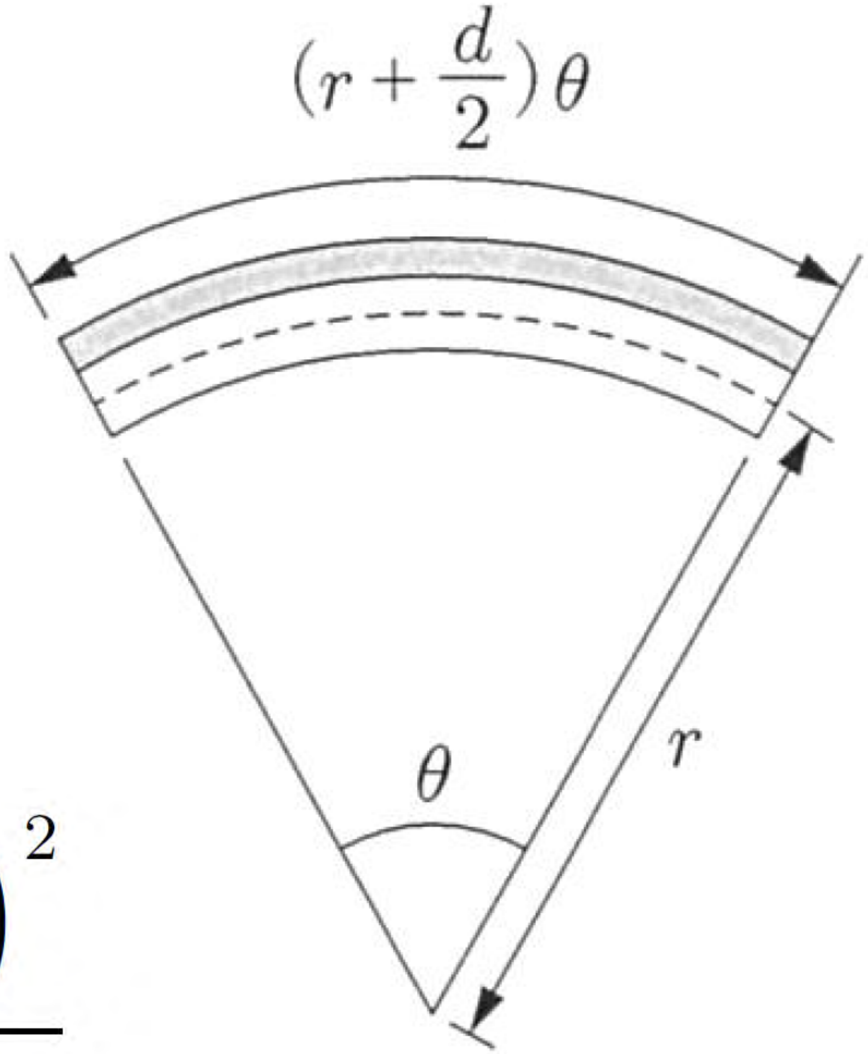
Resistive sensor - film resistive sensor

sensor element



film substrate

bending

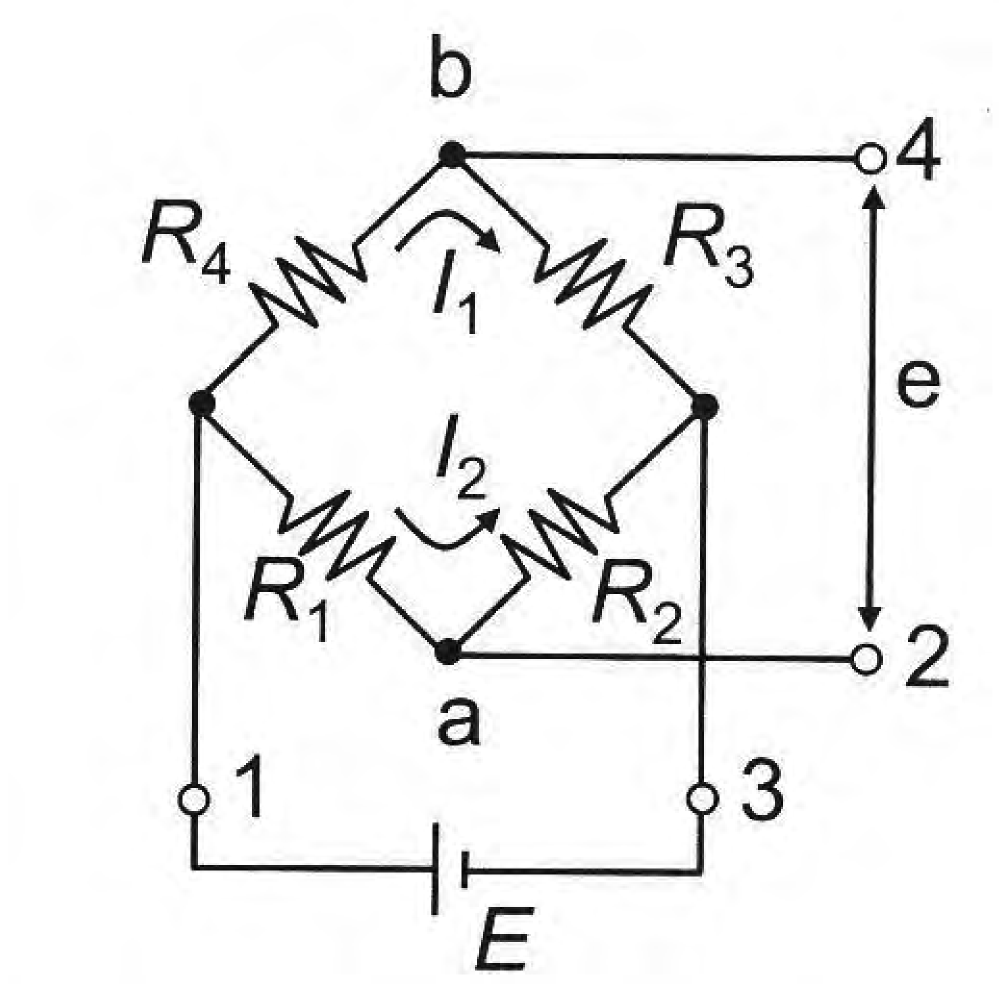


$$\varepsilon_L = \left(r+\frac{d}{2}\right)\frac{\theta}{L} - 1$$

$$R' = \rho\frac{L(1+\varepsilon_L)^2}{WD} = \rho\frac{L\left(1+\frac{d\theta}{2L}\right)^2}{WD}$$

How to measure small resistance change?

- Wheatstone bridge circuit



Potential difference *e* is

$$e = \frac{R_1R_3 - R_2R_4}{(R_1 + R_2)(R_3 + R_4)}E$$

For small change *ΔR* for R_1 ,

$$e = \frac{(R_1 + \Delta R)R_3 - R_2R_4}{(R_1 + \Delta R + R_2)(R_3 + R_4)}E$$

Assuming $R_1 = R_2 = R_3 = R_4$,

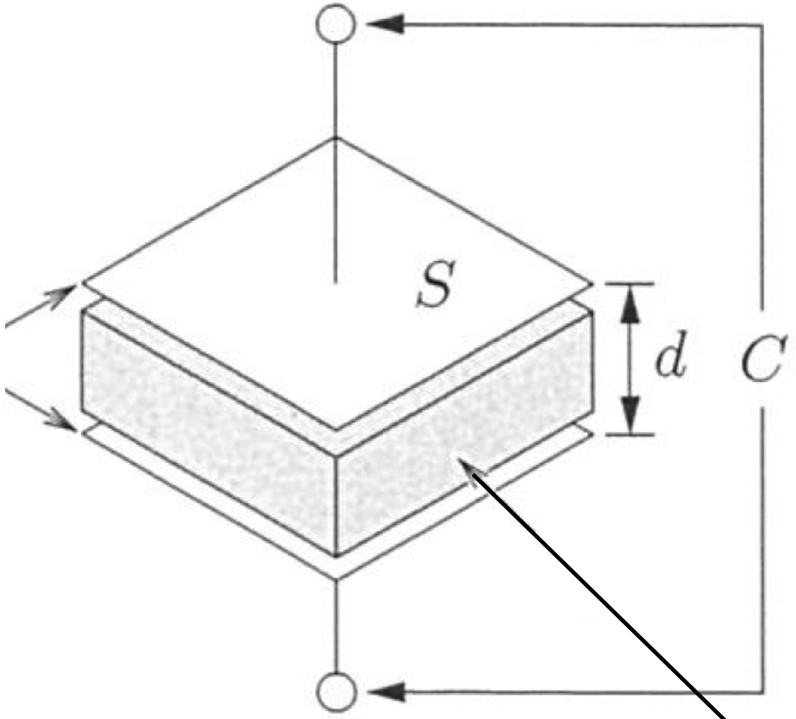
$$e = \frac{R^2 + R\Delta R - R^2}{(2R + \Delta R)2R}E$$

Approximate as follows,

$$e \cong \frac{1}{4} \cdot \frac{\Delta R}{R} \cdot E$$

Thus, you can observe *ΔR* from *e*.

Capacitive sensor



Electrodes

Dielectric substance
（誘電体）

Capacitance $C = \varepsilon \frac{S}{d}$

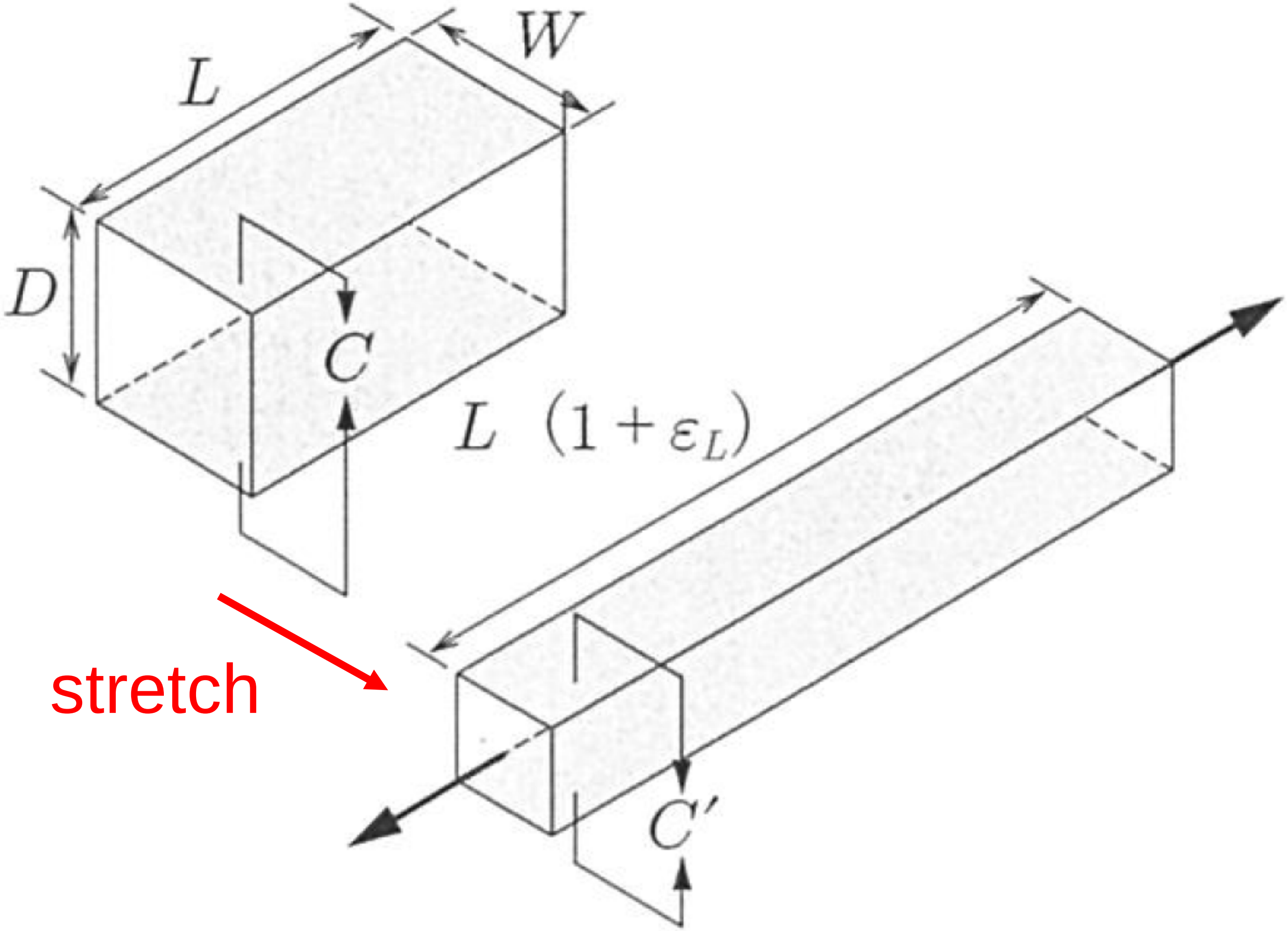
ε : Permittivity（誘電率）

Relative permittivity（比誘電率）:
Ratio to permittivity of vacuum

glass :	5.4～9.9
rubber :	2.0～3.5
paper :	2.0～2.6
air :	1.00059

(from Wikipedia)

Capacitive sensor



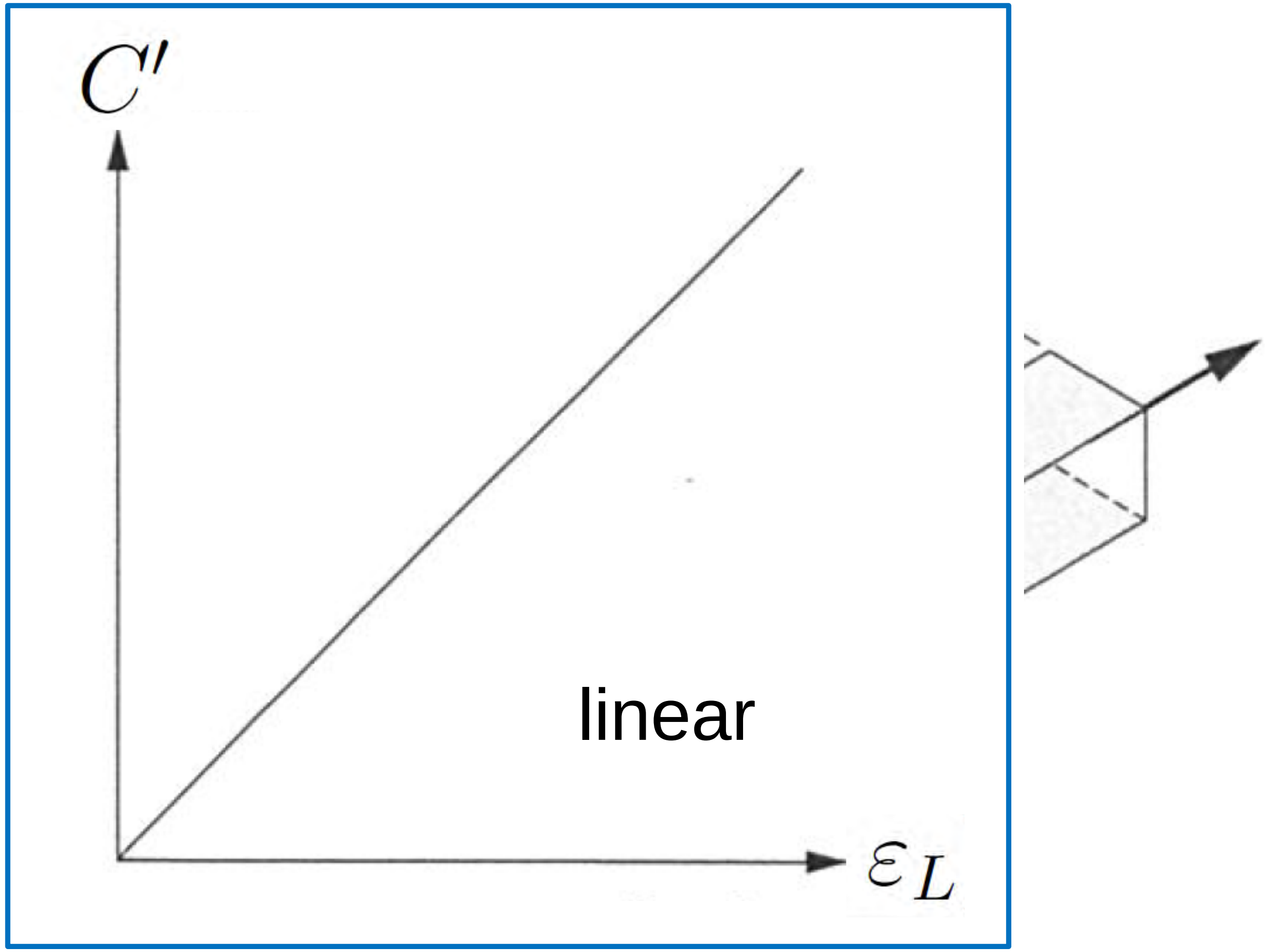
$$C = \varepsilon \frac{LW}{D}$$

ε_L : strain

Assuming that the volume is constant,

$$C' = \varepsilon \frac{LW(1+\varepsilon_L)}{D}$$

Capacitive sensor



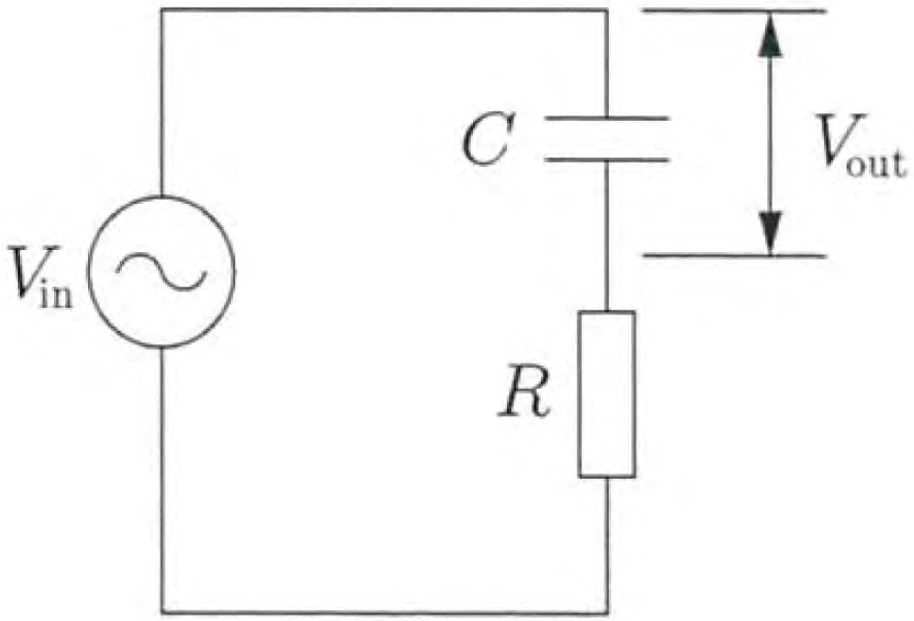
$$C = \varepsilon \frac{LW}{D}$$

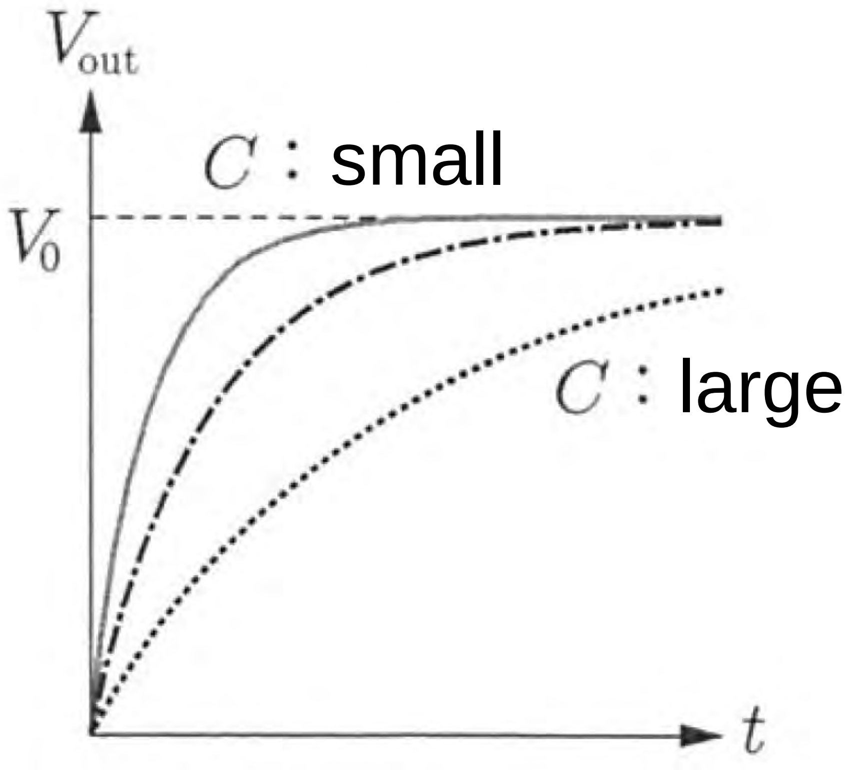
ε_L : strain

Assuming that the volume is constant,

$$C' = \varepsilon \frac{LW(1+\varepsilon_L)}{D}$$

How to measure capacitance? - RC circuit

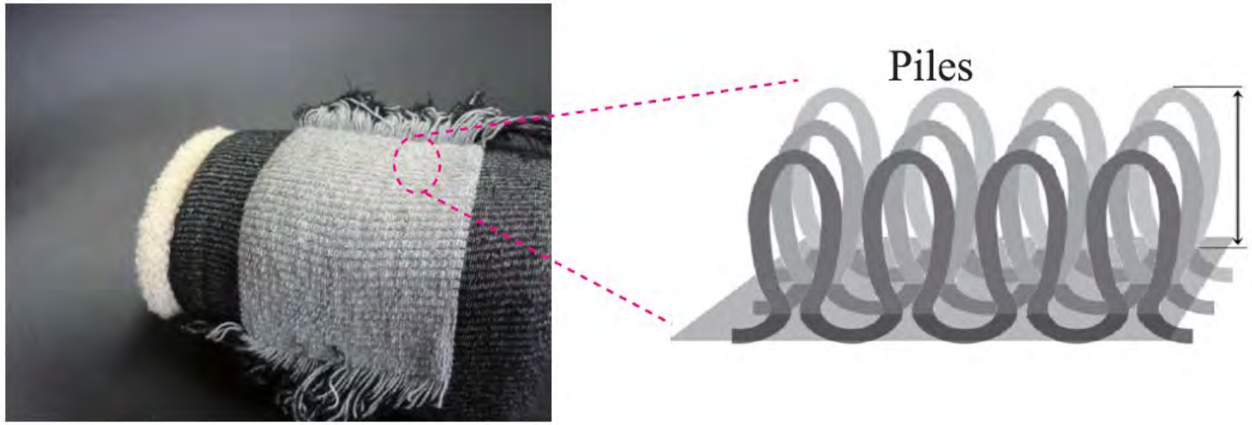




For a step input, $V_{\text{out}}(t) = V_0 \left\{ 1 - \exp\left(-\frac{1}{RC} t \right) \right\}$

C can be observed by measuring the raising of V_{out}.

Flexible Fabric Sensor



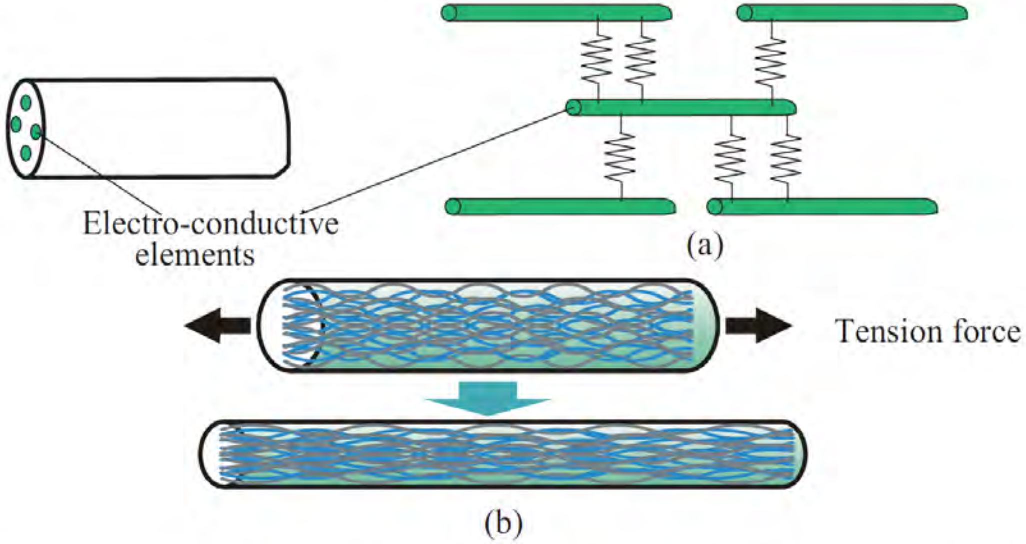
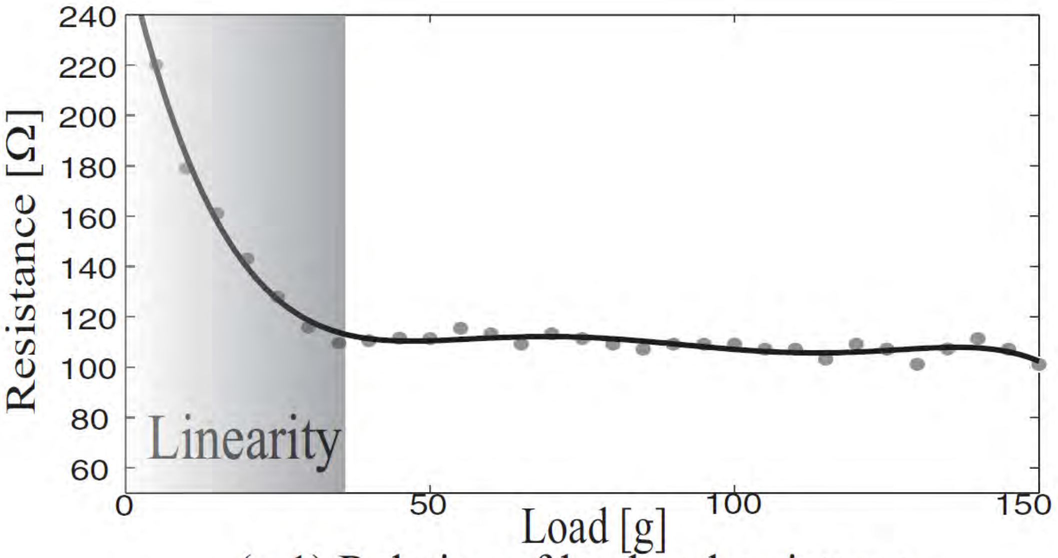
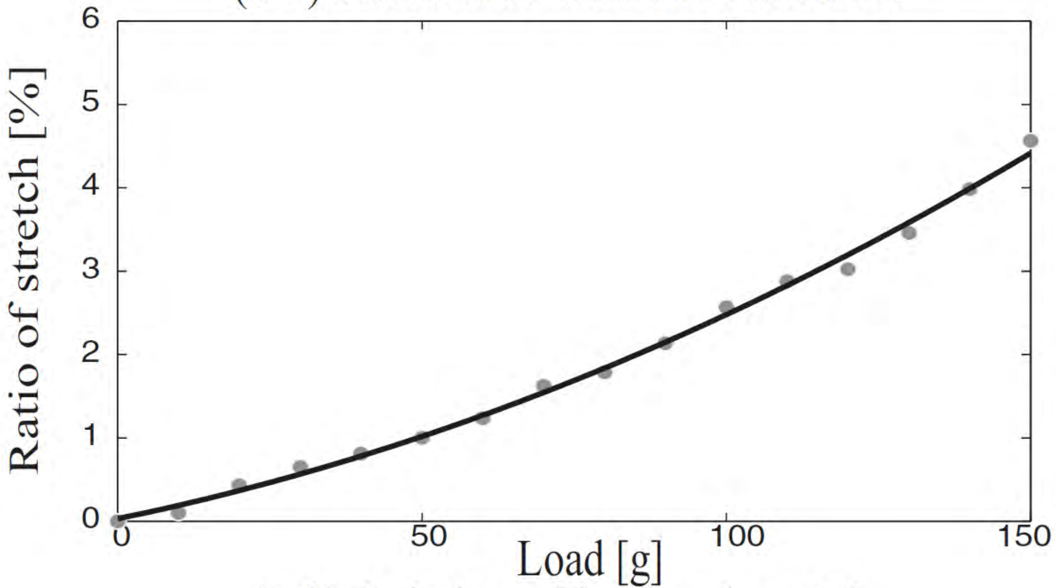


Fig. 2. Model of a tension-sensitive electro-conductive yarn. (a) Structure. (b) Density of conductive fibers (blue fiber) increases when tensile.



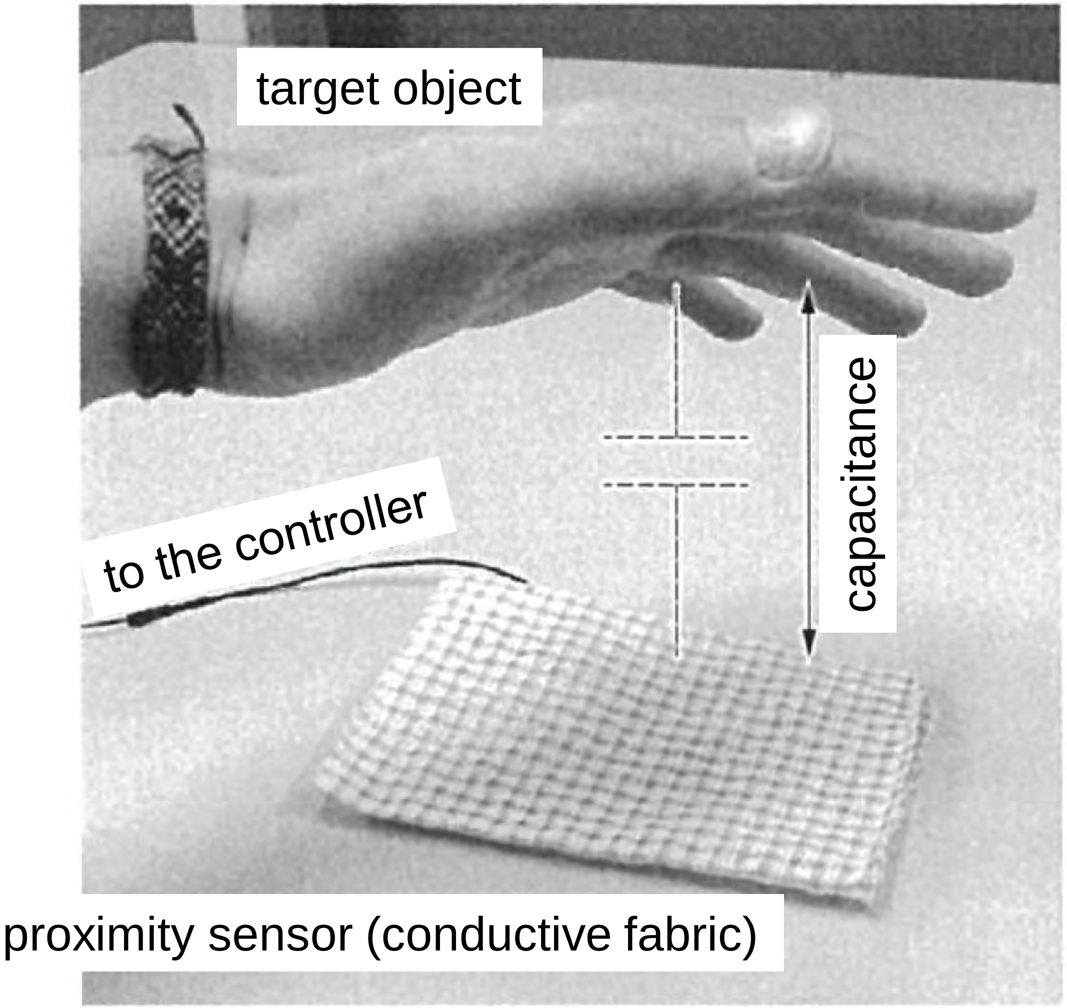
(a-1) Relation of load and resistance

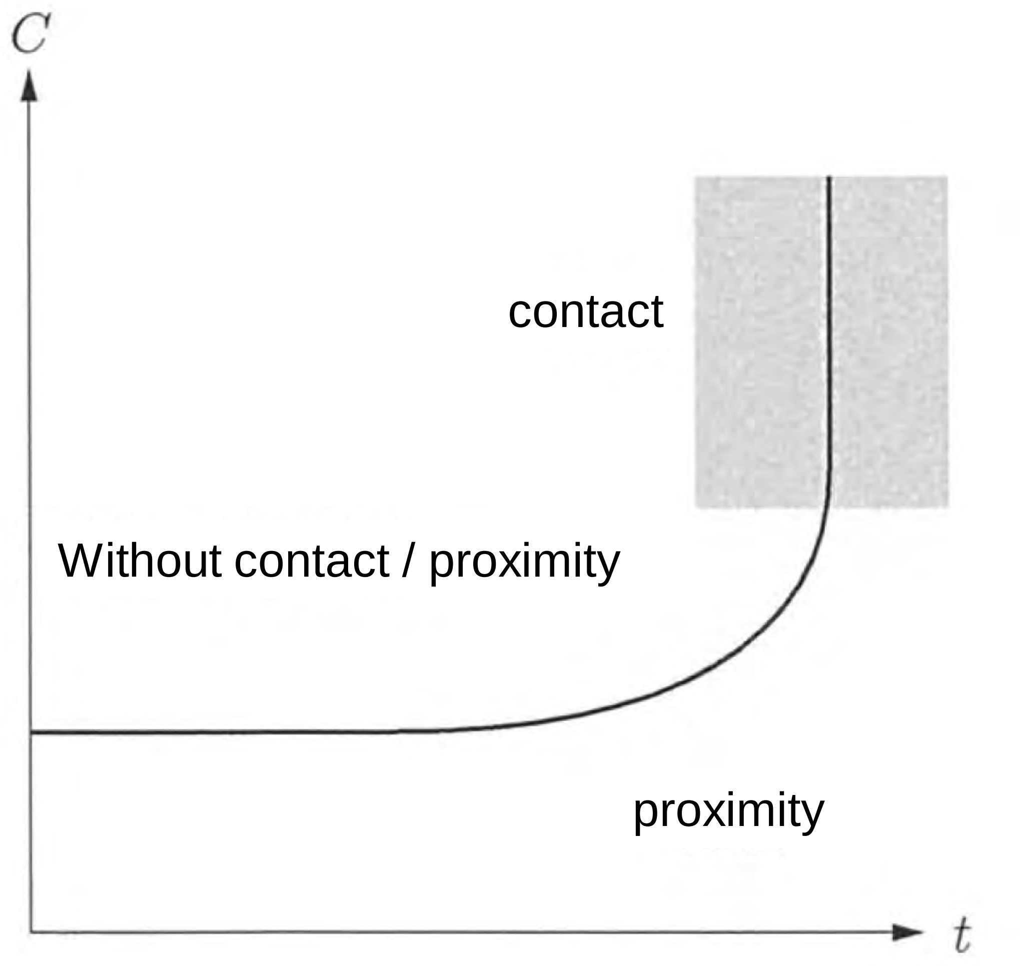


(a-2) Relation of load and stretch

Van Anh Ho et al., IEEE Sensors Journal (2013)

