2024 AMSM

Anisotropic Design of Materials for Sensors and Actuators in Soft Robotic Applications

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iMD LAB Intelligent Materials and Devices Laboratory

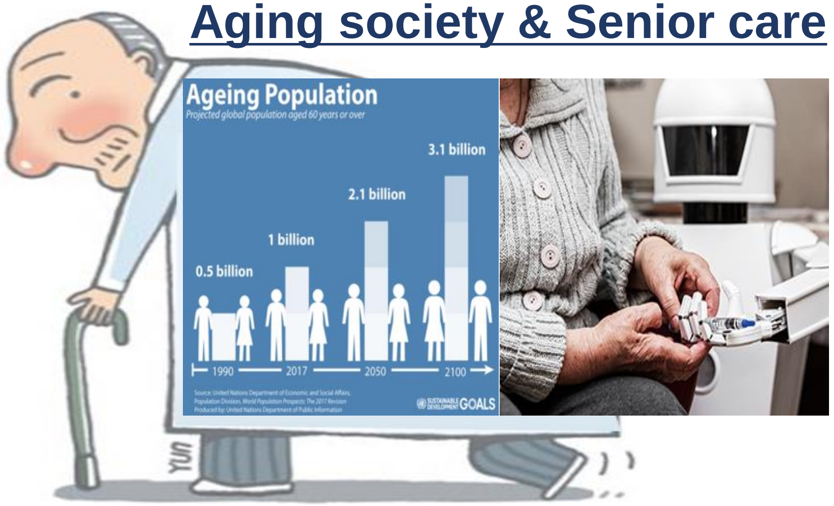
Need for Soft Robotics

Need for Soft Robotics

Need for Soft Robotics

National Agenda

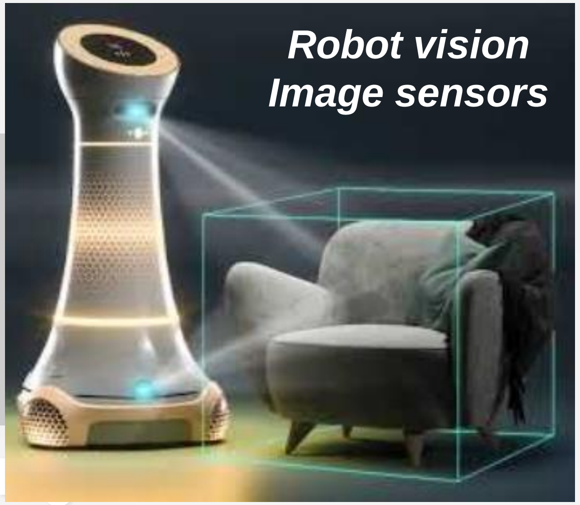
Aging society & Senior care

