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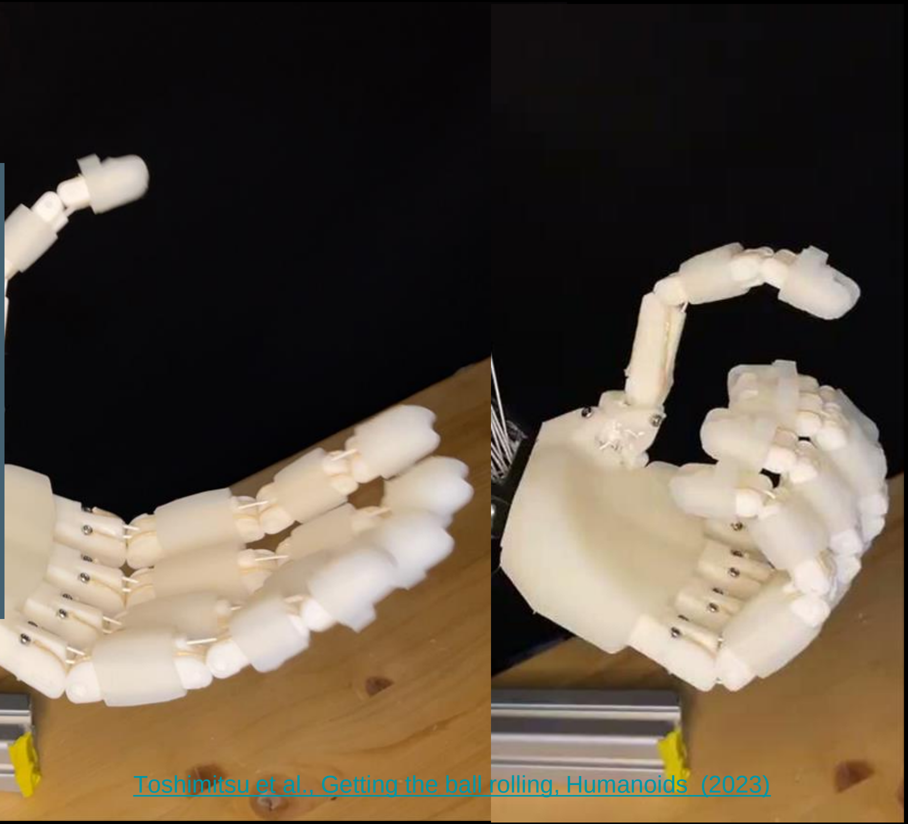
Sensors in Dexterous Manipulation

Robert Katzschmann

Soft Robotics Lab



Toshimitsu et al., Getting the ball rolling, Humanoids (2023)

SoftRobotics Laboratory

Plan for Today

1. Sensing

2. Sensing Mechanisms

3. Characterization

4. Kalman Filter

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Part 1: Sensing

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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.

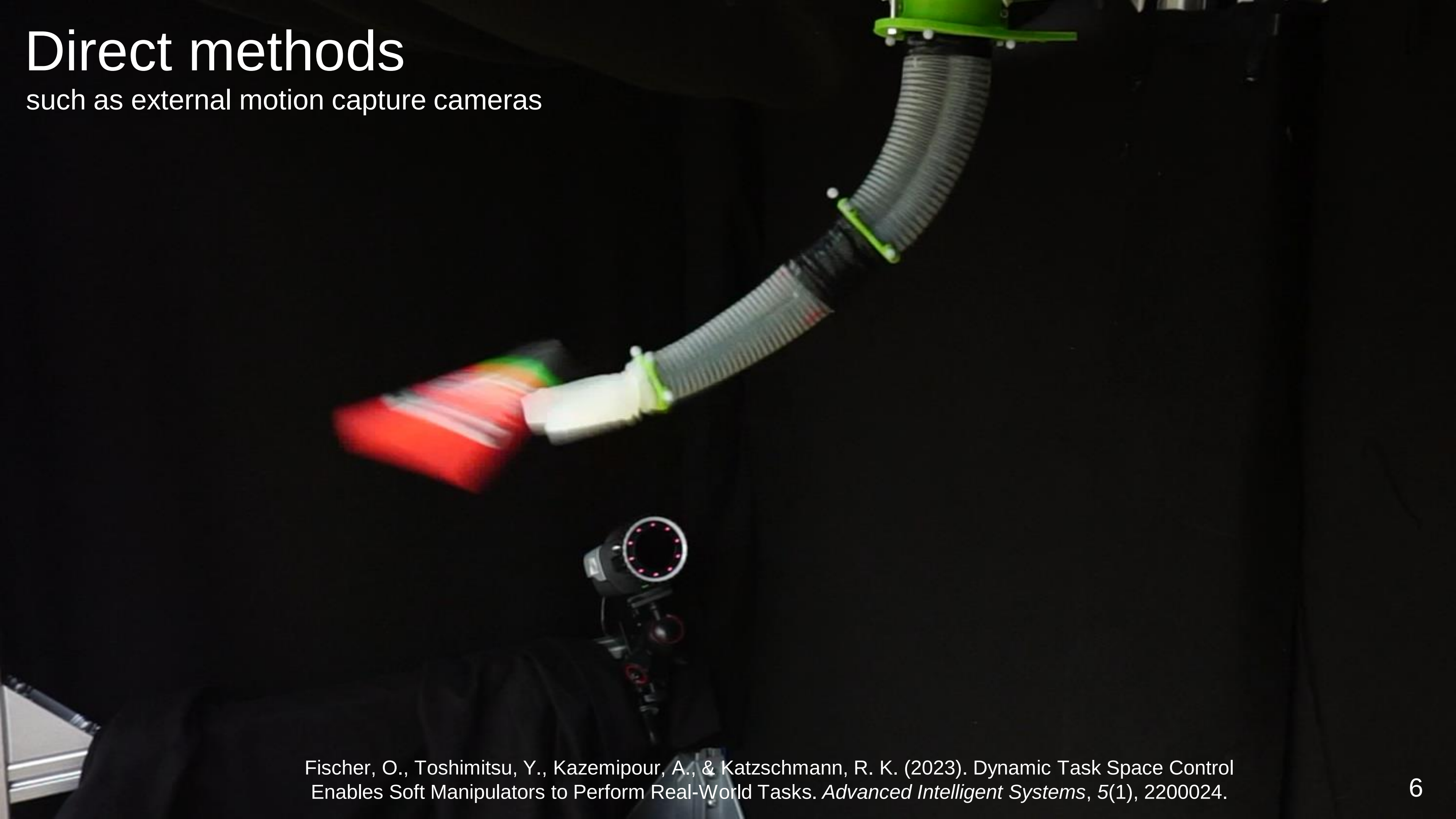
Sensing the pose: two methods

- 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

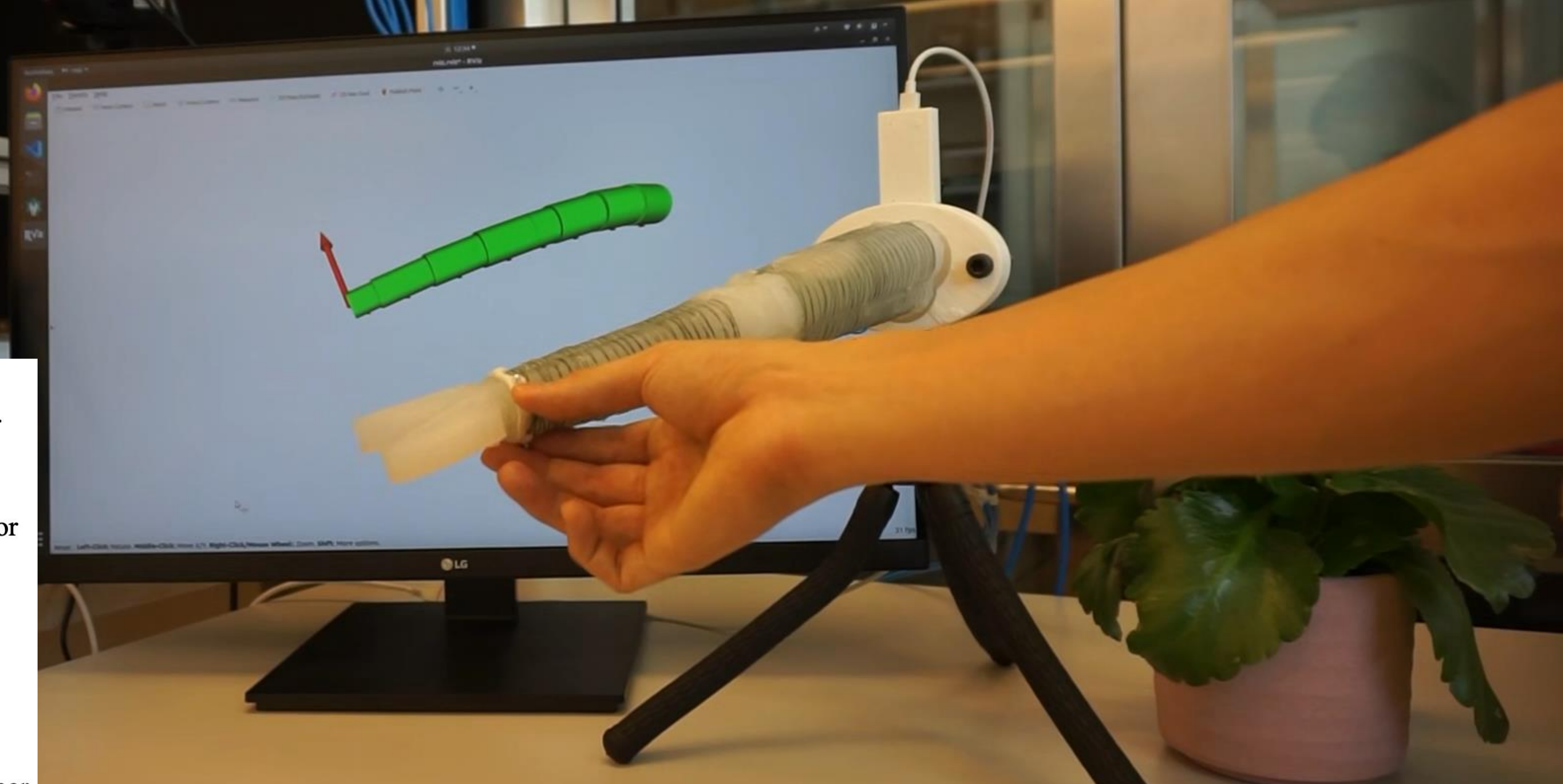
such as external motion capture cameras

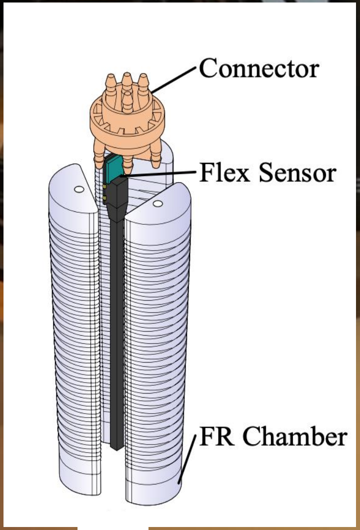


Fischer, O., Toshimitsu, Y., Kazemipour, A., & Katzschmann, R. K. (2023). Dynamic Task Space Control Enables Soft Manipulators to Perform Real-World Tasks. *Advanced Intelligent Systems*, *5*(1), 2200024.

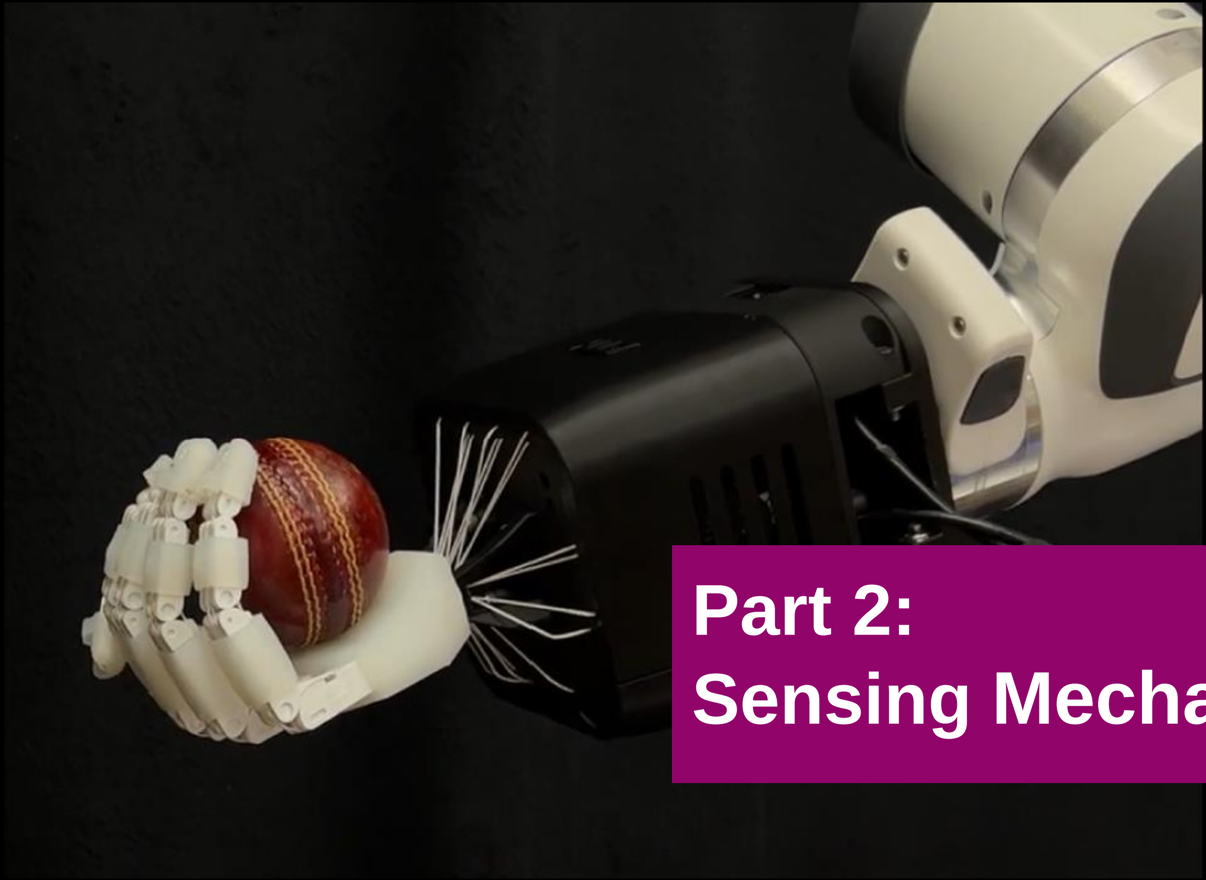
Indirect methods

such as built-in flex sensors





Toshimitsu, Y., Wong, K. W., Buchner, T., & Katzschmann, 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.



