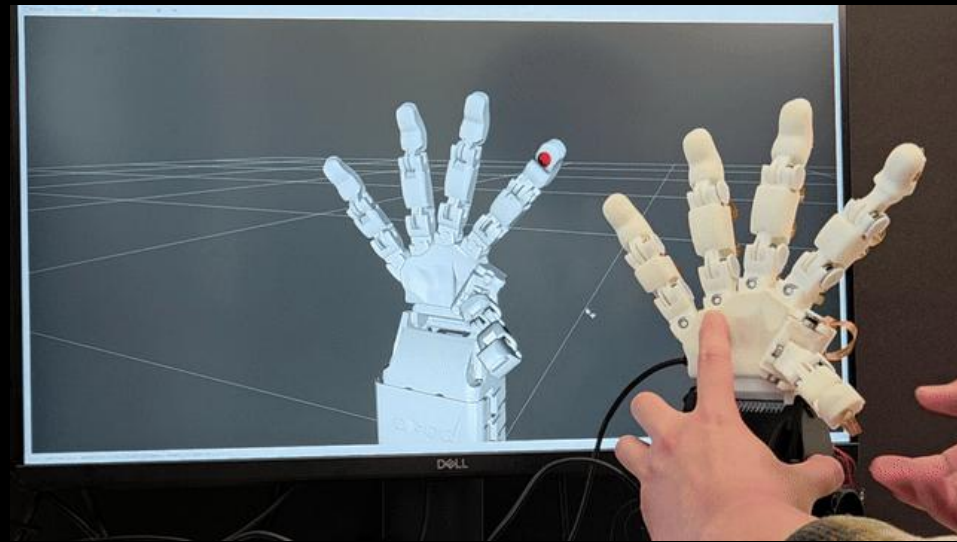


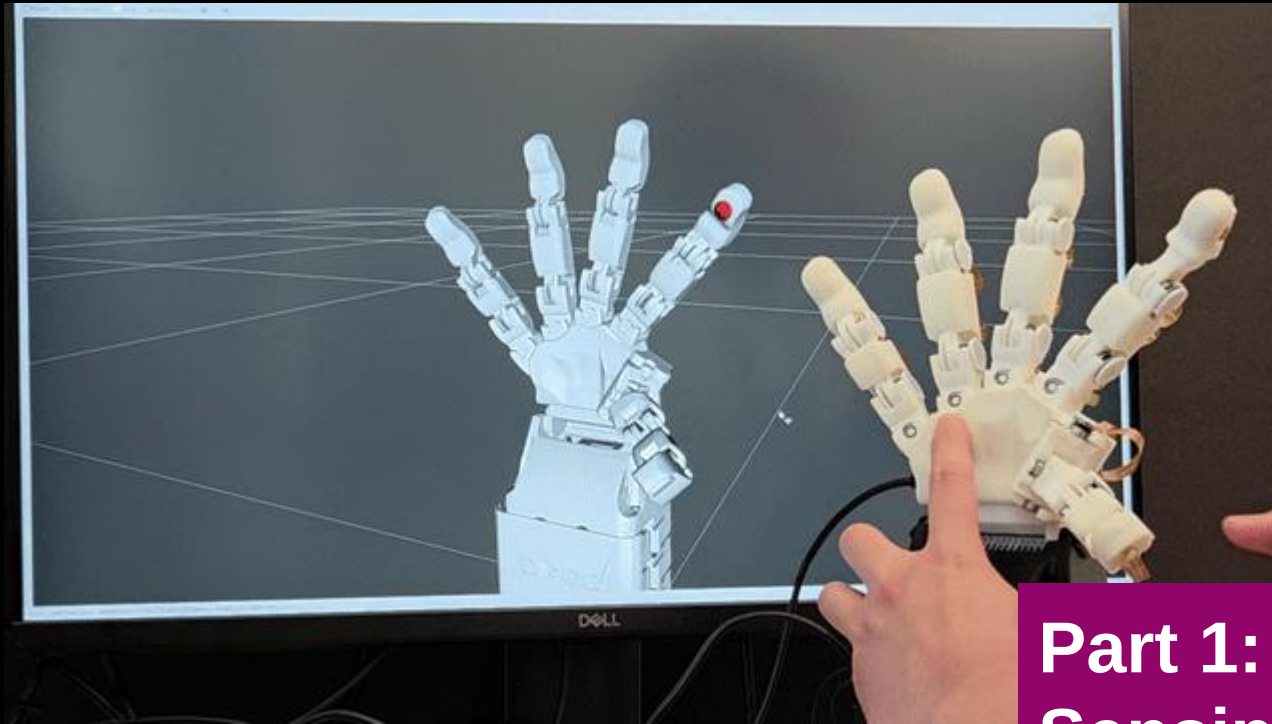
Sensors in Dexterous Manipulation

Jaehoon Kim

Plan for Today

1. Sensing
2. Why Sensing Matters
3. Sensing Mechanisms
4. Characterization
5. Kalman Filter





Part 1: Sensing

Classification of Robotic Sensor



1. Exteroceptive Sensor

- Acquire information from the robot's environment.
- Tactile sensors, proximity sensors, light intensity, and sound amplitude.

2. Proprioceptive Sensor

- Measure values internal to the system (robot).
- Motor speed, wheel load, joint angles, bending sensor, and battery voltage.

Roland Siegwart; Illah Reza Nourbakhsh; Davide Scaramuzza, "Perception," in *Introduction to Autonomous Mobile Robots*, MIT Press, 2011, pp.101-263.

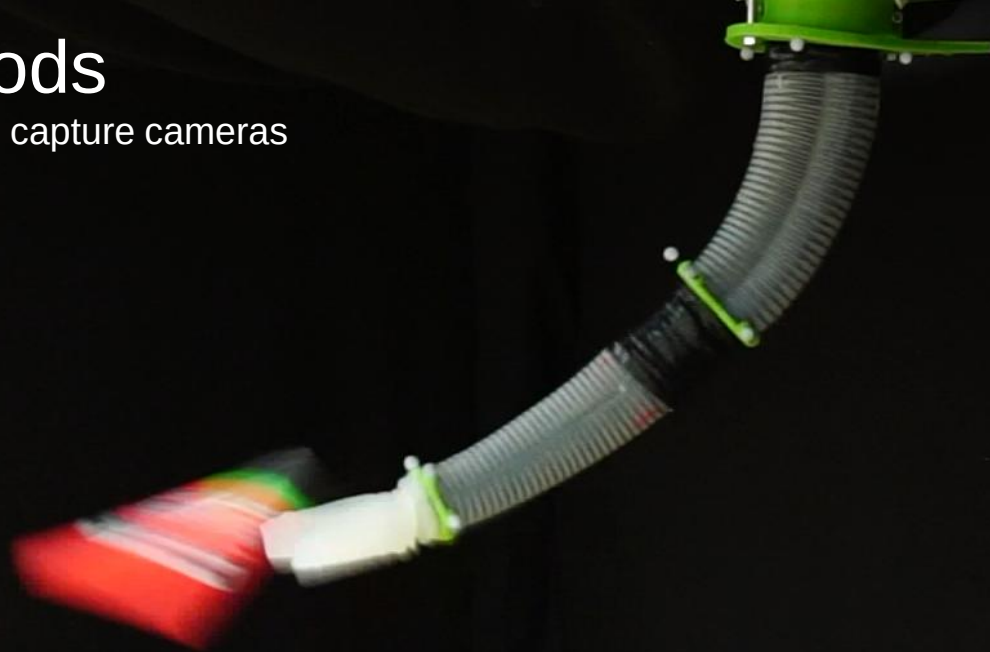
Sensing the pose: two methods



- **Direct** methods: Direct reference to the **world reference frame**
 - The sensors obtain the absolute value of the state we are measuring
- **Indirect** methods: Obtain a measurement with reference to a **second frame**
 - The sensors will estimate a relative measurement that can be transformed into an absolute measurement

Direct methods

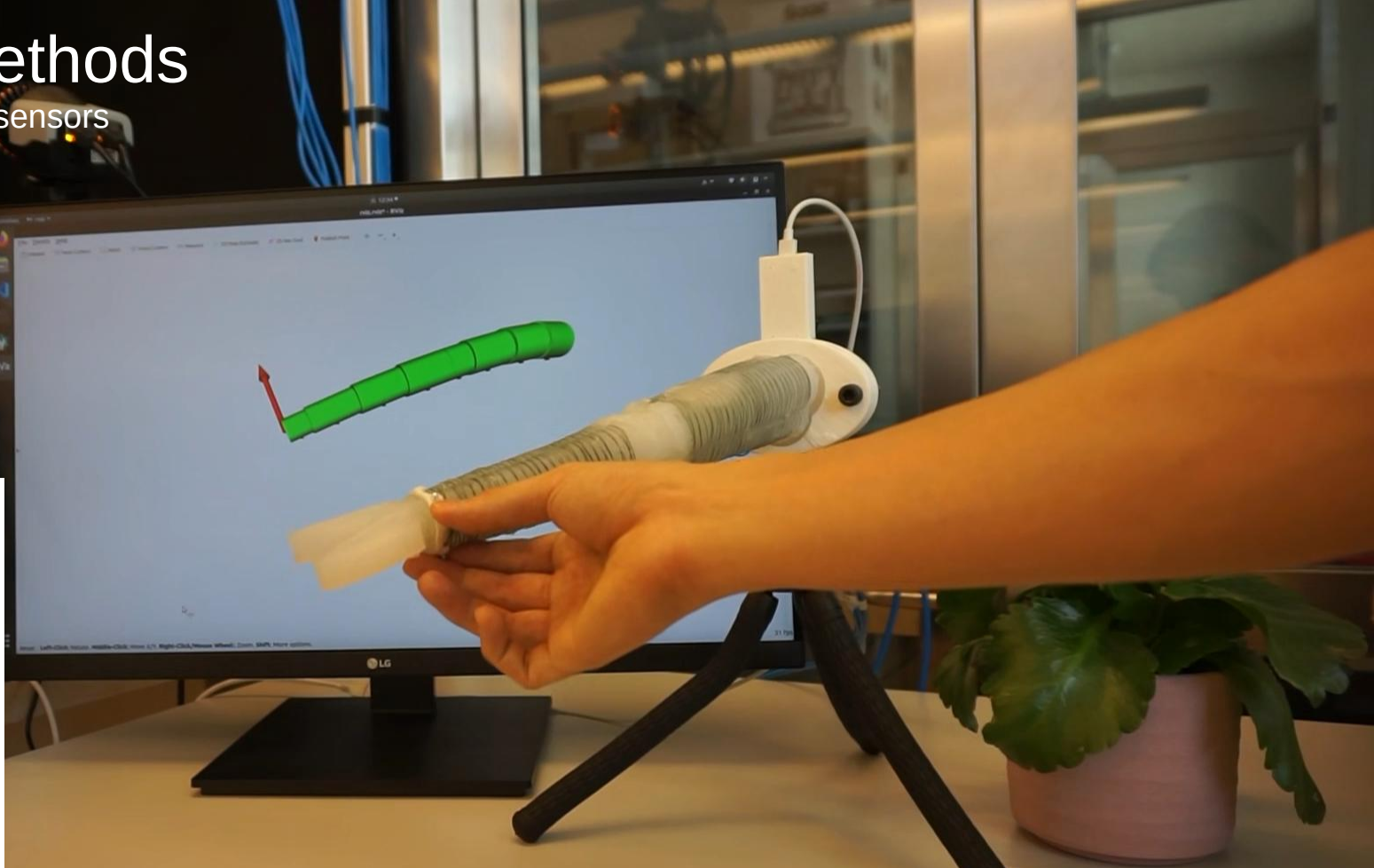
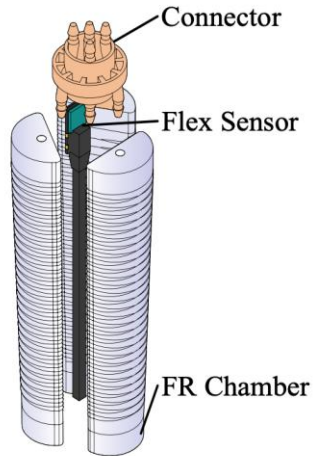
such as external motion capture cameras



