Opportunities of Strain Sensing in Smart Applications of Tactile Cyber-Physical Systems

(or What a System Developer Should Understand in Physics of Strain Gauges)

Keynote (online)

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Project: *Bionic methods of sensorics and ambient intelligence for Internet-based monitoring systems of human resilience in the conditions of Northern Territories*

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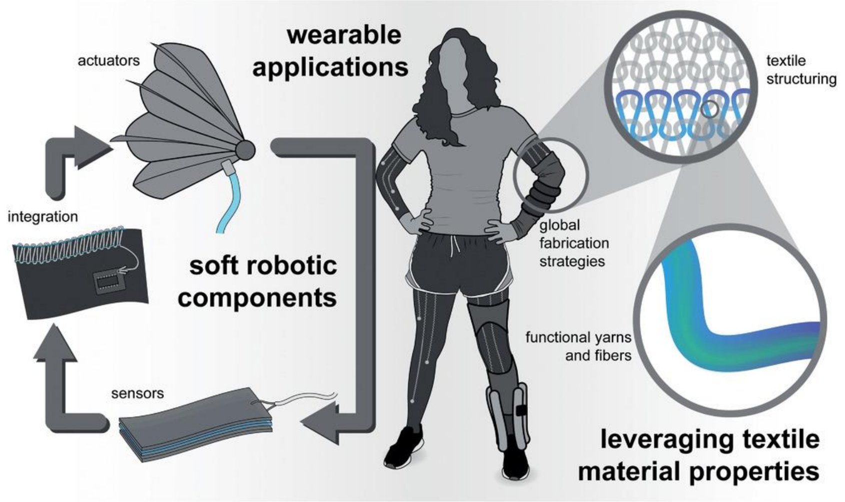
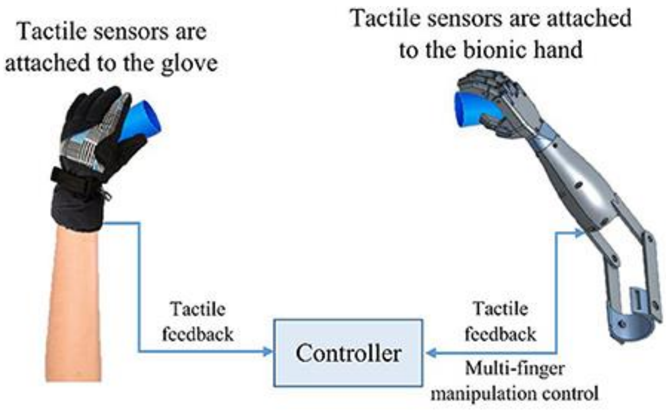
https://rscf.ru/en/project/22-11-20040/

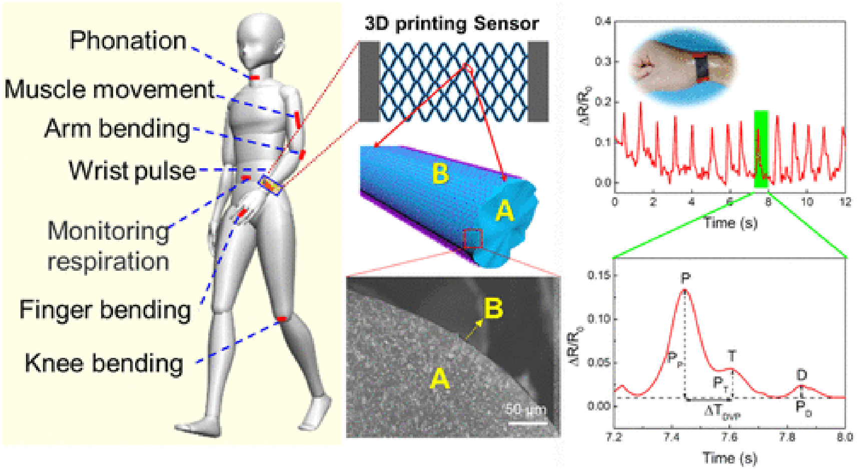
Studied Problem: Generic

Smart sensorics for IoT-enabled mobile systems

- Bionic suit, smart textile, gadgets:
  - extending human sensorics
- Interactive environments:
  - human-machine
  - human-human
- Edge computing on small devices
  - Wearable
  - Carriable
  - Surrounding
- Robotics
  - Mobile activity
  - Autonomous movement
  - Robot-manipulator