Part 2: Sensing Mechanisms

Sensing Mechanisms

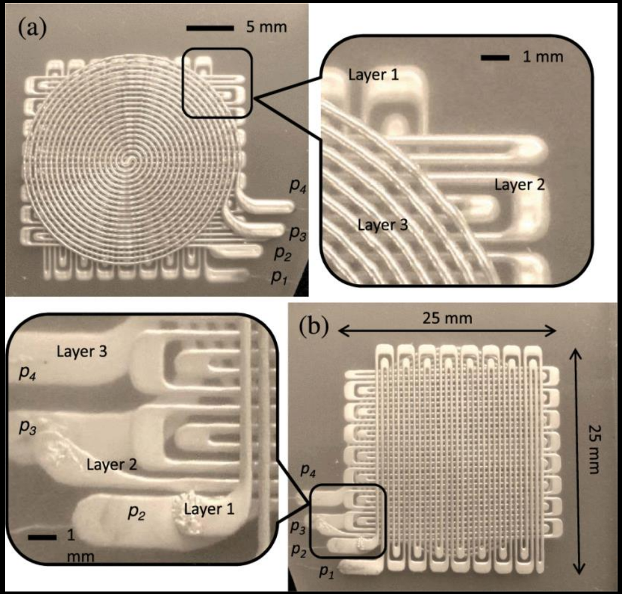
- Resistive Sensors and Piezoresistive Sensors
- Capacitive Sensors
- Magnetic Sensors
- Optical Sensors
- etc…

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.

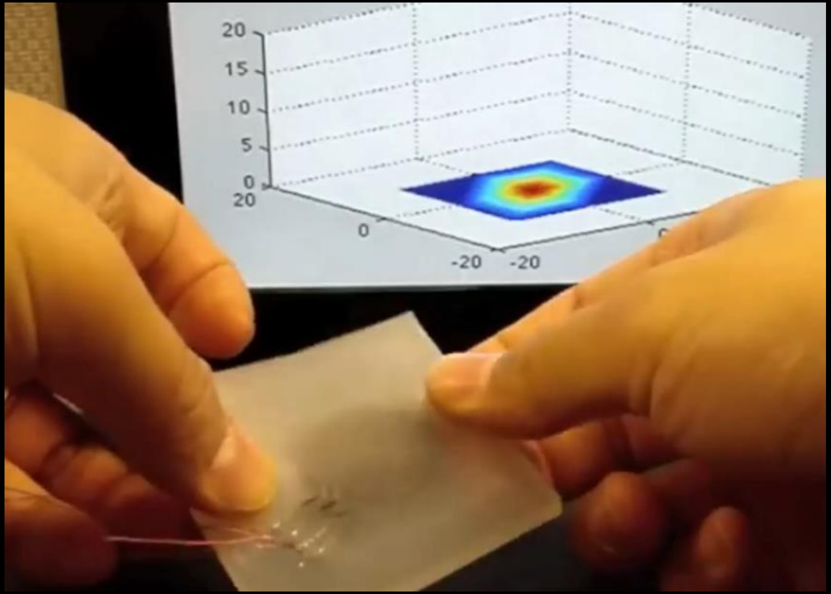
Tactile Sensors

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

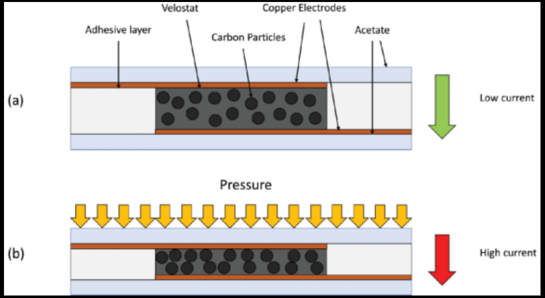


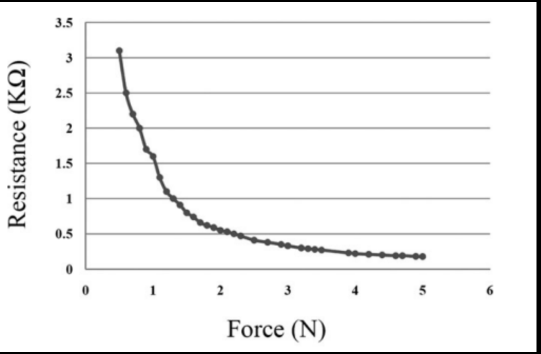
Hegde, C., Su, J., Tan, J. M. R., He, K., Chen, X., & Magdassi, S. (2023). Sensing in soft robotics. *ACS nano*, *17*(16), 15277-15307.
Park, Y. L., Chen, B. R., & Wood, R. J. (2012). Design and fabrication of soft artificial skin using embedded microchannels and liquid conductors. *IEEE Sensors journal*, *12*(8), 2711-2718.

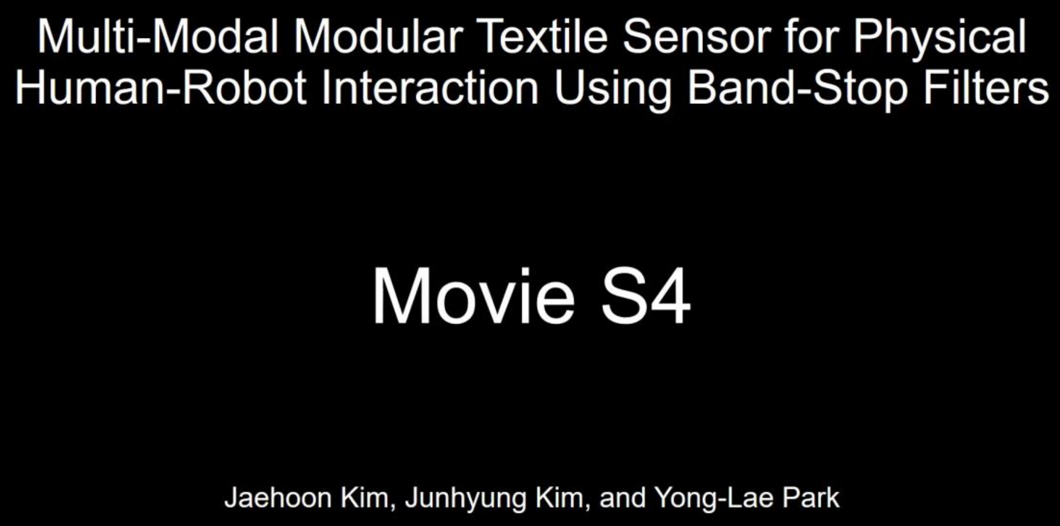
Tactile sensor: Resistive and Piezoresistive Sensors

- 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



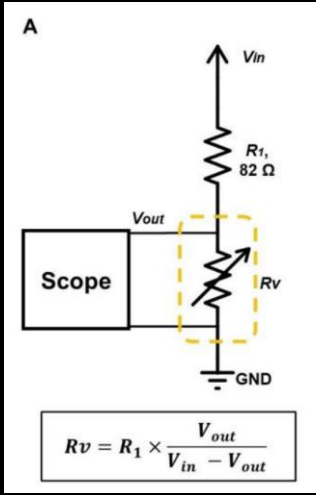




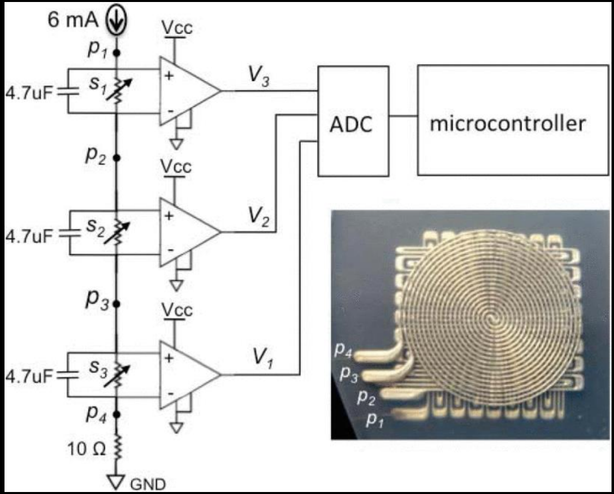
Hegde, C., Su, J., Tan, J. M. R., He, K., Chen, X., & Magdassi, S. (2023). Sensing in soft robotics. *ACS nano*, *17*(16), 15277-15307.
Yuan, L., Qu, H., & Li, J. (2021). Velostat sensor array for object recognition. *IEEE Sensors Journal*, *22*(2), 1692-1704.
Kalantari, M., Dargahi, J., Kövecses, J., 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

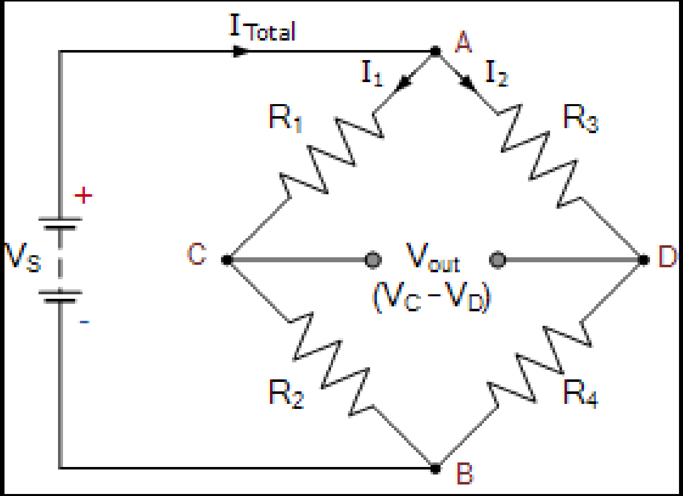
- Measurement using voltage divider, constant current source, and Wheatstone bridge circuits with analog-to-digital converter (ADC).



Voltage divider



Constant current source

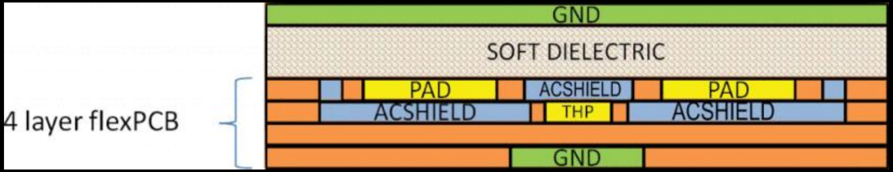


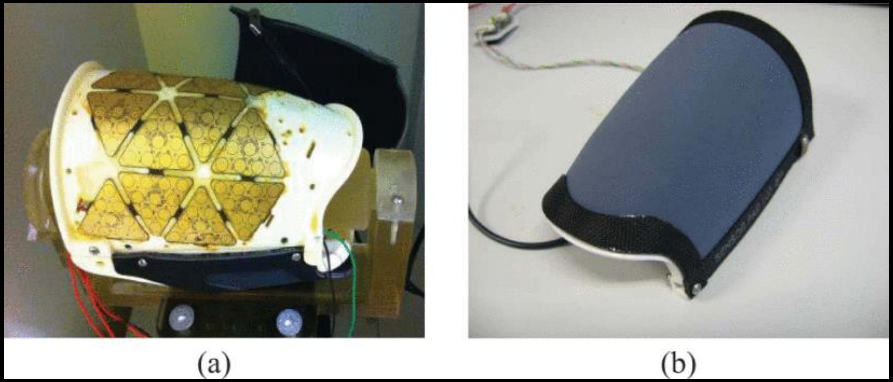
Wheatstone bridge

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.
Park, Y. L., Chen, B. R., & Wood, R. J. (2012). Design and fabrication of soft artificial skin using embedded microchannels and liquid conductors. *IEEE Sensors journal*, *12*(8), 2711-2718.
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.
https://www.electronics-tutorials.ws/blog/wheatstone-bridge.html, 12.10.2025

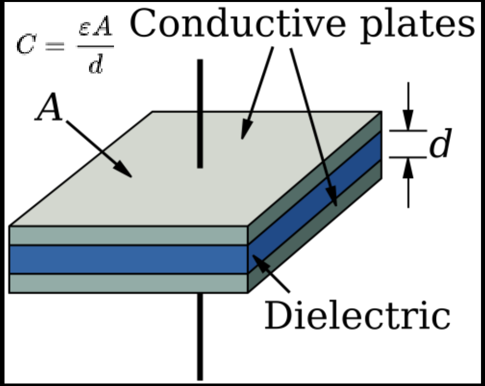
Tactile sensor: Capacitive Sensors

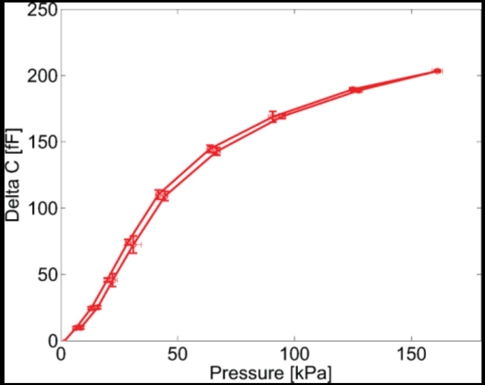
- Using capacitance changes.
- Parallel plate capacitors are commonly used because of their simple structure.