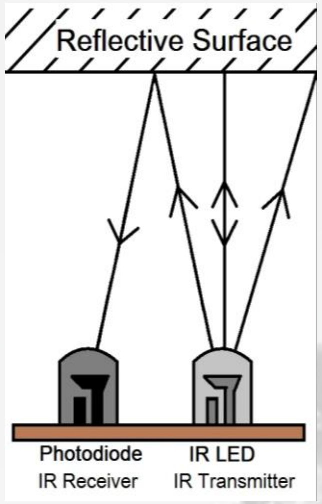


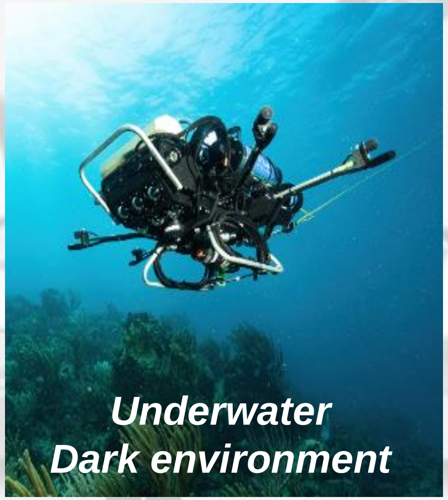
Quality of life

Limitations of Current Robots

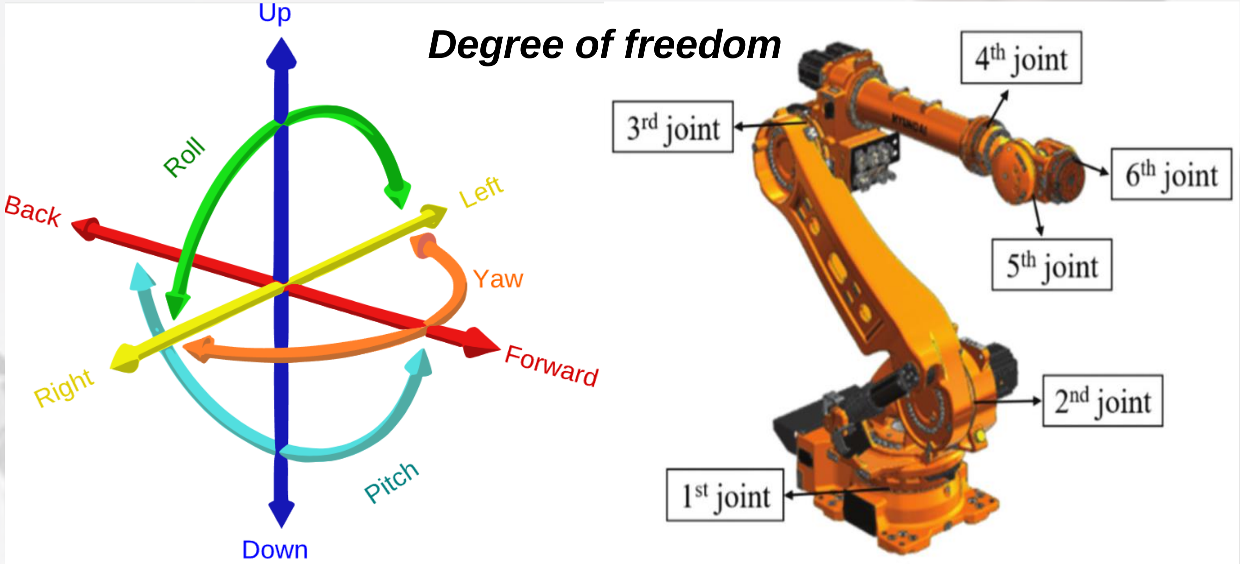
Limited recognition

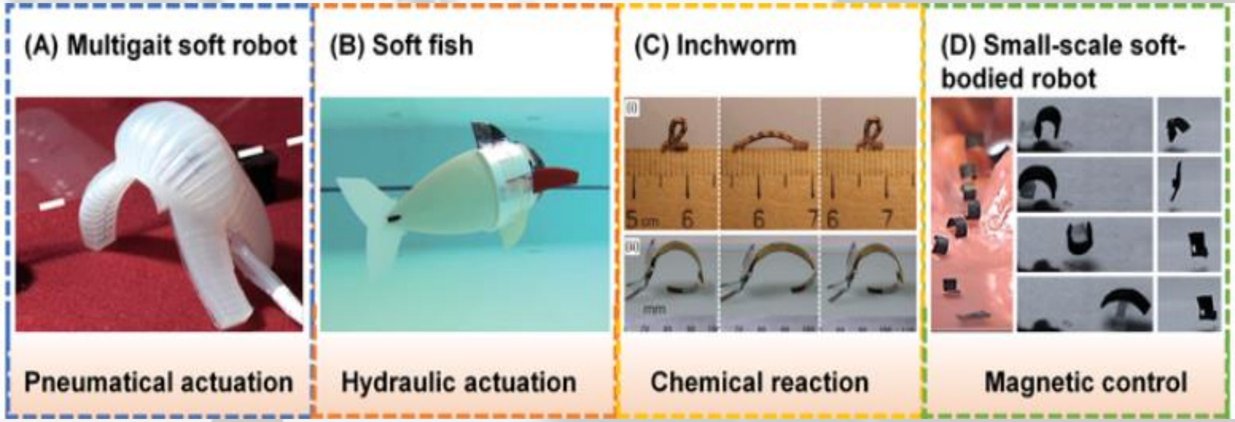






