Decoding Touch: Machine Learning and Spintronic Sensors Beneath Magnetic Skins

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Microssistemas e Nanotecnologias

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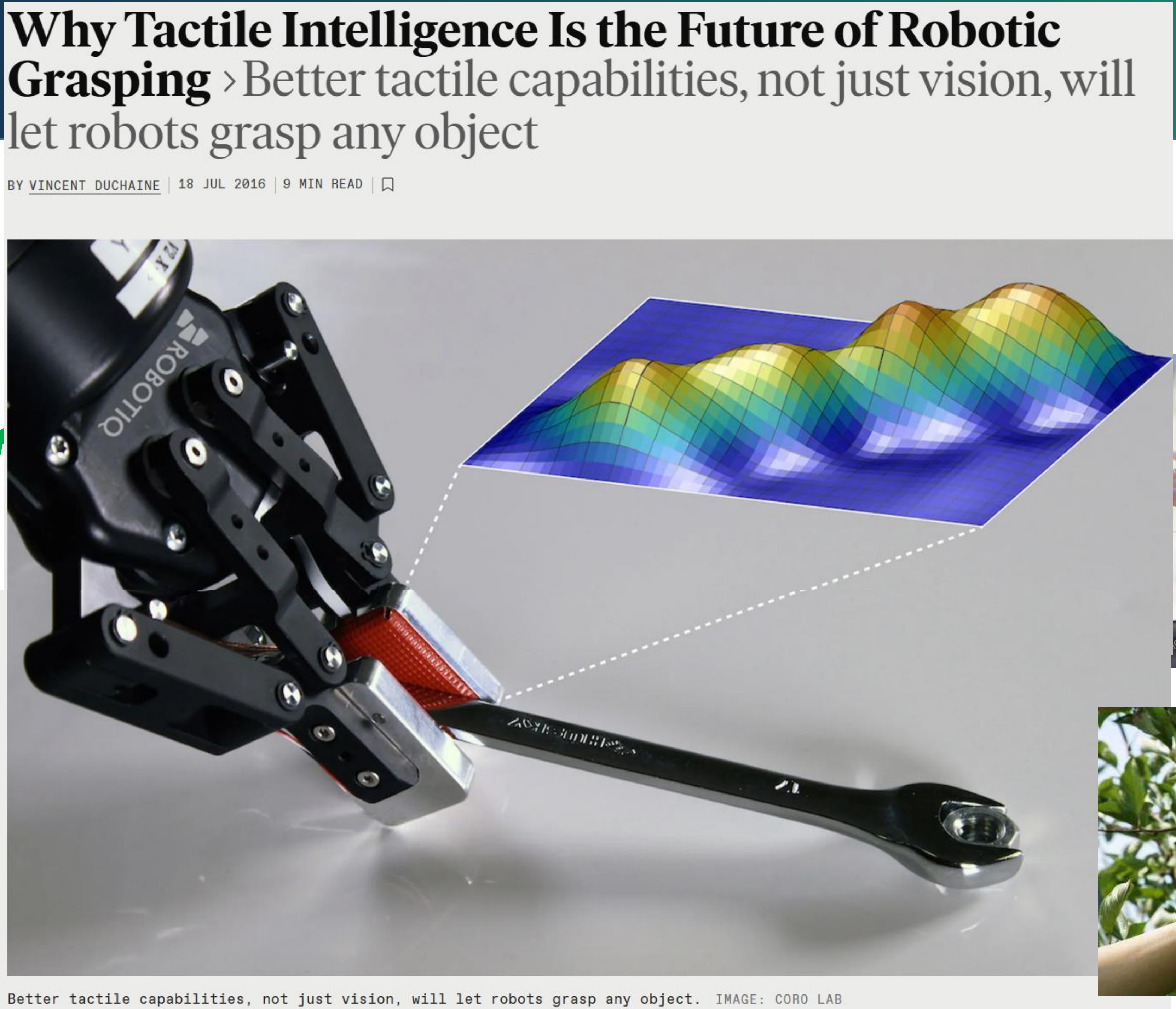
Lorenzo Jamone

Function of

Stiffnes



Why Tactile Intelligence Is the Future of Robotic Grasping › Better tactile capabilities, not just vision, will let robots grasp any object

BY VINCENT DUCHAINE | 18 JUL 2016 | 9 MIN READ

Better tactile capabilities, not just vision, will let robots grasp any object. IMAGE: CORO LAB

Perceptions

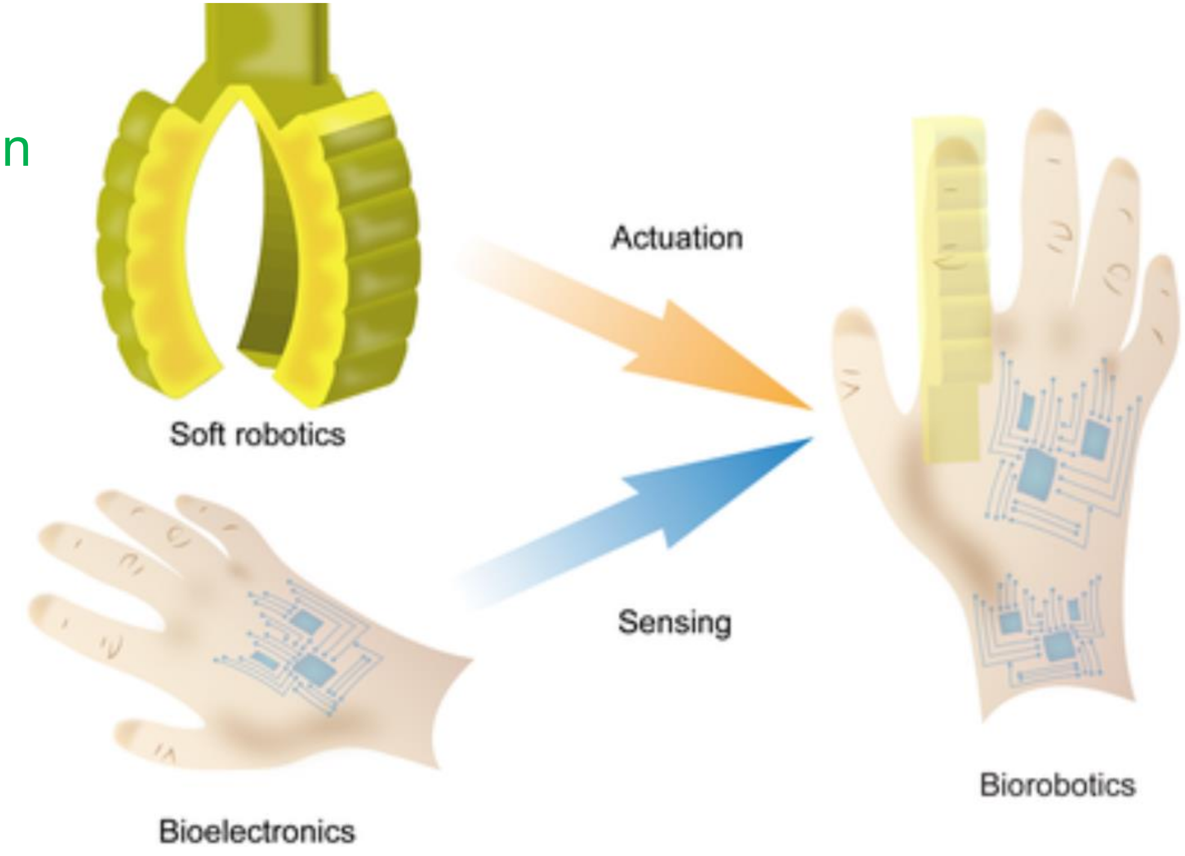
(speed, heat…)

OUTLOOK

Touch is essential for interaction, safety, and emotion

Machines struggle to interpret tactile feedback

Magnetic skins ➔ a pathway to mimic human sensation

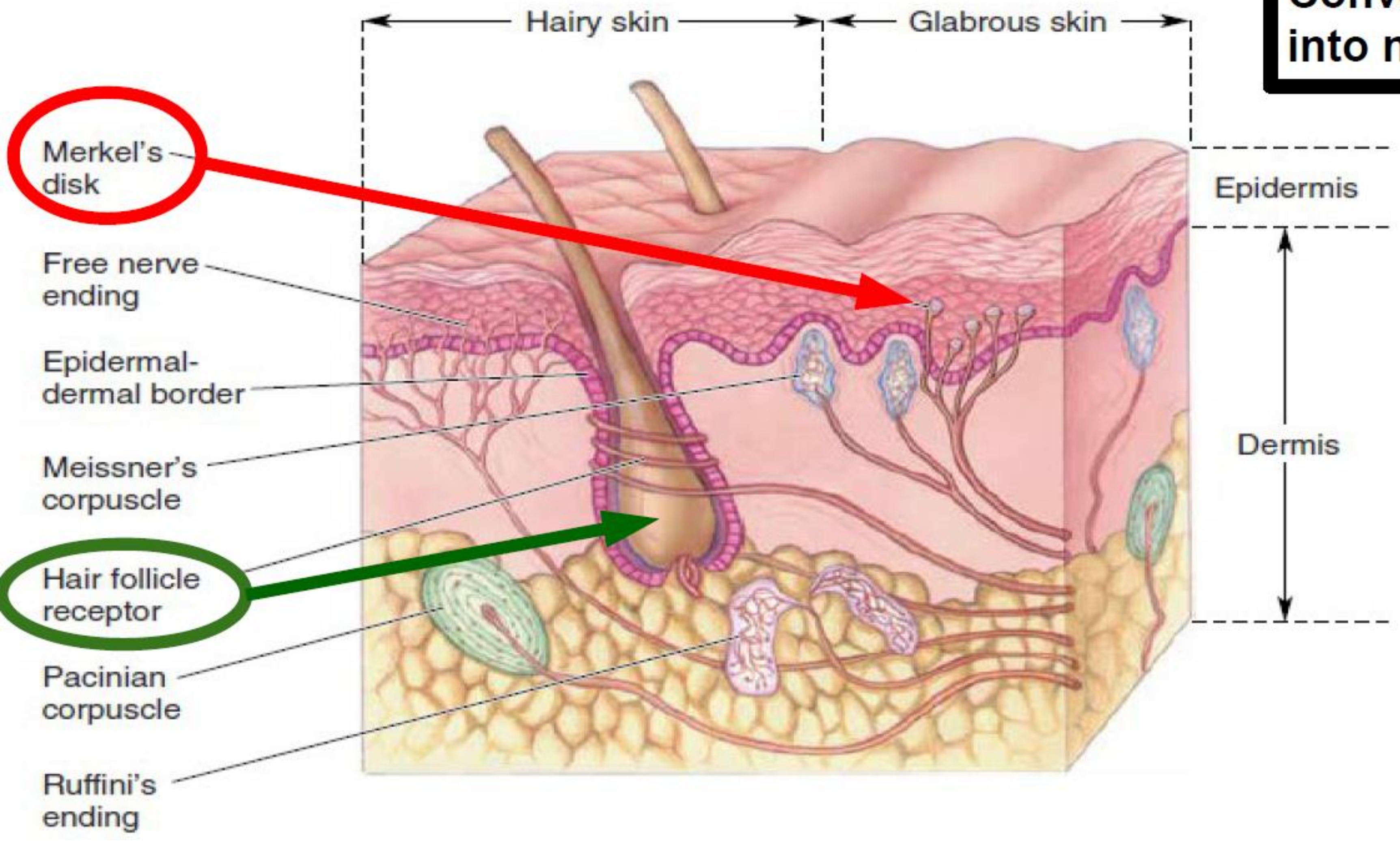


Our Ingredients:

Spintronic sensor Chip
Magnetic skin
Machine Learning

Biological sensing: receptors in the human skin

Mechanoreceptors:



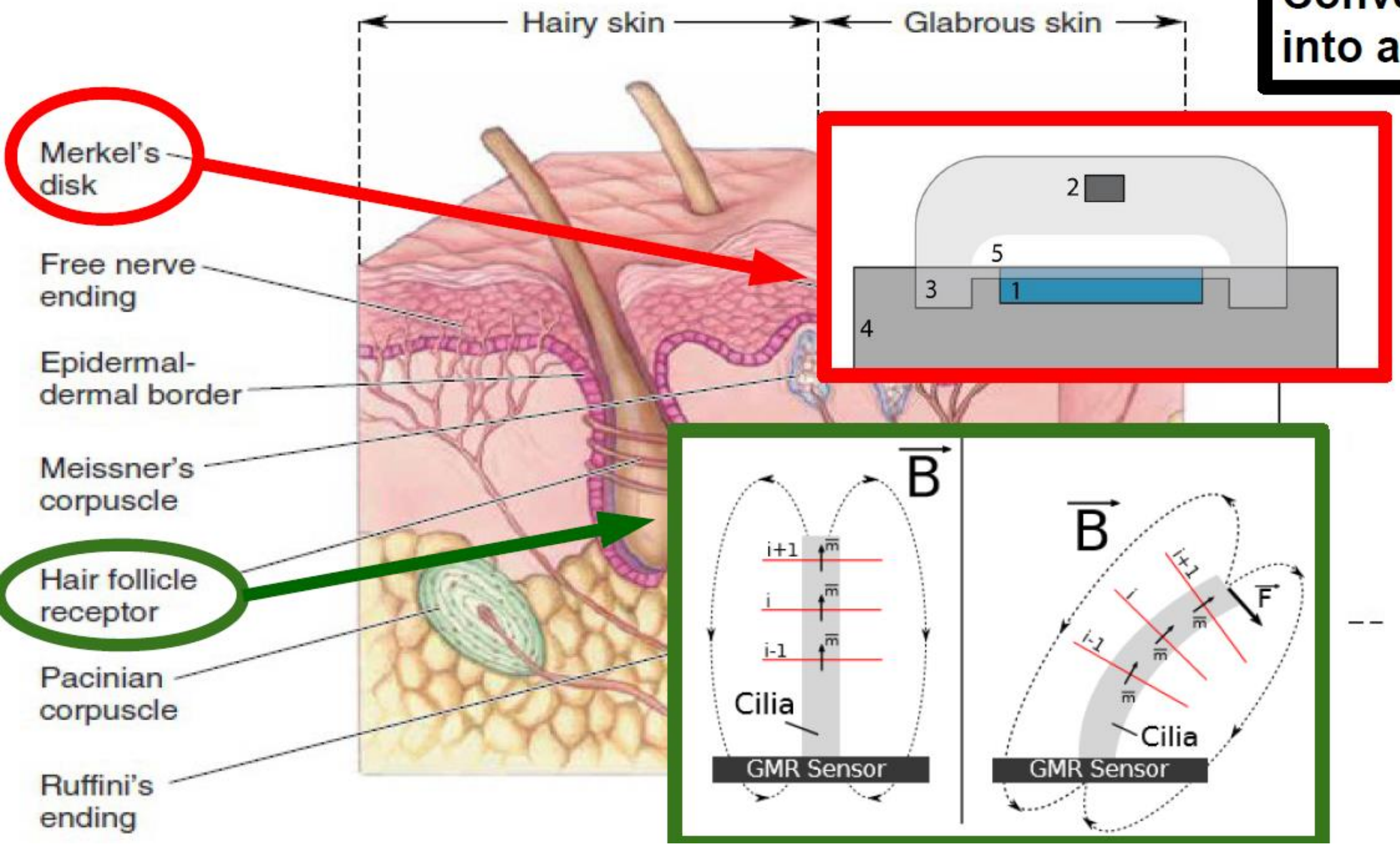
Convert a mechanical stimulation into neural activity.