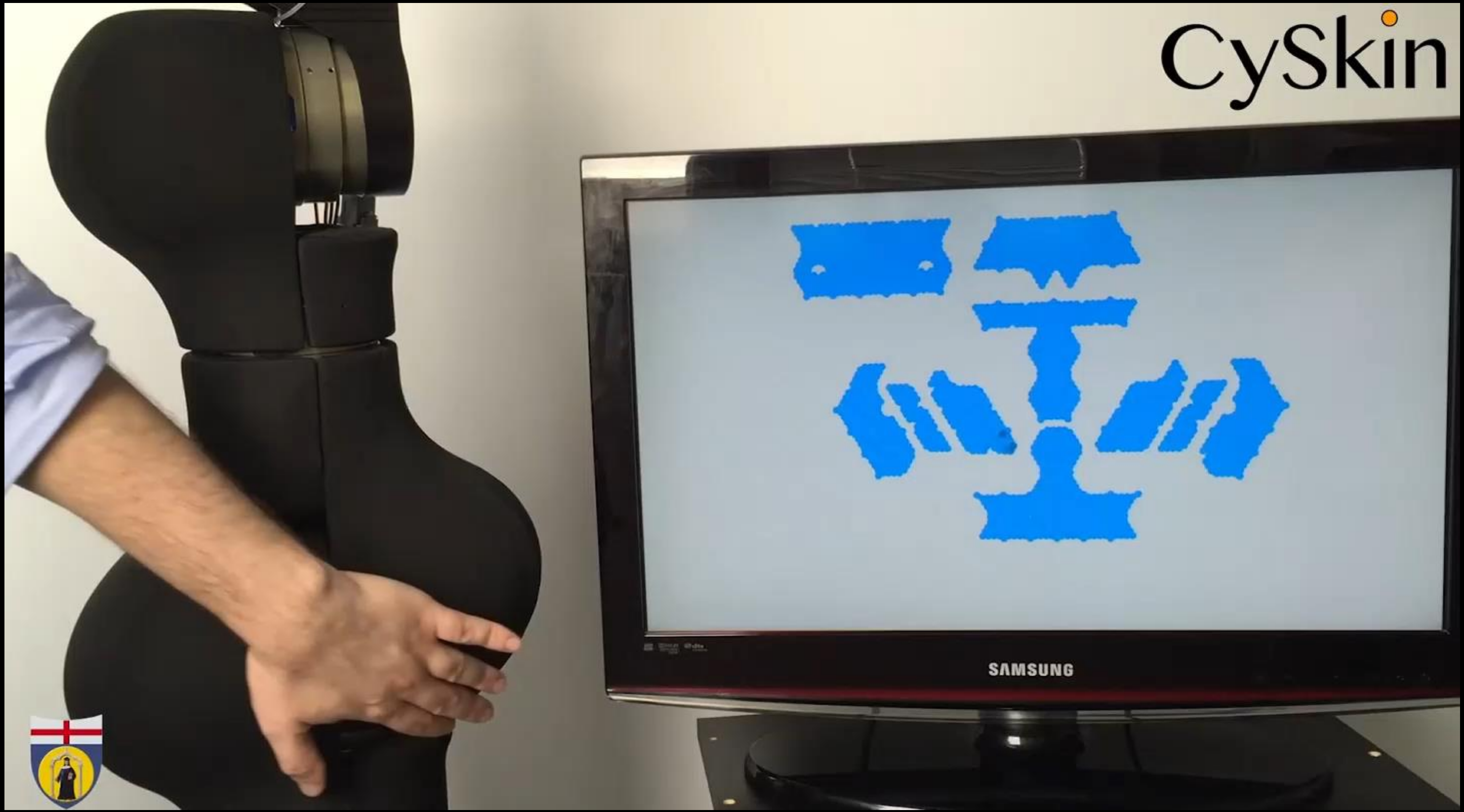
Capacitive sensor array





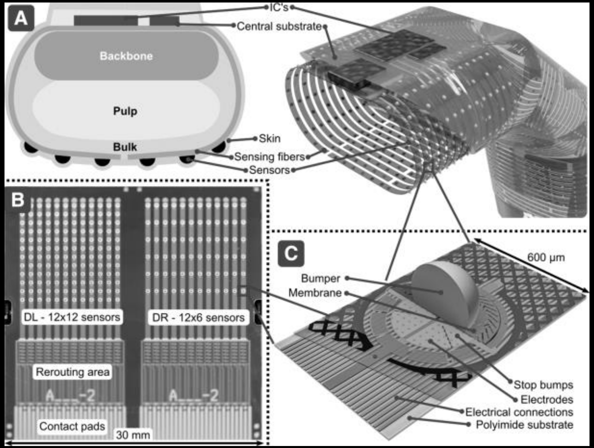
Maiolino, P., Maggiali, M., Cannata, G., Metta, G., & Natale, L. (2013). A flexible and robust large scale capacitive tactile system for robots. *IEEE Sensors Journal*, *13*(10), 3910-3917.
https://en.wikipedia.org/wiki/Capacitor, 11.10.2025
https://youtu.be/sU1KrwcEGyI?si=scjuyPLzZXx2n9g1, 12.10.2025

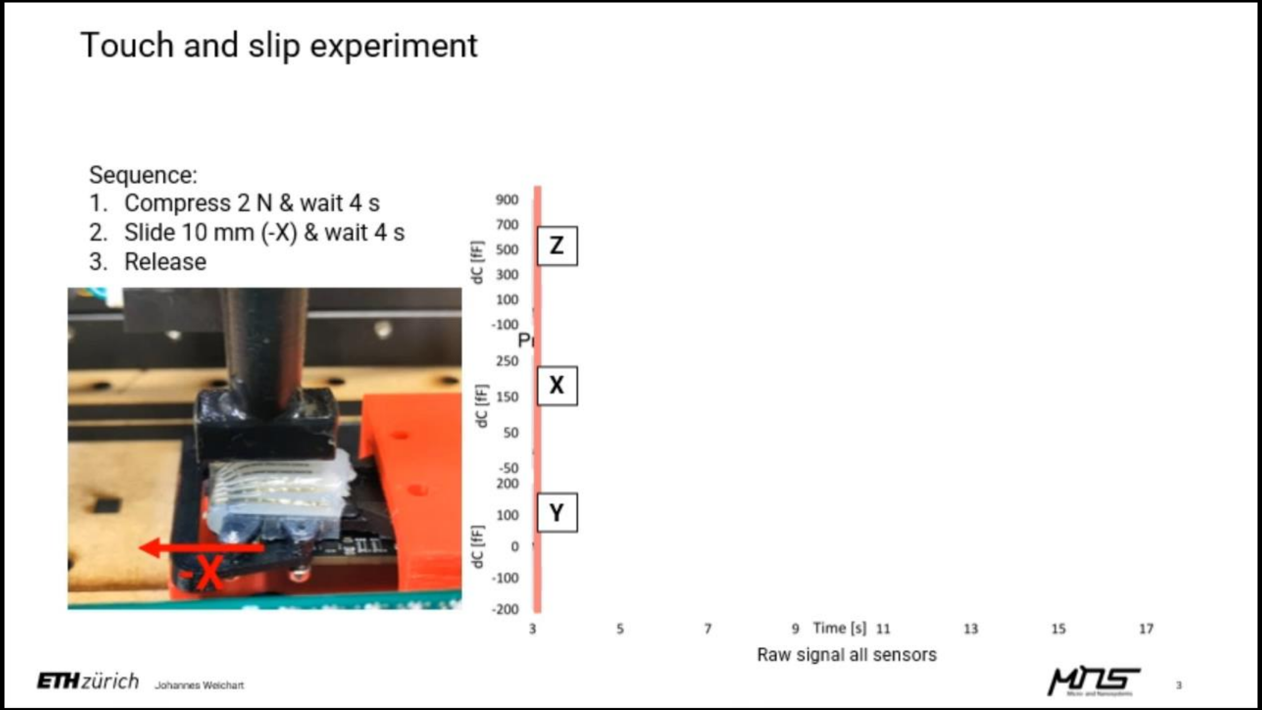
Tactile sensor: Capacitive Sensors



Maiolino, P., Maggiali, M., Cannata, G., Metta, G., & Natale, L. (2013). A flexible and robust large scale capacitive tactile system for robots. *IEEE Sensors Journal*, *13*(10), 3910-3917.
https://en.wikipedia.org/wiki/Capacitor, 11.10.2025
https://youtu.be/sU1KrwcEGyI?si=scjuyPLzZXx2n9g1, 12.10.2025

Tactile sensor: Capacitive Sensors





Weichart, J., Sivananthaguru, P., Coulter, F. B., Burger, T., & Hierold, C. (2024). Artificial Fingertip with Embedded Fiber-Shaped Sensing Arrays for High Resolution Tactile Sensing. *Soft Robotics*, *11*(4), 573-584.

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Tactile sensor: Capacitive Sensors

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

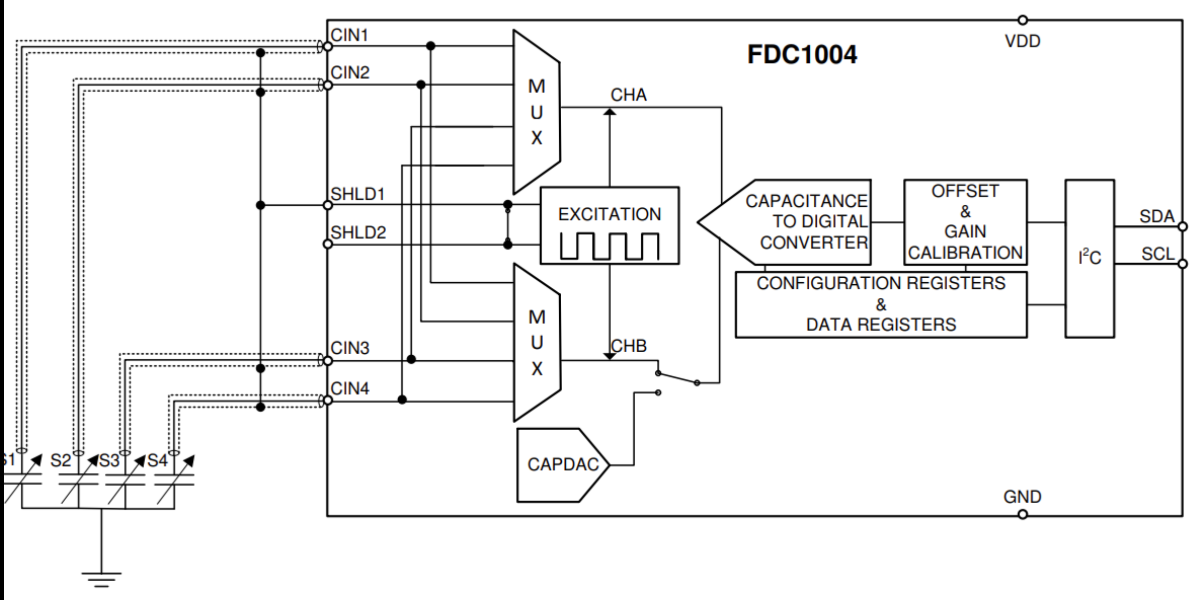
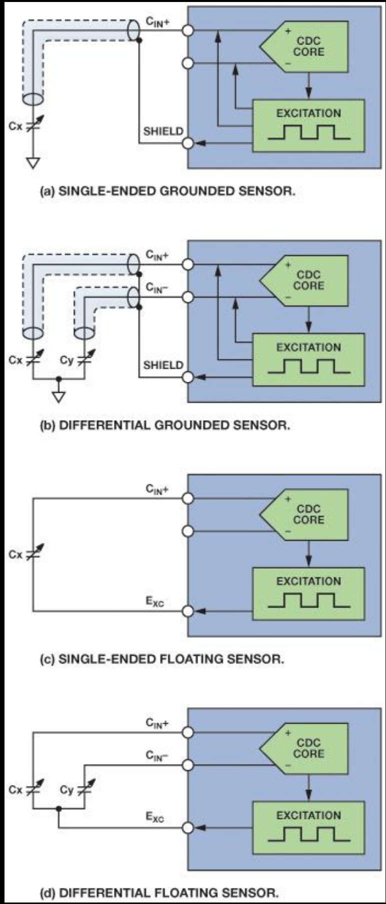


Figure 6-1. Single-Ended Configuration with CAPDAC Disabled

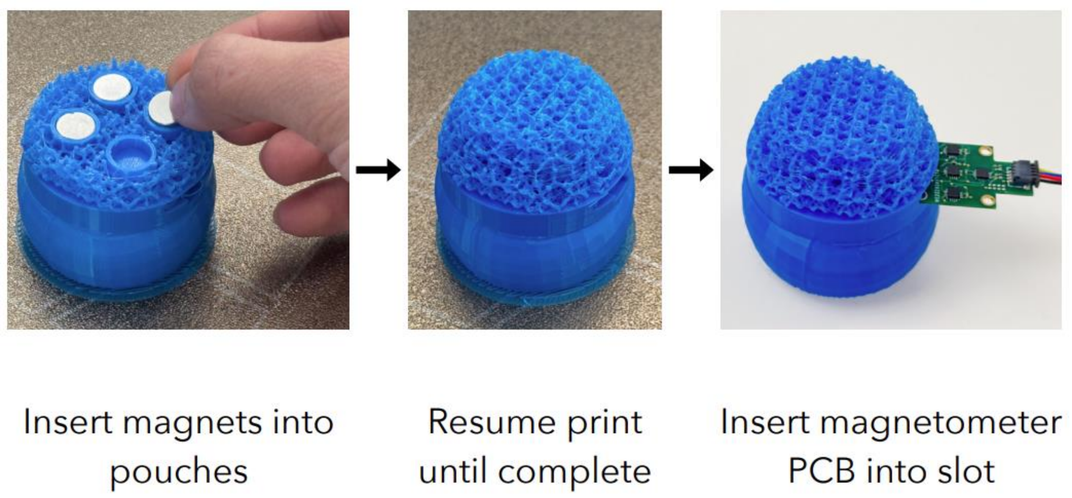


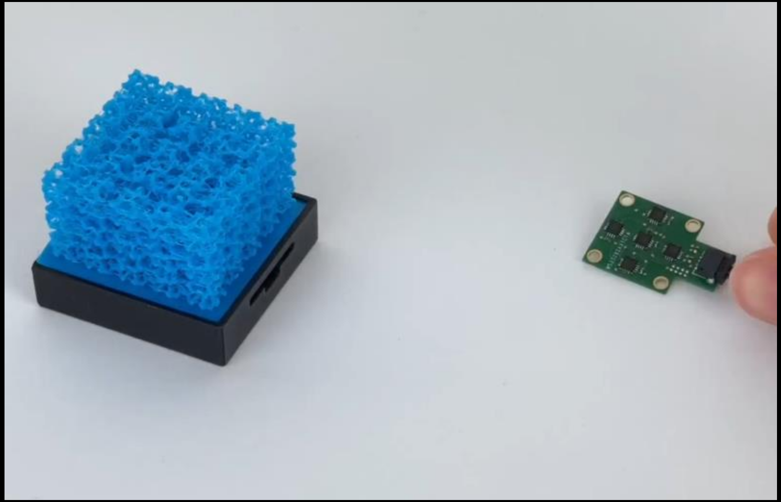
Sensor electrical configurations.

FDC1004 4-Channel Capacitance-to-Digital Converter for Capacitive Sensing Applications datasheet (Rev. C), Texas Instruments (2024).
https://www.analog.com/en/resources/analog-dialogue/articles/capacitance-to-digital-converter-technology-healthcare.html, 12.10.2025

Tactile sensor: Magnetic Sensors

- Using changes in magnetic field.





Magnetic tactile sensor

Pattabiraman, V., Huang, Z., Panozzo, D., Zorin, D., Pinto, L., & Bhirangi, R. (2025). eFlesh: Highly customizable Magnetic Touch Sensing using Cut-Cell Microstructures. *arXiv preprint arXiv:2506.09994*.

