Soft Sensors

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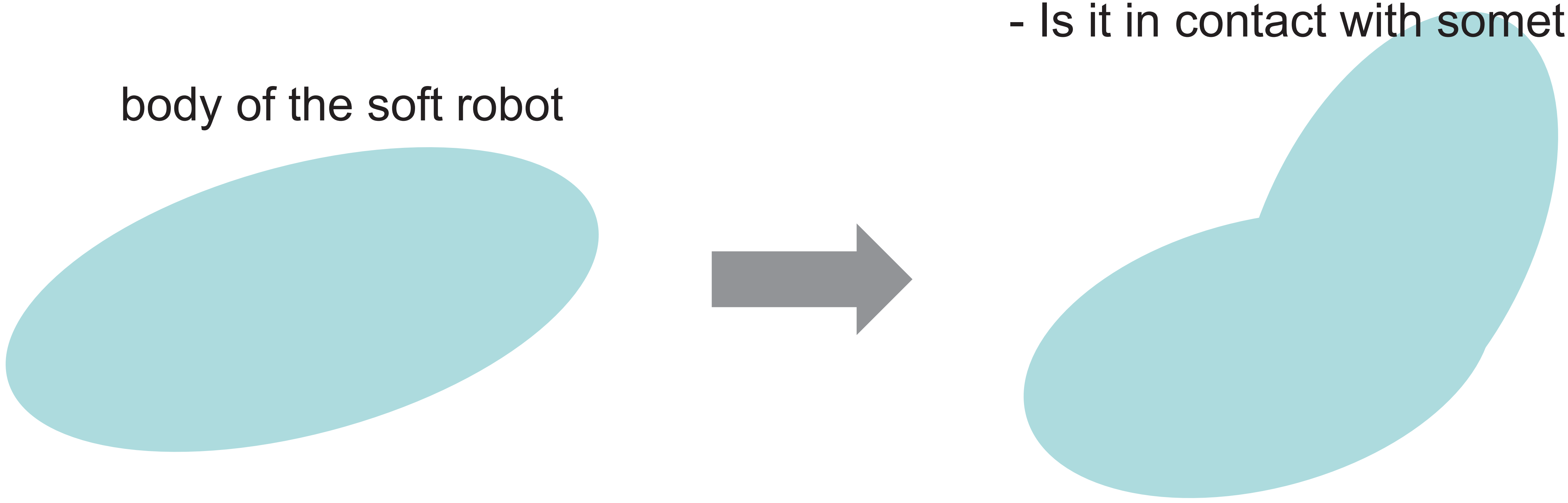
Sensor for soft robot

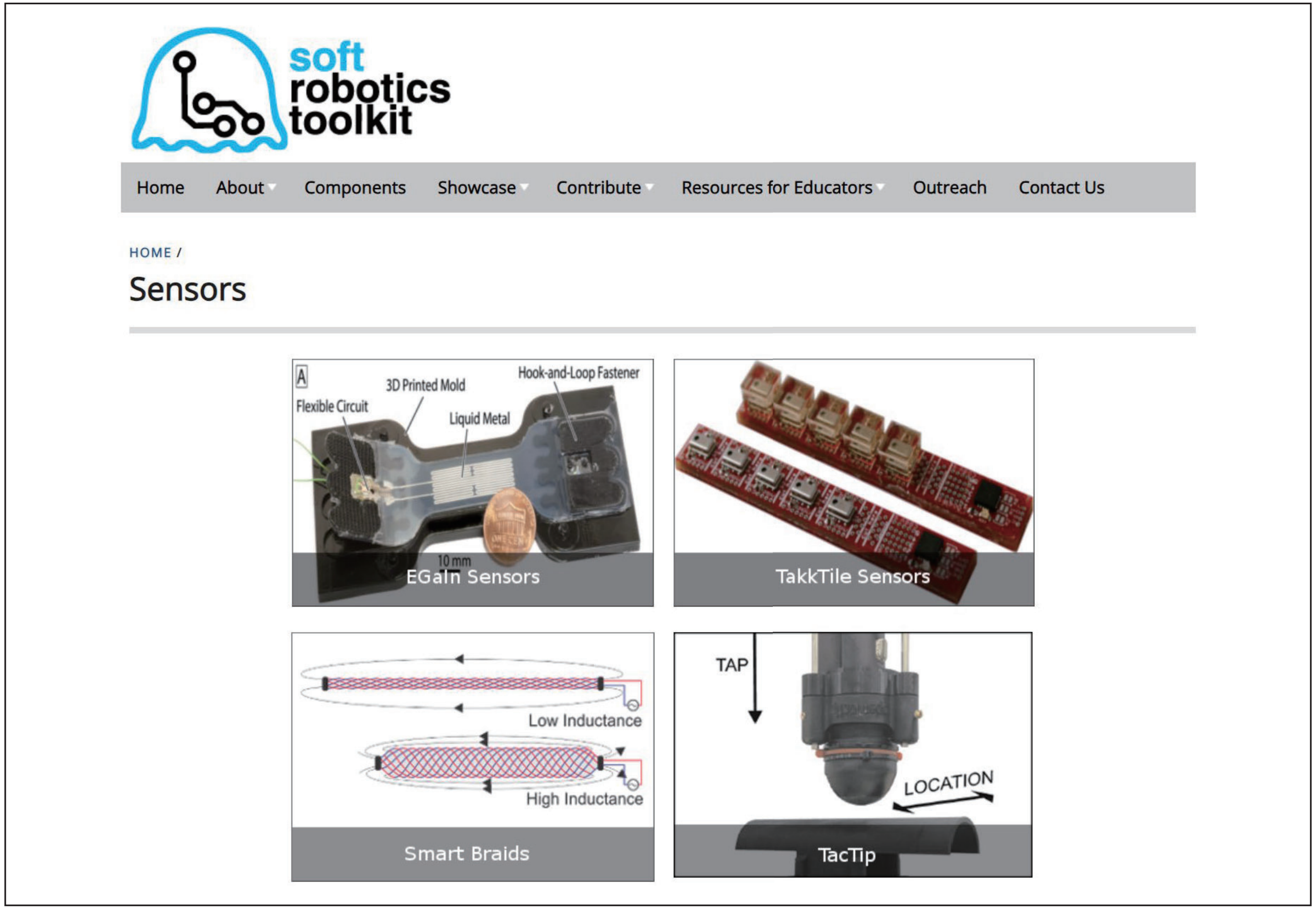


- How much bended?
- Are there external force?
- Is it in contact with something?

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



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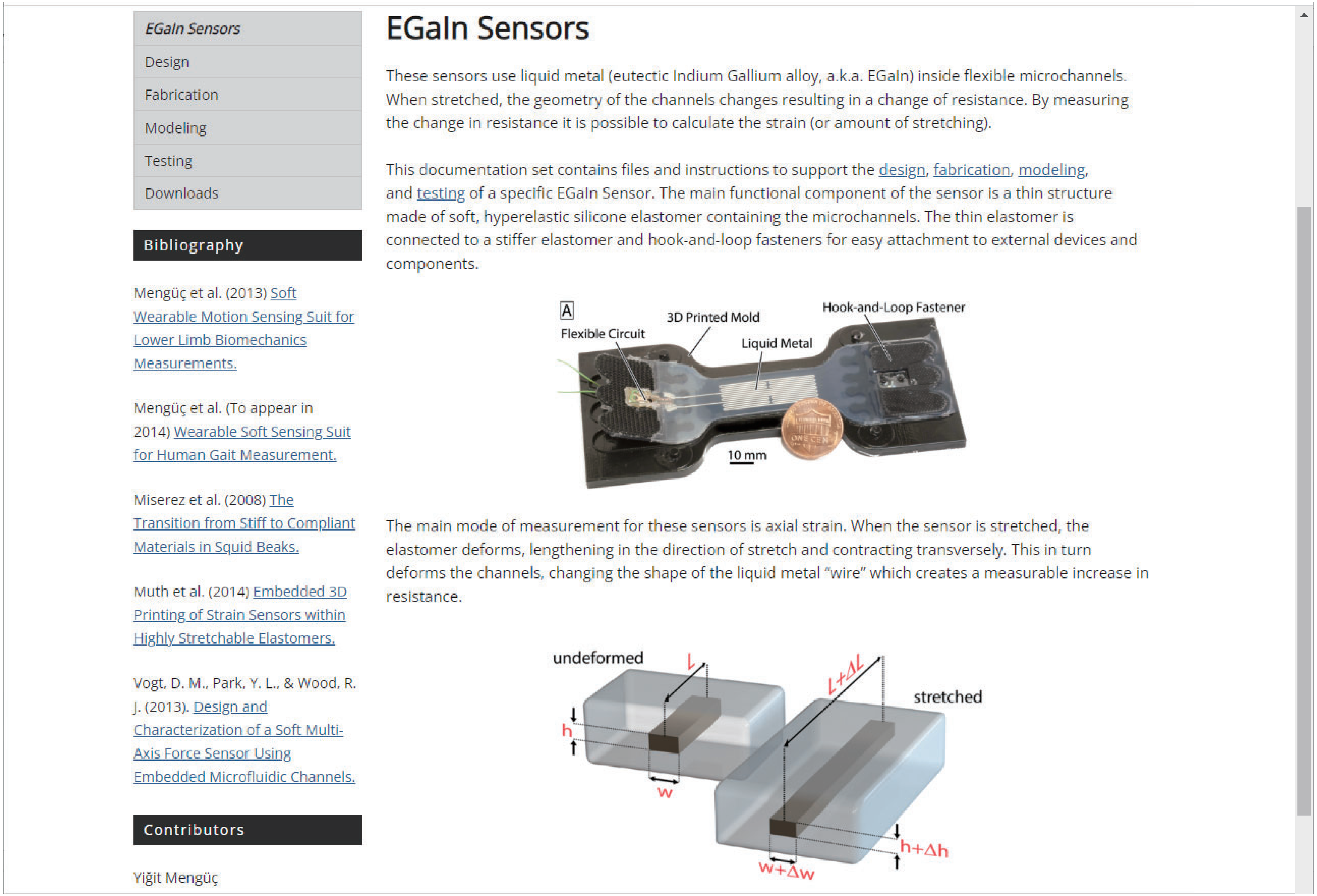
Sensors



EGaIn Sensors
Design
Fabrication
Modeling
Testing
Downloads

Bibliography

Mengüç et al. (2013) Soft Wearable Motion Sensing Suit for Lower Limb Biomechanics Measurements.

Mengüç et al. (To appear in 2014) Wearable Soft Sensing Suit for Human Gait Measurement.

Miserez et al. (2008) The Transition from Stiff to Compliant Materials in Squid Beaks.

Muth et al. (2014) Embedded 3D Printing of Strain Sensors within Highly Stretchable Elastomers.

Vogt, D. M., Park, Y. L., & Wood, R. J. (2013). Design and Characterization of a Soft Multi-Axis Force Sensor Using Embedded Microfluidic Channels.

Contributors

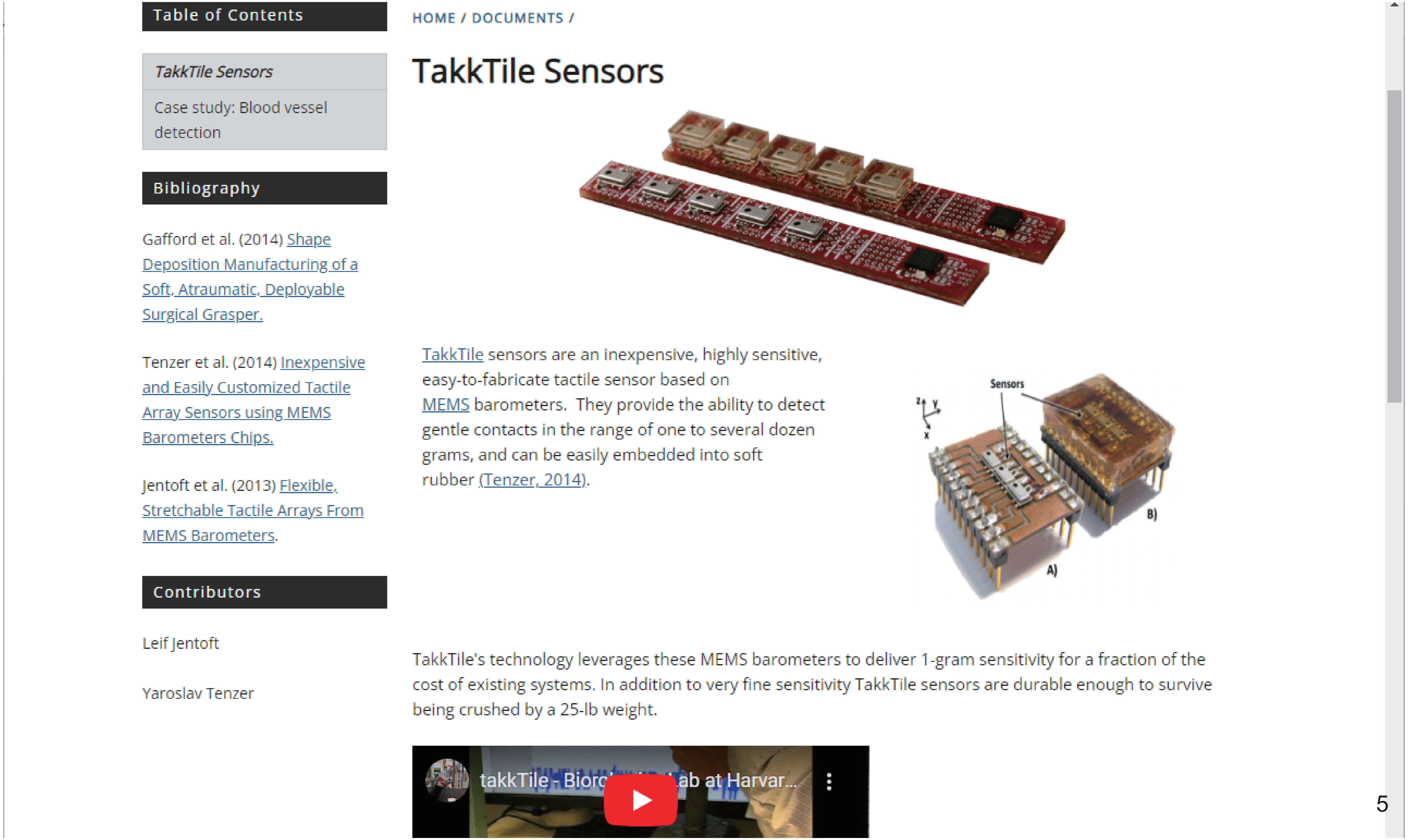
Yiğit Mengüç

EGaIn Sensors

These sensors use liquid metal (eutectic Indium Gallium alloy, a.k.a. EGaIn) inside flexible microchannels. When stretched, the geometry of the channels changes resulting in a change of resistance. By measuring the change in resistance it is possible to calculate the strain (or amount of stretching).

This documentation set contains files and instructions to support the design, fabrication, modeling, and testing of a specific EGaIn Sensor. The main functional component of the sensor is a thin structure made of soft, hyperelastic silicone elastomer containing the microchannels. The thin elastomer is connected to a stiffer elastomer and hook-and-loop fasteners for easy attachment to external devices and components.

The main mode of measurement for these sensors is axial strain. When the sensor is stretched, the elastomer deforms, lengthening in the direction of stretch and contracting transversely. This in turn deforms the channels, changing the shape of the liquid metal "wire" which creates a measurable increase in resistance.



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TakkTile Sensors

TakkTile sensors are an inexpensive, highly sensitive, easy-to-fabricate tactile sensor based on MEMS barometers. They provide the ability to detect gentle contacts in the range of one to several dozen grams, and can be easily embedded into soft rubber (Tenzer, 2014).

TakkTile's technology leverages these MEMS barometers to deliver 1-gram sensitivity for a fraction of the cost of existing systems. In addition to very fine sensitivity TakkTile sensors are durable enough to survive being crushed by a 25-lb weight.

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Bibliography

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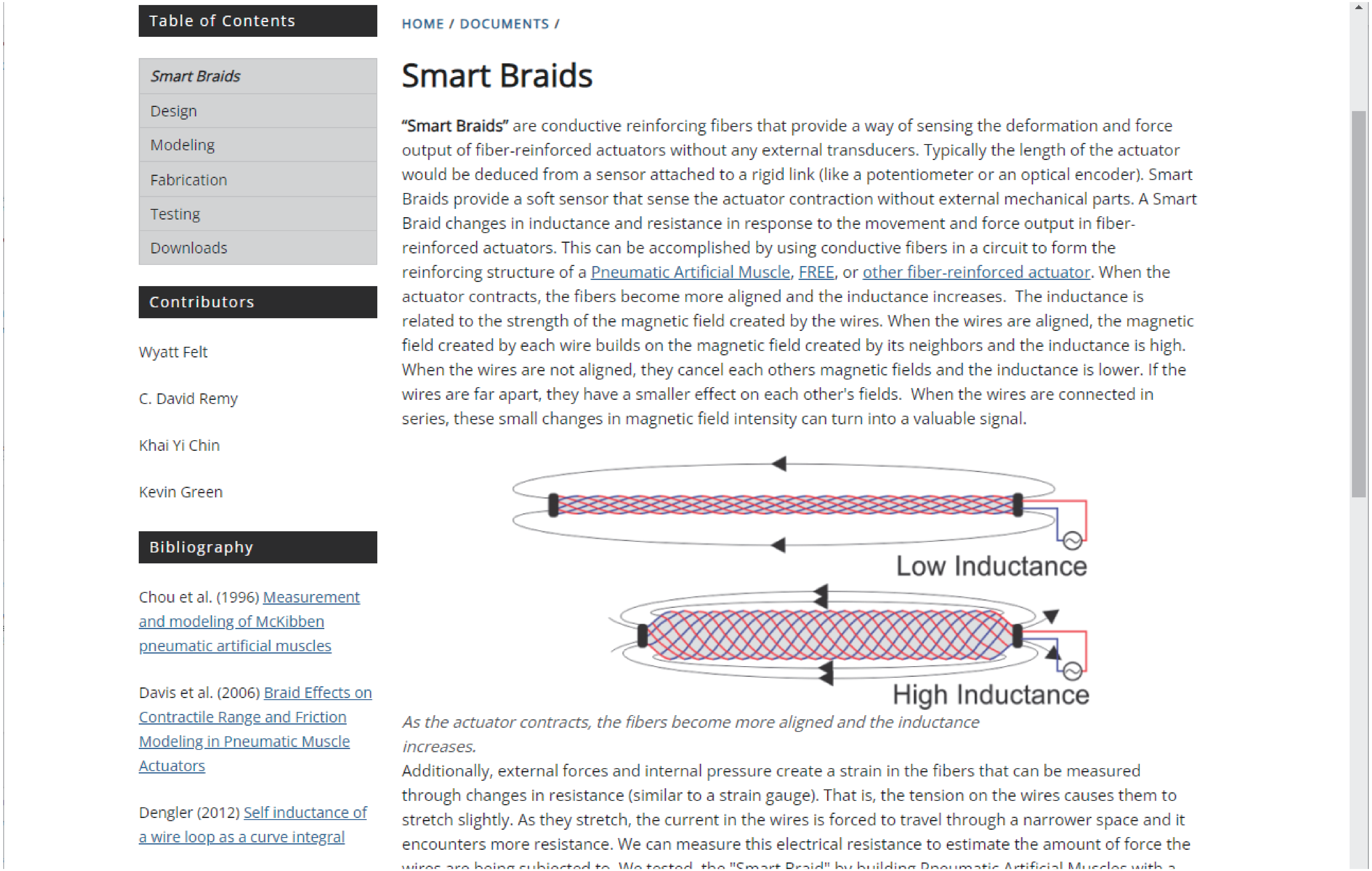
Tenzer et al. (2014) Inexpensive and Easily Customized Tactile Array Sensors using MEMS Barometers Chips.

Jentoft et al. (2013) Flexible, Stretchable Tactile Arrays From MEMS Barometers.

Contributors

Leif Jentoft

Yaroslav Tenzer



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Wyatt Felt

C. David Remy

Khai Yi Chin

Kevin Green

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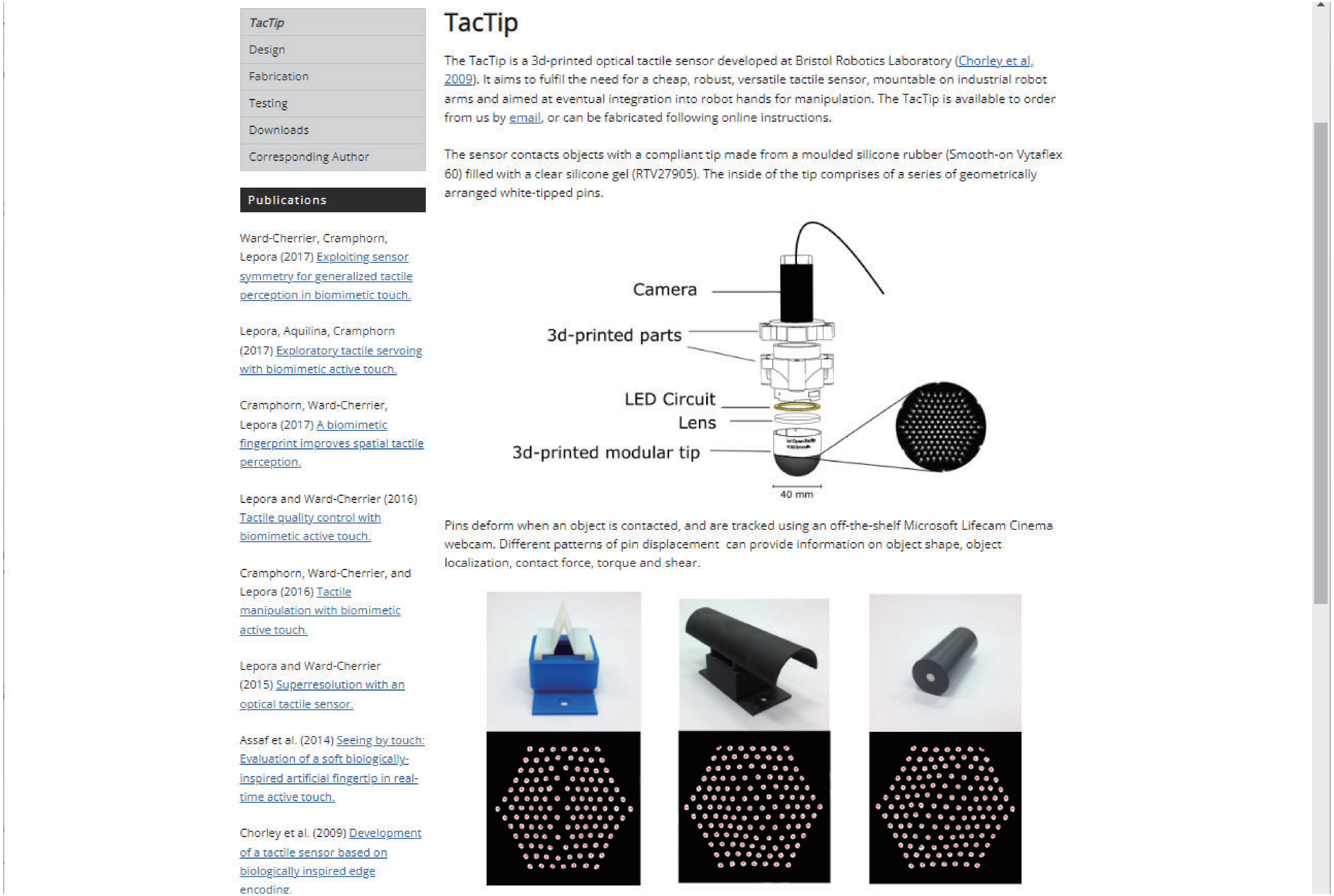
Smart Braids

"Smart Braids" are conductive reinforcing fibers that provide a way of sensing the deformation and force output of fiber-reinforced actuators without any external transducers. Typically the length of the actuator would be deduced from a sensor attached to a rigid link (like a potentiometer or an optical encoder). Smart Braids provide a soft sensor that sense the actuator contraction without external mechanical parts. A Smart Braid changes in inductance and resistance in response to the movement and force output in fiber-reinforced actuators. This can be accomplished by using conductive fibers in a circuit to form the reinforcing structure of a Pneumatic Artificial Muscle, FREE, or other fiber-reinforced actuator. When the actuator contracts, the fibers become more aligned and the inductance increases. The inductance is related to the strength of the magnetic field created by the wires. When the wires are aligned, the magnetic field created by each wire builds on the magnetic field created by its neighbors and the inductance is high. When the wires are not aligned, they cancel each others magnetic fields and the inductance is lower. If the wires are far apart, they have a smaller effect on each other's fields. When the wires are connected in series, these small changes in magnetic field intensity can turn into a valuable signal.