Capacitive sensor - proximity sensing





「ソフトロボット学入門」，第4章，図4.8

Low-Cost Sensor-Rich Fluidic Elastomer Actuators Embedded with Paper Electronics

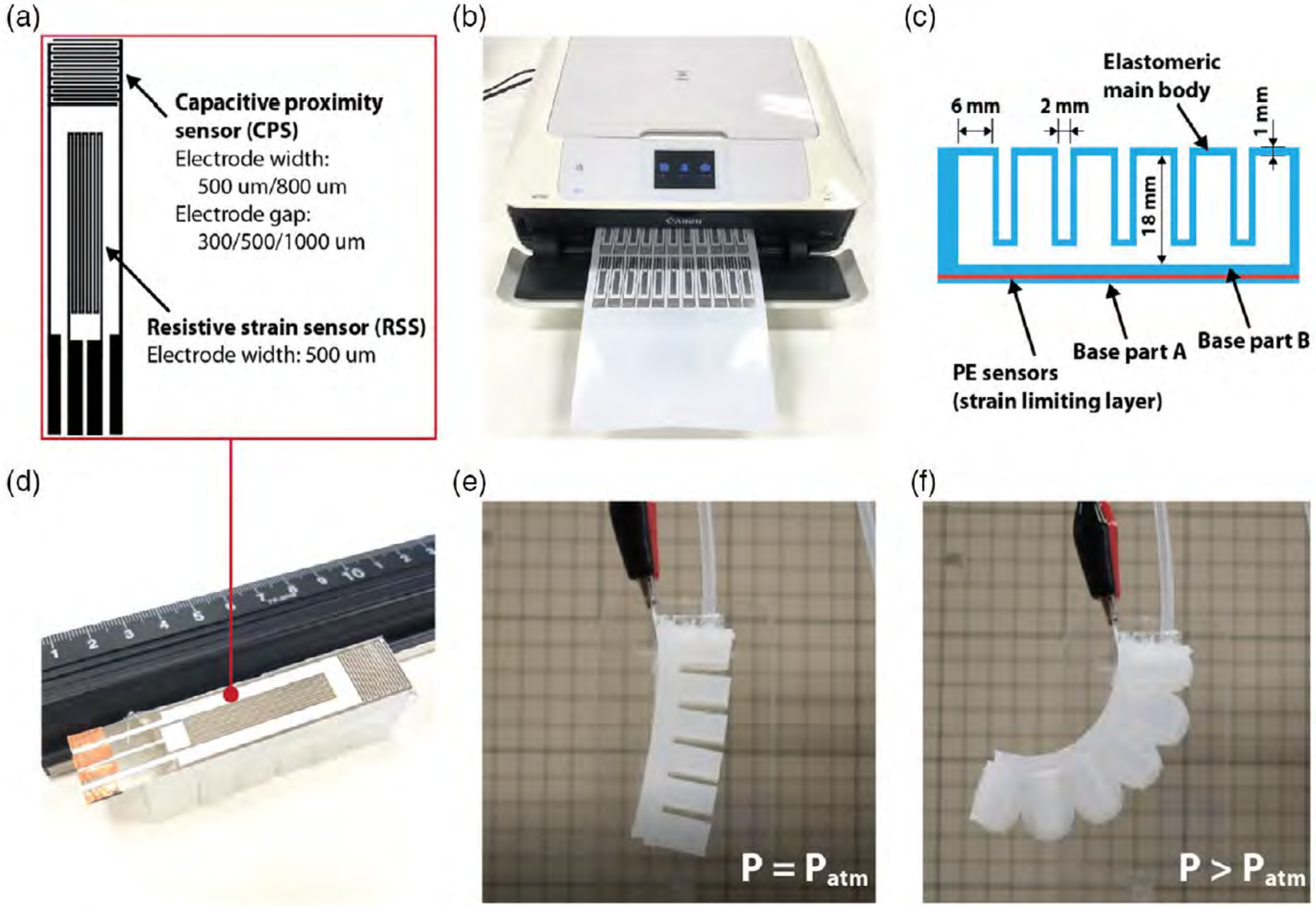


Figure 1. Integration of paper sensors (PE) and FEA. a) Layout and pattern of RSS and CPS on paper. b) Printing process of the sensing paper substrate. c) Cross-sectional view and dimensions of the PE-FEA where the sensing paper substrate is embedded as a strain-limiting layer. d) PE-FEA developed in this study. e) PE-FEA in the initial (i.e., unpressurized) state and f) pressurized state.

T.H.Yang et al., Adv. Intell. Syst. 2020, 2, 2000025

Low-Cost Sensor-Rich Fluidic Elastomer Actuators Embedded with Paper Electronics

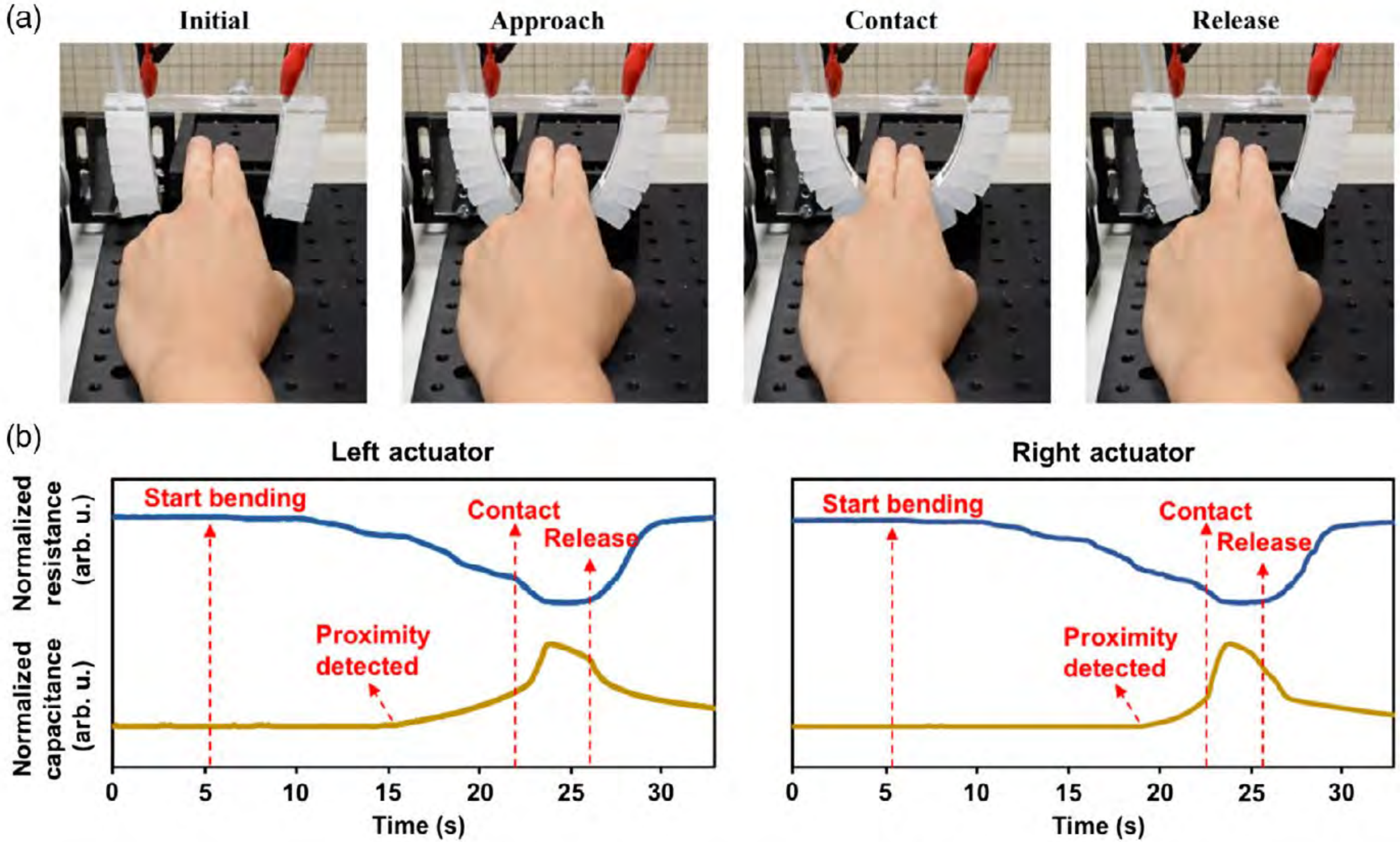


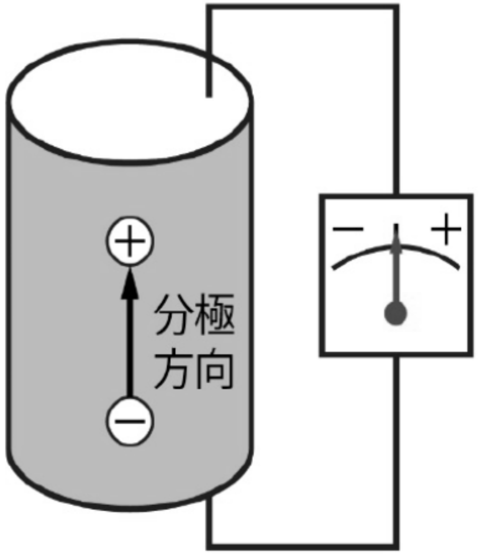
Figure 7. Intelligent soft gripper with the RSS and CPS paper sensors. a) Photograph showing the whole process where soft gripper grasped and released fingers. b) Variation in resistance and capacitance detected by the RSS and CPS integrated in both actuators of the gripper, respectively. The resistance and capacitance are normalized with respect to their respective initial values to emphasize their changes.

T.H.Yang et al., Adv. Intell. Syst. 2020, 2, 2000025

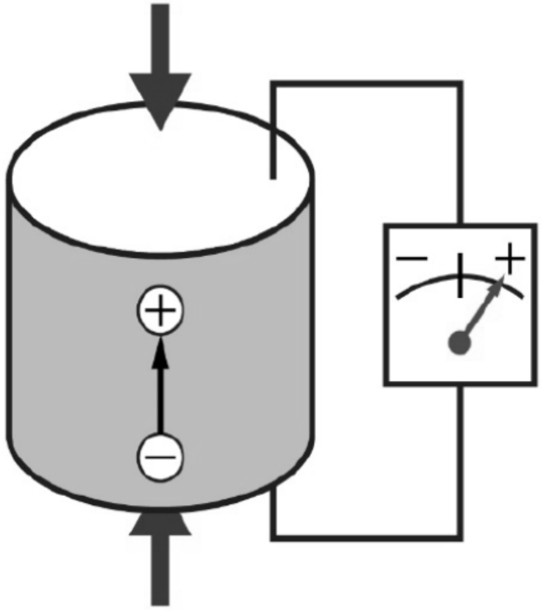
Piezoelectric sensor

Piezoelectric material（圧電体）:

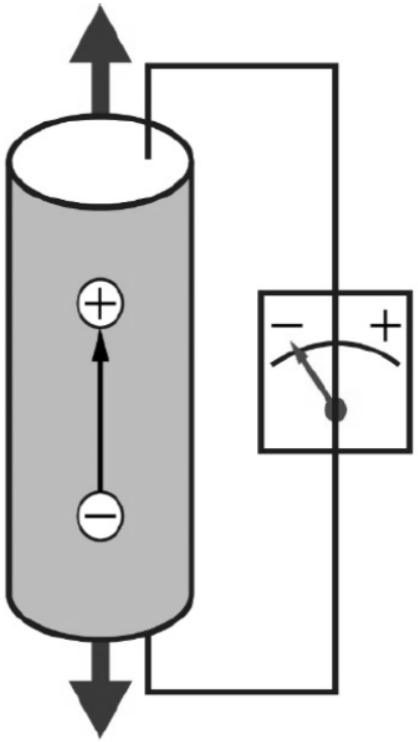
- A type of **dielectric material**（誘電体）, and that causes **piezoelectric phenomenon**（圧電現象） which converts mechanical and electrical energy in each other.
- **Polarization**（分極） occurs due to external stress.



No load



Positive voltage
for compression



Negative voltage
for extension

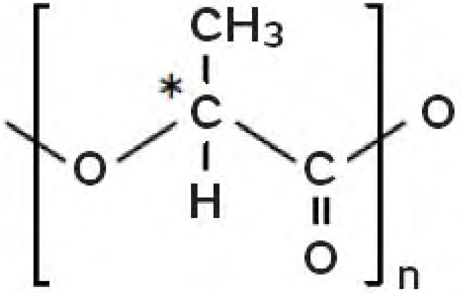
Piezoelectric sensor - piezoelectric materials

Piezoelectric ceramics（圧電セラミクス）
- Barium titanate（チタン酸バリウム）
- Lead zirconate titanate, PZT（チタン酸ジルコン酸鉛）

PVDF sensor

Fluorocarbon polymers（フッ素系樹脂）
- PVDF

Polylactic acid（ポリ乳酸）
- PLA



PLA

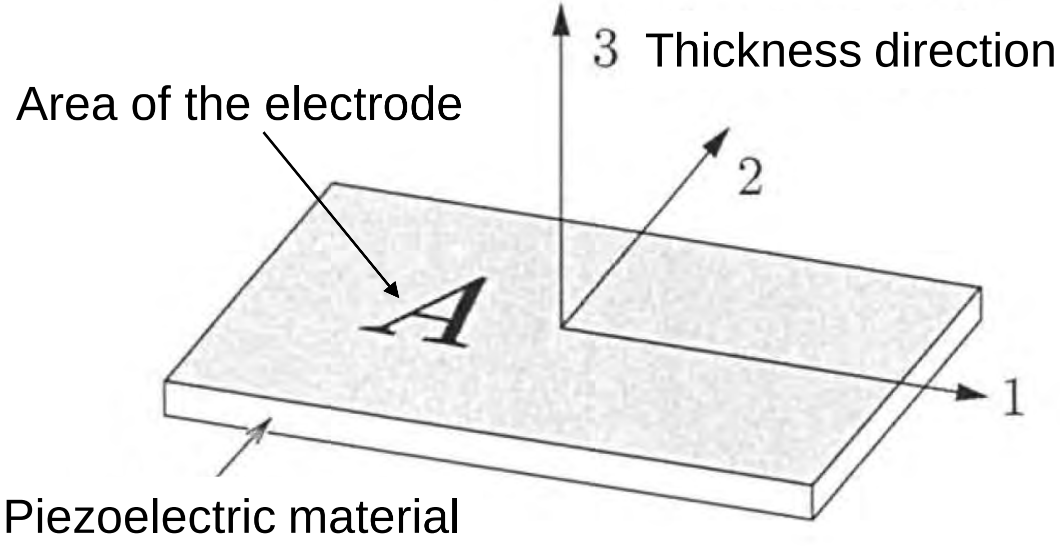
PLA sensor（Murata Manufacturing）

Piezoelectric sensor - piezoelectric material characteristics

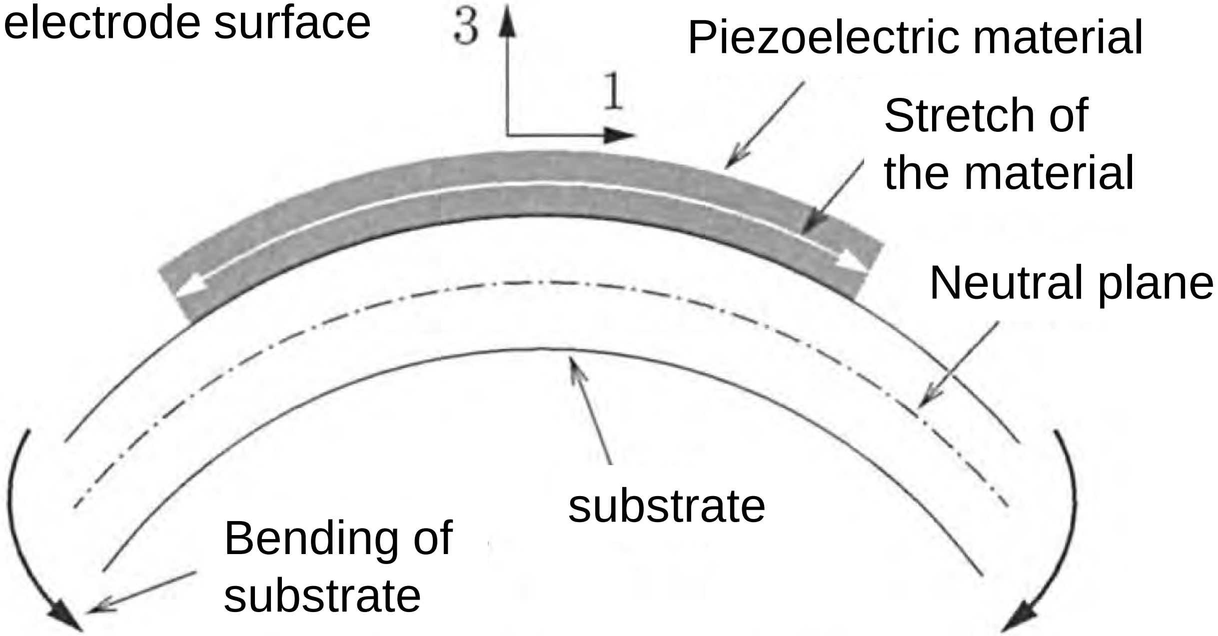
Piezoelectric constant d_{31}

Direction of strain (or stress)

Normal direction for electrode surface



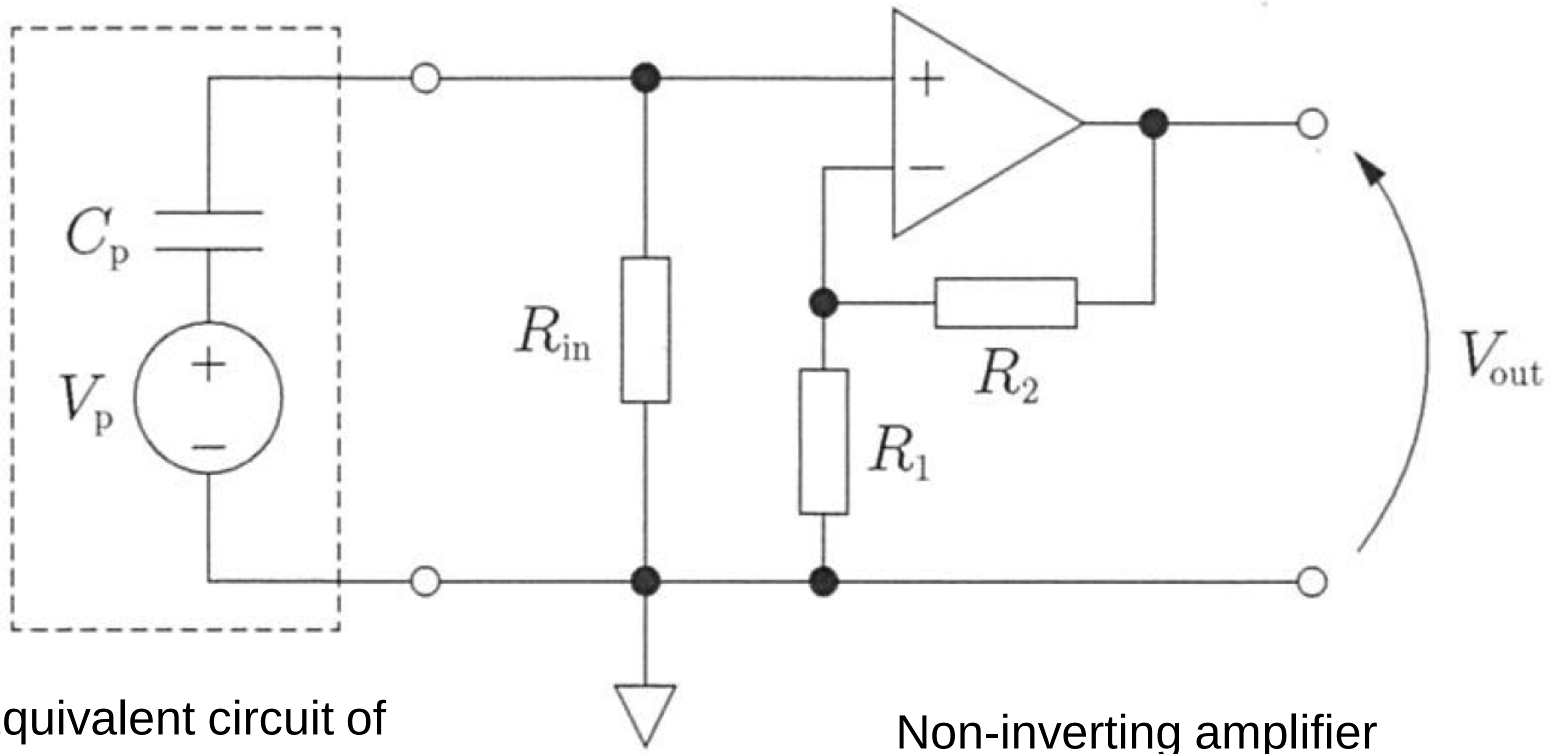
(a) Piezoelectric constant
（圧電定数）



(b) Deforming the piezoelectric material by bending, σ_1 is dominant.

Current between electrodes $$I_p = \frac{dQ_p}{dt} = A\left(d_{31}\frac{d\sigma_1}{dt} + d_{32}\frac{d\sigma_2}{dt} + d_{33}\frac{d\sigma_3}{dt}\right)$$

Piezoelectric sensor - voltage measurement circuit

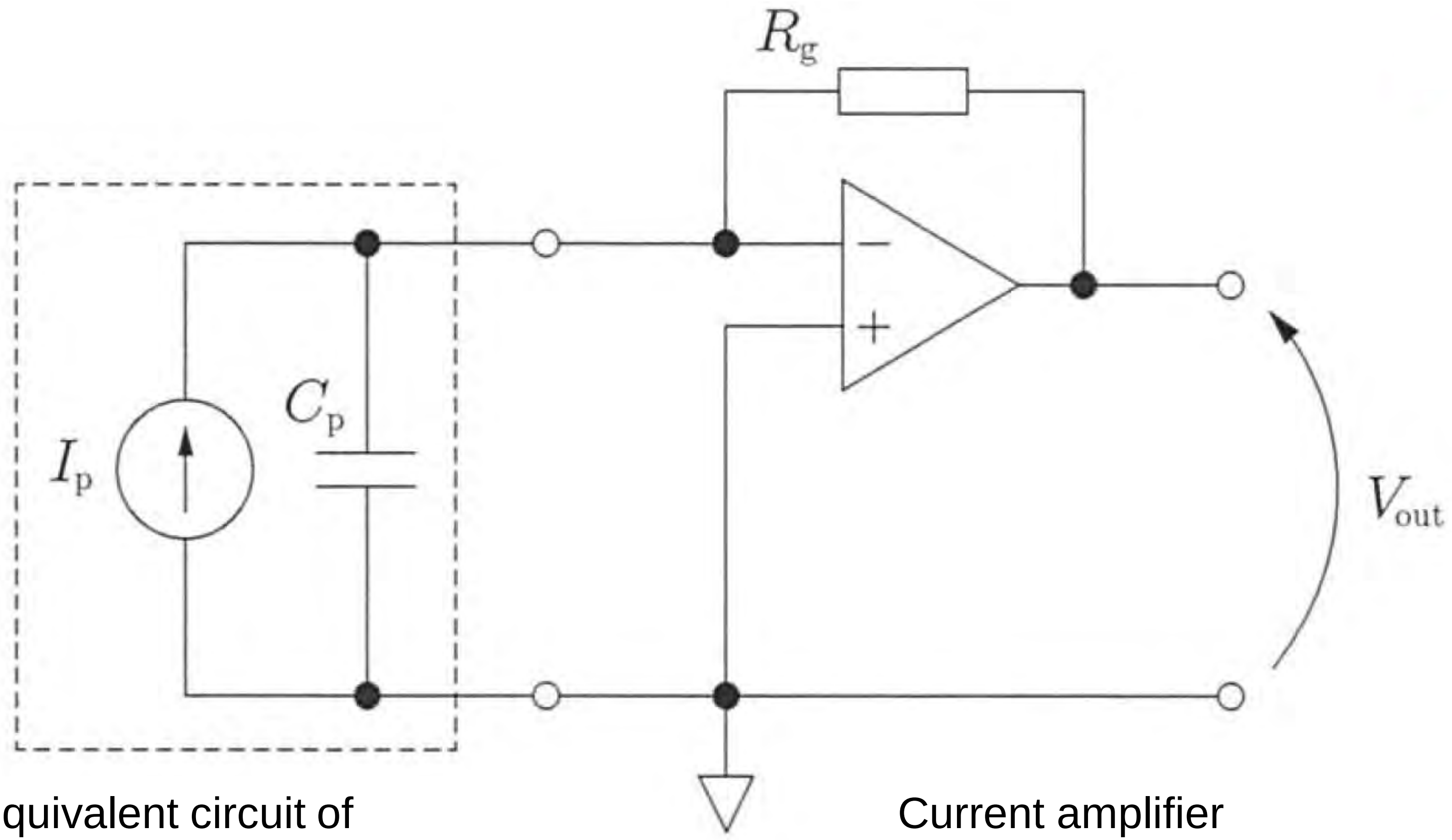


Equivalent circuit of
piezoelectric sensor
(as voltage source)

Non-inverting amplifier

$$V_{out} = \left(1 + \frac{R_2}{R_1}\right) V_p$$

Piezoelectric sensor - current measurement circuit

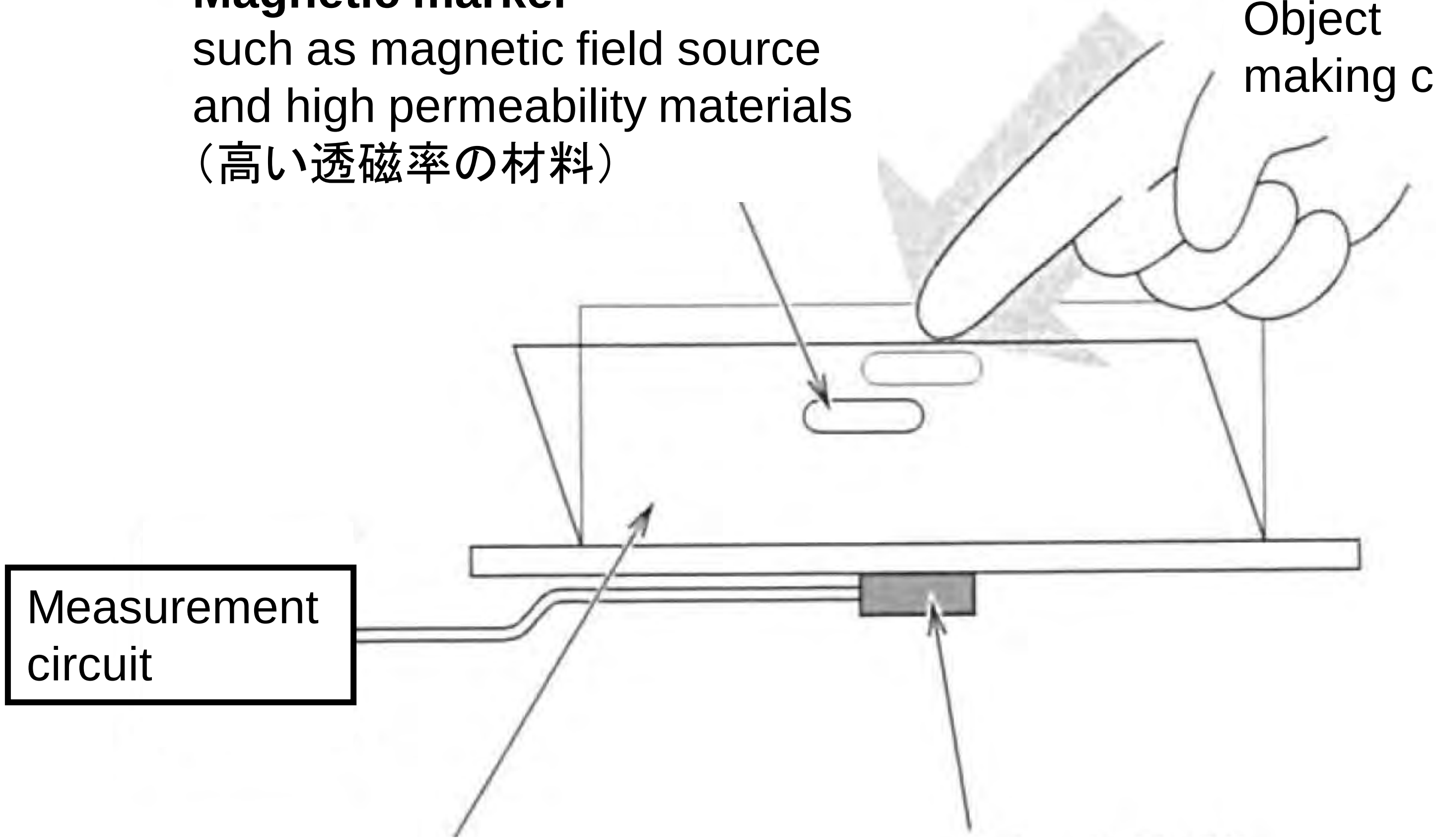


Equivalent circuit of
piezoelectric sensor
(as current source)

Current amplifier

$$V_{out} = R_g I_p$$

Magnetic sensor



Magnetic marker
such as magnetic field source
and high permeability materials
（高い透磁率の材料）

Object
making contact

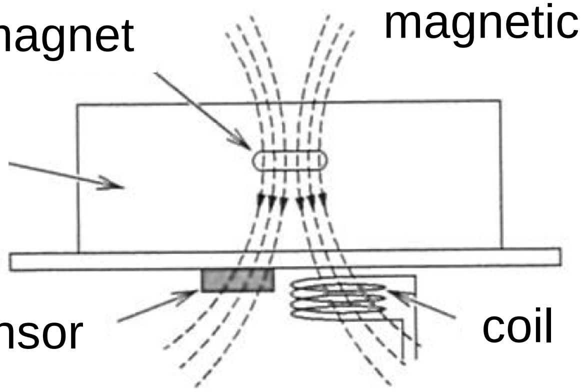
Measurement
circuit

Elastomer,
soft material such as
silicone rubber

Magnetic transducers
that convert changes of magnetic field
and permeability into electric signal

Magnetic sensor - sensing principle

i) Using permanent magnet



permanent magnet

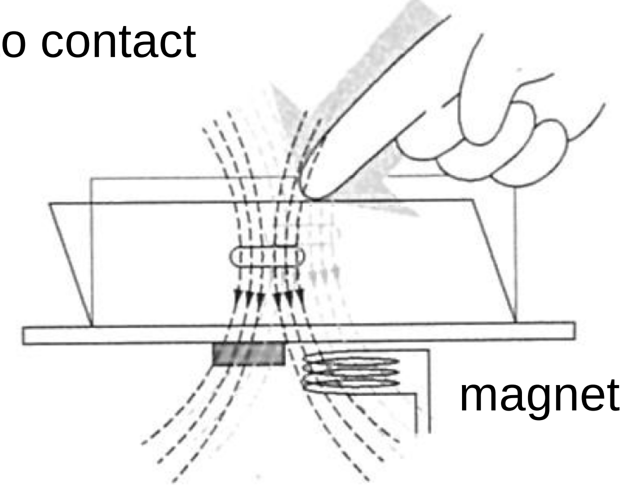
magnetic field

elastomer

magnetic sensor

coil

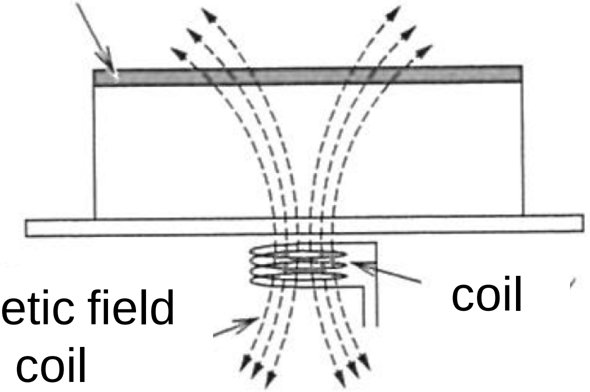
magnet movement
due to contact



magnetic field changes

ii) Using magnetic elastomer

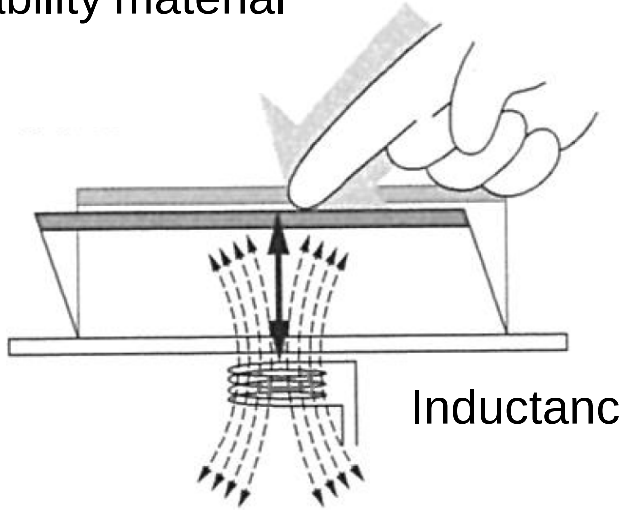
magnetic elastomer



coil

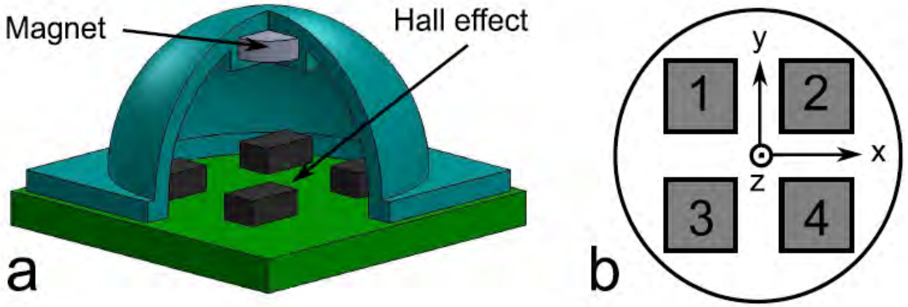
alternating magnetic field
generated by the coil