Fischer, O., Toshimitsu, Y., Kazemipour, A., & Katschmann, R. K. (2023). Dynamic Task Space Control Enables Soft Manipulators to Perform Real-World Tasks. *Advanced Intelligent Systems*, 5(1), 2200024.

Indirect methods

such as built-in flex sensors



Toshimitsu, Y., Wong, K. W., Buchner, T., & Katzschnmann, R. (2021, September). Sopra: Fabrication & dynamical modeling of a scalable soft continuum robotic arm with integrated proprioceptive sensing. In *2021 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)* (pp. 653-660). IEEE.



Sensor Performance Metrics

Accuracy: The degree of conformity between the sensor's measurement and the true value. It is not defined in a single universal way. Its definition depends on context.

Proportion of the true value

$$accuracy = 1 - \frac{|error|}{ground\ truth}$$

Maximum error (common in off-the-shelf sensors)

Datasheet of Pressure
sensor BMP581

Key features:

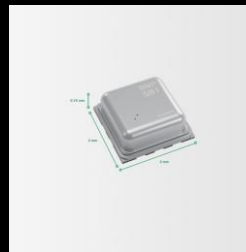
Pressure operating range: 30 .. 125 kPa

Temperature operating range: -40 .. 85°C

Ultra low noise and current consumption:

- ▶ Ultra low noise: < 0.1PaRMS natively (without low-pass filter enabled)
- ▶ 1.3 μ A 1Hz in low power mode

Absolute pressure accuracy: ± 0.5 hPa (max)



Statistical Metrics (common in papers; ex. Root Mean Square Error (RMSE))

$$RMSE = \sqrt{\frac{1}{N} \sum_{i=1}^N (\hat{y}_i - y_i)^2}$$

where y_i : actual value

$\hat{y}_i$: predicted value

N : number of samples

Sensor Performance Metrics



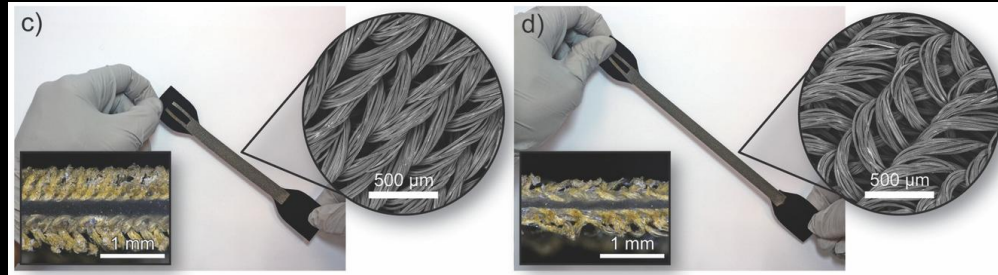
Sensitivity: The degree to which an incremental change in the target input signal changes the output signal.

$$\text{Sensitivity} = \frac{dY}{dX}$$

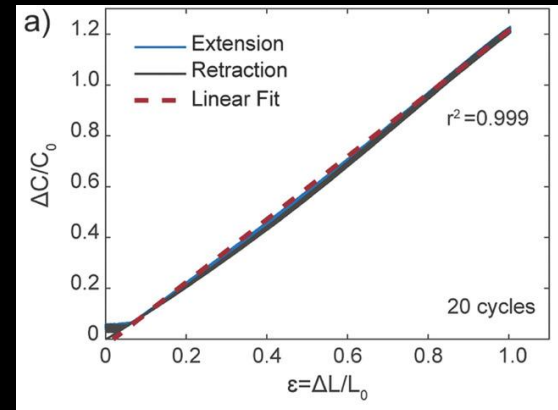
where, X : input (ex. Strain) Y : output (ex. Voltage)

Example: Gauge Factor of strain gauge (normalized sensitivity)

$$GF = \frac{\Delta R/R}{\varepsilon}$$



Silicone-Textile Composite Capacitive Strain Sensors



Relative capacitance change as a function of applied strain for 20 cycles.
Linear fit: gauge factor of 1.23

Sensor Performance Metrics



Resolution: The minimum difference between two values that can be detected by a sensor.

Off-the-shelf sensors (or sensor data read by Analog-to-digital converter (ADC)) with a digital output format:
The resolution is given by the number of bits.

$$Resolution = \frac{Full\ Scale}{2^{bits}}$$

Sampling rate: Data acquisition frequency.

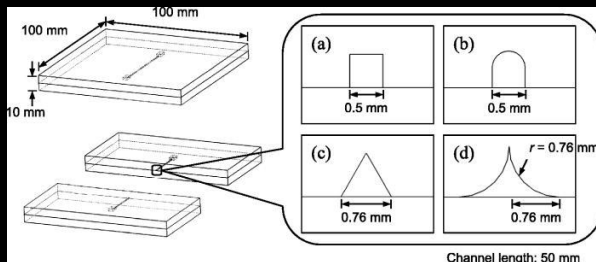
To avoid aliasing, the sampling rate must be at least twice the bandwidth of the target signal (Nyquist criterion).

Range : The maximum and minimum values of applied parameter that can be measured.

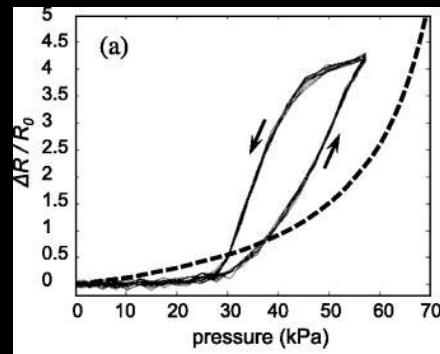


Sensor Performance Metrics

Hysteresis: Difference in output between loading and unloading at the same input.



Pressure sensor sample designs with different channel geometries



Experimental results of the resistance changes

Hysteresis arises from the **viscoelasticity** of soft materials.

Nonlinearity: The maximum deviation of actual data from the approximation straight line.

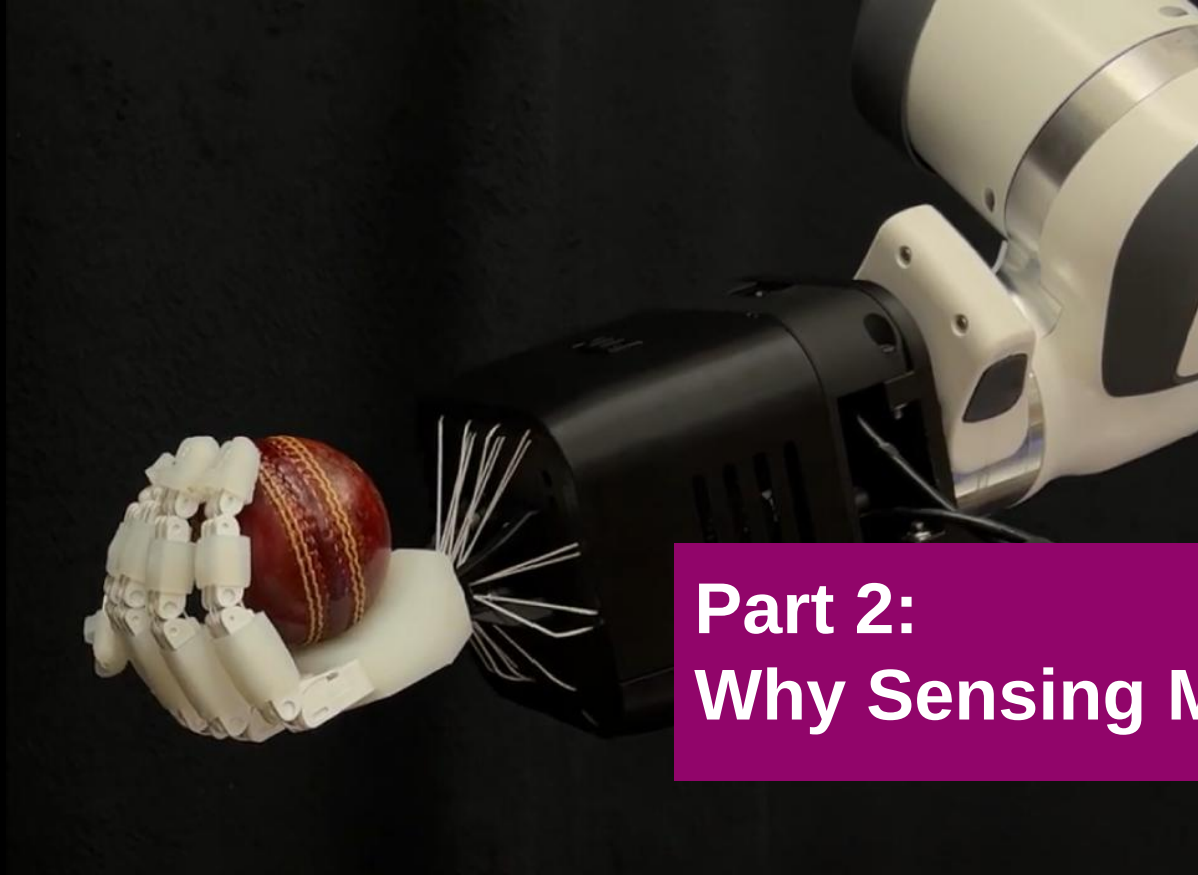
Response Time (Time constant), Durability, Drift, ...