As the actuator contracts, the fibers become more aligned and the inductance increases.

Additionally, external forces and internal pressure create a strain in the fibers that can be measured through changes in resistance (similar to a strain gauge). That is, the tension on the wires causes them to stretch slightly. As they stretch, the current in the wires is forced to travel through a narrower space and it encounters more resistance. We can measure this electrical resistance to estimate the amount of force the wires are being subjected to. We tested the "Smart Braid" by building Pneumatic Artificial Muscles with a



- *TacTip*
- Design
- Fabrication
- Testing
- Downloads
- Corresponding Author

Publications

Ward-Cherrier, Cramphorn, Lepora (2017) Exploiting sensor symmetry for generalized tactile perception in biomimetic touch.

Lepora, Aquilina, Cramphorn (2017) Exploratory tactile servoing with biomimetic active touch.

Cramphorn, Ward-Cherrier, Lepora (2017) A biomimetic fingerprint improves spatial tactile perception.

Lepora and Ward-Cherrier (2016) Tactile quality control with biomimetic active touch.

Cramphorn, Ward-Cherrier, and Lepora (2016) Tactile manipulation with biomimetic active touch.

Lepora and Ward-Cherrier (2015) Superresolution with an optical tactile sensor.

Assaf et al. (2014) Seeing by touch: Evaluation of a soft biologically-inspired artificial fingertip in real-time active touch.

Chorley et al. (2009) Development of a tactile sensor based on biologically inspired edge encoding.

TacTip

The TacTip is a 3d-printed optical tactile sensor developed at Bristol Robotics Laboratory (Chorley et al, 2009). It aims to fulfil the need for a cheap, robust, versatile tactile sensor, mountable on industrial robot arms and aimed at eventual integration into robot hands for manipulation. The TacTip is available to order from us by email, or can be fabricated following online instructions.

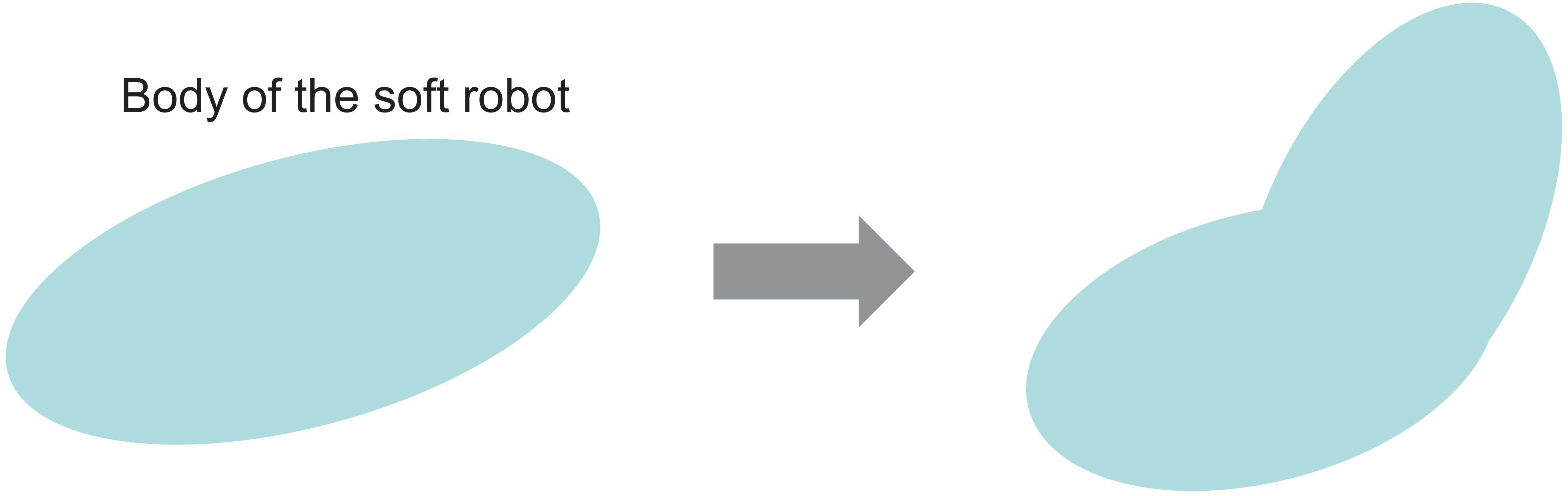
The sensor contacts objects with a compliant tip made from a moulded silicone rubber (Smooth-on Vytaflex 60) filled with a clear silicone gel (RTV27905). The inside of the tip comprises of a series of geometrically arranged white-tipped pins.

Pins deform when an object is contacted, and are tracked using an off-the-shelf Microsoft Lifecam Cinema webcam. Different patterns of pin displacement can provide information on object shape, object localization, contact force, torque and shear.

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

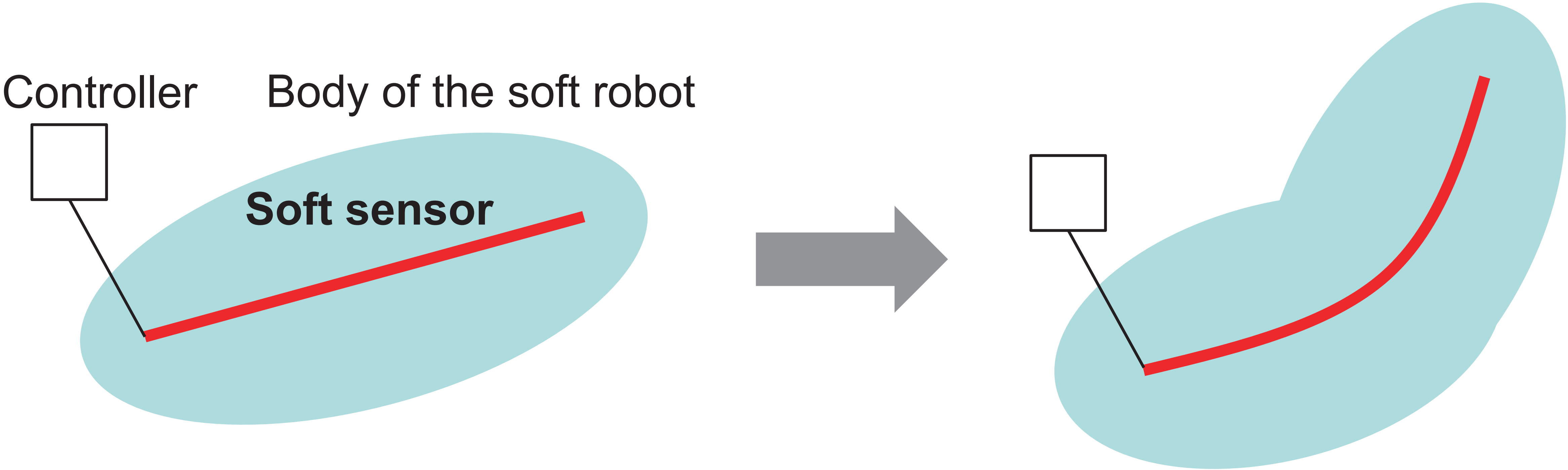
Classification by sensor form and installation



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.

Classification by sensor form and installation

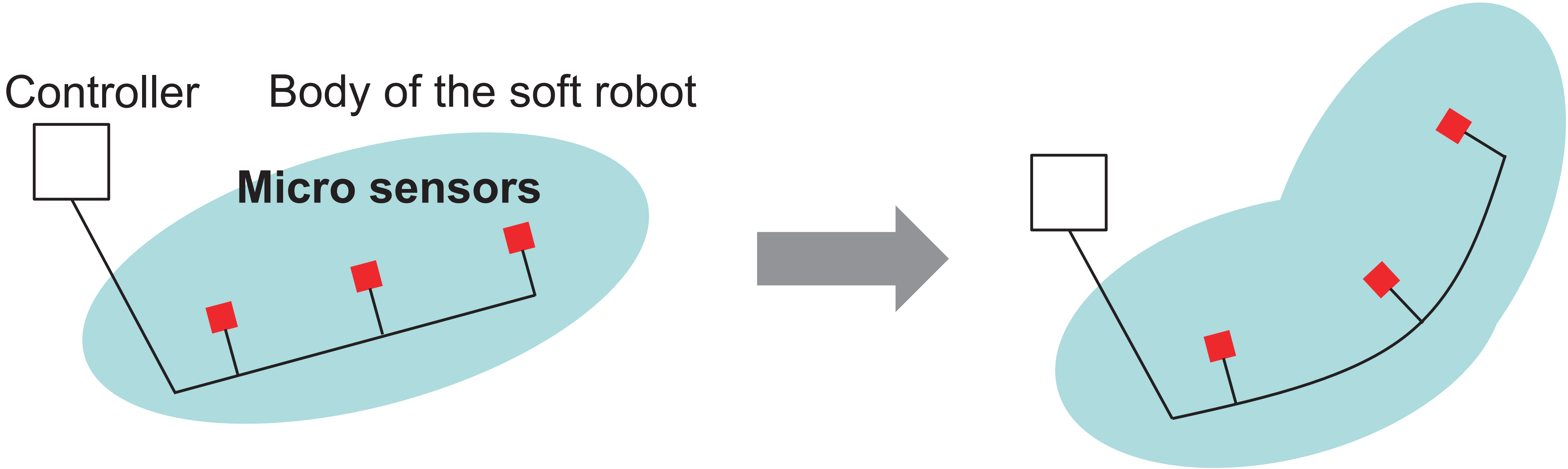
1) Embed soft and deformable sensors inside the body of the soft robot



- 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

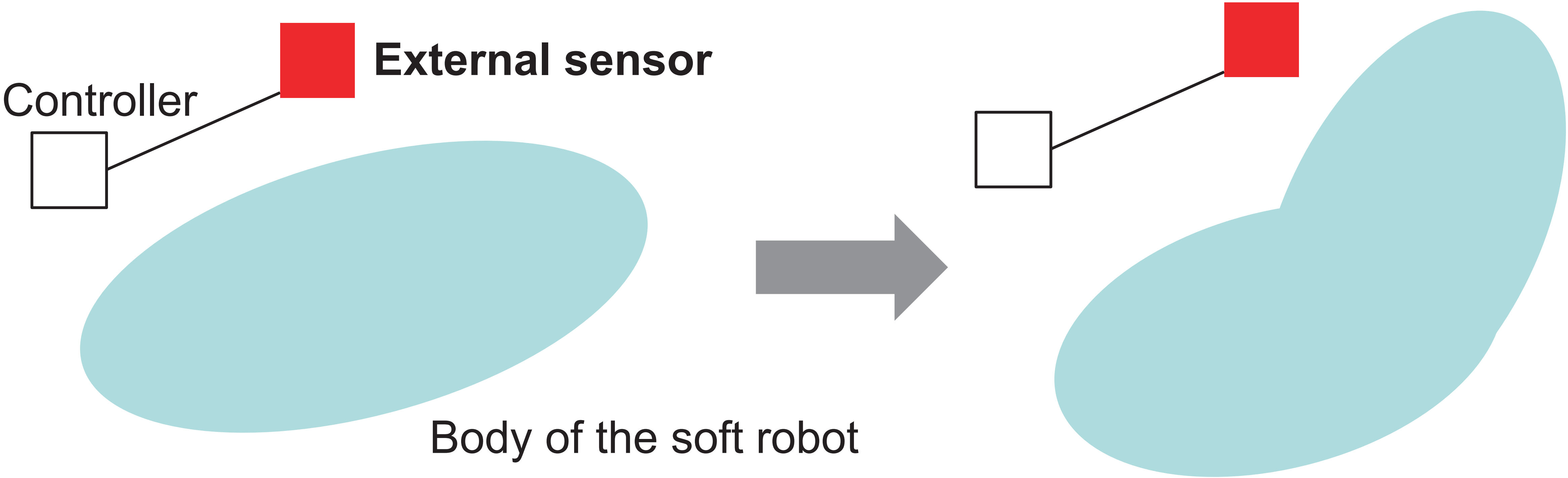
2) Embed micro-scaled sensors inside the body of the soft robot



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

Classification by sensor form and installation

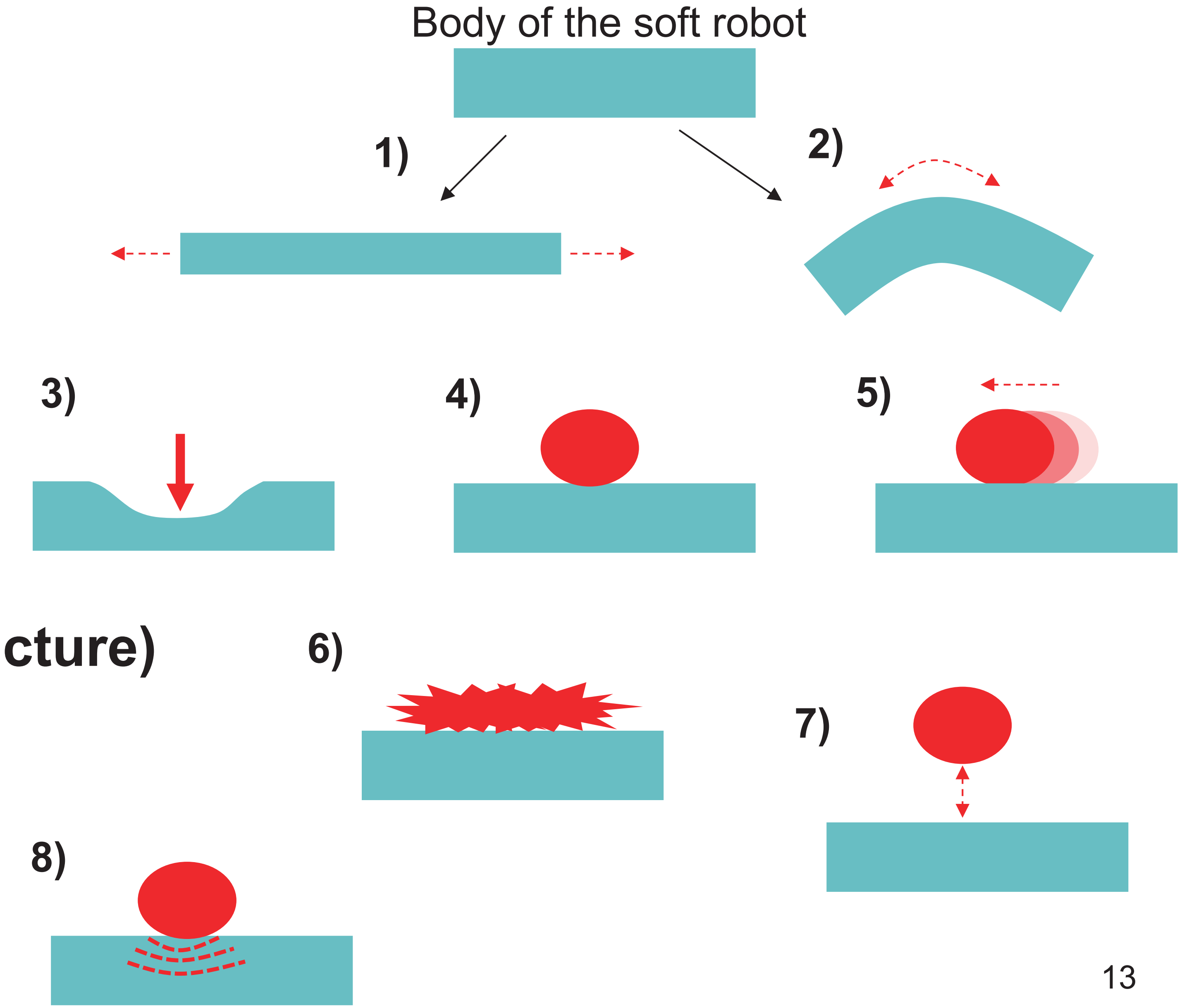
3) Put external sensor outside the body of the soft robot



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

Classification by physical quantities to be measured

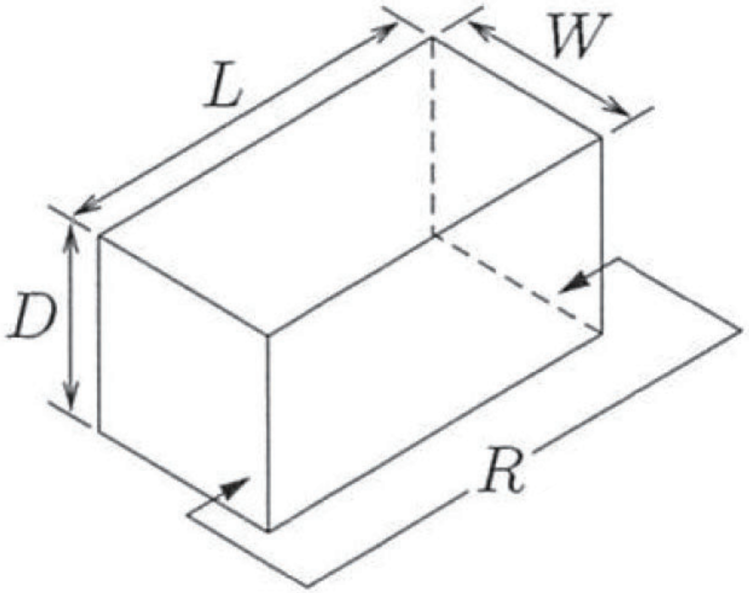
1) Stretching
2) Bending
3) Force
4) Contact
5) Slip
6) Texture (surface microstructure)
7) Proximity
8) Temperature



Classification by sensing principle

- Resistive sensor
- Capacitive sensor
- Piezoelectric sensor
- Magnetic sensor
- Optical sensor