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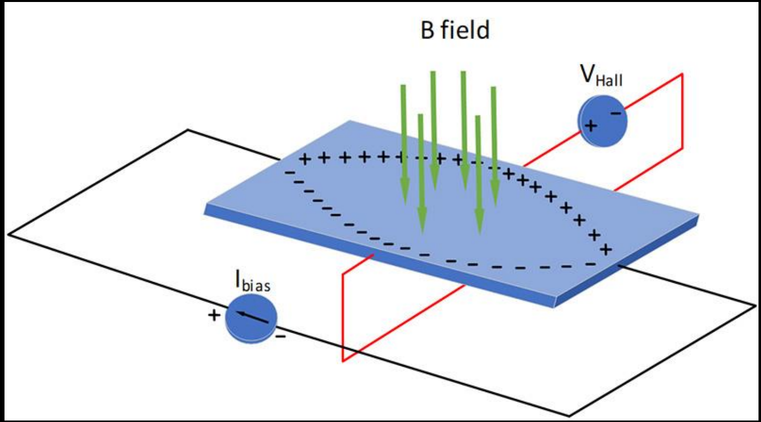
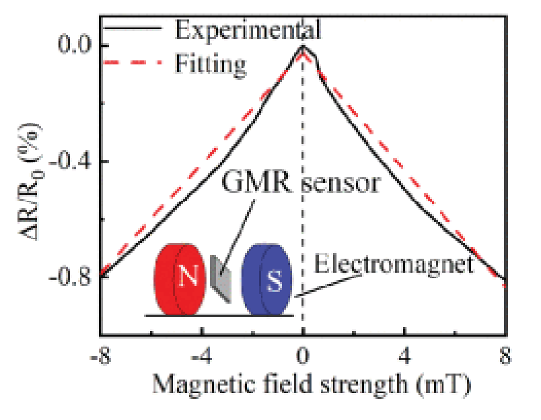
Tactile sensor: Magnetic Sensors

- 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

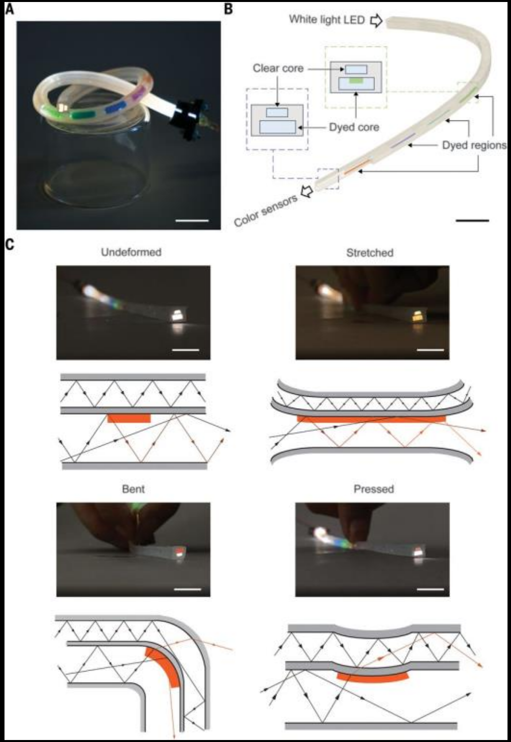


Resistance change in a magnetoresistive sensor

https://www.ti.com/document-viewer/lit/html/SSZT164, 12.10.2025
Li, J., Qin, H., Song, Z., Hou, L., & Li, H. (2024). A tactile sensor based on magnetic sensing: Design and mechanism. *IEEE Transactions on Instrumentation and Measurement*, *73*, 1-9.

Tactile sensor: Optical Sensors

- Using light intensity or color change.

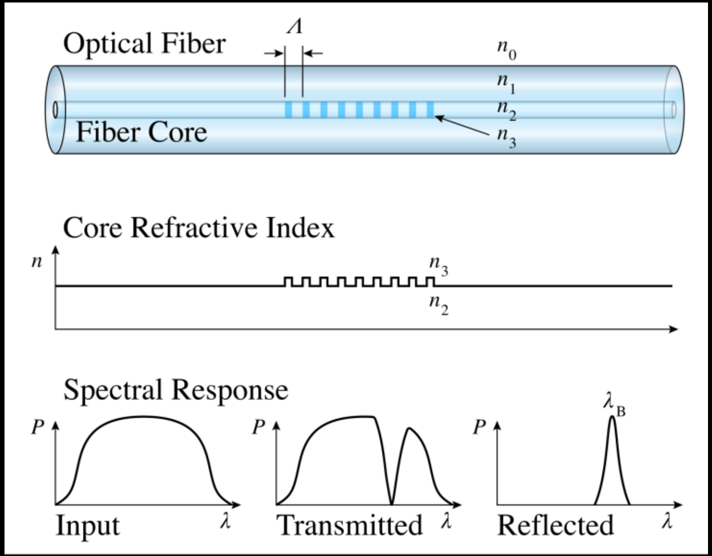


Silica-based distributed fiber-optic sensor systems

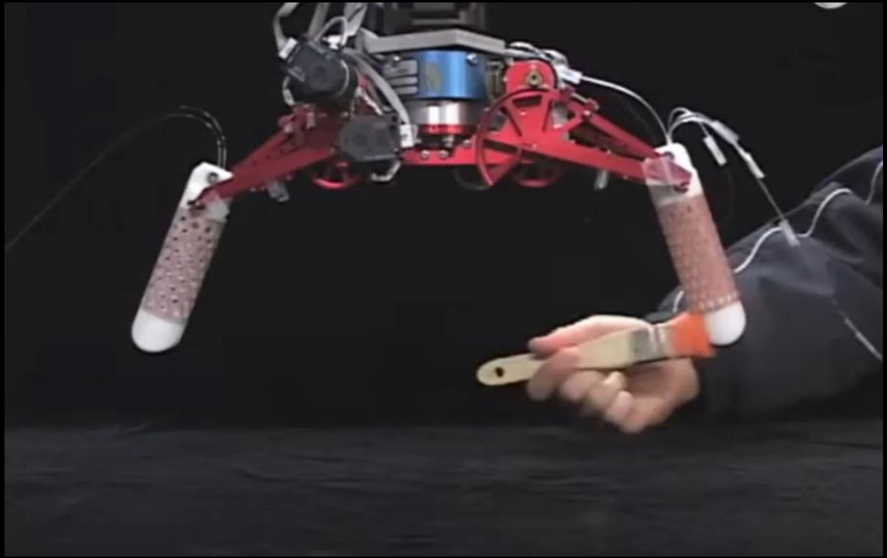
Bai, H., Li, S., Barreiros, J., Tu, Y., Pollock, C. R., & Shepherd, R. F. (2020). Stretchable distributed fiber-optic sensors. *Science*, *370*(6518), 848-852.

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

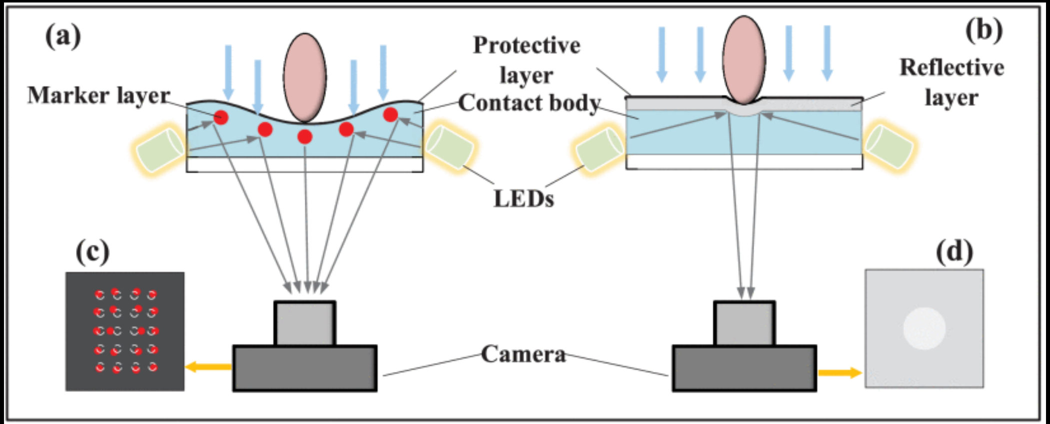


Fingertip force control

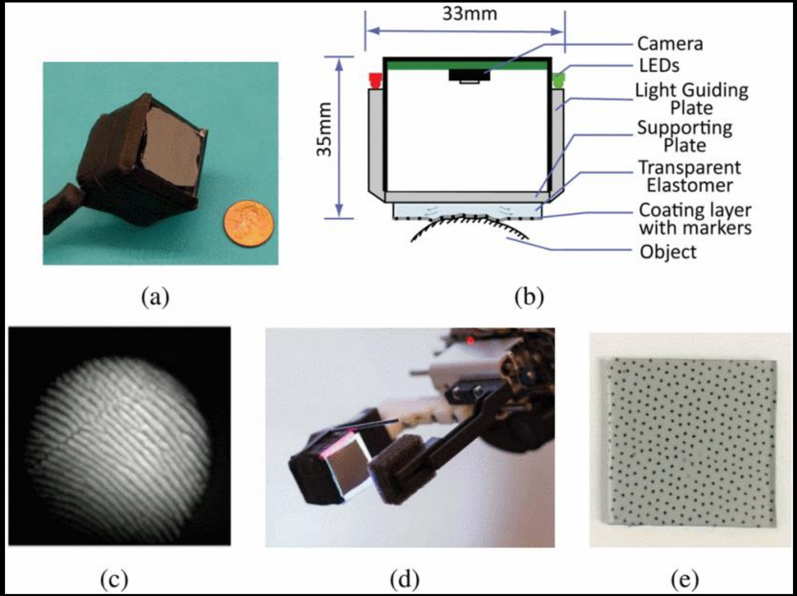
Park, Y. L., Ryu, S. C., Black, R. J., Chau, K. K., Moslehi, B., & Cutkosky, M. R. (2009). Exoskeletal force-sensing end-effectors with embedded optical fiber-Bragg-grating sensors. *IEEE Transactions on Robotics*, *25*(6), 1319-1331.
https://youtu.be/gO-6H1bi9PA?si=VnZgJxY6dbQQw8sO, 12.10.2025

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)

Zhang, S., Chen, Z., Gao, Y., Wan, W., Shan, J., Xue, H., ... & Fang, B. (2022). Hardware technology of vision-based tactile sensor: A review. *IEEE Sensors Journal*, *22*(22), 21410-21427.
Yuan, W., Li, R., Srinivasan, M. A., & Adelson, E. H. (2015, May). Measurement of shear and slip with a GelSight tactile sensor. In *2015 IEEE International Conference on Robotics and Automation (ICRA)* (pp. 304-311). IEEE.

Tactile sensor: Optical Sensors (Vision-based)

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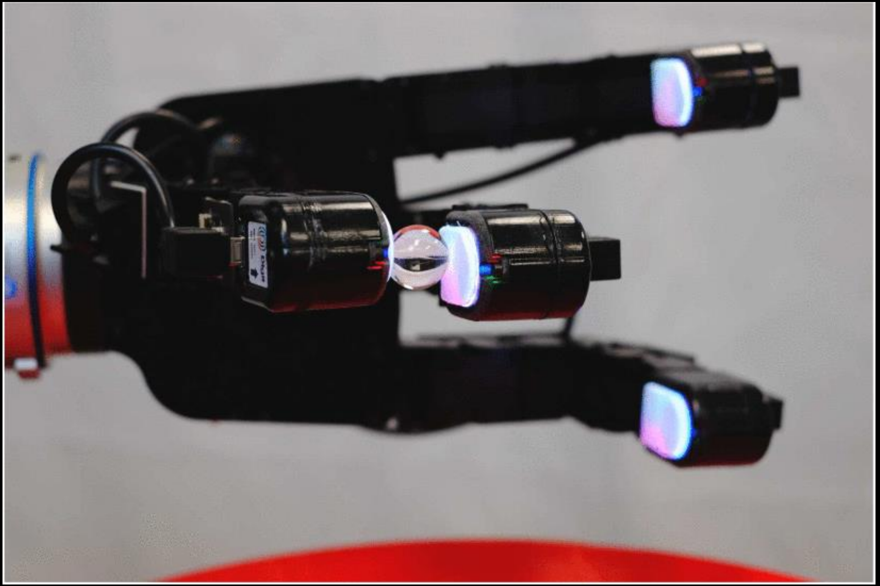
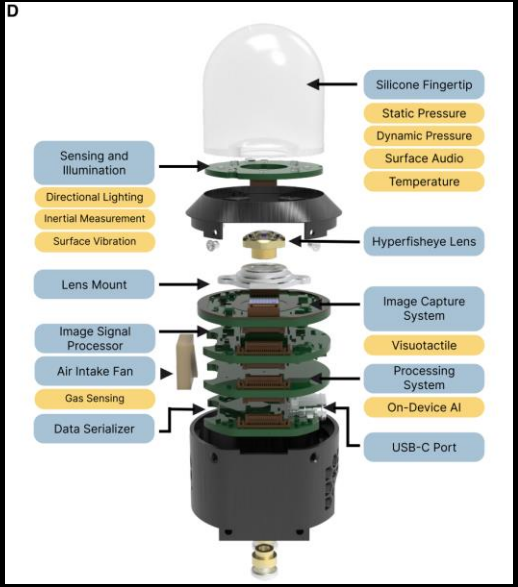


DIGIT (2020)



DIGIT 360 (2024)

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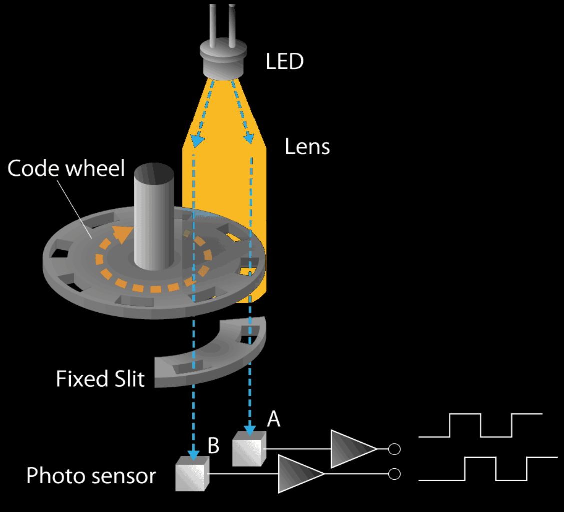
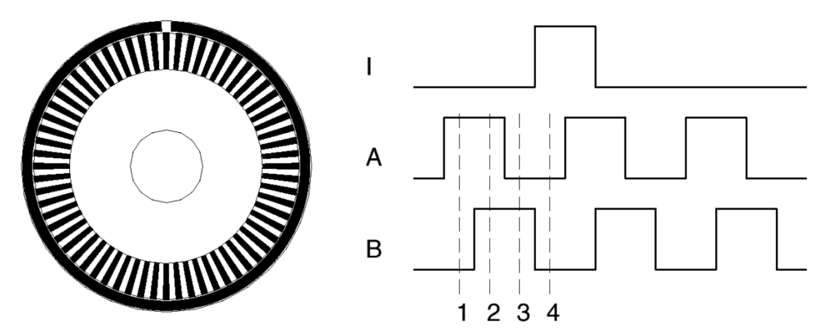
Lambeta, M., Chou, P. W., Tian, S., Yang, B., Maloon, B., Most, V. R., ... & Calandra, R. (2020). Digit: A novel design for a low-cost compact high-resolution tactile sensor with application to in-hand manipulation. *IEEE Robotics and Automation Letters*, *5*(3), 3838-3845.
Lambeta, M., Wu, T., Sengul, A., Most, V. R., Black, N., Sawyer, K., ... & Calandra, R. (2024). Digitizing touch with an artificial multimodal fingertip. *arXiv preprint arXiv:2411.02479*.

Joint Sensors

Joint Angle Sensor: Rotary Encoders (Optical)



Asahi Kasei Microdevices



State	Ch A	Ch B
s_1	*high*	*low*
s_2	*high*	*high*
s_3	*low*	*high*
s_4	*low*	*low*

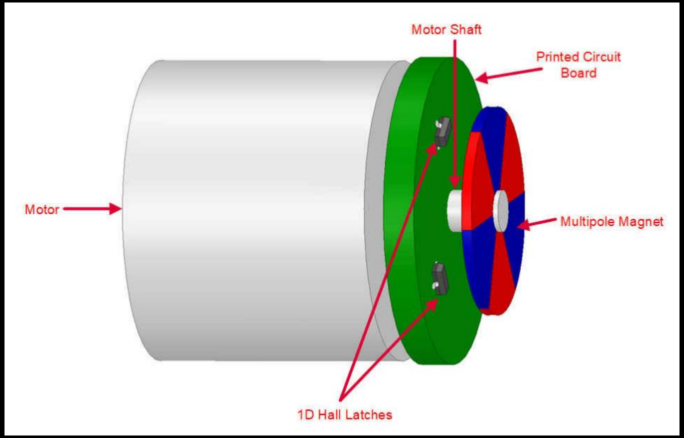
Quadrature encoder:

- 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.