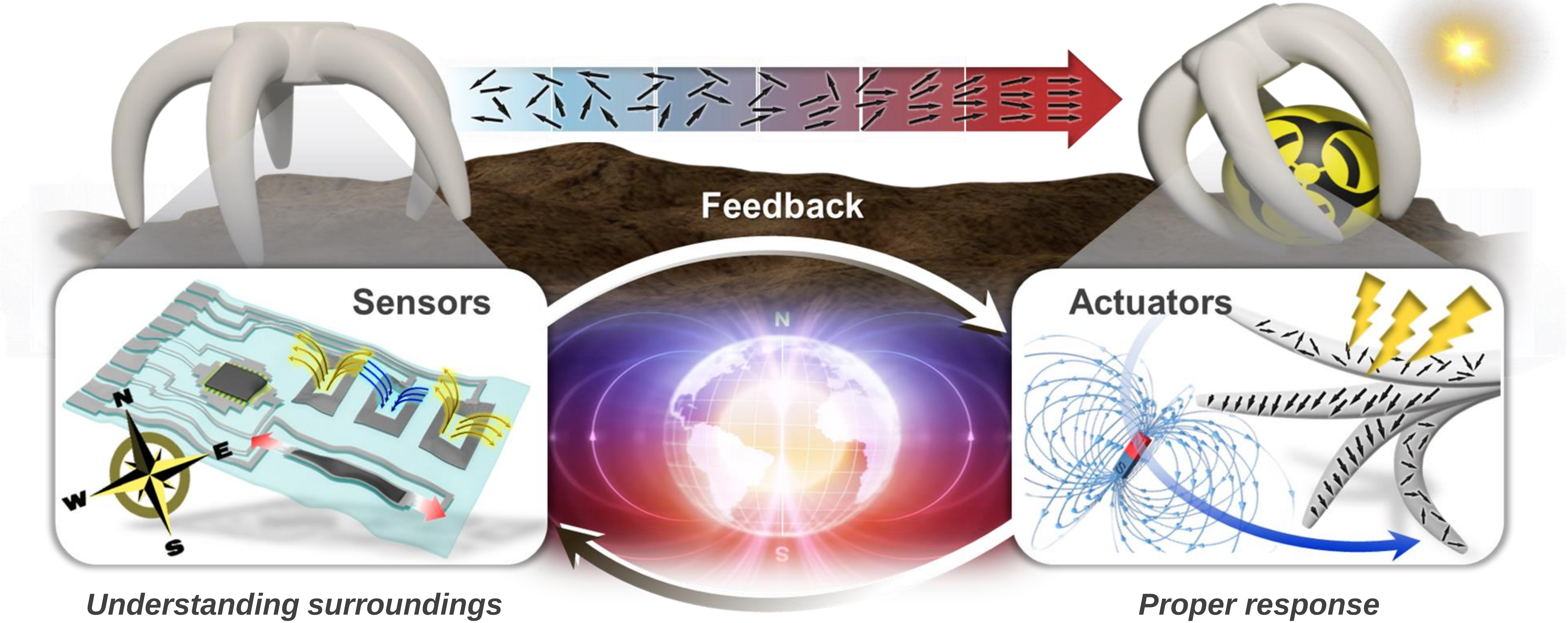
Limited operation





Sense and Response

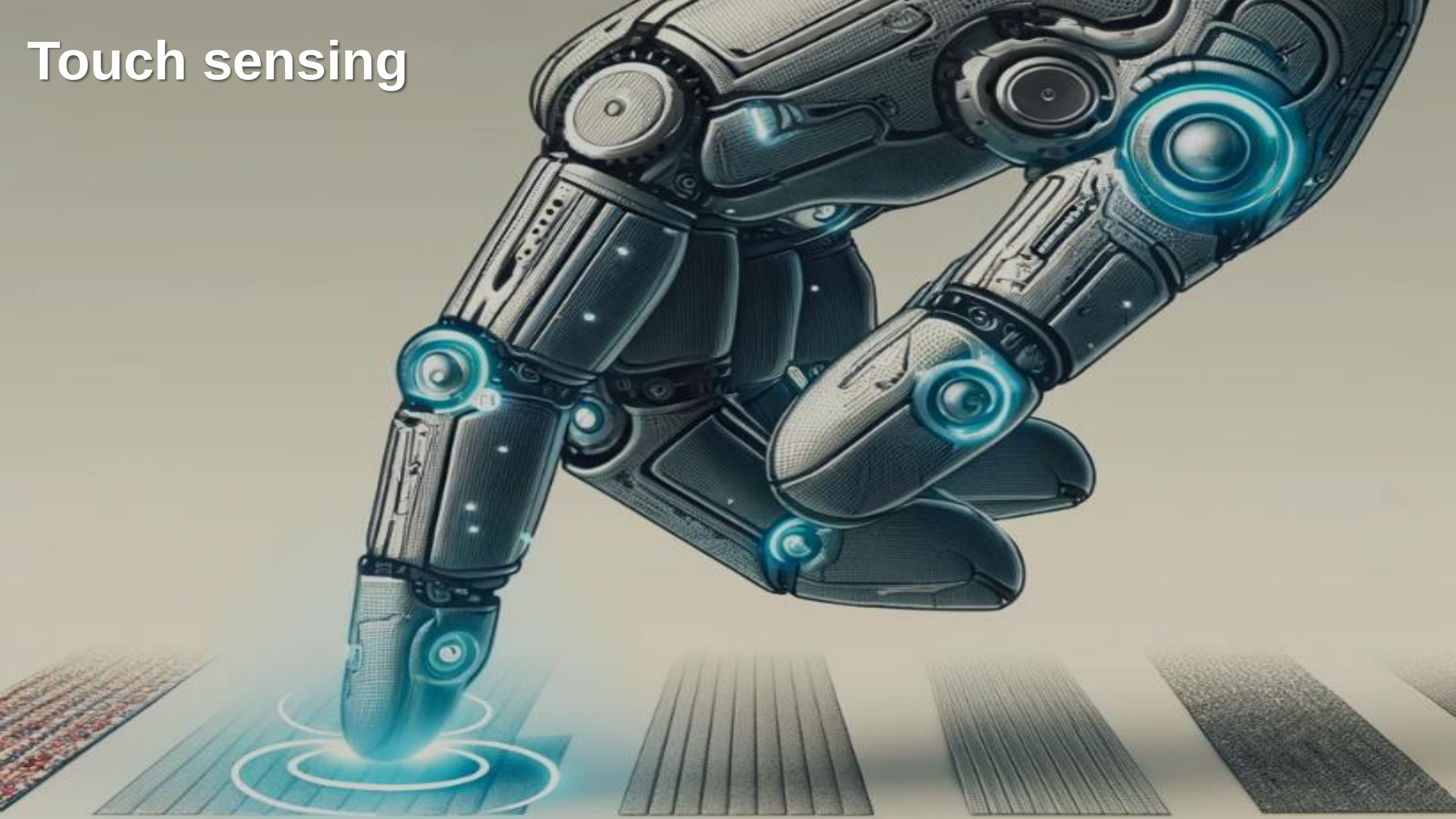
Materials' anisotropy helps robots handle different situations!