Resistive sensor



Resistance $R = \rho \frac{L}{WD}$

ρ [Ωm] : volume resistivity, or electrical resistivity

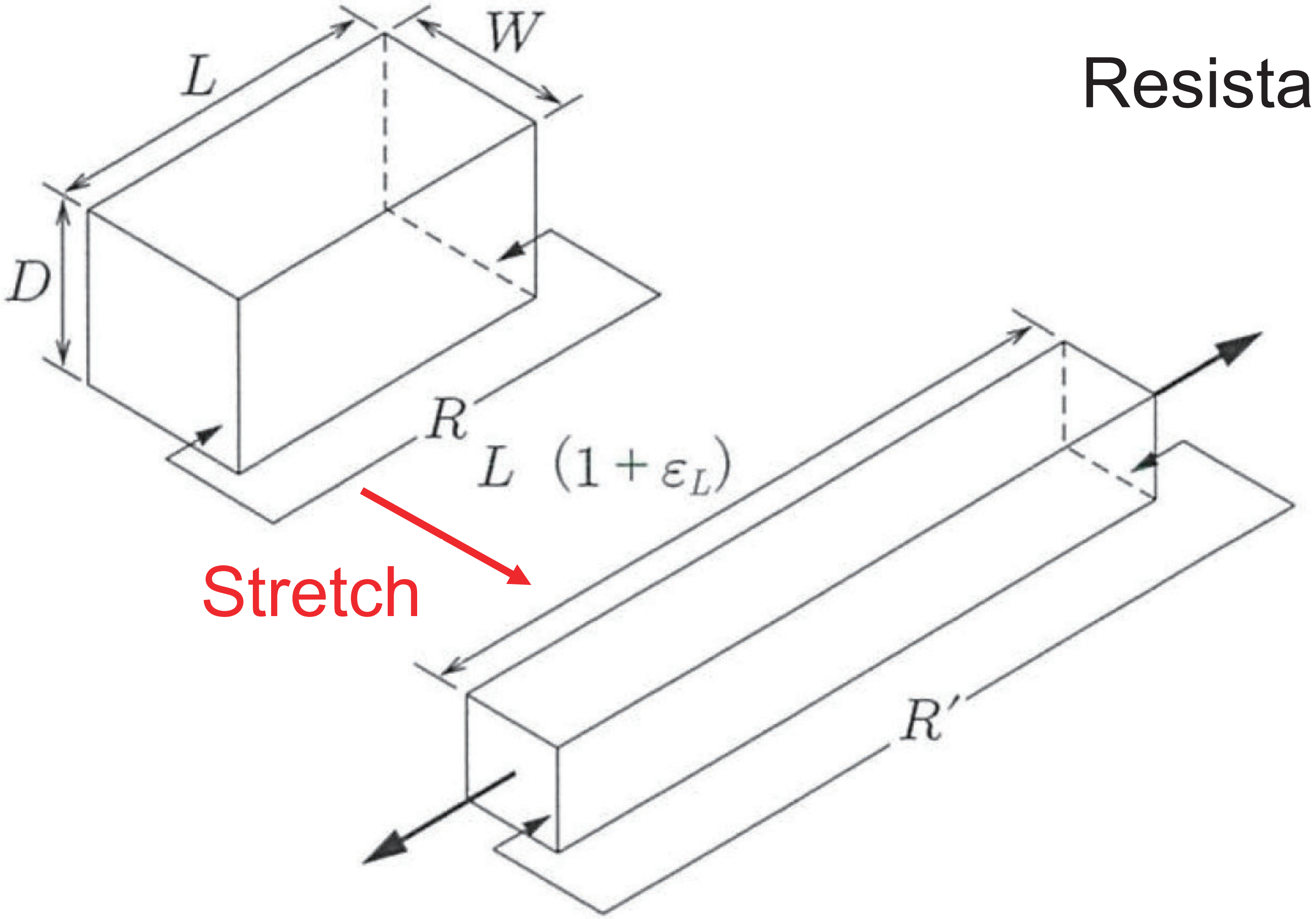
（体積抵抗率，電気抵抗率）

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



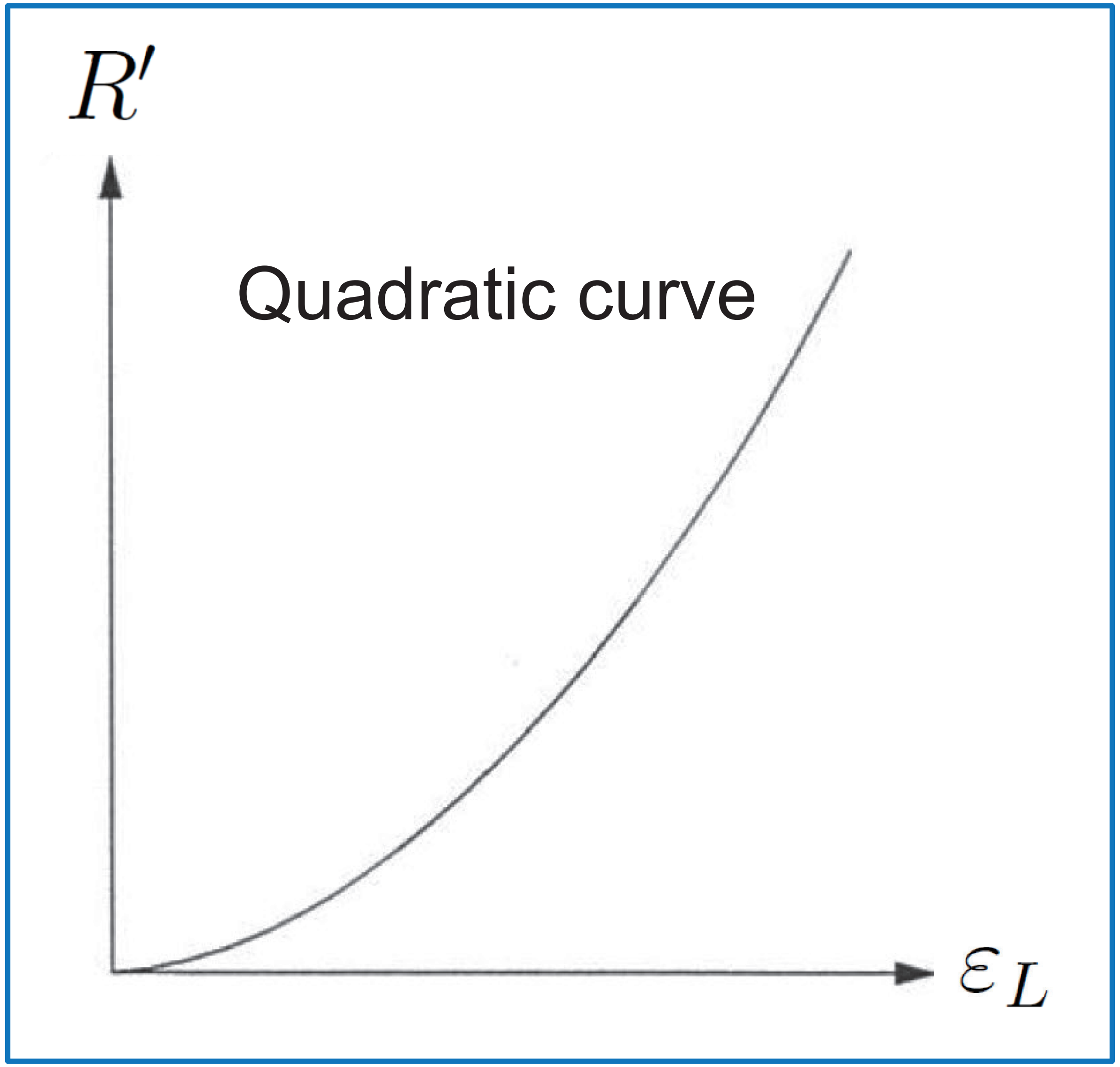
Resistance $R = \rho \dfrac{L}{WD}$

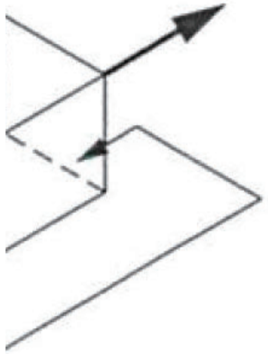
ε_L : strain

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,

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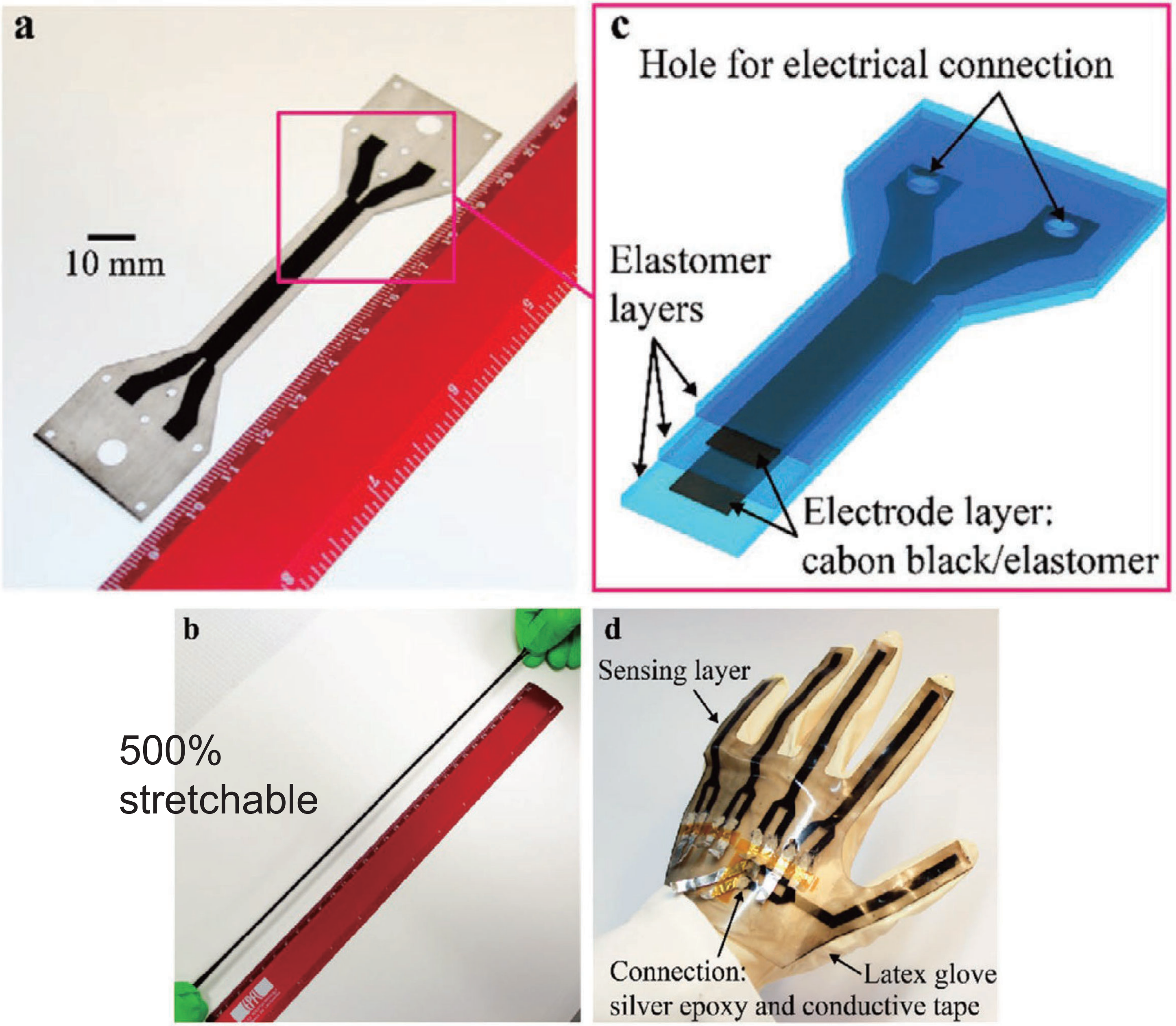
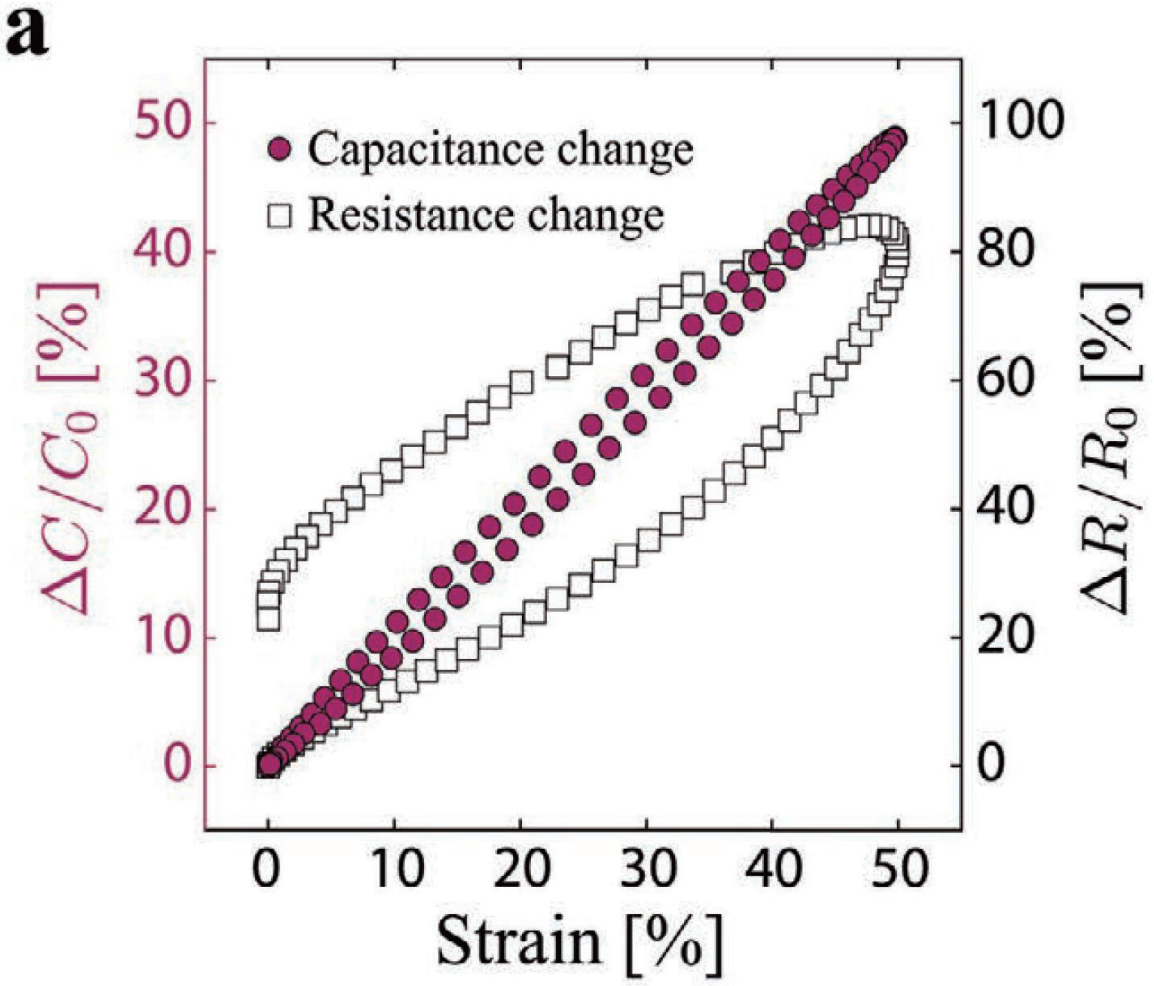
Ultrastretchable Strain Sensors Using Carbon Black-Filled Elastomer Composites and Comparison of Capacitive Versus Resistive Sensors

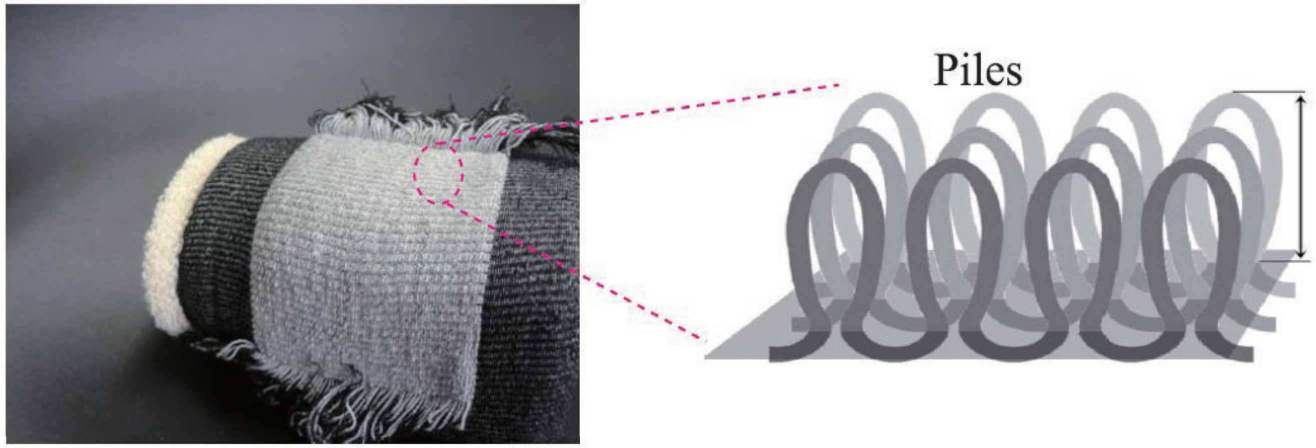


500% stretchable



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

Flexible Fabric Sensor



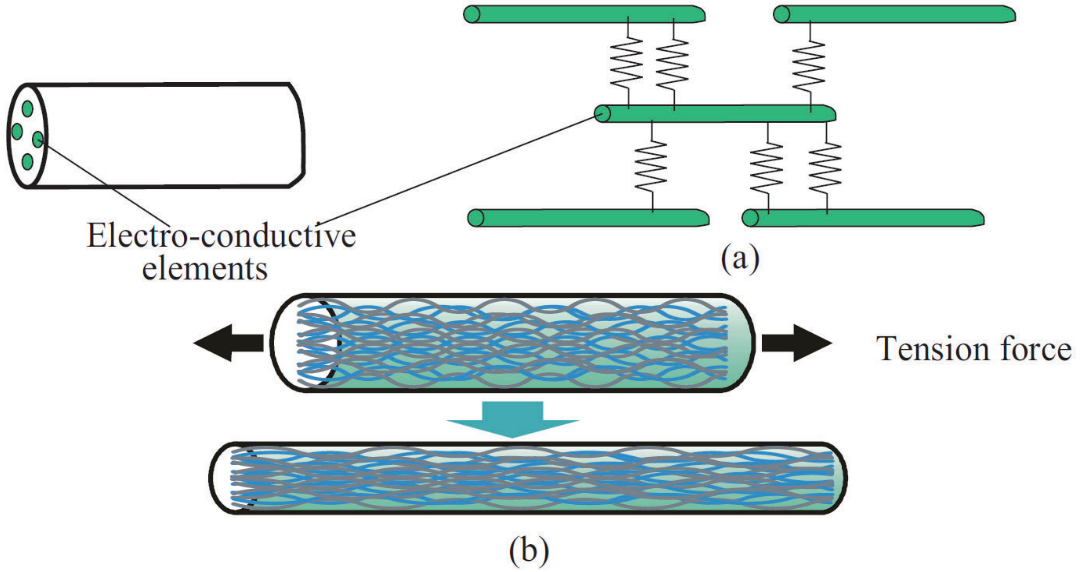
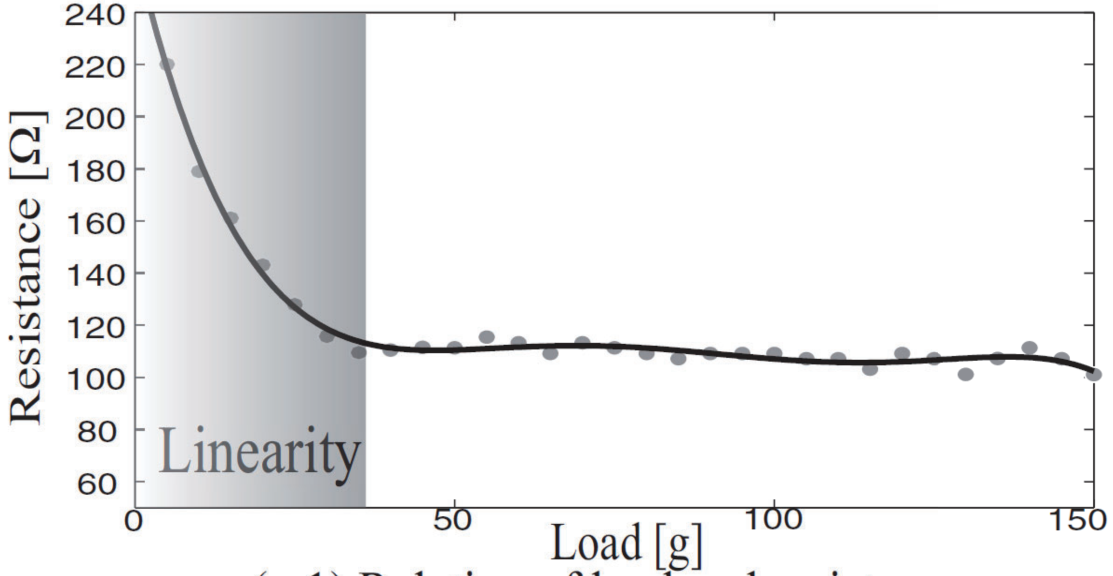
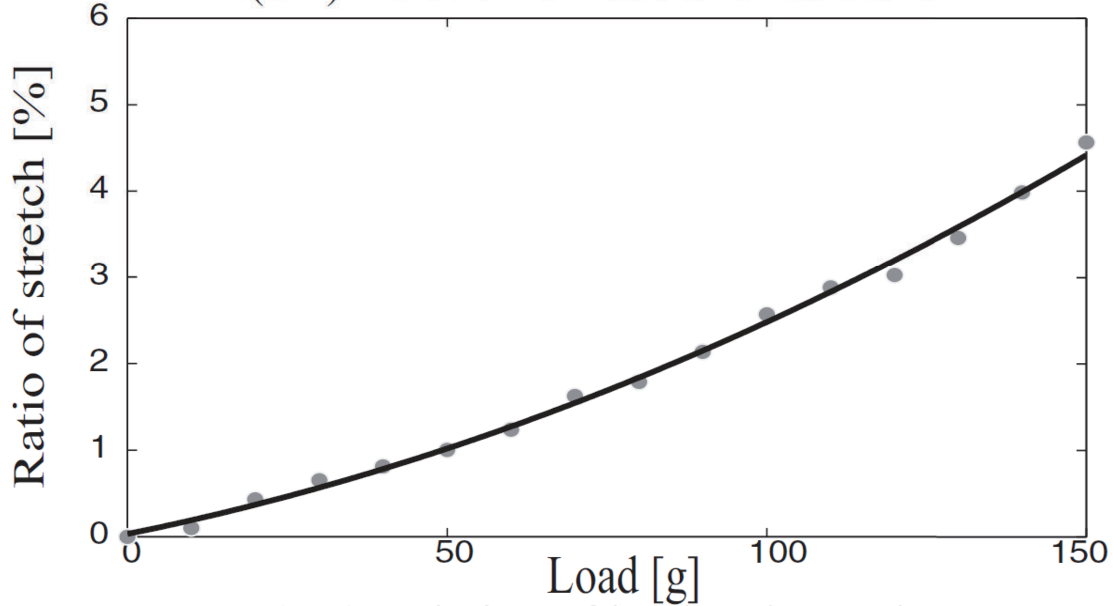


Fig. 2. Model of a tension-sensitive electro-conductive yarn. (a) Structure. (b) Density of conductive fibers (blue fiber) increases when tensile.



(a-1) Relation of load and resistance

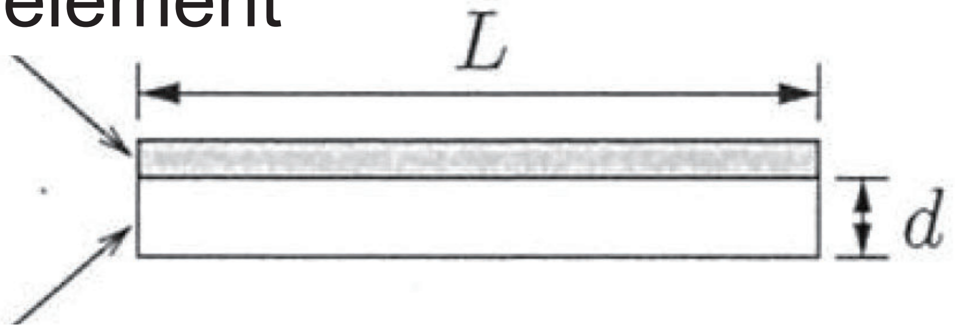


(a-2) Relation of load and stretch

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

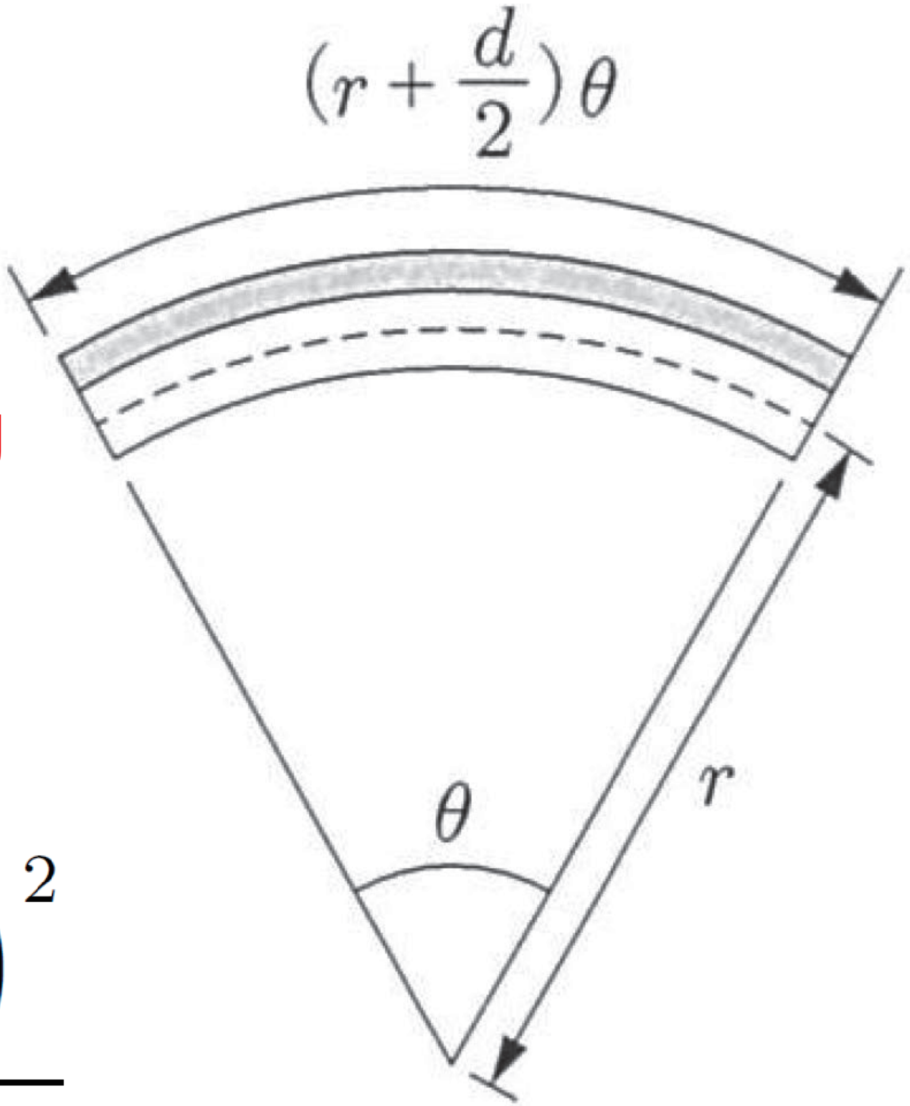
Resistive sensor - Film resistive sensor