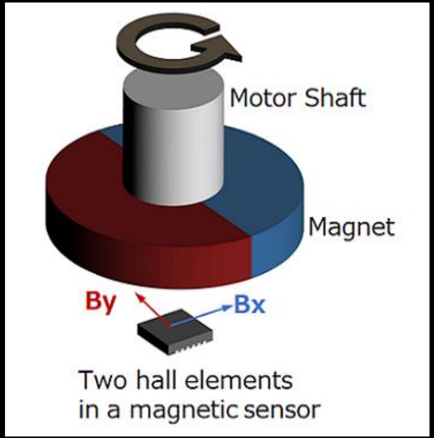
Roland Siegwart; Illah Reza Nourbakhsh; Davide Scaramuzza, "Perception," in *Introduction to Autonomous Mobile Robots* , MIT Press, 2011, pp.101-263.

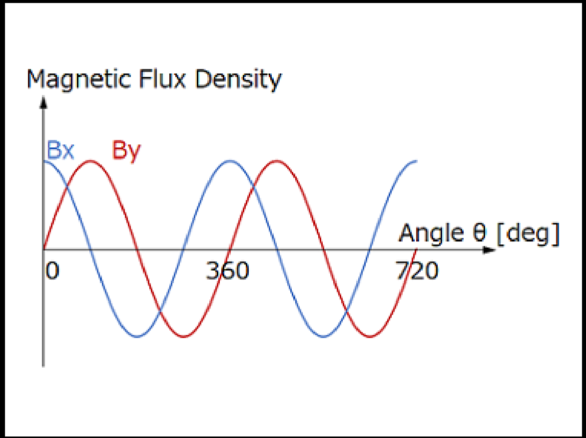
Joint Angle Sensor: Angle sensor (Magnetic)

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

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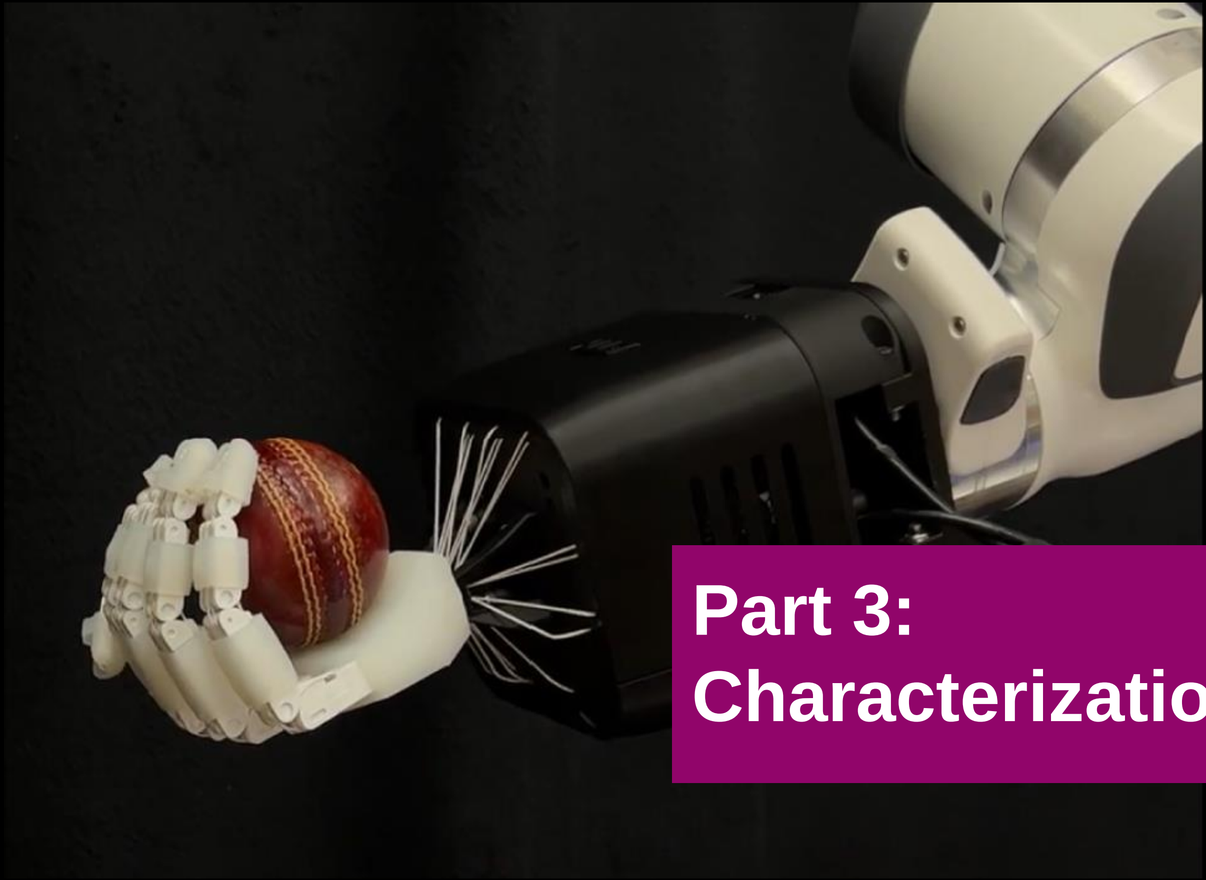

Part 3: Characterization

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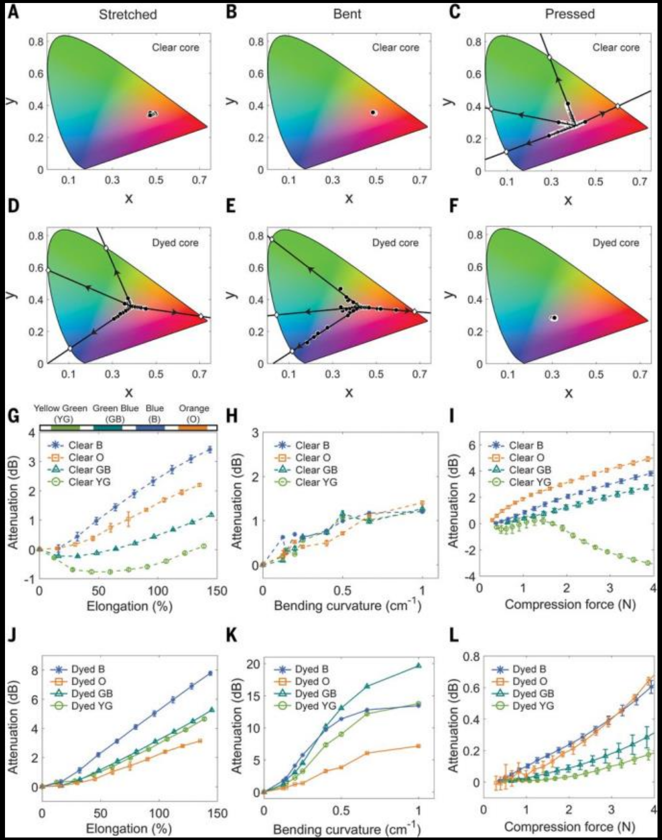
Characterization

Basic Characteristics:

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

Dynamic Characteristics:

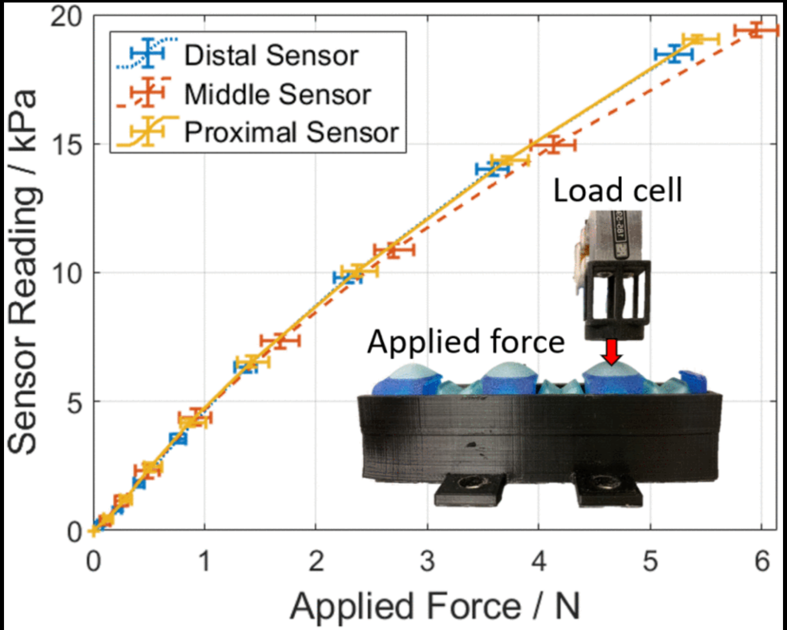
Response time, Bandwidth, etc.



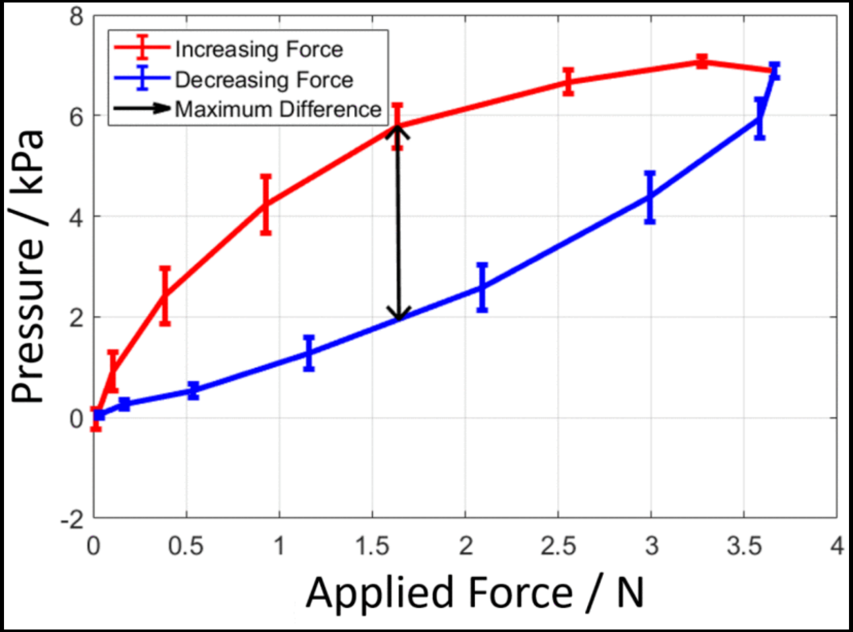
Characterization of SLIMS in different deformation modes.

Bai, H., Li, S., Barreiros, J., Tu, Y., Pollock, C. R., & Shepherd, R. F. (2020). Stretchable distributed fiber-optic sensors. *Science*, *370*(6518), 848-852.

Characterization



Static sensor output test



Hysteresis cyclic test

Shorthose, O., Albini, A., He, L., & Maiolino, P. (2022). Design of a 3D-printed soft robotic hand with integrated distributed tactile sensing. *IEEE Robotics and Automation Letters*, *7*(2), 3945-3952.

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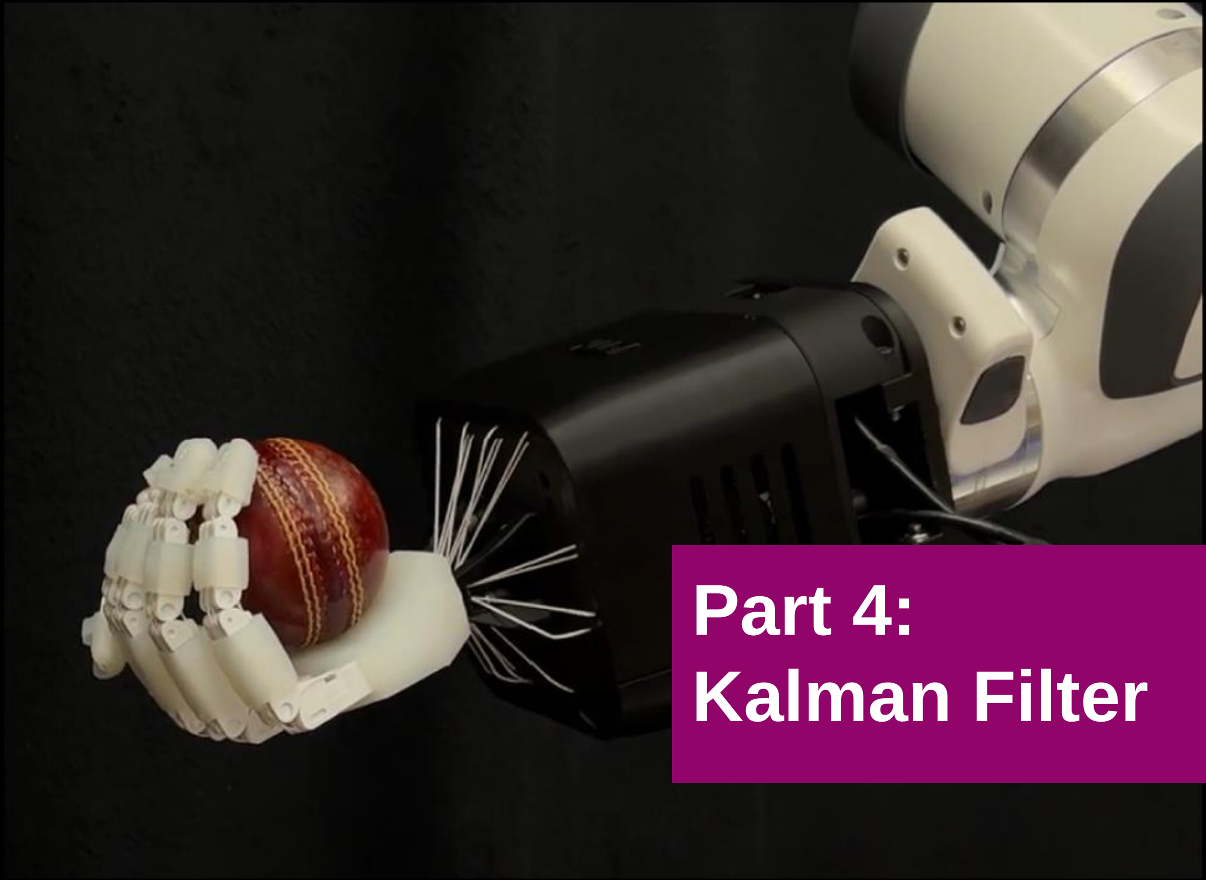