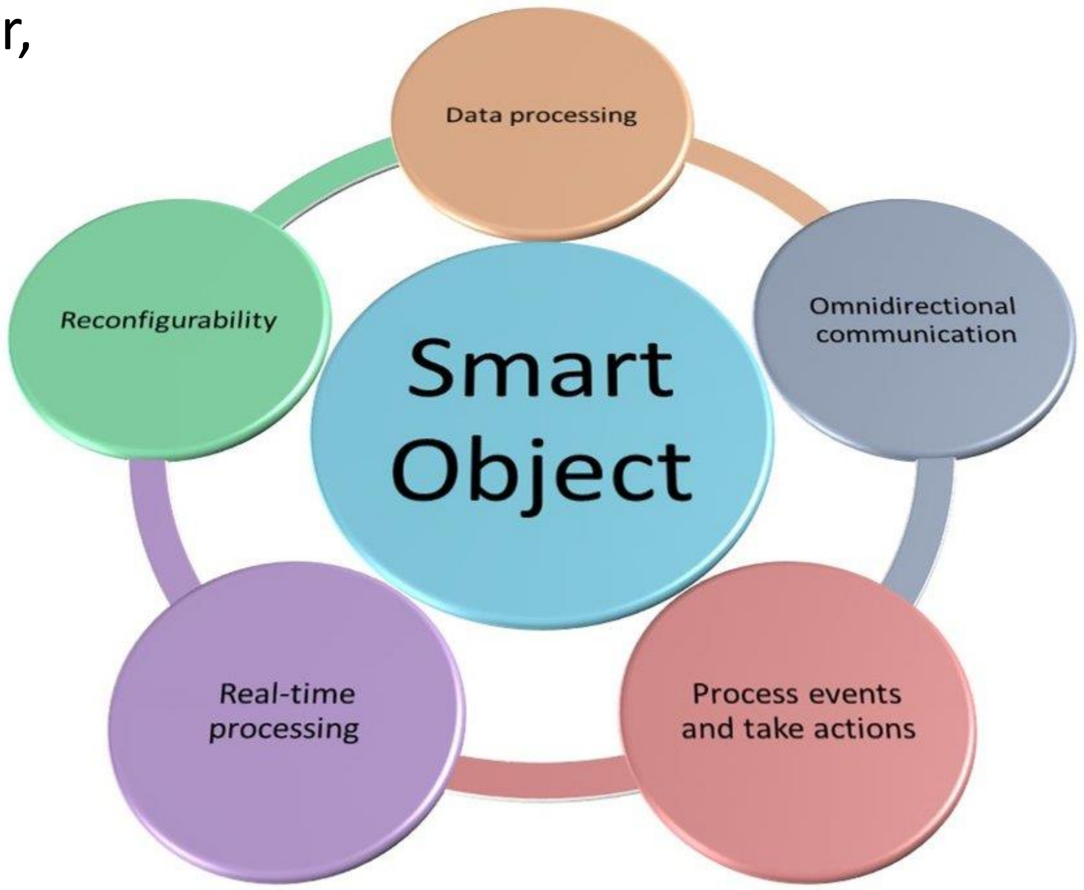






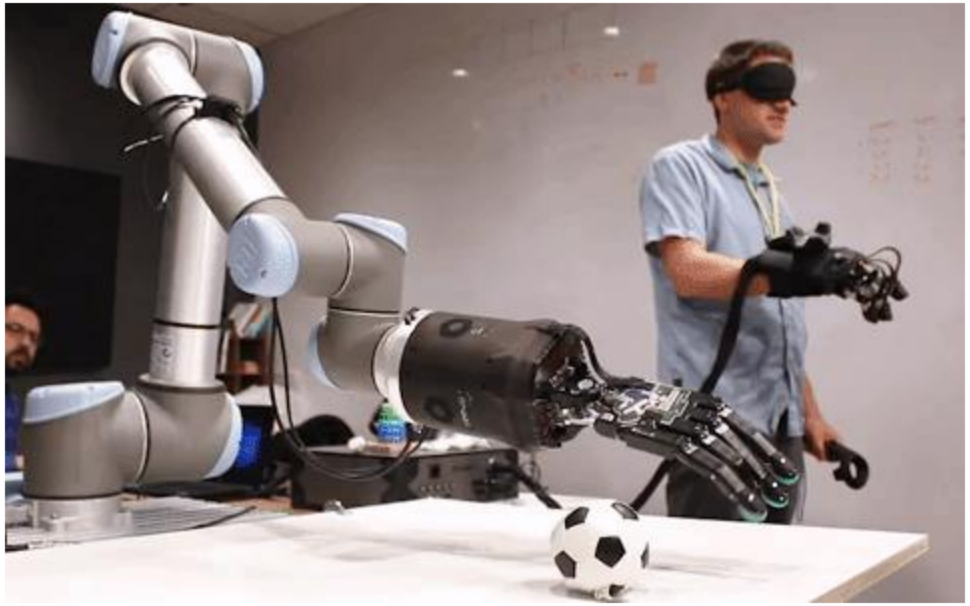
Smart Internet-Enabled Systems

- Monitoring
  - Remote objects to observe the state, behavior, and surrounding situation
- Internet of Things (IoT)
  - Objects become “smart”
  - Edge computing
- Sensorics
  - Embedded to the object
  - Tightly connected with the object under monitoring (virtual)
- The smart property
  - Data mining and decisions by an object itself
  - Cooperation of many objects
  - Smart space model for service construction



Tactile Cyber-Physical Systems (TCPS)

- Key property to realize:
  - Teleoperation with remote objects
  - In real-time, through Internet
  - Smart object can provide its data to human senses for analysis
- Tactile:
  - (Virtual) touching a remote object under monitoring
- Internet of Things (IoT)
- Industrial IoT (IIoT)



Example:

- Haptic glove lets human control robotic hand, feel what robot feels.

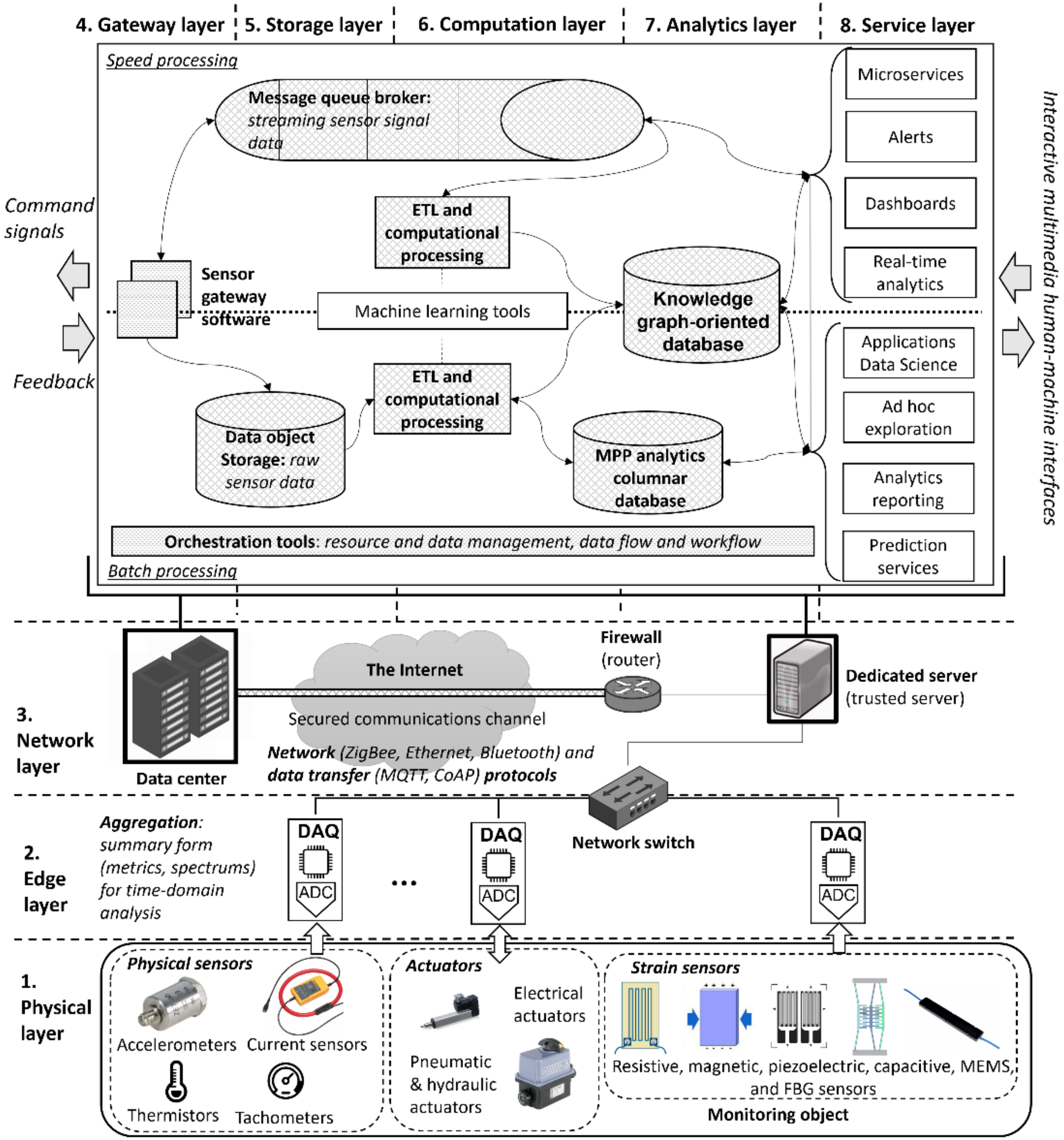
From: *HaptX and partners build first robotic hand to transmit touch across the Atlantic,* https://haptx.com/telerobots/

Sensorics in TCPS: Requirements

- Digitalization of the primary results of measurements.
- Use of a large number of sensors and sensor nodes for monitoring the state of one object, and processing of the data obtained simultaneously from a great number of sensors.
- Correction for noninformative factors (e.g., the influence of temperature on strain sensors).
- Identification of failures of nodes or communication lines and built-in fault-tolerance capability.
- The sensors used for monitoring are by themselves smart and able to function as nodes of IIoT.
- Wireless connection of the components of the system.
- The ability of the components of the system to communicate with each other in real-time mode.
- High-level characterization of the state of the object under monitoring (e.g., normal or dangerous).
- Identification of abnormal behavior of the object and making decisions on this base.
- The use of the machine learning methods for classification of the states of the object under monitoring.
- Flexibility of the system, i.e., possibility to re-configure it when necessary.