Sensor element



Film substrate

Bending

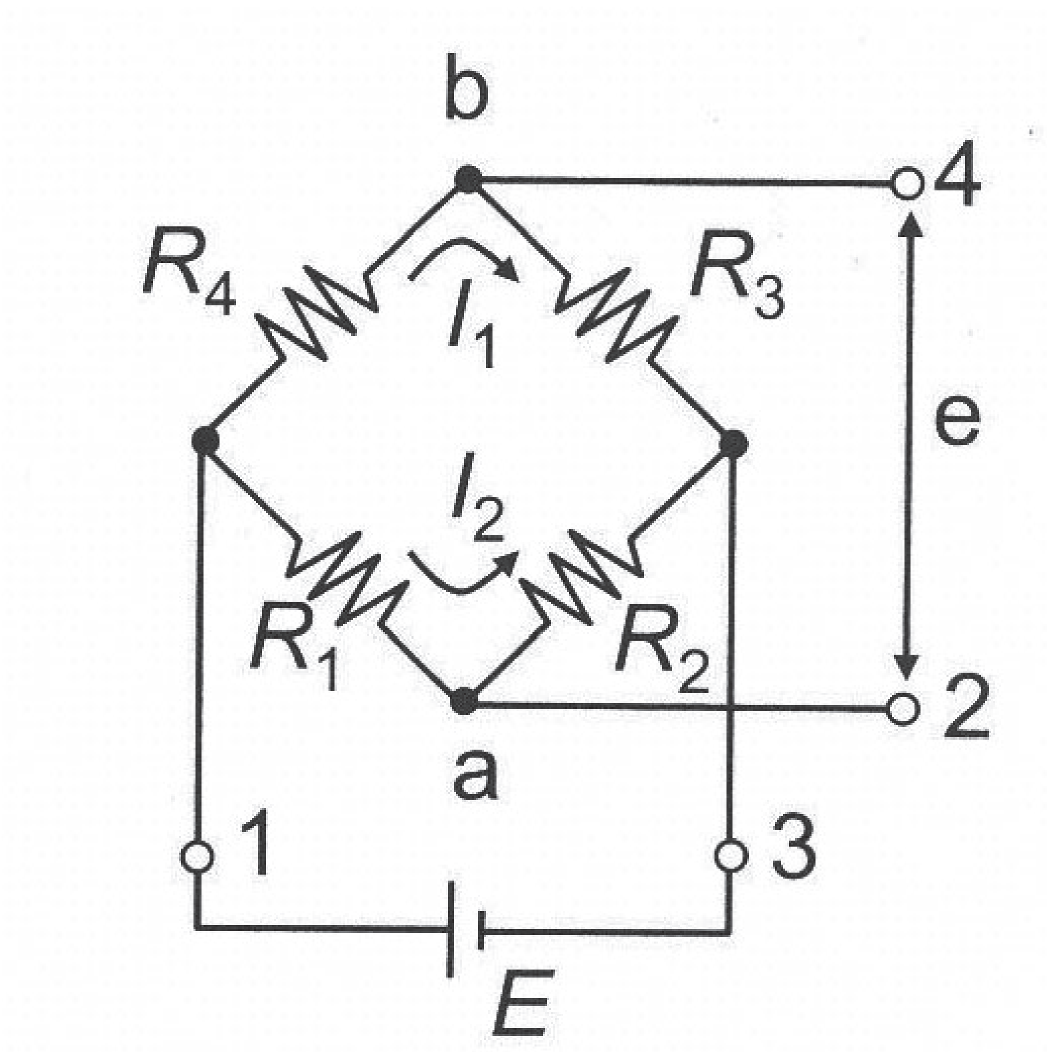


$$\varepsilon_L = \left(r + \frac{d}{2}\right)\frac{\theta}{L} - 1$$

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

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,

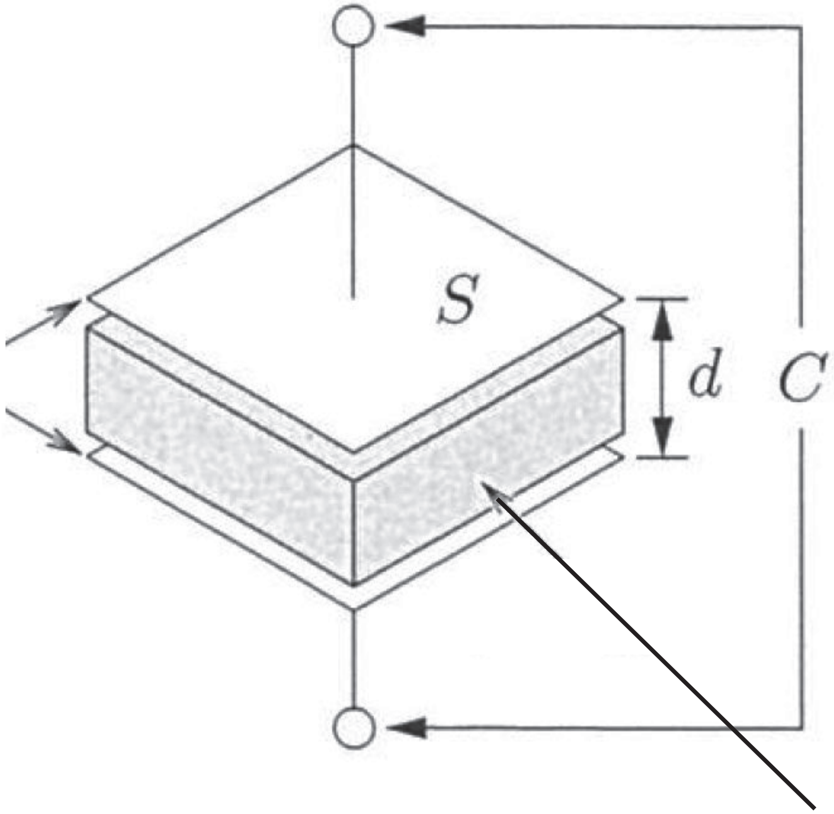
$$e \cong \frac{1}{4} \cdot \frac{\Delta R}{R} \cdot E$$

Thus, you can observe *ΔR* from *e*.

Capacitive sensor

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

ε : Permittivity（誘電率）



Electrodes

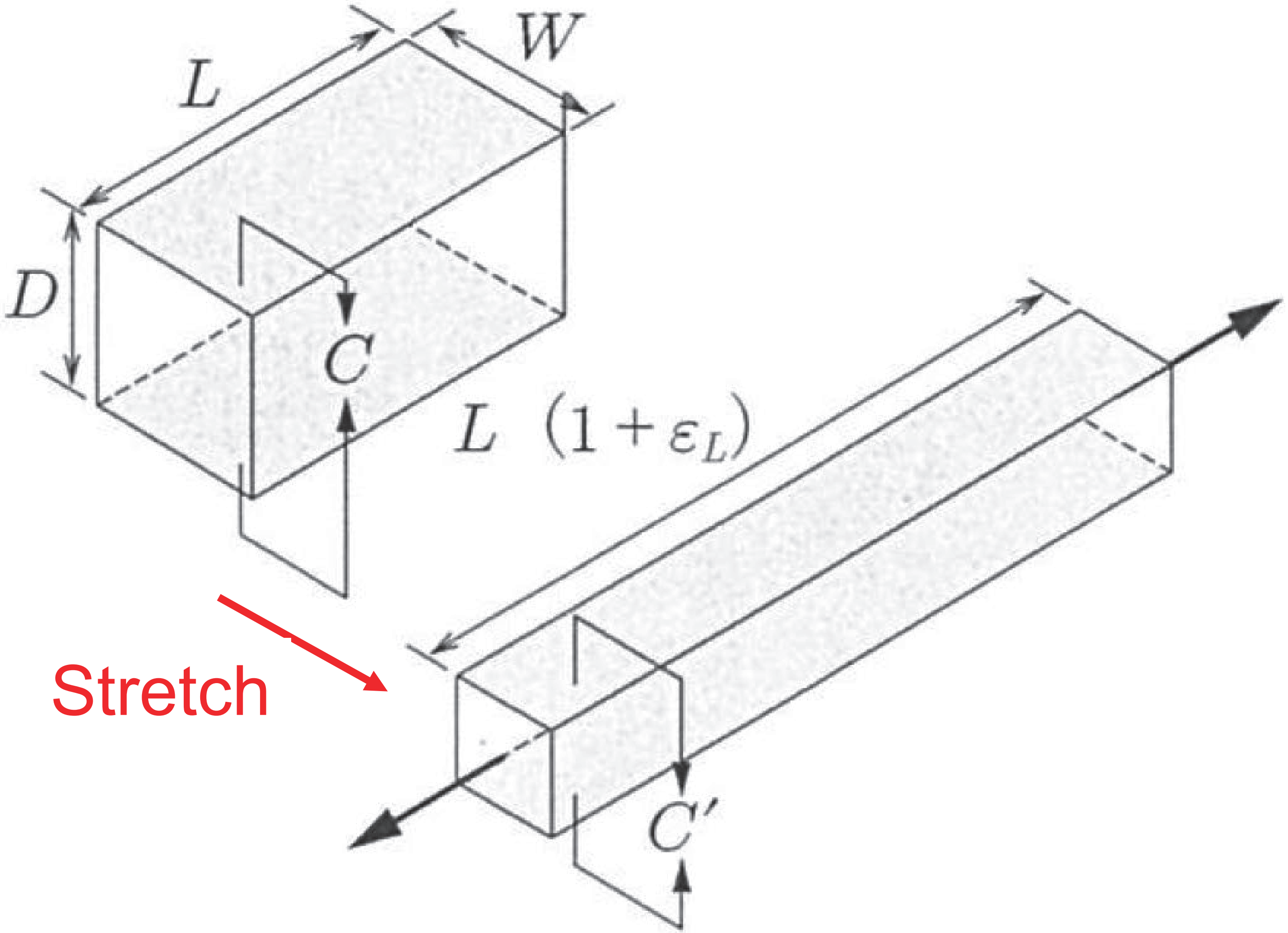
Dielectric substance
（誘電体）

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



Stretch

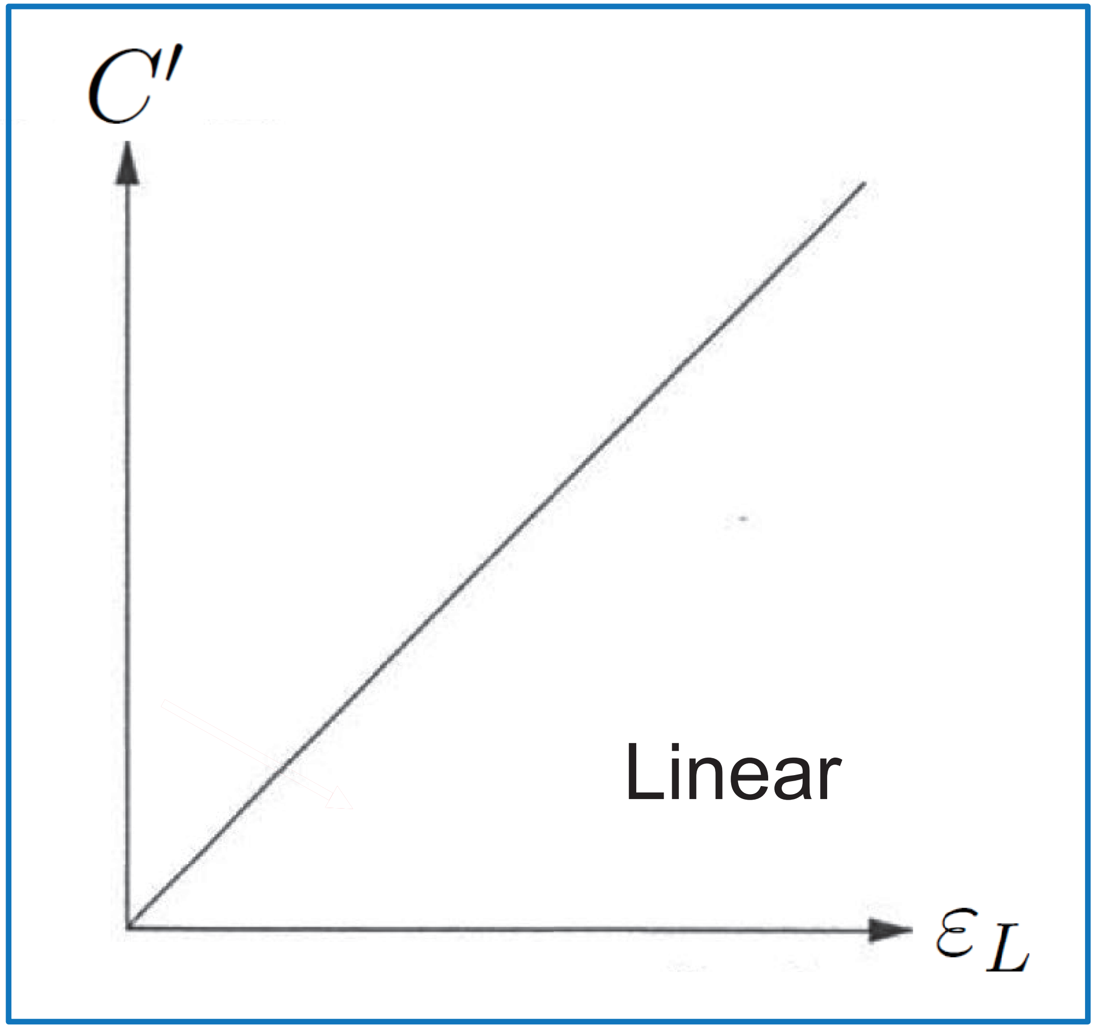
$$C = \varepsilon \frac{LW}{D}$$

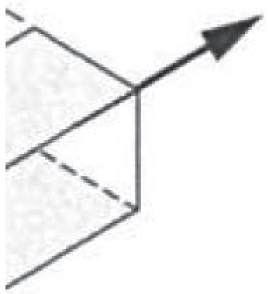
ε_L : strain

Assuming that the volume is constant,

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

Capacitive sensor





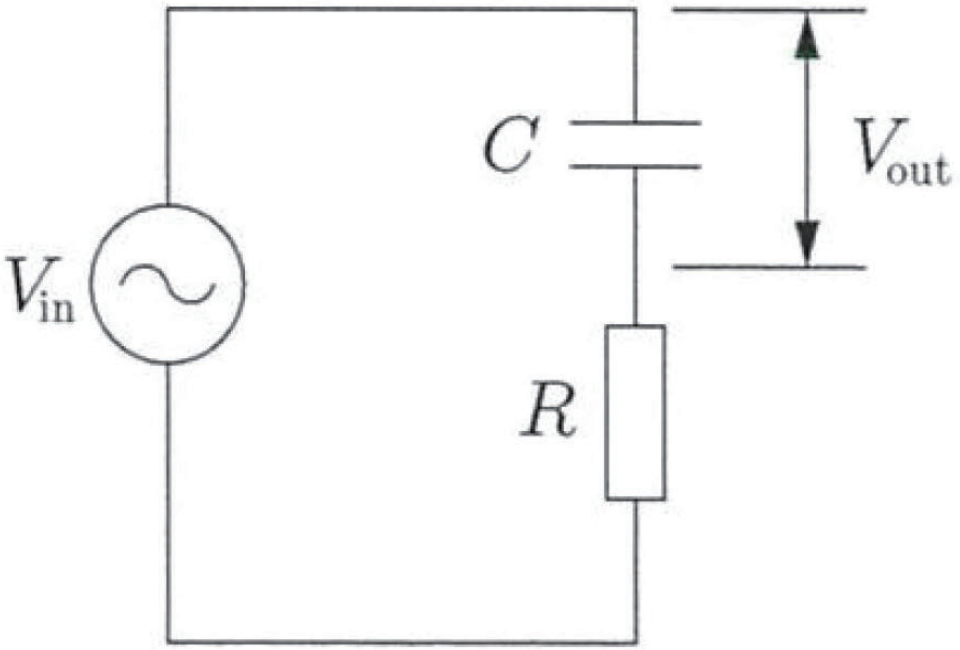
$$C = \varepsilon \frac{LW}{D}$$

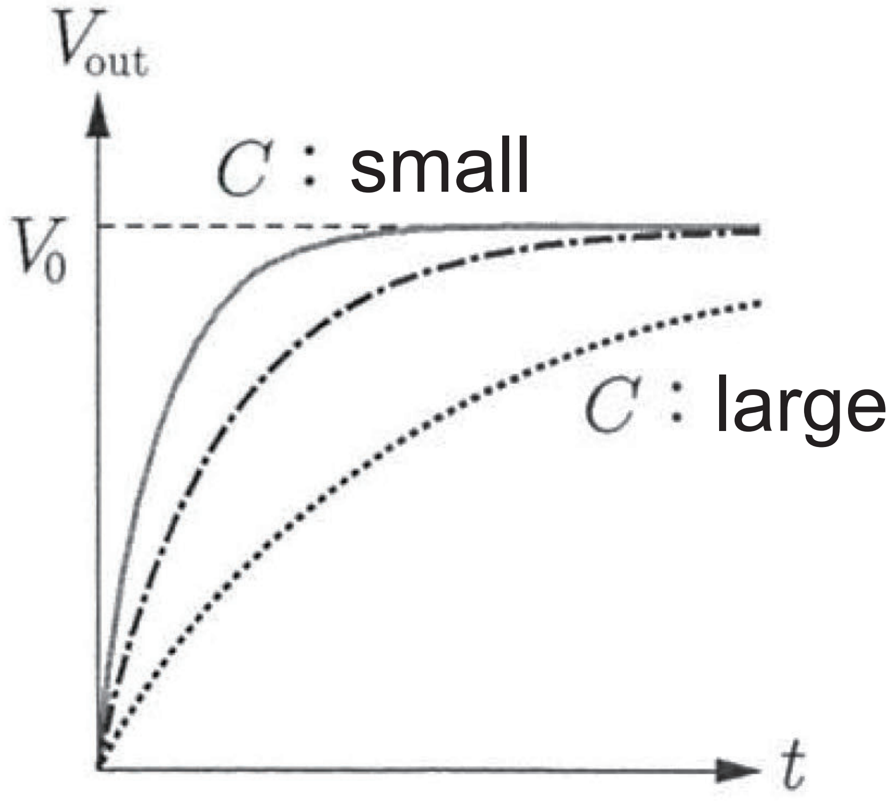
ε_L : strain

Assuming that the volume is constant,

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

How to measure capacitance? **- RC circuit**

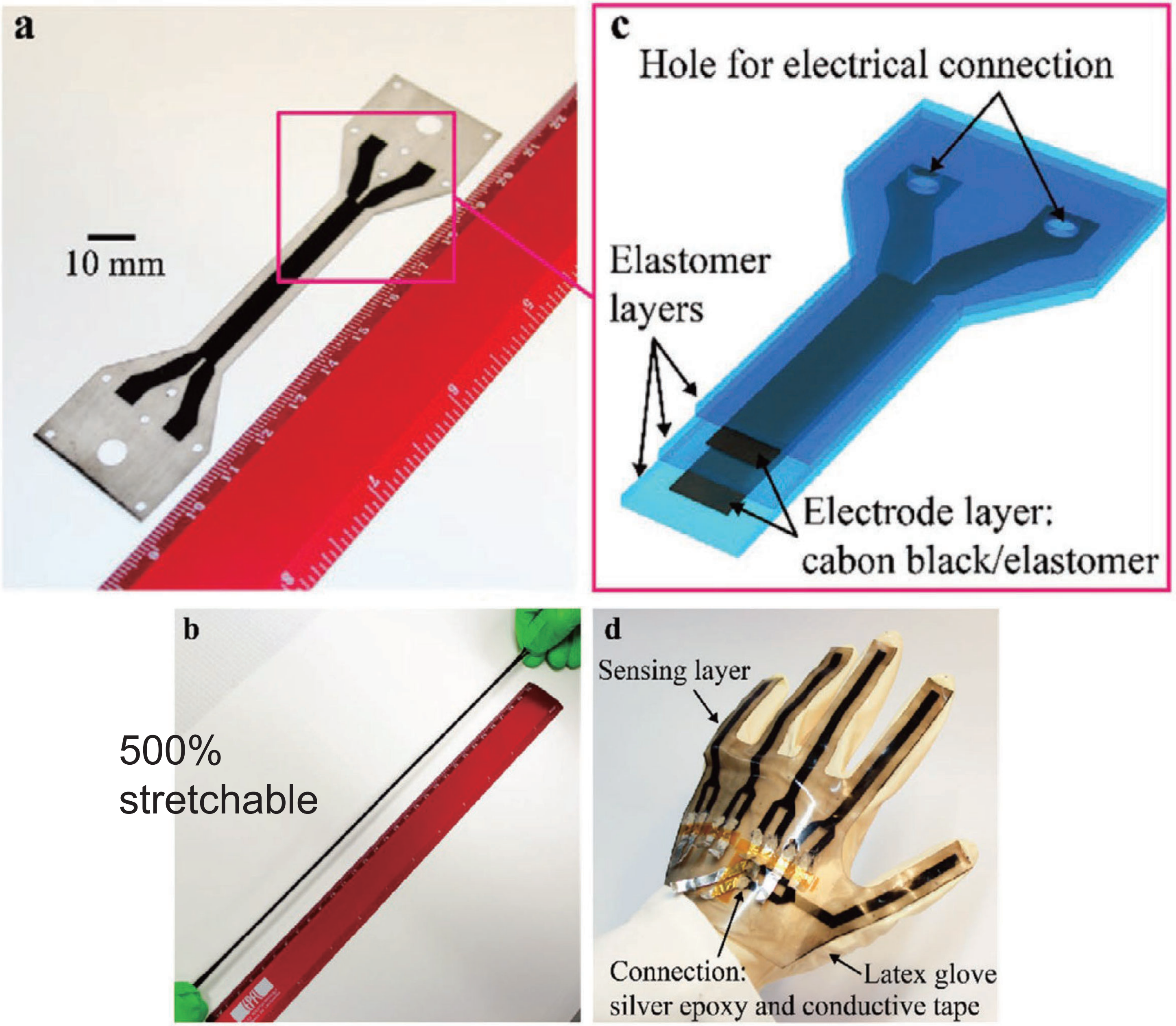




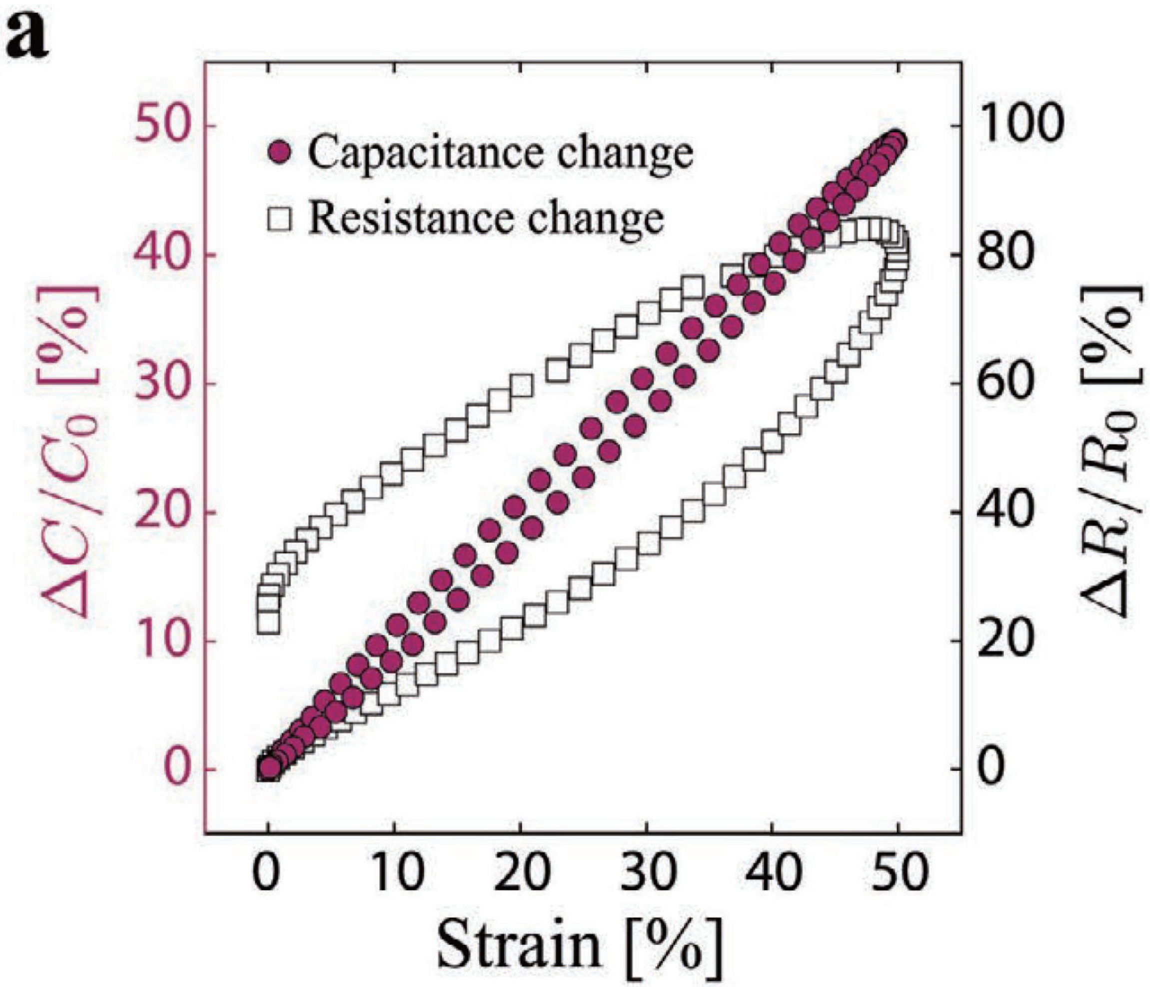
For a step input, $$V_{\text{out}}(t) = V_0 \left\{ 1 - \exp\left(-\frac{1}{RC} t \right) \right\}$$