Roland Siegwart; Illah Reza Nourbakhsh; Davide Scaramuzza, "Perception," in *Introduction to Autonomous Mobile Robots*, MIT Press, 2011, pp.101-263.

Fraden, J. (2004). *Handbook of modern sensors: physics, designs, and applications*. New York, NY: Springer New York.

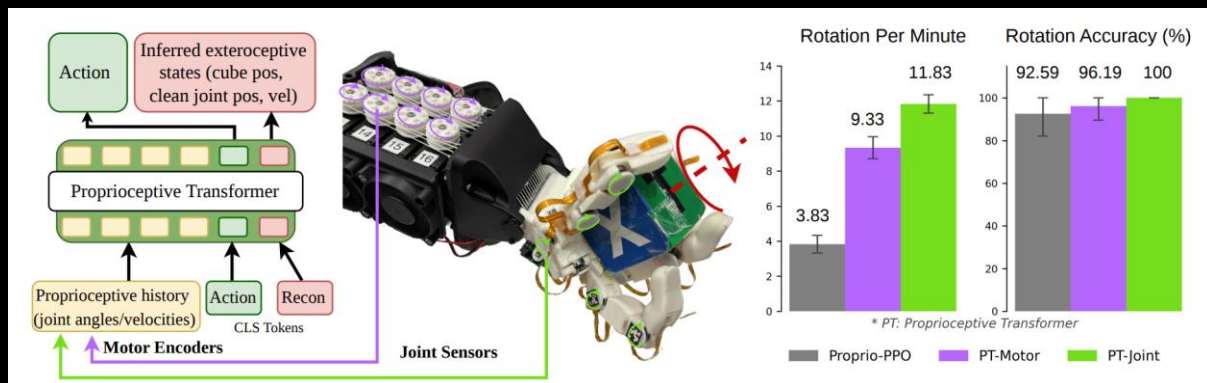
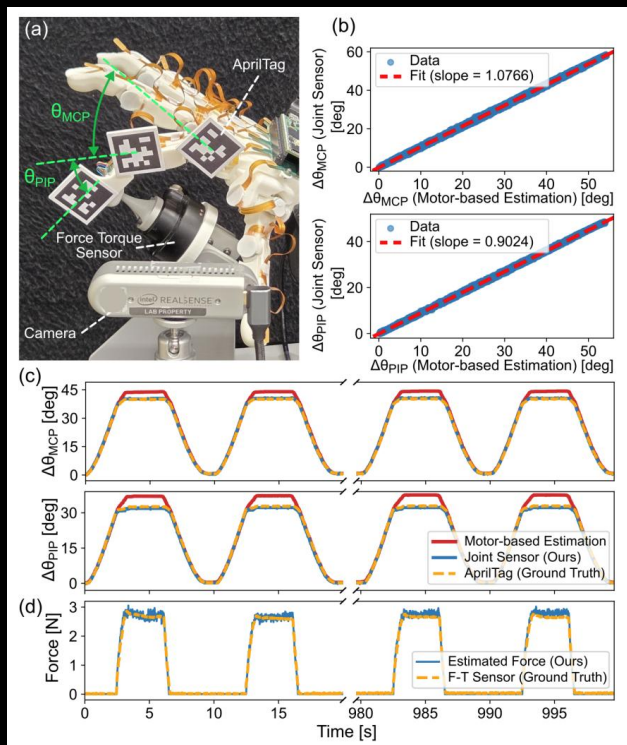
Wilson, J. S. (2004). *Sensor technology handbook*. Elsevier.

Park, Y. L., Tepayotl-Ramirez, D., Wood, R. J., & Majidi, C. (2012). Influence of cross-sectional geometry on the sensitivity and hysteresis of liquid-phase electronic pressure sensors. *Applied physics letters*, 101(19).



Part 2: Why Sensing Matters

Joint Sensing for Tendon-Driven Hands



Accurate sensing during contact

- Tendon limits motor-based joint estimation.
- Direct joint sensing captures actual joint motion.

Better manipulation performance

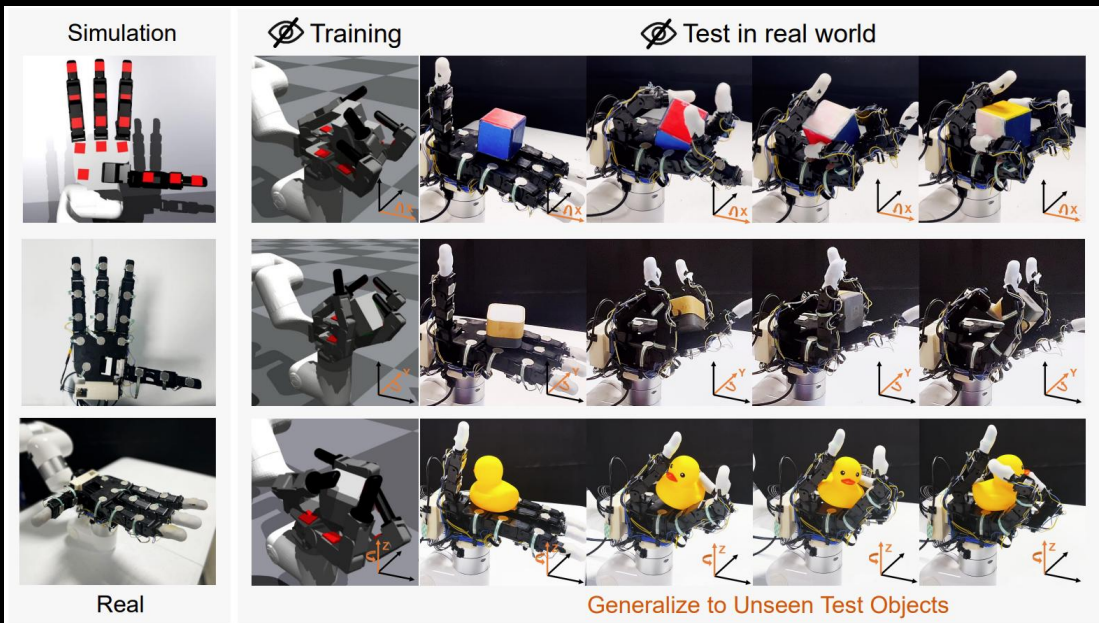
- Accurate joint sensing improves policy performance.

J. Kim, B. An, L. Christoforidis, M. Papadakis, V. Kartsch and R. K. Katzschmann, "High-Speed, Scalable Sensor Readout for Dexterous Robotic Hands via Shift-Register Multiplexing," in IEEE Robotics and Automation Letters. Yao, Senlan, et al. "Learning Robust Dexterous In-Hand Manipulation from Joint Sensors with Proprioceptive Transformer." arXiv preprint arXiv:2605.21330 (2026).



Tactile Sensing for Dexterity

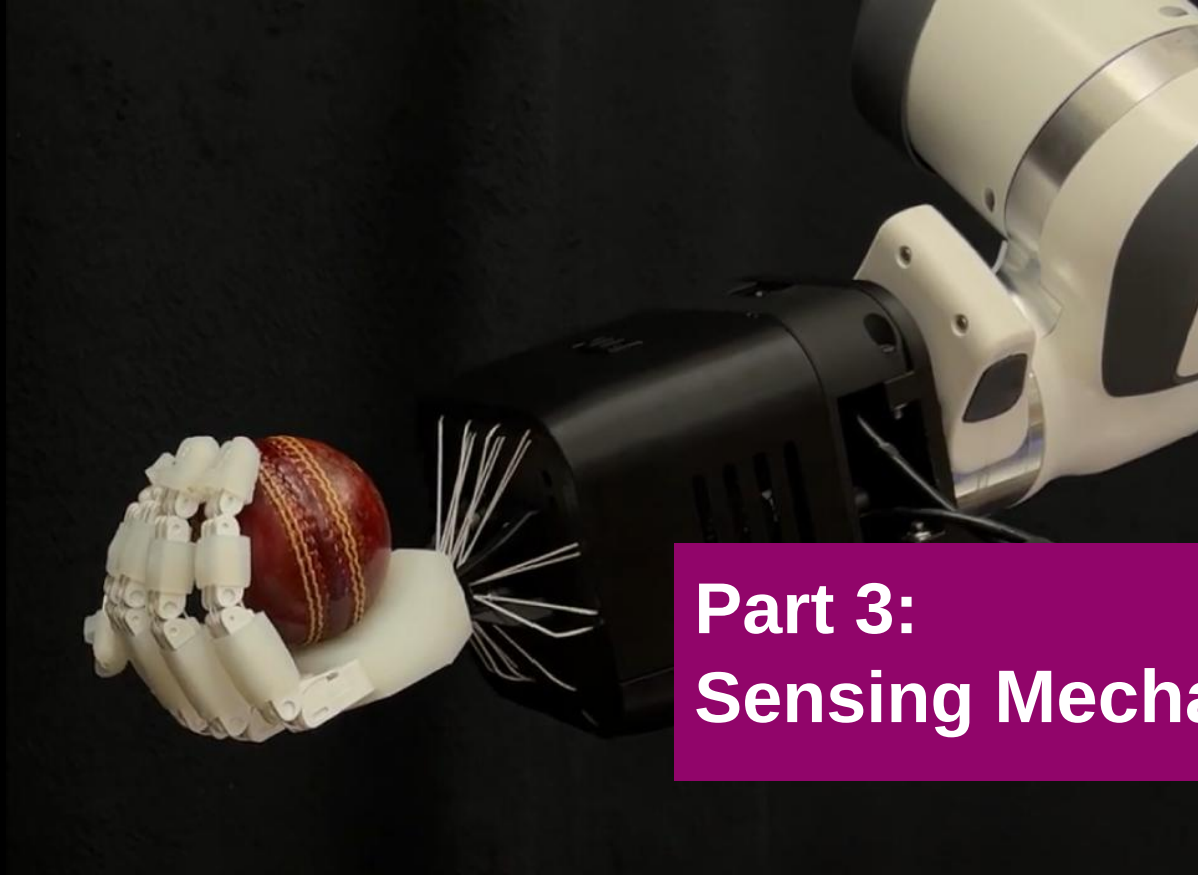
- Tactile sensors provide direct feedback on hand-object contact.
- Adding binary touch to joint feedback improves in-hand rotation.