Multi-layer TCPS Architecture

- For near real-time intelligent analysis of sensor data
- Digitalization of manufacturing industry
- Integrating physical and information processes to make decisions
- Digital shadow (the basic component of Digital Twin)



Smart Applications

Where strain gauges are useful

- Human-machine interactive environments
  - Tactile interaction
  - Bionic suite and smart textile
- Mobile robotics
  - Autonomous movement
  - Manipulation
- Production machinery
  - Technical state
  - Utilization conditions
  - Diagnostics and prognostics

Application	Role of strain gauges
1. Remote manipulation of real or virtual objects in inaccessible and dangerous conditions	Tracking movement and position of human body parts by flexible strain sensors
2. Monitoring the state of transport vehicles, ship hulls and airframes, wind turbines, railway lines, dams, oil drilling platforms, structural components of bridges and buildings	Detection of early structural damage based on the analysis of strain measurements; data source in wireless telemetry system; measurement of mechanical resonance frequencies of structures
3. Design and exploitation of aerospace and aircraft technologies	Comparison of deformations arising under the action of various forces with the results of CAD (Computer Aided Design) and FEA (Finite Element Analysis) simulations; monitoring the actual stresses in mechanical parts during flight to ensure that it is safe
4. The control of deformations of parts during processing to adjust the pressing forces by robotic metalworking equipment	Strain measuring of the part during machine processing by the pressure of the cutter (e.g., during drilling)
5. Measurement of the torque applied by a motor, turbine, etc. to generators, wheels, etc. for optimization of the regime of the equipment	The torque is calculated from the measured strain and the rotational speed on a shaft
6. Manufacturing of weight and pressure measuring devices for the creation of robotic systems for industrial production	Strain sensors are the basic (sensing) elements of load cells

Strain Sensing

- The elementary types of strains are linear tensile and compressive strains
- Can be expressed in terms of absolute and relative elongation

$$\Delta l = l - l_0 \text{ [m]},\ \ \varepsilon = \frac{\Delta l}{l_0}\ [\frac{\text{m}}{\text{m}}]$$

where Δl is absolute elongation, l_0 and l are original and resulting length, respectively.

- When a compressive strain is applied, both values are negative

- The unit for strain ε is “m/m” in the SI (Système International), i.e., “one”.
- In practice, it is called “strain” and designated as ε.
- Since the changes of length are usually very small, the standard fractional prefix is used.
- Micrometer per meter (μm/m = 10^6 m/m = ppm) and με (microstrain) are generally used in the symbol notation.
- The tensile and compressive strain correspond to normal stresses which are perpendicular to the surface and given by the ratio of applied force F and the cross-sectional area A:

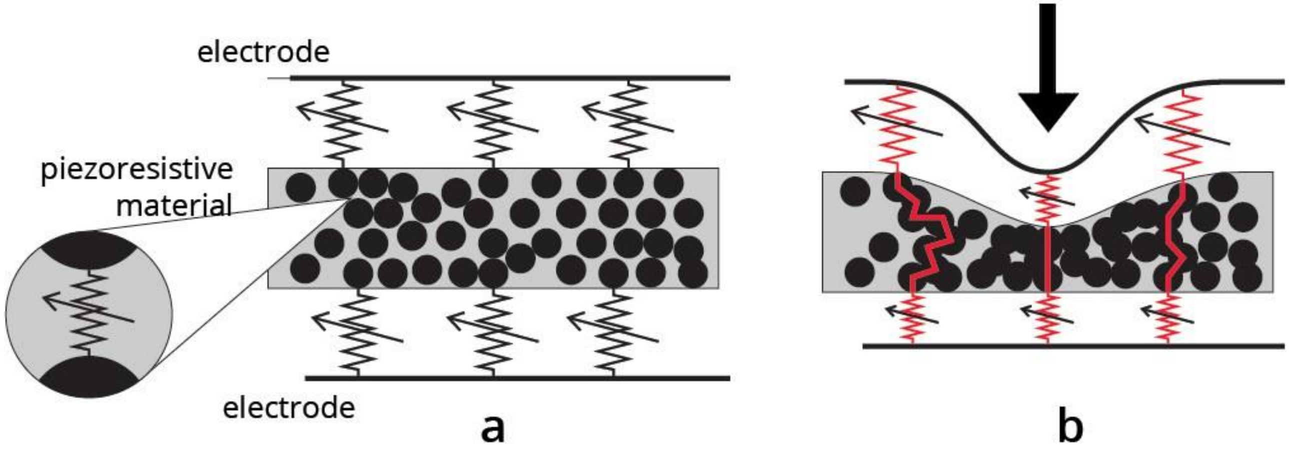
$$\sigma = \frac{F}{A}\ \text{[Pa]}$$

Considered Types of Strain Sensors

1. Resistive and Piezoelectric Sensors
2. Capacitive Sensors
3. Sensors Based on Magnetic Phenomena
4. Micro-ElectroMechanical Systems (MEMS)
5. Fiber-Optic Sensors

1. Resistive and Piezoelectric Sensors

- Piezoresistivity (Piezo: from Ancient Greek πιέζω, “to press”)
- Output signals:
  electric resistance or voltage
- Simple for signal processing



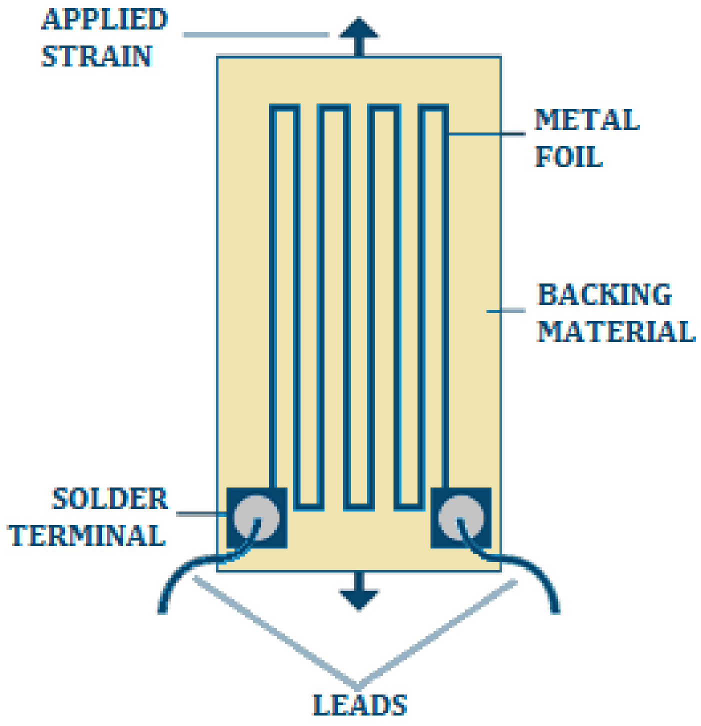
https://fab.cba.mit.edu/classes/865.21/topics/metrology/03_sensors.html

Stress: the internal pressure occurs when a force is applied on material.
- Due to the internal pressure, the shape has deformation.
- Stress is given as change in force per unit area.