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

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

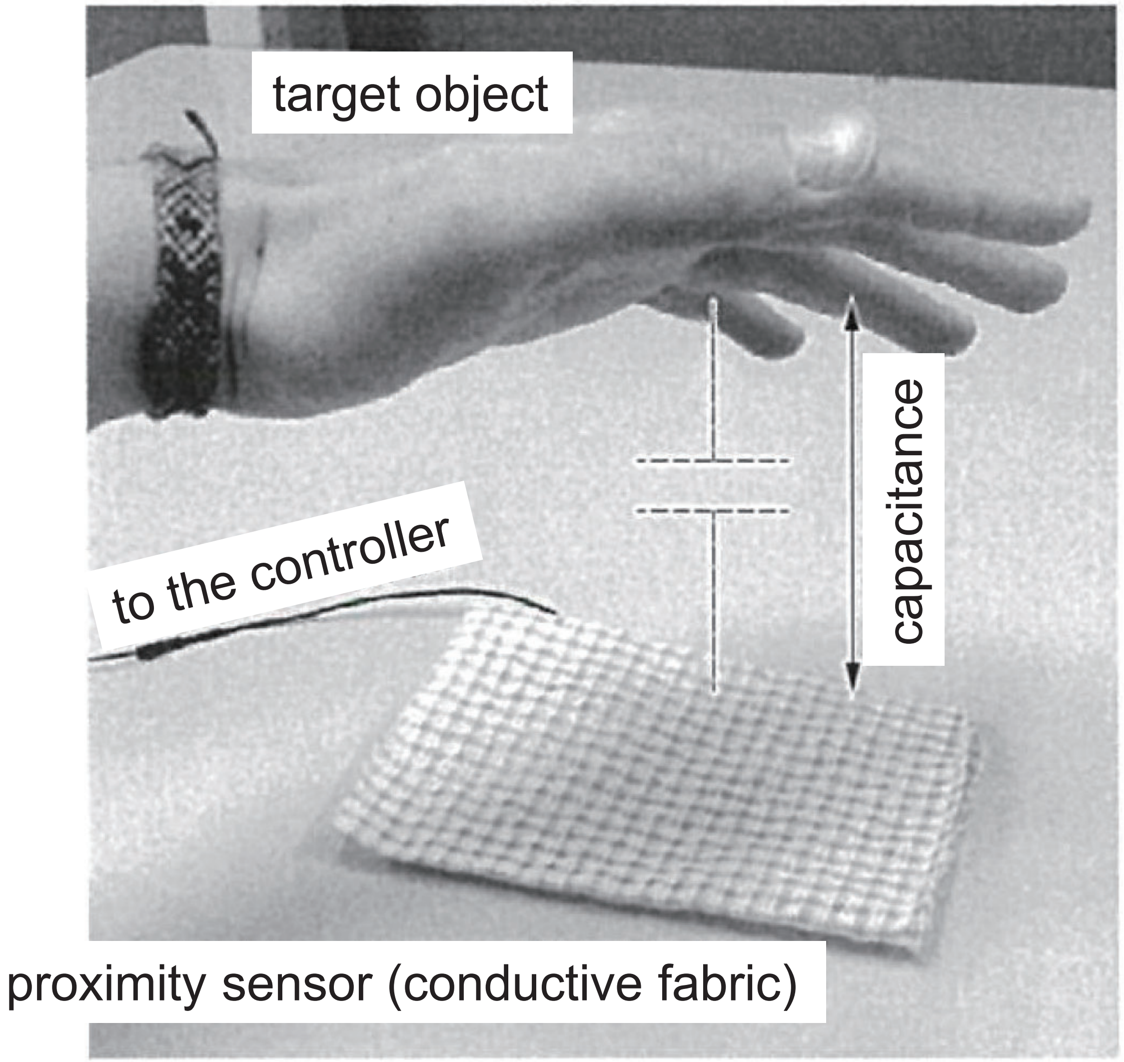


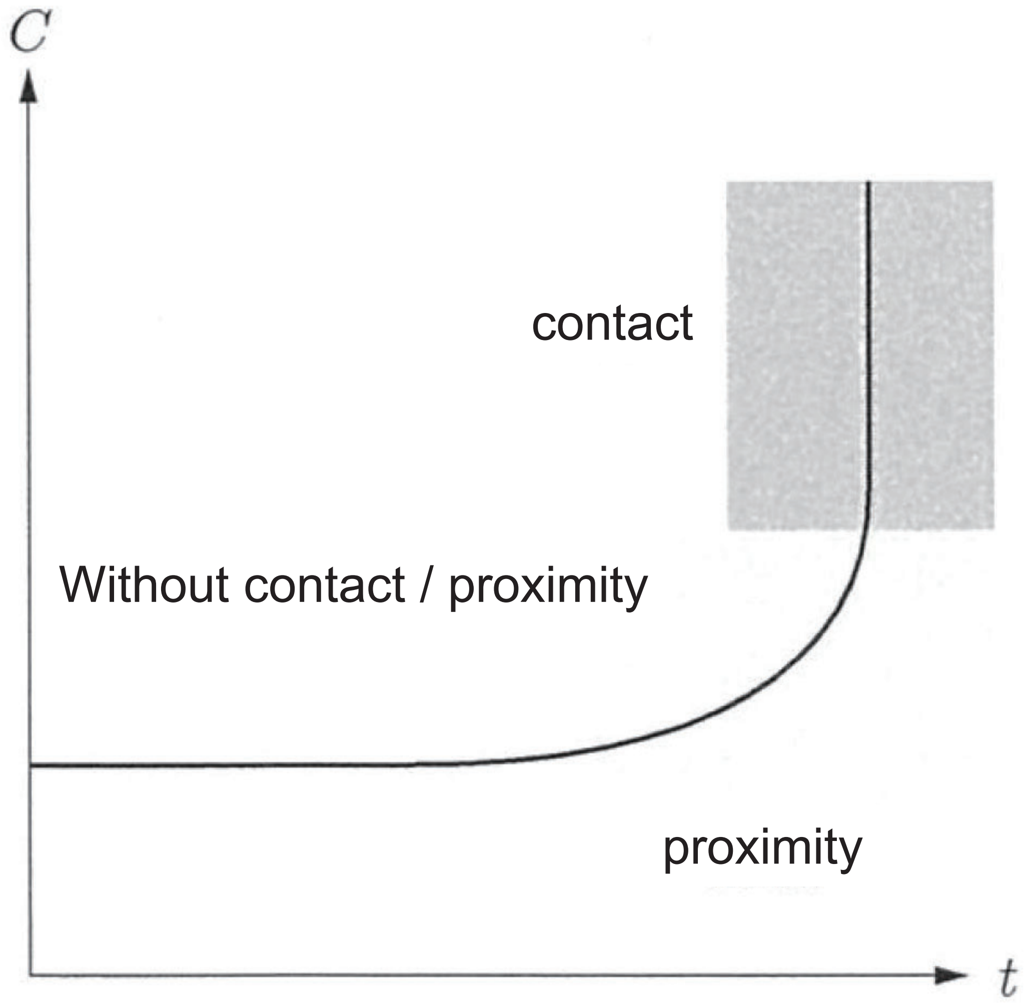
500% stretchable



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

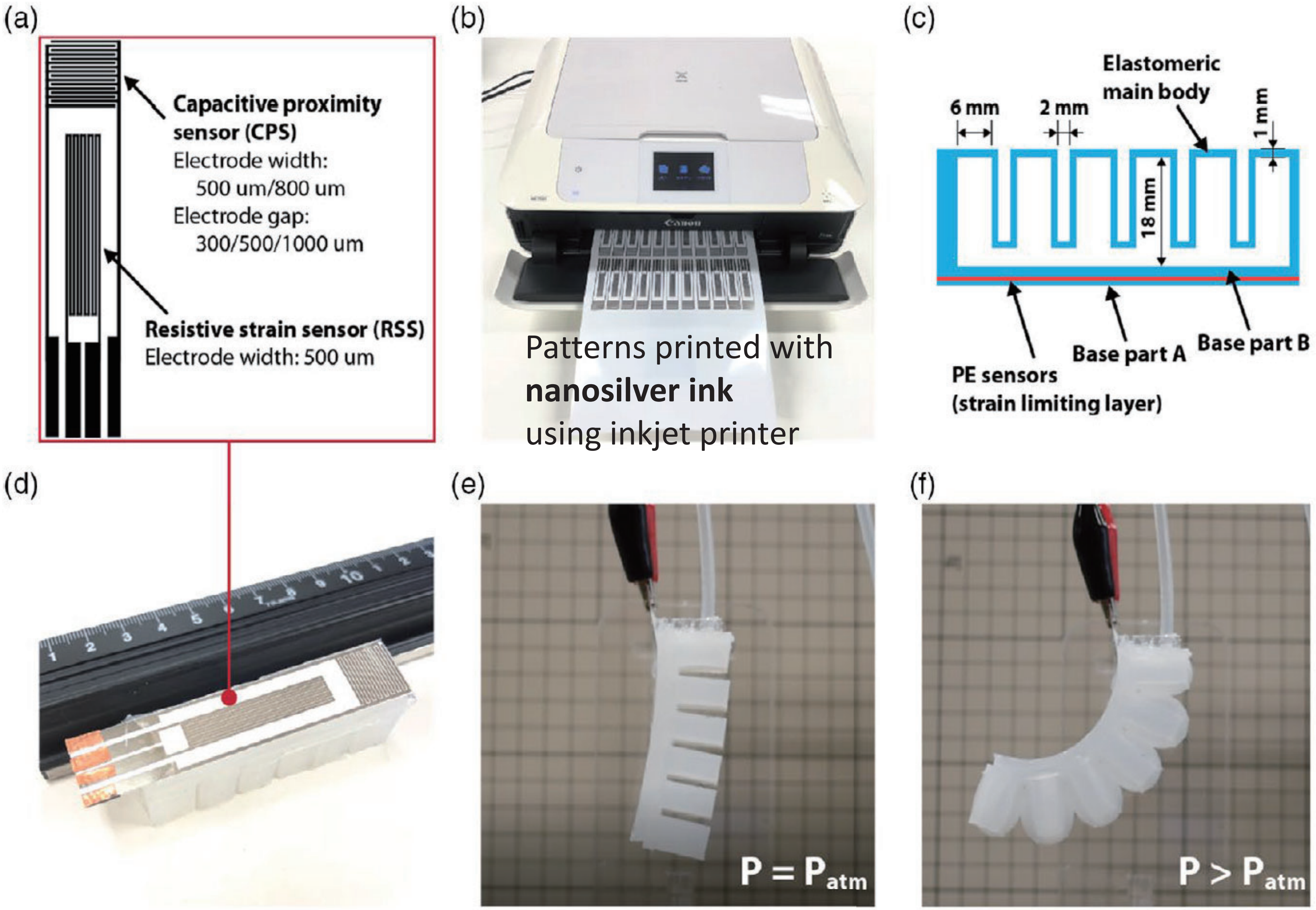
Capacitive sensor - Proximity sensing





「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



Patterns printed with **nanosilver ink** using inkjet printer

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

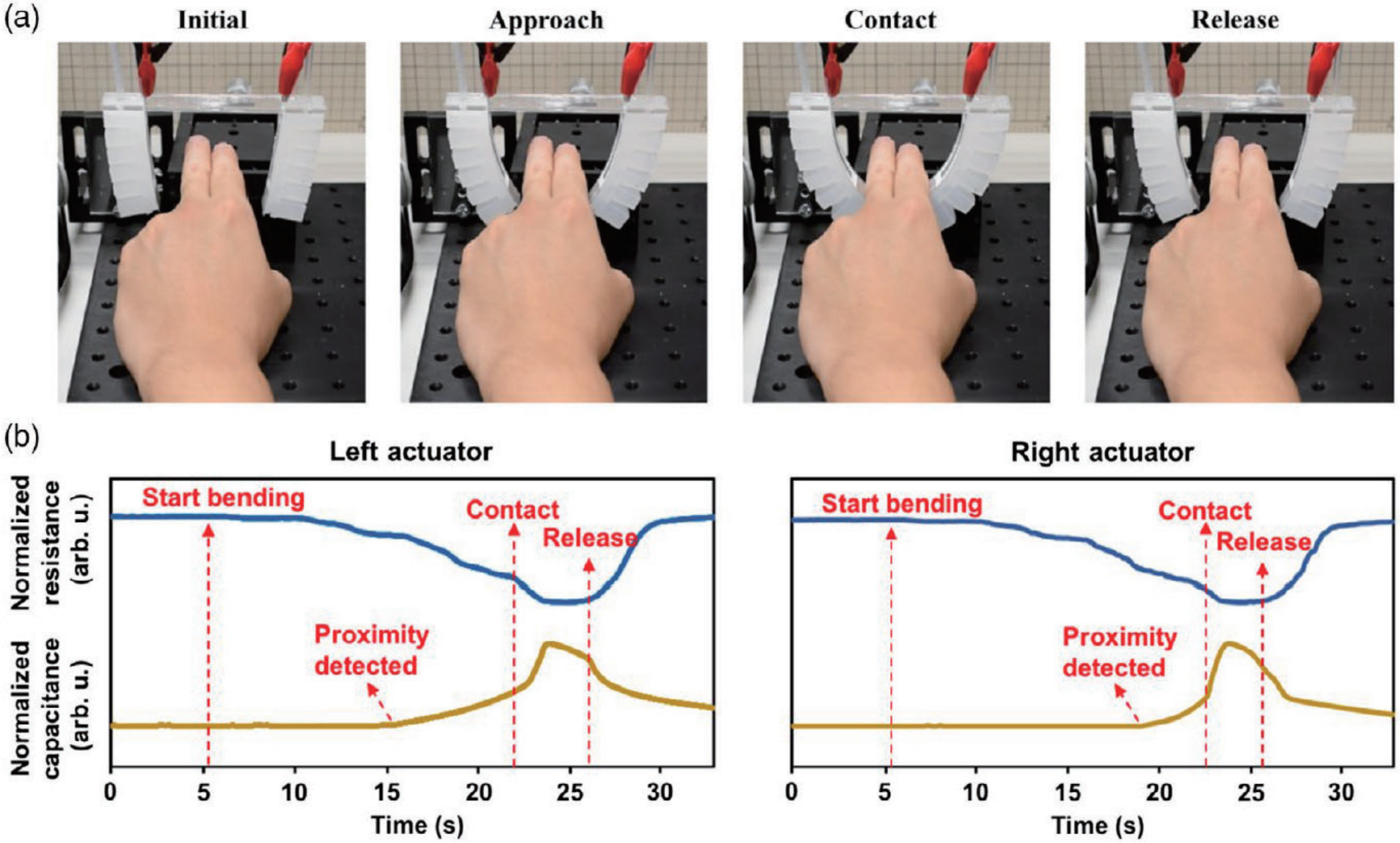


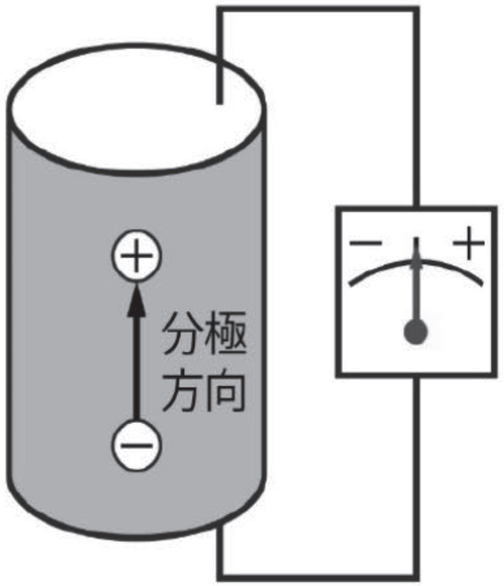
Figure 7. Intelligent soft gripper with the RSS and CPS paper sensors. a) Photograph showing the whole process where soft gripper grasped and released fingers. b) Variation in resistance and capacitance detected by the RSS and CPS integrated in both actuators of the gripper, respectively. The resistance 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

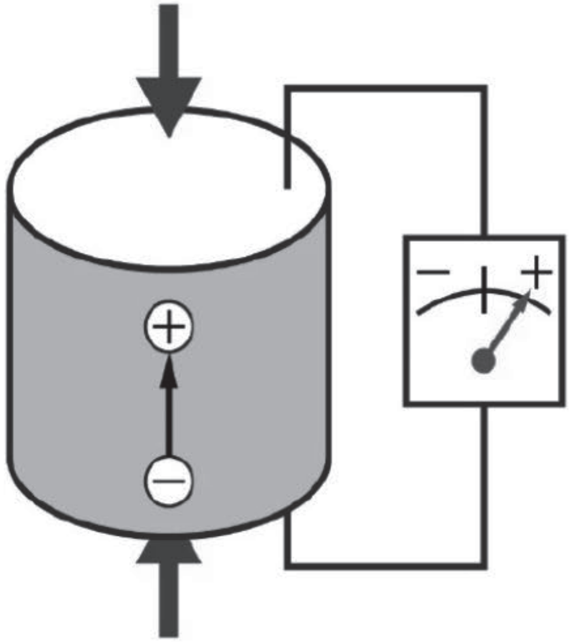
Piezoelectric sensor

Piezoelectric material（圧電体）:

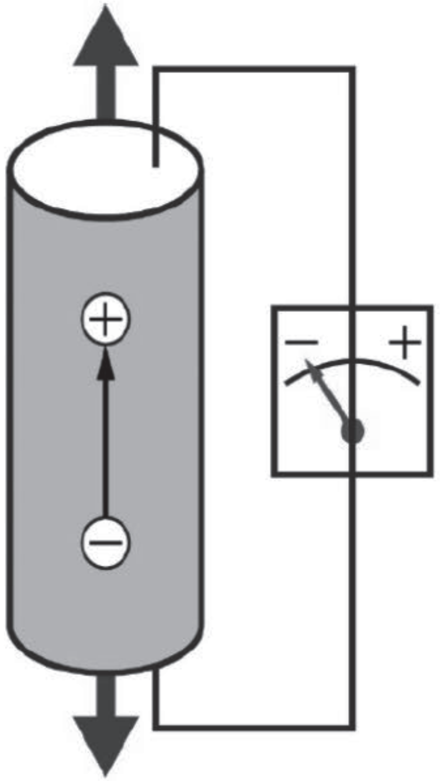
- A type of **dielectric material**（誘電体）, and that causes **piezoelectric phenomenon**（圧電現象） which converts mechanical and electrical energy in each other.
- **Polarization**（分極） occurs due to external stress.



No load



Positive voltage
for compression



Negative voltage
for extension

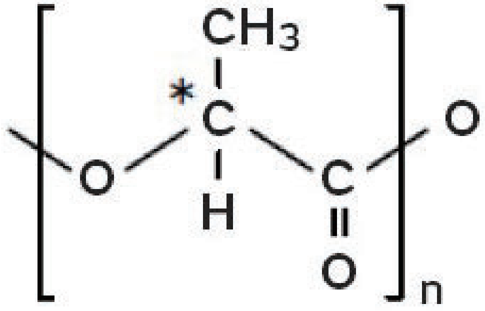
Piezoelectric sensor - Piezoelectric materials

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

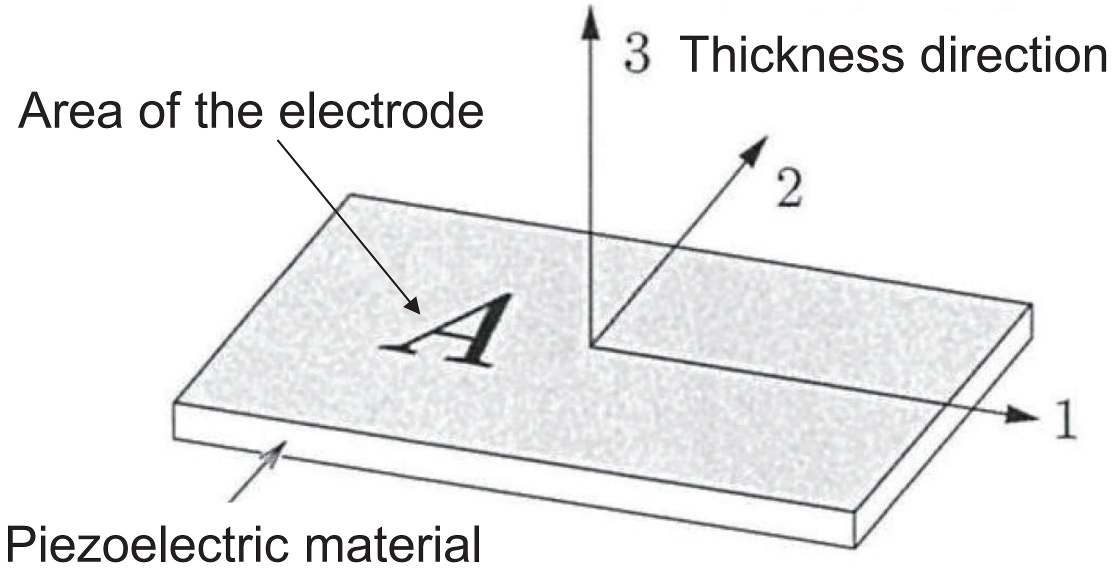
PLA sensor（Murata Manufacturing）

Piezoelectric sensor - Piezoelectric material characteristics

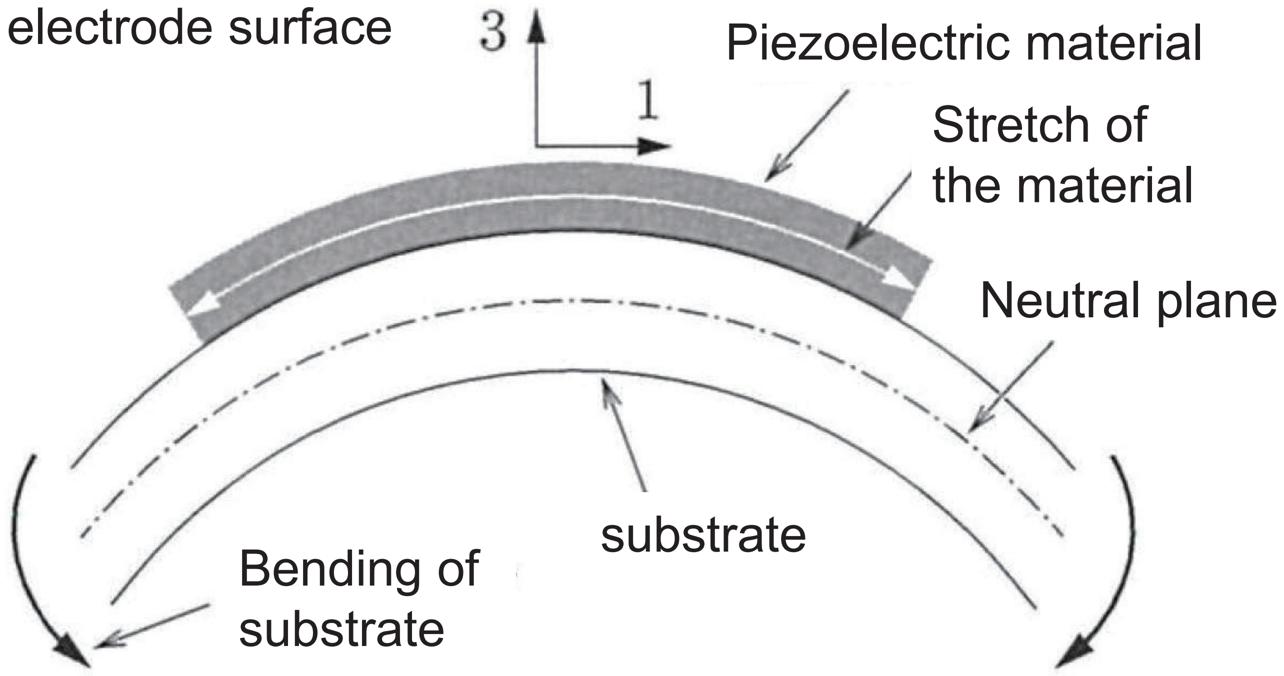
Piezoelectric constant d_{31}

Direction of strain (or stress)