Detect pressure/force. Important for regulating grip strength when manipulating objects.

Detect hair motion. Important to sense very small forces (e.g. air flow).

Artificial sensing: soft tactile sensors for robots

Mechanoreceptors:

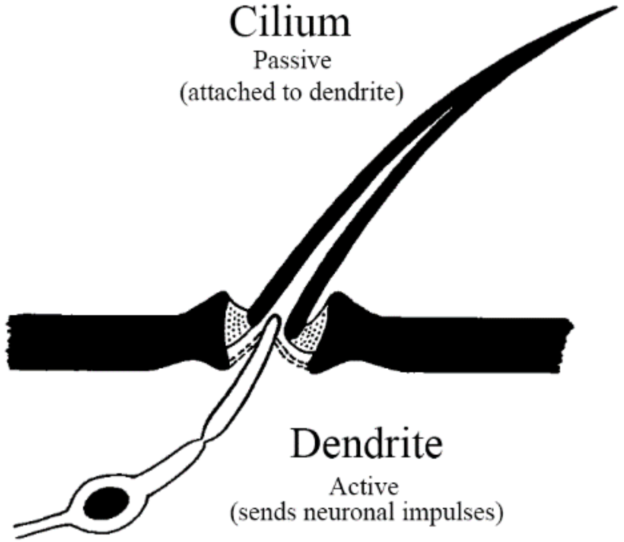


Convert a mechanical stimulation into an electronic signal.

A small low-cost device to sense 3D force with high sensitivity.

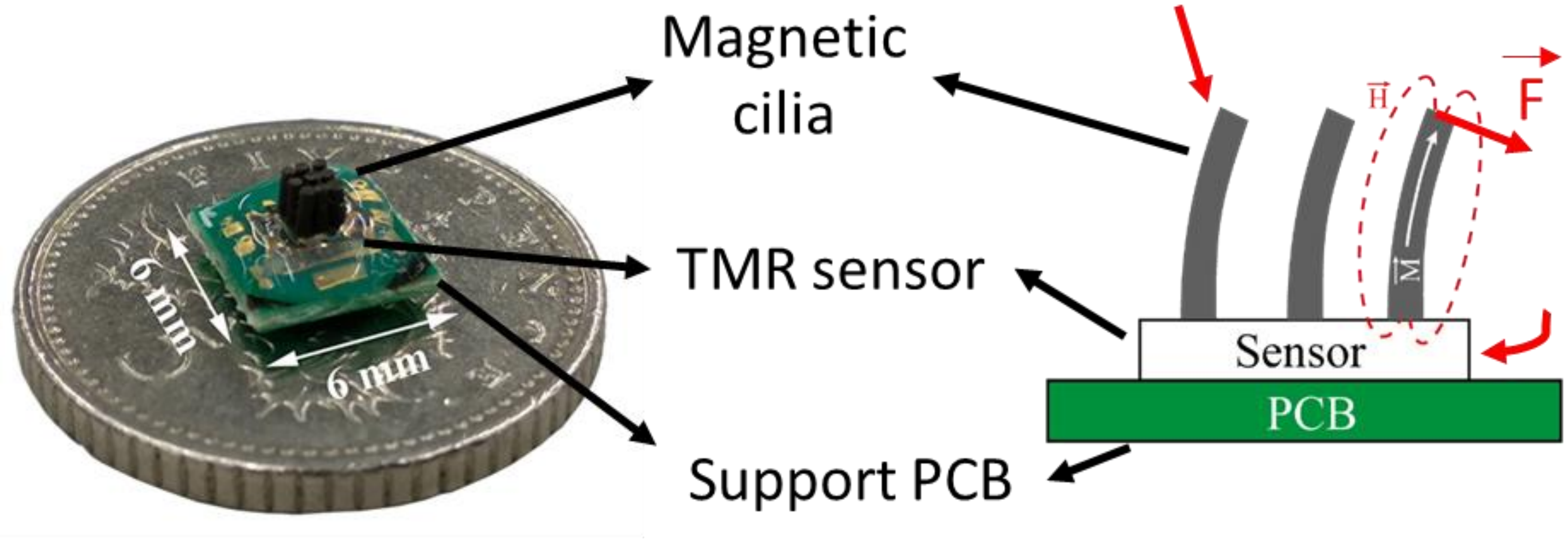
An artificial cilia to sense fine textures.

Tactile inspired in nature



Magnetic cilia bending **induces** magnetic profile variation

Spintronic sensor transduces variation into an electrical signal

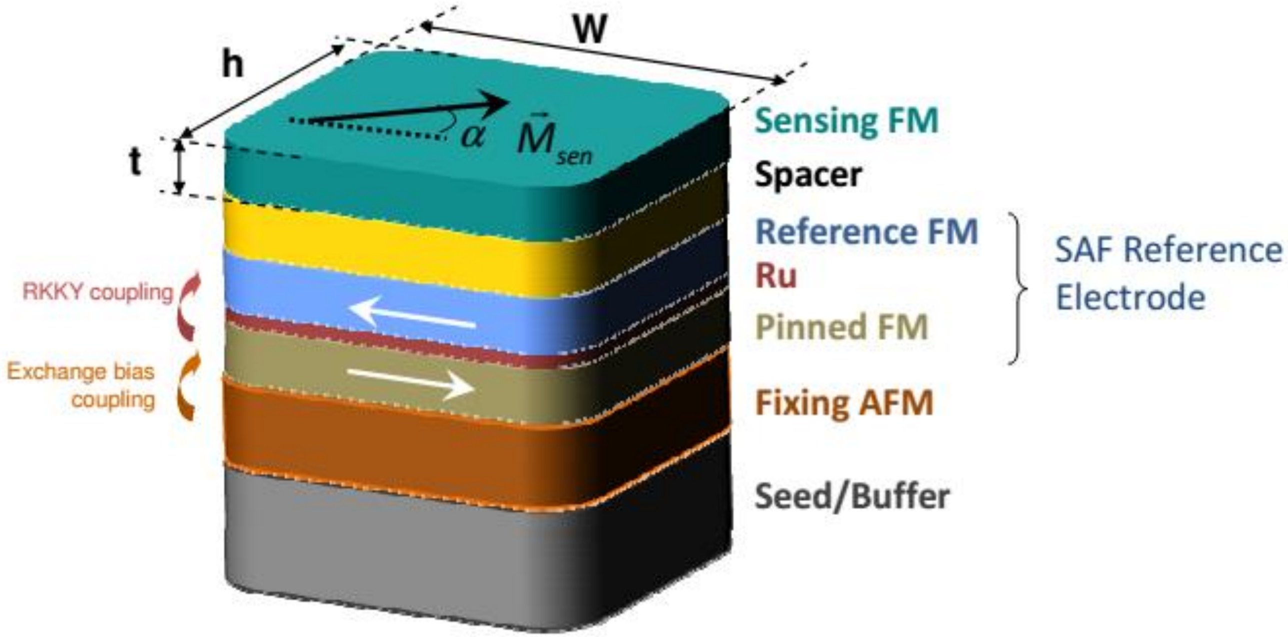


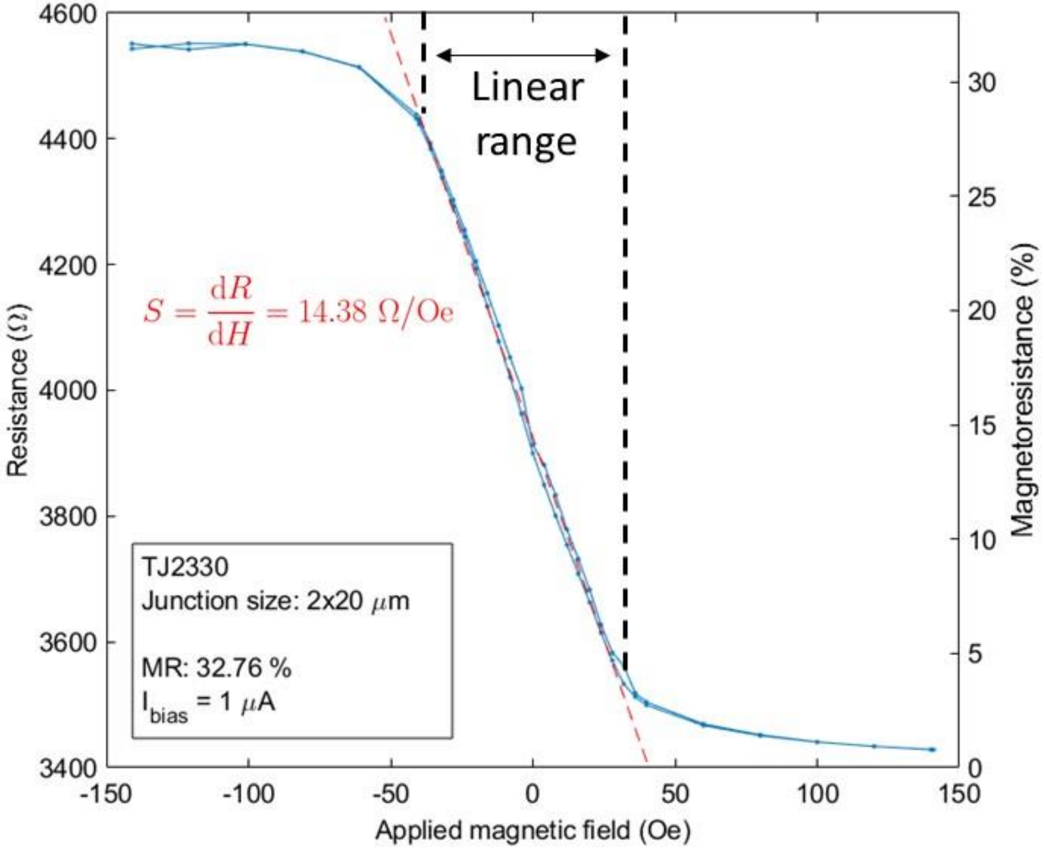
P. Ribeiro et al. IEEE Transactions on Magnetics 53(11), 2017.
P. Ribeiro et al. IEEE ICRA 2020; P. Ribeiro et al. IEEE IROS 2020.
A. Alfadhel and J. Kosel, Advanced Materials, 27, 7888–7892, 2015.
P. Ribeiro, et.al. IEEE Robotics and Automation Letters, 2, 971–976, 2017.

Spintronic Sensors

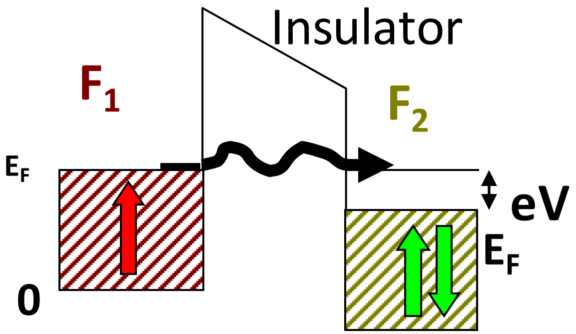
Magnetoresistance

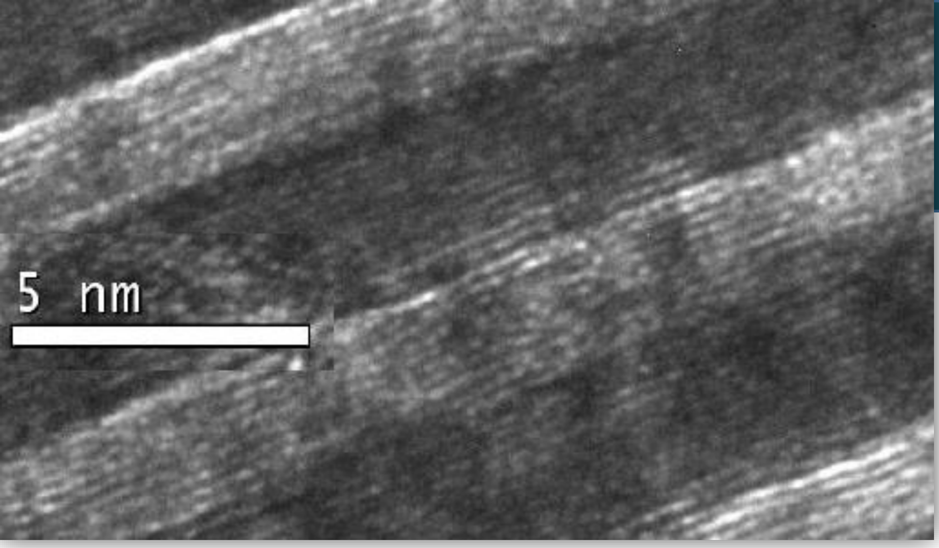
$$\mathrm{MR} = \frac{R_{max} - R_{min}}{R_{min}}$$