Unseen	Tomato		Apple	
	CRA	TTF	CRA	TTF
OL	0.25 ± 0.25	20.00 ± 17.32	0.67 ± 0.76	20.00 ± 17.32
No-Sensor	0.00 ± 0.00	0.00 ± 0.00	0.33 ± 0.58	10.00 ± 17.32
CT-Sensor	0.33 ± 0.29	12.33 ± 15.70	0.42 ± 0.52	15.33 ± 15.01
Ours	1.08 ± 0.14	27.33 ± 4.62	2.67 ± 1.04	30.00 ± 0.00

- Unseen: objects not used during training.
- OL(Open-loop): Fixed trajectory replay.
- No-Sensor: Joint feedback only.
- CT-Sensor: Joint + continuous tactile feedback.
- Ours: Joint + binary tactile feedback.
- CRA: Total rotation (turns).
- TTF: Time before falling (seconds, max. 30).

Yin, Zhao-Heng, et al. "Rotating without seeing: Towards in-hand dexterity through touch." arXiv preprint arXiv:2303.10880 (2023).



Part 3: Sensing Mechanisms

Sensing Mechanisms



- Resistive Sensors and Piezoresistive Sensors
- Capacitive Sensors
- Magnetic Sensors
- Optical Sensors
- etc...

Hegde, C., Su, J., Tan, J. M. R., He, K., Chen, X., & Magdassi, S. (2023). Sensing in soft robotics. *ACS nano*, 17(16), 15277-15307.

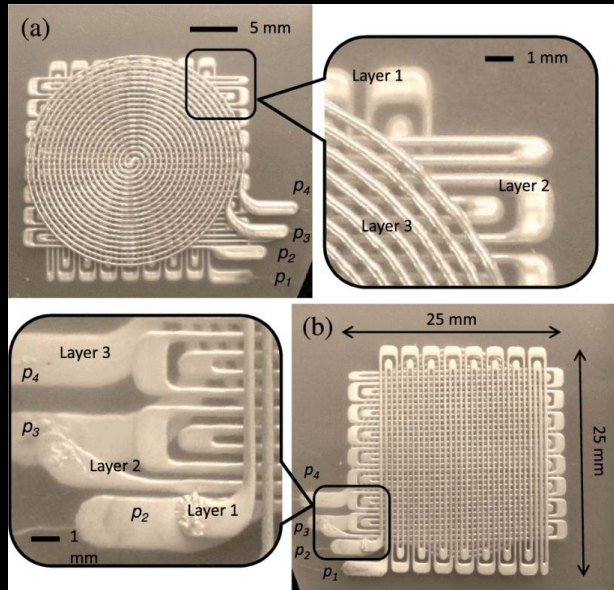


Tactile Sensors

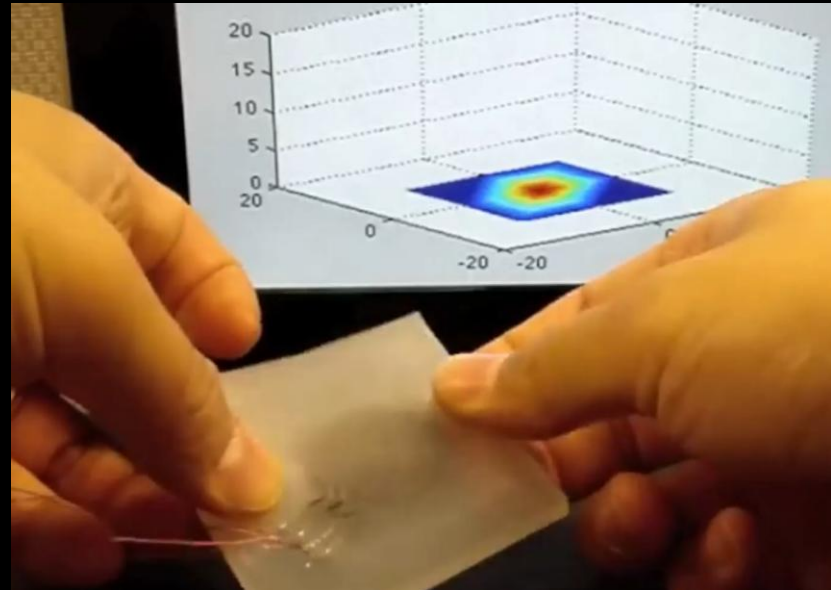
Tactile sensor: Resistive and Piezoresistive Sensors



- Resistive and piezoresistive sensors use resistance as the indicator of the variation of pressure or strain resulting from external stimuli.



Multilayered soft artificial skin sensor with embedded EGaIn microchannels

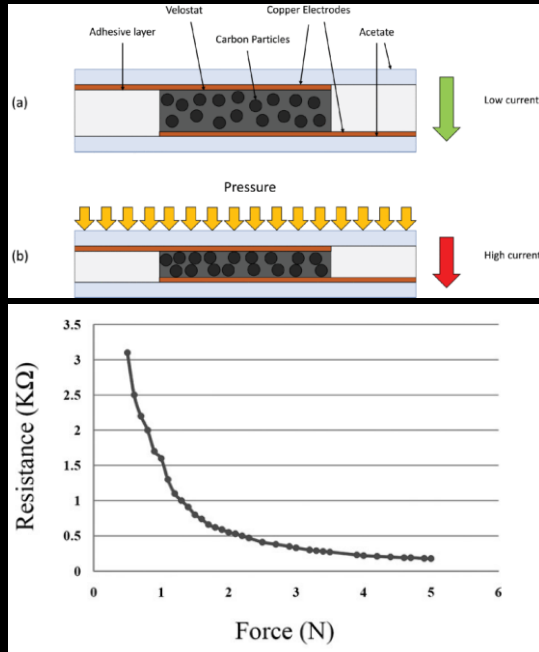


Tactile sensor: Resistive and Piezoresistive Sensors



- Resistive and piezoresistive sensors use resistance as the indicator of the variation of pressure or strain resulting from external stimuli.

Resistance change of piezoresistive material under pressure



Multi-Modal Modular Textile Sensor for Physical Human-Robot Interaction Using Band-Stop Filters

Movie S4

Jaehoon Kim, Junhyung Kim, and Yong-Lae Park

Hegde, C., Su, J., Tan, J. M. R., He, K., Chen, X., & Magdassi, S. (2023). Sensing in soft robotics. *ACS nano*, 17(16), 15277-15307.

Yuan, L., Qu, H., & Li, J. (2021). Velostat sensor array for object recognition. *IEEE Sensors Journal*, 22(2), 1692-1704.

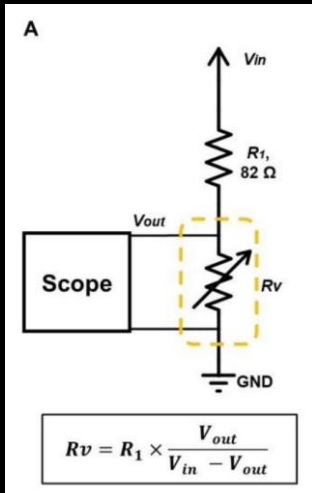
Kalantari, M., Dargahi, J., Kovacs, J., Mardasi, M. G., & Nouri, S. (2011). A new approach for modeling piezoresistive force sensors based on semiconductive polymer composites. *IEEE/ASME Transactions on Mechatronics*, 17(3), 572-581.

Kim, J., Kim, J., & Park, Y. L. (2024). Multi-modal modular textile sensor for physical human-robot interaction using band-stop filters. *Advanced Functional Materials*, 34(7), 2308571.

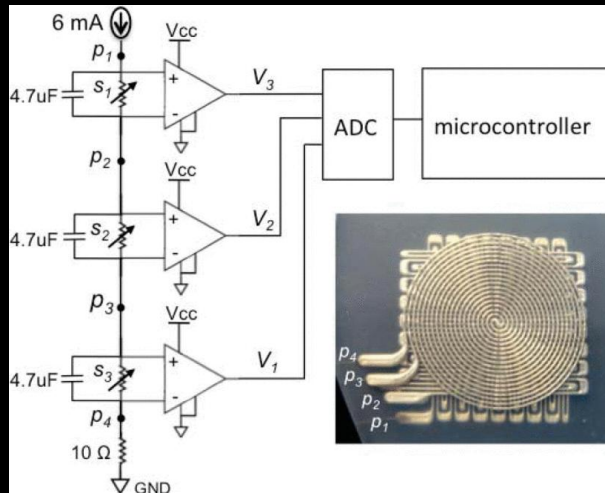
Tactile sensor: Resistive and Piezoresistive Sensors



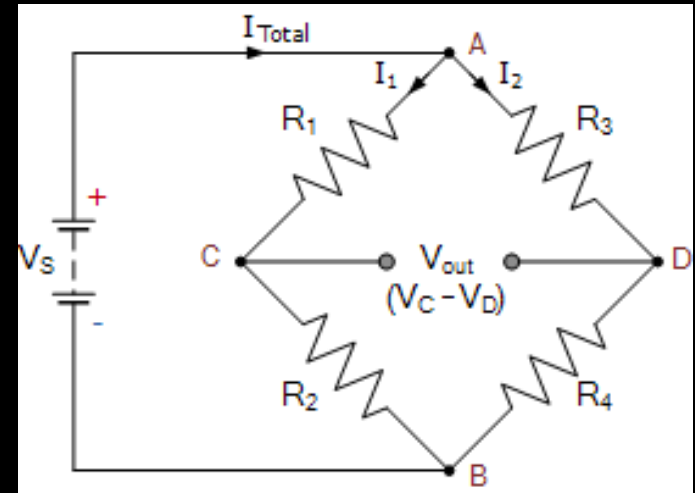
- Measurement using voltage divider, constant current source, and Wheatstone bridge circuits with analog-to-digital converter (ADC).