Normal direction for electrode surface



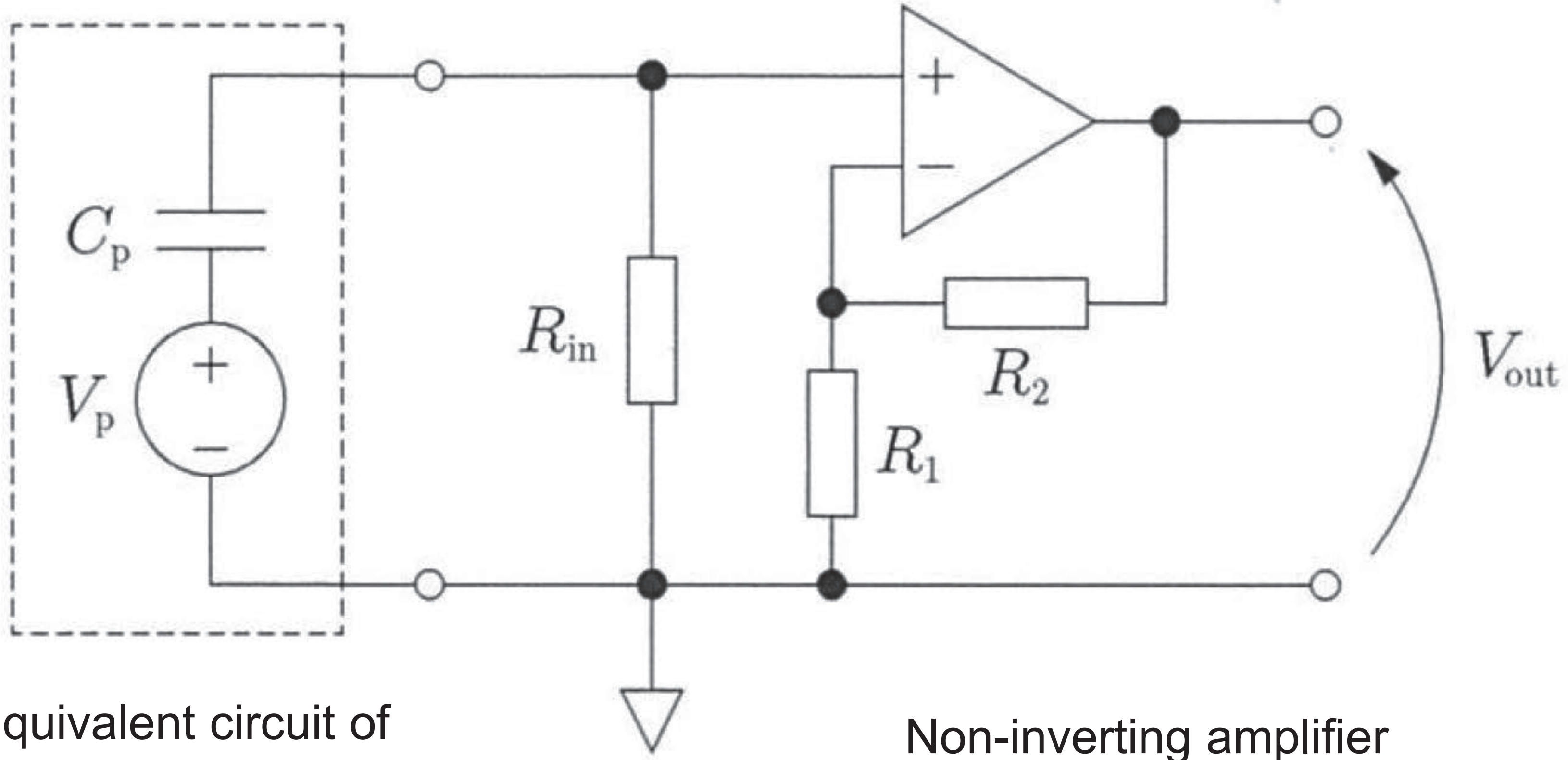
(a) Piezoelectric constant
（圧電定数）



(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

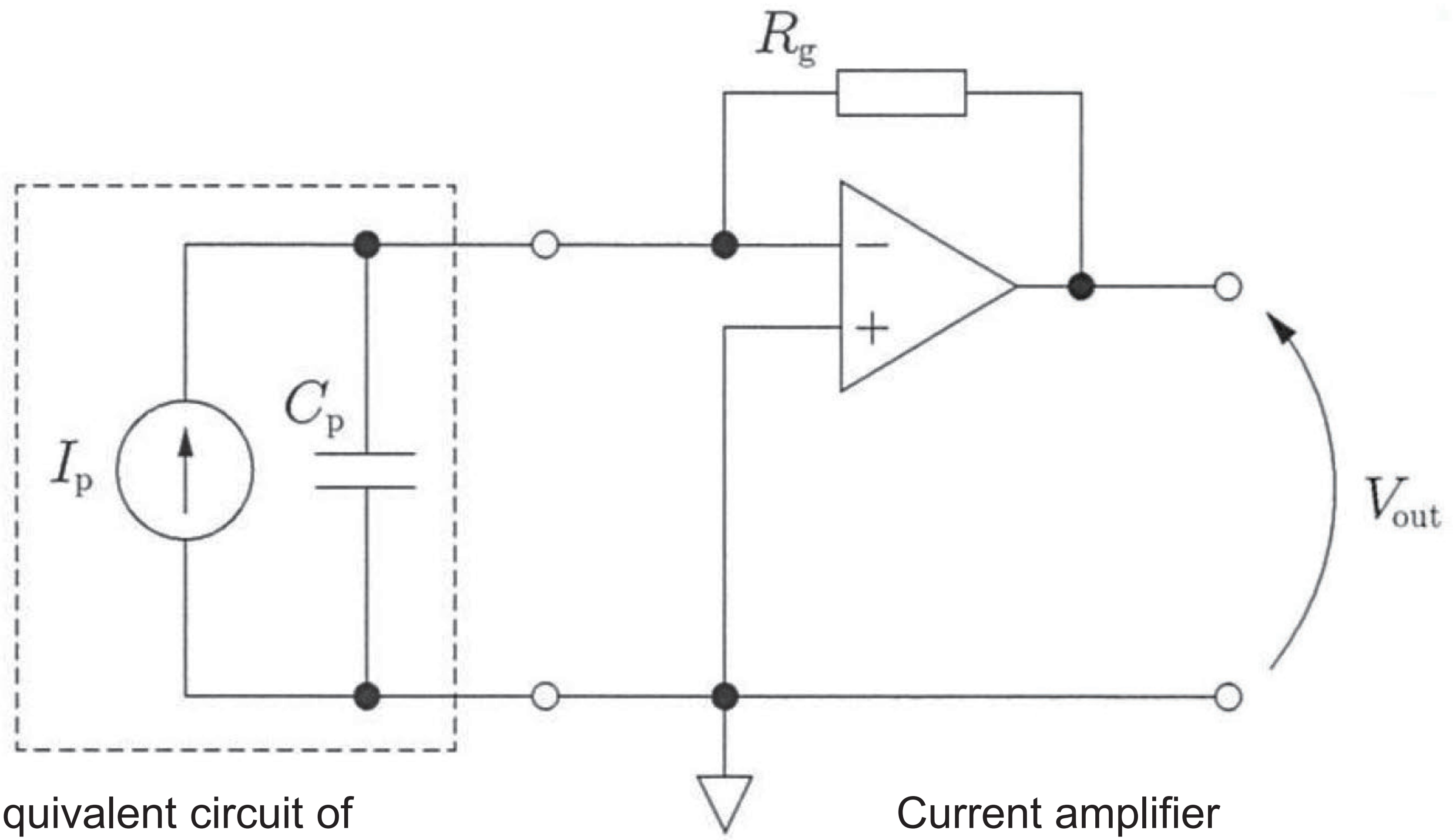


Equivalent circuit of
piezoelectric sensor
(as voltage source)

Non-inverting amplifier

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

Piezoelectric sensor - Current measurement circuit

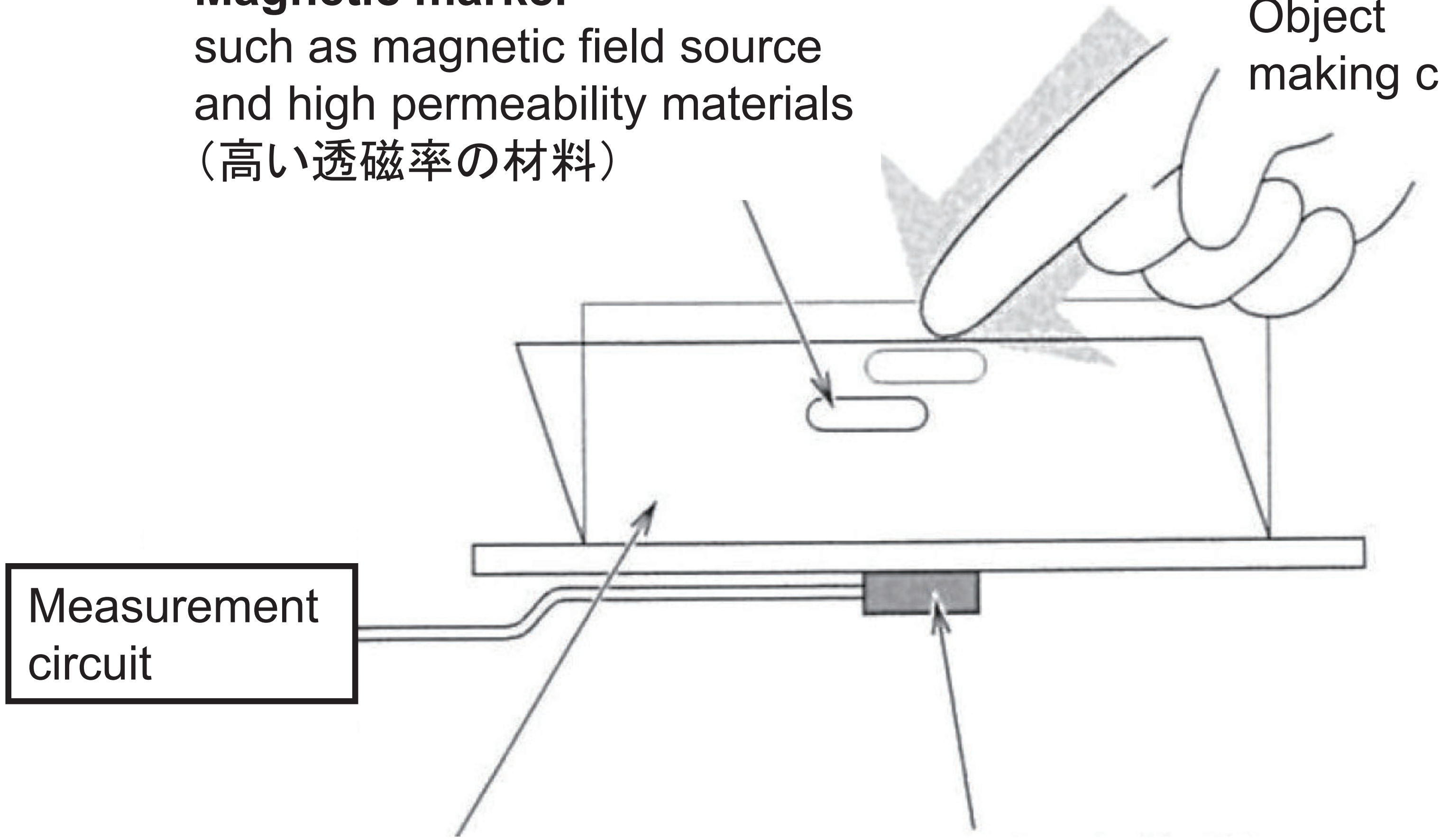


Equivalent circuit of
piezoelectric sensor
(as current source)

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

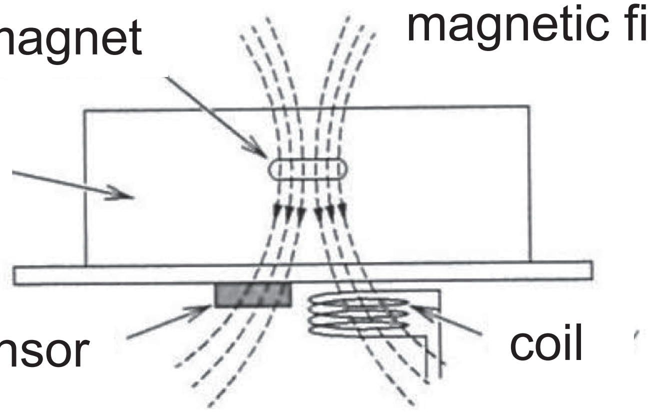
Measurement
circuit

Elastomer,
soft material such as
silicone rubber

Magnetic transducers
that convert changes of magnetic field
and permeability into electric signal
e.g. Coil, Hall sensor（ホール素子）

Magnetic sensor - Sensing principle

i) Using permanent magnet



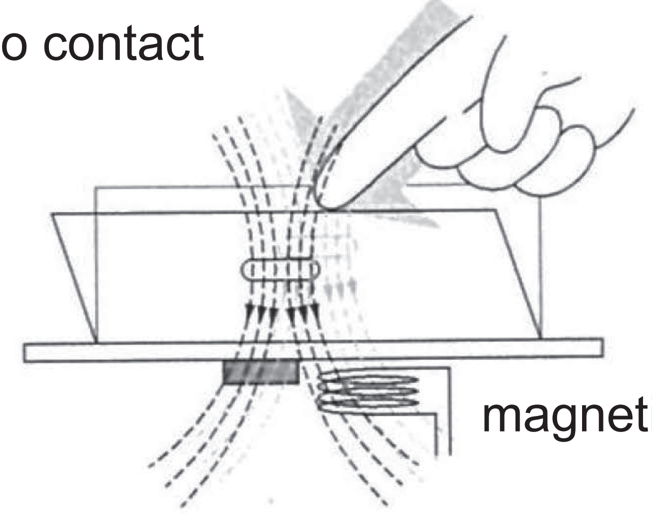
permanent magnet

magnetic field

elastomer

magnetic sensor

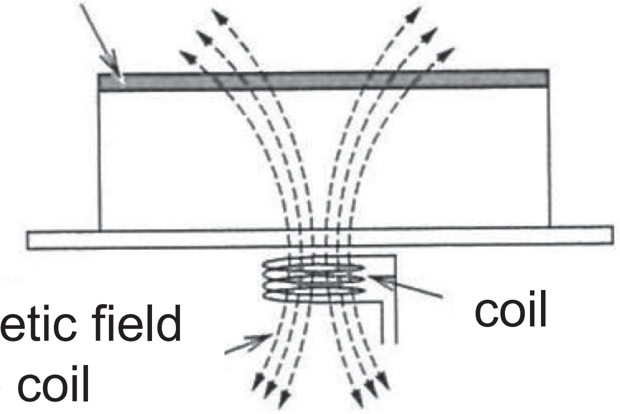
coil



magnet movement
due to contact

magnetic field changes

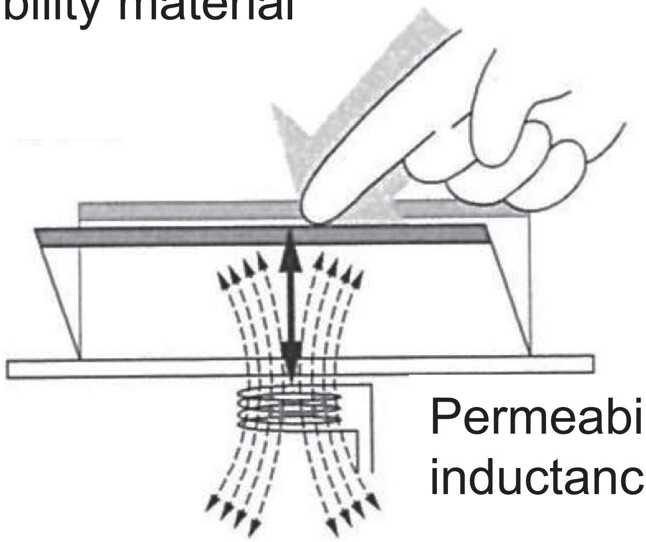
ii) Using magnetic elastomer



magnetic elastomer

alternating magnetic field
generated by the coil

coil



High permeability material
approaches

Permeability changes and
inductance increases

Flexible tactile sensor based on inductance measurement

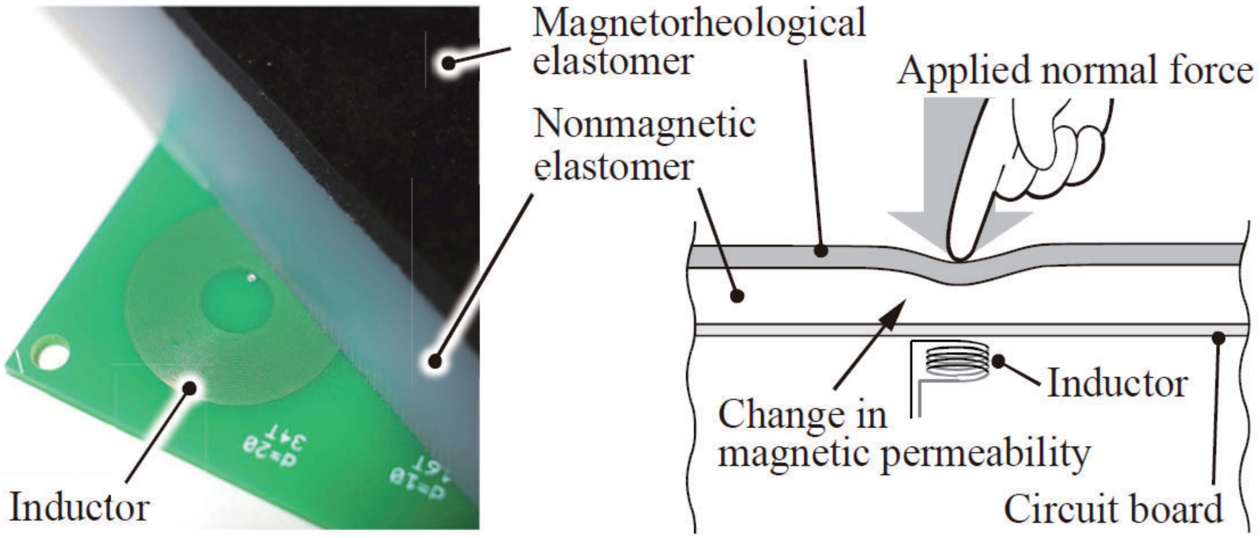
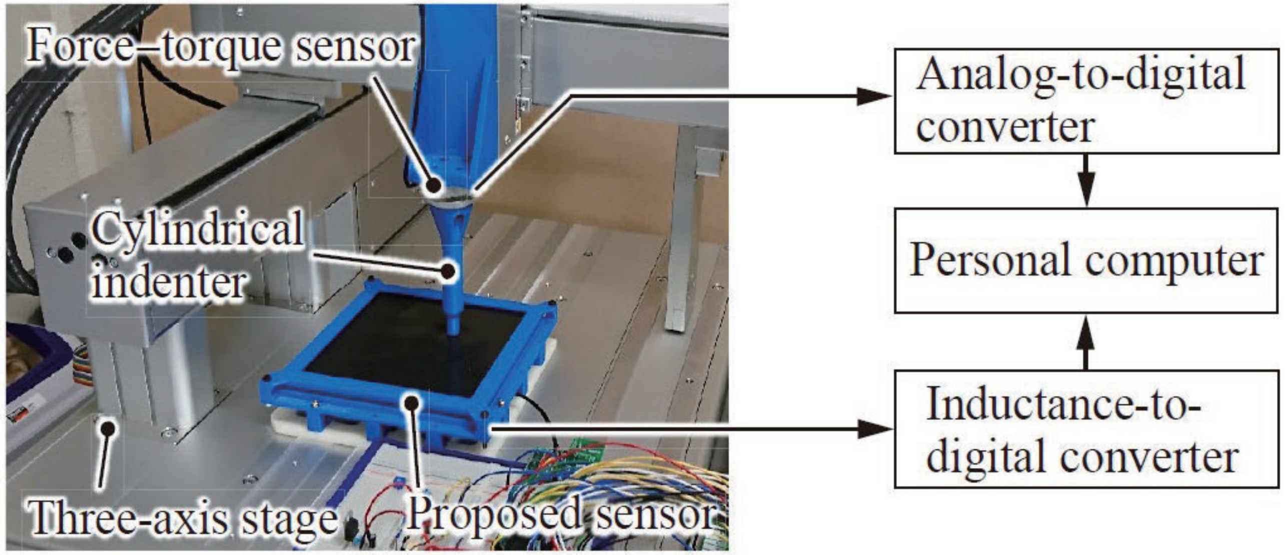
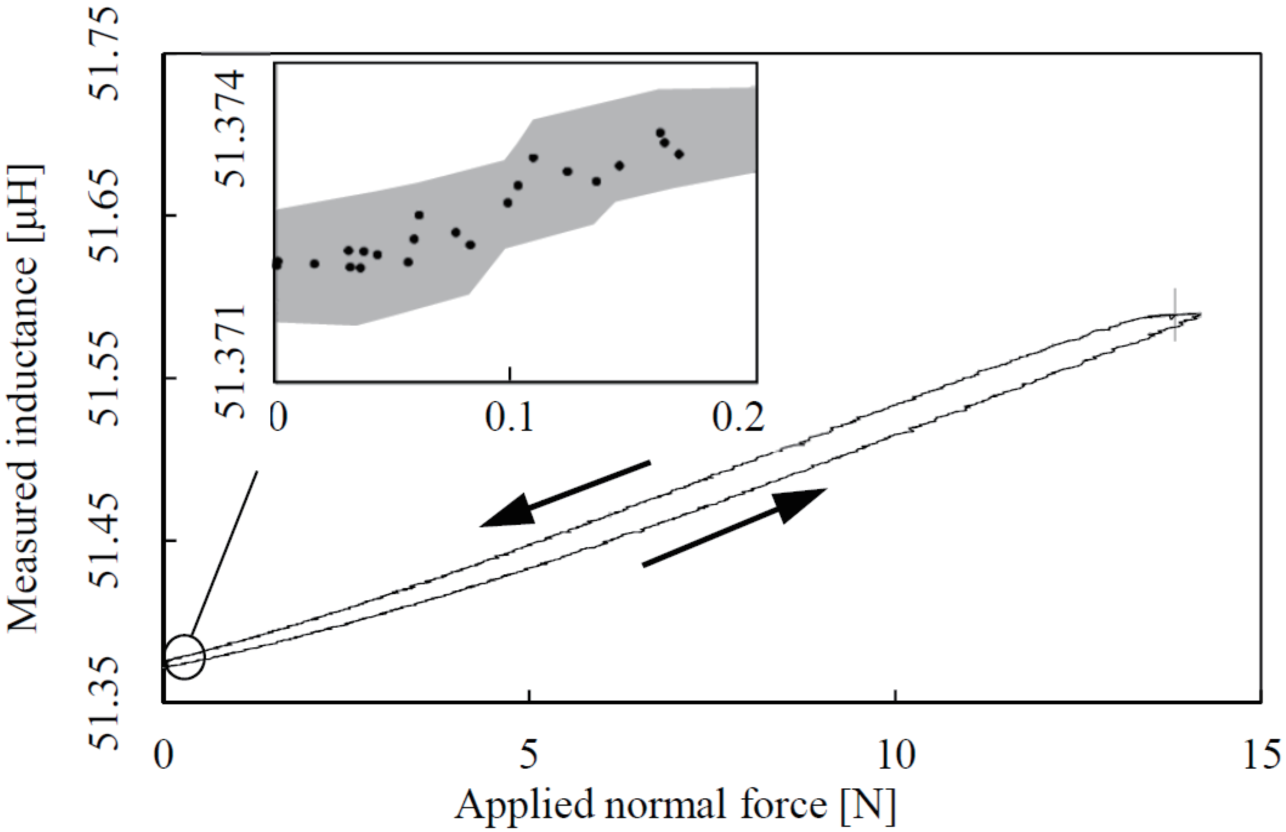


Fig. 1. Appearance of the proposed sensor and its cross-sectional schematic. An inductor is printed on a circuit board while magnetorheological and nonmagnetic base elastomers cover the board.