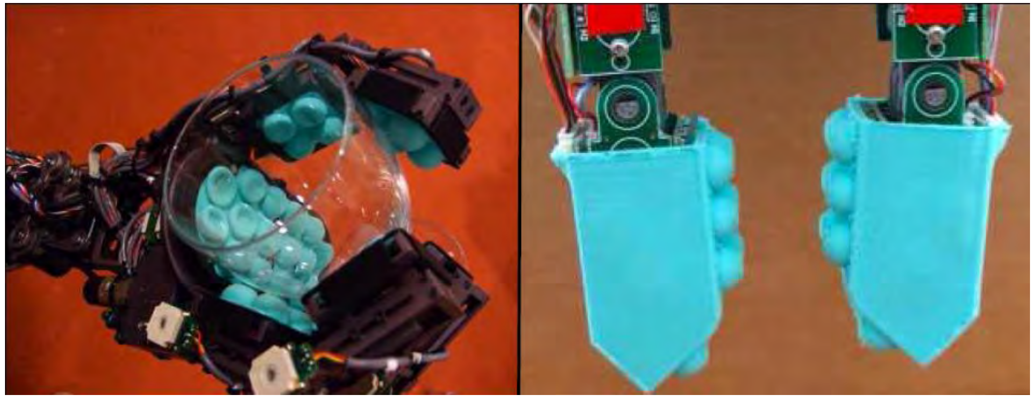
High permeability material
approaches



Inductance increases

Contact Behavior of Soft Spherical Tactile Sensors





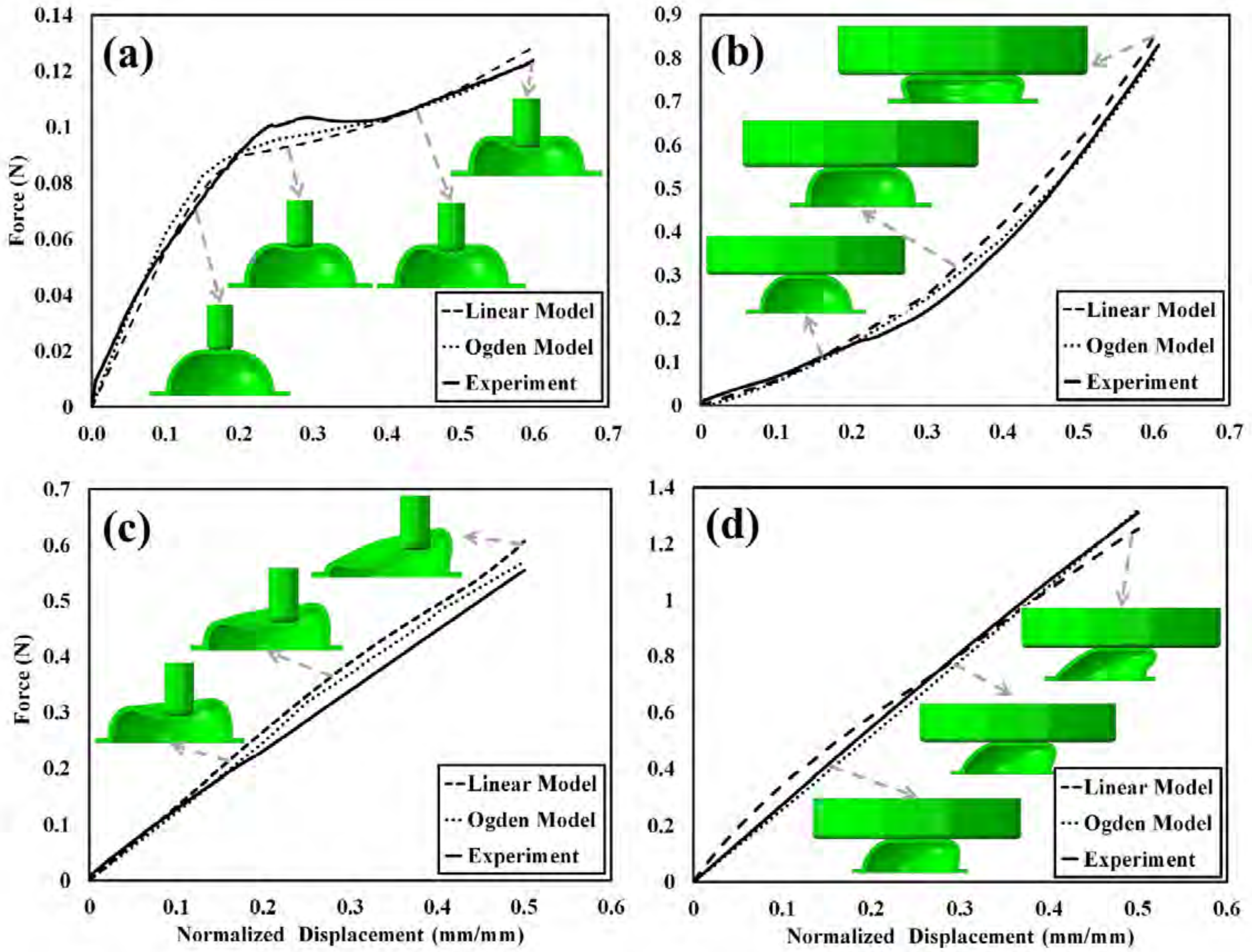


Fig. 6. Comparison of the experimental data and simulation results. The horizontal axes are normalized by the radius of the spherical shell. (a) Normal load applied by the small cylinder. (b) Normal load applied by the flat plate. (c) Shear load applied by the small cylinder. (d) Shear load applied by the flat plate.

S.Youssefian et al., IEEE Sensors Journal (2014)

Flexible tactile sensor based on inductance measurement

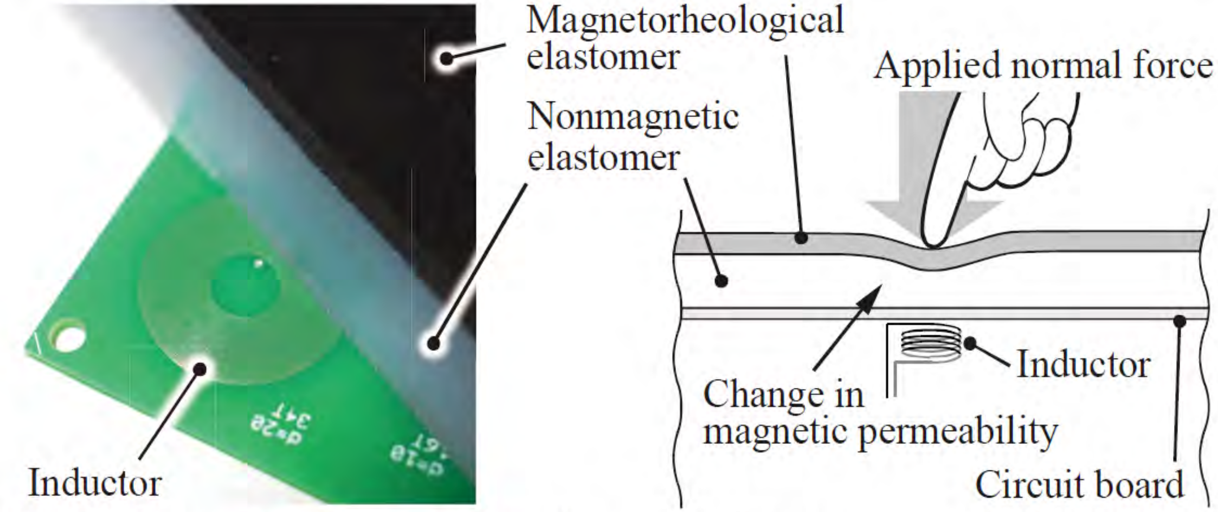
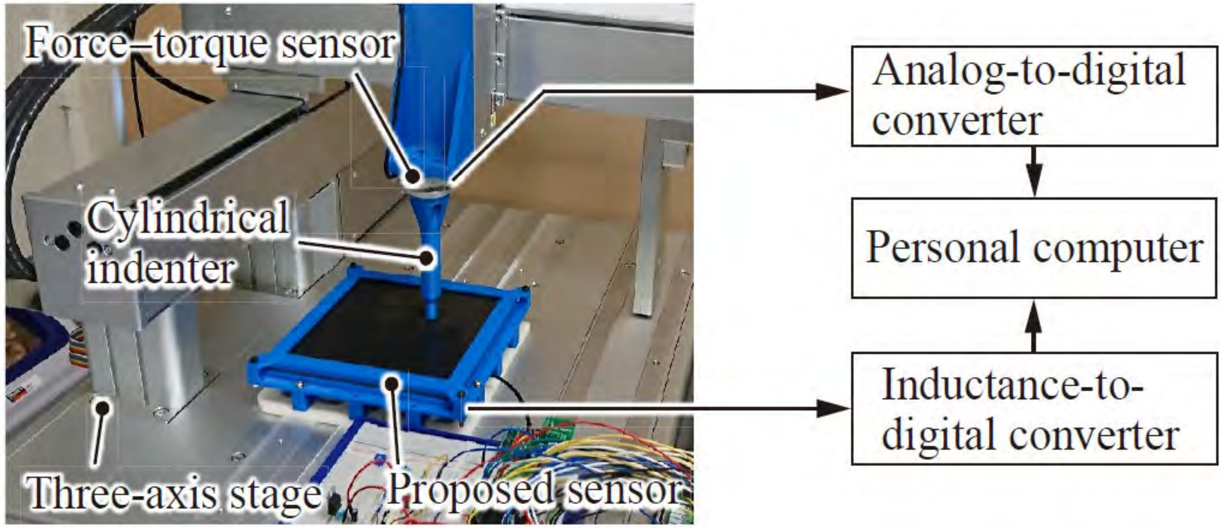
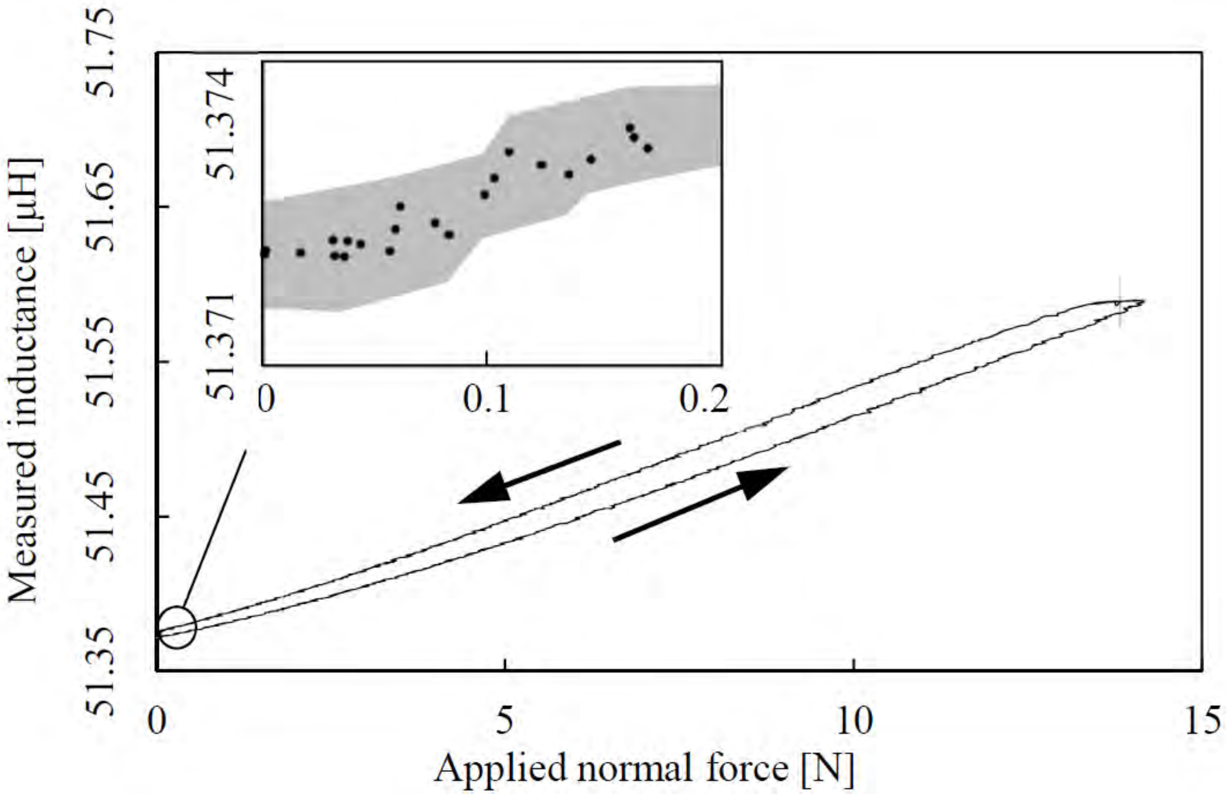


Fig. 1. Appearance of the proposed sensor and its cross-sectional schematic. An inductor is printed on a circuit board while magnetorheological and nonmagnetic base elastomers cover the board.



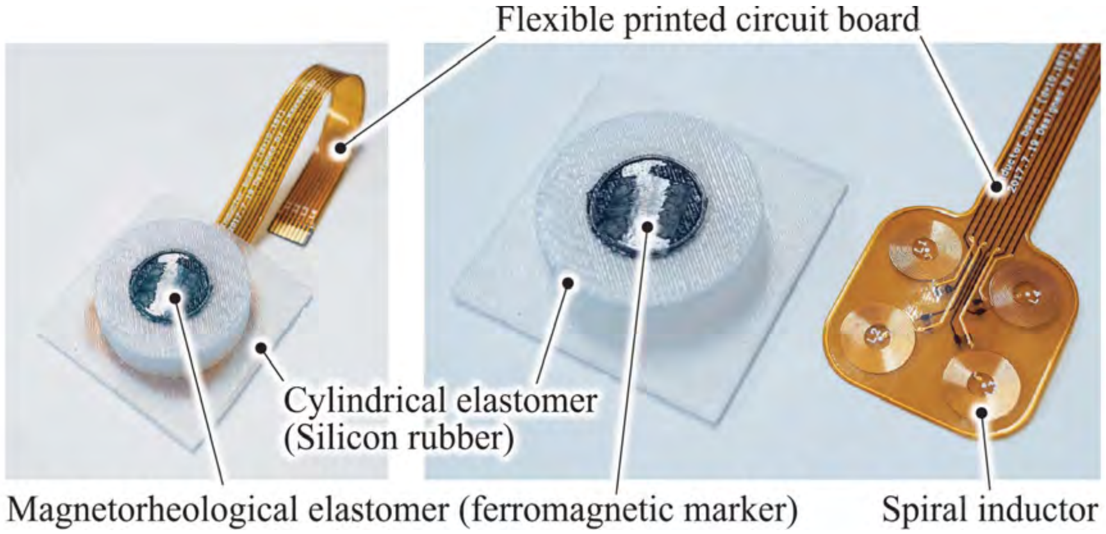
Measure displacement of the magnetic elastomer from inductance

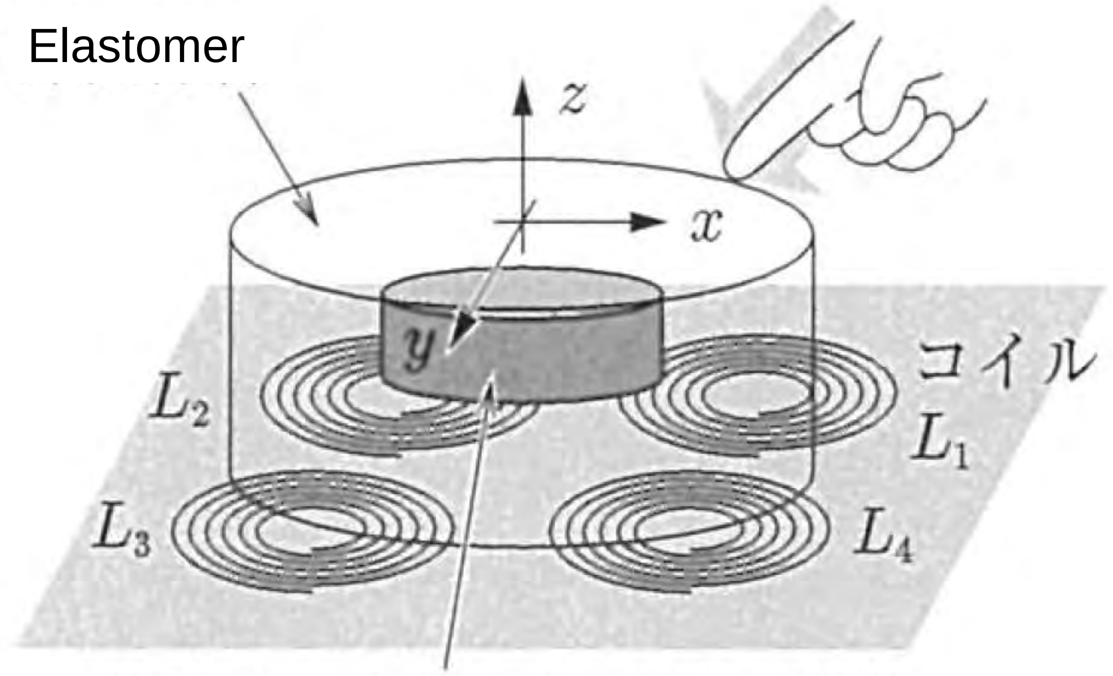


T. Kawasetsu et al., In Proc. of IEEE Sensors (2017)

Flexible Tri-Axis Tactile Sensor Using Spiral Inductor and Magnetorheological Elastomer

By using multiple coils, movement of the marker in three dimensional space can be measured.





Magnetic marker moves three dimensionally

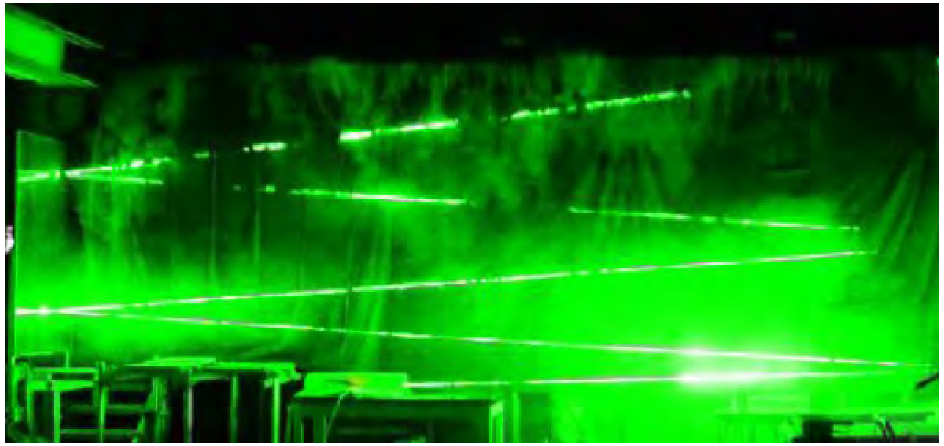
$$\begin{cases} L_x = (L_1 + L_4) - (L_2 + L_3) \\ L_y = (L_1 + L_2) - (L_3 + L_4) \\ L_z = L_1 + L_2 + L_3 + L_4 \end{cases}$$

T. Kawasetsu et al., IEEE Sensors Journal (2018)

Optical sensor

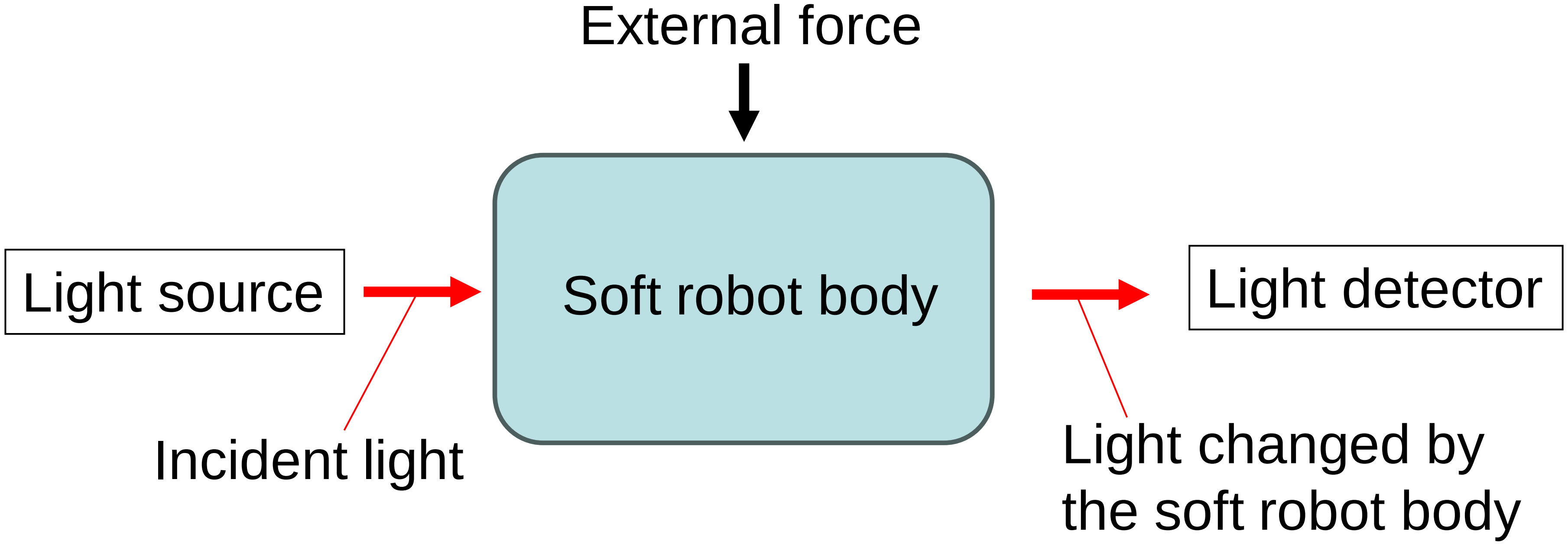
Nature of light

- Travels at about 300,000 km per second
- Travels straight ahead
- Can be bent by interaction with objects, such as reflection or refraction

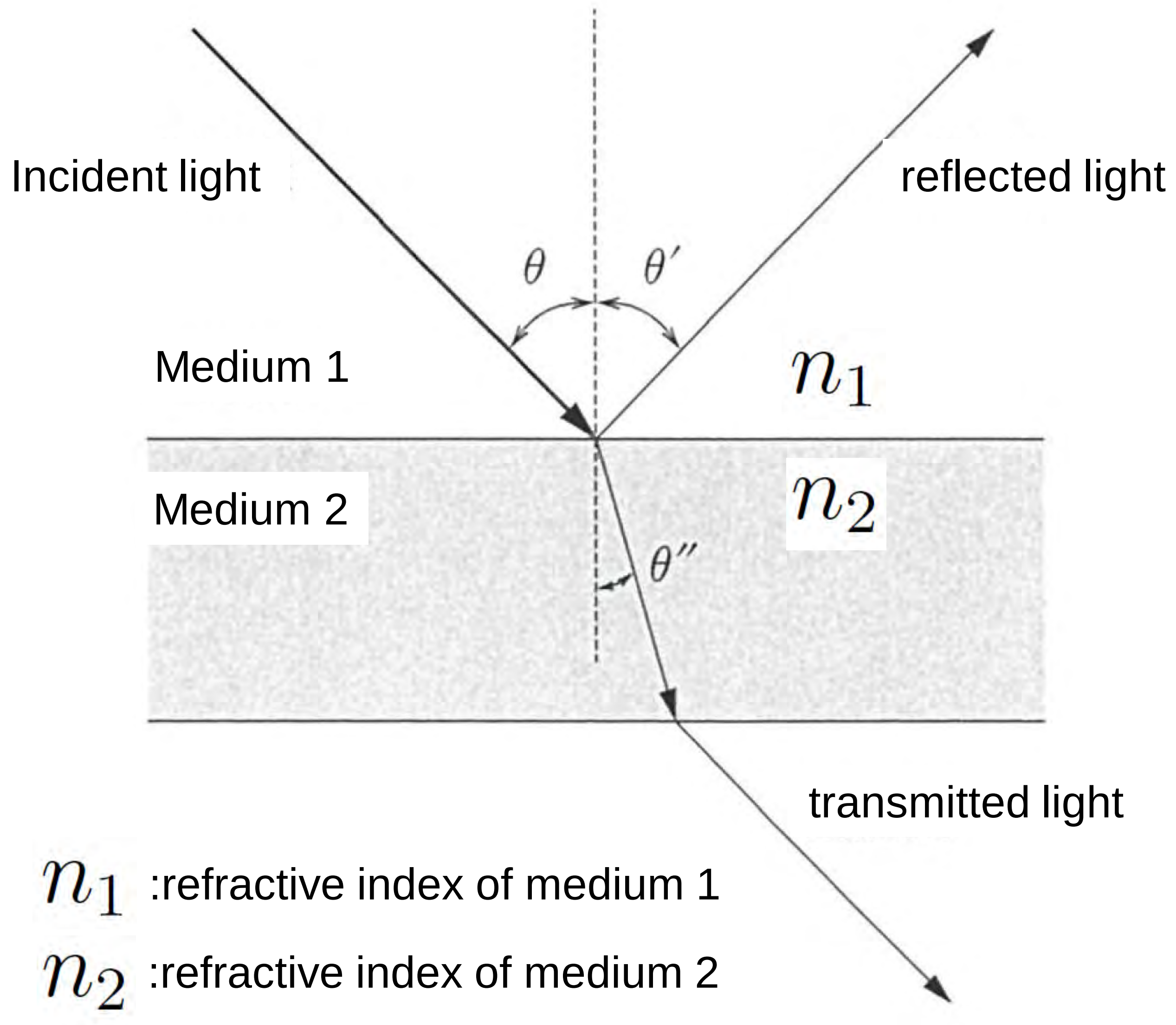


Etoh et al., Sensors, 2019

General structure of optical sensors



Optical sensor - interaction of light and objects



n_1 :refractive index of medium 1

n_2 :refractive index of medium 2

Reflection（反射）

- Specular reflection（正反射）

$$\theta = \theta'$$

- Diffuse reflection（乱反射）

Transmission（透過）

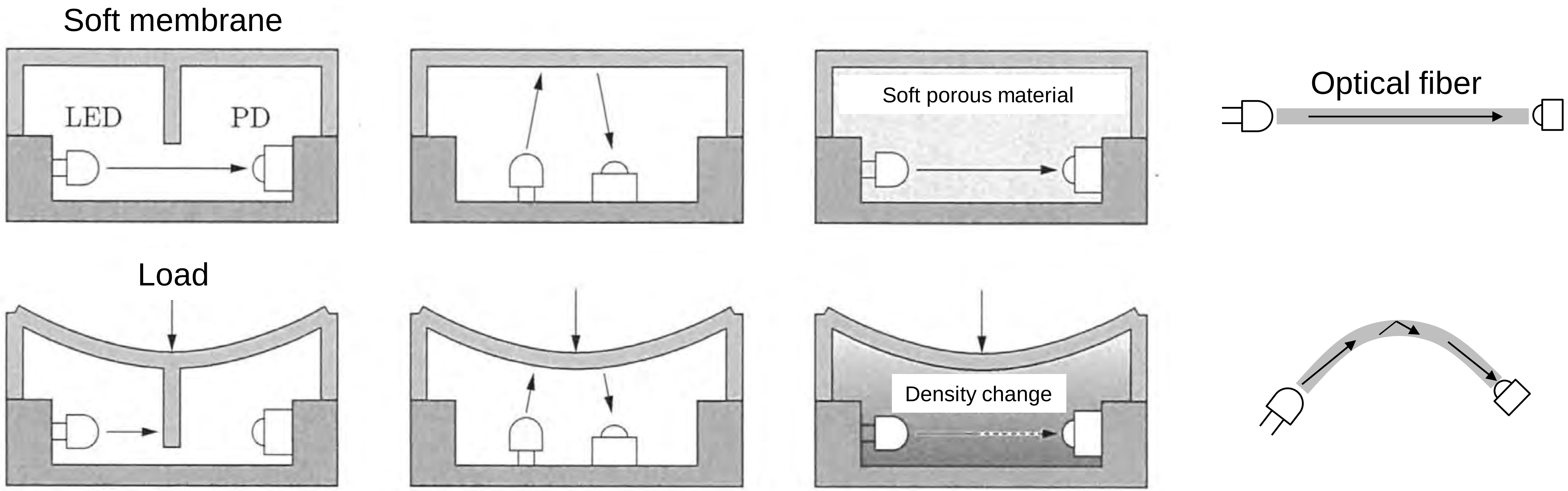
- Direct transmission（直接透過）

$$n_1 \sin\theta = n_2 \sin\theta''$$

（Snell’s law）

- Diffuse transmission（散乱透過）

Optical sensor - typical configuration



(a) Blocking the light

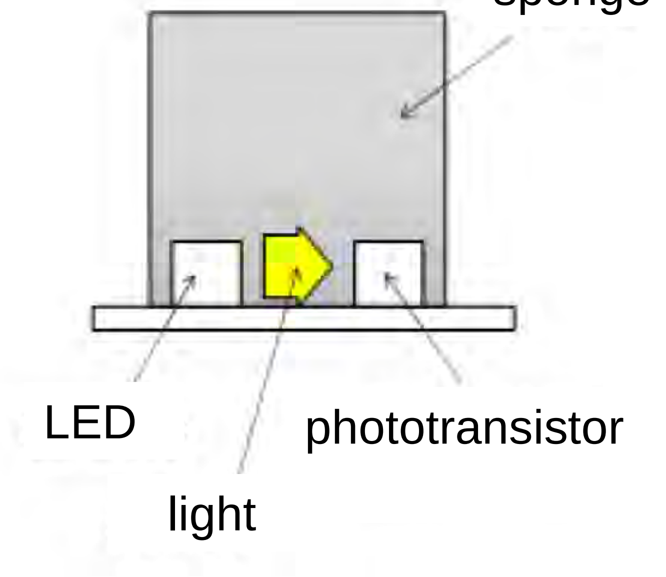
(b) Change of
the reflected light

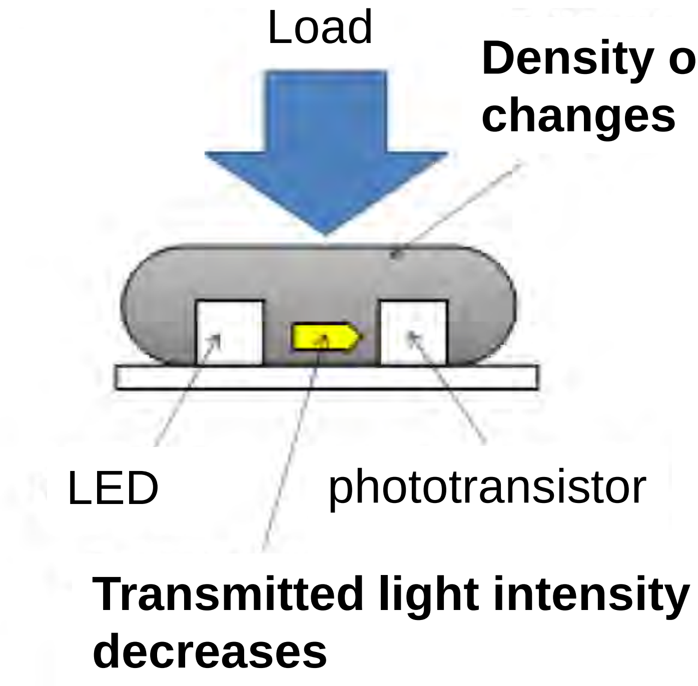
(c) Change of
the transmitted light

(d) Change of the light
due to deformation
of the optical fiber

Touchence Shokac Cube

- Capable of detecting 0.6 mm of deformation of the sponge based on the response of the phototransistor
- Not damaged even when a large force is applied to the sponge