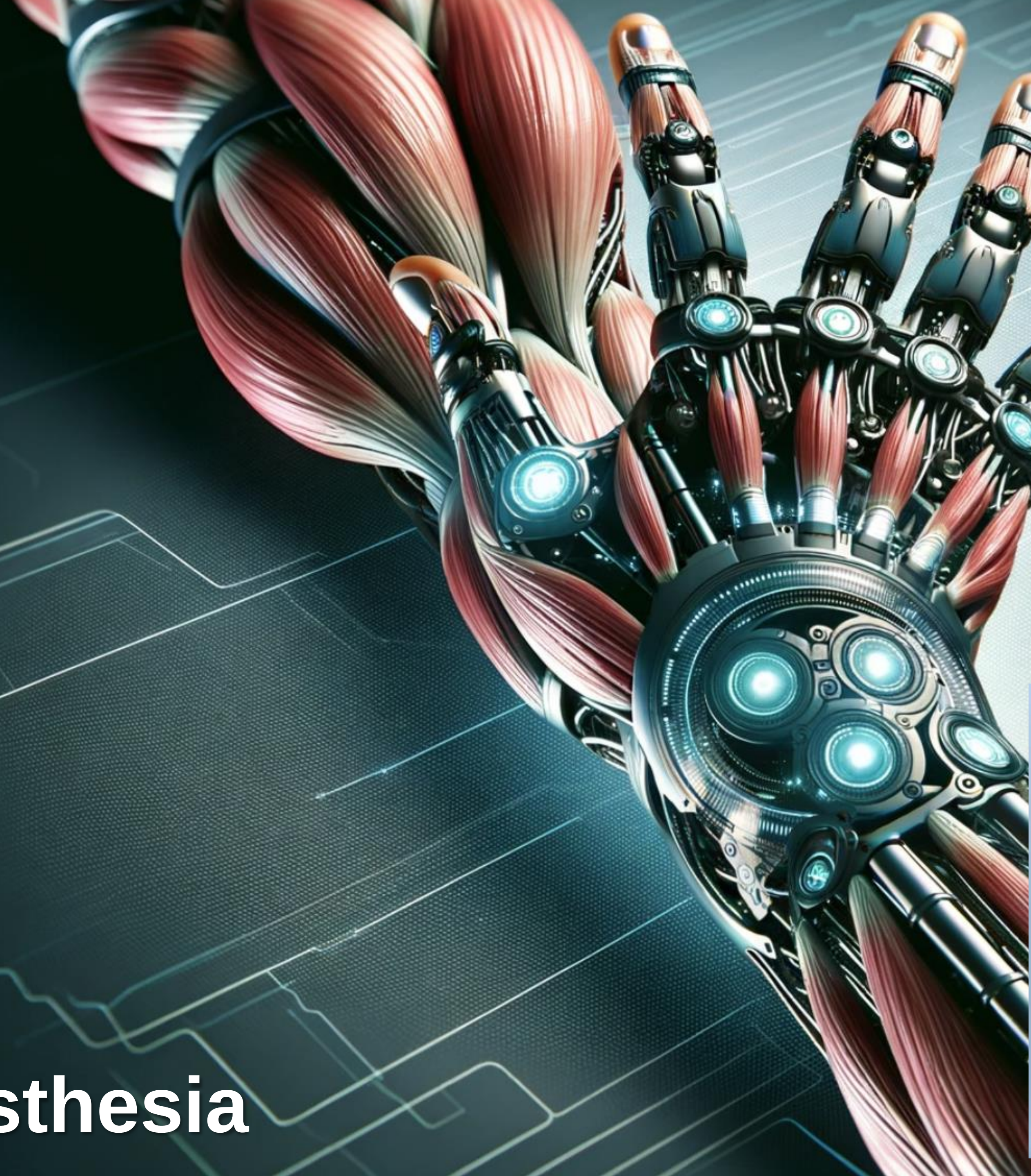


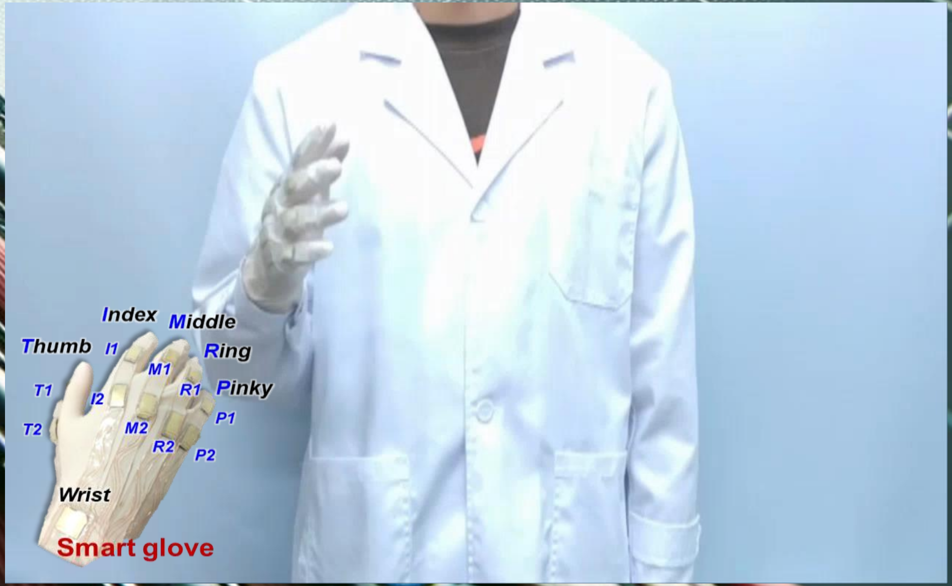
Understanding surroundings ***Proper response***