Part 4:
Kalman Filter

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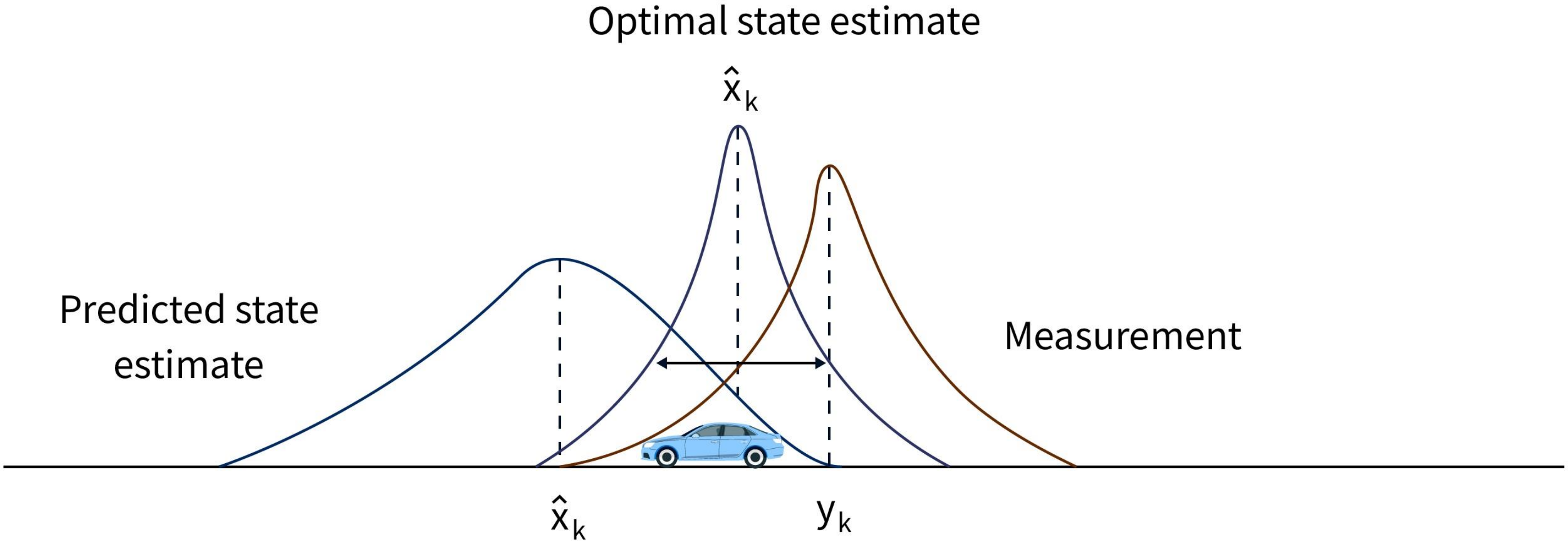
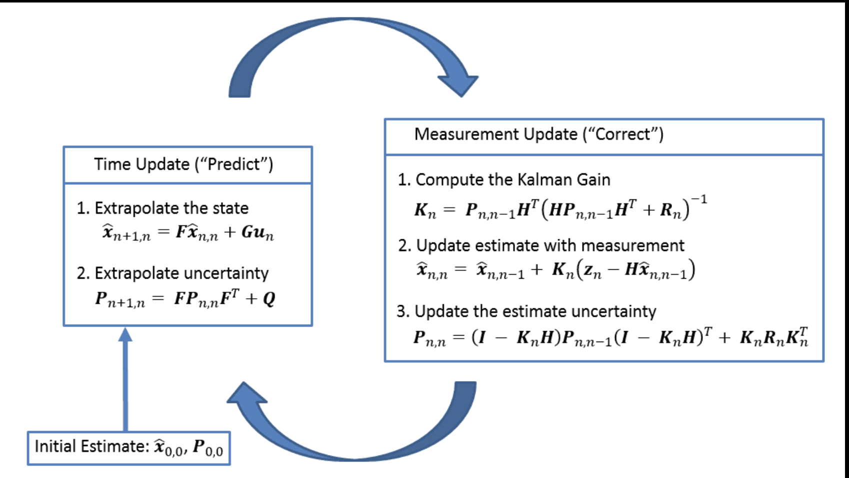
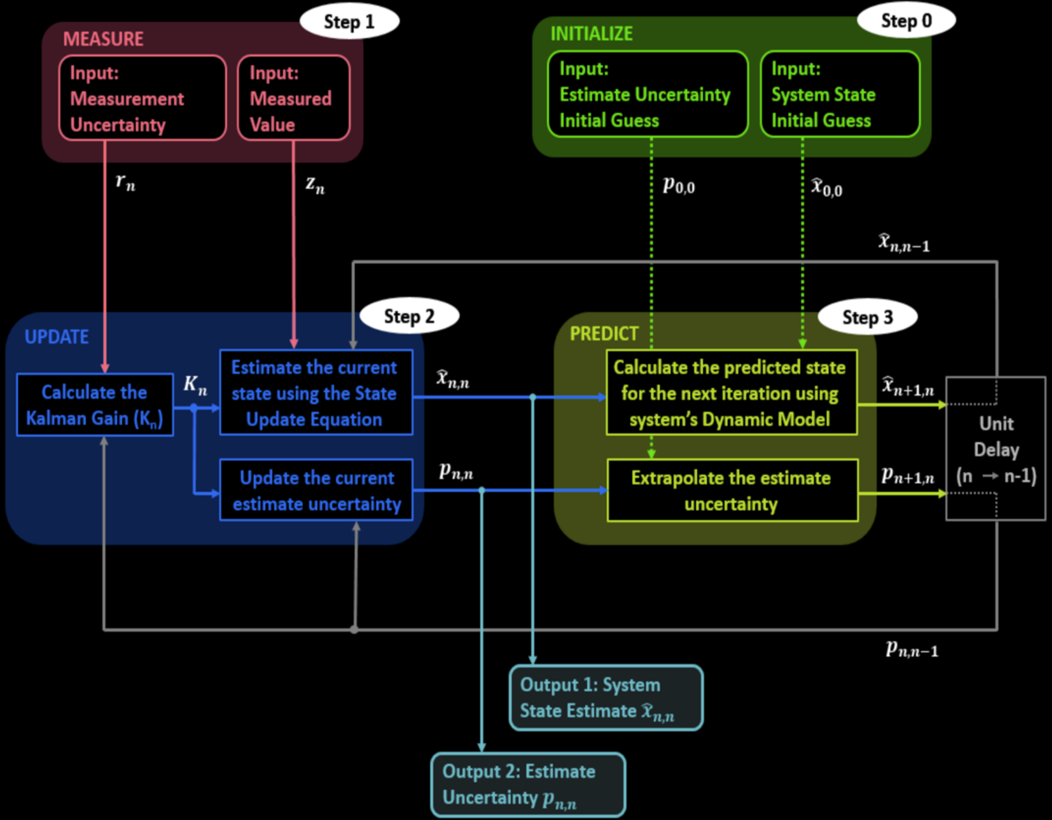
Kalman Filter – The Intuition



Kalman Filter





Kalman Filter

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

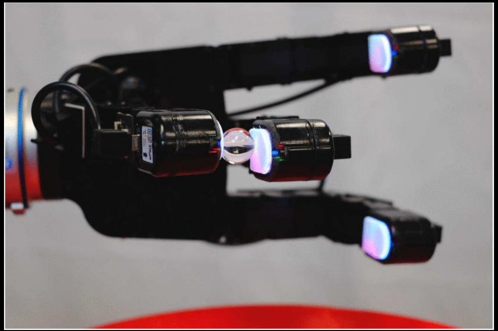
- Requirements
  - Linear system, Gaussian noise, Known system model

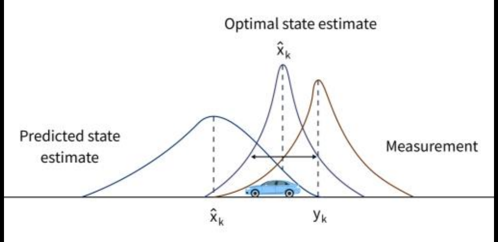
Alternatives: Extended Kalman Filter (EKF), Unscented Kalman Filter (UKF), Particle Filter (PF)

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

Sensing Summary

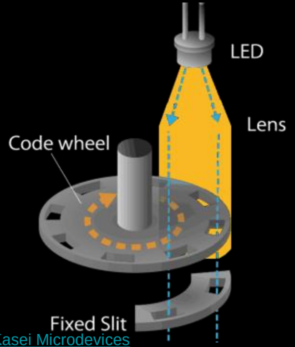
- Sensing
    - Classification of Robotic Sensor
- Sensing Mechanisms
    - Tactile sensors
    - Joint sensors
- Characterization
- Kalman Filter





Sensor options

Rotary Encoders



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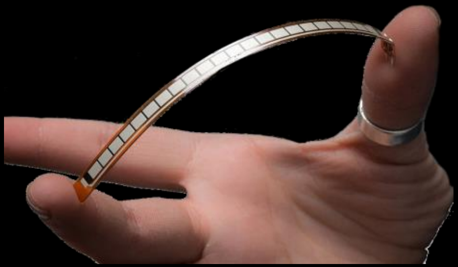
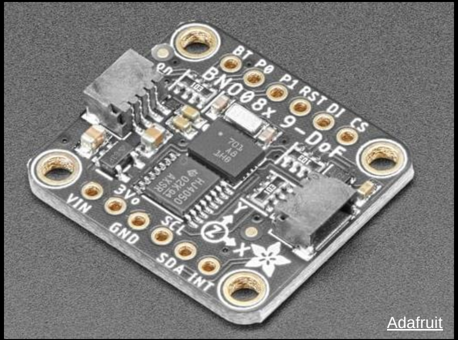
Flex Sensors



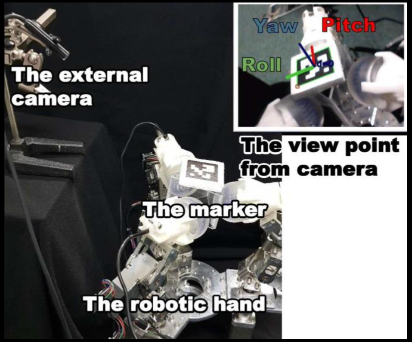
AdaFruit

Inertial Measurement Unit



Adafruit

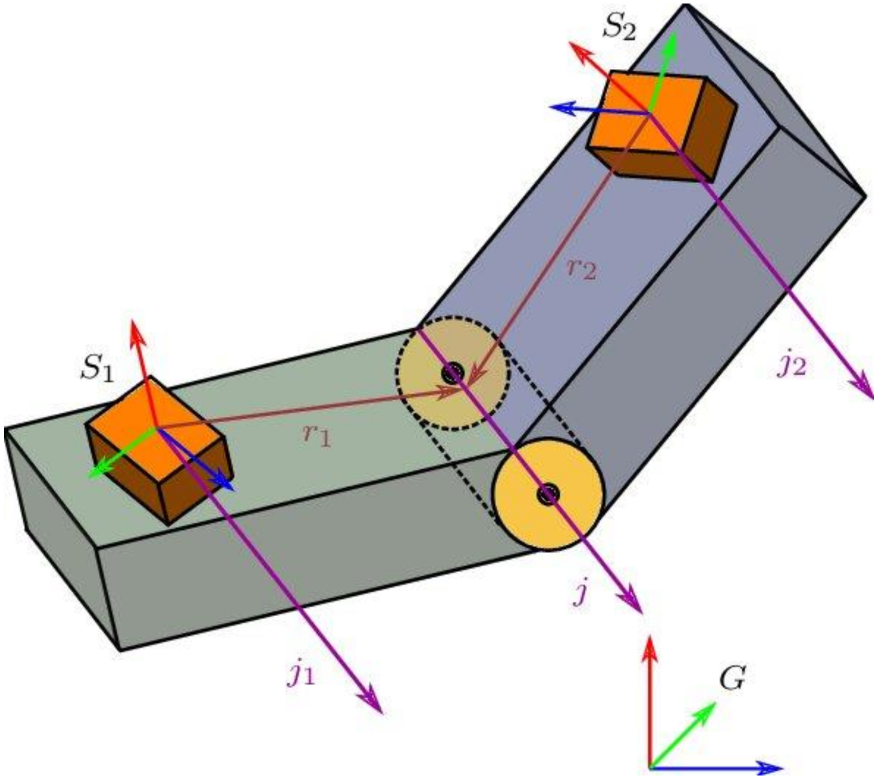
Camera



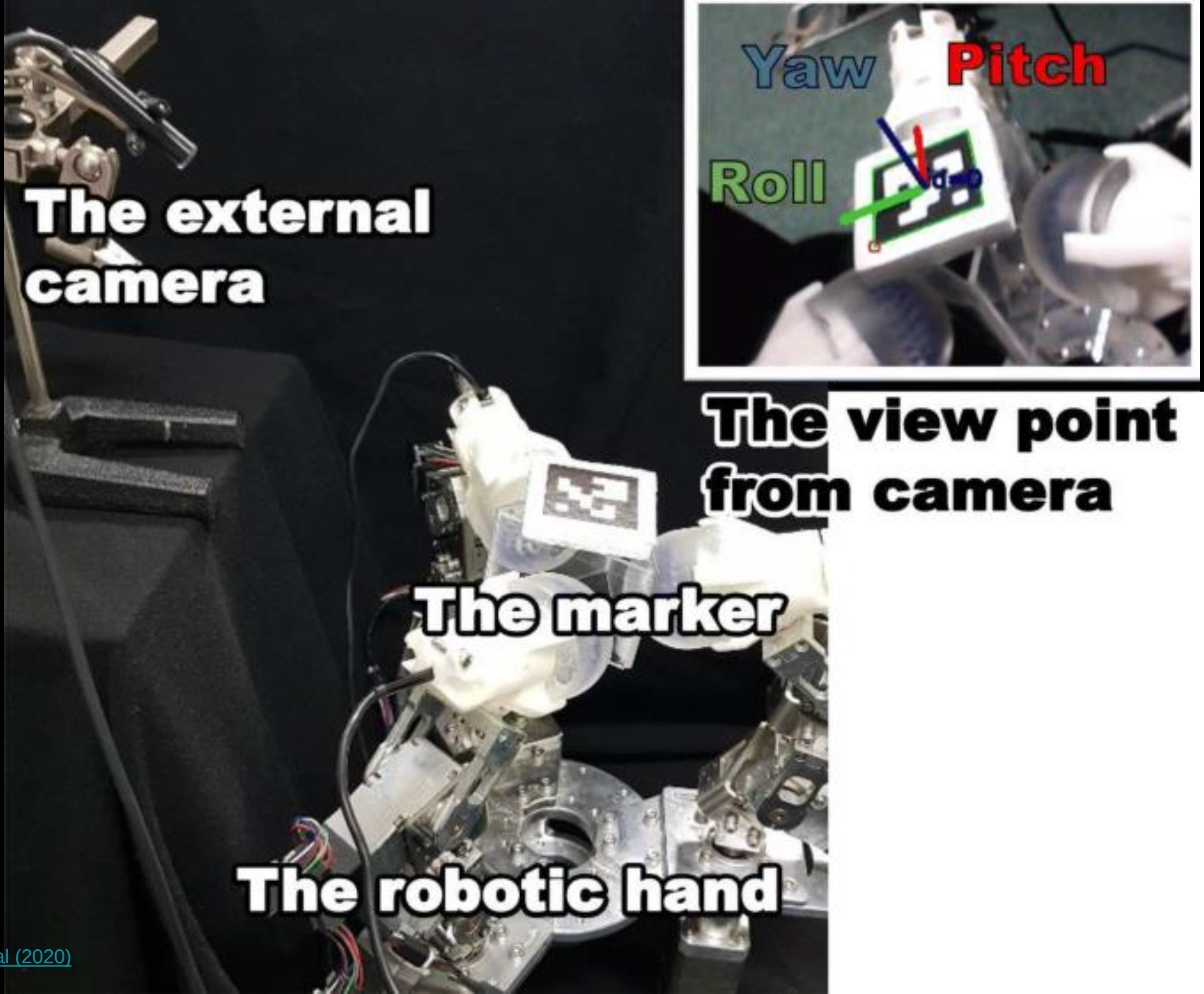
Choi, Tahara. Robomech Journal (2020)

Flex Sensors

Inertial Measurement Unit



Olsson, F., Seel, T., Lehmann, D., & Halvorsen, K. (2019, July). Joint axis estimation for fast and slow movements using weighted gyroscope and acceleration constraints. In *2019 22th International Conference on Information Fusion (FUSION)* (pp. 1-8). IEEE.