Voltage divider



Constant current source



Wheatstone bridge



Tactile sensor: Capacitive Sensors

- Using capacitance changes.
- Parallel plate capacitors are commonly used because of their simple structure.

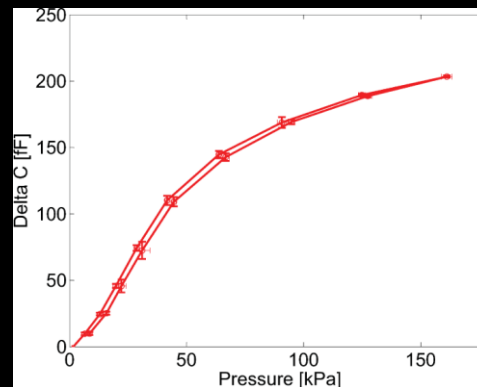
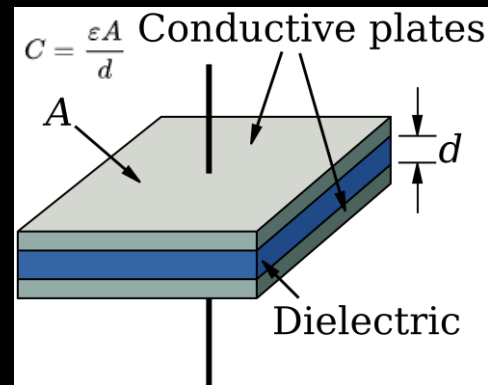


(a)

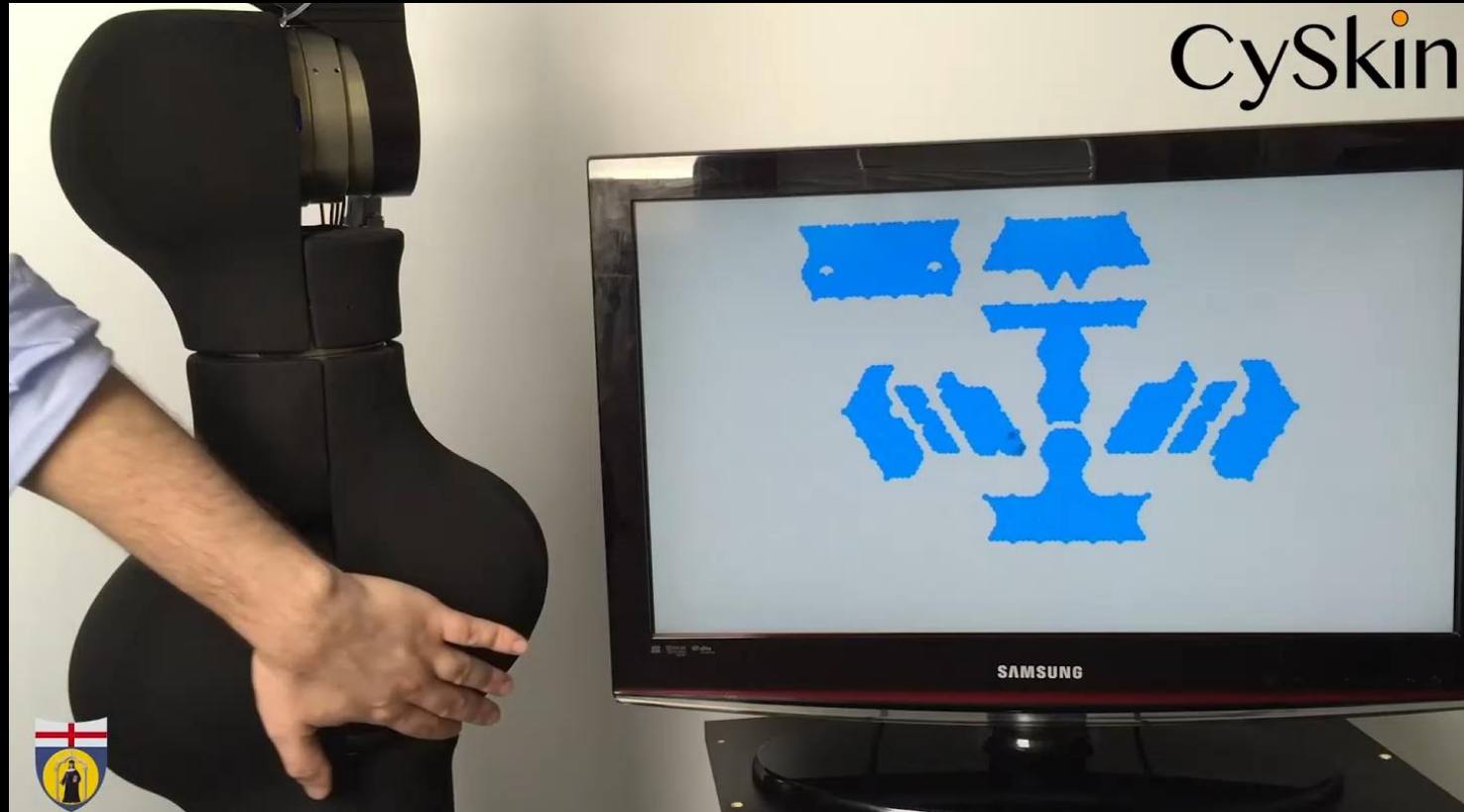


(b)

Capacitive sensor array

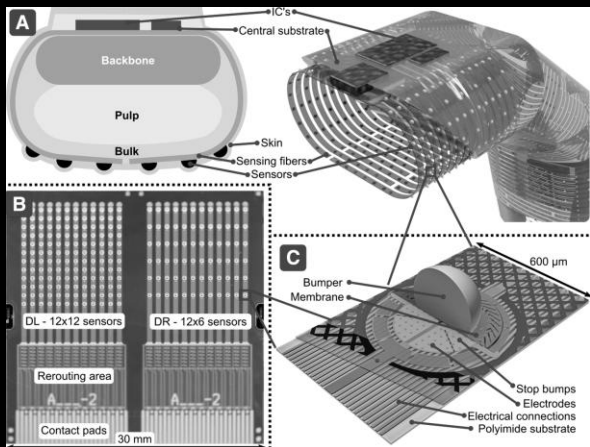


Tactile sensor: Capacitive Sensors





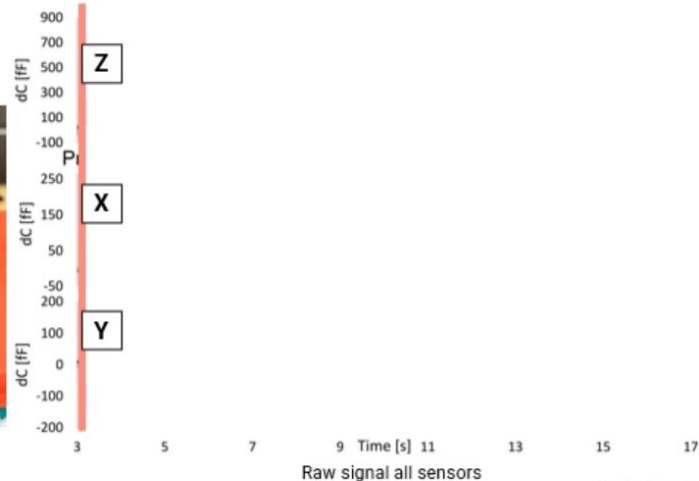
Tactile sensor: Capacitive Sensors



Touch and slip experiment

Sequence:

1. Compress 2 N & wait 4 s
2. Slide 10 mm (-X) & wait 4 s
3. Release

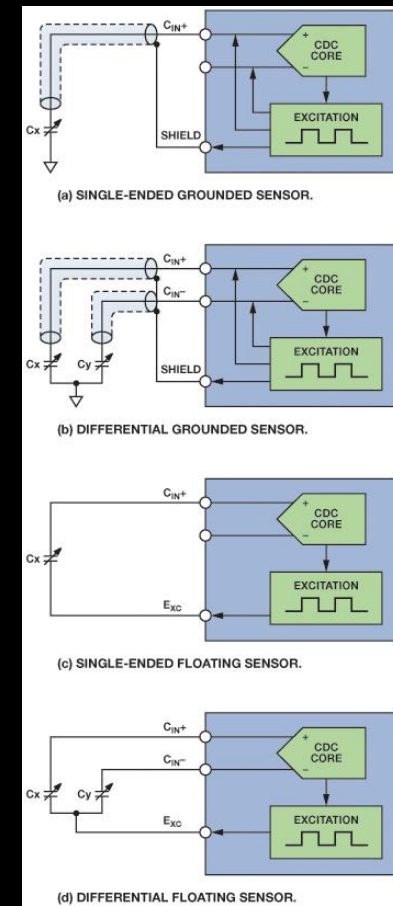
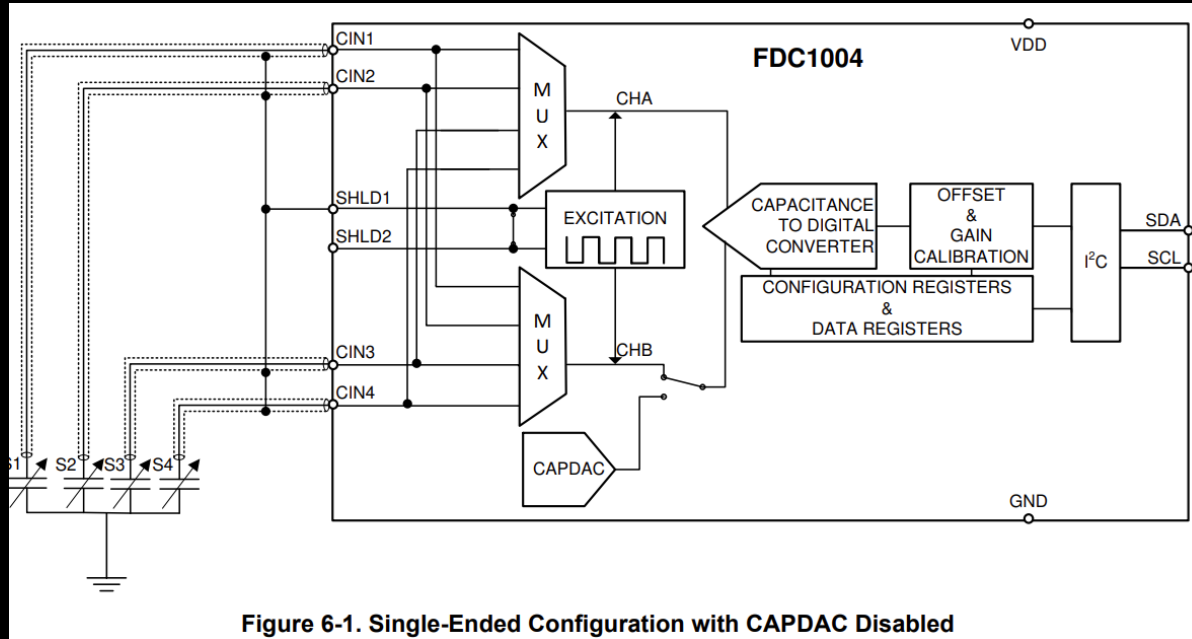


ETH zürich Johannes Weichert

MRS

Tactile sensor: Capacitive Sensors

- Measurement using capacitance-to-digital converter (CDC).