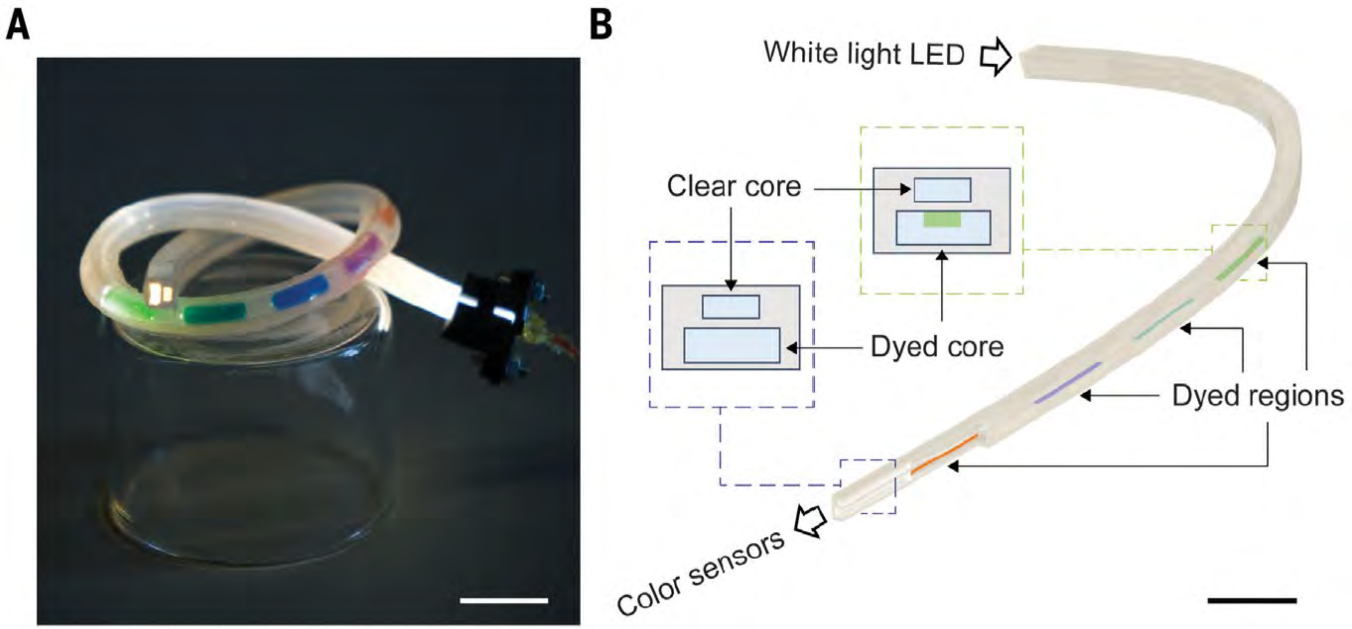


Density of the sponge changes

Transmitted light intensity decreases

タッチエンス株式会社 http://touchence.jp/

Stretchable distributed fiber-optic sensors



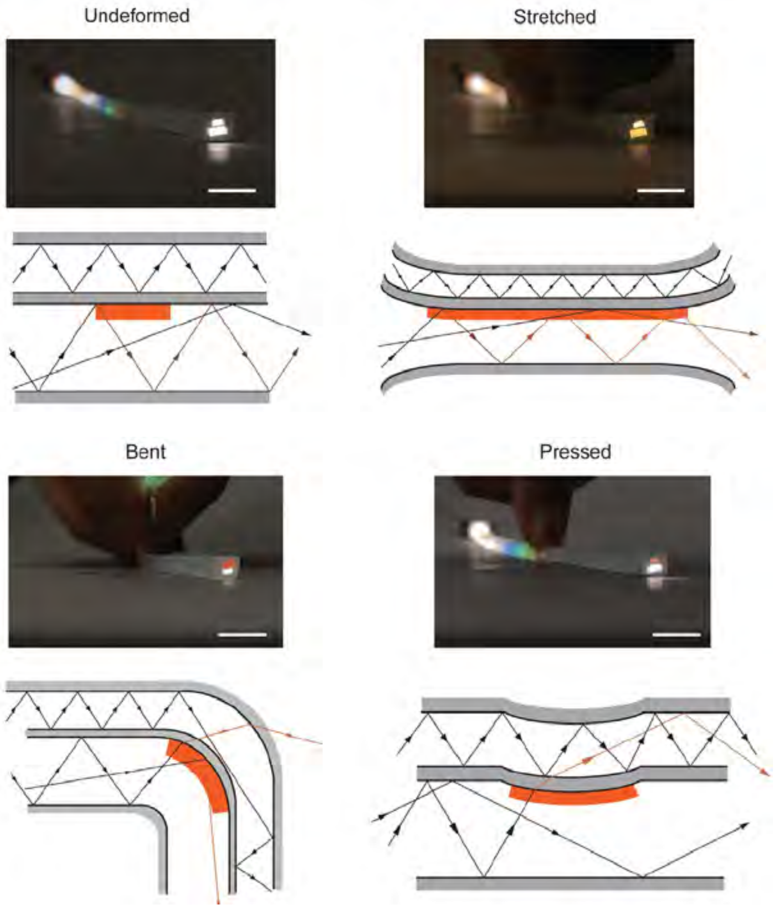
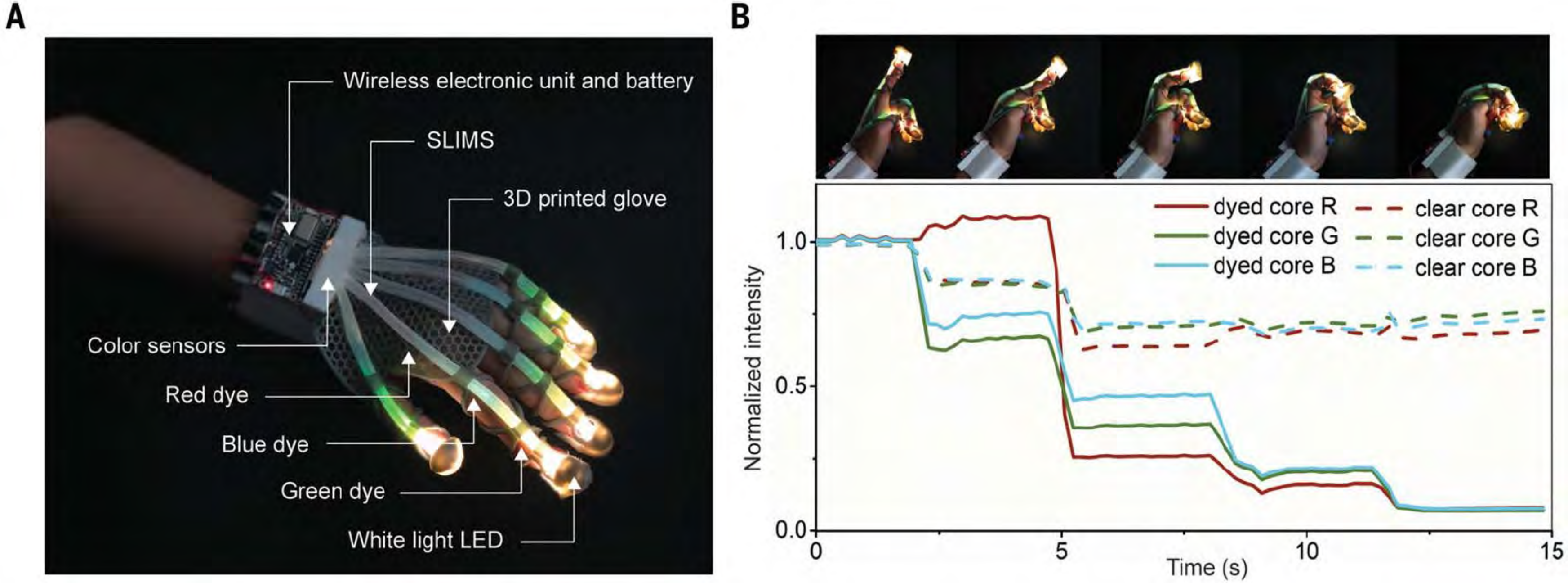


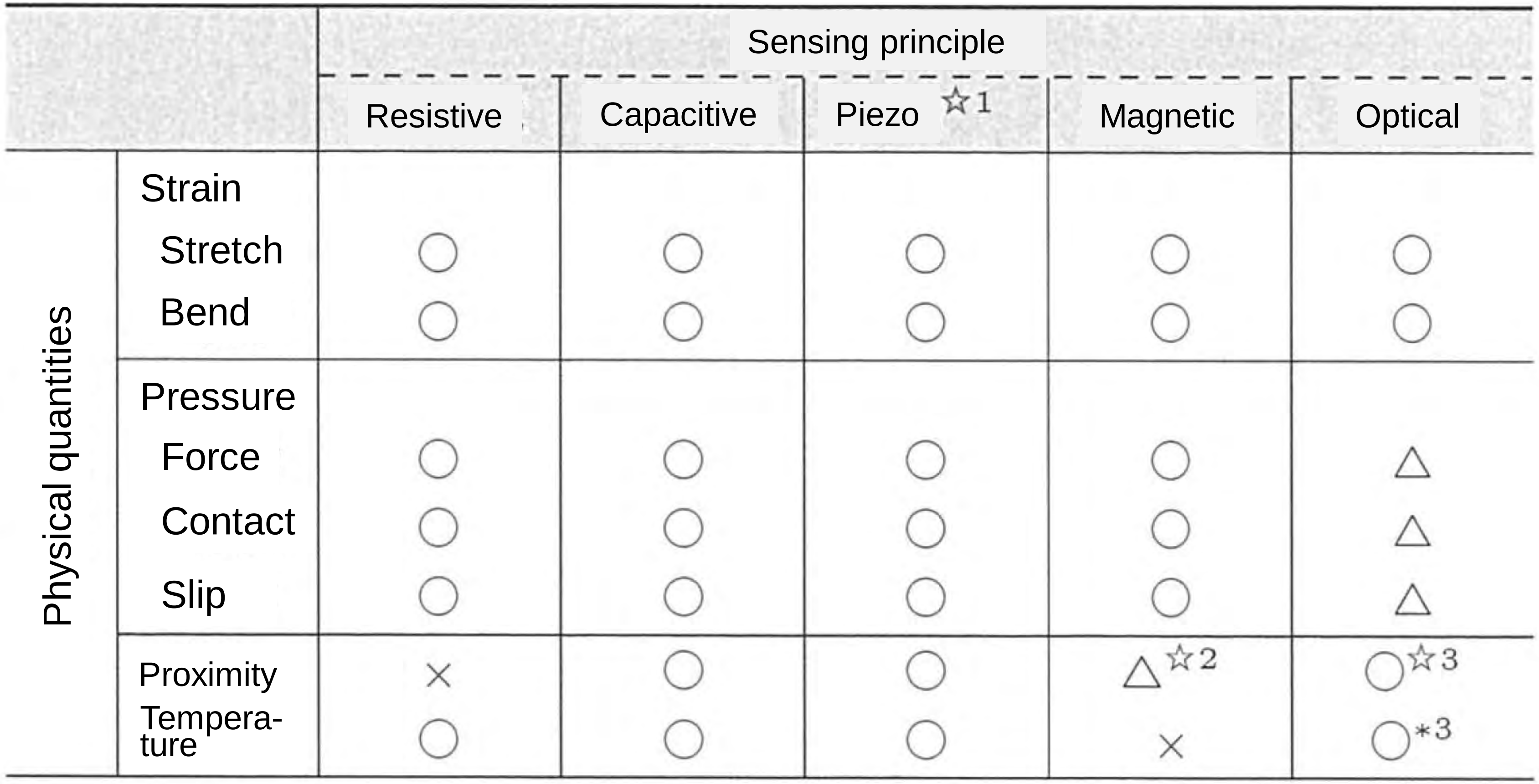
Fig. 1. SLIMS. (**A**) Image of a SLIMS tied into a knot. (**B**) Schematic of the SLIMS showing the discrete dyed regions, the design of the collateral cores, and its coupling to a light source and color sensors. (**C**) Optical outputs and ray diagrams of SLIMS when it is undeformed, stretched, bent, and pressed. Scale bars, 1 cm.



H. Bai et al., Science (2020)

Physical quantities and sensing principle

(○ : Detectable with high accuracy , △ : Detectable but poor compared to other methods , × : Undetectable)



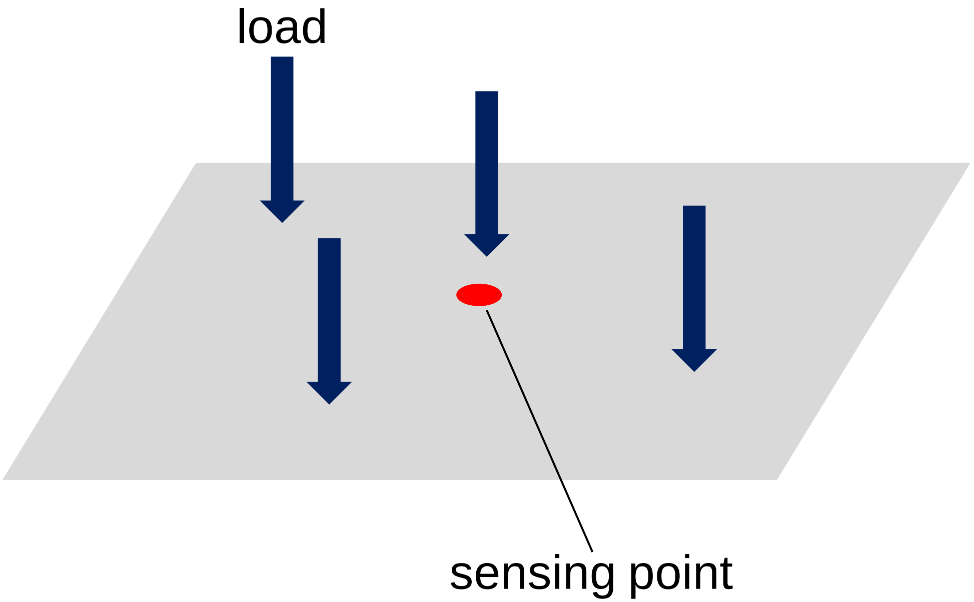
		Sensing principle				
		Resistive	Capacitive	Piezo ☆1	Magnetic	Optical
Physical quantities	Strain					
	Stretch	○	○	○	○	○
	Bend	○	○	○	○	○
	Pressure					
	Force	○	○	○	○	△
	Contact	○	○	○	○	△
	Slip	○	○	○	○	△
	Proximity	×	○	○	△☆2	○☆3
	Temperature	○	○	○	×	○*3

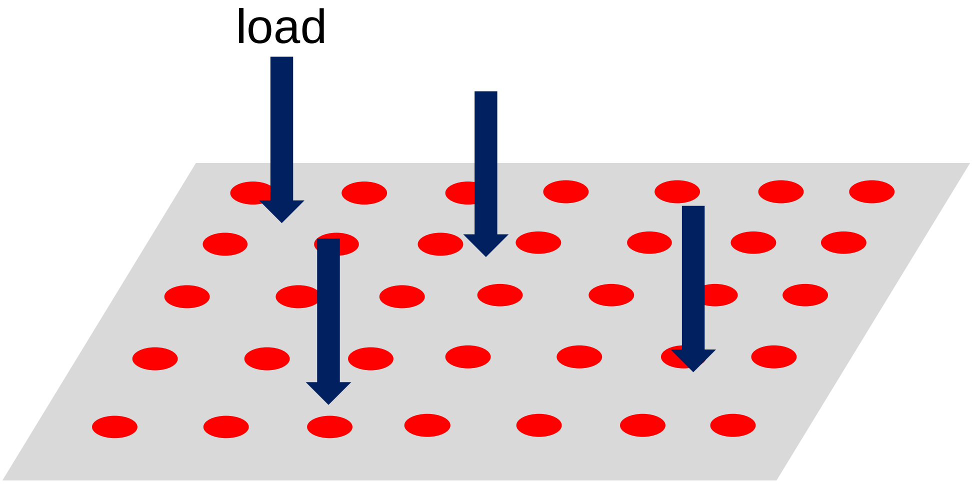
☆1 : Piezoelectric, capable of detecting time-varying dynamic input

☆2 : Capable of detecting magnetic materials and metals

☆3 : Need a 3D camera and thermal imaging (infrared) camera

Distributed sensor for large area sensing





Single sensor :

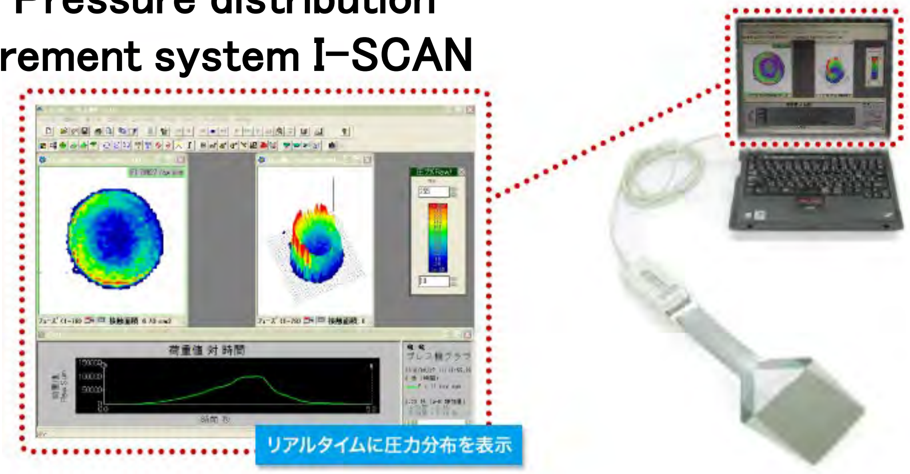
- Measure the force at the single sensing point or averaged force around the sensing point
- Cover narrow area

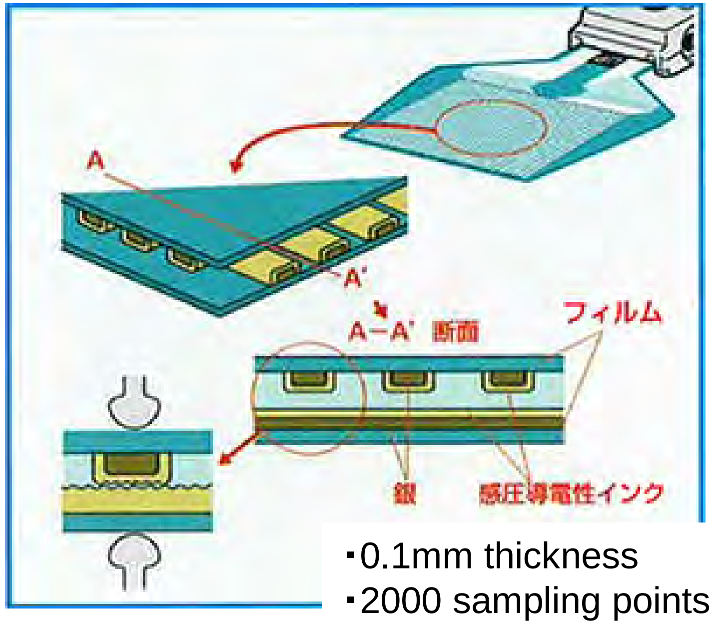
Distributed sensor :

- Measure the force at each point and get spatial distribution of the force
- Cover large area

Examples of distributed tactile sensor

NITTA Pressure distribution measurement system I-SCAN

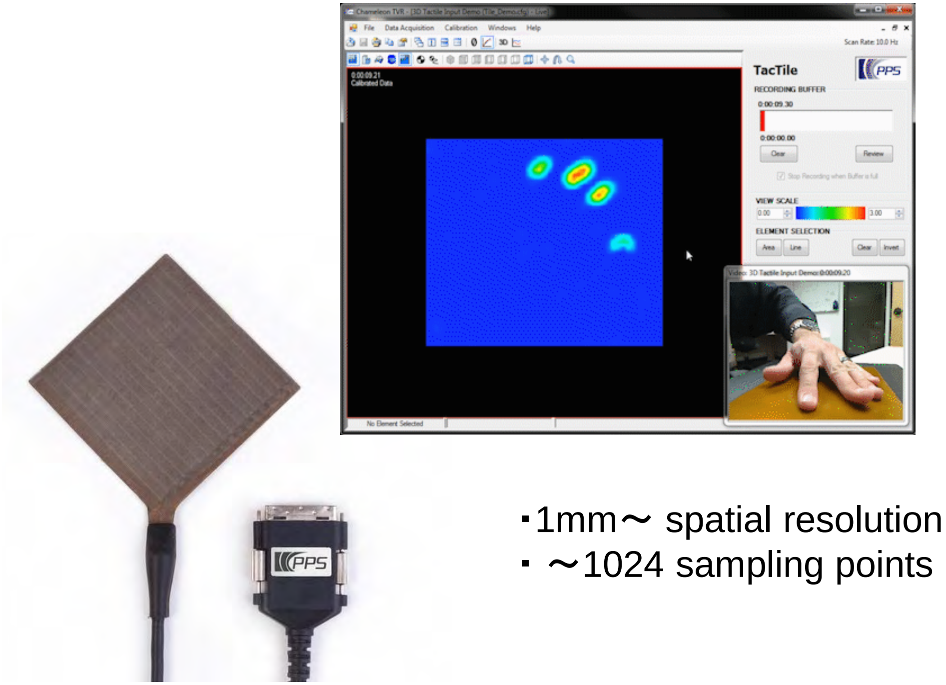




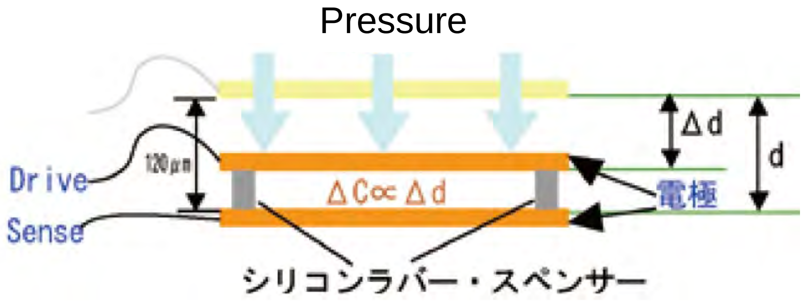
- 0.1mm thickness
- 2000 sampling points
- 100Hz sampling rate

https://www.nitta.co.jp/product/sensor/I-SCAN/

Pressure Profile Systems Tactile array sensor



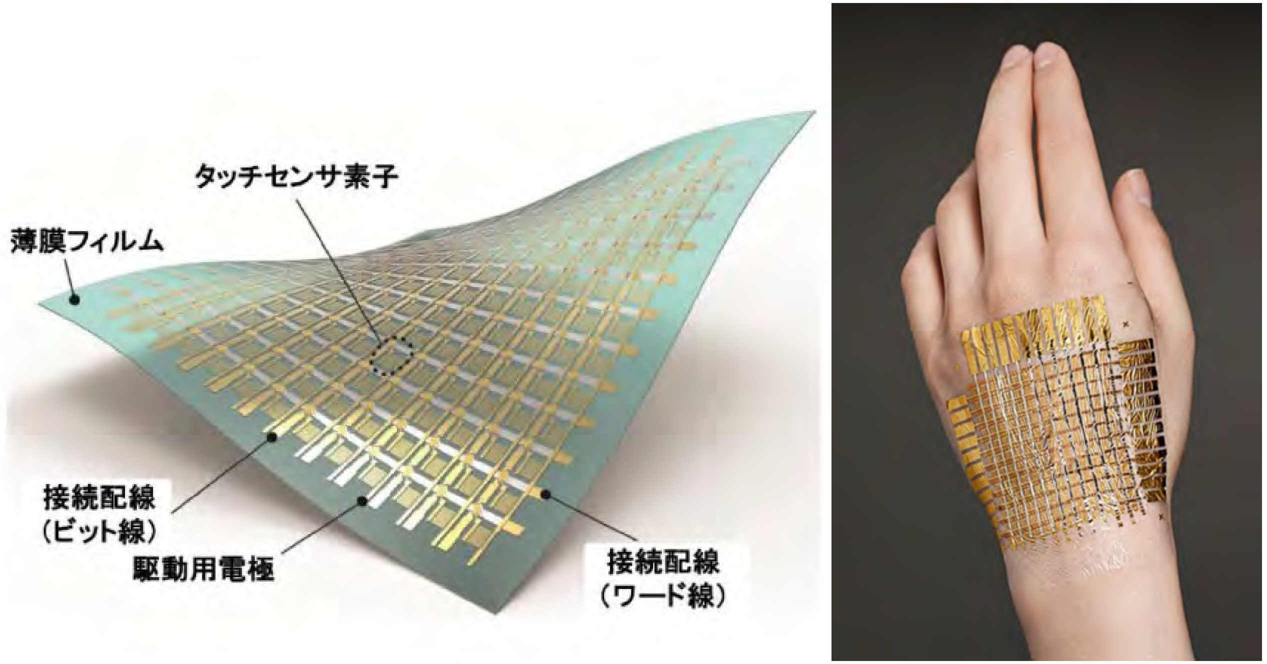
- 1mm～ spatial resolution
- ～1024 sampling points



https://syscom-corp.jp/products/syokkaku-sensor/

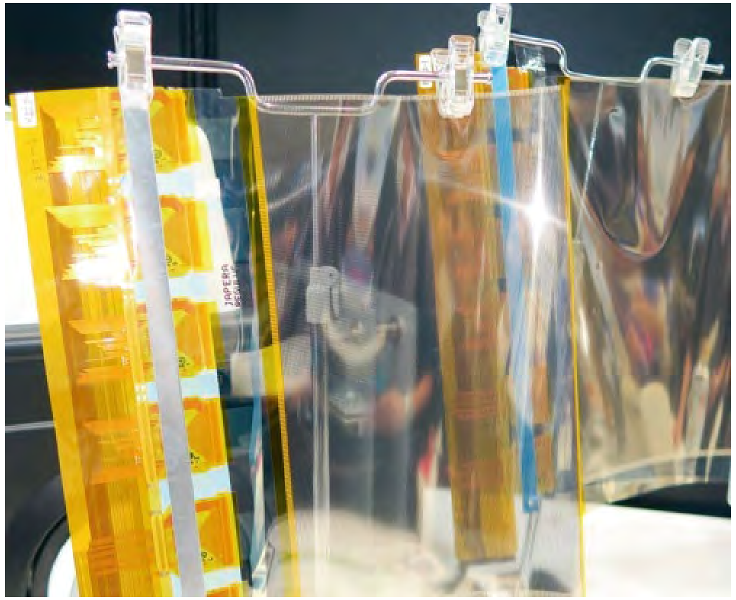
Examples of distributed tactile sensor

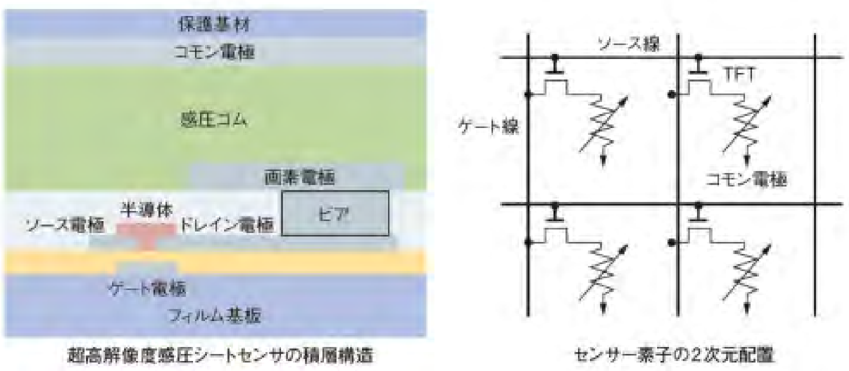
Flexible electronics and printed electronics



Organic transistors arranged in flexible sheet

e-skin
T.Someya, 2013



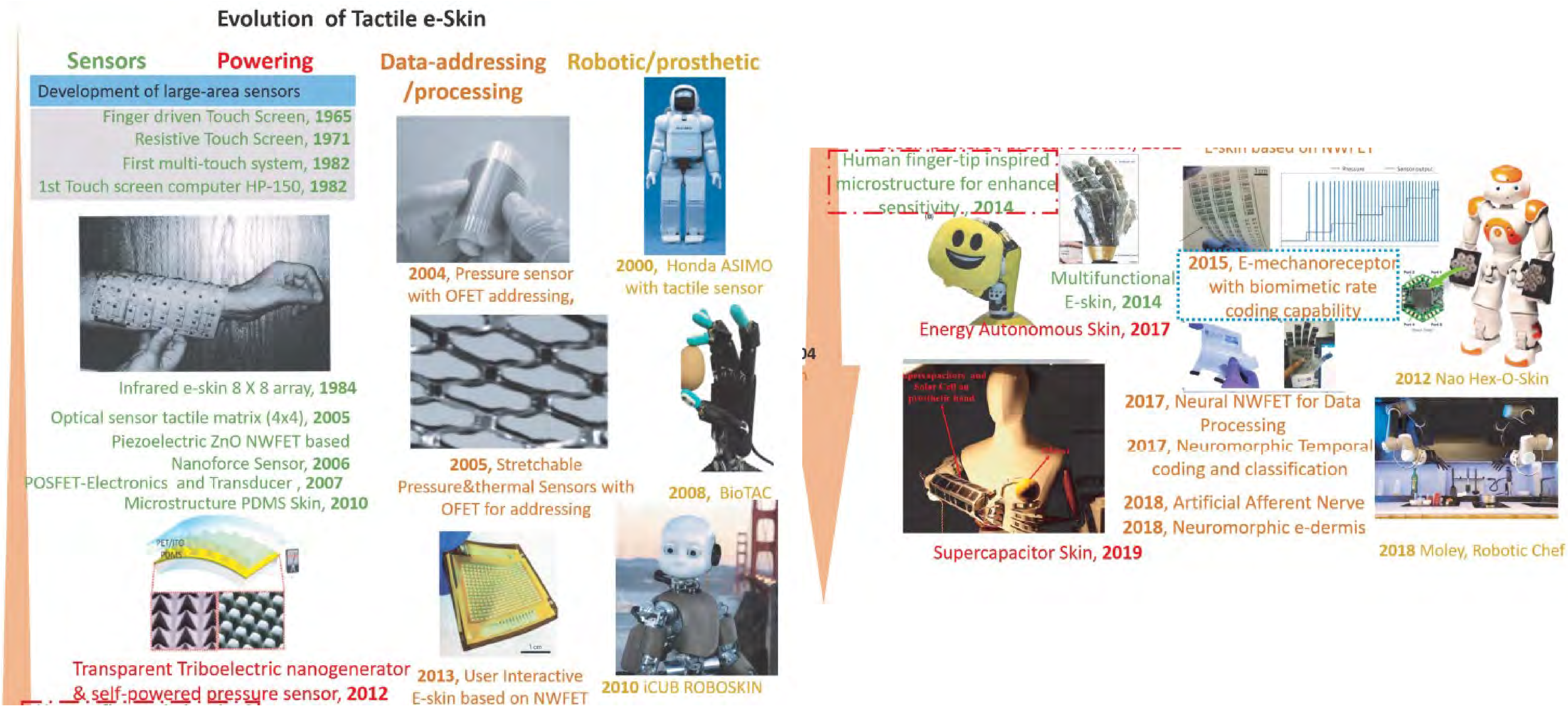


超高解像度感圧シートセンサの積層構造

センサー素子の2次元配置

Pressure-sensitive sheets with printed electronics, NEC, 2018

Large-Area Soft e-Skin: The Challenges Beyond Sensor Designs

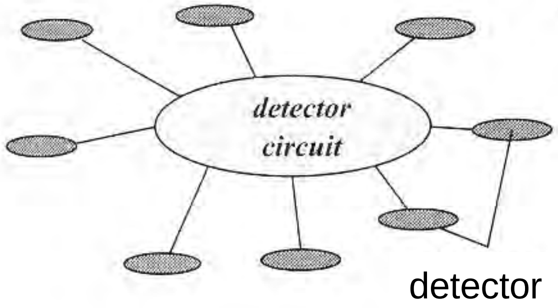


R.Dahiya et al., Proceedings of the IEEE, 2019.

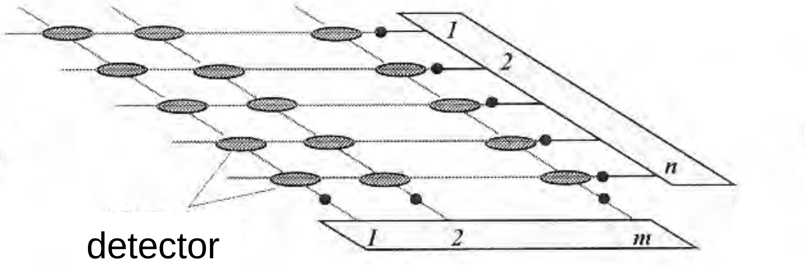
Wiring problem

In distributed sensors, wiring for control signals and output readout to many distributed detector elements can be a problem.