Strain: occurs due to stress.
- Due to the stress applied, the material will be elongated or compressed.
- Strain is ratio of change in length due to force to the original length of the material.

Strain Gauge (Metallic)

- Resistive sensing element is realized as: meander-like folded metal wire, strip of foil, or semiconductor film.
- Stretching the strip causes a change in its resistance
- Foil strain gauges are more common than wire-based ones.



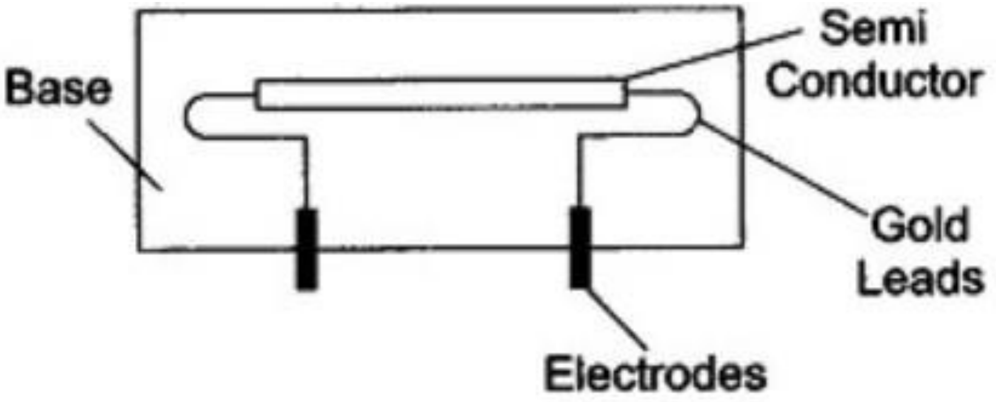
- Typical strain gauge uses metal foil adhesively glued to the part under testing.
- Values of the relative elongation for such strain gauges are of the order of 10^{-3}. Loads for typical sizes are of the order of tens of Newtons.
- Let the wire or fragment of foil have a cross-sectional area A, length l_0 and resistivity ϱ. Let the load cause its elongation. Then its resistance and its relative change can be estimated

$$R_0 = \varrho l_0 / A \,, \; \frac{\Delta R}{R_0} = K_f \cdot \frac{\Delta l}{l_0}$$

- The K_f coefficient is commonly called gauge factor (GF) or “strain sensitivity”; the larger it is, the greater is the relative change in resistance at some given strain.

Semiconductor Strain Gauge

- Silicon or germanium is used.
- Nominal resistance values convenient for operation for smaller sizes than for metal ones
- Sensitivity is tens of times higher than for metal ones.
- Dependence of their resistance on strain is nonlinear
- Dependence of the signal on temperature is much stronger than that for the metallic ones. Compensation for this dependence is difficult.



Semiconductor Strain Gauge

Parameter	Metal strain gauge	Semiconductor strain gauge
Measurement range, με	0.1..40000	0.001..3000
GF	2.0..4.5	50..200
Resistance, Ω	60..10000	1000..5000
Resistor tolerance, %	0.1..0.2	1..2
Size, mm	0.4..150 (standard 3..6)	1..5

Opportunities

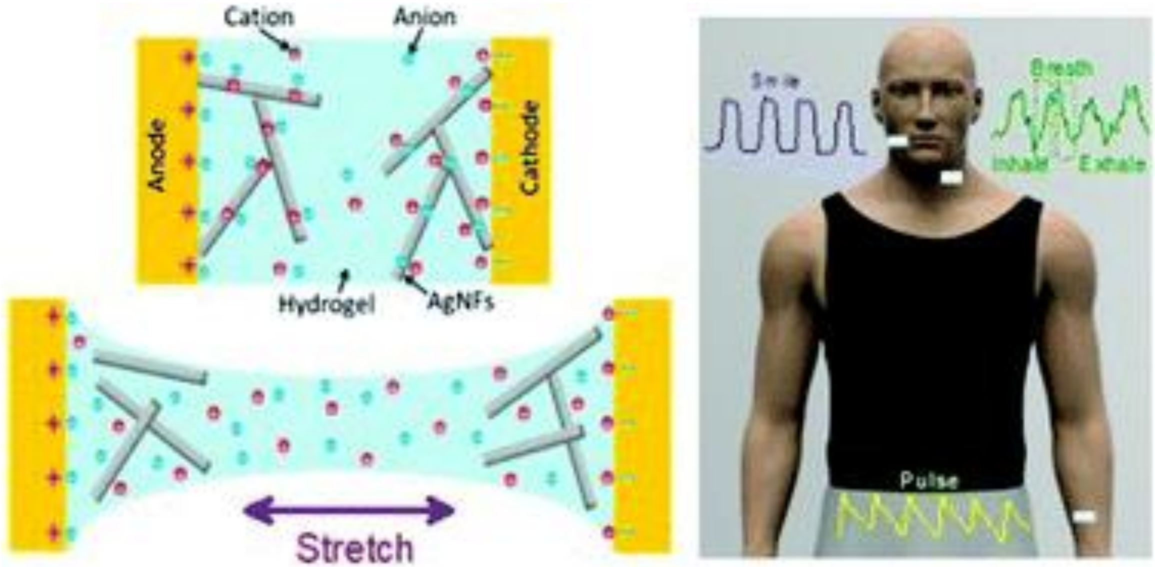
- **Conventional resistive metallic strain gauges** are relatively cheap and easy to use, and suitable for measurement strains up to 10^{-3}.
- Workhorses for typical applications, but not for high-strain areas like wearable electronics.
- Disadvantages are the influence of external conditions like temperature and humidity on GF, the need for special protection measures in a high-temperature or aggressive environment, minor changes in the resistance of the sensing elements.
- The latter requires using low noise instrumental amplification circuits, which are available on the market.

- **Semiconductor gauges** are stronger influenced by the external conditions, first by temperature, and can be generally used in a narrow temperature range or require the usage of temperature signal compensation.
- One more disadvantage is the monocrystal structure of most materials, which makes manufacturing more complicated.
- At the same time, the semiconductor technology allows one to develop a single-chip IC which integrates the transducer itself, processing and compensating circuits, etc.
- Strain limits are not high, also.