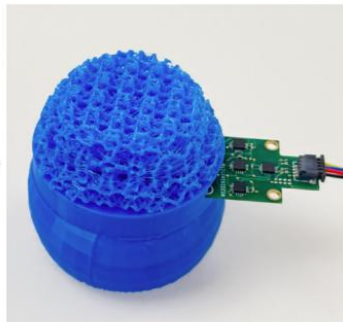
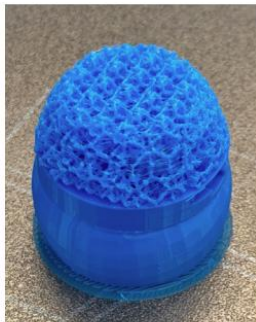


Sensor electrical configurations.



Tactile sensor: Magnetic Sensors

- Using changes in magnetic field.

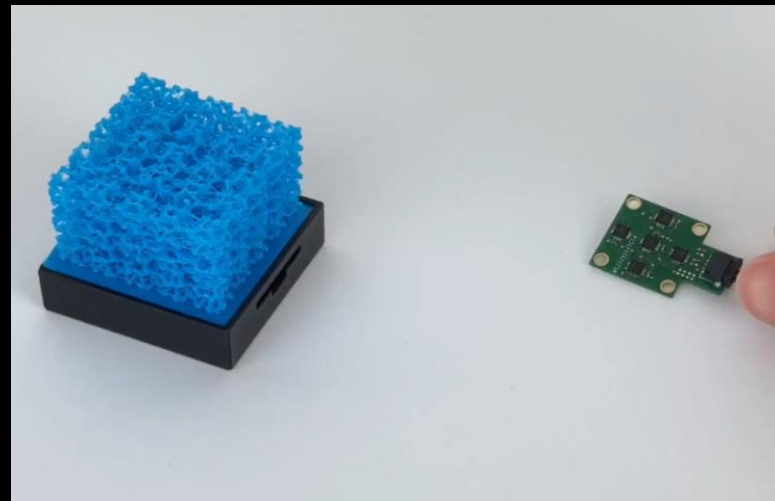


Insert magnets into
pouches

Resume print
until complete

Insert magnetometer
PCB into slot

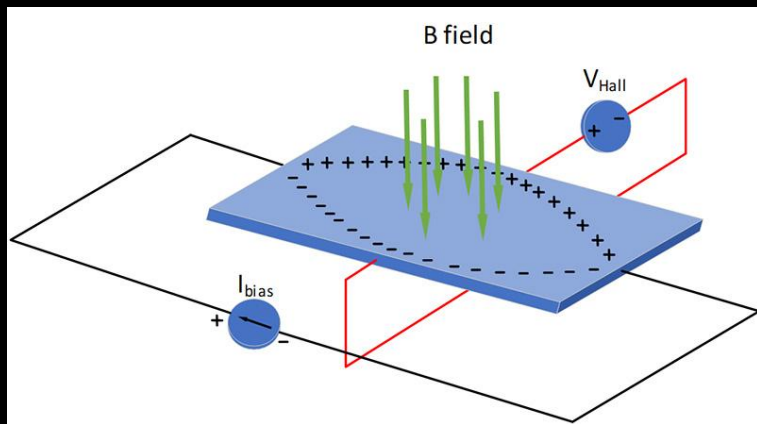
Magnetic tactile sensor



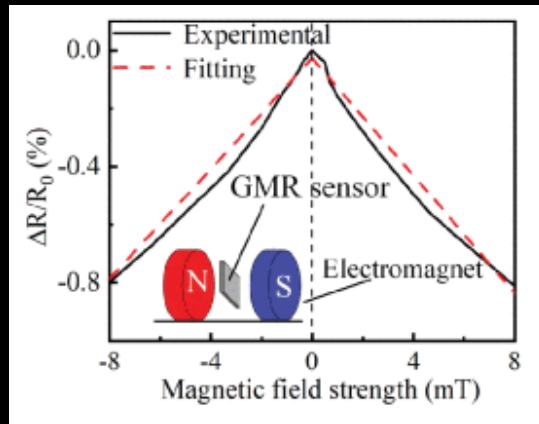


Tactile sensor: Magnetic Sensors

- Measurement using hall-effect sensor or magnetoresistive sensor
- Hall-effect: a small voltage develops across a conductor when current flows through it and a magnetic field is applied.
- Magnetoresistance effect: the resistance of a conductor changes when current flows through it and a magnetic field is applied. (ex. GMR, TMR, etc.)



Hall-effect

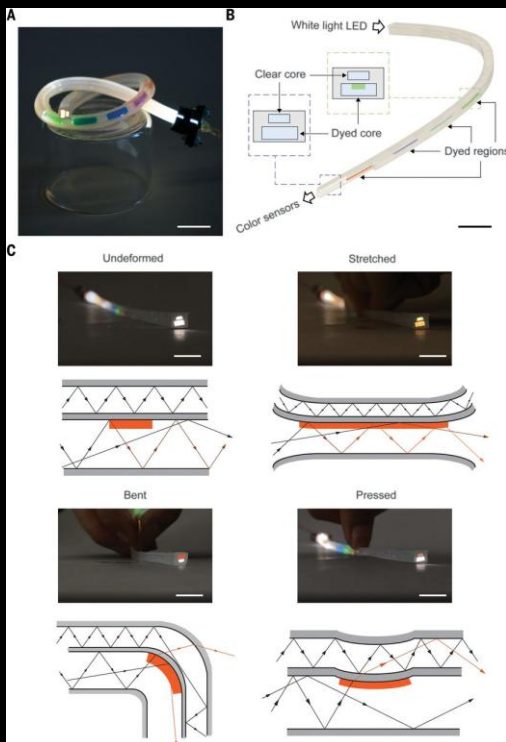


Resistance change in a magnetoresistive sensor



Tactile sensor: Optical Sensors

- Using light intensity or color change.

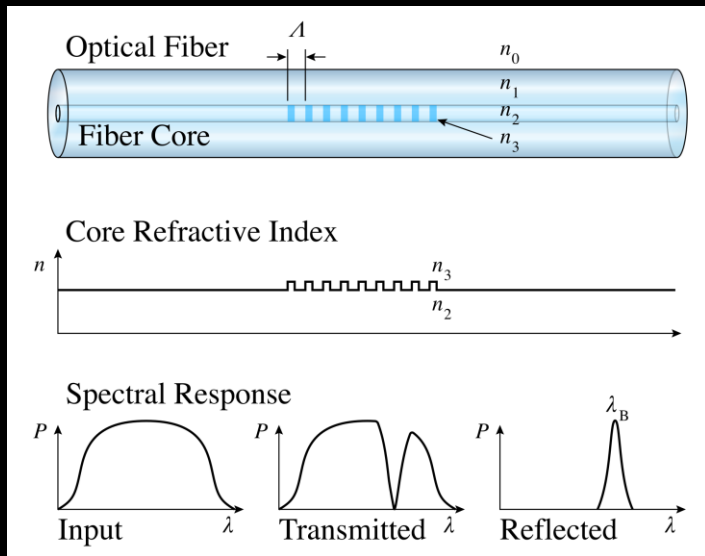


Silica-based distributed fiber-optic sensor systems

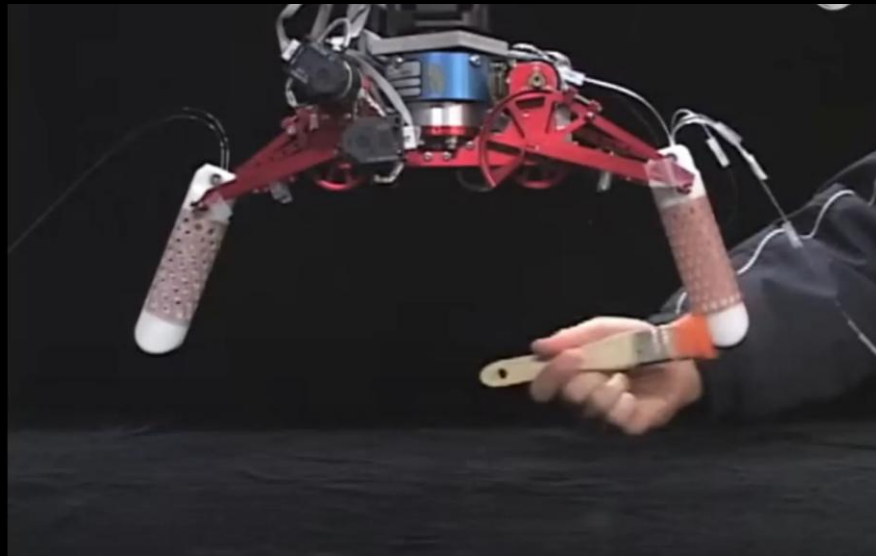


Tactile sensor: Optical Sensors

- Using fiber Bragg grating (FBG) sensor
- The reflected wavelength of an FBG sensor shifts in proportion to the strain applied to it.