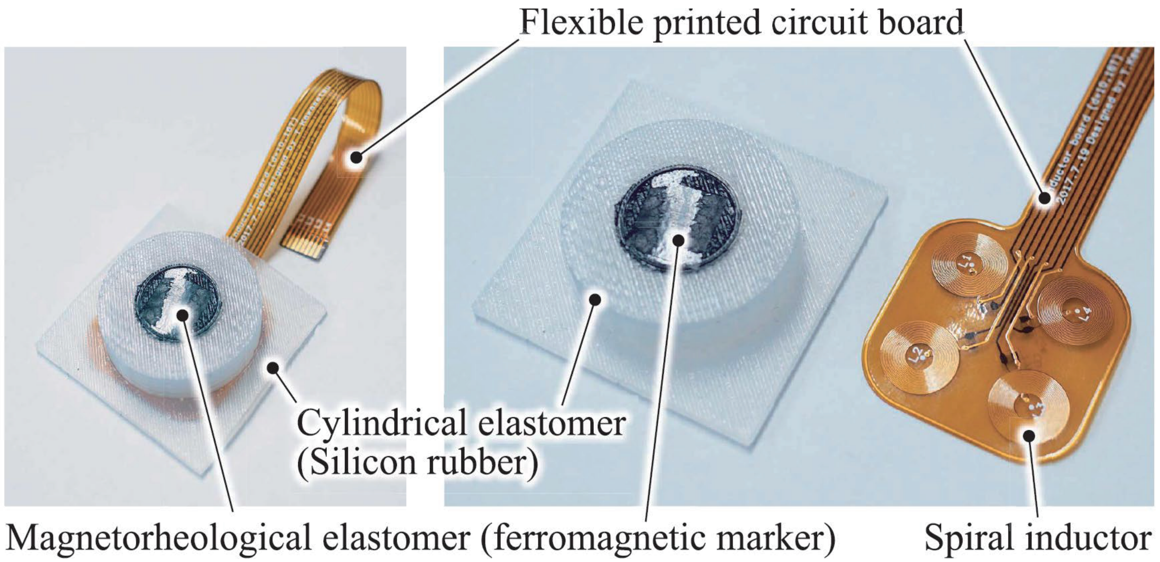
Measure displacement of the magnetic elastomer from inductance

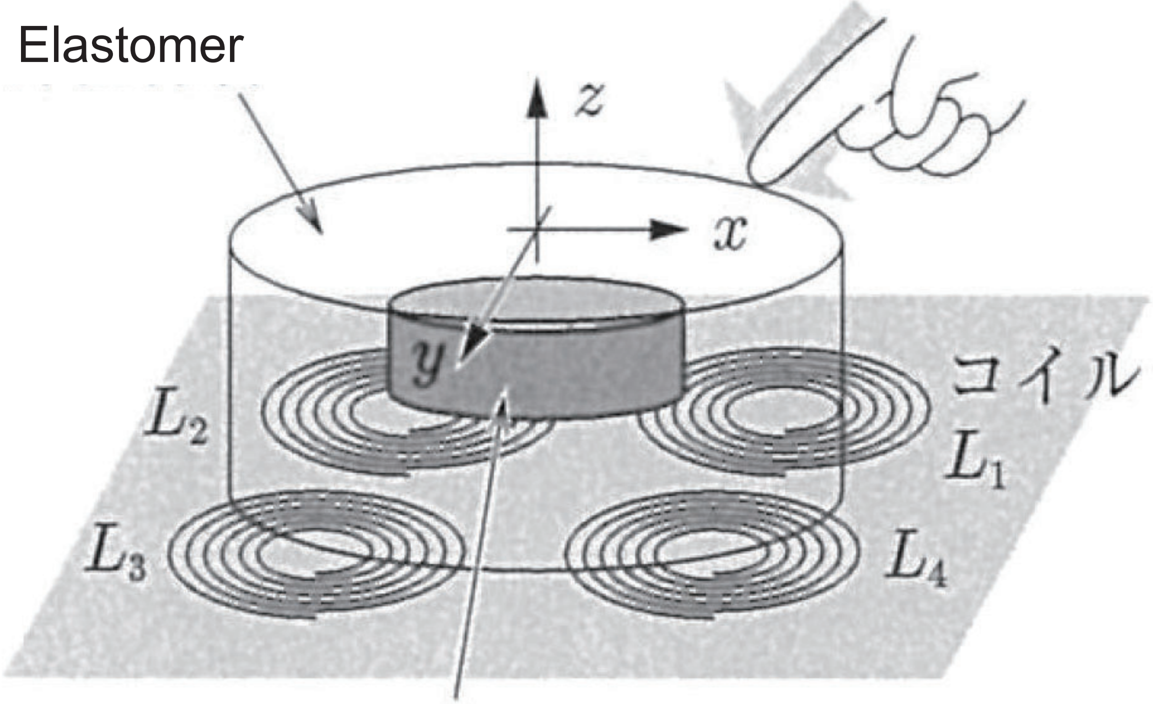


T. Kawasetsu et al., In Proc. of IEEE Sensors (2017)

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.





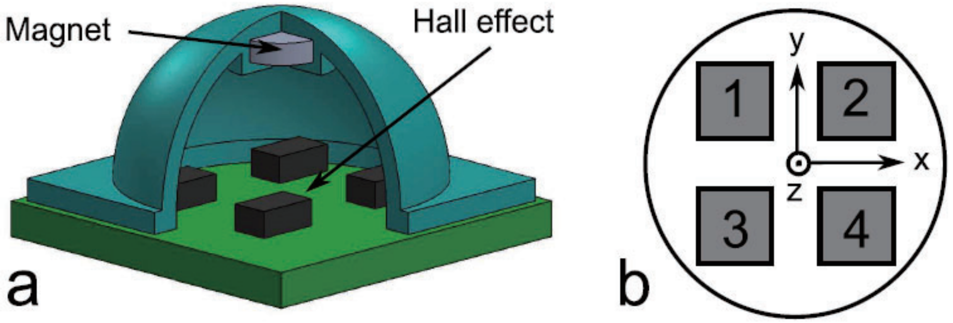
Magnetic marker moves three dimensionally

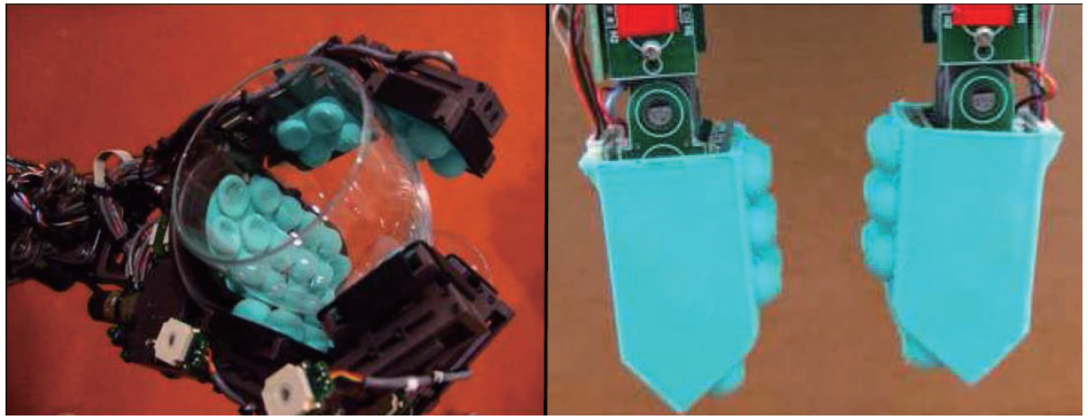
Inductance

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

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

Contact Behavior of Soft Spherical Tactile Sensors





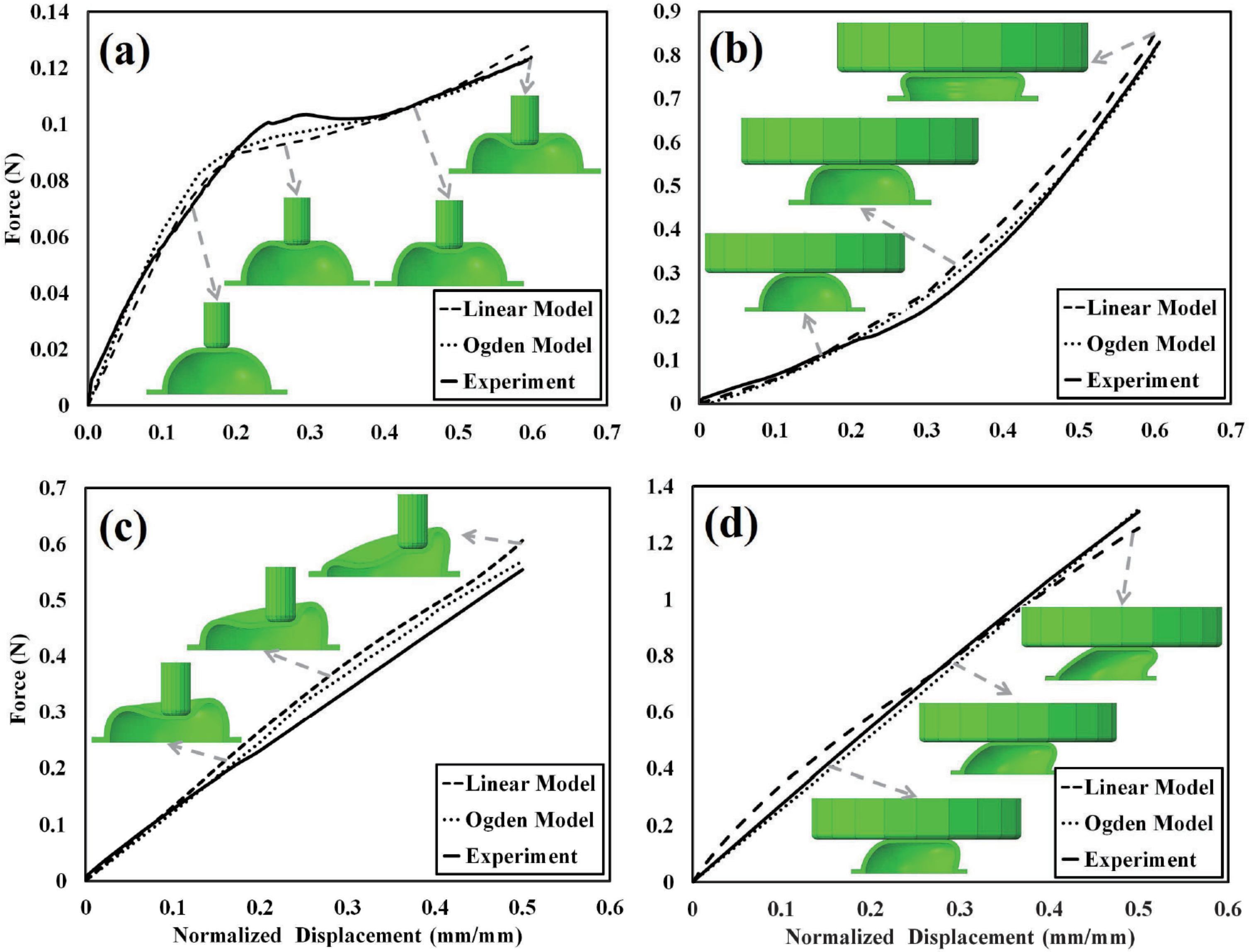


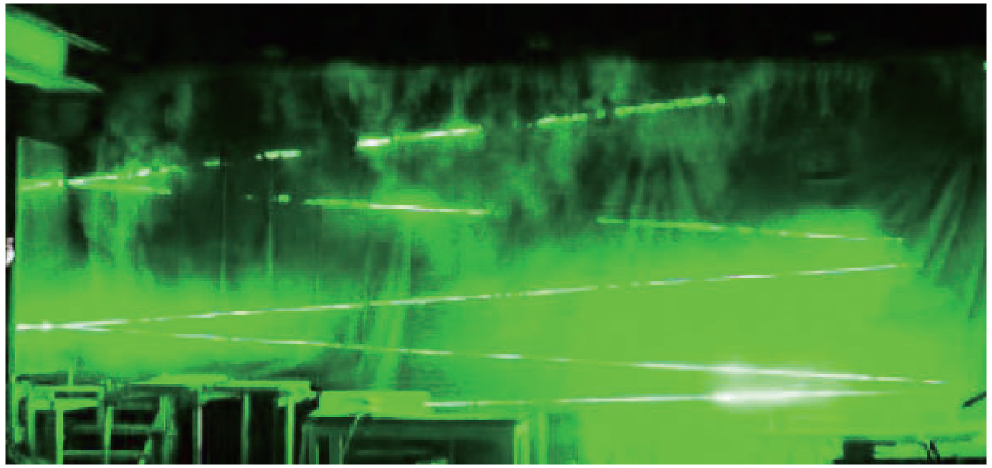
Fig. 6. Comparison of the experimental data and simulation results. The horizontal axes are normalized by the radius of the spherical shell. (a) Normal load applied by the small cylinder. (b) Normal load applied by the flat plate. (c) Shear load applied by the small cylinder. (d) Shear load applied by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

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

Optical sensor

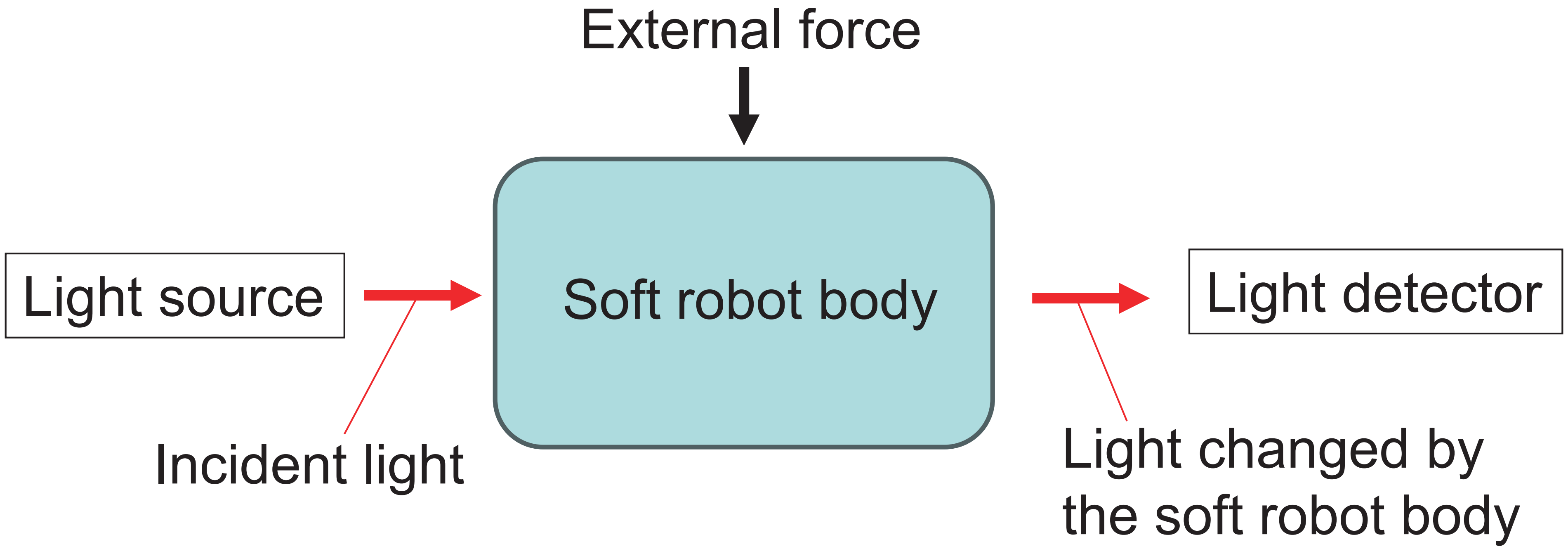
Nature of light

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



Etoh et al., Sensors, 2019

General structure of optical sensors



External force

Light source

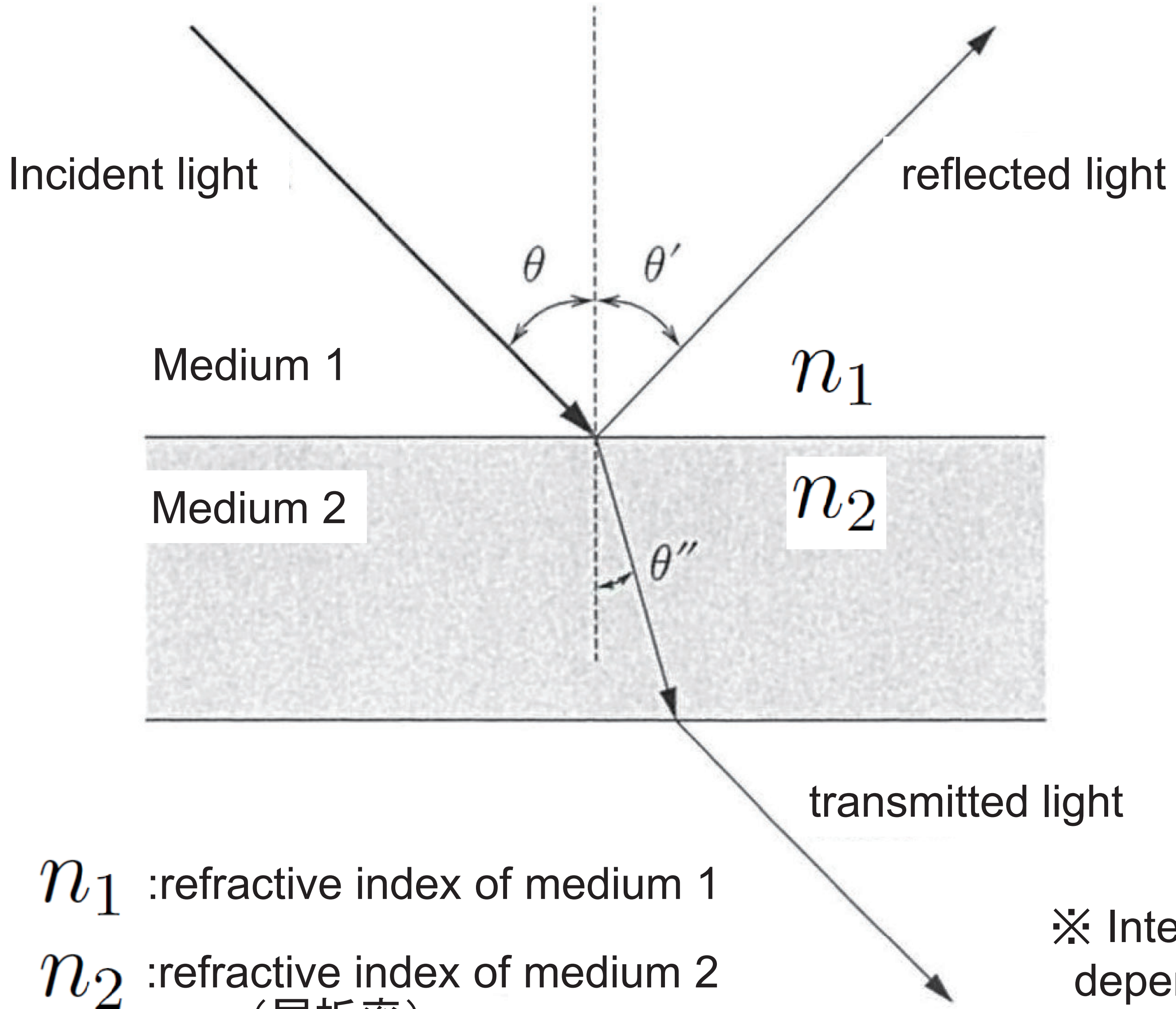
Soft robot body

Light detector

Incident light

Light changed by
the soft robot body

Optical sensor - Interaction of light and objects



n_1 :refractive index of medium 1

n_2 :refractive index of medium 2
（屈折率）

Reflection（反射）

- Specular reflection（正反射）

$$\theta = \theta'$$

- Diffuse reflection（乱反射）

Transmission（透過）

- Direct transmission（直接透過）

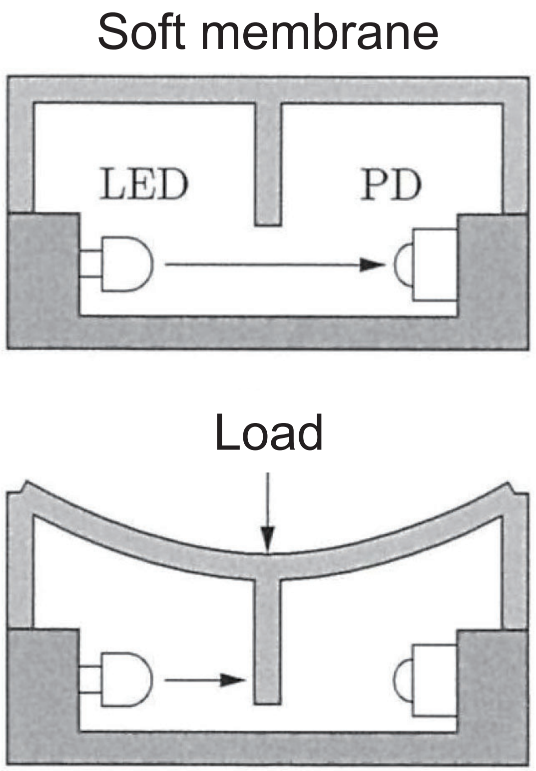
$$n_1 \sin\theta = n_2 \sin\theta''$$

（Snell’s law）

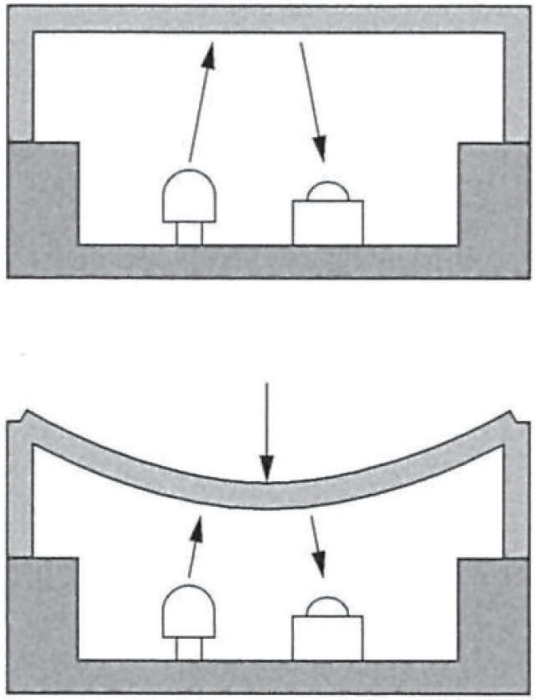
- Diffuse transmission（散乱透過）

※ Intensity of reflected light and transmitted light depend on **reflectance**（反射率）and **transmittance**（透過率）, respectively.