- **Piezoelectric sensors** can sense moderate strains up to 10^{-3}, also.
- But they convert strain directly to voltage and don’t require an external power supply.
- They can be manufactured of small dimensions, various shapes and, thus, integrated into a high-density device or IC chip.
- The main disadvantage is the impossibility to sense static strain due to small generated electrical charge and leakages, but the response to high frequencies is much better than that for the resistive.
- Due to the small charge, the output signal is relatively low, and an amplification circuit is often required.
- The piezoelectric sensors are strongly affected by the external conditions, also – temperature and humidity, firstly.

2. Capacitive Sensors

- Change of capacitance when stretching the capacitor plates or changing the inter-plate distance, with direct measurement of capacitance.
- Low power consumption (compared with resistive sensors)
- For flexible material:
  - wearable devices, "electronic skin", etc.
  - errors due to internal friction at low deformations, and cracking of elements, slippage in contacts, etc. at high deformations
- More complicated signal processing



An ultra-stretchable, highly sensitive and biocompatible capacitive strain sensor from an ionic nanocomposite for on-skin monitoring, https://pubs.rsc.org/en/content/articlelanding/2019/nr/c8nr08589g

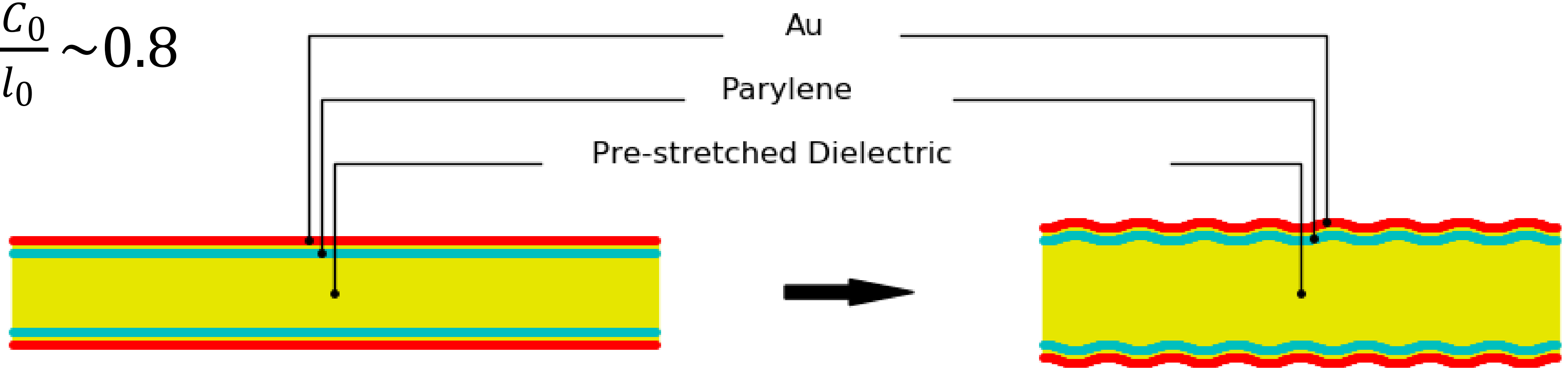
Capacitive sensors of mechanical strain, https://iopscience.iop.org/article/10.1088/1757-899X/1155/1/012097

Elastomers

- Working easily with great strains
- E.g., given sensitive area l_0 =70 mm and initial capacity of $C_0 \approx 450$ pF,
- stretching up to 80% and elongation sensitivity of ~5 pF/mm,

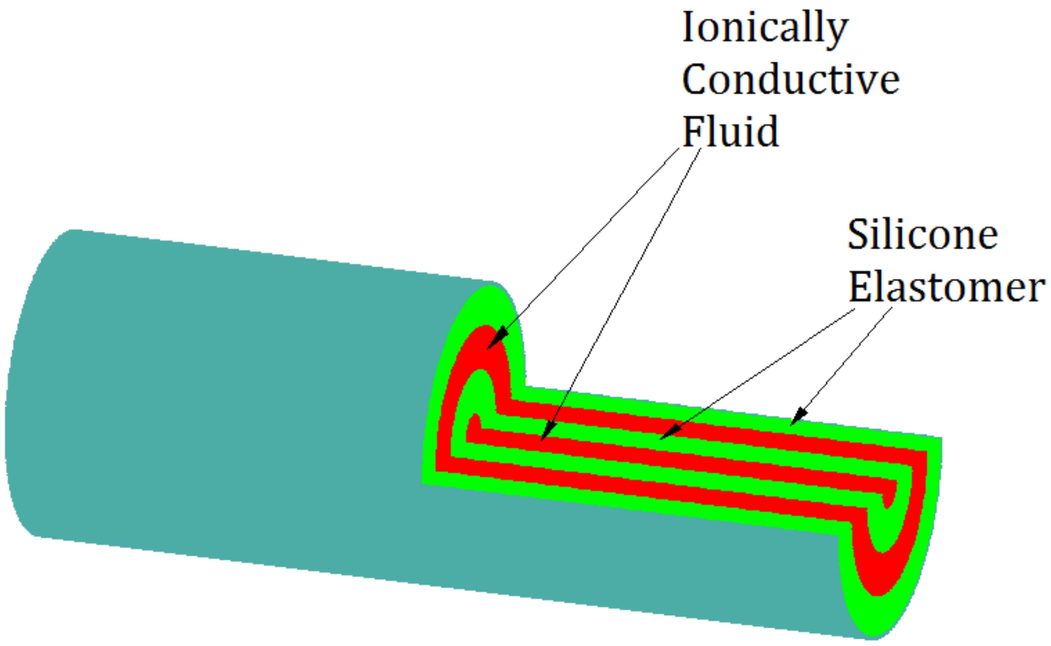
  so that $GF = \frac{\Delta C/C_0}{\Delta l/l_0} \sim 0.8$

- Increasing the gauge factor beyond its limit for flat electrodes
  - Gauge factor reaches 3 at the maximum value of the applied strain of $\frac{\Delta l}{l_0}$ =140%.
  - Sensor shows high linearity (R^2 = 0.98) and minimal hysteresis