FBG structure

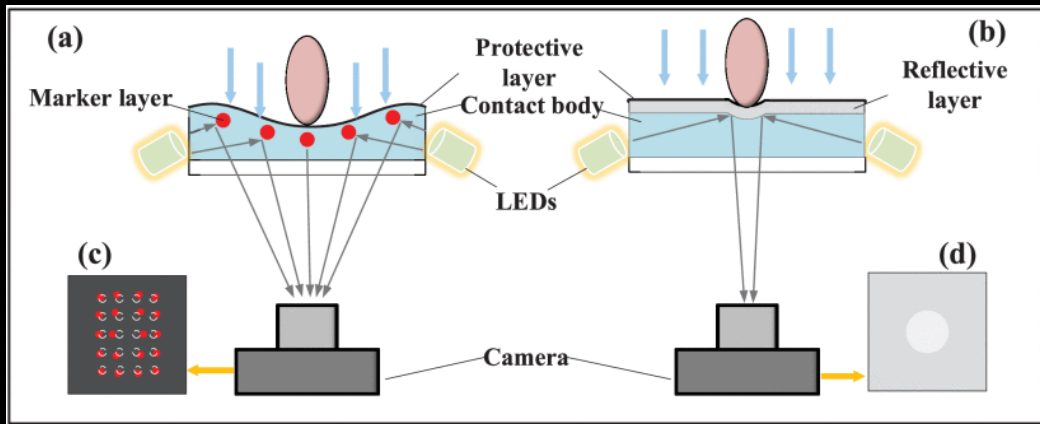


Fingertip force control

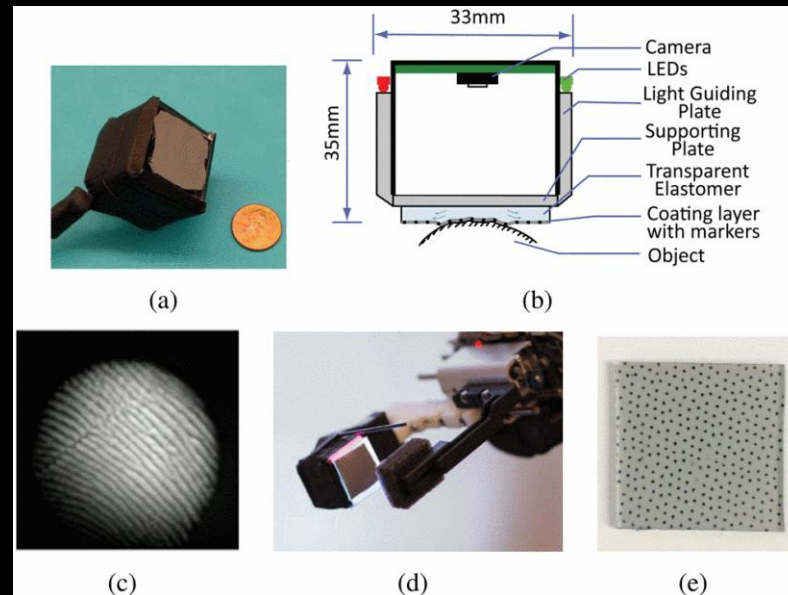


Tactile sensor: Optical Sensors (Vision-based)

- Capturing the inner side of the sensing surface using a camera or an event-based camera to measure surface deformation.



- (a) The markers move according to the deformation of the contact body.
(b) Surface deformation leads to irregular light refraction.

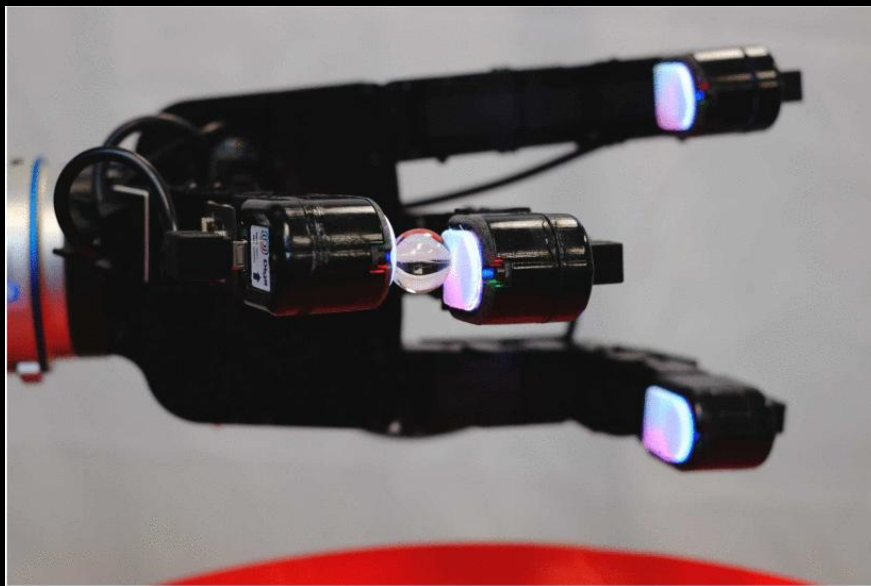


GelSights (2015)

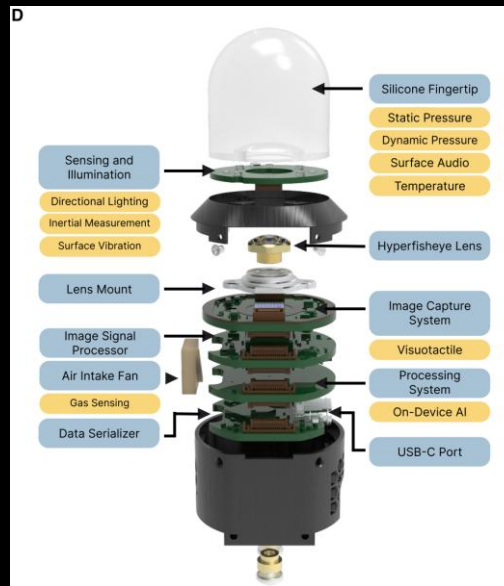


Tactile sensor: Optical Sensors (Vision-based)

- Capturing the inner side of the sensing surface using a camera or an event-based camera to measure surface deformation.



DIGIT (2020)



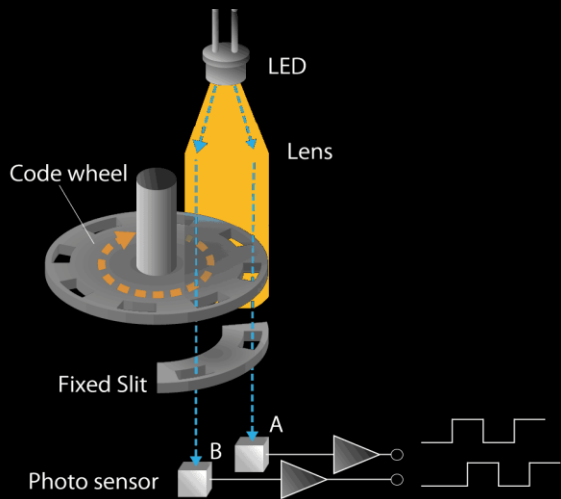
DIGIT 360 (2024)



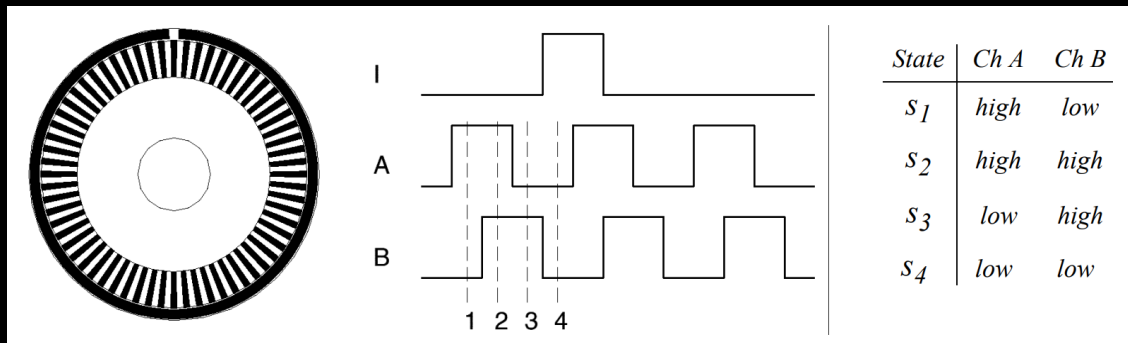
Joint Sensors



Joint Angle Sensor: Rotary Encoders (Optical)



Asahi Kasei Microdevices



Quadrature encoder:

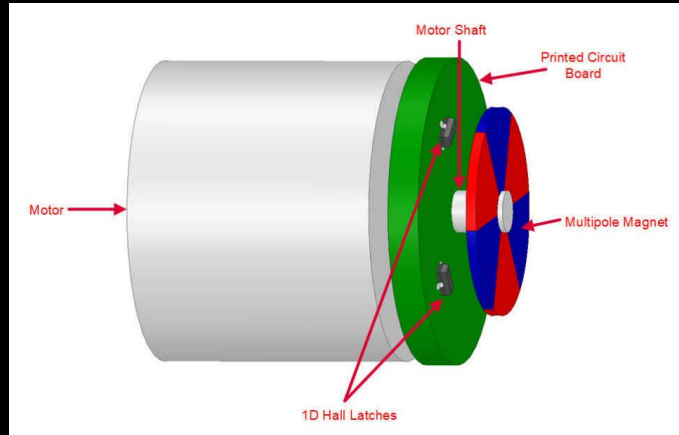
- A second illumination and detector pair is placed 90 degrees shifted with respect to the original.
- Four detectably different states improve the resolution by a factor of four with no change to the rotor disc.

Roland Siegwart; Illah Reza Nourbakhsh; Davide Scaramuzza, "Perception," in *Introduction to Autonomous Mobile Robots*, MIT Press, 2011, pp.101-263.