H. Kwon, <u>M. Ha</u>* *Nanoscale* 2024, 16, 6778-6819.

Touch sensing

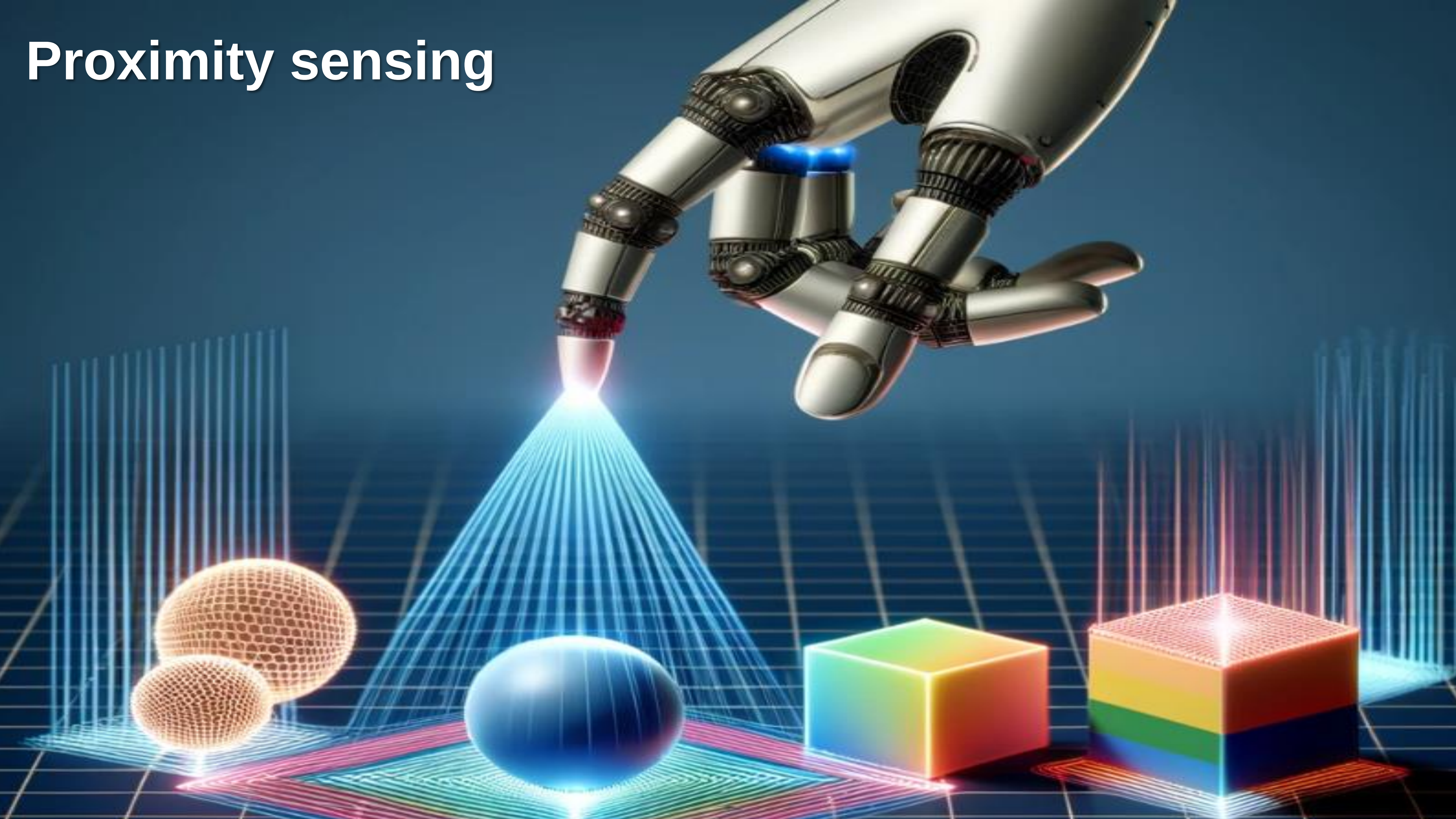






Kinaesthesia

Proximity sensing



Response and Actuation

Approaches for Soft Robotic Sensors and Actuators

Aim

Soft Smart Materials

Flexible electronics

Sensors
Actuators

Tactile	Vision	Proximity/motion	Stimuli-responsive
Effective stress transmission	Anti-reflective	In-plane field sensing	Directional response
Electronic skins	Flexible photodetectors	Printable proximity sensors	Soft actuators
M. Ha et al., J. Mater. Chem. B 2018, 6, 4043. M. Ha et al., Adv. Funct. Mater. 2015, 25, 2841.	M. Ha et al., ACS Omega 2019, 4, 9996. M. Ha et al., Adv. Optical Mater. 2018, 6, 1800615.	M. Ha et al., Adv. Mater. 2021, 33, 2005521. M. Ha et al., ACS Nano 2018, 12, 3964. M. Ha et al., ACS Nano 2015, 9, 3421.	M. Ha et al., Adv. Mater. 2021, 33, 2008751. M. Ha et al., Nano Energy 2018, 48, 275.