Conducting Liquid

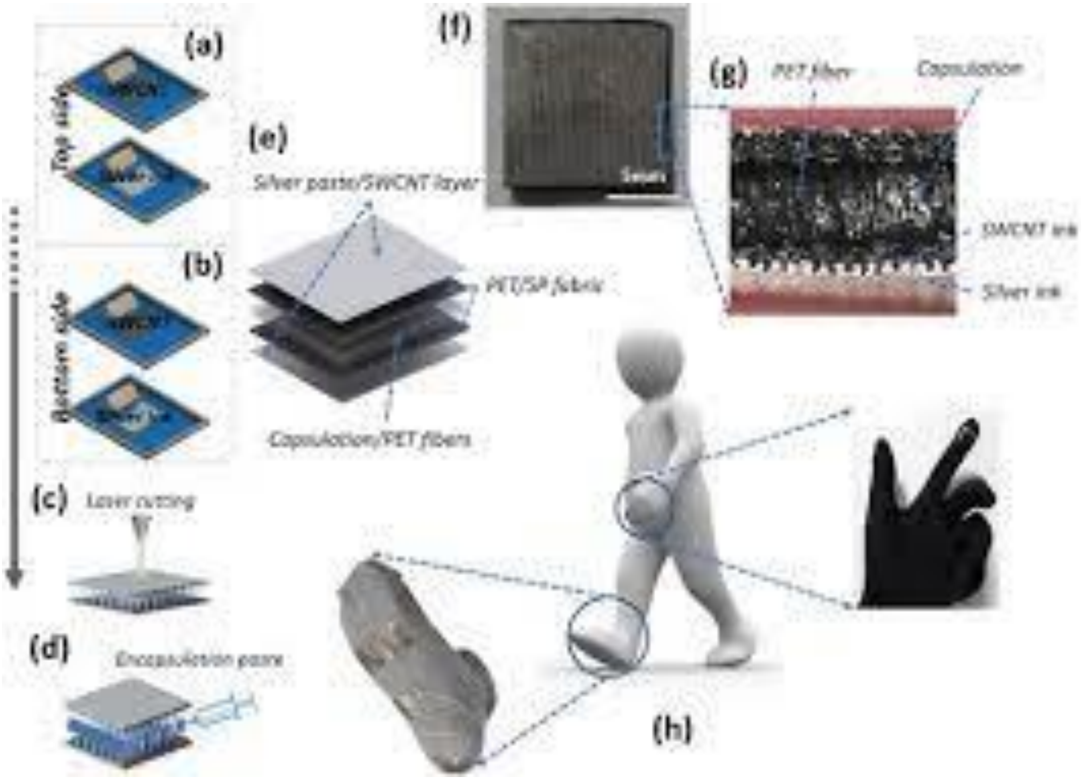
- Lifetime of such sensors under periodic large strains
  - Silicone elastomer
  - Conducting ionic liquid
- Liquid serves as plates of the capacitor
  - according to the coaxial scheme
  - coaxial elements are by 3D printing,
  - filled with a liquid ionic conductor.
- Electrical contacts are silver wires inserted into a liquid conductor.
- Sensor can withstand strains up to 250 % with no hysteresis under static and dynamic loads.



Schematic representation of the design of a capacitive sensor based on an elastomer and a conducting liquid, https://onlinelibrary.wiley.com/doi/abs/10.1002/adma.201500072

Opportunities

- Existing solutions for capacitive sensors allow measuring relative strains
  - from 10^{-4} up to 10^{2} % (~1-10^{6} με)
- Applicable to a wide range of tasks
  - e.g., smart textiles.
- Developed circuitry solutions minimize additive errors
  - when changing temperature, humidity, etc.
- Currently developed measurement techniques and hardware support measuring both
  - value of the capacity (which usually is small)
  - its minor changes under the applied strain.
- Relatively cheap ICs are commercially available
  - for measuring small capacities with fF resolution.



Highly elastic capacitive pressure sensor based on smart textiles for full-range human motion monitoring, https://www.sciencedirect.com/science/article/pii/S092442471932343X

3. Sensors Based on Magnetic Phenomena

The classification is presented in:
Sensors of Mechanical Stresses and Deformations Based on Magnetic Phenomena,
https://ieeexplore.ieee.org/document/9211074

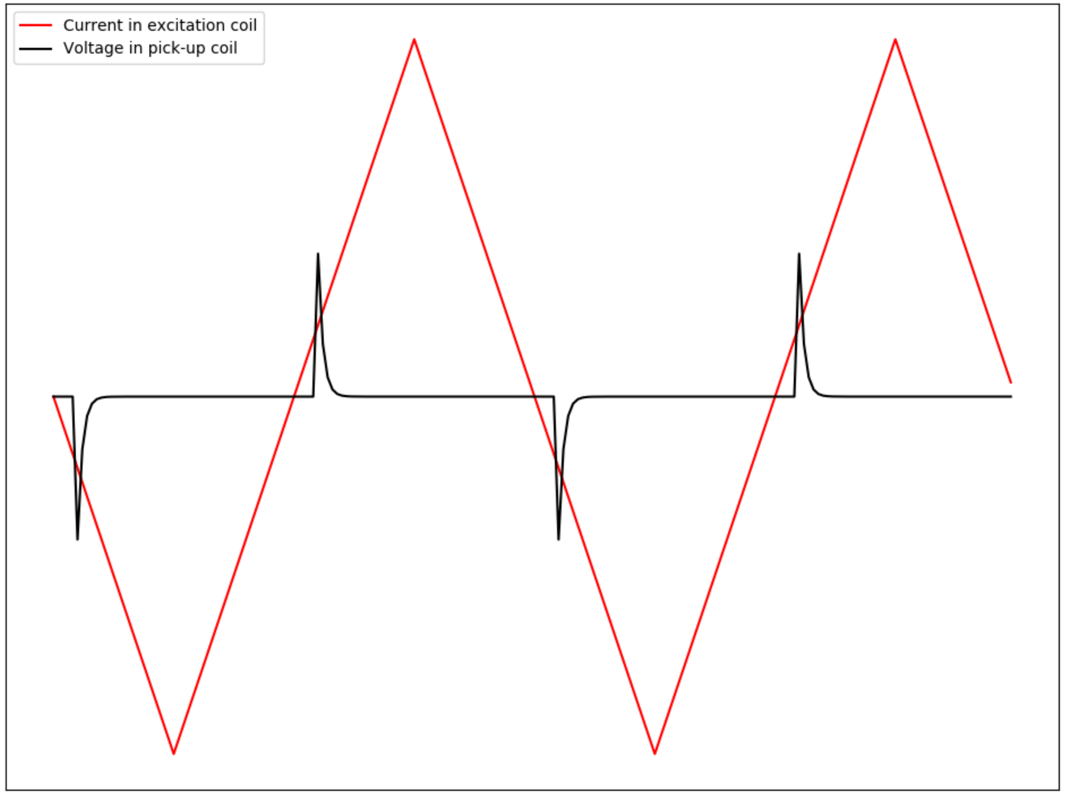
1. Magnetism plays an auxiliary role or trivial magnetic effects are used.
2. Magnetoelastic phenomena are used.
3. Other effects associated with magnetic phenomena are used.
4. Tunneling of spin-polarized electrons.