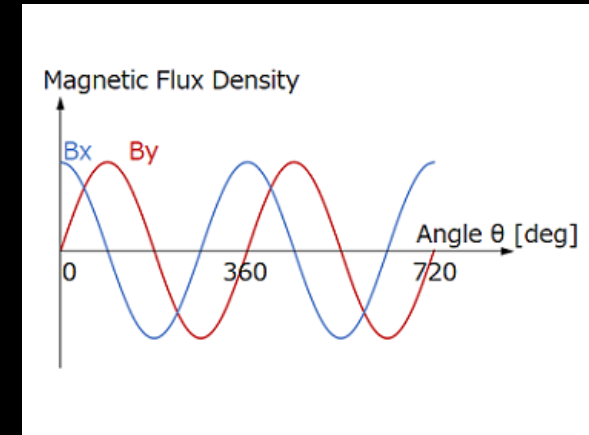
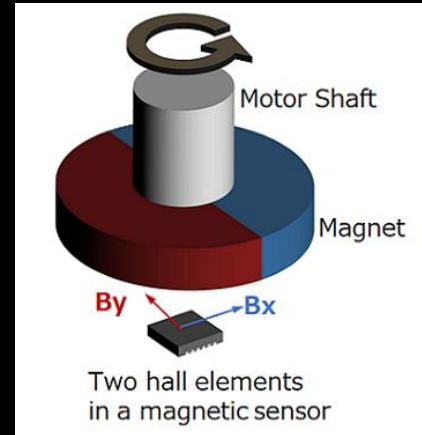
Joint Angle Sensor: Angle sensor (Magnetic)



Incremental Magnetic Encoder



Absolute Magnetic Encoder



Mesganaw, M., & Lara, I. (2022). *Differences between optical and magnetic incremental encoders*. Technical report, Texas Instruments.
<https://www.akm.com/global/en/products/rotation-angle-sensor/tutorial/magnetic-encoder/> 08.10.2025



Part 4: Characterization

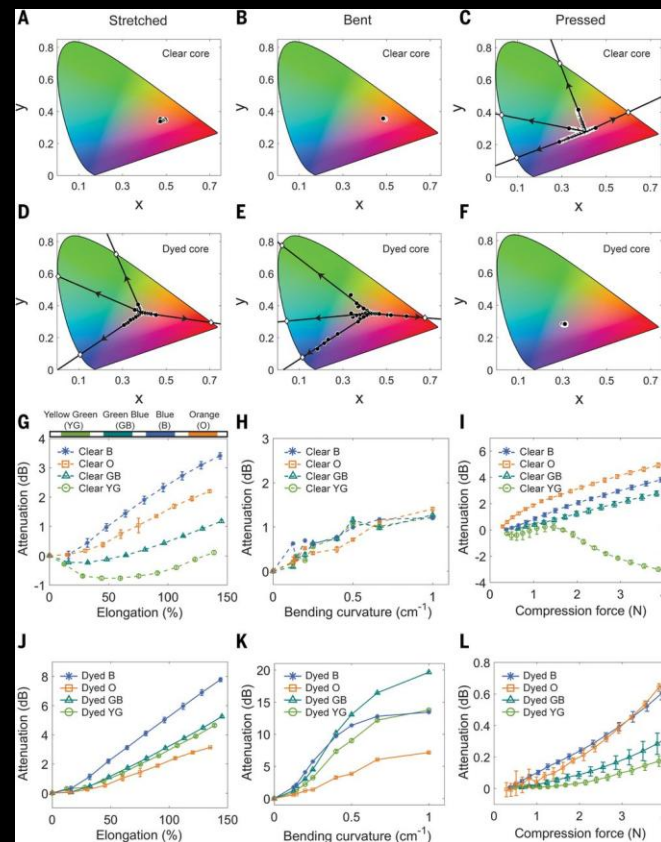
Characterization

Basic Characteristics:

Sensitivity, Resolution, Range, Linearity, Hysteresis, Accuracy, Precision, etc.

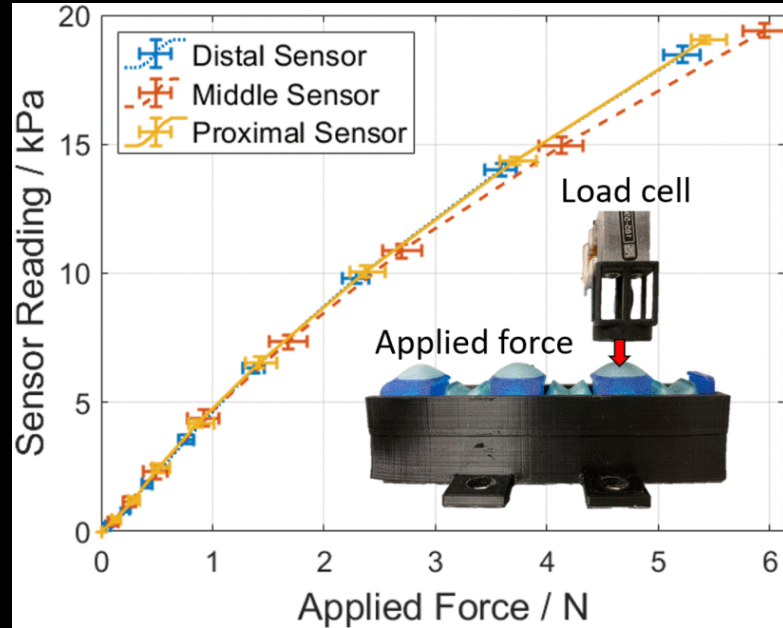
Dynamic Characteristics:

Response time, Bandwidth, etc.

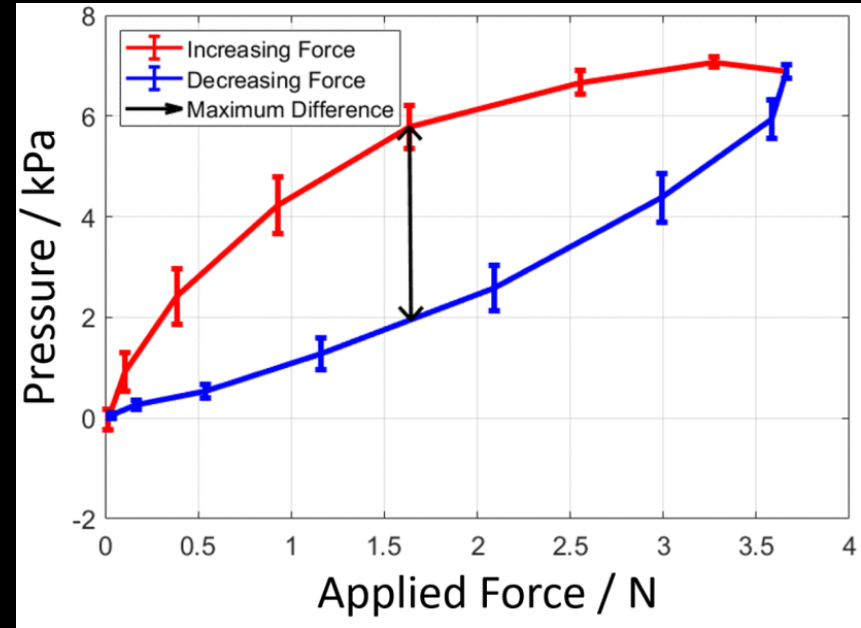


Characterization of SLIMS in different deformation modes.

Characterization



Static sensor output test

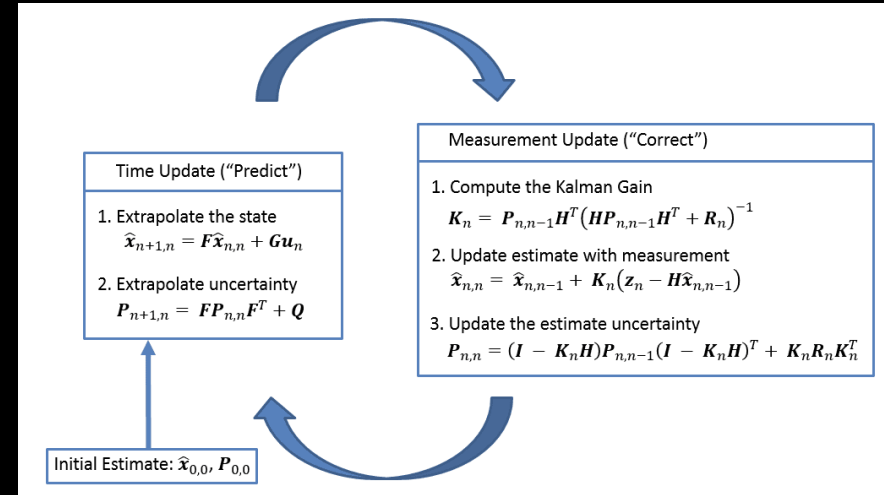
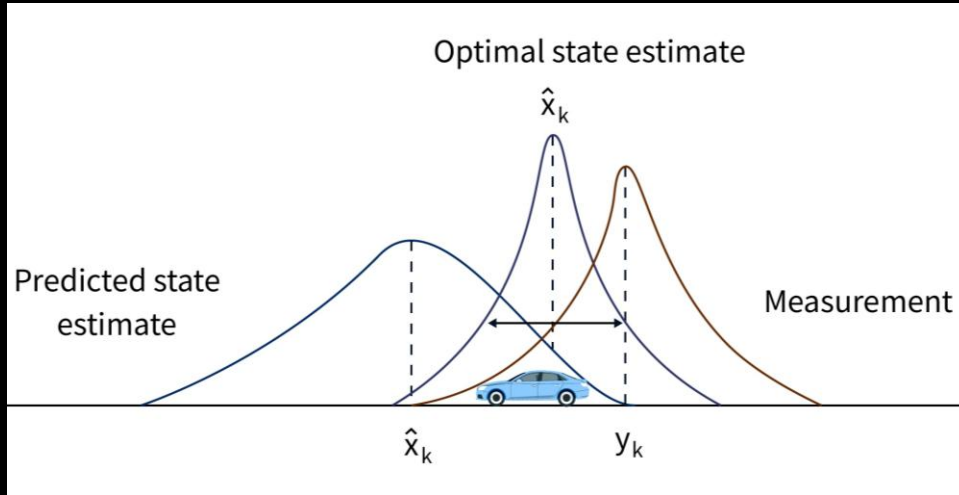


Hysteresis cyclic test



Part 5: Kalman Filter

Kalman Filter



1. Prediction: Predict the current state using the system model.
2. Correction: Combine the prediction with noisy sensor measurements based on their uncertainties.

Kalman Filter



Optimal recursive algorithm for estimating the state of a linear dynamic system from noisy measurements.

- Requirements
 - Linear system, Gaussian noise, Known system model
- Alternatives
 - Extended Kalman Filter (EKF), Unscented Kalman Filter (UKF), Particle Filter (PF)

Check out next semester's "Recursive estimation" class by Prof. D'Andrea.

Sensing Summary

- Sensing
 - Classification of Robotic Sensor
- Why Sensing Matters
- Sensing Mechanisms
 - Tactile sensors
 - Joint sensors
- Characterization
- Kalman Filter