MIT, 1996
IBM, 1997
INESC, 1997



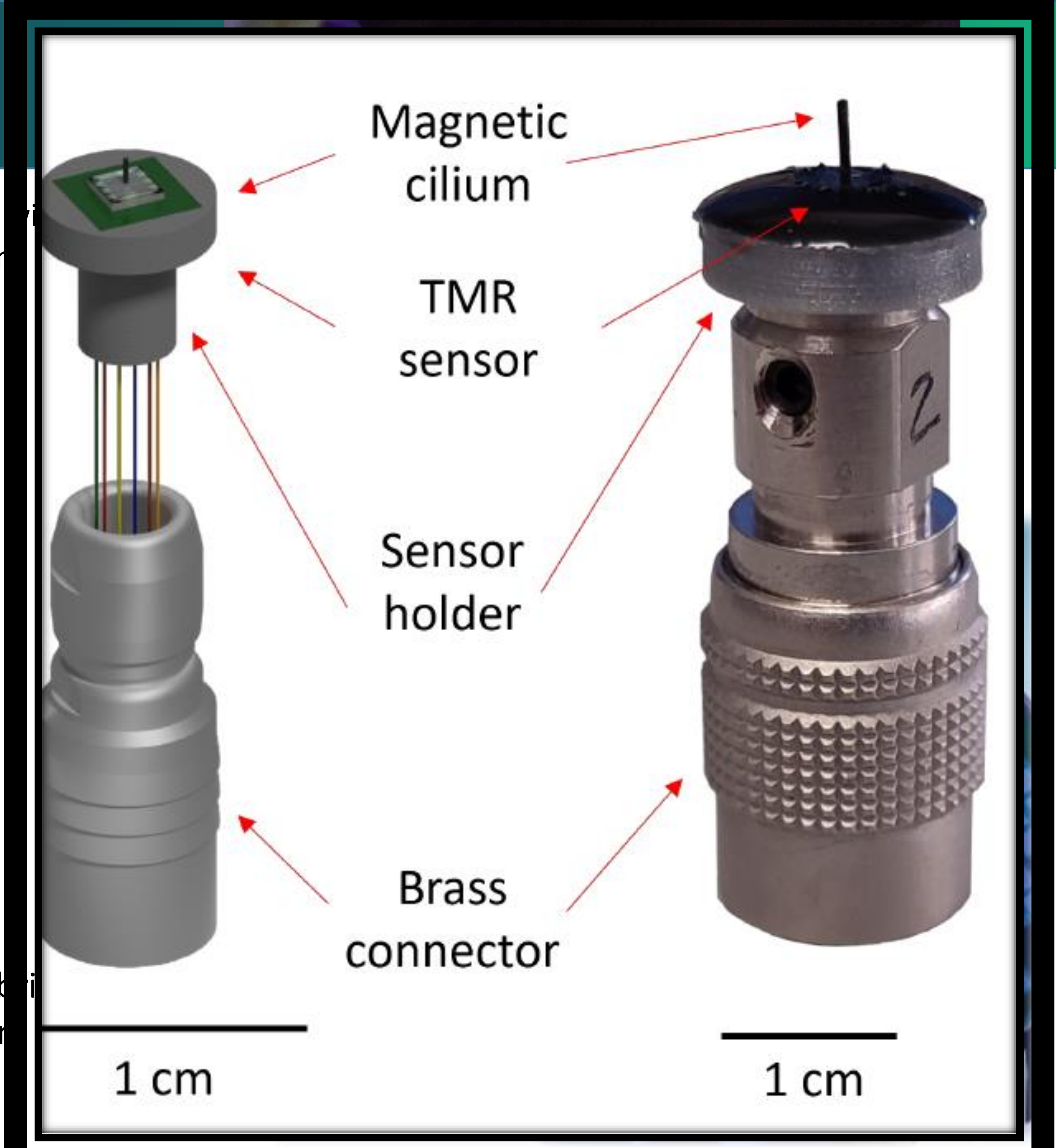


MgO target wi
Argon plasm

Film thickness:
Controlled at the atomic scale
1 Å = 0.1 nm

Multilevel device
patterning

Wafer microfabri
in a Clean Roon



CILIA SIMULATION – 3 STEPS

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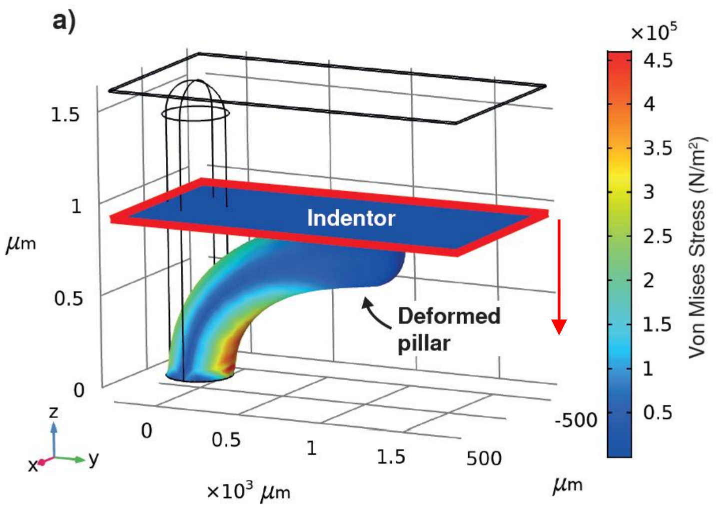
Mechanical simulation (FEM – with COMSOL)



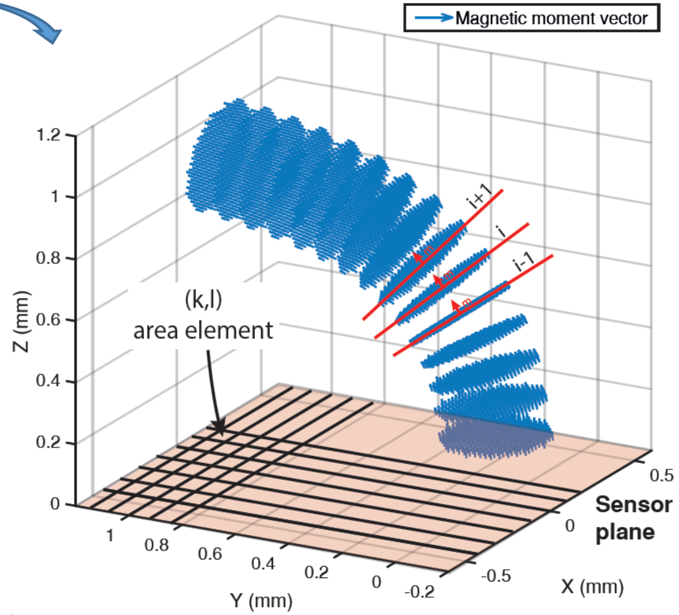
Simulation: indentor iteratively lowered against cilia

Steps of 100 µm

Discretized into cross-sections

Deformation

Magnetic moment simulation



$$\mathbf{v_{i-1}} = \overrightarrow{i-1, i}; \ \mathbf{v_{i+1}} = \overrightarrow{i, i+1}$$

$$\mathbf{v_i} = \frac{\mathbf{v_{i+1}} + \mathbf{v_{i-1}}}{2}.$$

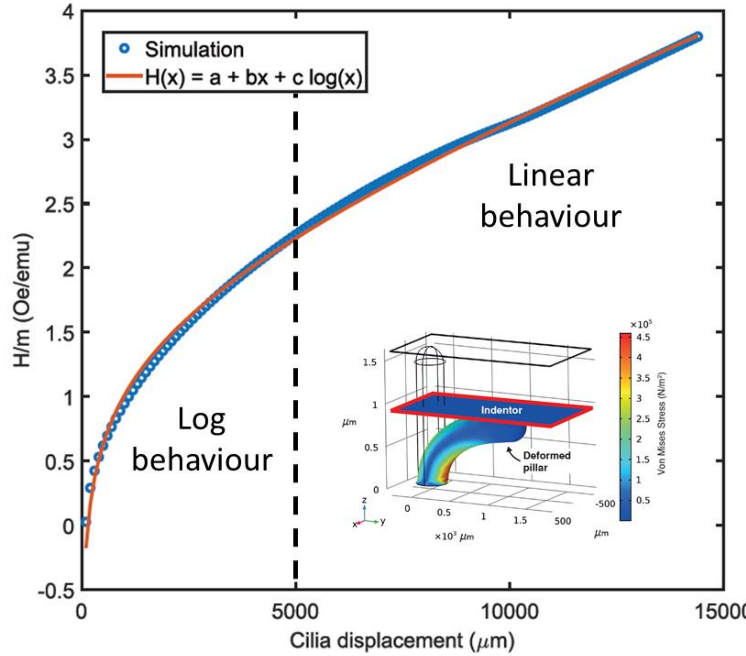
Estimation of **m** direction

$$\mathbf{H_j}(r_{j,(k,l)}) = \frac{1}{4\pi}\left(\frac{3\mathbf{r_{j,(k,l)}}(\mathbf{m_j}\cdot\mathbf{r_{j,(k,l)}})}{|\mathbf{r_{j,(k,l)}}|^5} - \frac{\mathbf{m_j}}{|\mathbf{r_{j,(k,l)}}|^3}\right)$$

H (x direction) over surface

Magnetic field

Magnetic moment simulation



$$\langle \mathbf{H_{inc}} \rangle = \frac{\sum_{k=1}^{N_k}\sum_{l=1}^{N_l}\sum_{j=1}^{N}\mathbf{H_j}(r_{j,(k,l)})}{N_k N_l}$$

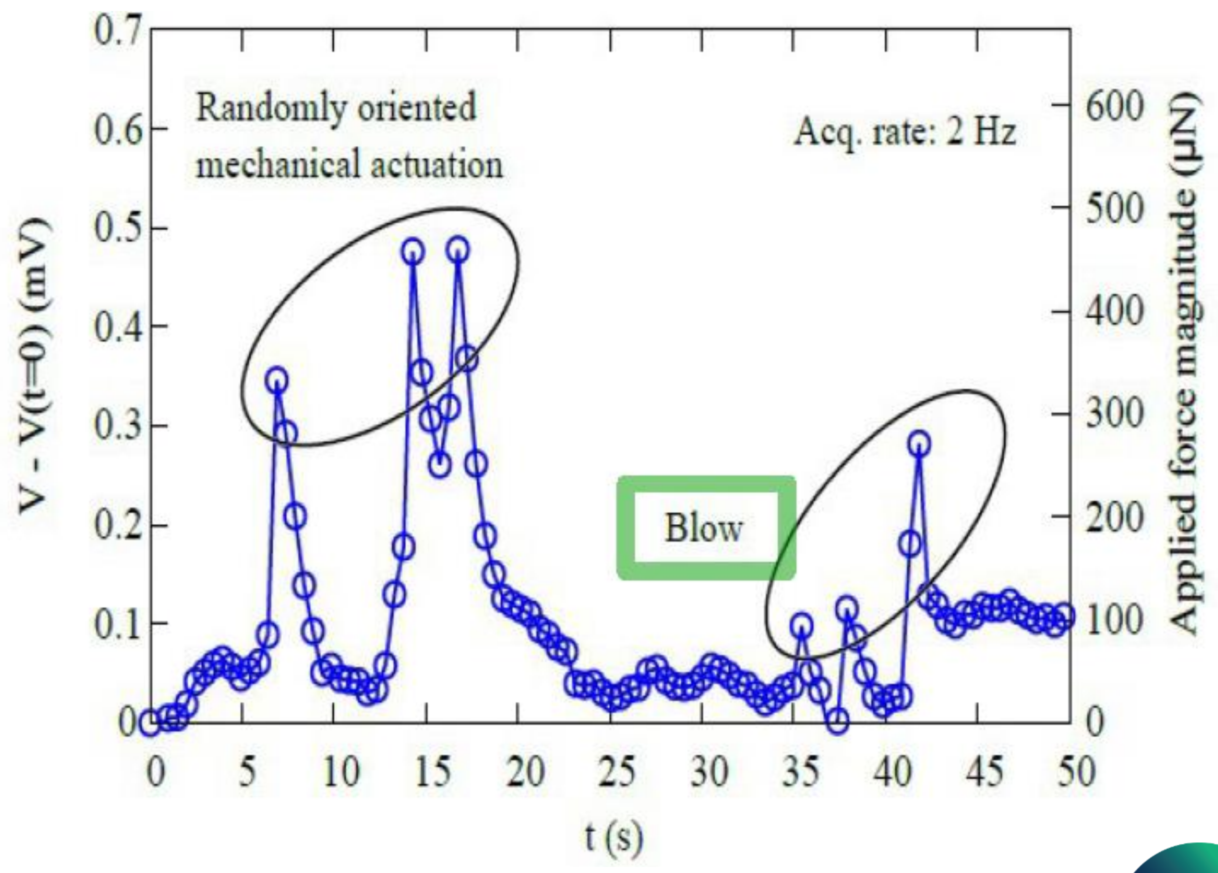
Average field over sensor area

$$\langle H \rangle(x) = ax + b\log(x) + c$$

Best fitting function describing field

Detection of very small forces

Air and fluidics motion



KAUST Patent

US010768058B2

(12) **United States Patent**
Alfadhel et al.

(10) **Patent No.:** **US 10,768,058 B2**
(45) **Date of Patent:** **Sep. 8, 2020**

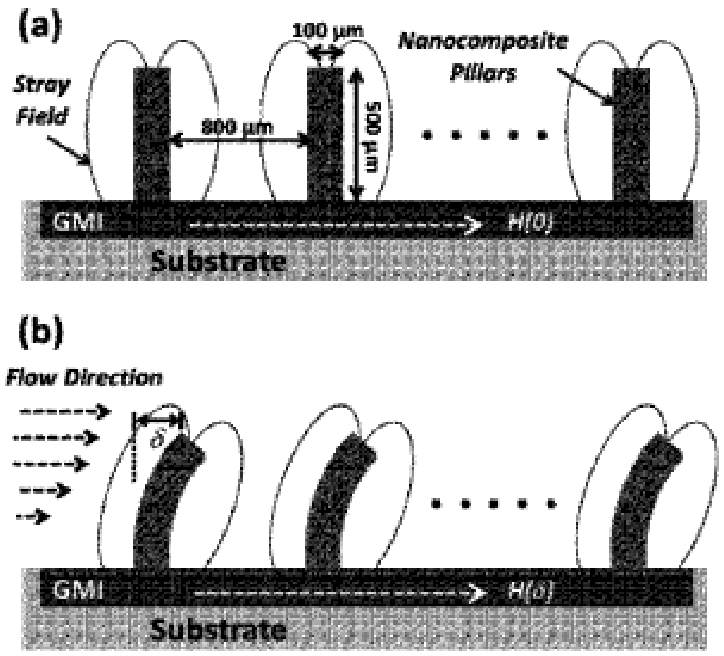
(54) **MAGNETIC NANOCOMPOSITE SENSOR**

(71) Applicant: **KING ABDULLAH UNIVERSITY OF SCIENCE AND TECHNOLOGY**, Thuwal (SA)

(72) Inventors: **Ahmed Alfadhel**, Thuwal (SA); **Bodong Li**, Thuwal (SA); **Jurgen Kosel**, Thuwal (SA)

(52) **U.S. Cl.**
CPC ***G01L 1/12*** (2013.01); ***G01F 1/28*** (2013.01); ***G01L 1/044*** (2013.01); ***G01R 33/063*** (2013.01); *B82Y 15/00* (2013.01); *G01R 33/09* (2013.01)

(58) **Field of Classification Search**
CPC G01L 25/003; G01L 1/12; G01L 1/044; G01R 33/09; G01R 33/063; B82Y 15/00; H01F 7/08; G01F 1/28