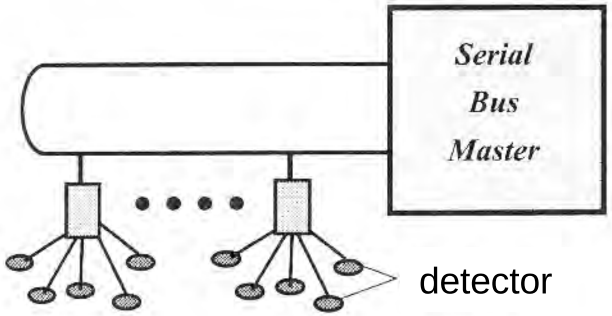
Typical wiring methods



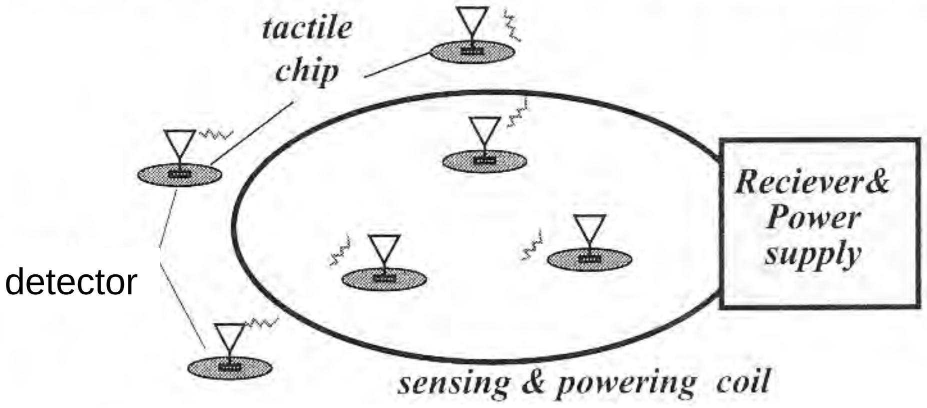
One by one wiring



Matrix wiring and scanning



Serial bus



Wireless connection

触覚認識メカニズムと応用技術，下条他編，S&T出版

Distributed Tactile Sensor Using Video Signal Output

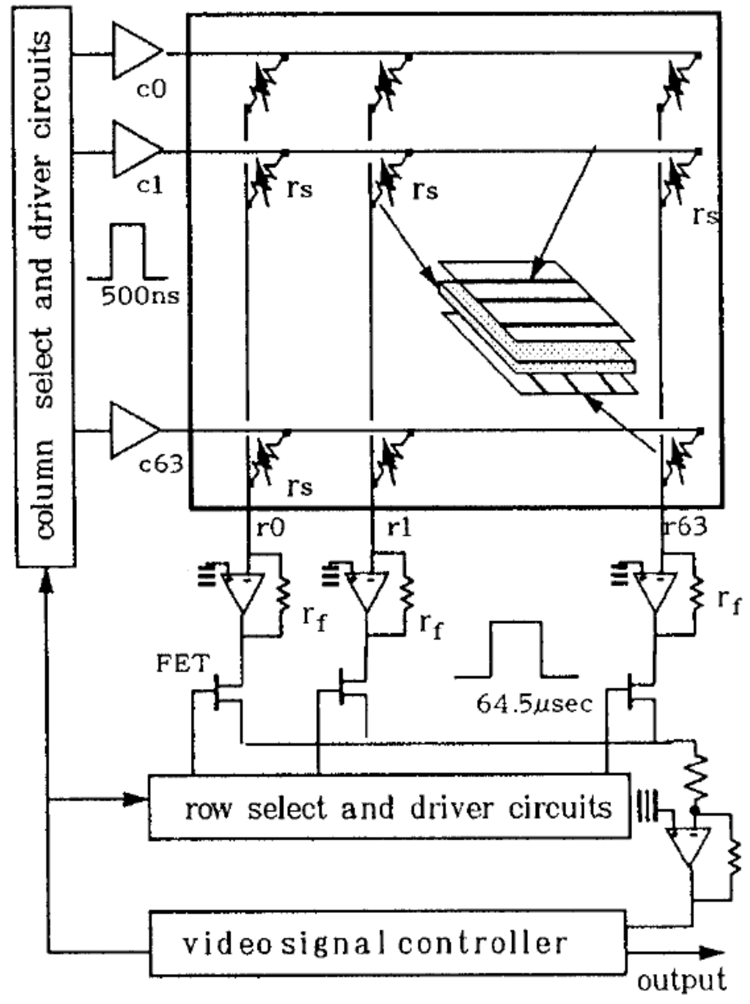
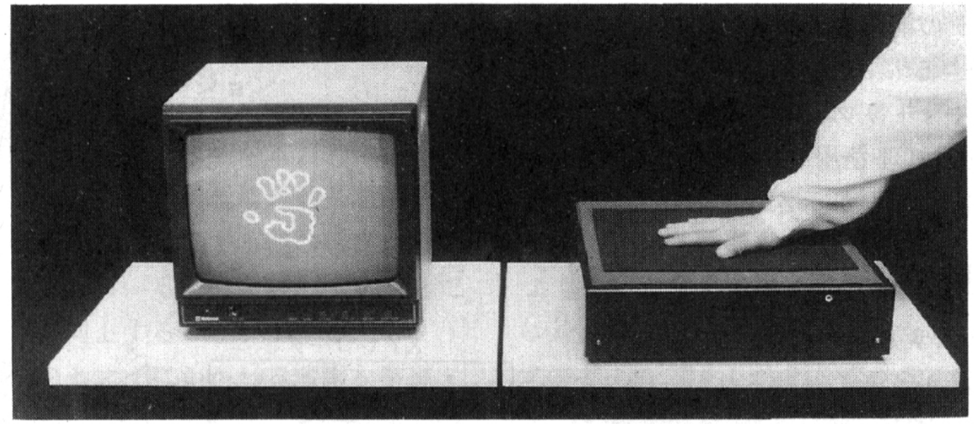
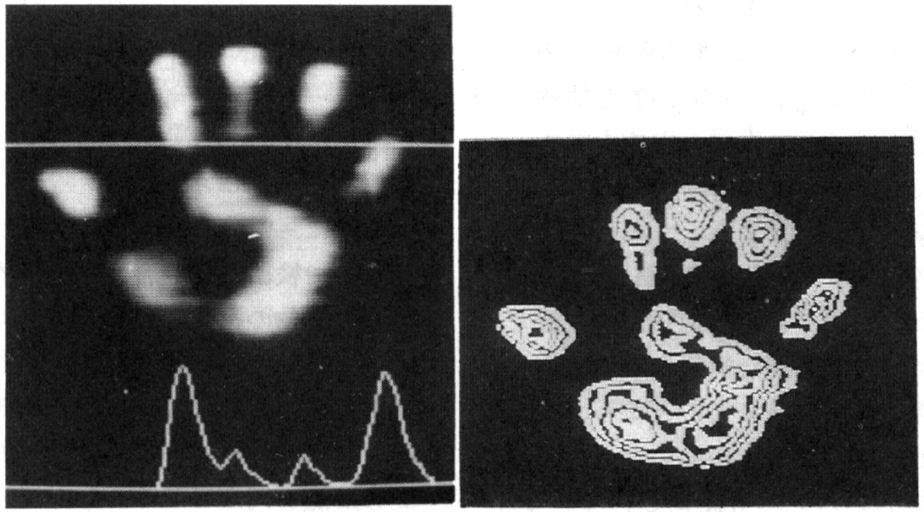


Fig. 2 Structure of the sensor and scanning circuit using zero potential method.



（a）　触覚イメージングセンサ



（b）　圧力分布像　　　（c）　等圧線像

図3　触覚イメージングの例（64×64）

石川正俊，“触覚のセンシング技術，” 精密工学会誌，vol.55, no.9, 1989.

Image sensor

Scanning circuit selects pixels one by one and read out their pixel values from an array of millions of pixels in tens of milliseconds.

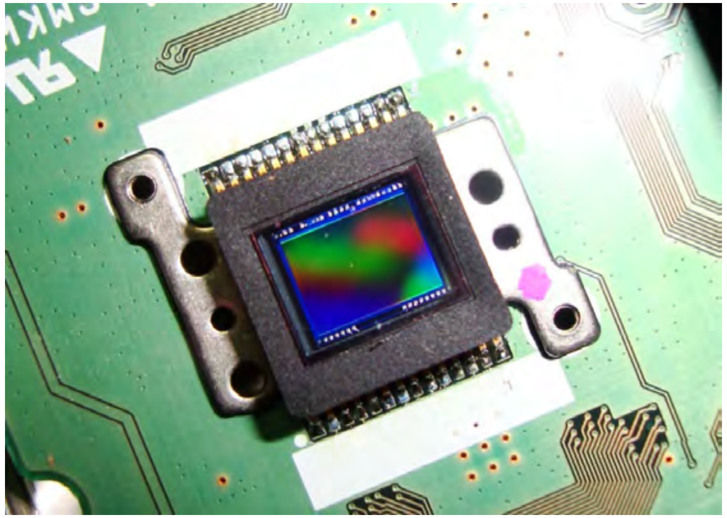
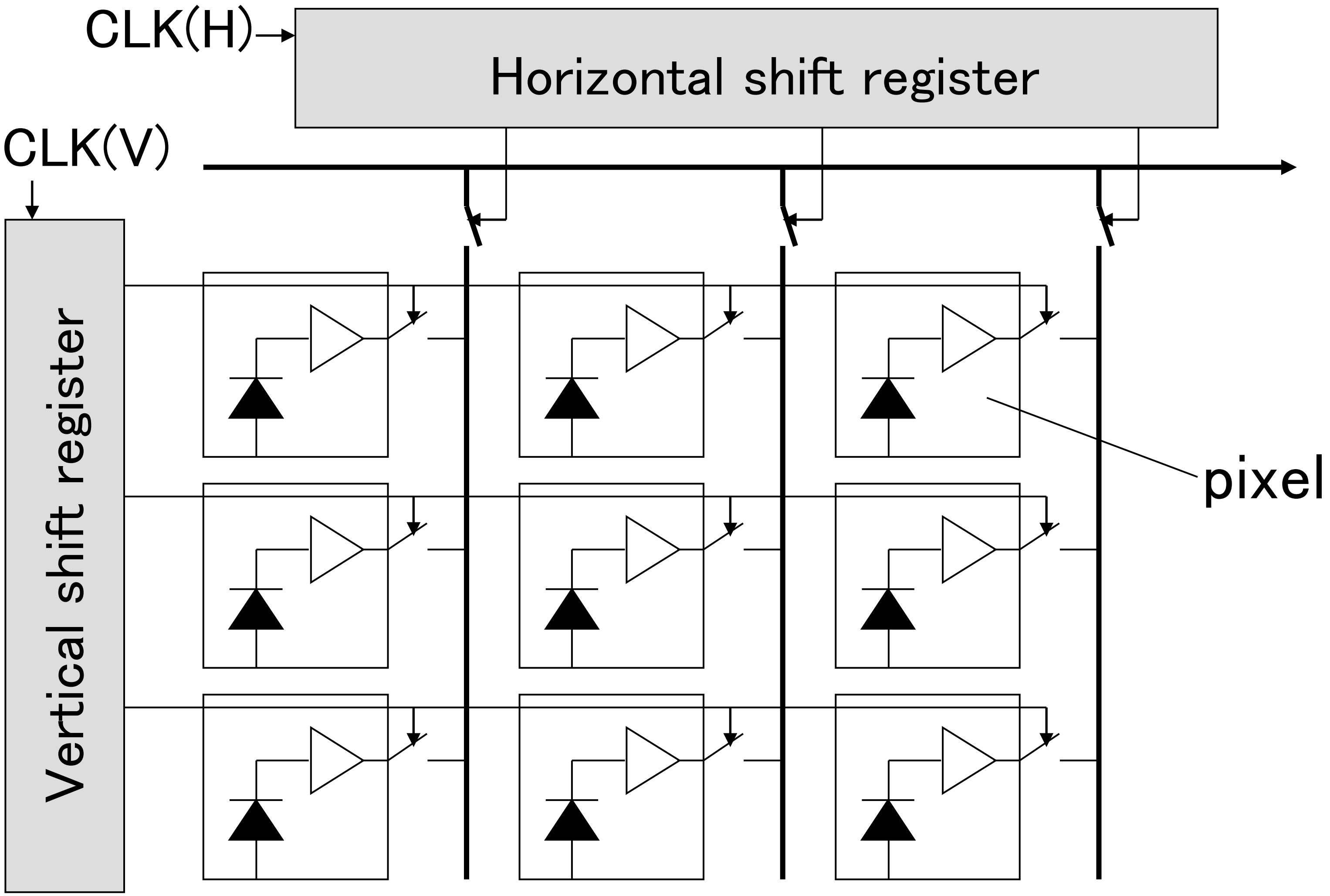
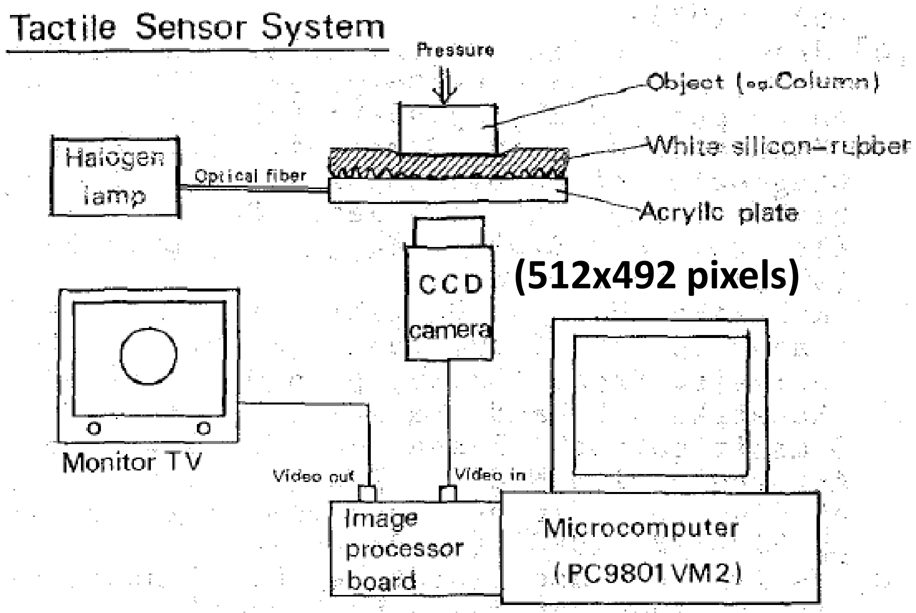


Image sensor



Distributed Tactile Sensor Using Camera

An Object Profile Detection by a High Resolution Tactile Sensor Using an Optical Conductive Plate



(512x492 pixels)

Fig.1 Genaral layout of the sensor system

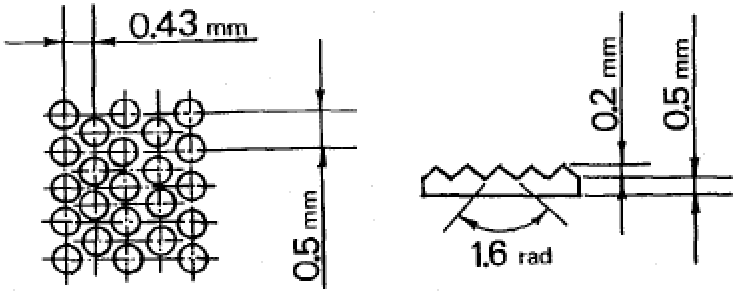
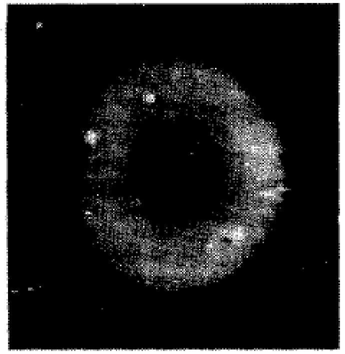
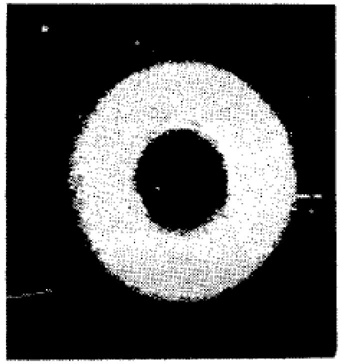


Fig.3 Structure of the sheet



(a) Enhancement



(b) Binarization

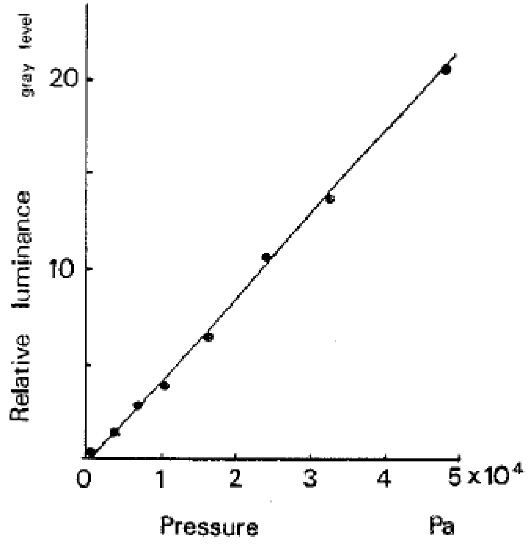
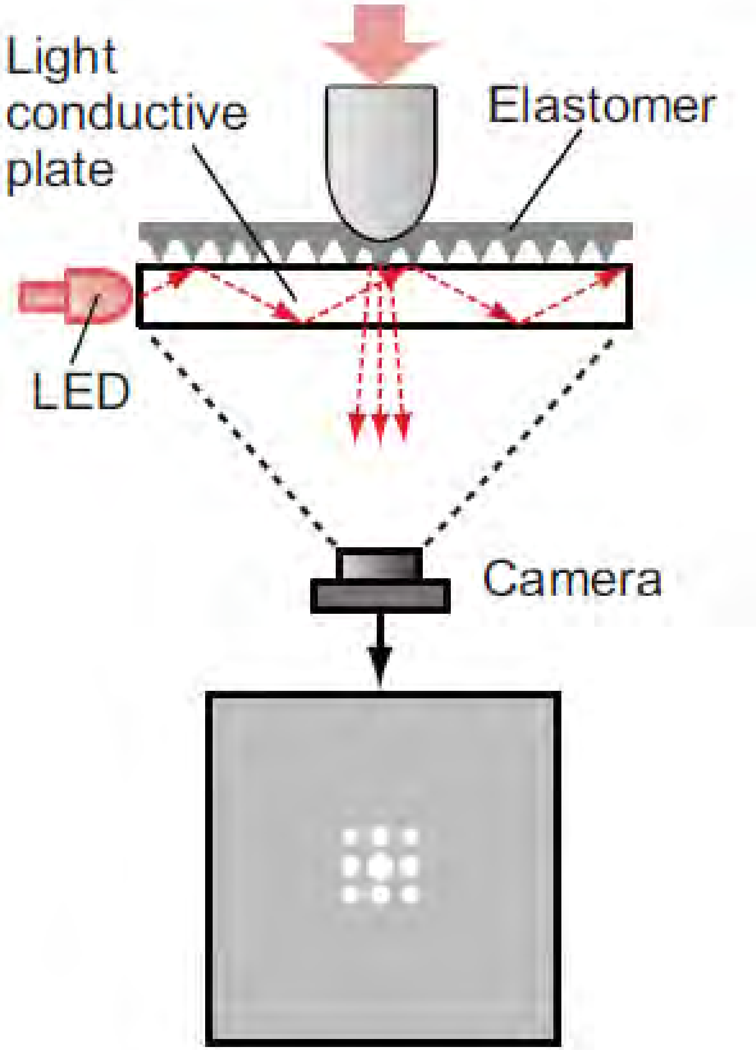


Fig.11 Relation between the applied pressure and the averaged output of the CCD

H.Hiraishi, N.Suzuki, M.Kaneko, K.Tanie, Proc.IECON’88 (1988)

Light conductive plate method



Shimonomura, *Sensors*, 2019

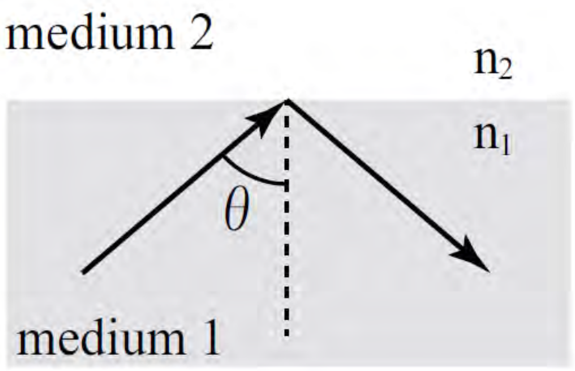
- A total reflection occurs, and light travels inside the light conductive plate while reflecting.

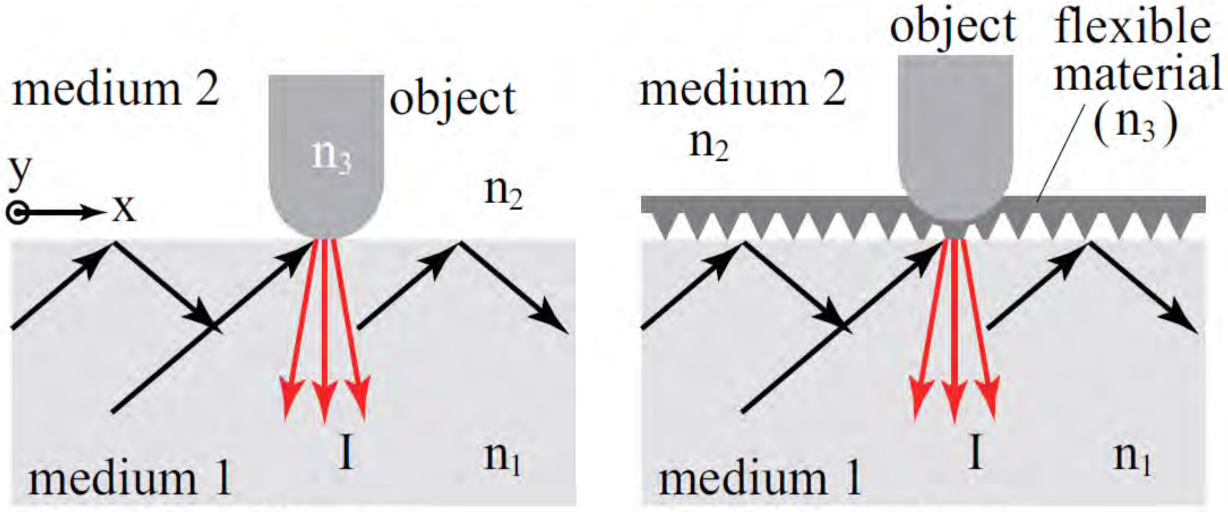
- When an object contacts the light conductive plate, light leaks from the contact area.

- By capturing this scattered light with a camera, the location of contact can be detected.

- It is suitable for detecting the contact area.

Light conductive plate method





direct

indirect

Shimonomura, *Sensors*, 2019

Refractive index of the light conductive plate : n_1
Refractive index of the medium outside : n_2
Critical angle（臨界角）θ_m is

$$\theta_m = \sin^{-1}\frac{n_1}{n_2}$$

（For air and acrylic, θ_m is about 42° ）

Condition of a total reflection is

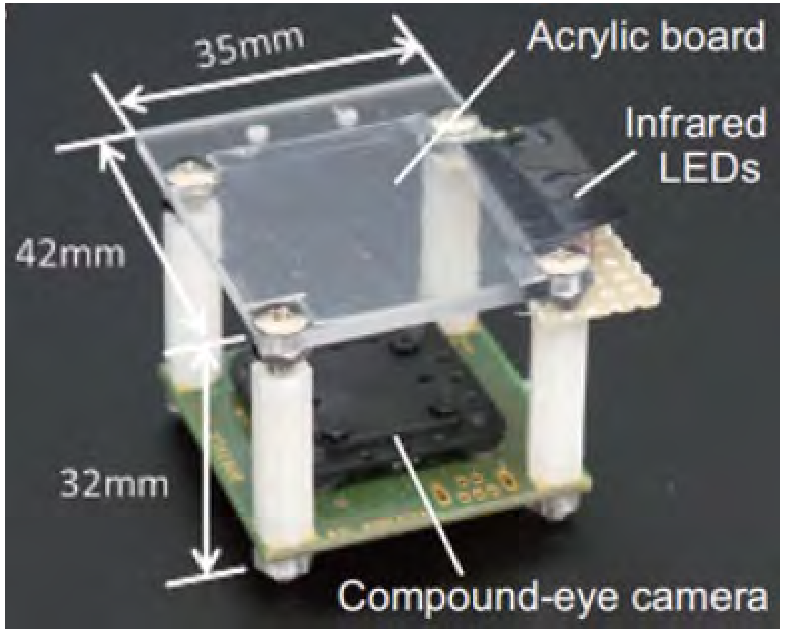
$$\theta > \theta_m$$

When an object contacts the sensor surface, light that do not satisfy the condition of total reflection at that area leak out of the light conductive plate and are reflected on the surface of the contacted object.
This light can be observed by a camera as

$$I(x,y,\lambda) = \rho(\lambda)E(x,y,\lambda)$$

$\rho(\lambda)$: Spectral reflectance of object surface
$E(x,y,\lambda)$: Light intensity applied on the object

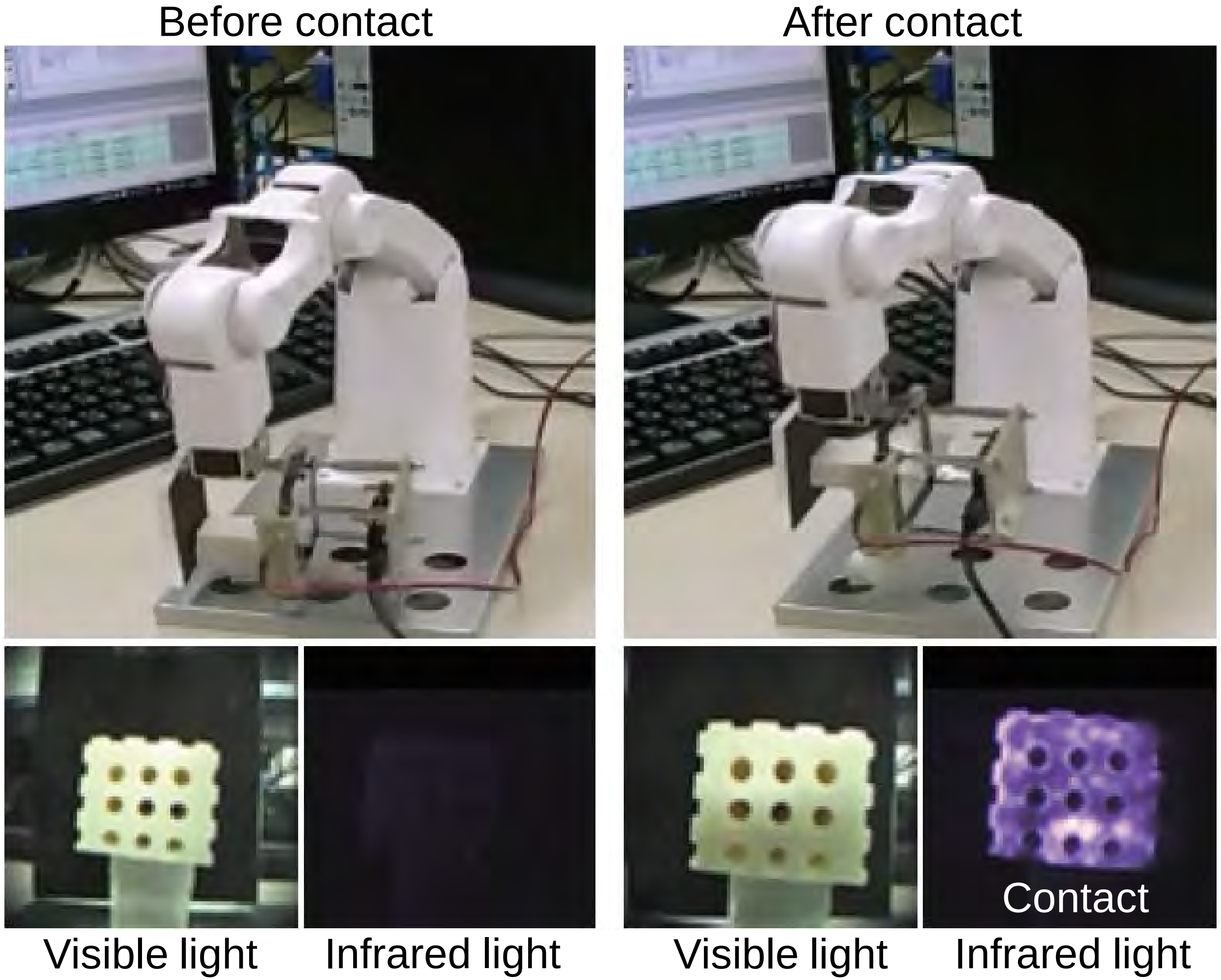
Tactile sensor using camera based on light conductive plate method



- Objects directly contact with the light conductive plate

- Near-infrared light is irradiated inside the light conductive plate

- Visible light image and Infrared images are acquired simultaneously

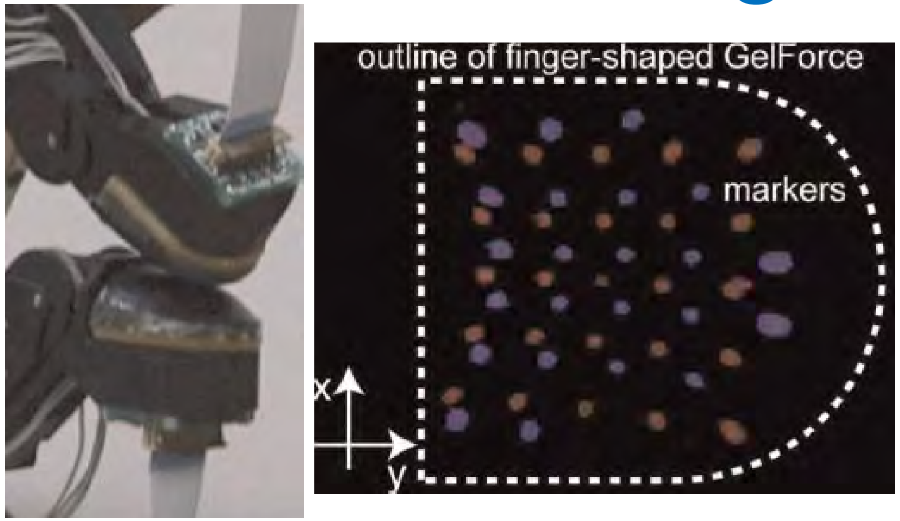

Before contact

After contact

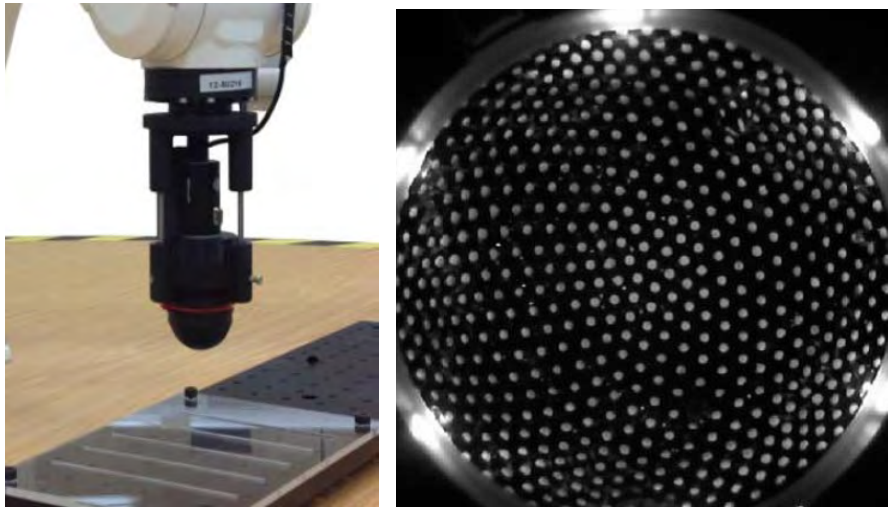
Visible light   Infrared light   Visible light   Infrared light

Shimonomura, Nakashima, *IEEE ICRA2016*

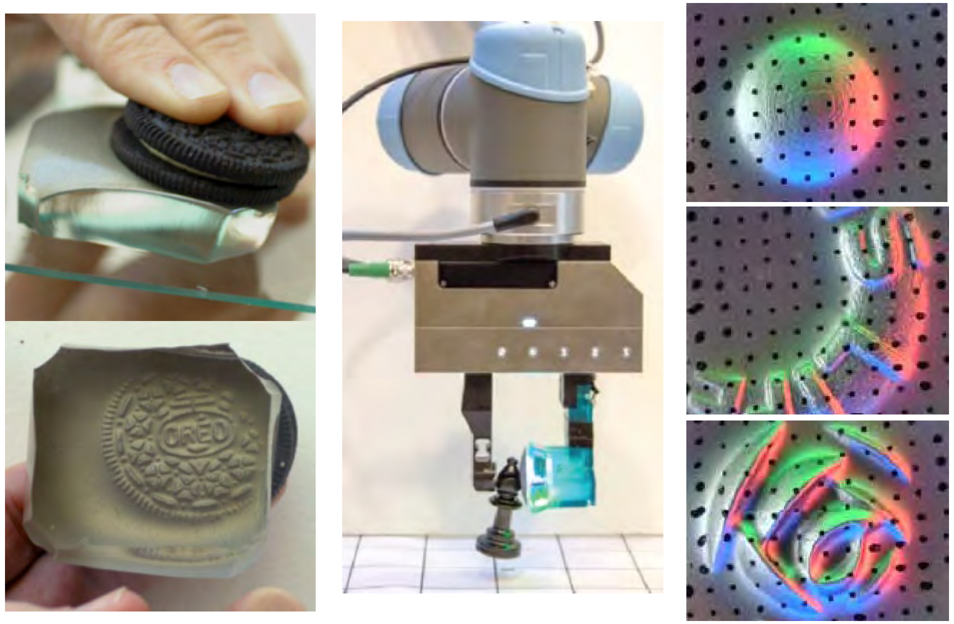
Tactile sensors using camera



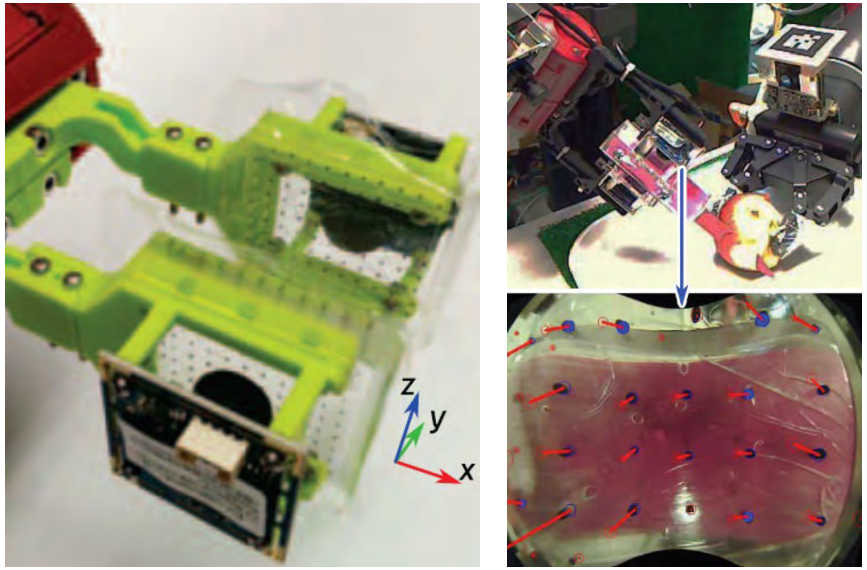
GelForce, Tachi et al., Univ. of Tokyo



TacTip, Lepora et al., Univ. of Bristol

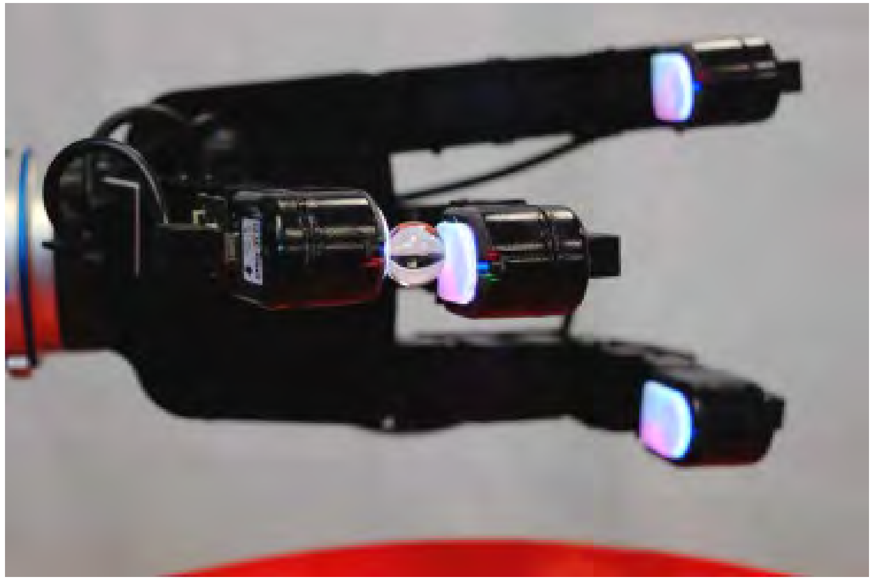


GelSight, Adelson et al., MIT

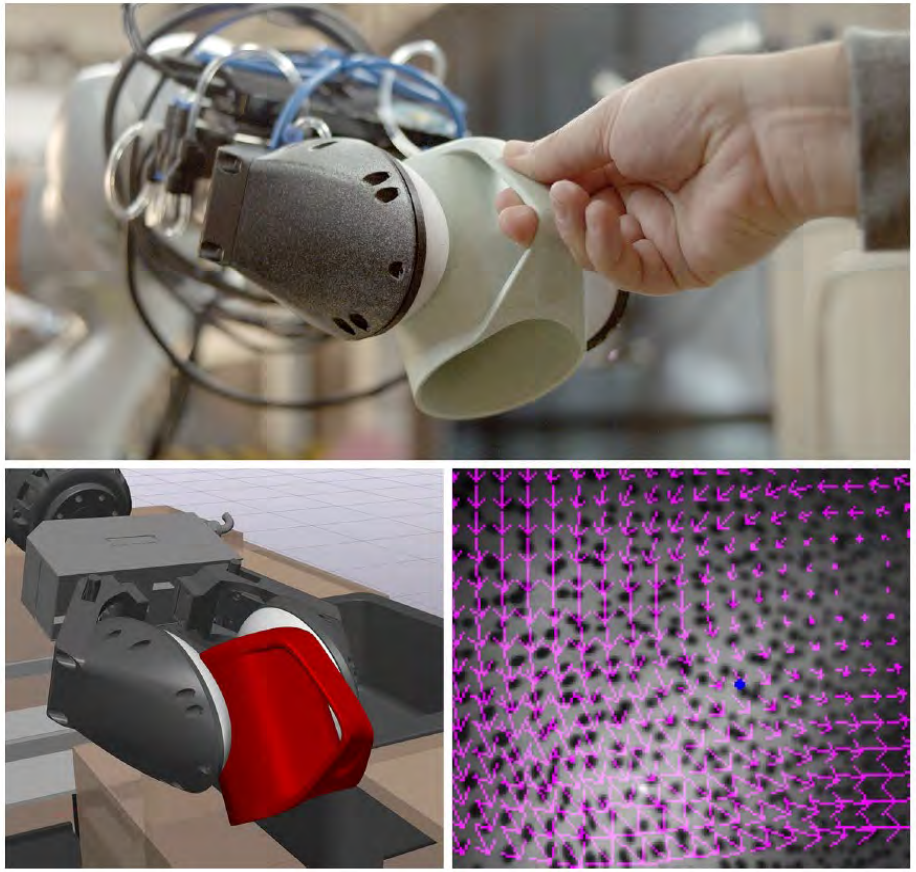


Finger Vision, Yamaguchi et al., Tohoku Univ.