The Simplest Case: Magnetism Plays an Auxiliary Role

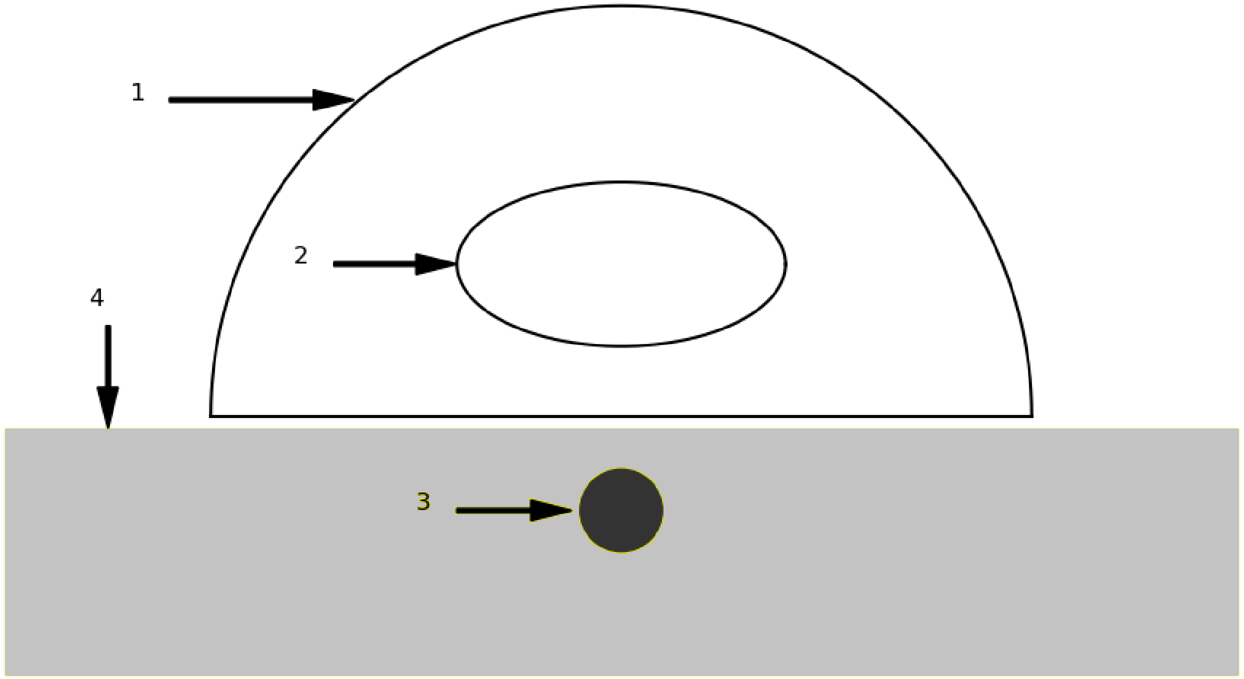
- Changes in device characteristics during mechanical movement of a magnetic sample
  - E.g., a change in the inductance of a coil when moving its magnetic core.
  - mutual movements of various objects, including movements of individual sections of deformable bodies.
- Changes in characteristics of the device when bringing the magnet closer
  - E.g., displacement sensor based on bringing a magnet close to the core of the coil.
  - Bringing the magnet close to the core changes the effective permeability of the core for a small signal.
  - usually two coils are used to linearize the signal with respect to displacement.
- Changes in the parameters of LC circuits; magnetic field pulse is used only for their excitation
  - E.g., monitoring the frequency of the oscillatory circuit, in which the inductance and capacitance depend on strain.
  - The inductance and capacitance themselves can be realized in the form of films on piezoelectric, magnetostrictive, or purely dielectric materials,
  - the resonant frequency is determined by non-contact excitation of the coil of the specified circuit by magnetic field.

Contactless Measurements: Taylor-Ulitovsky Method

- Example design: glass-coated magnetic microwires



The waveforms of the current in the excitation coil and voltage in the pick-up coil due to domain switching in a magnetic wire (left)



Scheme (in cross-section) of contactless measurement using of a single-domain wire (right).
1 & 2: excitation and pick-up coils
3: steep remagnetization of the wire, 4: base

Opportunities

- Contactless measurement with obtaining a signal from a small spatial area
- Twisting deformations are measured as well as stretching ones
- Techniques to distinguish stretching and twisting from a complex strain involving the superposition of both types
- Measuring not only tension but also torsional strains
- Existing solutions are able to measure:
  - relative tensile strains from ~ $1 \cdot 10^{-6}$ to $0.5 \cdot 10^{-3}$
  - torsion-induced shear strains from $4 \cdot 10^{-3}$ to close to unity

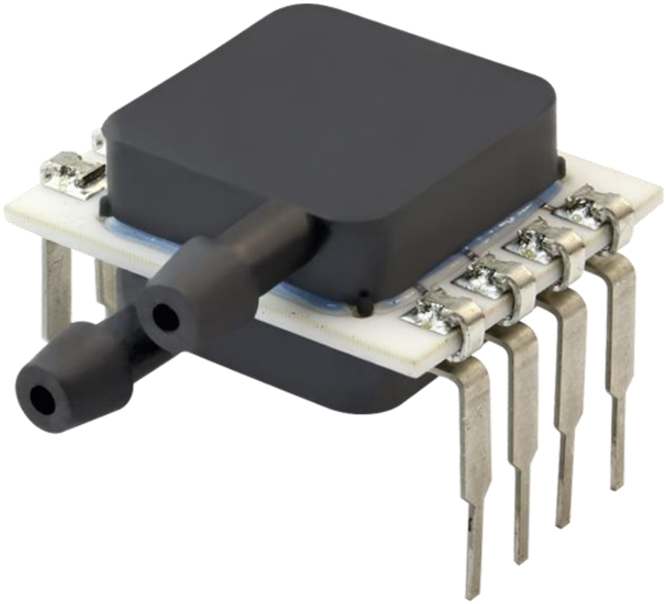
  low errors caused by the changes in temperature, external magnetic fields, etc.

Estimates for minimal detectable values of measured mechanical stresses and strains

- magnetoelastic effects:
  - for stretching – 0.2 MPa ($\varepsilon \sim 10^{-5}$),
  - for twisting ~ 0.1 deg/cm
- measuring HSW:
  - σ =2 MPa ($\varepsilon = 2 \cdot 10^{-5}$)
- giant magnetoresistance (GMR) effect based sensors:
  - $\varepsilon = 2 \cdot 10^{-5}$

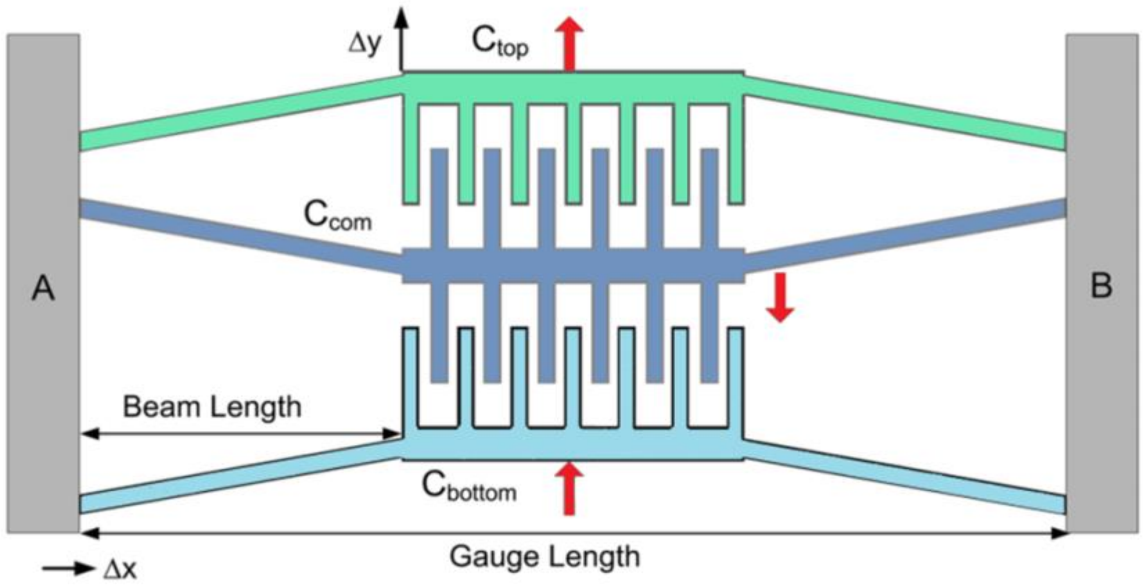
4. Micro-ElectroMechanical Systems (MEMS)