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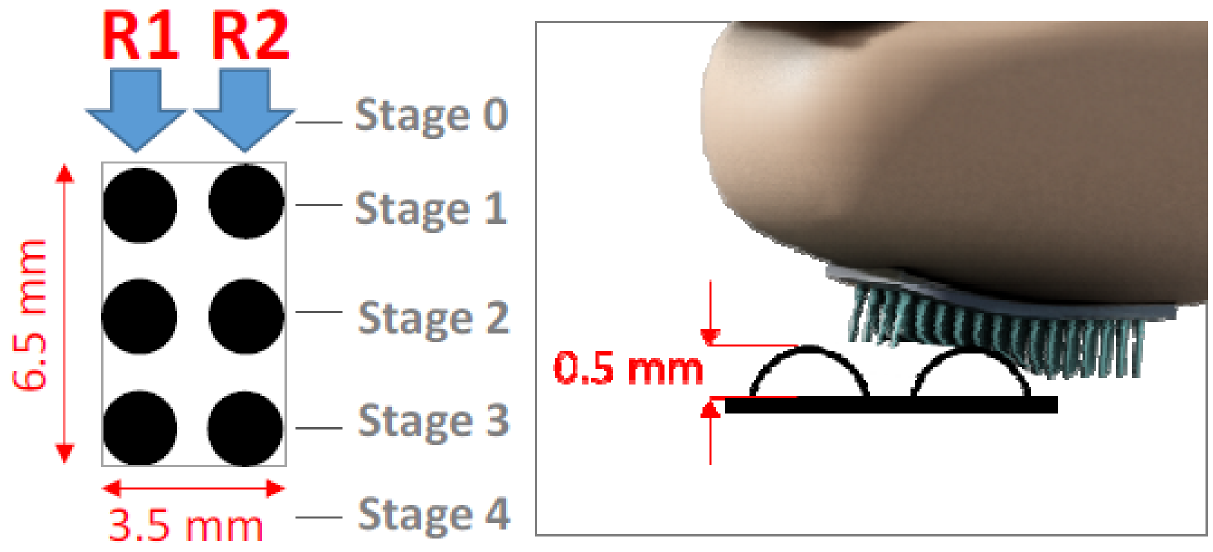
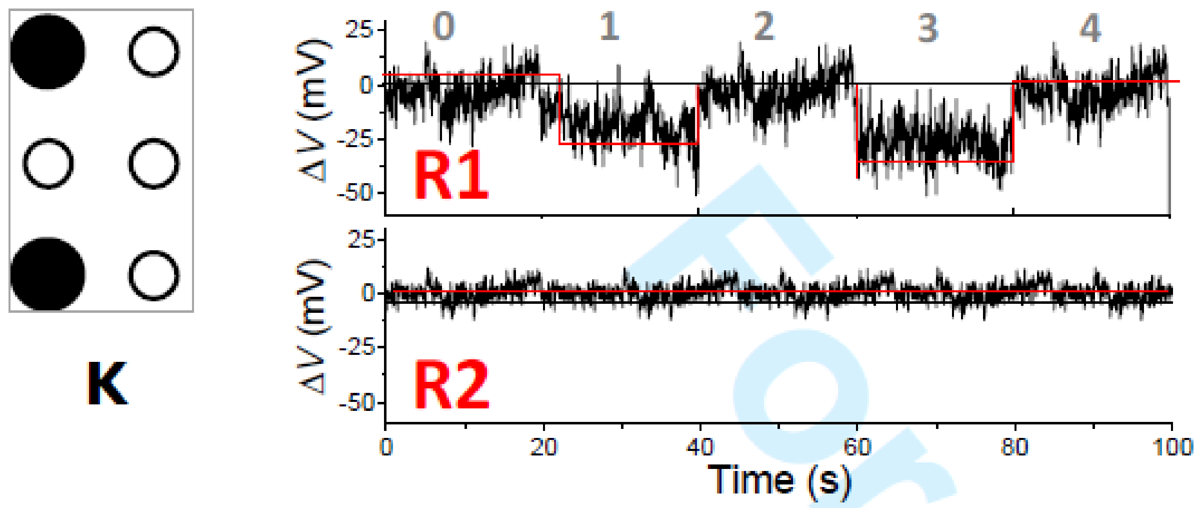
KAUST

Sensors for surface exploration

Braille reading





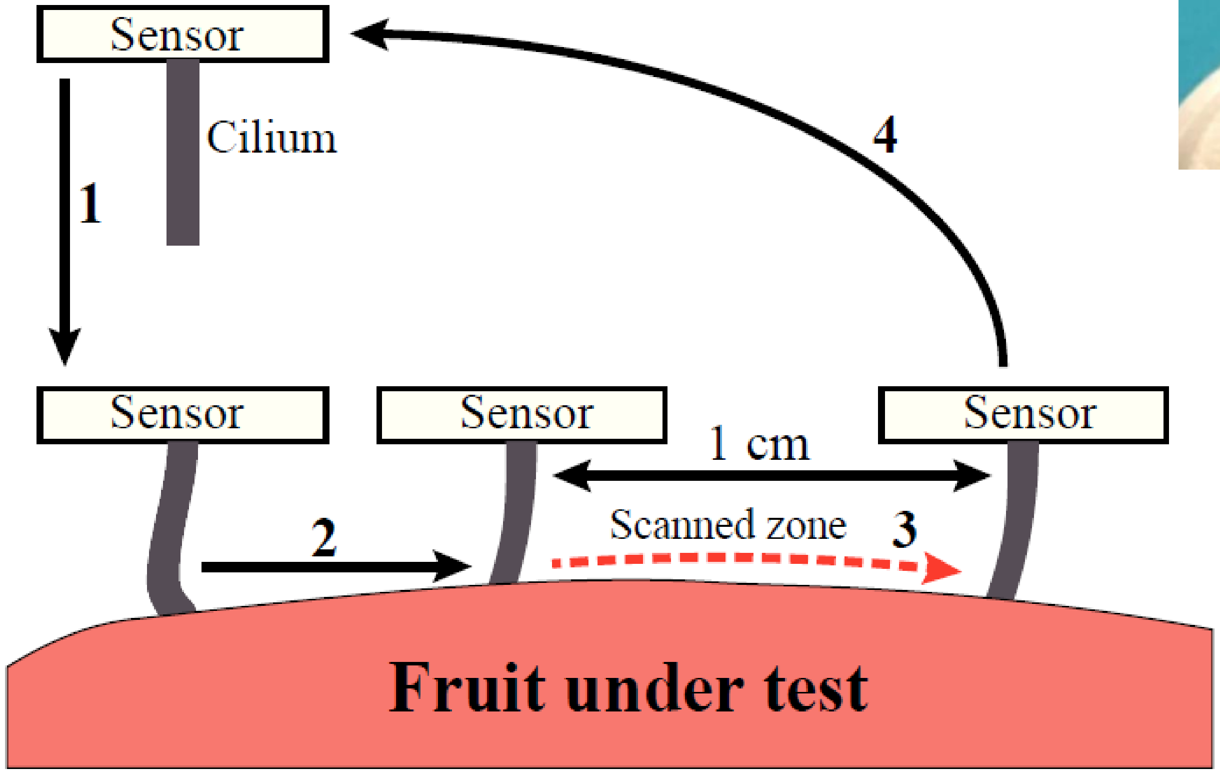
Alfadhel, S. Cardoso, J. Kosel,
IEEE Sensors Journal, 16 (24), 8700 (2016)

Proof of concept - Fruit quality classifier

Braeburn apples
- 12 ripe fruits
- 12 senescent fruits

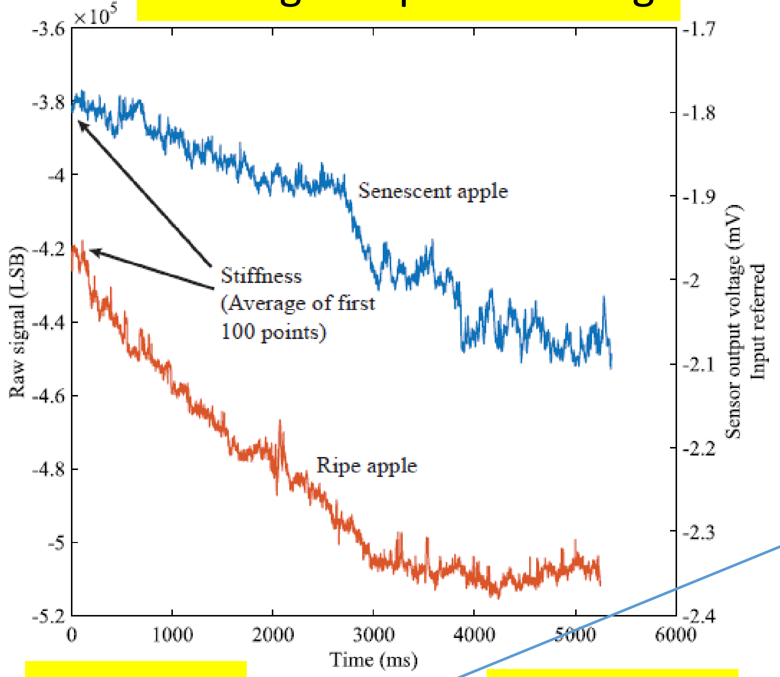
Sabrina strawberries
- 12 ripe fruits
- 12 senescent fruits

Data acquisition
- Data rate: 1 kSPS
- Scan speed: 1 mm/s
- 10 consecutive scans in each area
- 2 areas per fruit

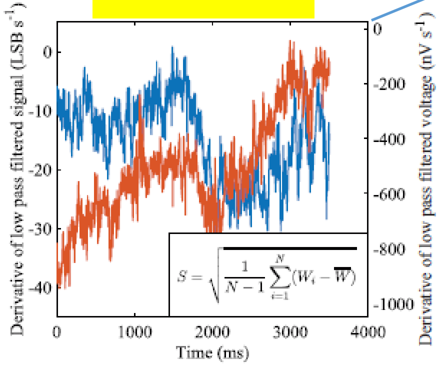


FRUIT QUALITY SENSING - RESULTS

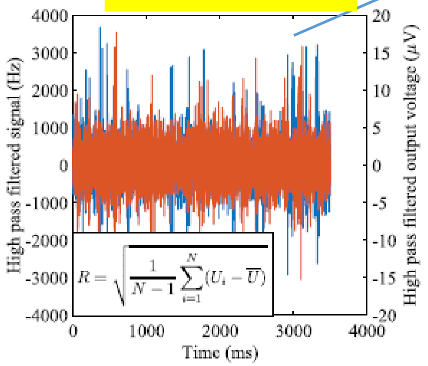
Raw signal upon scanning



Waviness



Roughness



FEATURE	WHAT IS MEASURED	PHYSICAL CHARACTERISTIC
Stiffness (**E**)	Sensor signal with achieved contact	**Fruit hardness**
Waviness (**S**)	Std. deviation of 100 point moving average	**Deformation over fruit surface**
Roughness (**R**)	Std. deviation of high-pass filtered (f > 150 Hz) signal	**Fruit surface texture**

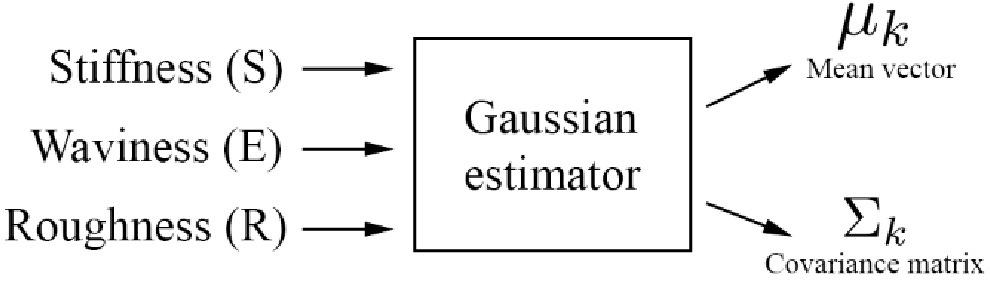
Fruit can be classified into two classes

Ripe

Senescent

FRUIT QUALITY SENSING - ALGORITHM

Gaussian Naive Bayes



F_k - Fruit belonging to class k

$$P(F_k|S_i,E_i,R_i) = P(F_k)\prod_i^n \frac{P(S_i,E_i,R_i|F_k)}{P(S_i,E_i,R_i)}$$

0.5

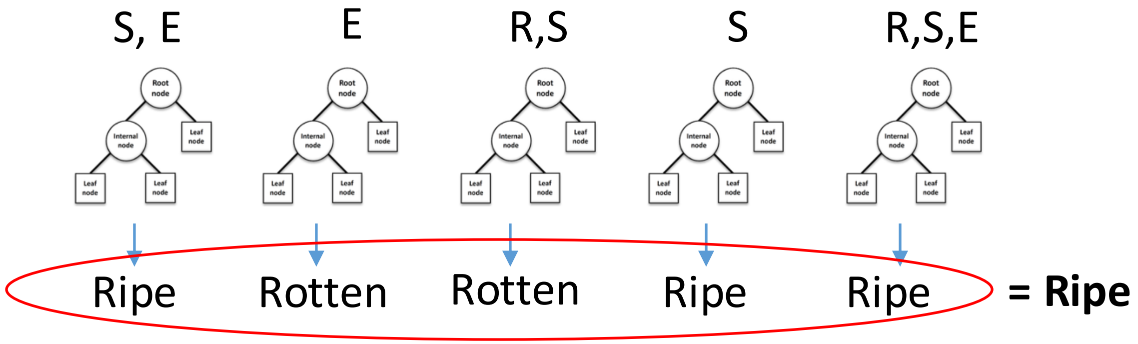
Probability of class k is updated with each scan

$$\hat{F}_k = \arg\max_{F_k} P(F_k|S_i,E_i,R_i)$$

After 10 scans, the most likely class is the decision result

Methods were tested using **leave-one-out cross validation**

Random Forest classifier (Matlab R2016b implementation)