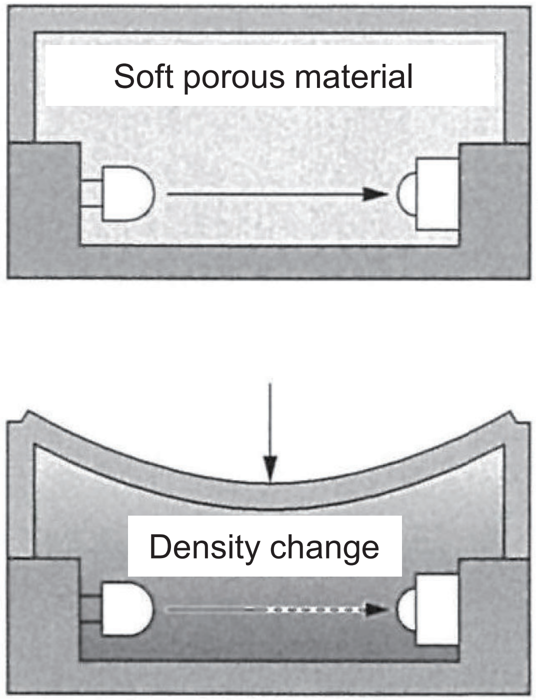
Optical sensor - Typical configurations



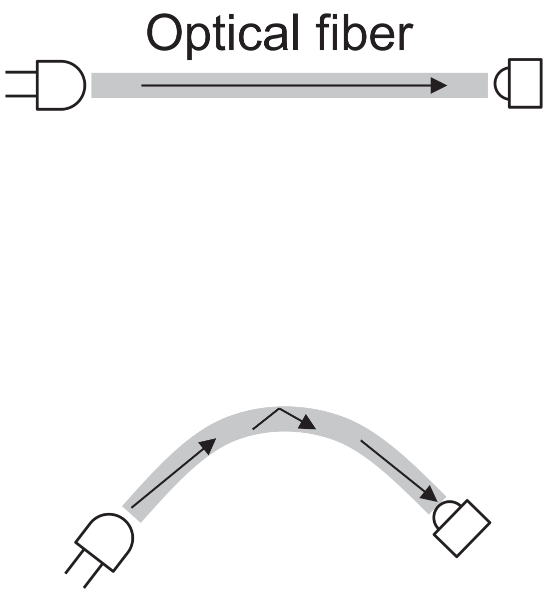
(a) Blocking the light



(b) Change of the reflected light

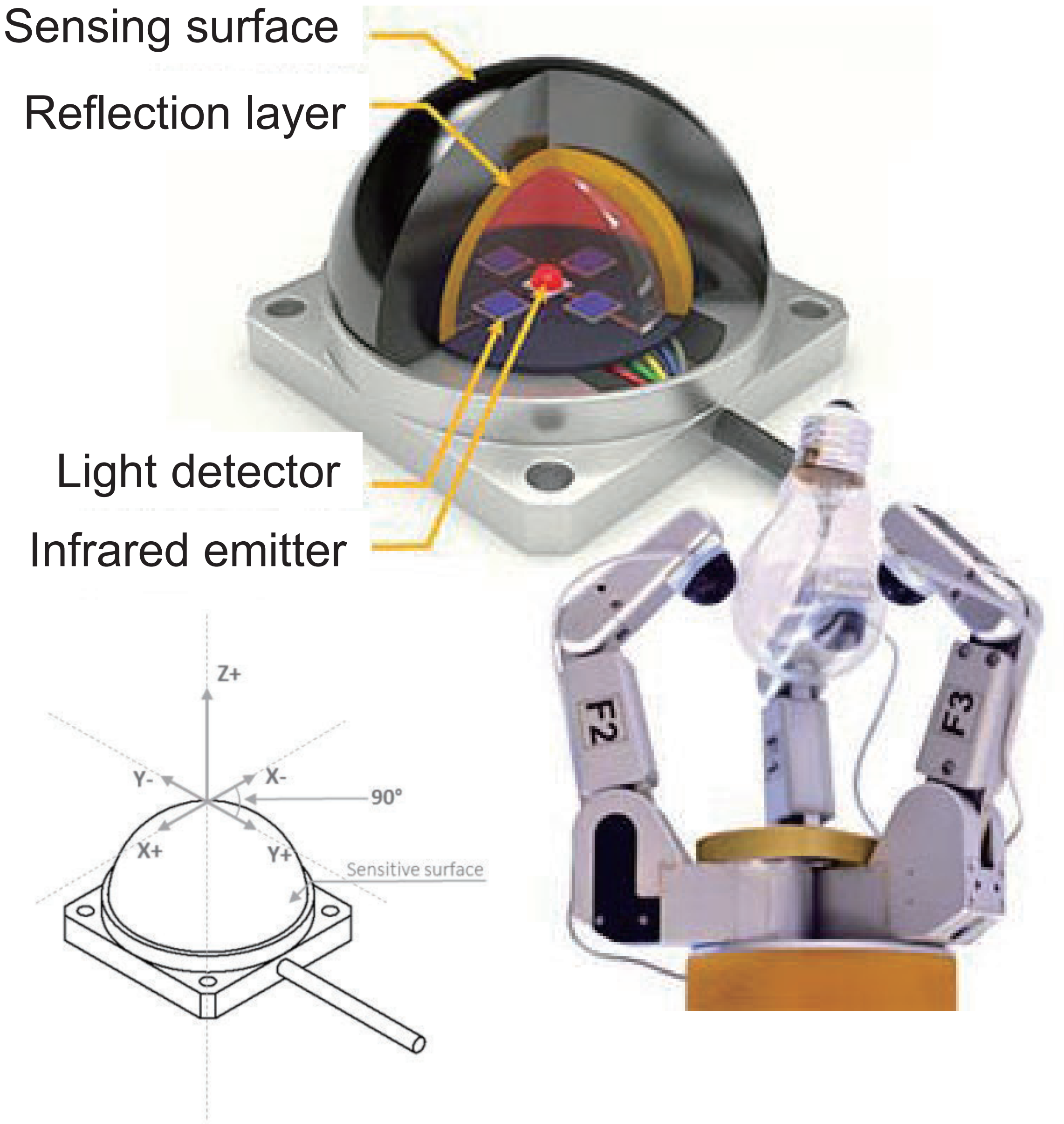


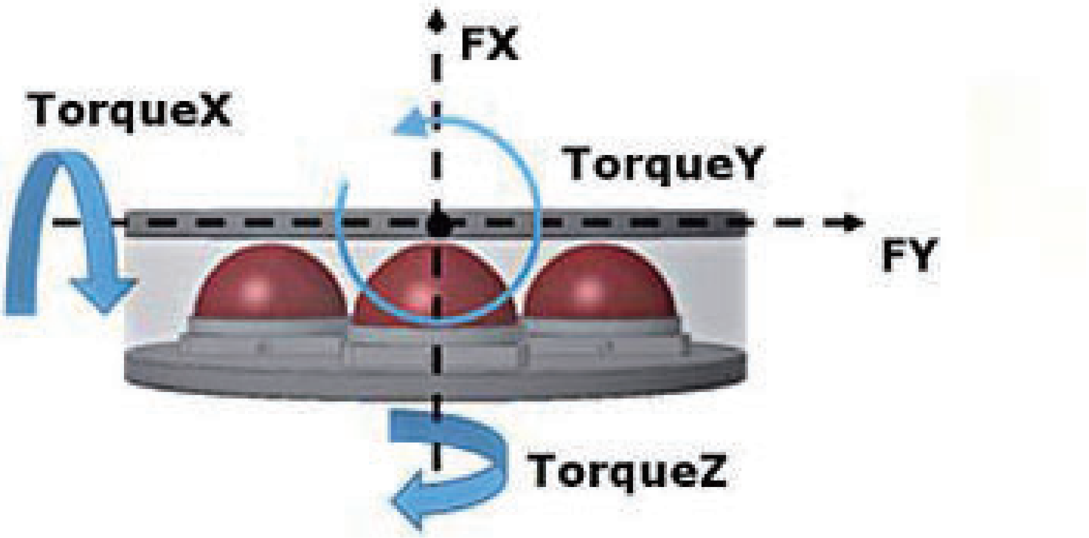
(c) Change of the transmitted light



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

OptoForce (marged with OnRobot in 2018)



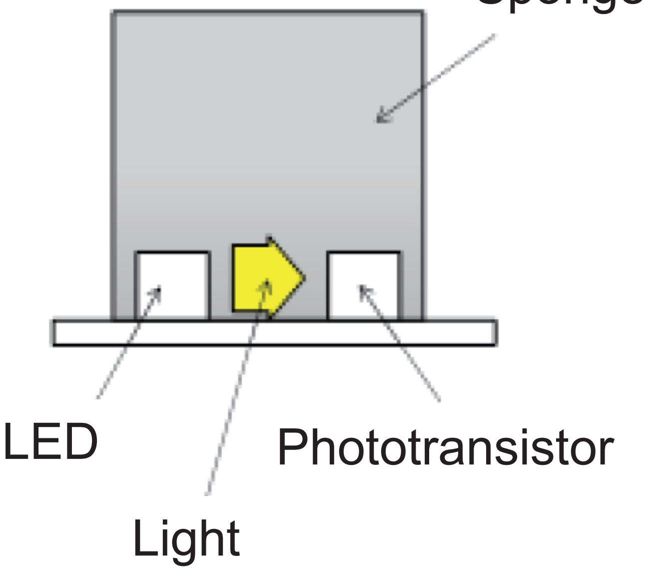


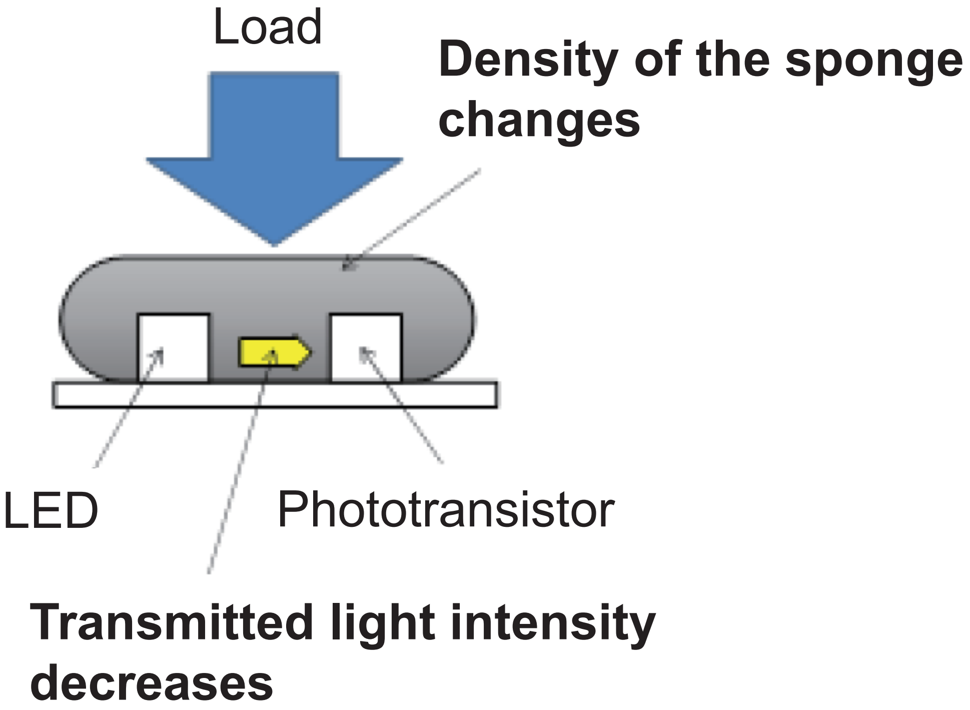
6-axis force/torque sensor

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

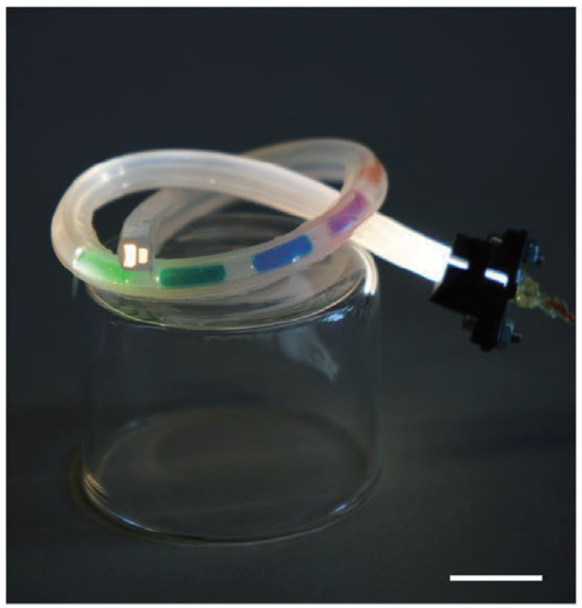




タッチエンス株式会社 http://touchence.jp/

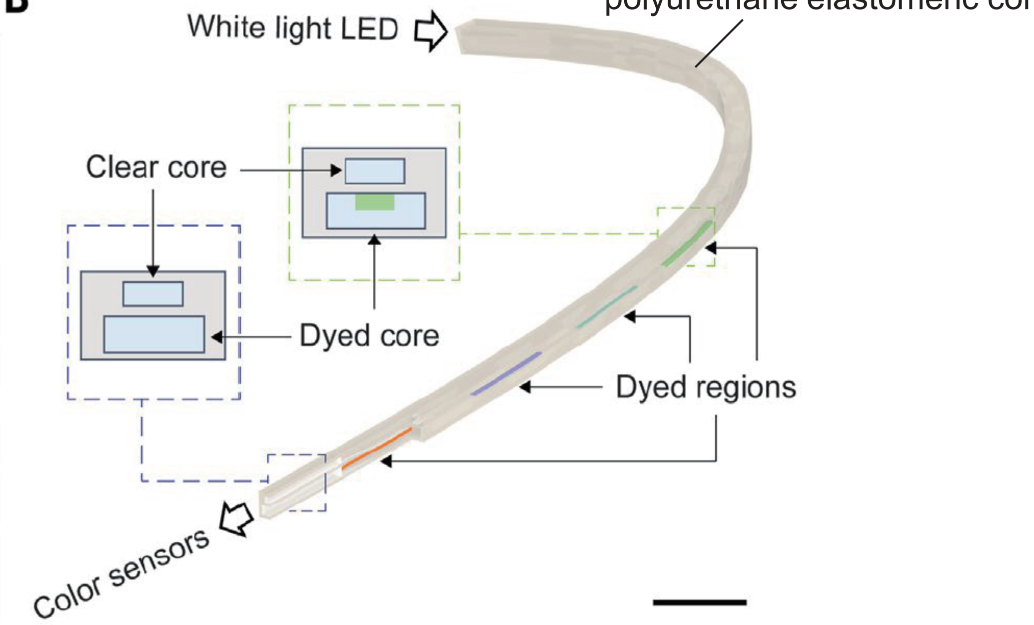
Stretchable distributed fiber-optic sensors

A



B

lightguide consisting of two polyurethane elastomeric cores



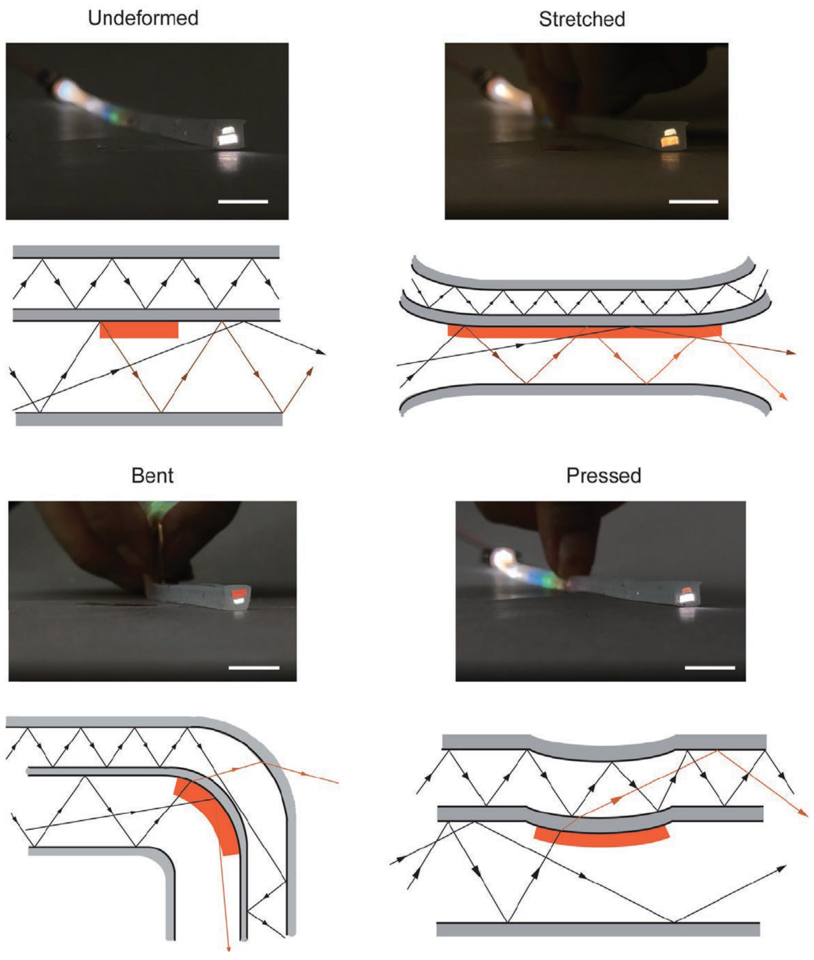
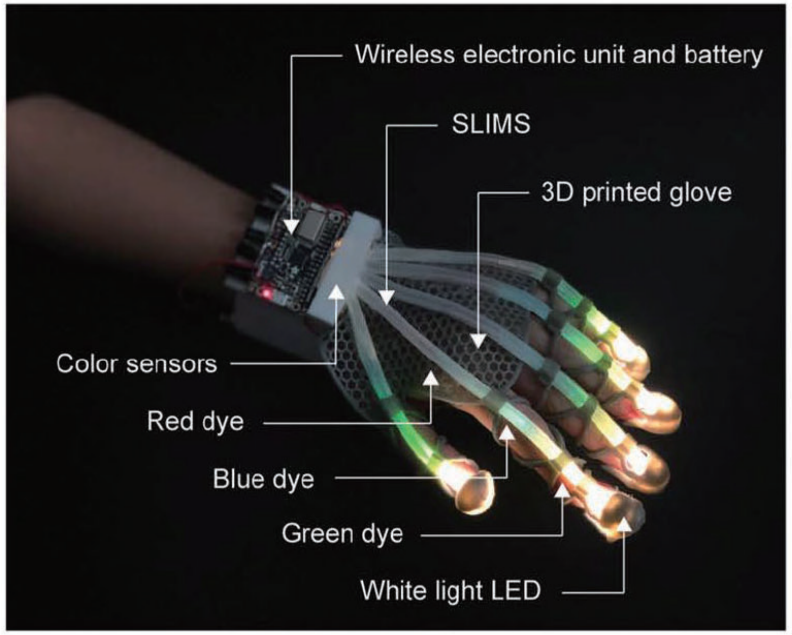
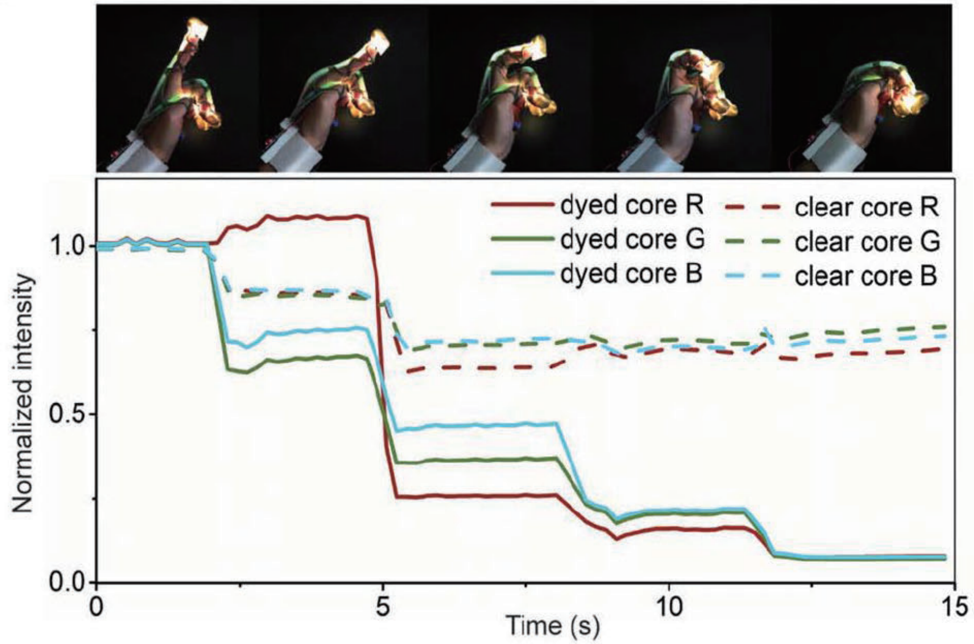


Fig. 1. SLIMS. (**A**) Image of a SLIMS tied into a knot. (**B**) Schematic of the SLIMS showing the discrete dyed regions, the design of the collateral cores, and its coupling to a light source and color sensors. (**C**) Optical outputs and ray diagrams of SLIMS when it is undeformed, stretched, bent,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

A



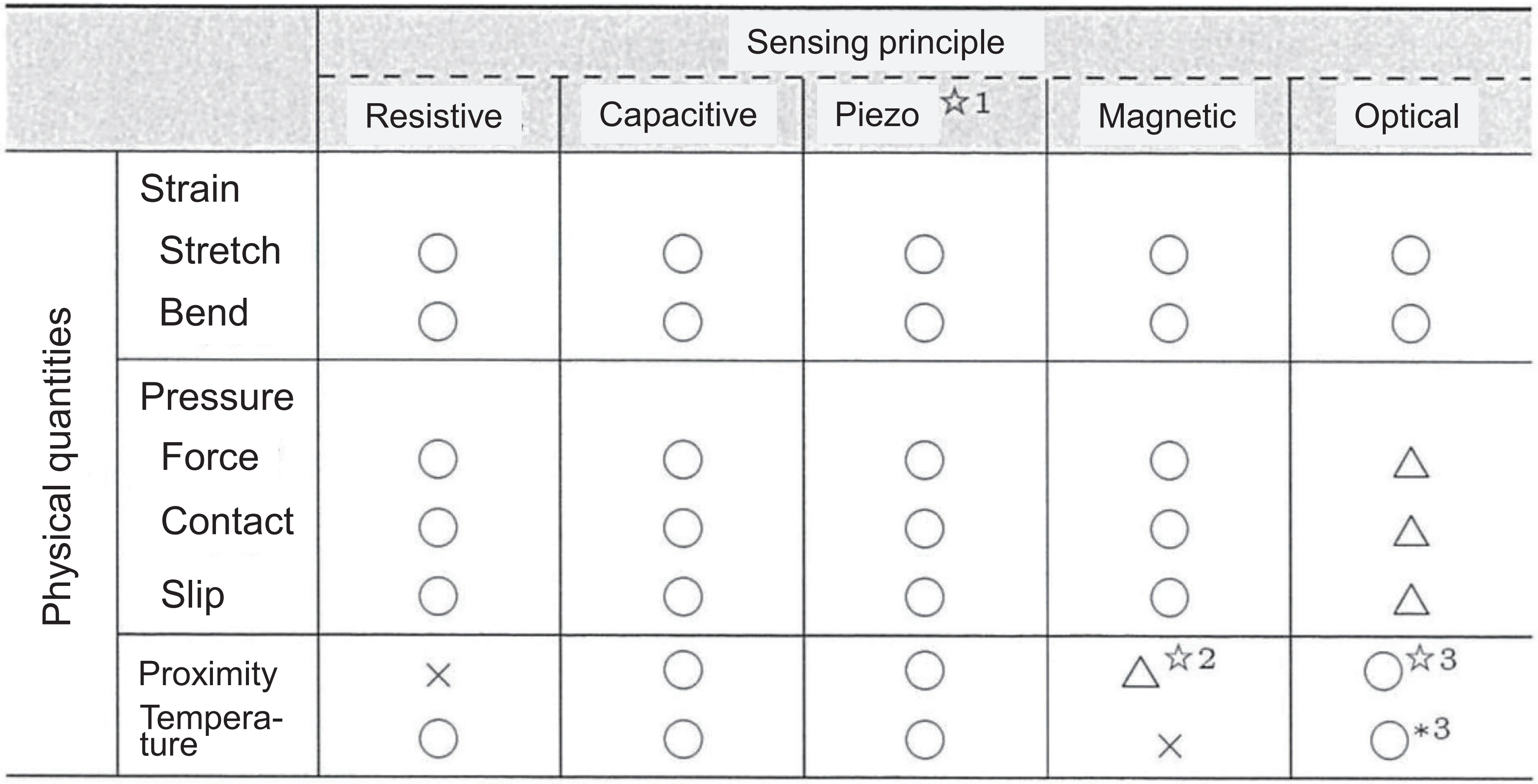
B



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 distance sensing such as ToF sensor and 3D camera ∗3 : Need infrared (thermal) sensing