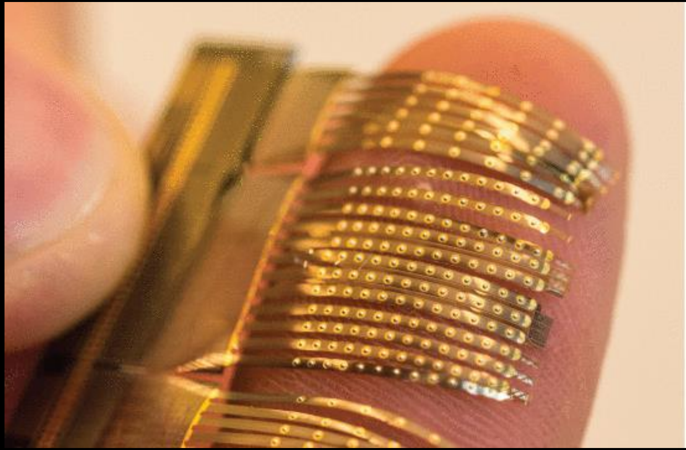
Choi, Tahara. Robomech Journal (2020)

Sensing the touch:

Force Sensing Resistors

Ohmite

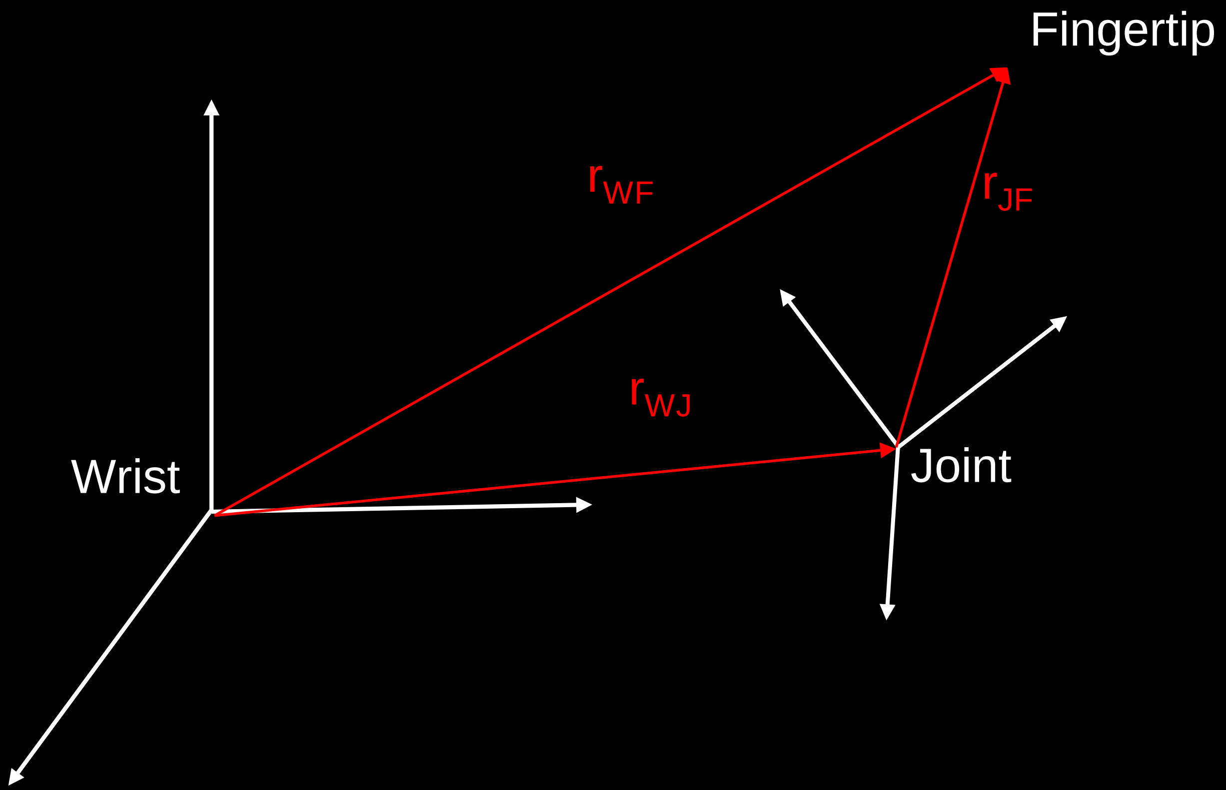
Artificial Skin



Weichart et al. *Tactile Sensing With Scalable Capacitive Sensor Arrays on Flexible Substrates (2021)*

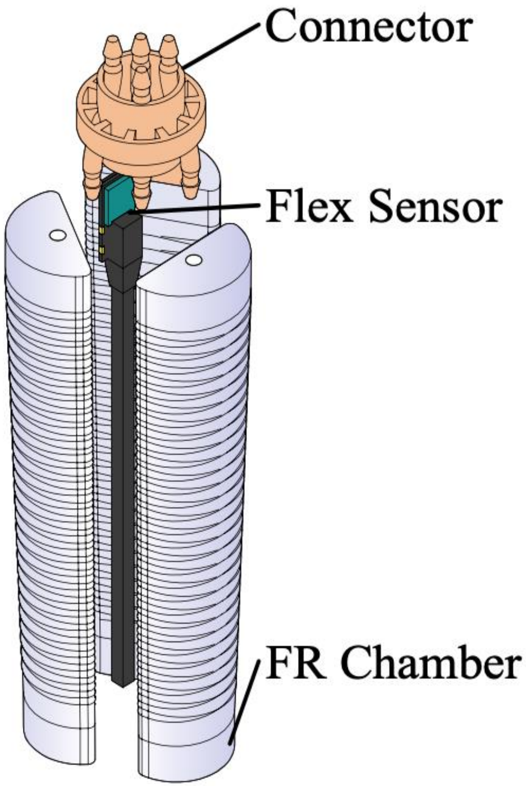
Backup Slides

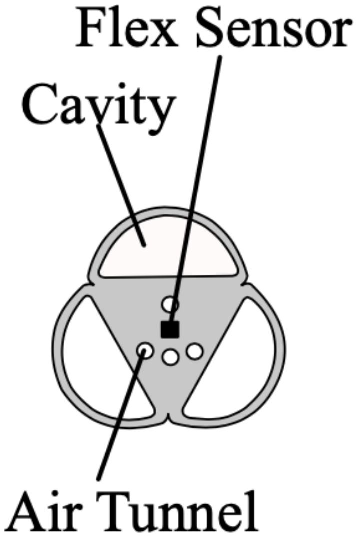
Second solution

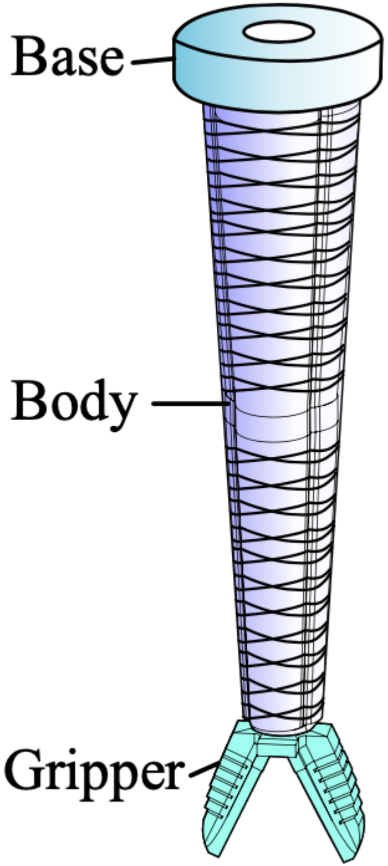


Indirect methods

e.g., Built-in Flex Sensor





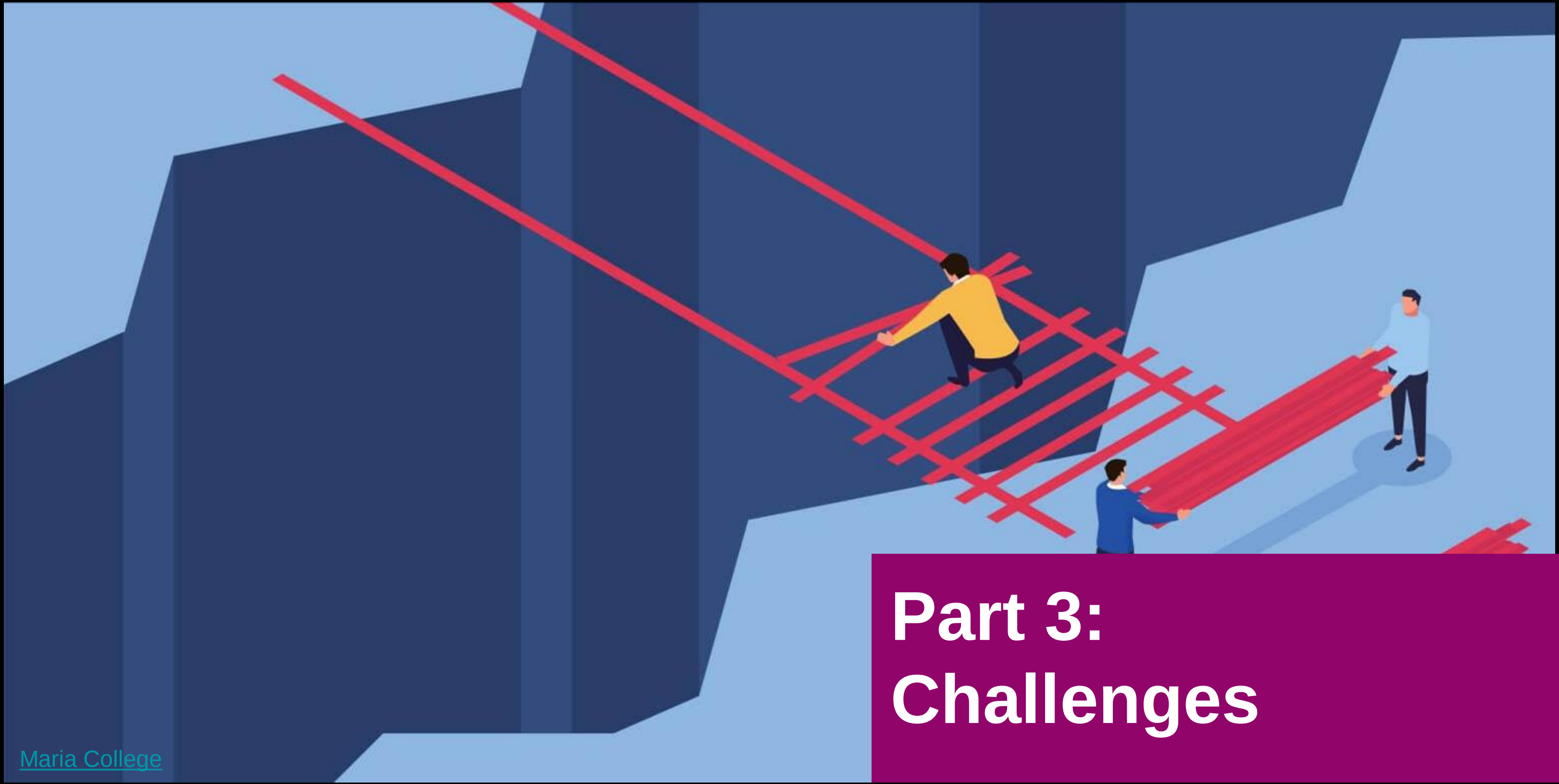


Toshimitsu, Y., Wong, K. W., Buchner, T., & Katzschmann, R. (2021, September). Sopra: Fabrication & dynamical modeling of a scalable soft continuum robotic arm with integrated proprioceptive sensing. In *2021 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)* (pp. 653-660). IEEE.

Outro no slide

Useful links

https://link.springer.com/book/10.1007/978-3-319-54413-7
https://smartlabai.medium.com/a-brief-overview-of-imitation-learning-8a8a75c44a9c
https://underactuated.csail.mit.edu/index.html
https://www.kalmanfilter.net/default.aspx

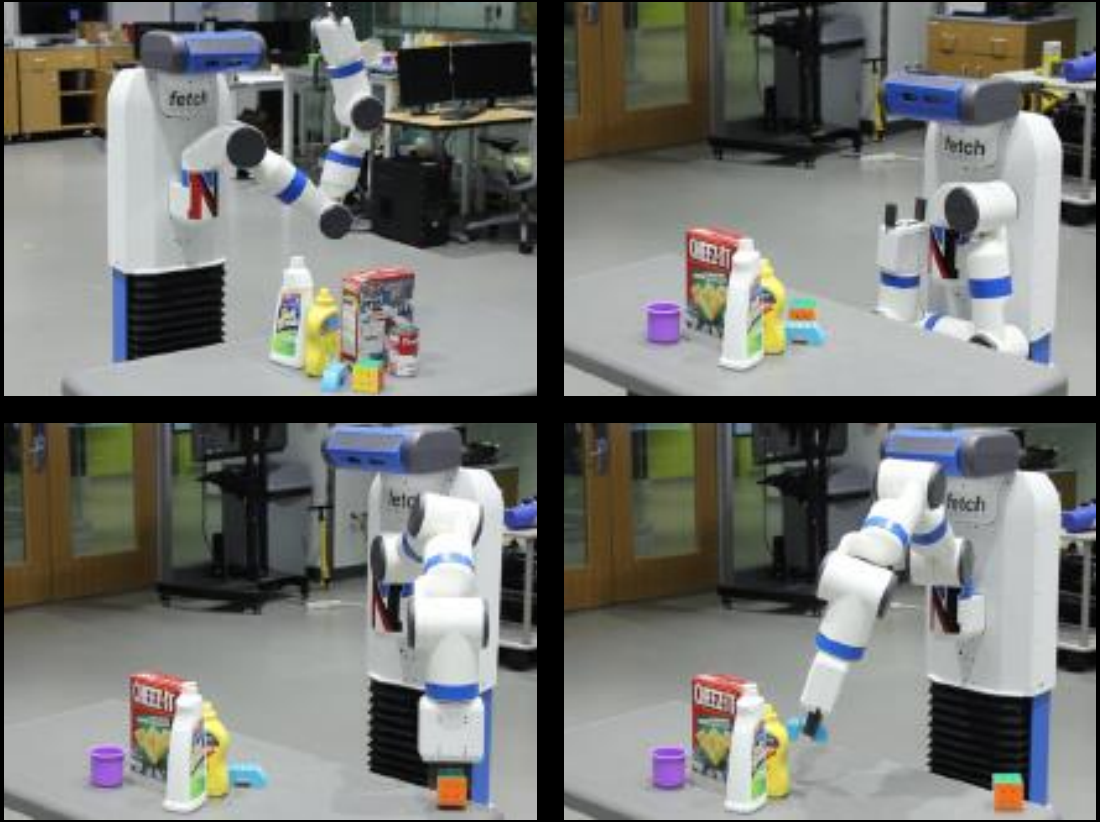

Maria College

Part 3: Challenges

What should you expect?