Majority settles decision

F_k - Fruit belonging to class k

$$P(F_k|S_i,E_i,R_i) = \frac{T_k}{T_T}$$

T_k: Number of trees choosing fruit class k

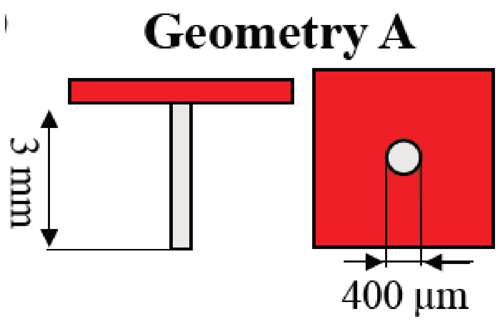
T_T: Total number of trees

$$P(F_k) = \prod_i^n P(F_k|S_i,E_i,R_i)$$

$$\hat{F}_k = \arg\max_{F_k} P(F_k|S_i,E_i,R_i)$$

Fruit quality sensing - Results

Stiffness (E) → Fruit hardness



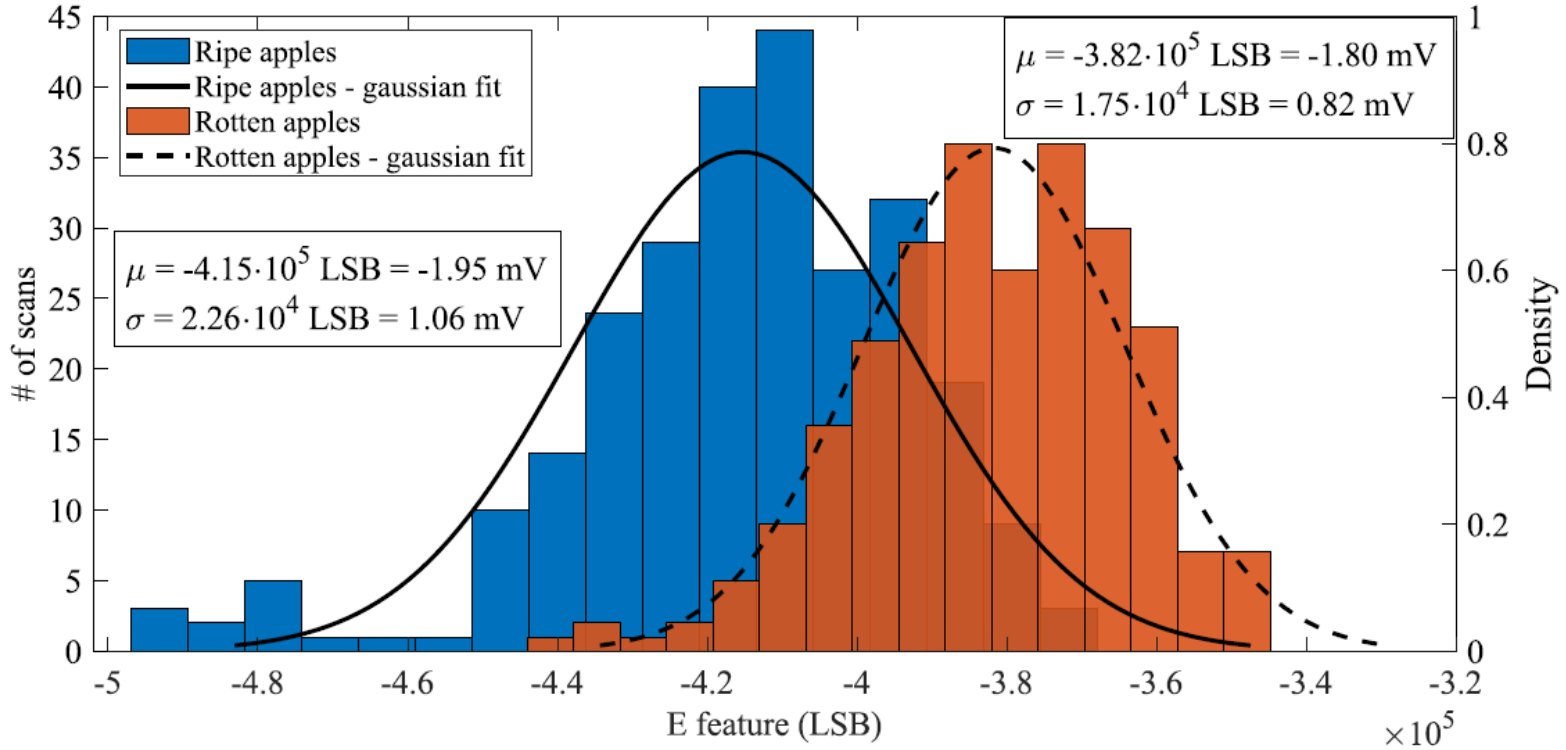
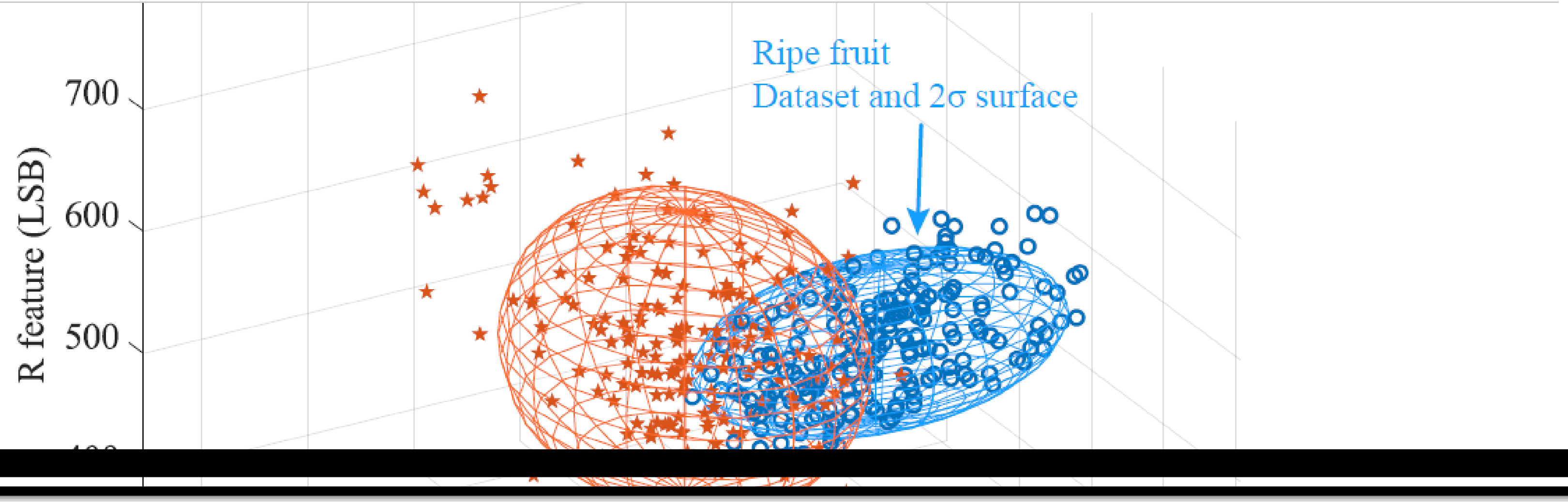


Figure 6.4: Computed E parameter histogram from all scans of apples scanned using a geometry A ciliary sensor.

Gaussian classifier

(Gaussian Näive Bayes)



Combining R, S, E

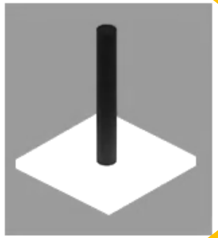
Sensor	Fruit	1 feature (E)	2 features ($E+R$)	3 features ($S+E+R$)
B	Apple	0.83	0.92	0.96
	Strawberry	0.63	0.79	0.71
D	Apple	0.71	0.88	0.88
	Strawberry	0.67	0.67	0.71
E	Apple	0.58	0.71	0.71
	Strawberry	0.63	0.83	0.83

Table 6.3: Accuracy vs number of features used for classification with Gaussian Näive Bayes algorithm.

Apple

Strawberry

Conf. A



h = 3 mm
ϕ = 400 µm

Apple

	True positive	True negative	Accuracy
Naïve Bayes	11/12	12/12	0.96
Random Forest	10/12	12/12	0.92

Strawberry

	True positive	True negative	Accuracy
Naïve Bayes	7/12	10/12	0.71
Random Forest	8/12	11/12	0.79

Conf. B

h = 1.6 mm
ϕ = 320 µm

Apple

	True positive	True negative	Accuracy
Naïve Bayes	10/12	11/12	0.88
Random Forest	10/12	11/12	0.88

Strawberry

	True positive	True negative	Accuracy
Naïve Bayes	10/12	7/12	0.71
Random Forest	10/12	10/12	0.83

Conf. C

h = 3 mm
ϕ = 400 µm

Apple

	True positive	True negative	Accuracy
Naïve Bayes	9/12	8/12	0.71
Random Forest	9/12	11/12	0.83

Strawberry

	True positive	True negative	Accuracy
Naïve Bayes	10/12	10/12	0.83
Random Forest	10/12	10/12	0.83

The motivation: tactile sensors for human-friendly robot "Vizzy"

- Robot for Children support
- 2D sensitivity
- Capable of detecting force with sub-mN resolution
- Small enough to fit Vizzy robotic hand: < 3x3 mm^2
- Fabricated/mounted as a distributed array

Too young to have cilia/hair…

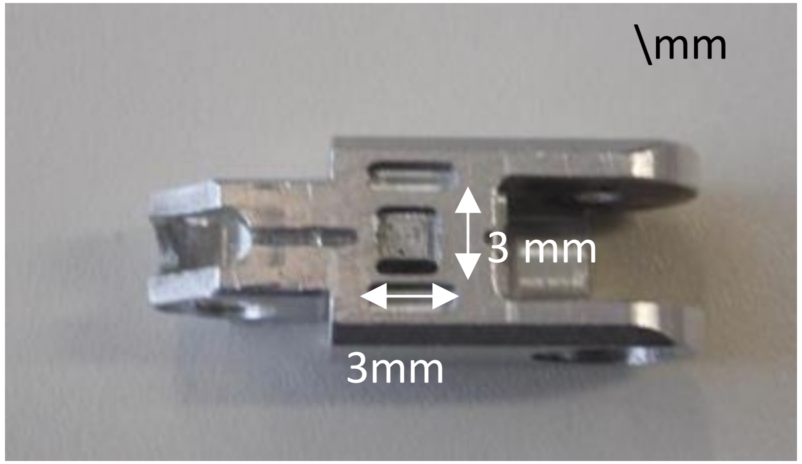
Commercial solutions are not compatible with Vizzy:

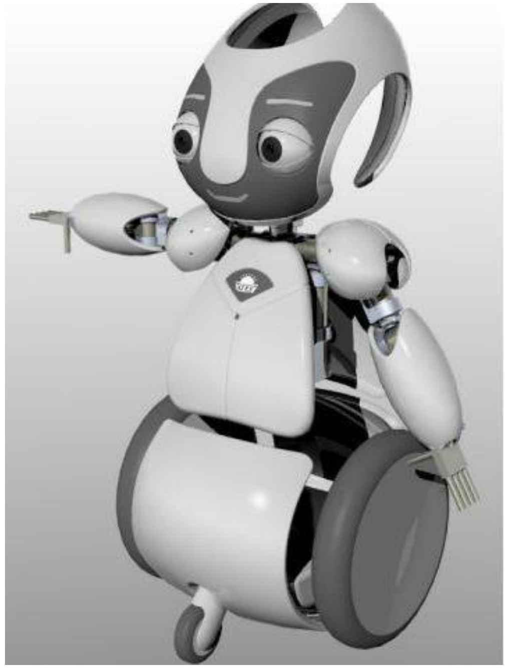
ATI Nano 17-E

Optoforce

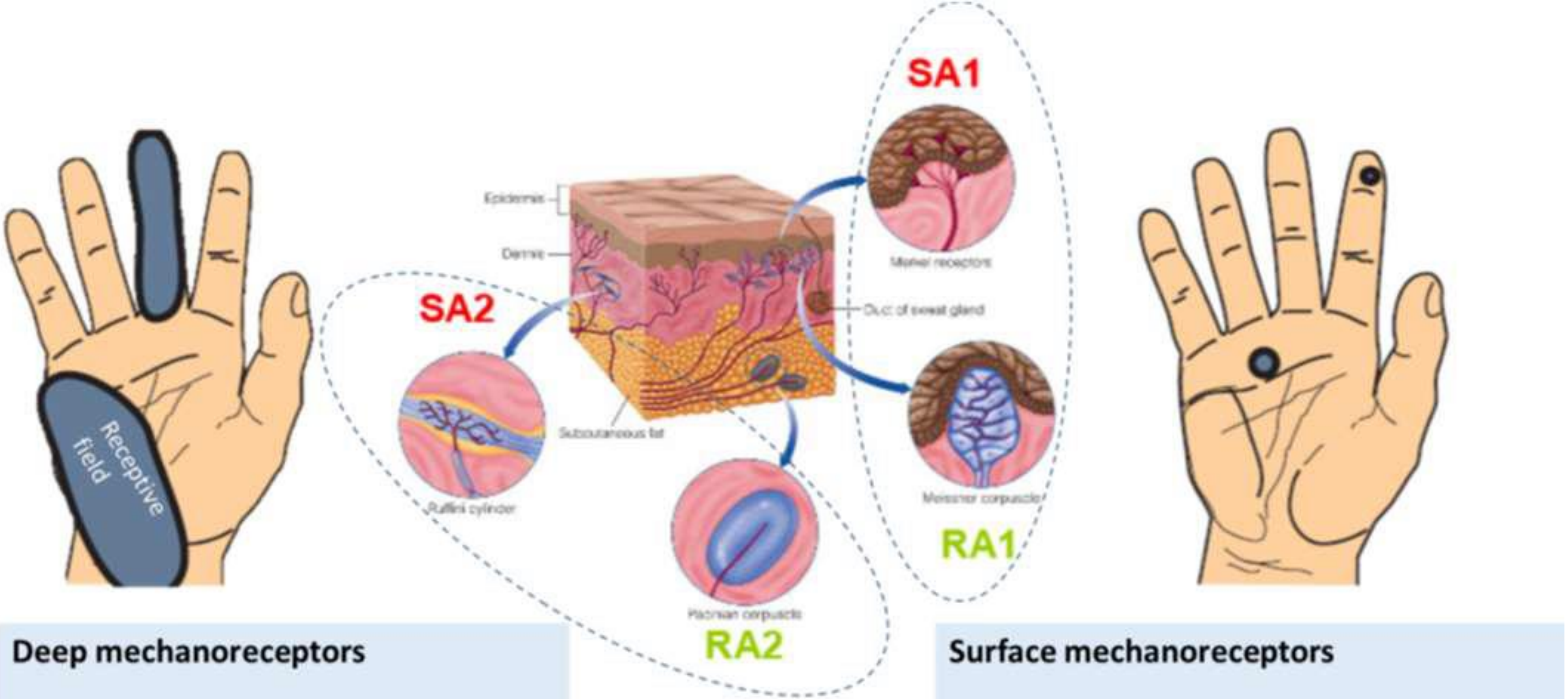
- Big and bulky
- Resolution > 1 mN

Vizzy, the robot





Where to locate the sensors?
How many sensors?