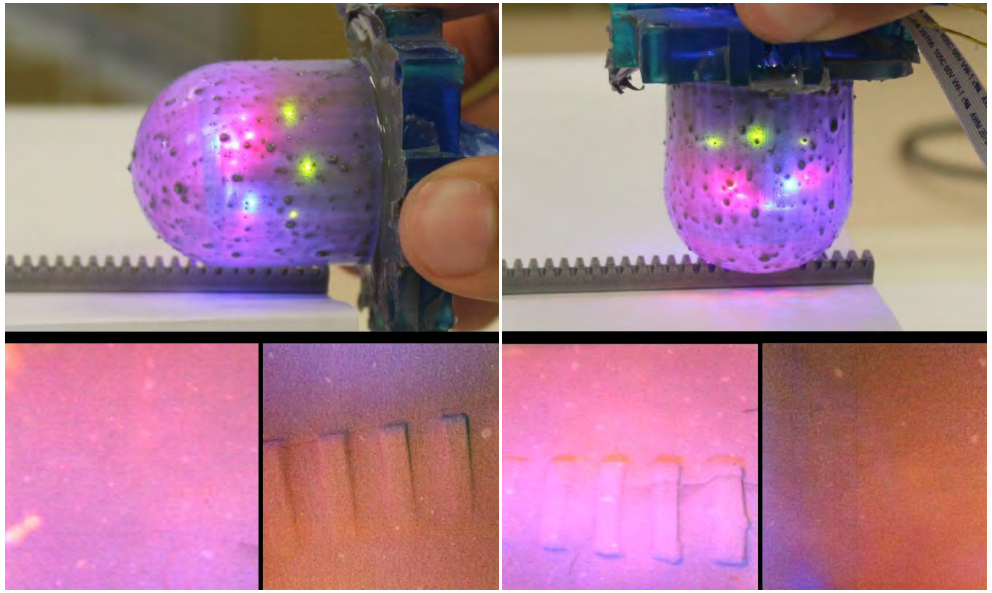
Tactile sensors using camera



M.Lambeta et al. (Facebook), “DIGIT: A Novel Design for a Low-Cost Compact High-Resolution Tactile Sensor with Application to In-Hand Manipulation,” IEEE RA-L, 2020.2.

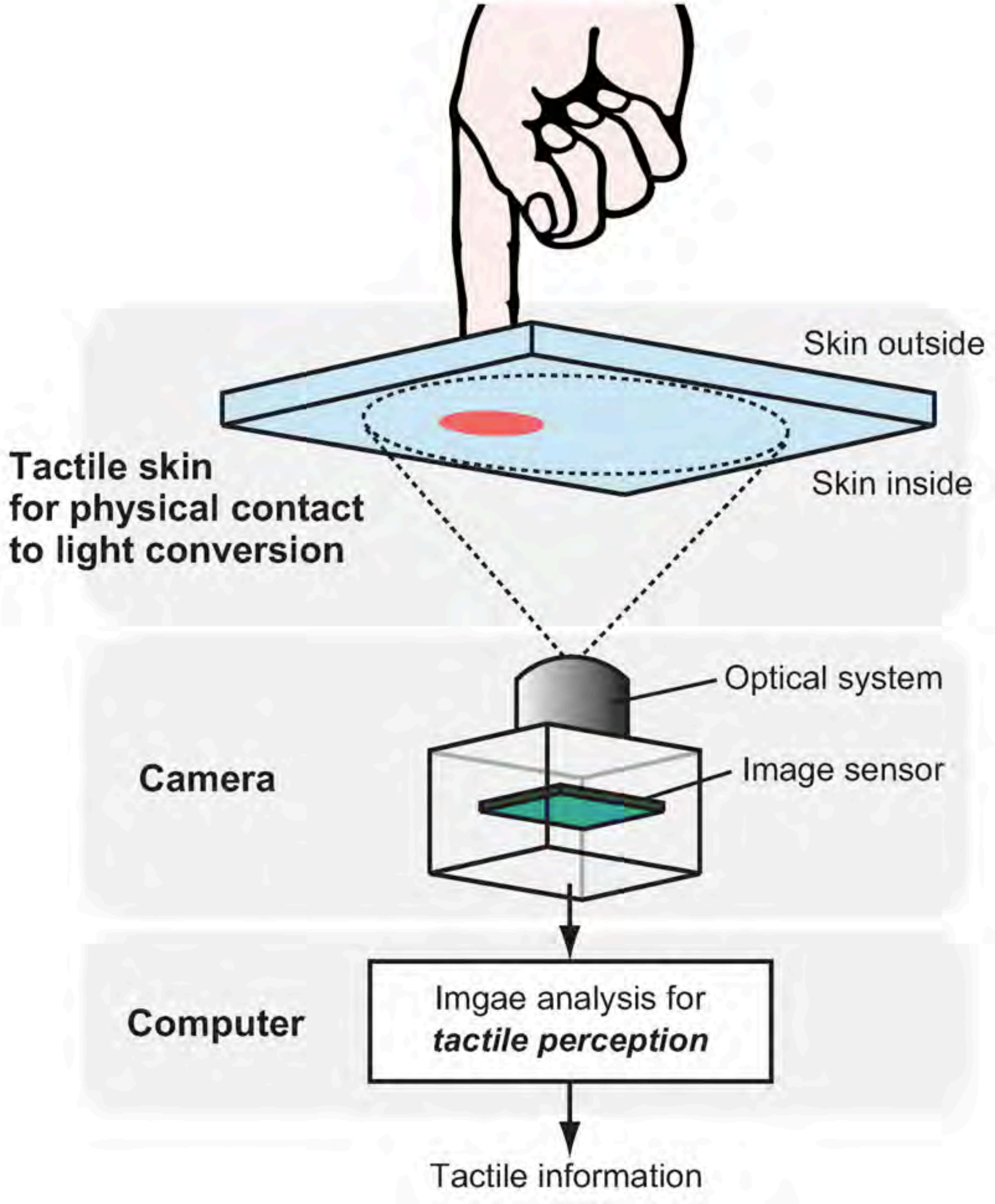


N.Kuppuswamy et al. (Toyota Research Institute), “Soft-bubble grippers for robust and perceptive manipulation,” arXiv:2004.03691v1, 2020.4.



A.Padmanabha et al. (UC Berkeley) “OmniTact: A Multi-Directional High-Resolution Touch Sensor,” arXiv:2003.06965v1, 2020.3.

Tactile sensor using camera - basic structure



Sensor surface (Interaction layer)

Physical contact with a contact surface is converted into optical information. Typical methods are:

- **Light conductive plate method**
- **Marker displacement method**
- **Reflective membrane method**

Camera

The sensor surface is captured from the back side.
Use appropriate lighting if necessary.

Computer

The camera image is analyzed and tactile information is extracted.

Shimonomura, K.; Tactile Image Sensors Employing Camera: A Review. Sensors **2019**, 19, 3933.

Advantages of the tactile sensor using camera

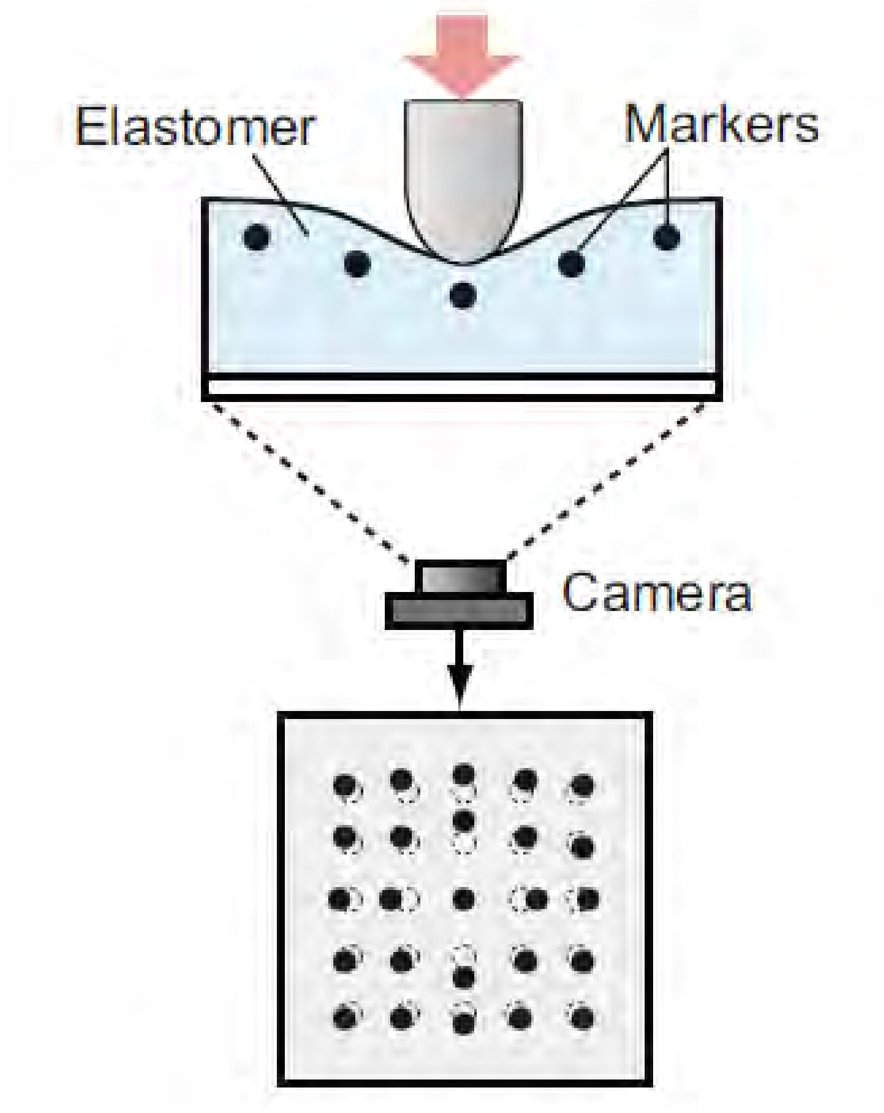
1. **High spatial resolution**
   The measurement range on the sensor surface is measured with the resolution of the number of camera pixels. Spatial resolution on the order of μm is possible.

2. **Flexible adjustment of sensing area**
   Measurement range can be easily adjusted by lens angle of view.
   In particular, it is easier to cover a large sensing area than with other methods.
   (However, there is a trade-off with thickness.)

3. **Robust against failure due to impact**
   The contact sensor surface is physically separated from the camera.
   Only the sensor surface part can be replaced.

4. **Computer vision algorithms and tools can be applied**
   Suitable for use with OpenCV and for applying image recognition methods based on deep learning.

Marker displacement method



Shimonomura, *Sensors*, 2019

- Embed the markers inside the transparent flexible material.

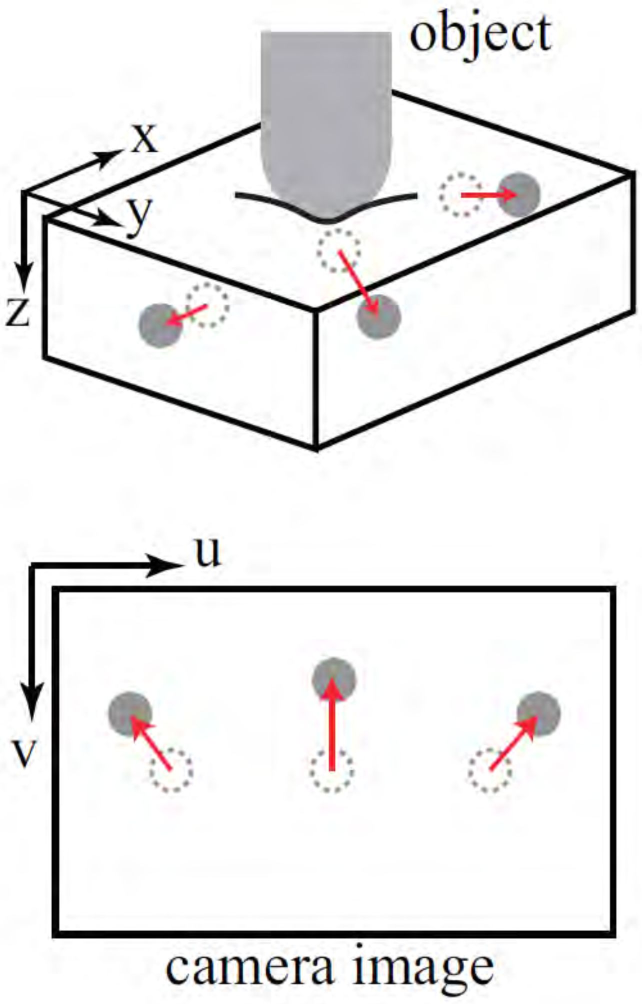
- When a force is applied to the flexible material by contact and the flexible material deforms, the marker inside changes its position.

- Capture this marker displacement with a camera as image.

- The correspondence between the displacement of the markers and the desired tactile information (e.g., force) is calculated.

- Suitable for force measurement, especially in shear direction.

Marker displacement method



Shimonomura, *Sensors*, 2019

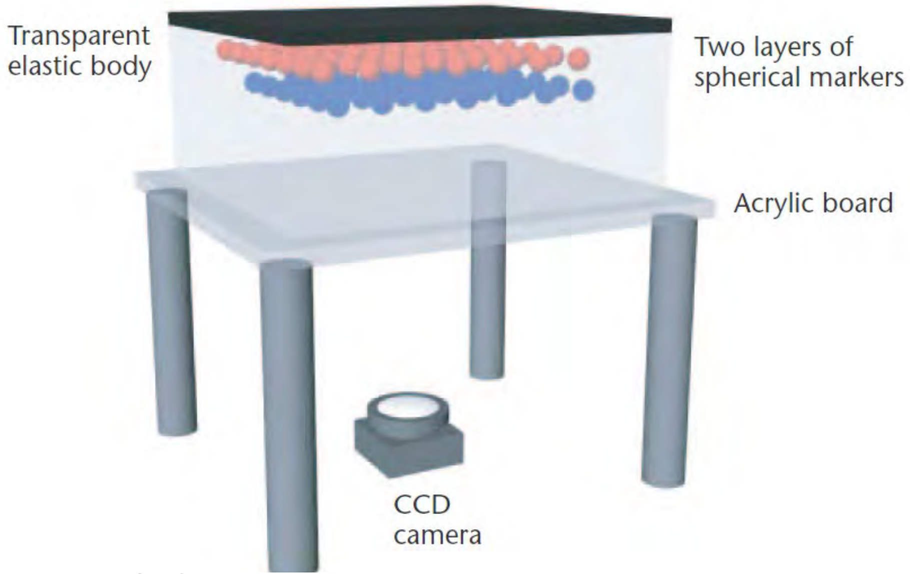
Position in the 3D coordinate of the maker i at the time t corresponds to $\boldsymbol{u}_i(t)$ in the image coordinate.
P is perspective camera matrix.

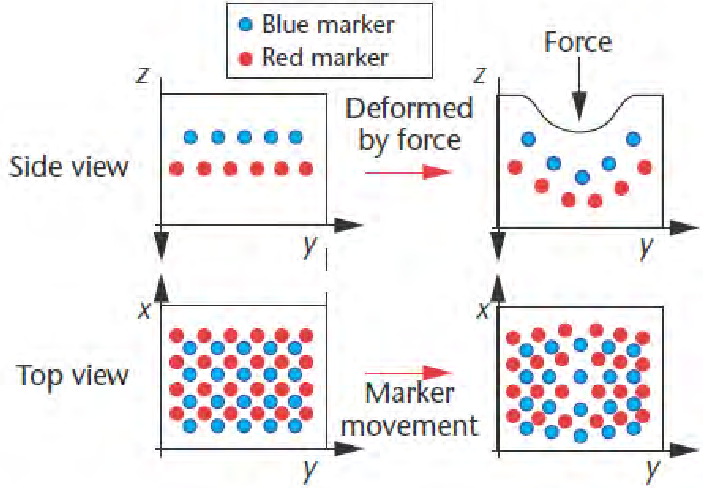
$$\boldsymbol{u}_i(t) = \begin{bmatrix} su_i(t) \\ sv_i(t) \\ s \end{bmatrix} = P \begin{bmatrix} x_i(t) \\ y_i(t) \\ z_i(t) \\ 1 \end{bmatrix}$$

To detect the displacement in z direction, you can
- use multiple camera, or
- measure diameter change of the marker on the image

Tactile information such as contact position, force, etc. are estimated from the change of each marker from its initial position or the change between consecutive times.

Vision-Based Sensor for Real-Time Measuring of Surface Traction Fields





5 **Representing depth information through color.**

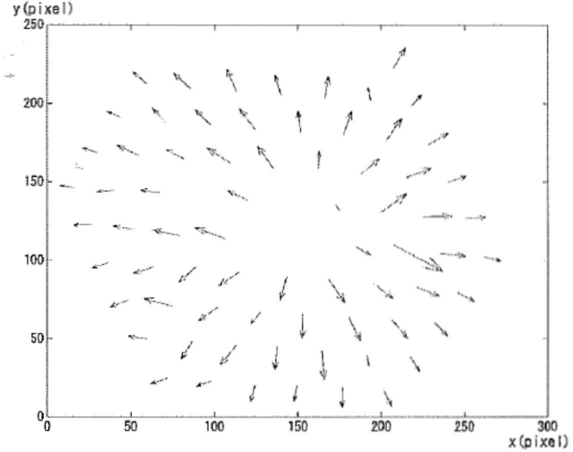


Fig. 6. Calculate movement vectors of red markers when given z-directional force

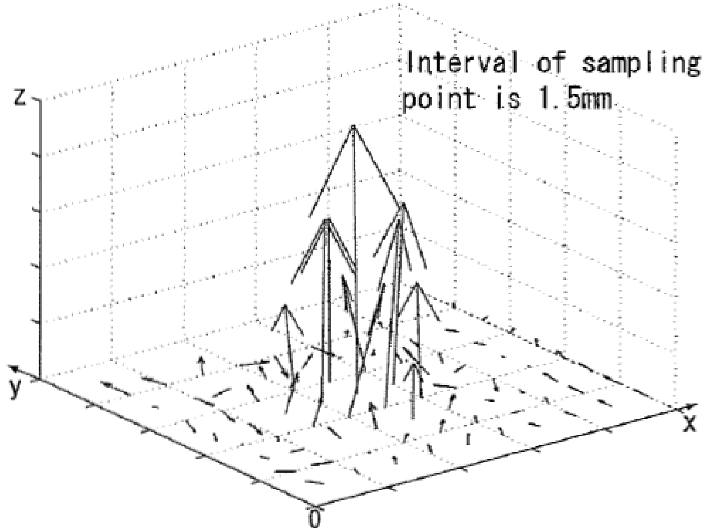
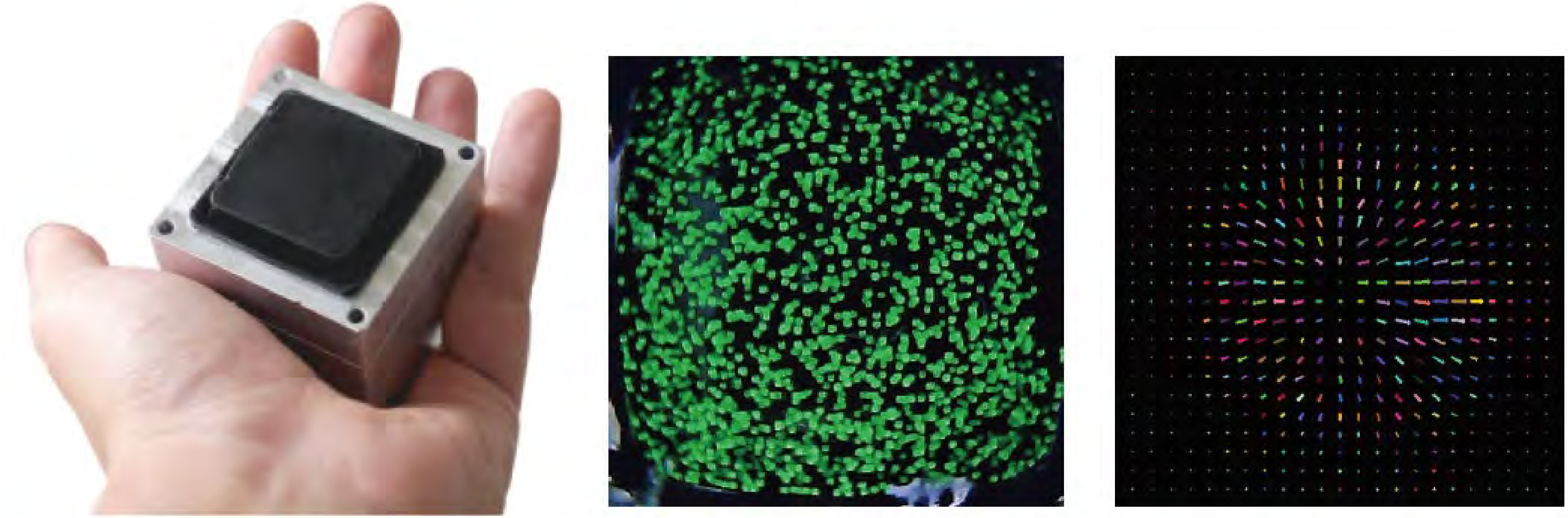


Fig. 7. Distribution of force vector using circular cylinder of 5mm diameter

K.Kamiyama, K.Vlack, T.Mizota, H.Kajimoto, N.Kawakami, S.Tachi, *IEEE Computer Graphics and Applications*, (2005)

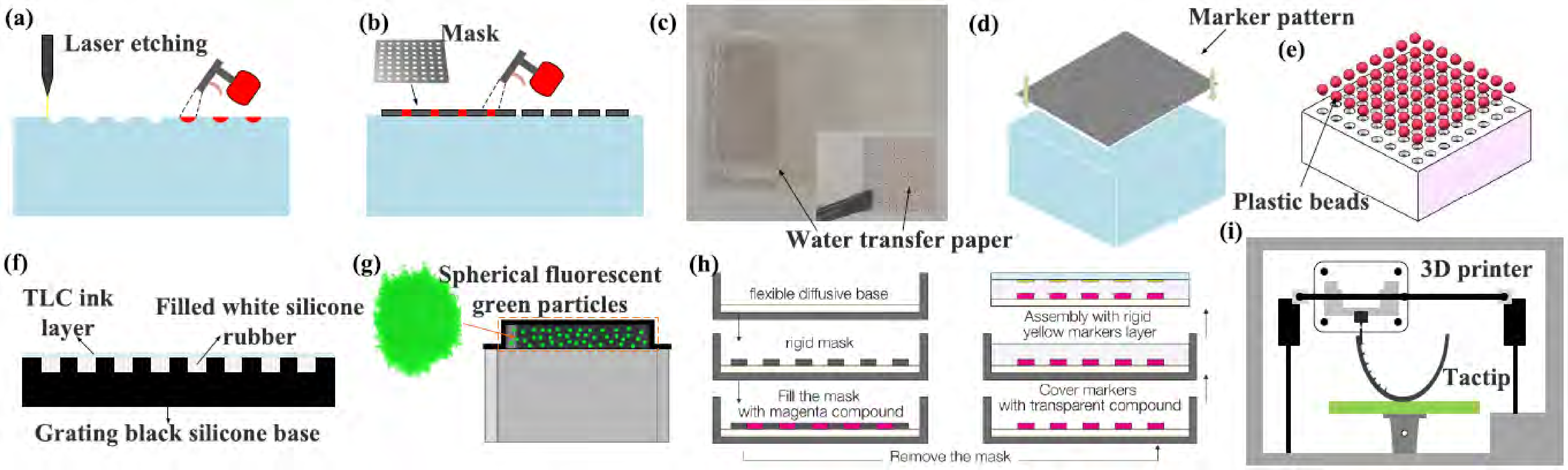
Design, Motivation and Evaluation of a Full-Resolution Optical Tactile Sensor



- A large number of measurement points (361 points) are realized by embedding a large number of small particles of 0.5 mm in diameter randomly and obtaining dense optical flow.
- The distribution of normal force was estimated using deep learning.

C. Sferrazza and R. D’Andrea, *Sensors*, 19, 2019

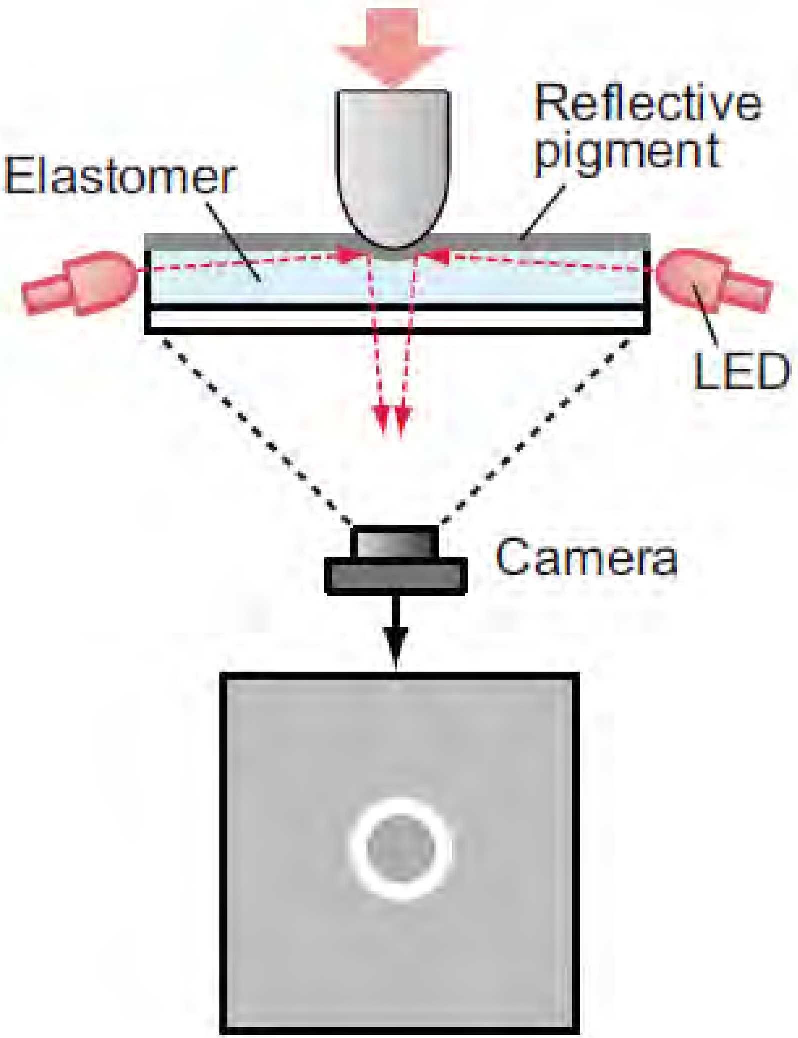
Fabrication: Marker preparation



(a) Laser etching locates marker holes and then sprays paint. **(b)** Spray paint on the template to print markers. **(c)** Attach water transfer paper to the contact surface to print markers. **(d)** Stick a semitransparent pattern of random color pixels on the contact surface. **(e)** Embed plastic beads in the holes. **(f)** White silicone is filled into the grooves. **(g)** Spherical fluorescent green particles are mixed into the contact body. **(h)** Two marker layers are separately fabricated inside the contact body. **(i)** 3-D printer prints tip and pins.

S. Zhang et al., “Hardware Technology of Vision-Based Tactile Sensor: A Review”, IEEE Sensors Journal, 2022.

Reflective membrane method



- The surface of a sheet of transparent flexible material is coated with a thin reflective membrane.

- The sensor surface with the reflective membrane deforms according to the surface shape of the object in contact.

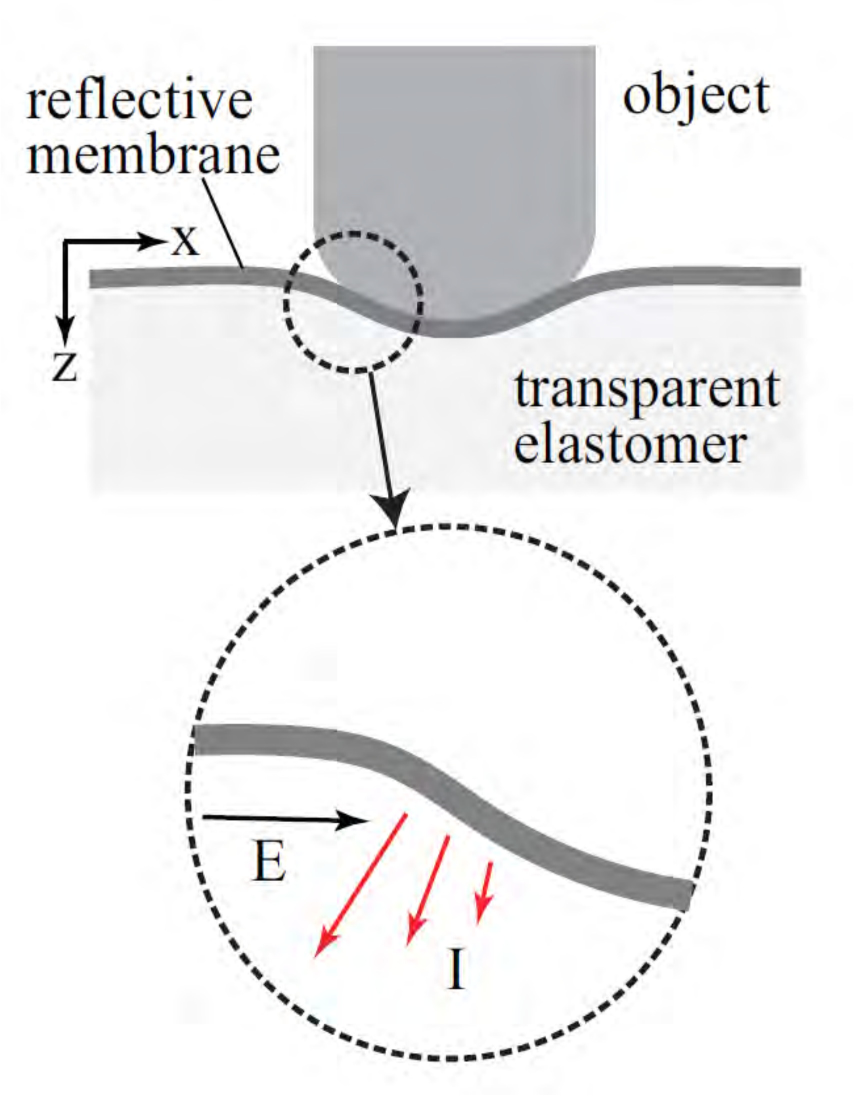
- By illuminating the backside of the reflective membrane from the side, the edges of the deformed area are illuminated and become brighter.

- Captur this reflective membrane from the backside with a camera.

- Suitable for detecting minute structure (texture) on the surface of an object.