- Uncertainty and Partial Observability
- Long Horizon
- Under/Over actuation
- Sim-to-real gap
- Tendon strain + skin non-linearity
- Encoder's sensibility

Uncertainty and Partial Observability



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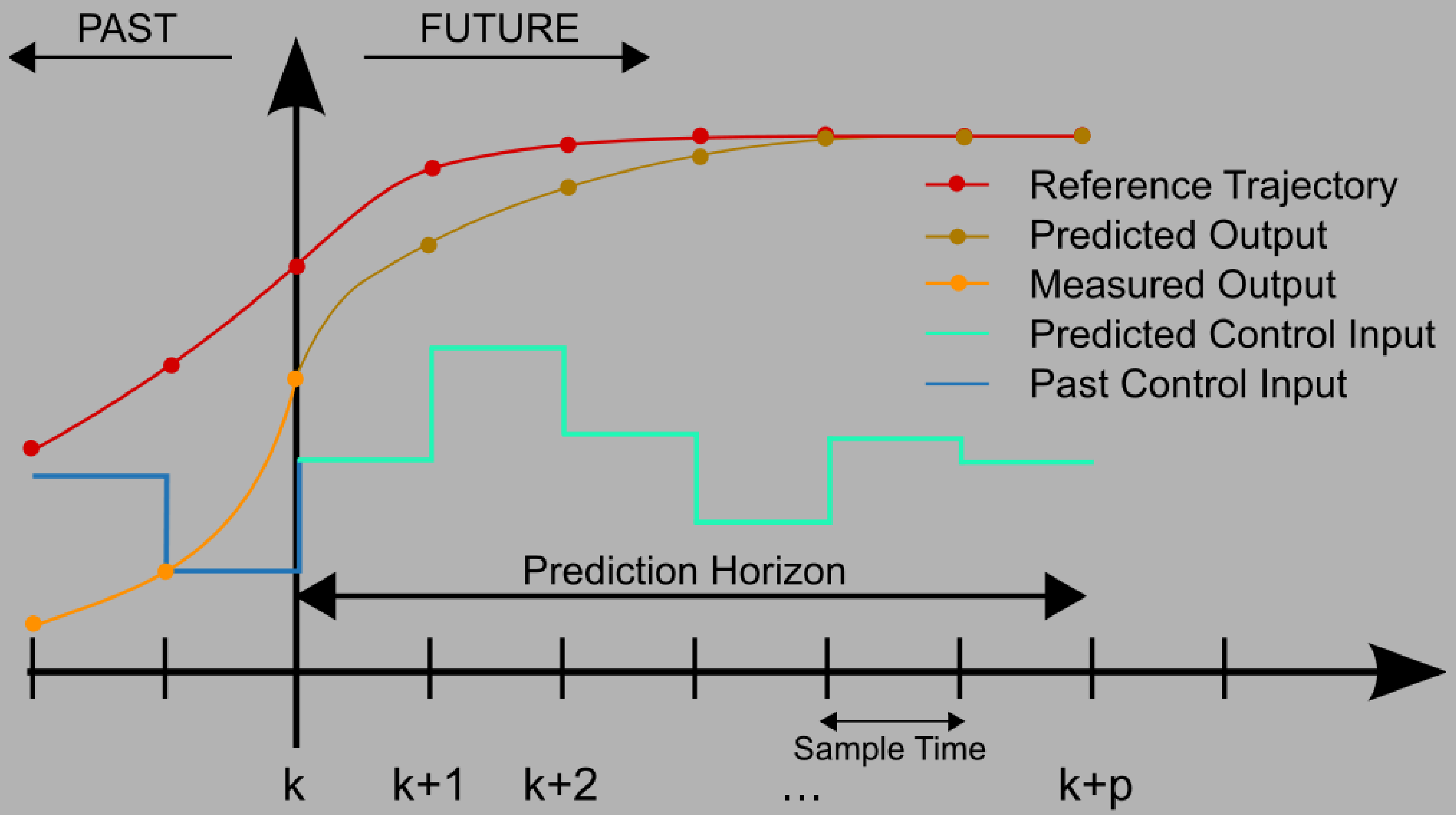
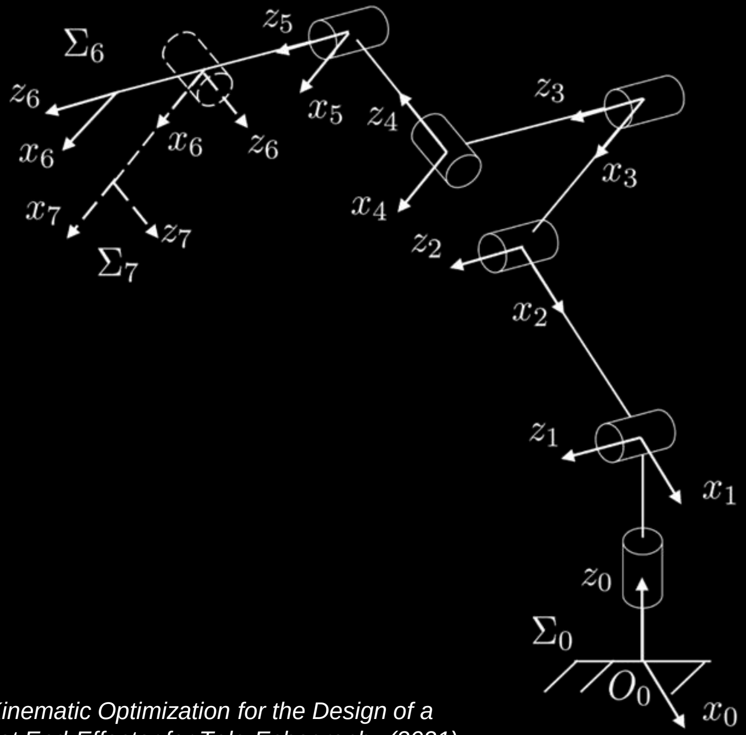
[Yuchen Xiao, Sammie Katt, Andreas ten Pas, Shengjian Chen, Christopher Amato.
Online Planning for Target Object Search in Clutter under Partial Observability.
IEEE International Conference on Robotics and Automation (ICRA), Montreal, Canada, May 2019.]

Long Horizon

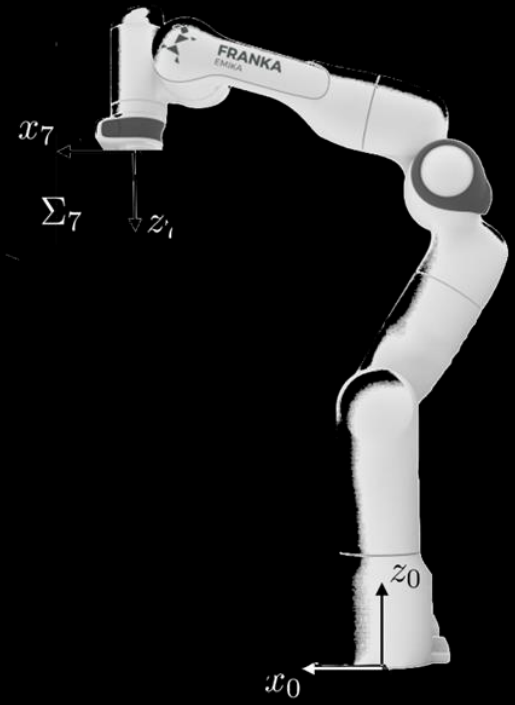


MPC and constrained systems , TU Eindhoven

Underactuation and Overactuation



(a)



(b)

Filippeschi et al. *Kinematic Optimization for the Design of a Collaborative Robot End-Effector for Tele-Echography (2021)*

Sim-to-real gap

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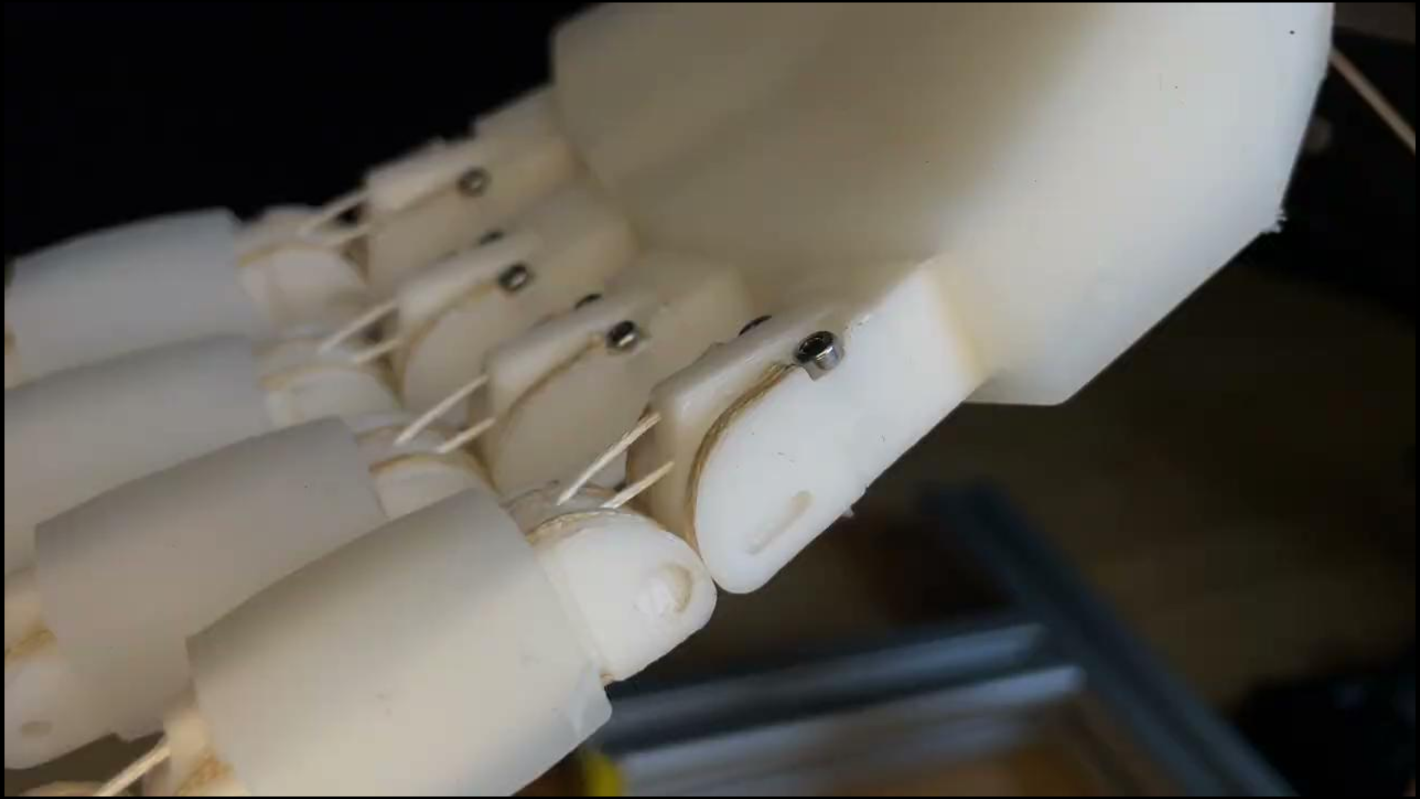
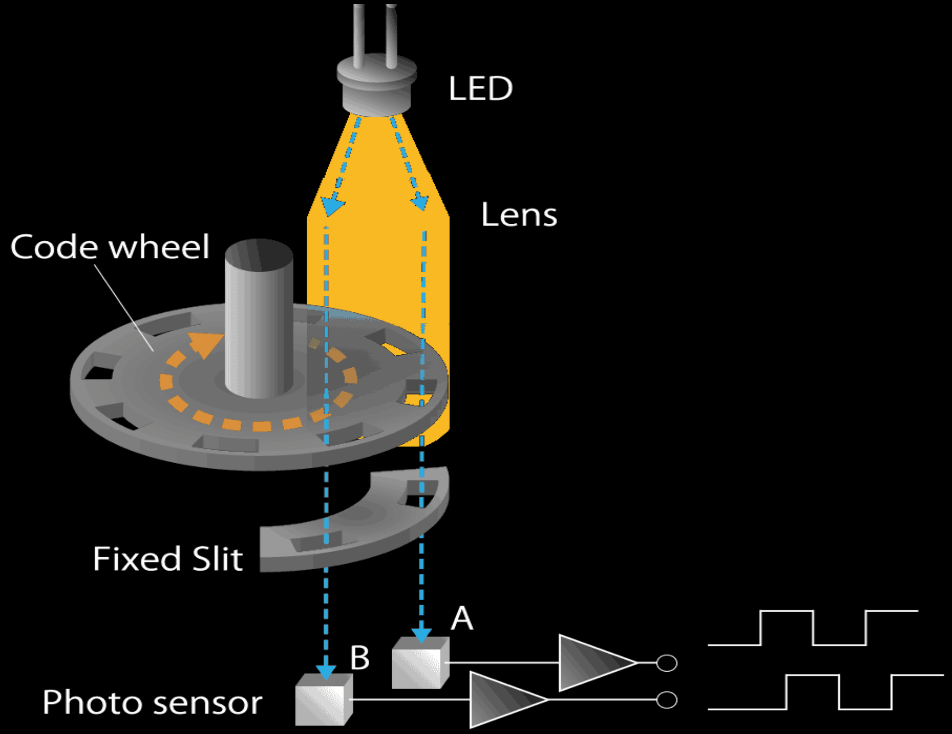
[Everyday Robots]

Tendon strain + skin non-linearity



Encoder’s sensibility



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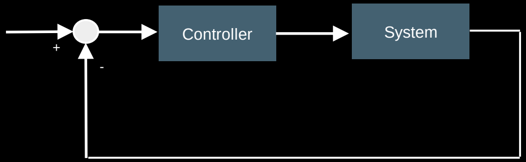
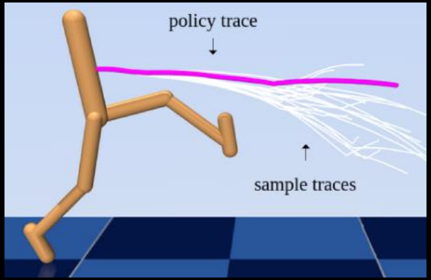
Wrap up

1. Sensing

2a. Feedback Control



2b. Model Predictive Control



3. Challenges