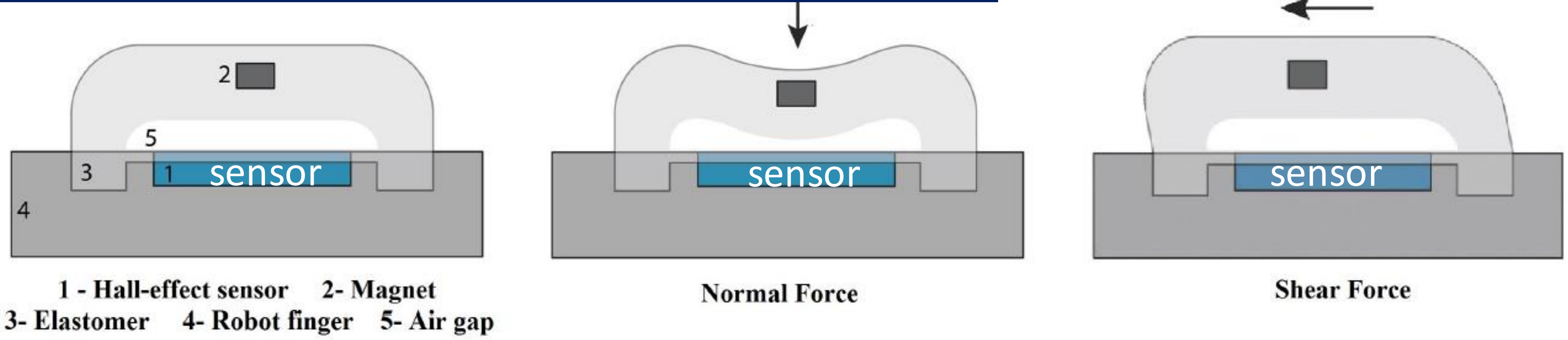
Deep mechanoreceptors

- have large receptive fields
- respond to high frequency stimuli

Surface mechanoreceptors

- have small receptive fields
- respond to low frequency stimuli

Magnetic field created by the magnet displacement

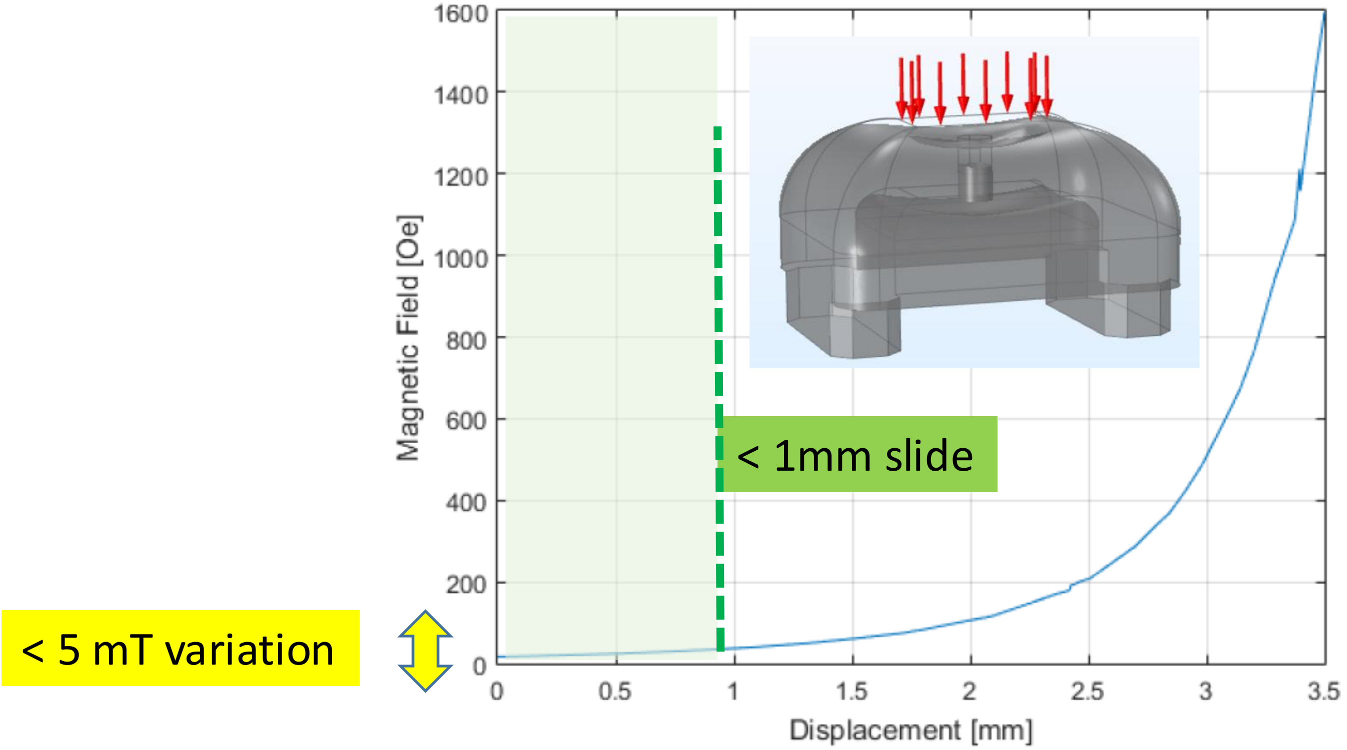


T. Paulino et al. IEEE ICRA 2017

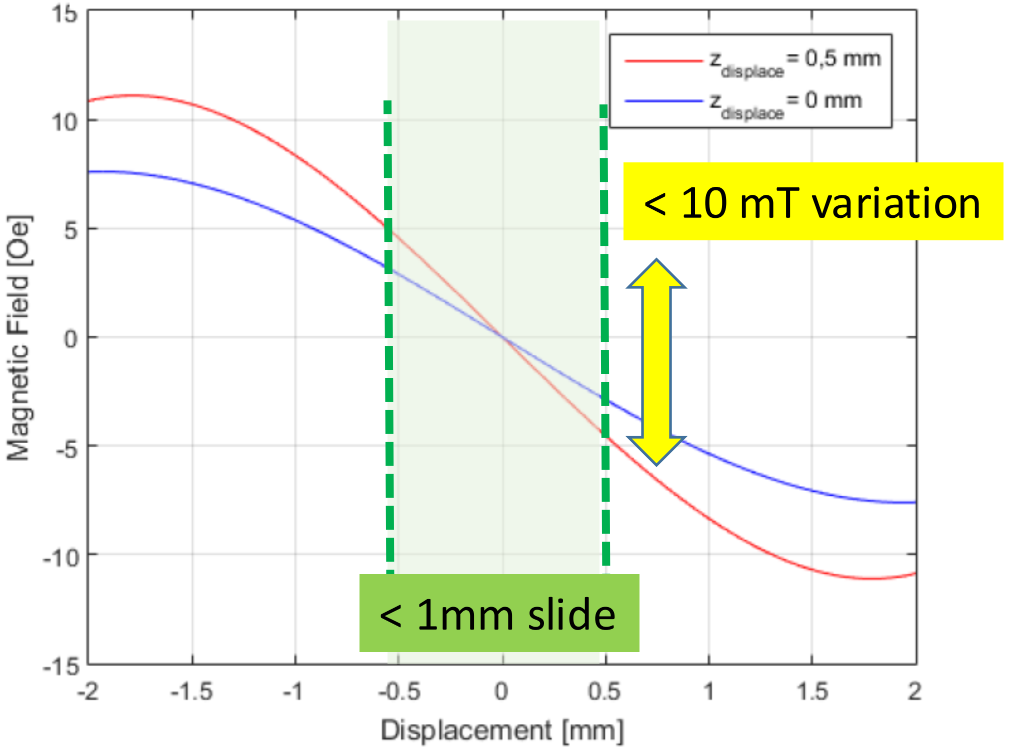
L.Jamone et al. IEEE Sensors, 15(8). 2015

For sensitive touch:

Magnet displacement – vertical direction Z

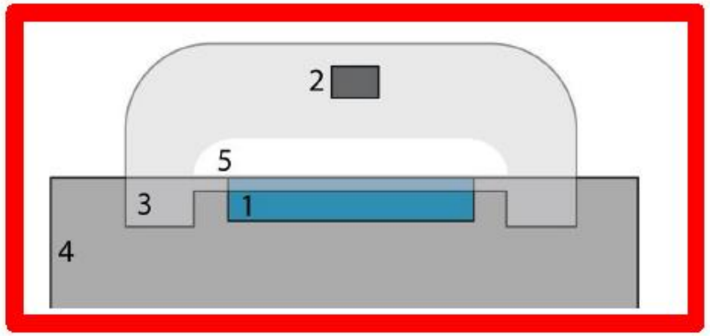


Magnet displacement– lateral directions X, Y

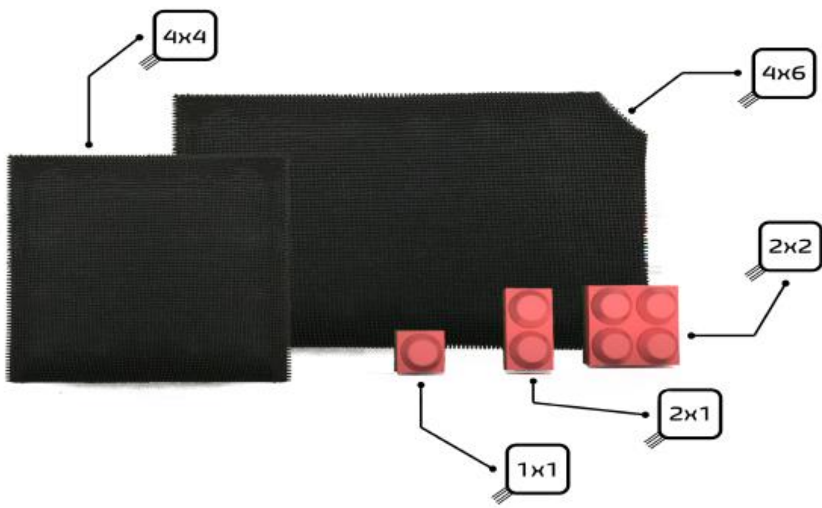


Soft sensitive skin for dexterous robot hands

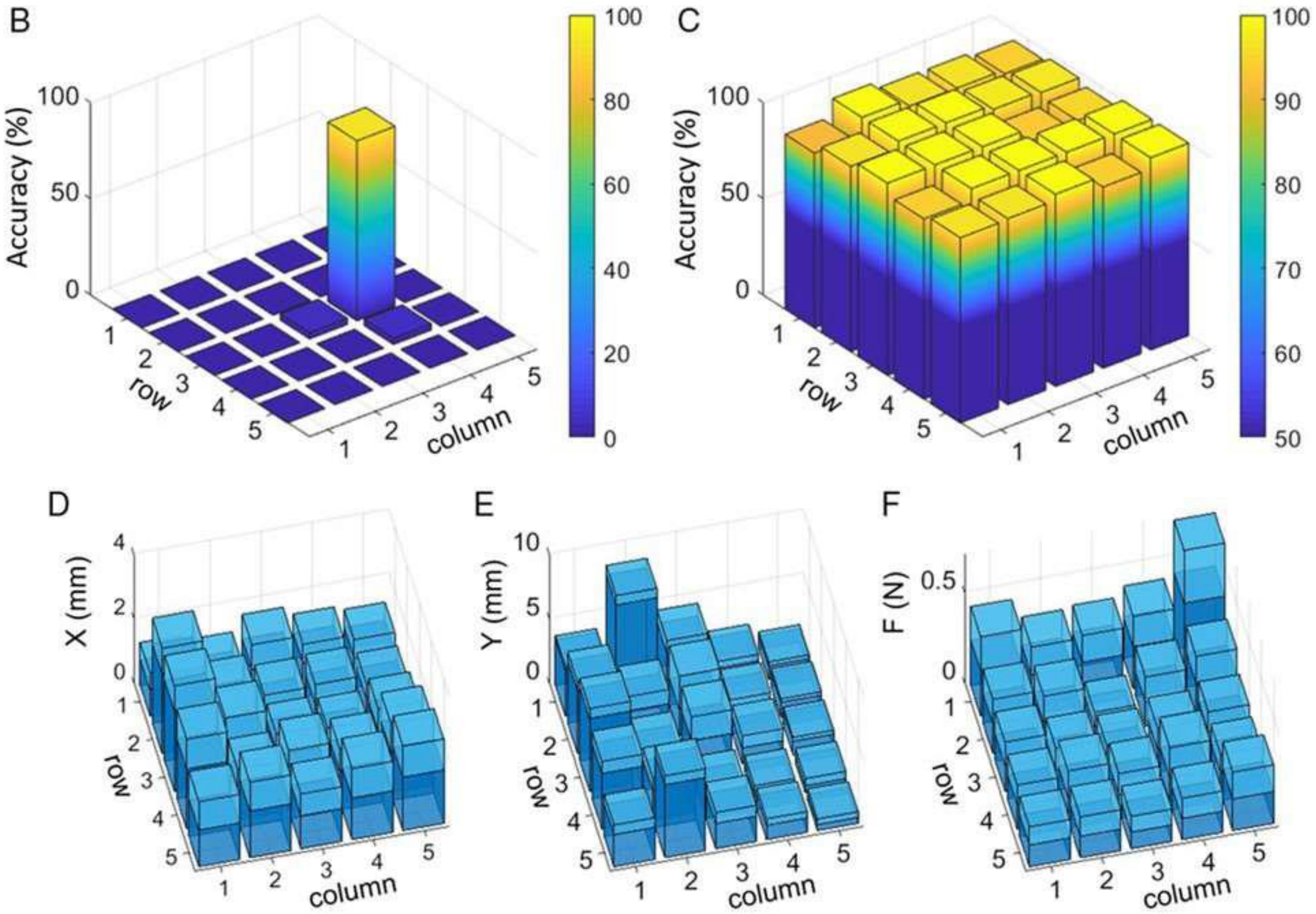
Available on the market.