- A new generation of MEMS and optical strain sensors
- Possible sensor types:
  - Capacitive sensors,
  - Resistive sensors,
  - Piezoelectric sensors,
  - Resonant strain sensors.
- Possibility to:
  - significant miniaturization,
  - precision manufacturing,
  - reduced power consumption,
  - increased sensitivity



MEMS Sensor based on Interdigital Capacitor

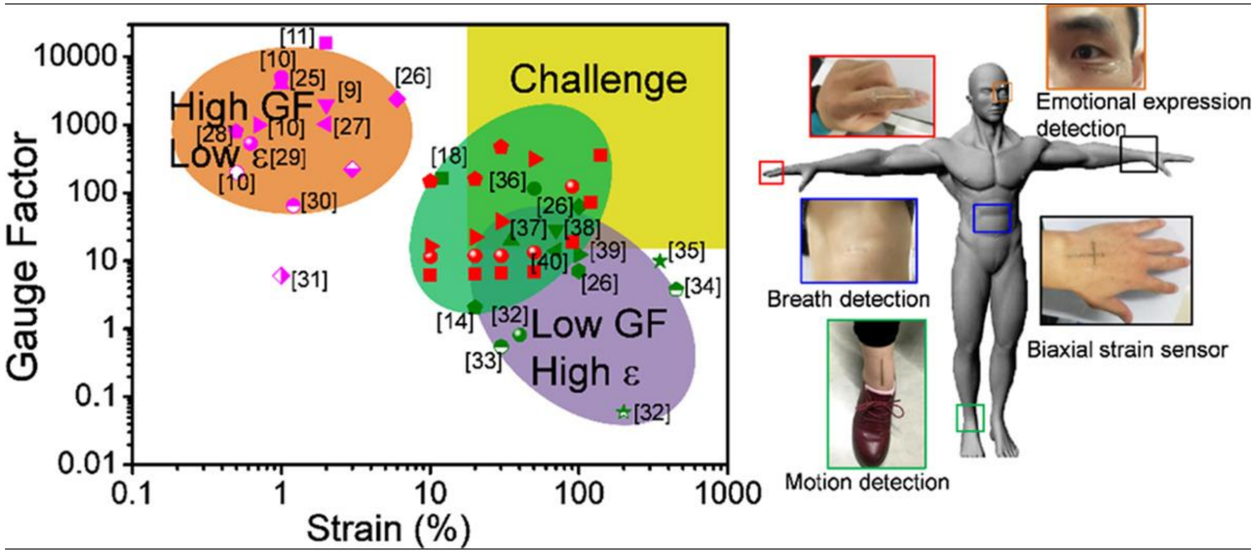
- Example design
- Three amplifying bent-beam suspensions with interdigitated comb fingers
  - positioned at the structural center.
- Capacity change occurs due to changing the plates overlapping area
  - providing linear response
- the output characteristic is close to linear (1.9% full-scale non-linearity)
  - with the sensitivity was 265 aF/(μm/m)
- Temperature change of capacity in range from room to 150 ° C: 10 fF
  - with a nominal sensor capacity of 440 fF.
- Measured noise level:
  - 0.24 aF/√Hz (0.24 aF/√Hz)
  - or 0.9 nm/m/√Hz (nε/√Hz).



A: Differential capacitive MEMS sensor
B: SEM image of four manufactured sensors
Red arrows show deflection directions

Opportunities

- Basic pluses:
  - small dimensions and weight
  - high sensitivity and resolution
  - immunity to electro-magnetic fields
  - radiation resistance,
  - remote measurements and dielectric strength
  - wide dynamic range
  - multiplexing signals
  - Point and distributed sensing
  - fire safety
- High cost of both the sensor itself and the measuring equipment



Example application:
Breathable and Skin-Mountable Strain Sensor with Tunable Stretchability, Sensitivity, and Linearity via Surface Strain Delocalization for Versatile Skin Activities' Recognition, https://pubs.acs.org/doi/abs/10.1021/acsami.8b14365

Discussion

The needs of tactile cyber-physical systems

- Possibility of “touching” remote objects in Internet

Emerging smart applications

- IoT-enabled interactive environments
- Bionic suits and wearable&carriable systems
- Mobile robotics and autonomous movement

Sensor type	Resolution, με	Strain measurement range, με	Advantages
Resistive (piezoresistive) **- metal** **- semiconductor**	~0.1 $\sim10^{-3}\div10^{-2}$	Up to $\sim10^{4}$ Up to $\sim10^{3}$	- simple measurement and low price - dynamic and static deformations
Piezoelectric	Up to 10^{-4}	Up to $\sim10^{3}$	Direct conversion of strain to electrical voltage
Capacitive **- elastomer-based** **- with a liquid conductor** **- with a thick dielectric**	Up to ~ 1 ~ 10^{4} ~ 0.1-1	Up to $\sim10^{6}$ Up to $\sim10^{6}$ Up to $\sim10^{2}$	Large limit deformations, two-axis measurements, torsional strain measurement Large limit deformations, torsional and complex strain measurement Larger GF
Magnetic **- magnetoelastic effects in amorphous and nanocrystalline ribbons** **- Barkhausen jumps based (microwires)**	~ 10 ~ 1-10	~ 10^{3} ~ 10^{3}	non-contact measurements, strains in small spatial areas
MEMS **- capacitive** **- piezoresistive** **- piezoelectric** **- resonance**	 1-10 ~ 0.1-1 ~ 0.1-1 Up to 10^{-4}	 Up to $\sim10^{2}$ $\sim10^{3}$ 10^{2}-10^{3} Up to 10^{2}	Miniaturization, integration in a single smart chip sensor, low consumption
FBG sensors	~ 0.1÷1	Up to 10000	The possibility of multiplexing sensors
Fiber-optic distributed sensors **- Distributed sensor BTDR** **- Distributed sensor OFDR** **- Rayleigh (ϕ)OTDR**	 ~ 1 ~ 1 ~ 0.001÷0.01	 - - -	Measurement of the strain field along the fiber with spatial resolution

Conclusion

- Tactile cyber-physical systems (TCPS)
  - Key property to realize: “touching” a remote object under monitoring
  - Many smart applications in TCPS with real-time sensorics
    - Sensorics for bionic suits and IoT-enabled interactive environments
    - Sensorics for mobile robotics
- Promising physical principles of strain measurements:
  - resistive, piezoelectric strain sensors
  - capacitive strain sensors
  - strain sensors based on magnetic phenomena
  - new generation of MEMS and optical strain sensors

Thank you!

Forward your questions and comments to dkorzun@cs.karelia.ru