Shimonomura, *Sensors*, 2019

Reflective membrane method



Shimonomura, *Sensors*, 2019

Height z at the point (x,y) is expressed as:

$$z = f(x, y)$$

The gradient of the surface is

$$p = \frac{\partial f}{\partial x}, \quad q = \frac{\partial f}{\partial y}$$

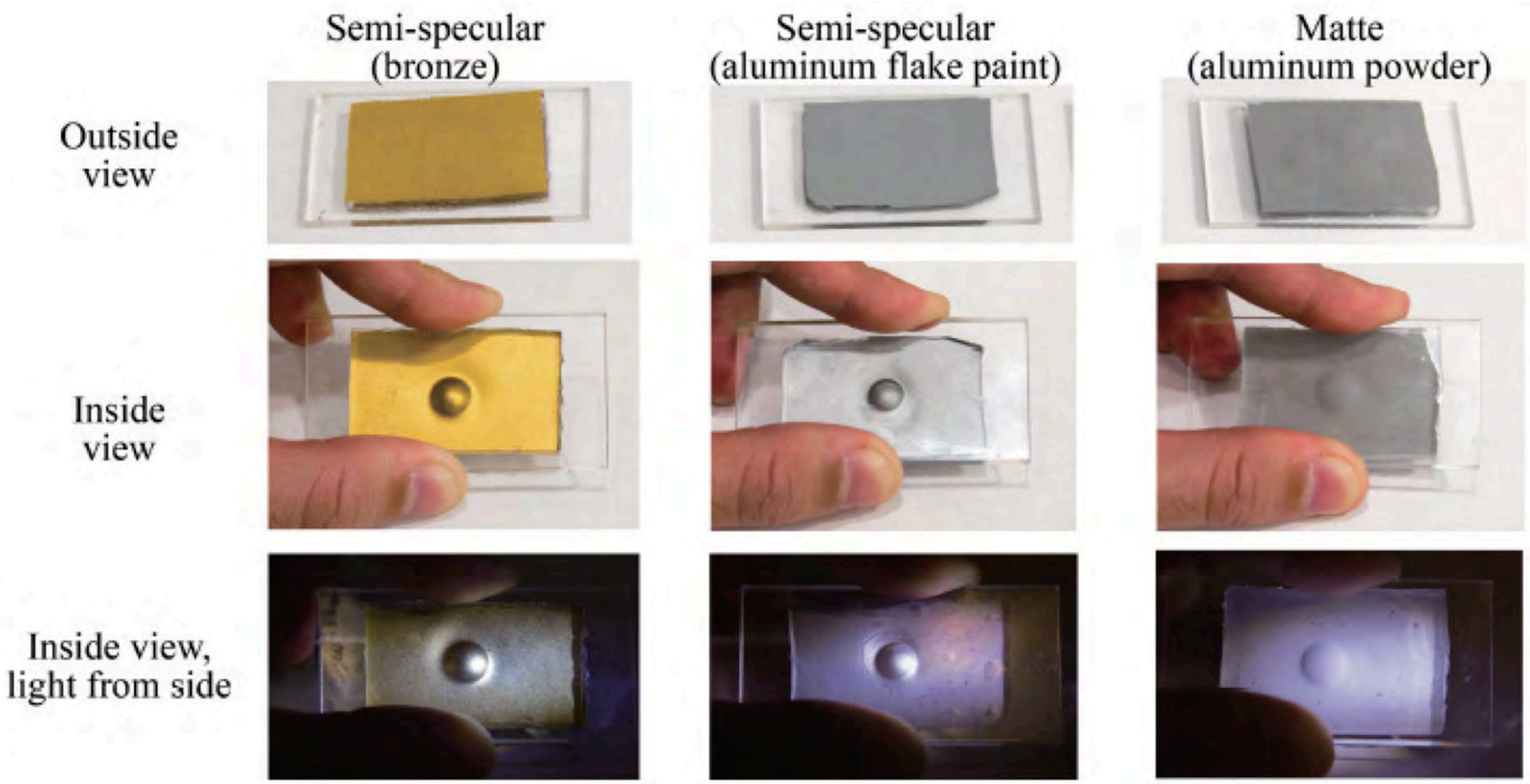
The intensity of the reflected light at the point (x,y)

$$I(x, y) = R(p, q)E(x, y)$$

where E is intensity of the illumination light,
R is reflectance map.

By illuminating the reflective membrane from the side parallel to the sensor surface, even slight bump on the backside of the sensor surface can be well visualized.

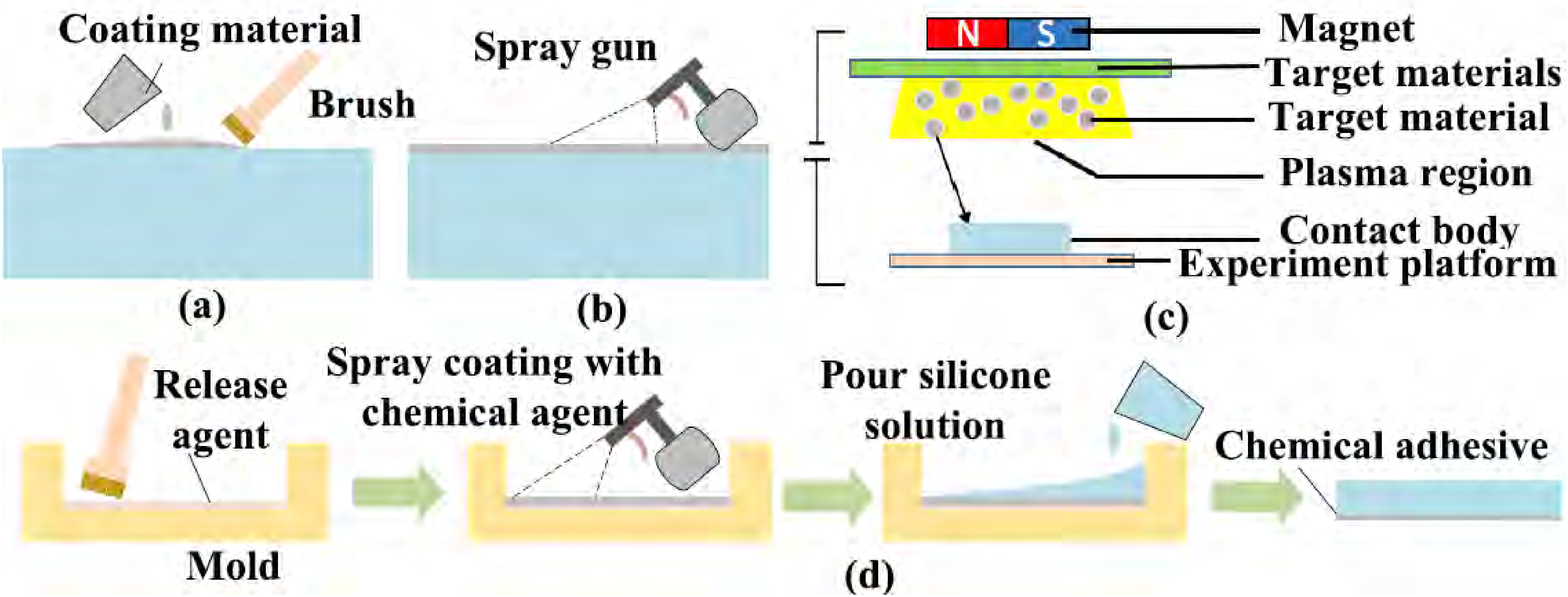
Examples of reflective membrane



微細な表面凹凸テクスチャを得るには，正反射成分が比較的大きな反射膜の方がよい．

W. Yuan, S. Dong, and E. H. Adelson, “GelSight: High-Resolution Robot Tactile Sensors for Estimating Geometry and Force,” *Sensors*, 17, 2017

Fabrication: Reflective membrane preparation

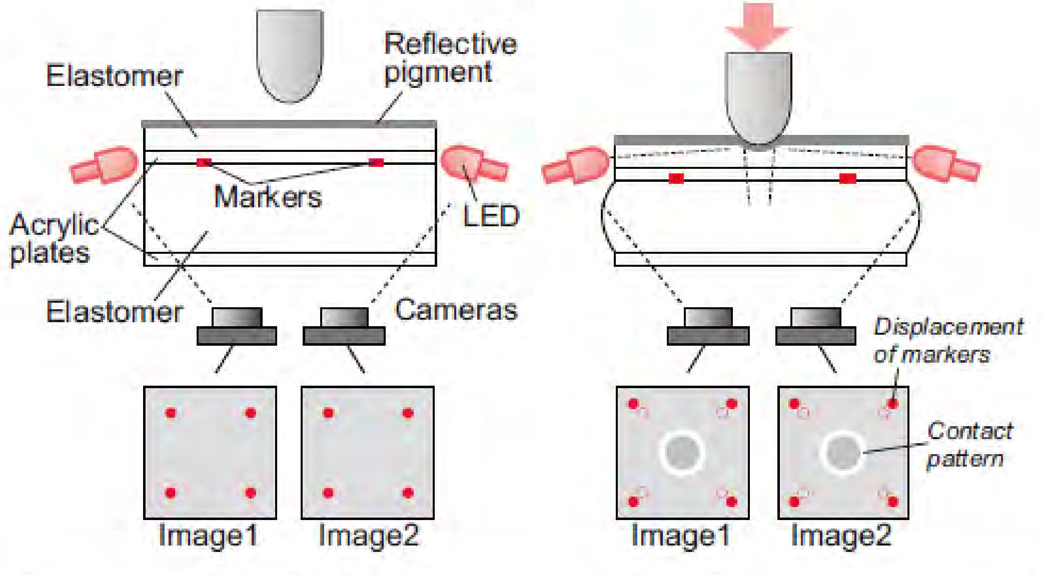


(a) Brushing paint on the contact surface is the simplest approach to fabricating a coating. However, it has low uniformity. **(b)** Spraying is an effective method to improve uniformity, but it depends on the skill and feel of the operator. **(c)** We prefer the sputtering process because it can provide a smooth coating.
It has a limitation in durability because of low adhesion between metal and silicone. **(d)** Preparation process of chemical adhesion. The uncured paint and silicone form a strong chemical bond to improve adhesion.

S. Zhang et al., “Hardware Technology of Vision-Based Tactile Sensor: A Review”, IEEE Sensors Journal, 2022.

Combined sensor for in-hand localization and force measurement

Inserting a bolt into a target hole based on tactile information.



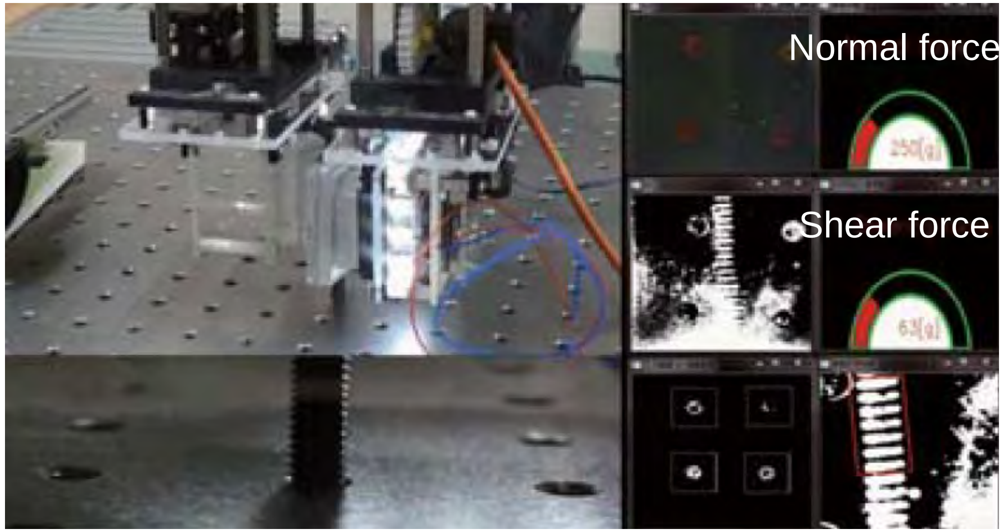
In-hand localization of the bolt

To align the bolt tip position and orientation with the target hole

Force estimation at the tip of the bolt

To know if the bolt tip has inserted the hole

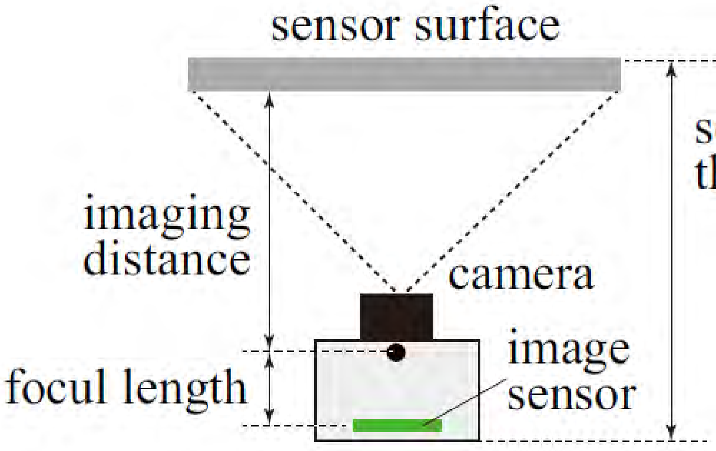
→ Combine **Reflective membrane** and **Marker displacement methods**



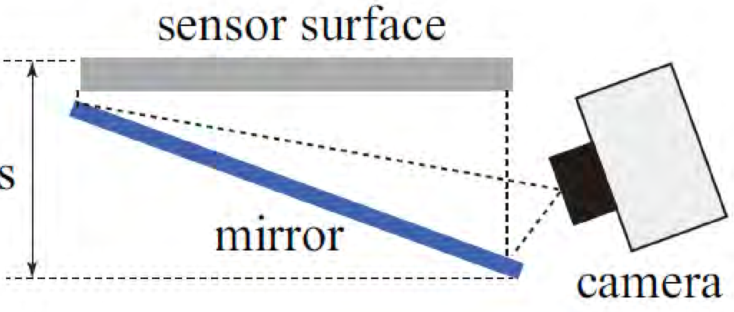
Bolt localization

Nozu, Shimonomura, *IEEE/ASME AIM2018*

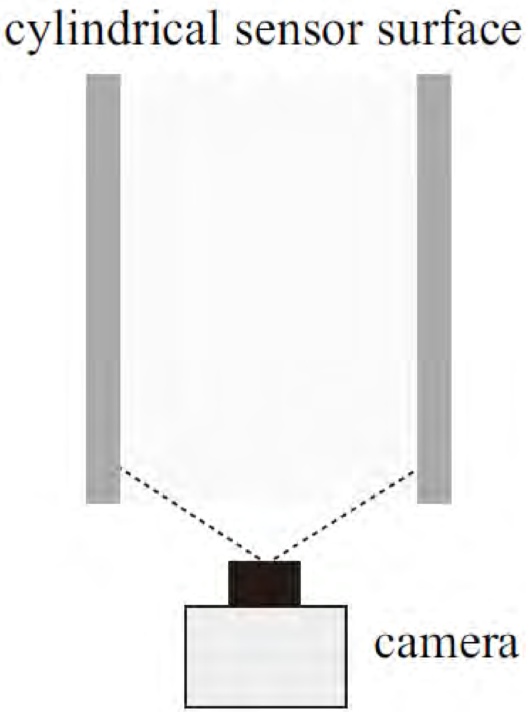
Shape of the sensor



Standard camera arrangement



Thinner sensor



Cylindrical sensor

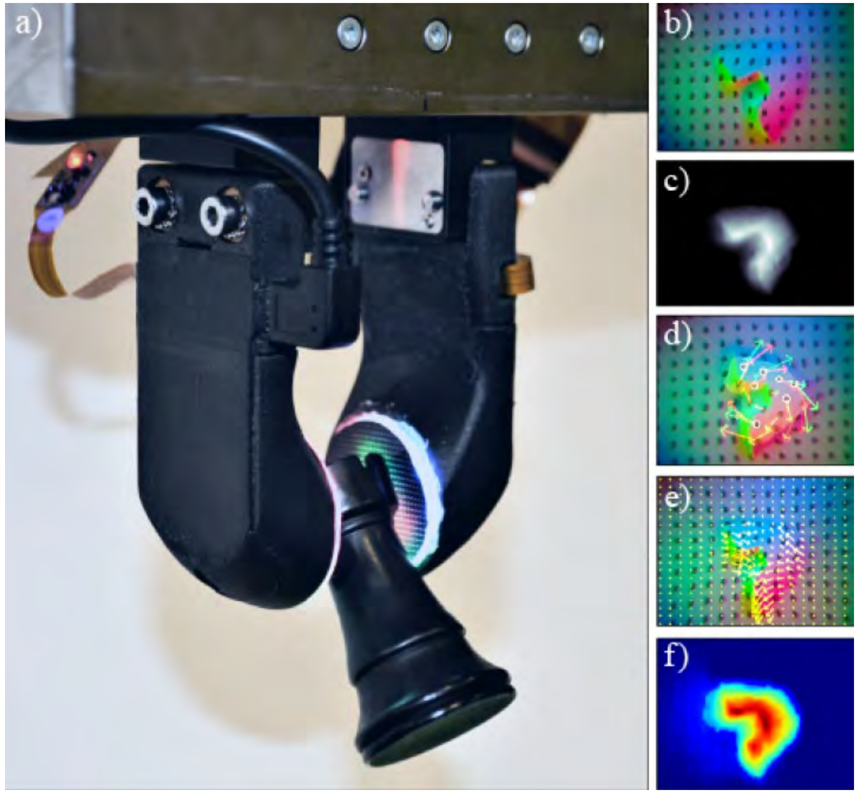
- When the sensor is attached to a finger of a gripper, the large thickness of the sensor may interfere with the gripping motion.

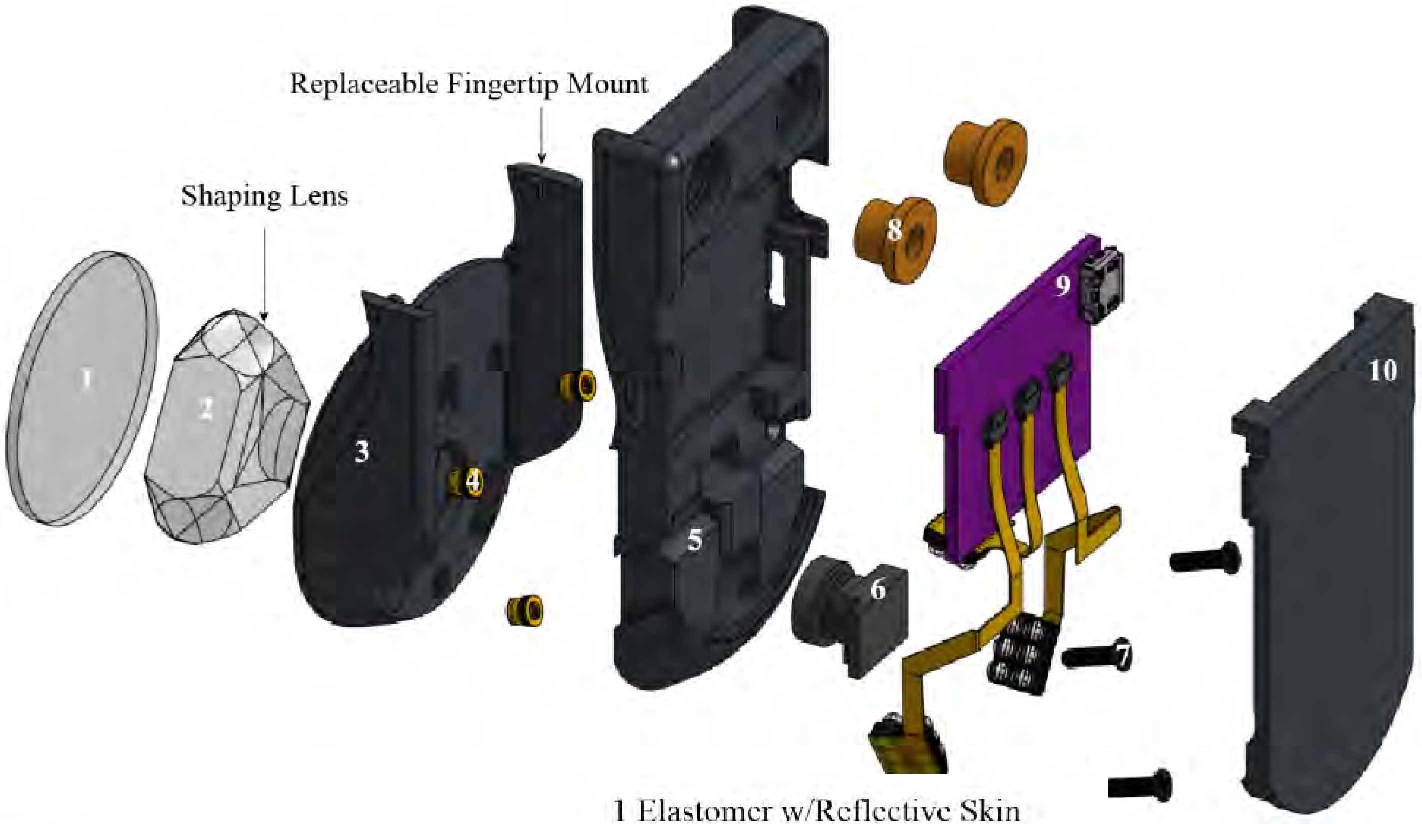
- Thinner sensor with a structure that uses a mirror to capture the reflected image of the sensor surface. （Donlon et al., *IEEE/RSJ IROS2018*）

- Acquires tactile information on the entire outer surface of the cylindrical sensor body.
- Suitable for the link part of a robot arm （Duong et al., *IEEE Robosoft2019*）

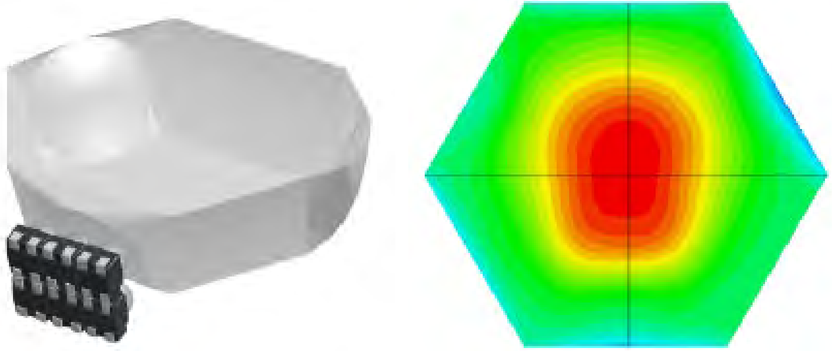
Shimonomura, *Sensors*, 2019

GelSlim 3.0: High-Resolution Measurement of Shape, Force and Slip in a Compact Tactile-Sensing Finger





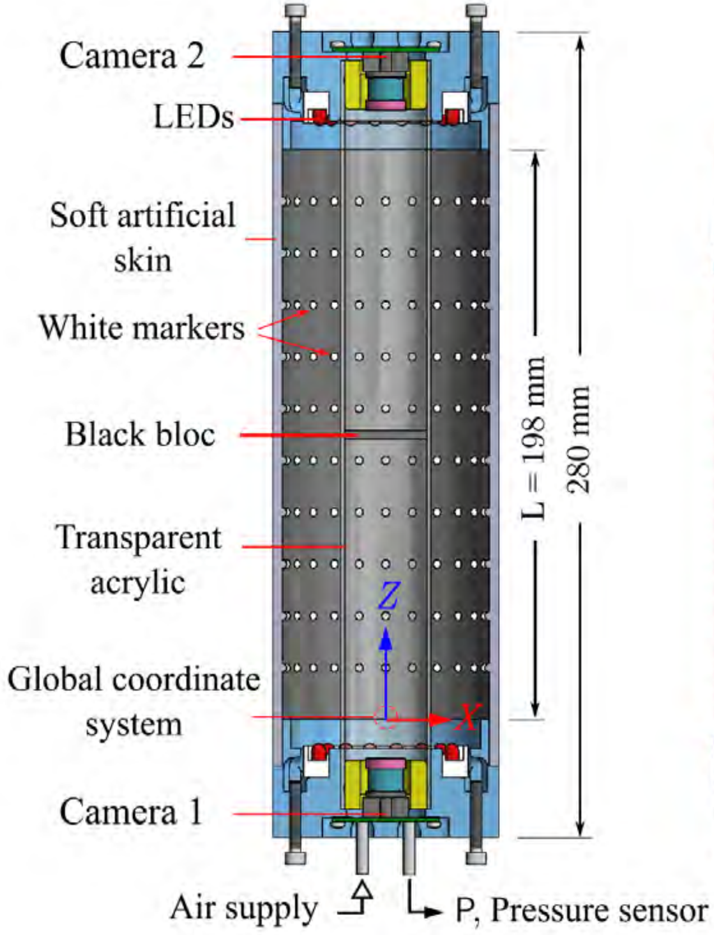
1 Elastomer w/Reflective Skin
2 Acrylic Lens
3 Fingertip
4 Heat Inserts
5 Finger-Body
6 Camera Module
7 Screws
8 Mounting Bearing
9 Integrated Illumination Controller
10 Finger-Back

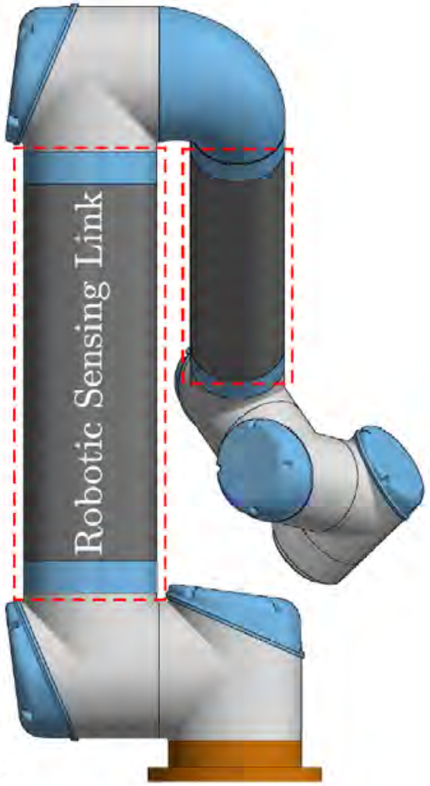


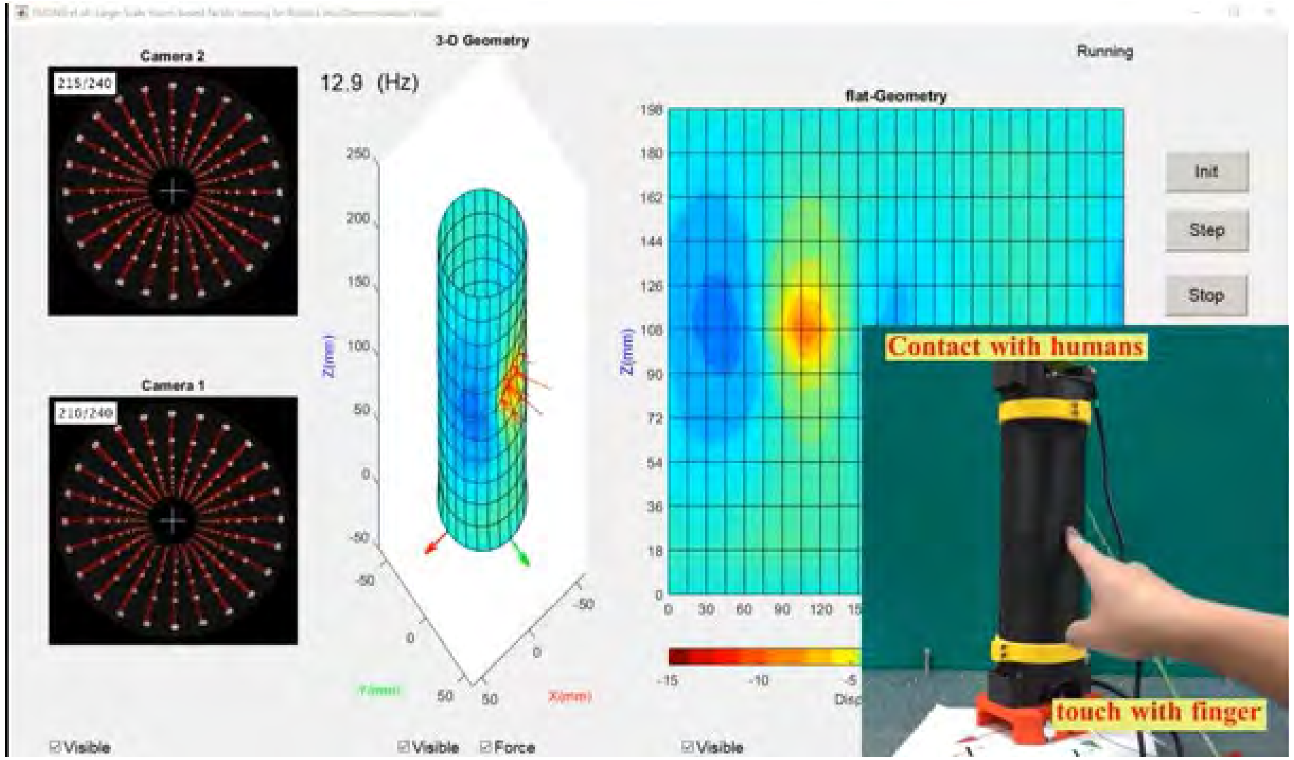
simulated radiant flux across the surface of the sensor

I.H. Taylor et al., ICRA2022

Large-scale vision-based tactile sensing for robot links





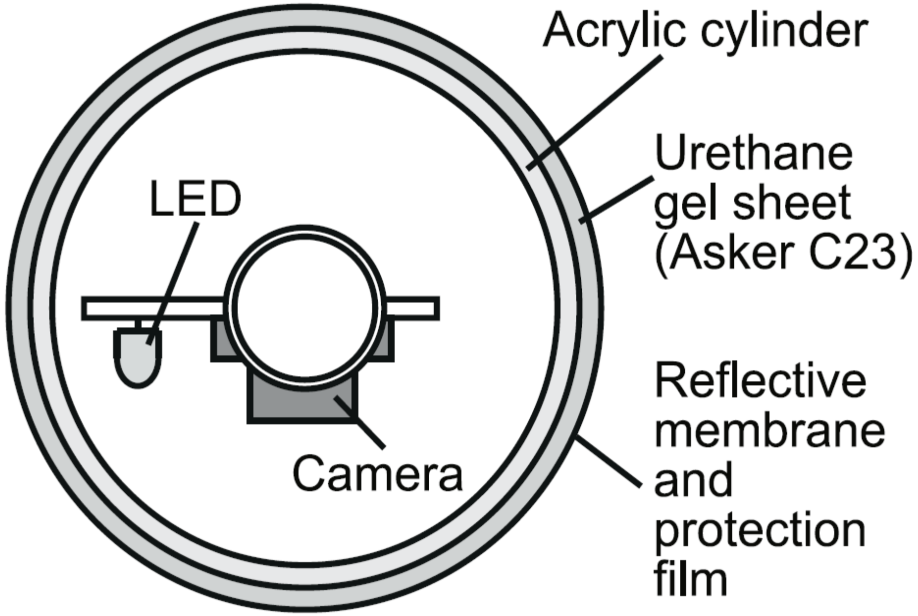


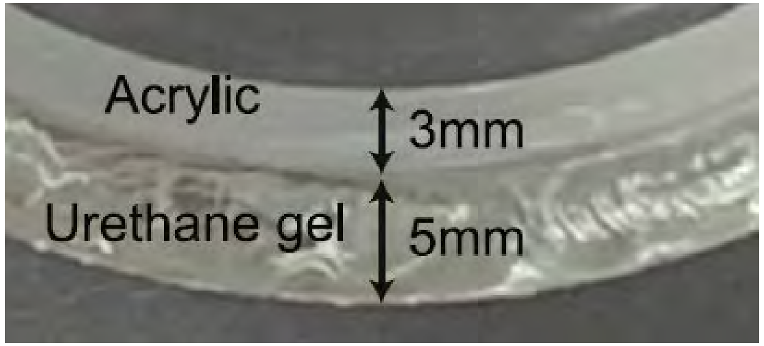
https://www.youtube.com/watch?v=uvDtyXpf2HU

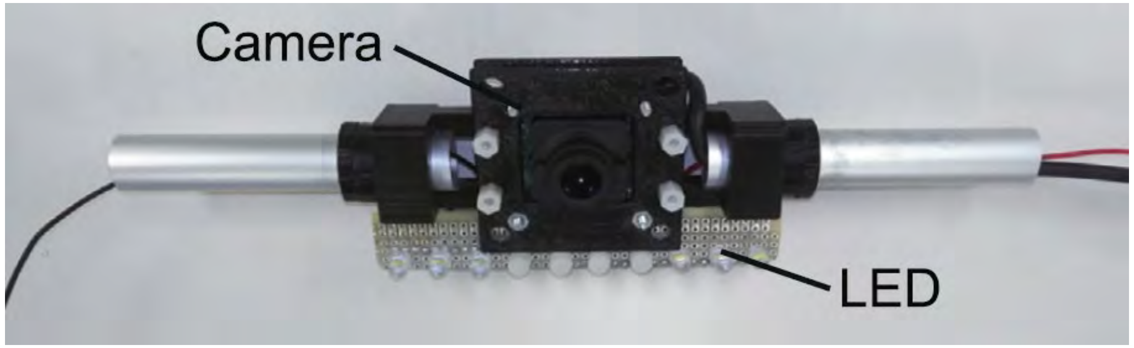
L.V.Duong et al., IEEE Trans. on Robotics, 2020.