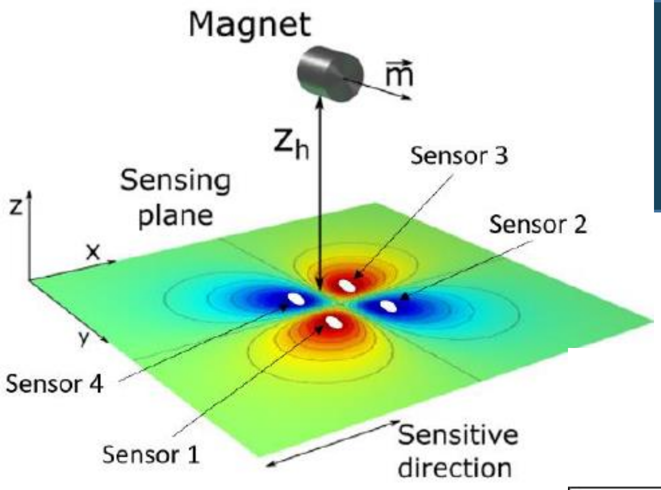
XELA ROBOTICS



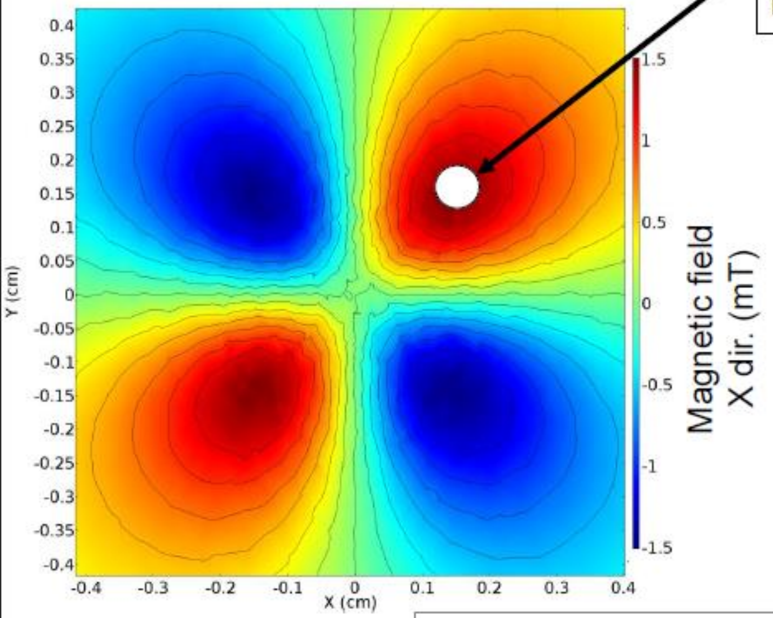
Do we need 3D sensors to understand the deformations?



How to detect the position of a magnet with 1D sensors?



Simulation



Magnet position:
(x,y,z_h) = (0, 0, 2.5) mm

Magnet characteristics:
Br = 1.35 T
h = ϕ = 1mm

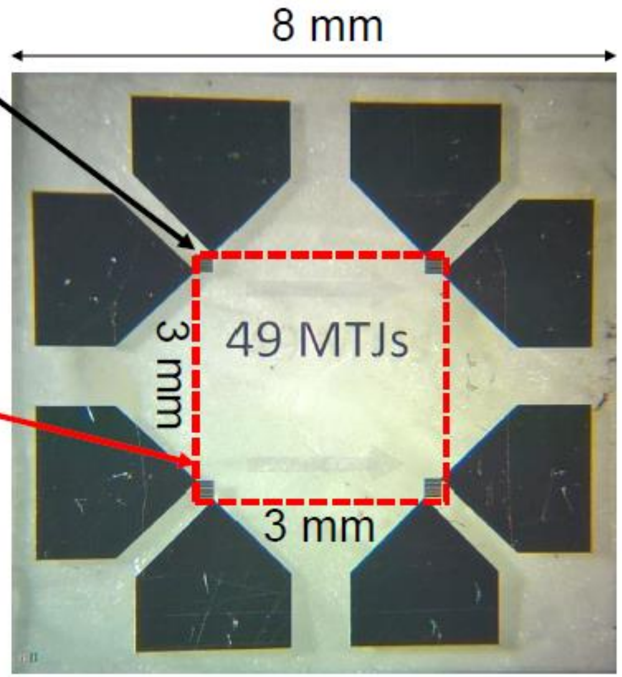
Sensor position coincides with maximum field areas

Increased sensitivity

9 mm² active area

Small footprint

Fabricated device



P.Ribeiro, IEEE Trans. Magn. 54 (11), 9401605 (2018)

2D position mapping

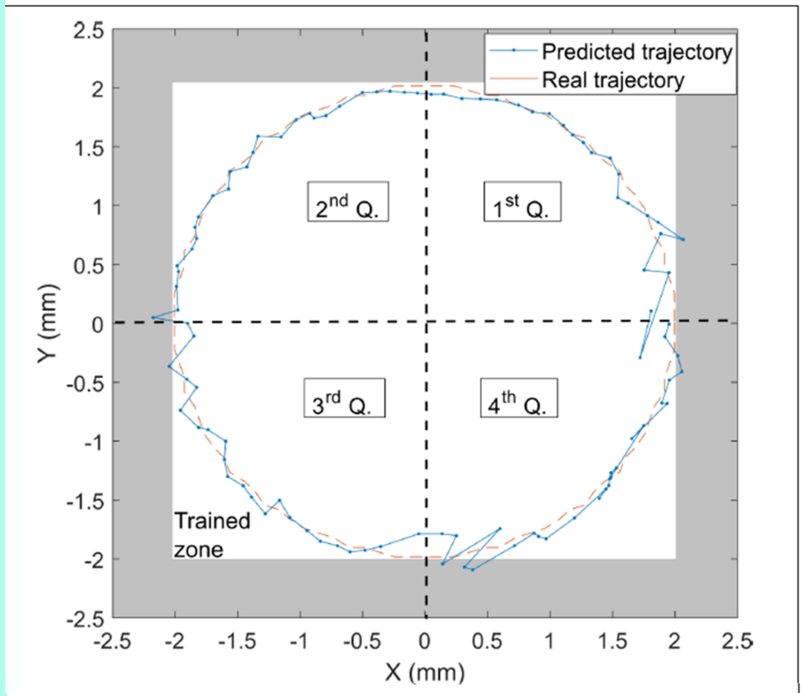
Predictive algorithms (Top performers)

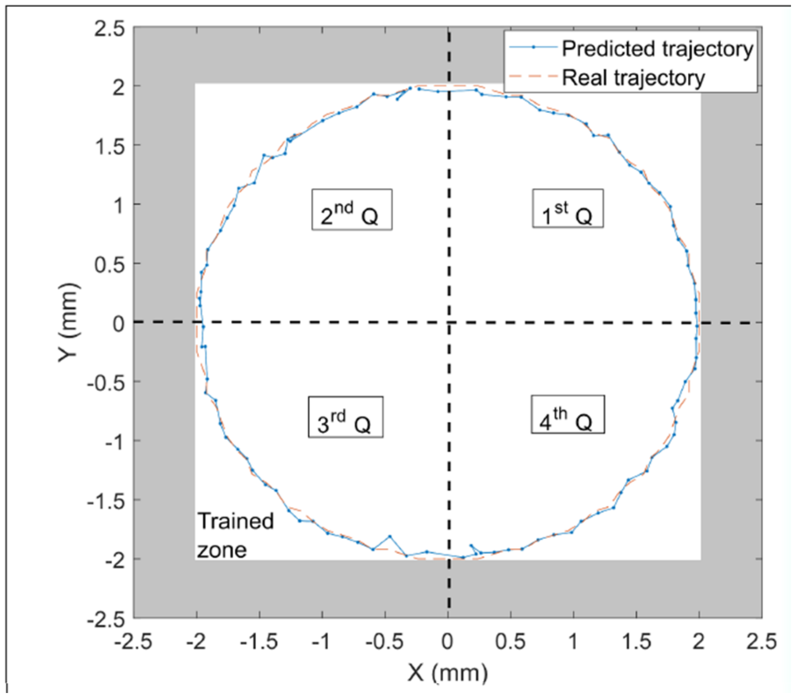
Trained correlation

MAPPING METHOD

10201 Magnetic field/ Magnet position pairs → Trains → Artificial Neural Network [7] / Regression Forest [8] → Magnetic field/Magnet position correlation

ARTIFICIAL NEURAL NETWORK





REGRESSION FOREST

2D magnet position mapping achieved with µm resolution

Computation ~10 KB

Computation ~98 MB

RMS error **~170 µm**

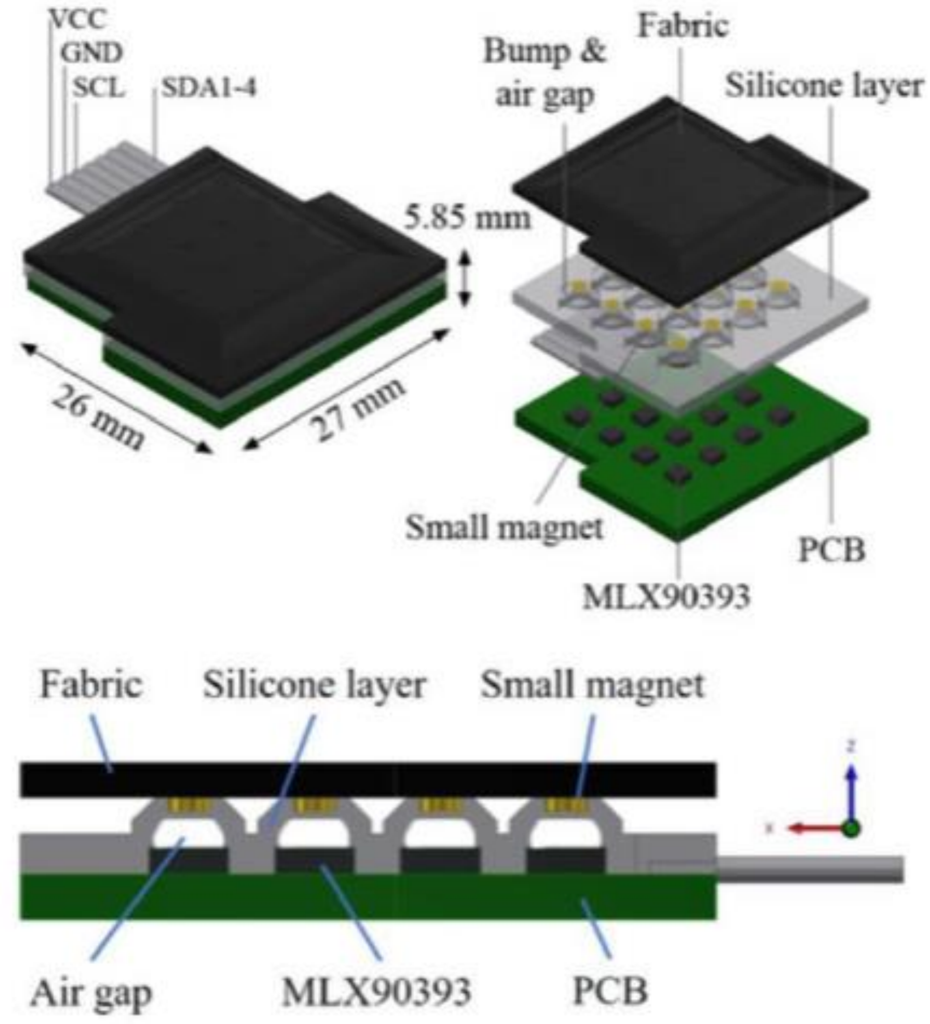
RMS error **~96 µm**

P.Ribeiro, IEEE Trans. Magn. 54 (11), 9401605 (2018)

Cover larger areas:

- Few sensors
- Distributed magnets

Distributed magnetic skin



T. P. Tomo et al., "A New Silicone Structure for uSkin—A Soft, Distributed, Digital 3-Axis Skin Sensor and Its Integration on the Humanoid Robot iCub," in IEEE Robotics and Automation Letters, vol. 3, no. 3, pp. 2584-2591, July 2018, doi: 10.1109/LRA.2018.2812915.

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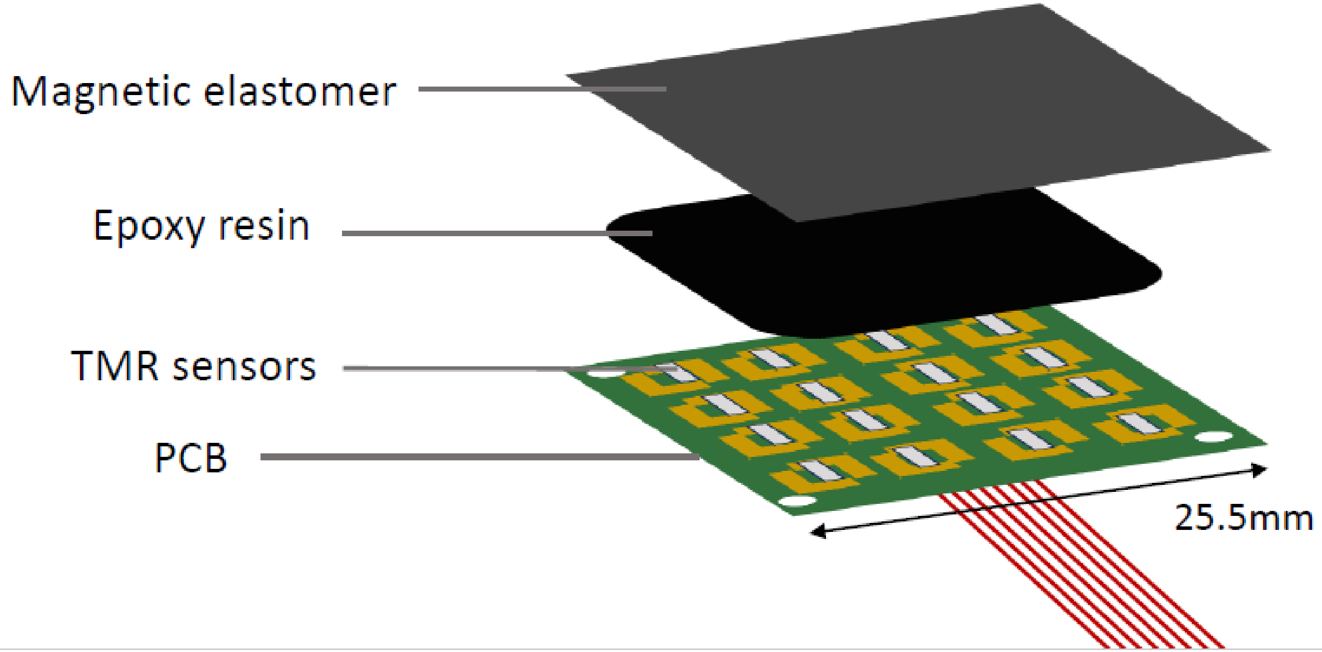
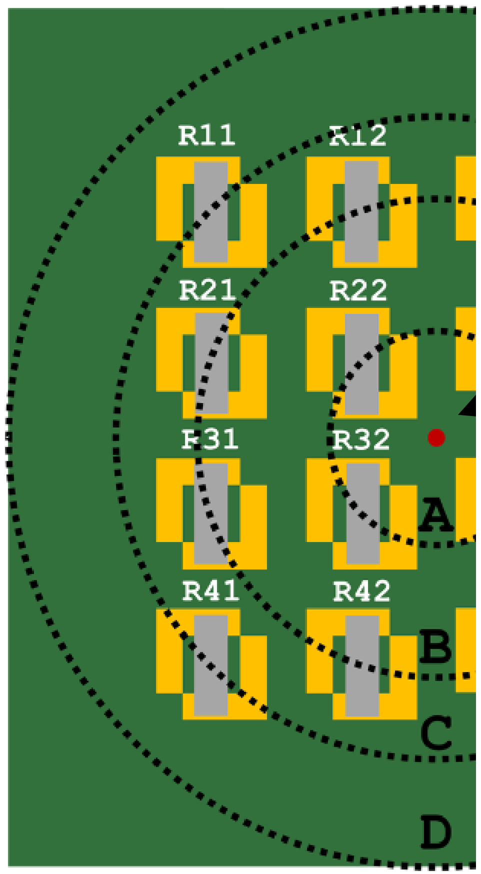
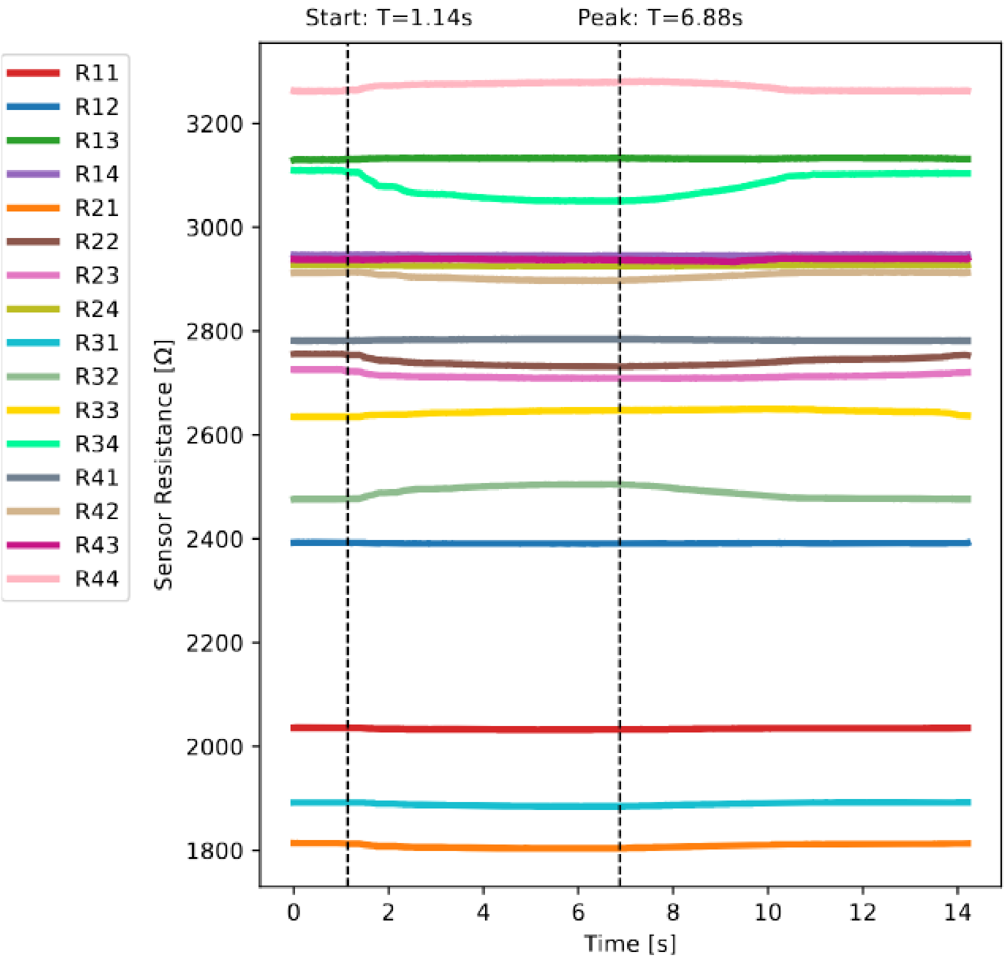
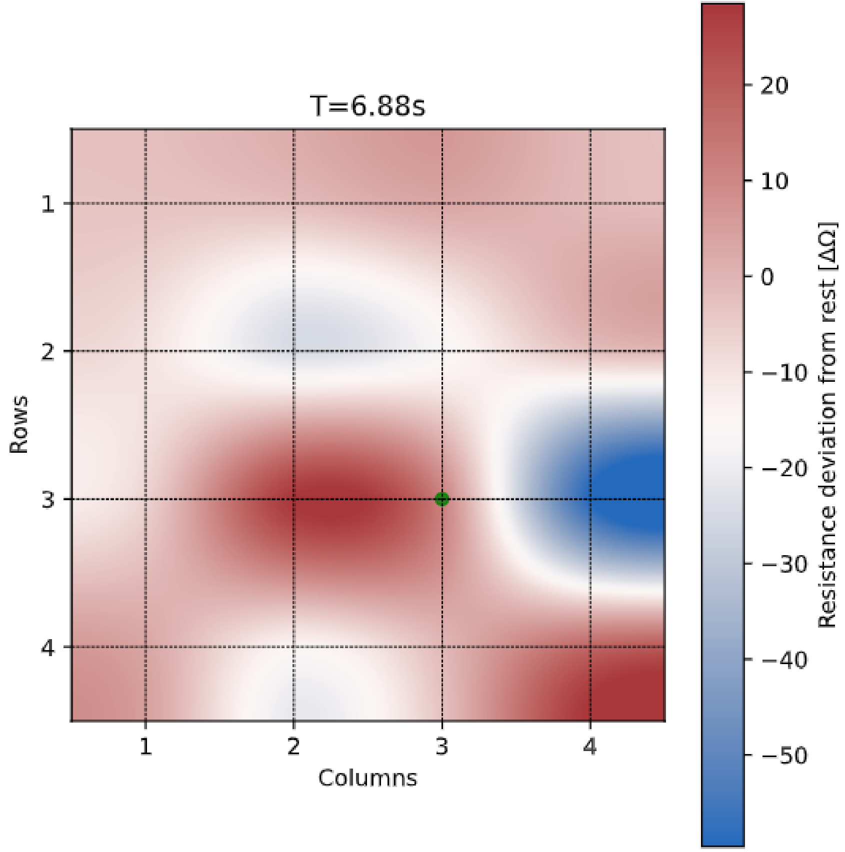


Application point for the force







SUMMARY

Pressure sensors

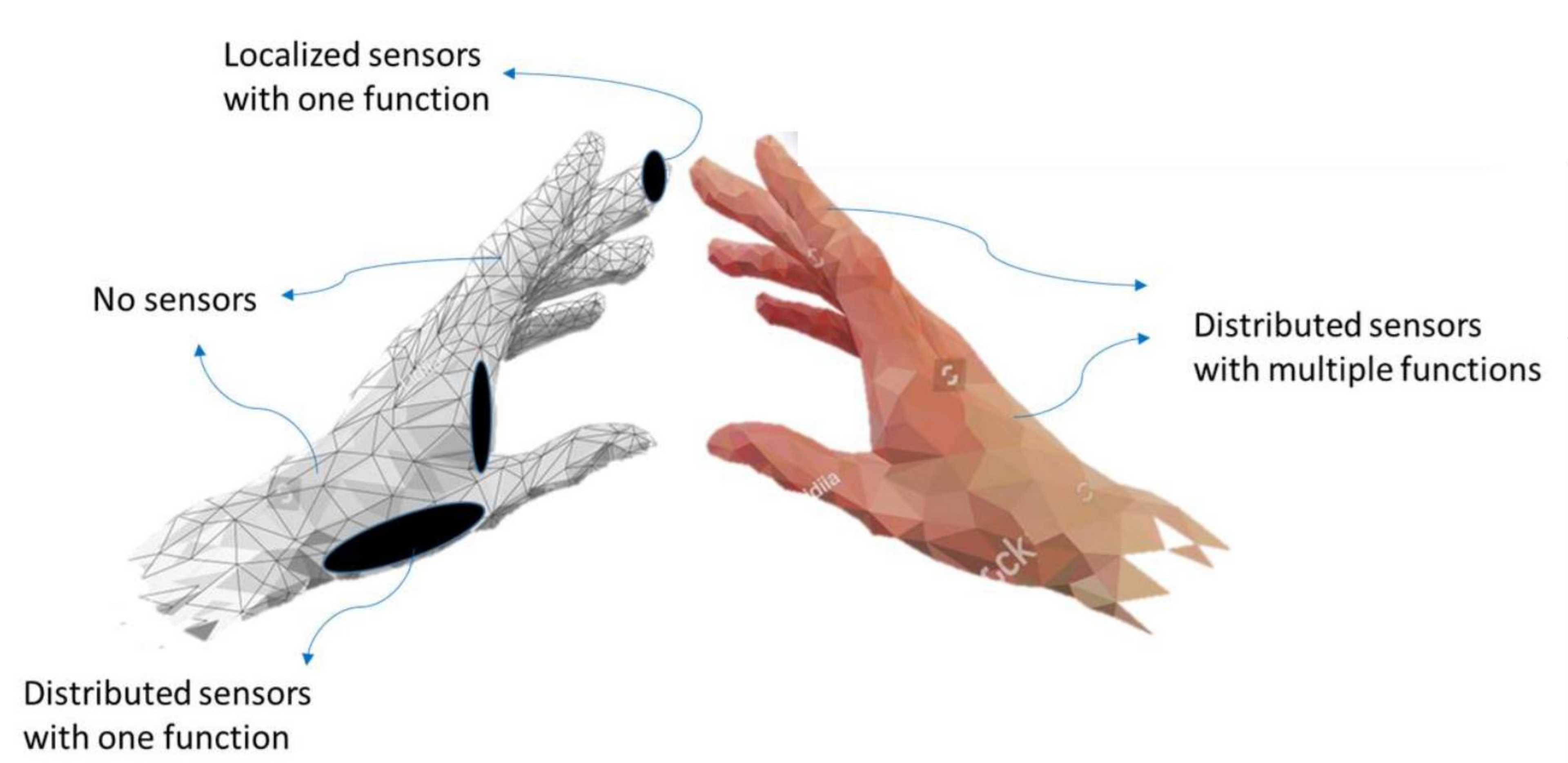
Texture sensors

Soft s

Bulk magı

3D Hall sensoı

rotten



Acknowledgments

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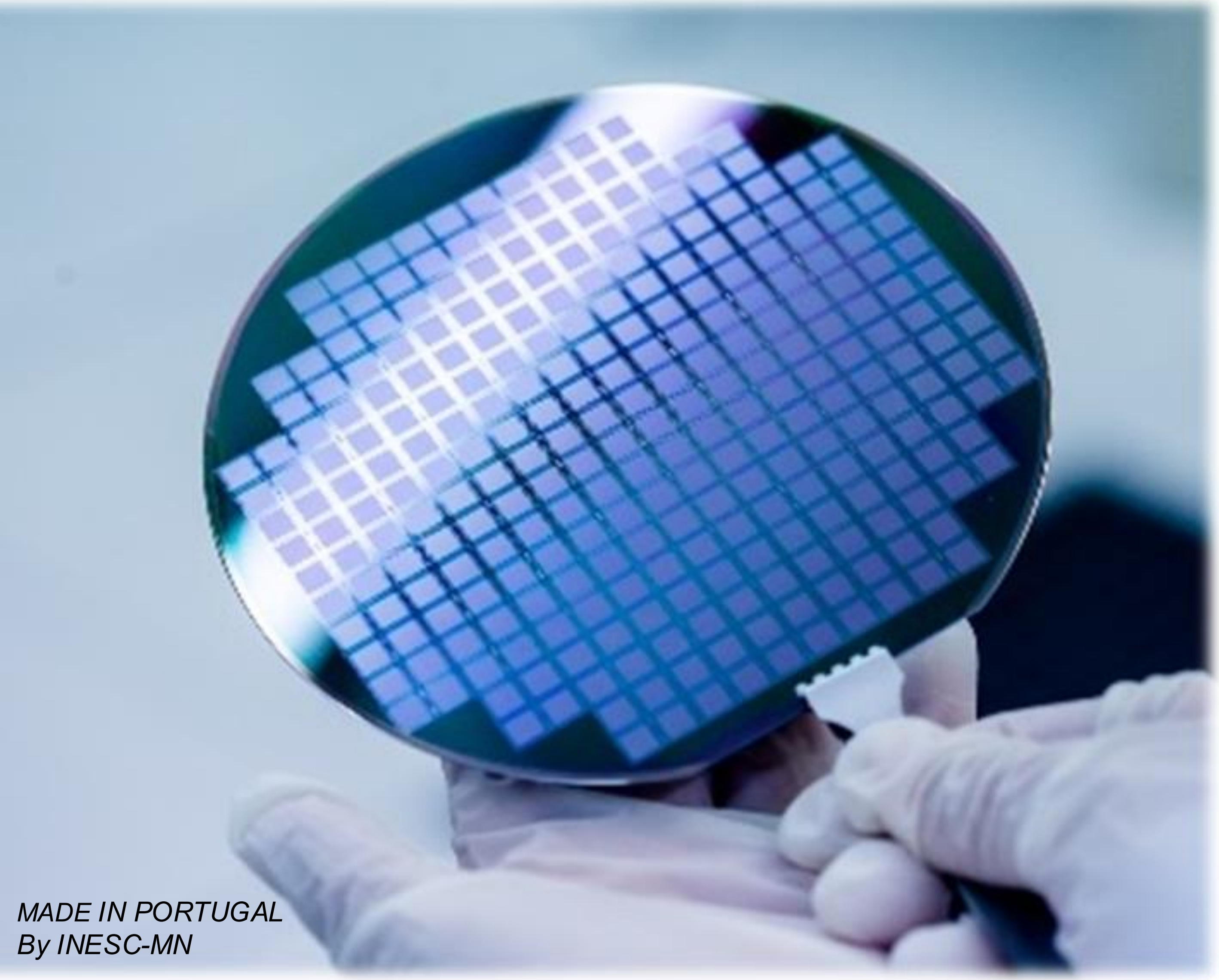

Advanced Research + Invention Agency ARIA

MI MISSÃO INTERFACE

ANI AGÊNCIA NACIONAL DE INOVAÇÃO

REPÚBLICA PORTUGUESA

PRR Plano de Recuperação e Resiliência

Financiado pela União Europeia NextGenerationEU

IAPMEI

fct Fundação para a Ciência e a Tecnologia

nffa.eu research infrastructure

UK Project started March 2025

Computer Science
UCL East – Intelligent Robotics

MagTecSkin:
Novel Tactile Sensitive Electronic Skin based on Magnetic Technology

Lorenzo Jamone (UCL, UK)
Emiliano Bilotti (Imperial College London, UK)
Susana Freitas (INESC-MN, PT)
Stefan Navarro (Universidad de O'Higgins, Chile)