Roller tactile image sensor

<u>The sensor surface is roller-shaped and rolls over the target surface for continuous sensing over a wide area.</u>



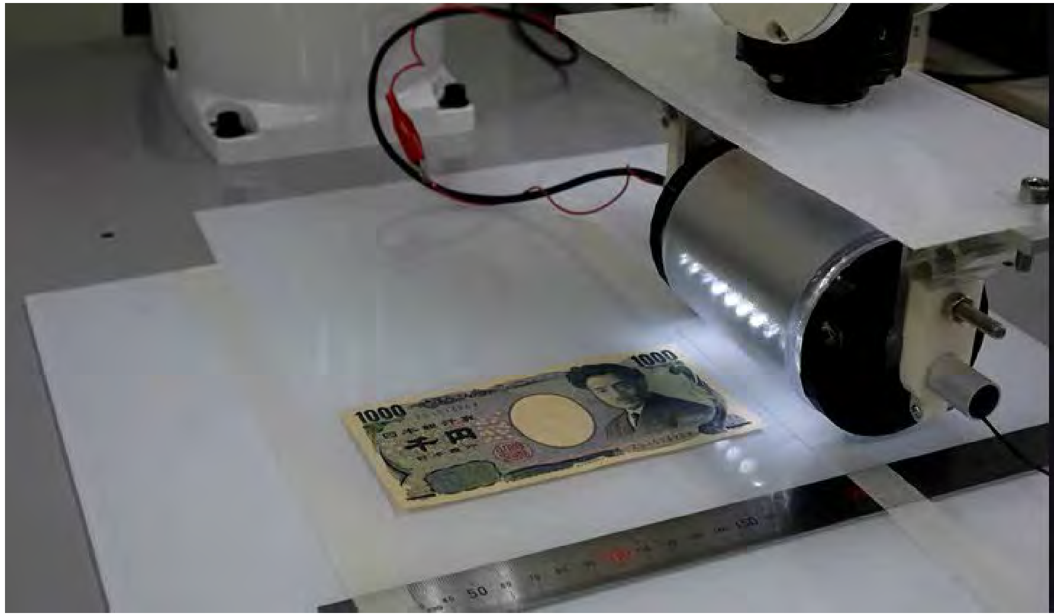


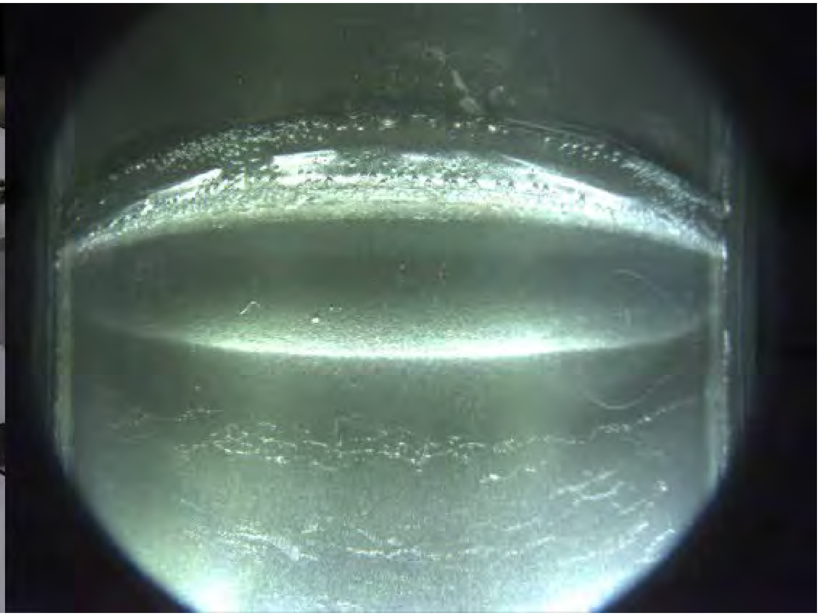


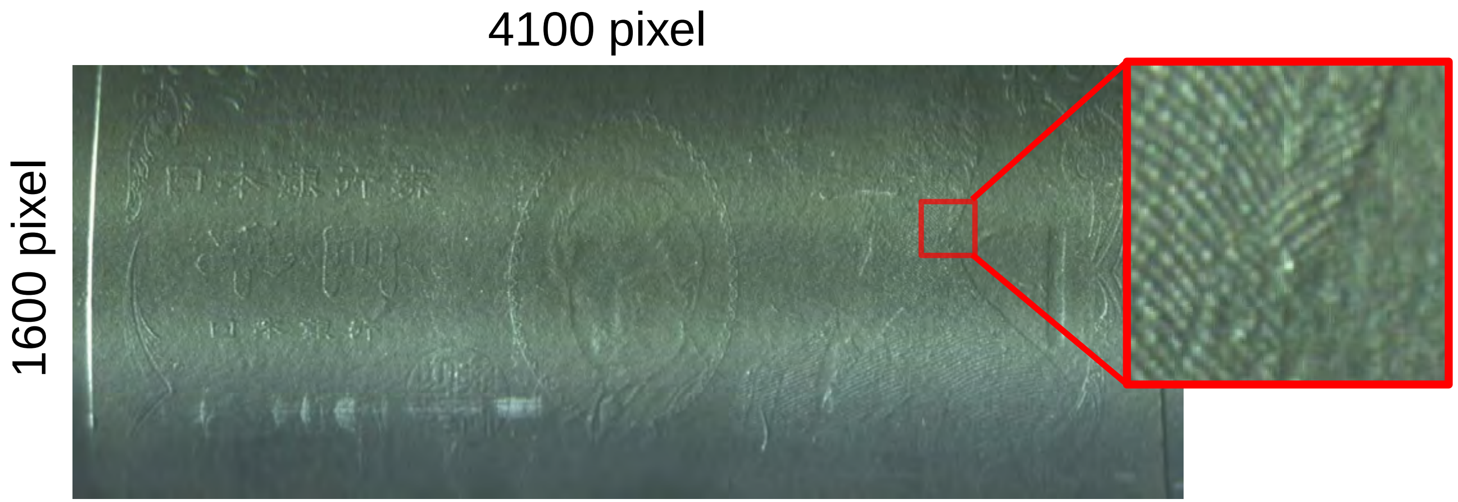
Shimonomura, Chang, Murata, ***Frontiers in Robotics and AI,*** 2021

Roller tactile image sensor

The sensor surface is roller-shaped and rolls over the target surface for continuous sensing over a wide area.



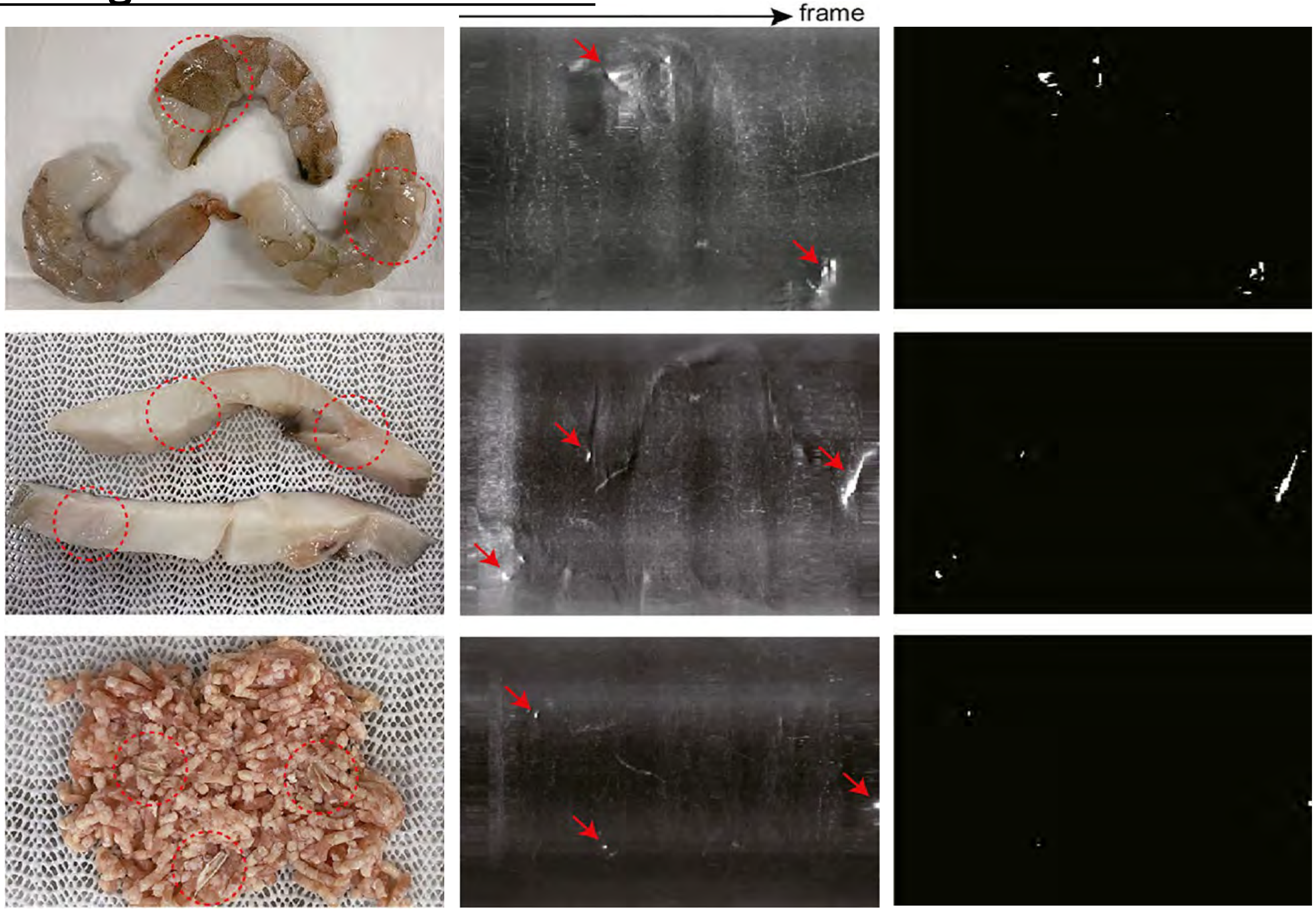




Spatial resolution 78 μm/pixel, bump with 5 μm of height can be detect

Roller tactile image sensor: Application for food inspection

Detection of hard foreign bodies in soft foods



Shrimp shell

Fish bone

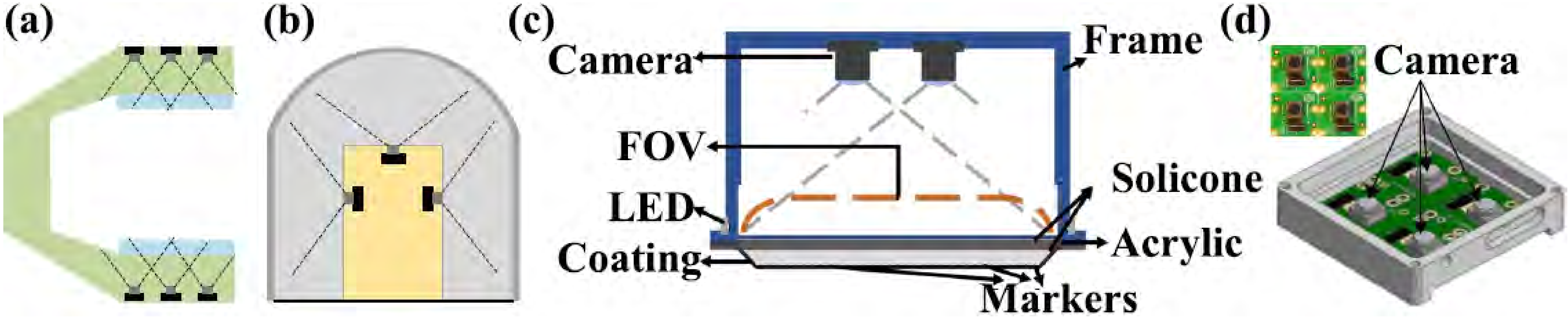
Small bone in minced meat

Food to be inspected

Sensor output

Detection result

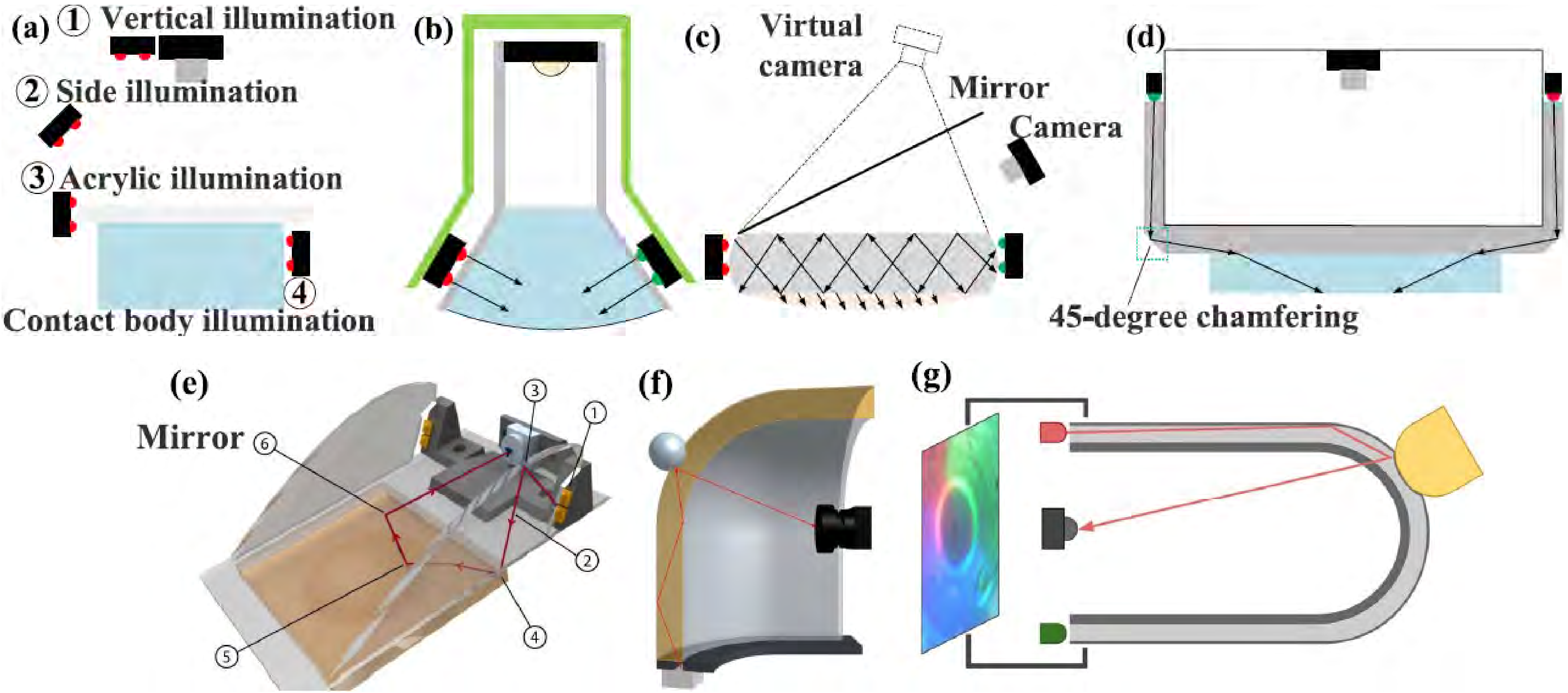
Multiple cameras installation



(a) Cameras are placed into a parallel gripper to cover the entire perception region.
(b) Cameras are spatially distributed to acquire global perception.
(c) Binocular camera is used to capture 3-D information.
(d) Four cameras can enlarge perception regions and provide 3-D information.

S. Zhang et al., “Hardware Technology of Vision-Based Tactile Sensor: A Review”, IEEE Sensors Journal, 2022.

LED position and optical path design

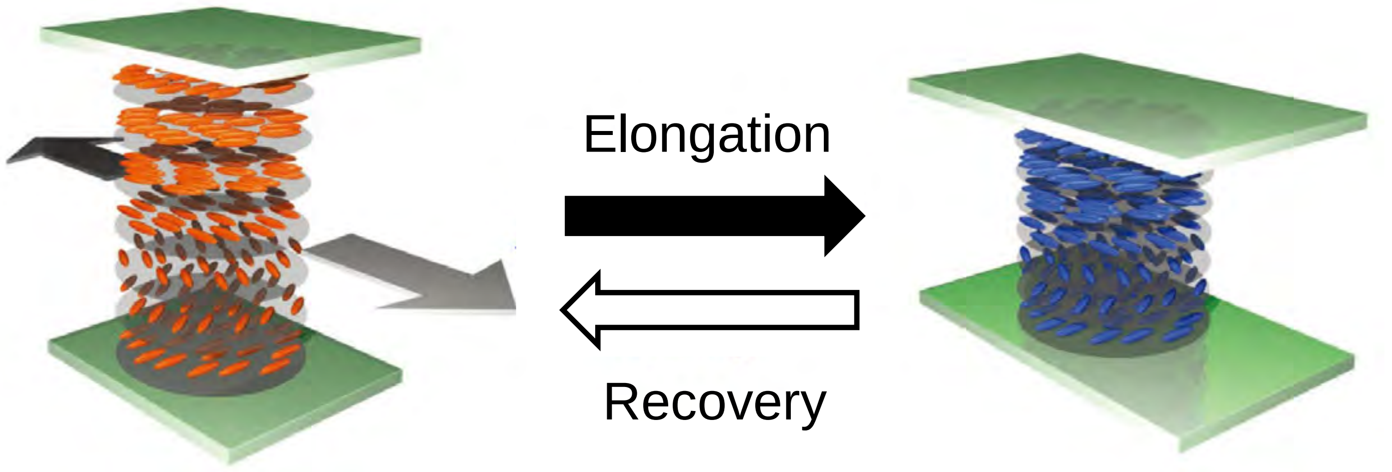


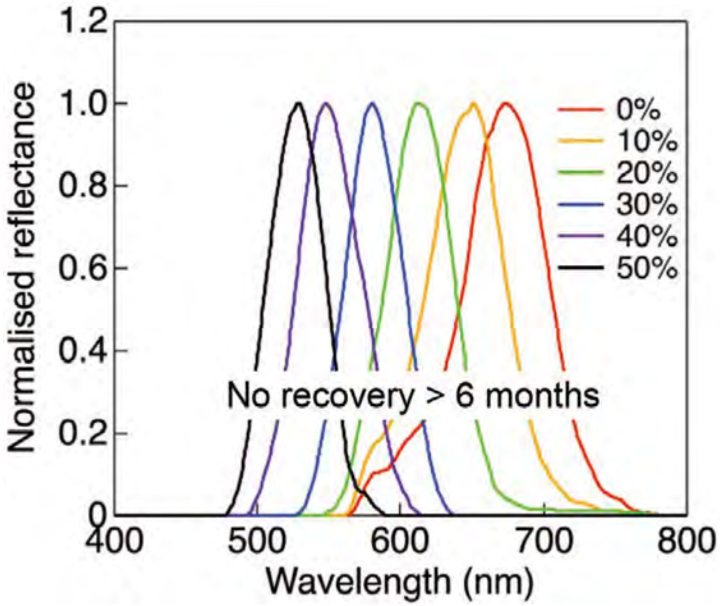
(a) Vertical illumination is limited by the sensor size. Side illumination causes edge regions to lack brightness. Acrylic and contact body illumination can provide uniform light through TIR. **(b)** and **(c)** Light is refracted through the acrylic plate into the contact surface. **(d)** 45◦ chamfering is used to change the direction of the refracted light. **(e)** Donlon et al. adopted the parabolic reflection principle and TIR to plan an optical path. **(f)** and **(g)** TIR is performed inside the contact body.
The deformation causes a change in the optical path.

S. Zhang et al., “Hardware Technology of Vision-Based Tactile Sensor: A Review”, IEEE Sensors Journal, 2022.

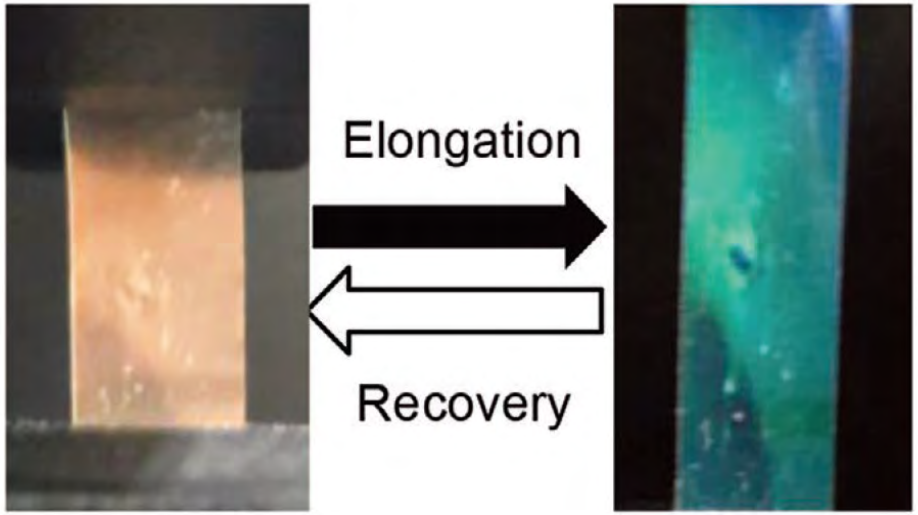
Strain sensing polymer

- The helical molecular arrangement of the chiral liquid crystal elastomer produces wavelength-selective reflections（Bragg reflection）.
- When the pitch of the helical structure changes due to strain, the reflected wavelength changes.





Relationship between strain and spectral reflectance

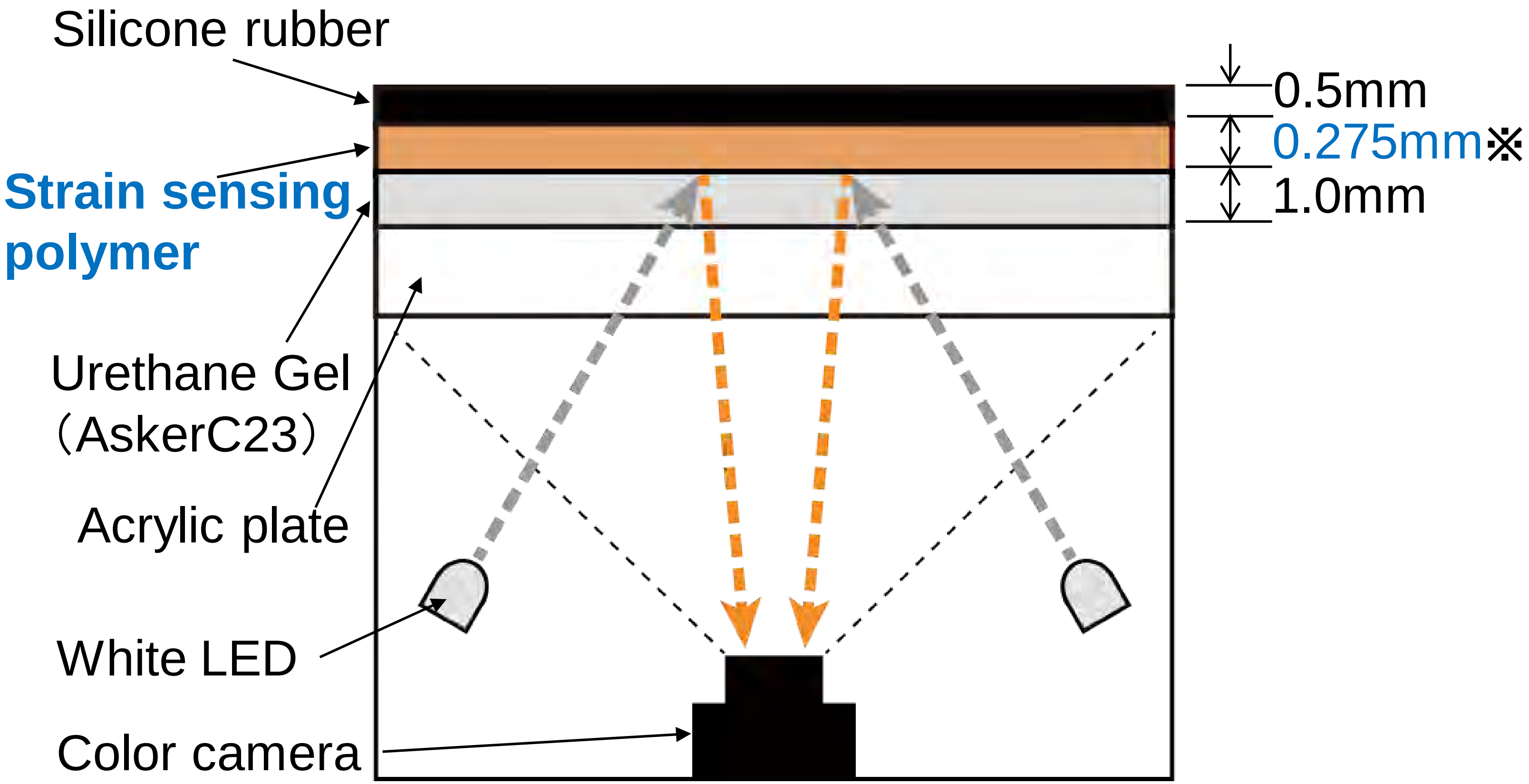


Color change by extension

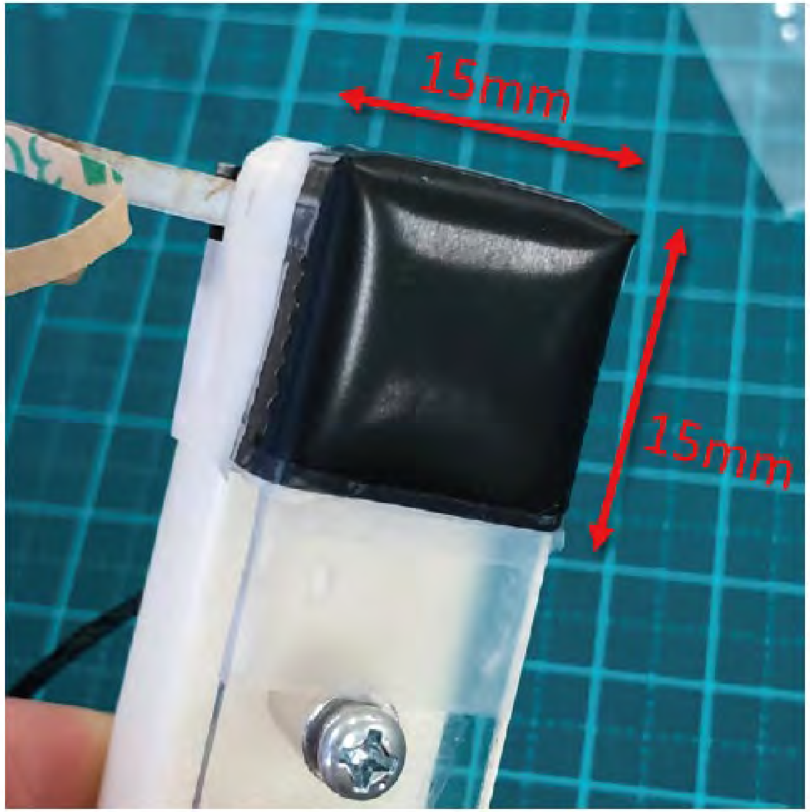
K.Hisano et al., ” Mechano-Optical Sensors Fabricated with Multilayered Liquid Crystal Elastomers Exhibiting Tunable Deformation Recovery,” ***Advanced Functional Materials***, 31(40), (2021).

Structure of the sensor with strain sensing polymer

Cross section



Prototype sensor



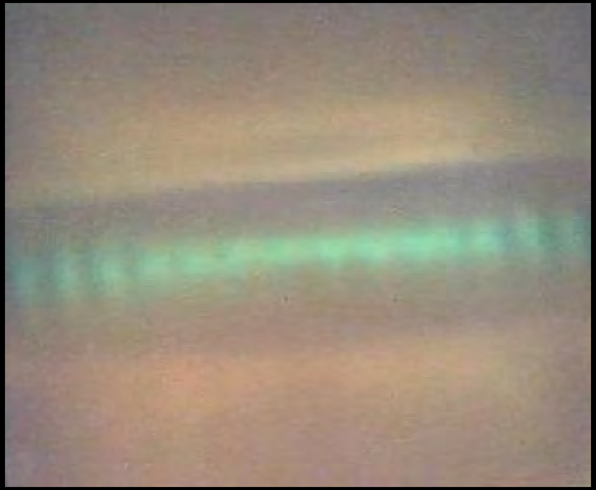
※ **Polymer sheet with** 0.055mm thickness is sandwiched
by PDMS film with 0.11mm thickness

Shimonomura et al., RSJ2023

Sensor output images

Metal ball

Nut（M3）



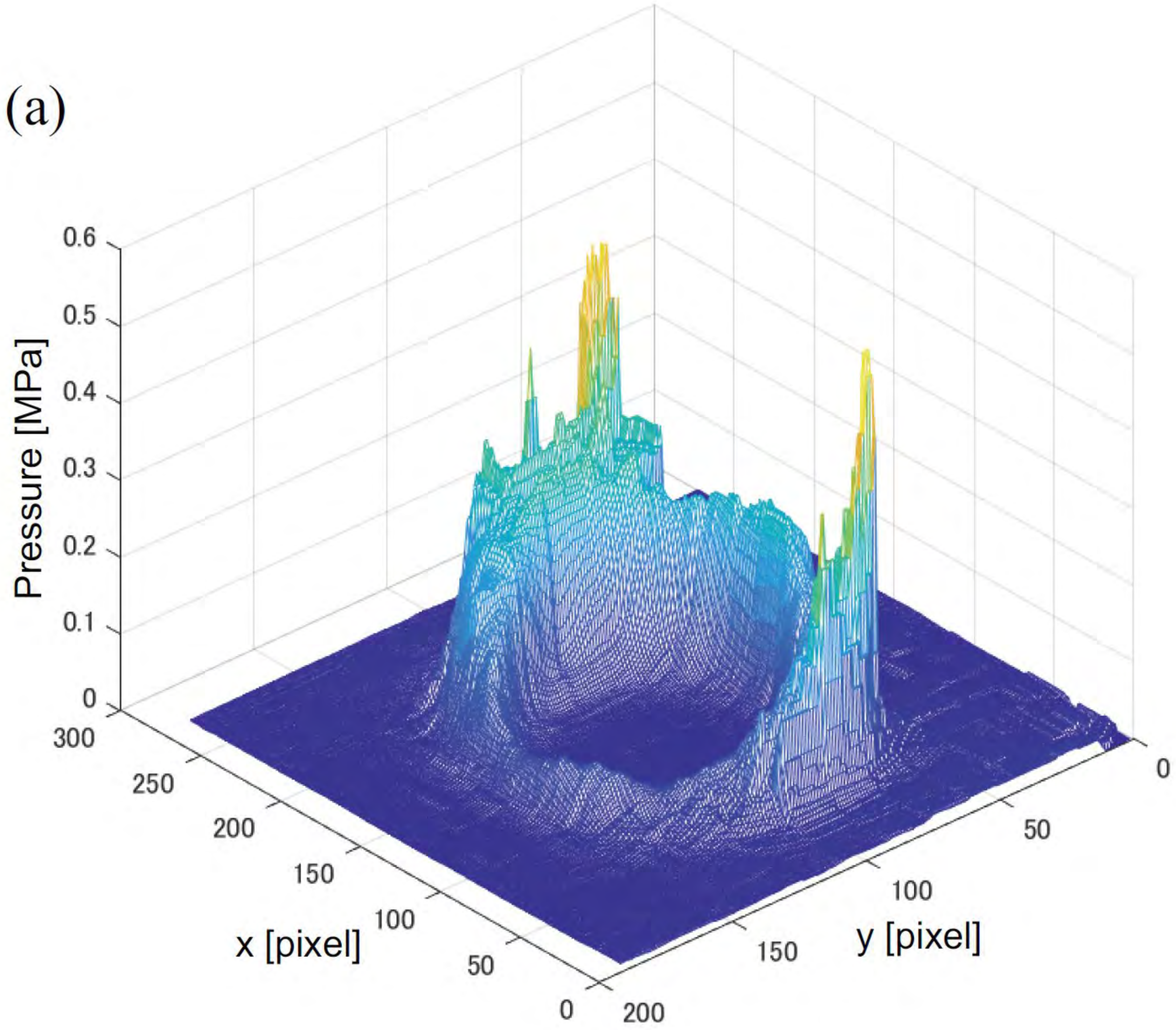
Bolt（M6）

Nylon thread（Φ0.5mm）

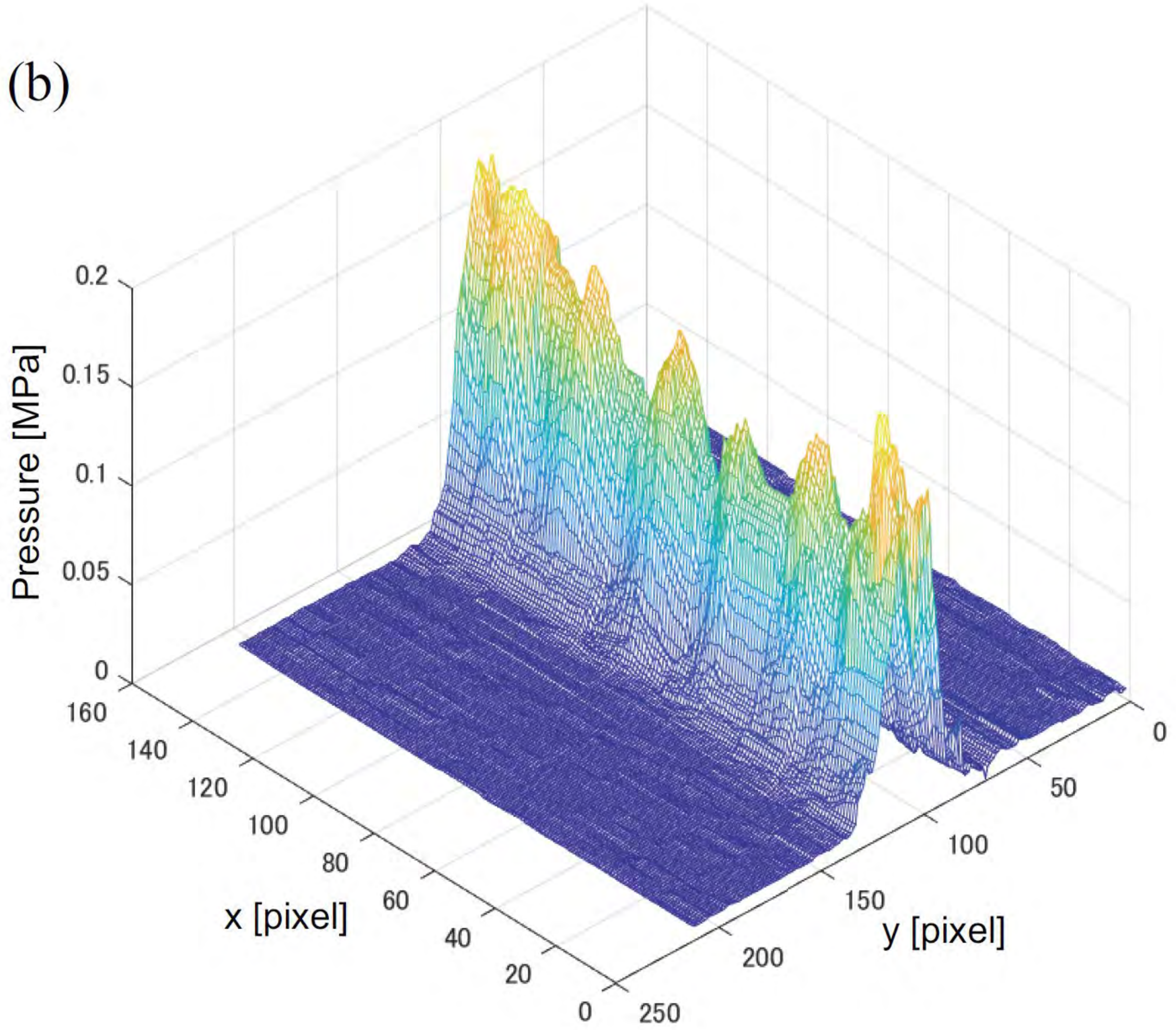
Toy block

Shimonomura et al., RSJ2023

Estimation of pressure distribution



Cylindrical metal spacer



Screwthread of M6 Bolt

Shimonomura et al., RSJ2023

Future Challenges in tactile sensor using camera

1. **Integration into grippers and robot hands**
    - Miniaturization and thinning: Elemental technologies such as optical system and illumination are important
    - Integration into multi-fingered hand

2. **Method of converting contact to image information**
    - Methods other than typical methods introduced here
    - it is expected to develop new methods for easy extraction of tactile information, such as materials that change color according to stress.

3. **Methods for extracting tactile information from images**
    - For high speed, image processing should be as simple as possible
    - Using deep learning

4. **Application to assembly work, inspection, etc.**