Shape anisotropy in micro- and nanomaterials,

along with significant changes in their physical properties,

plays an effective role in…

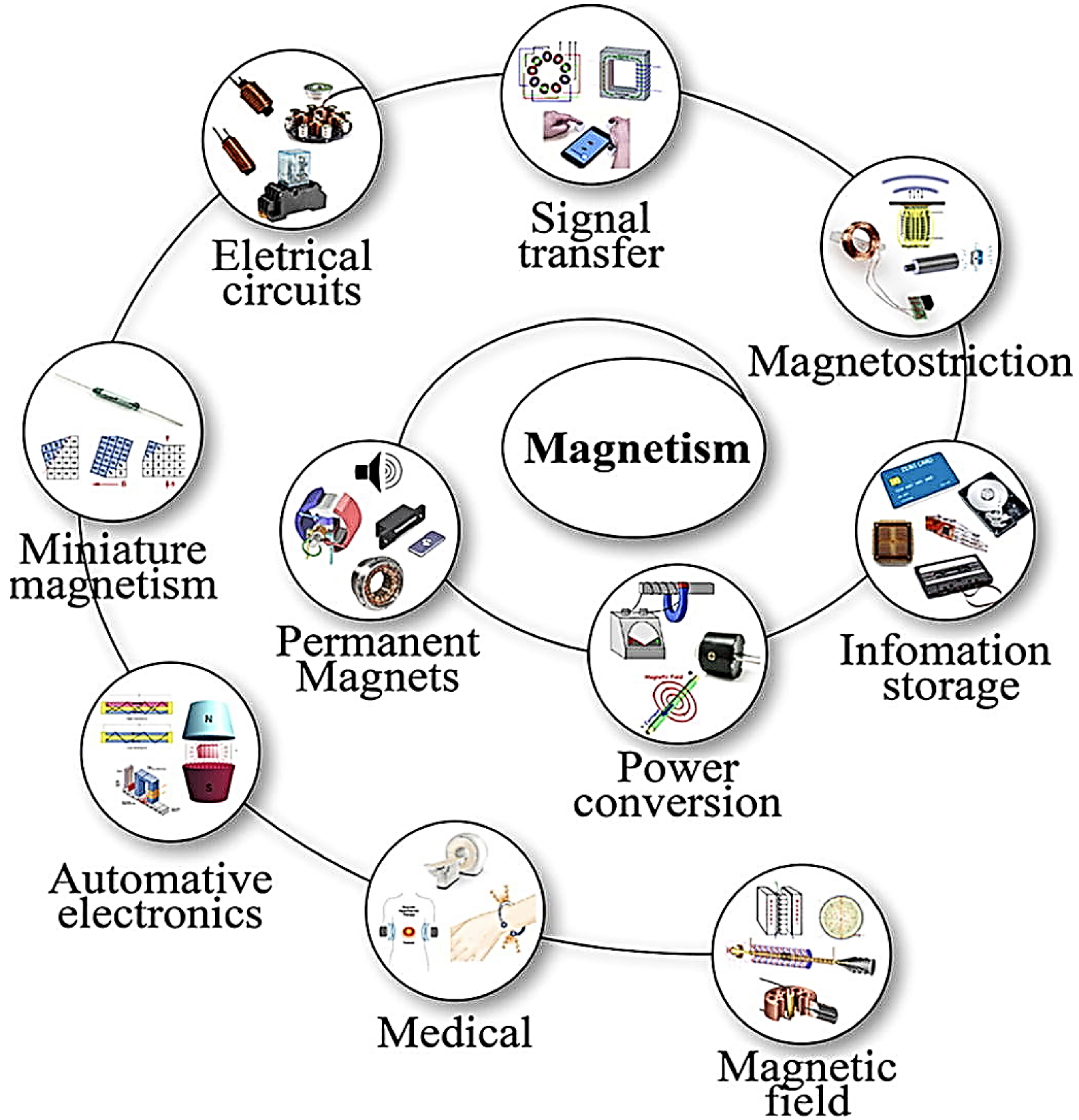
↓

Physical sensors (touch/touchless manner)

Soft actuators (displacement)

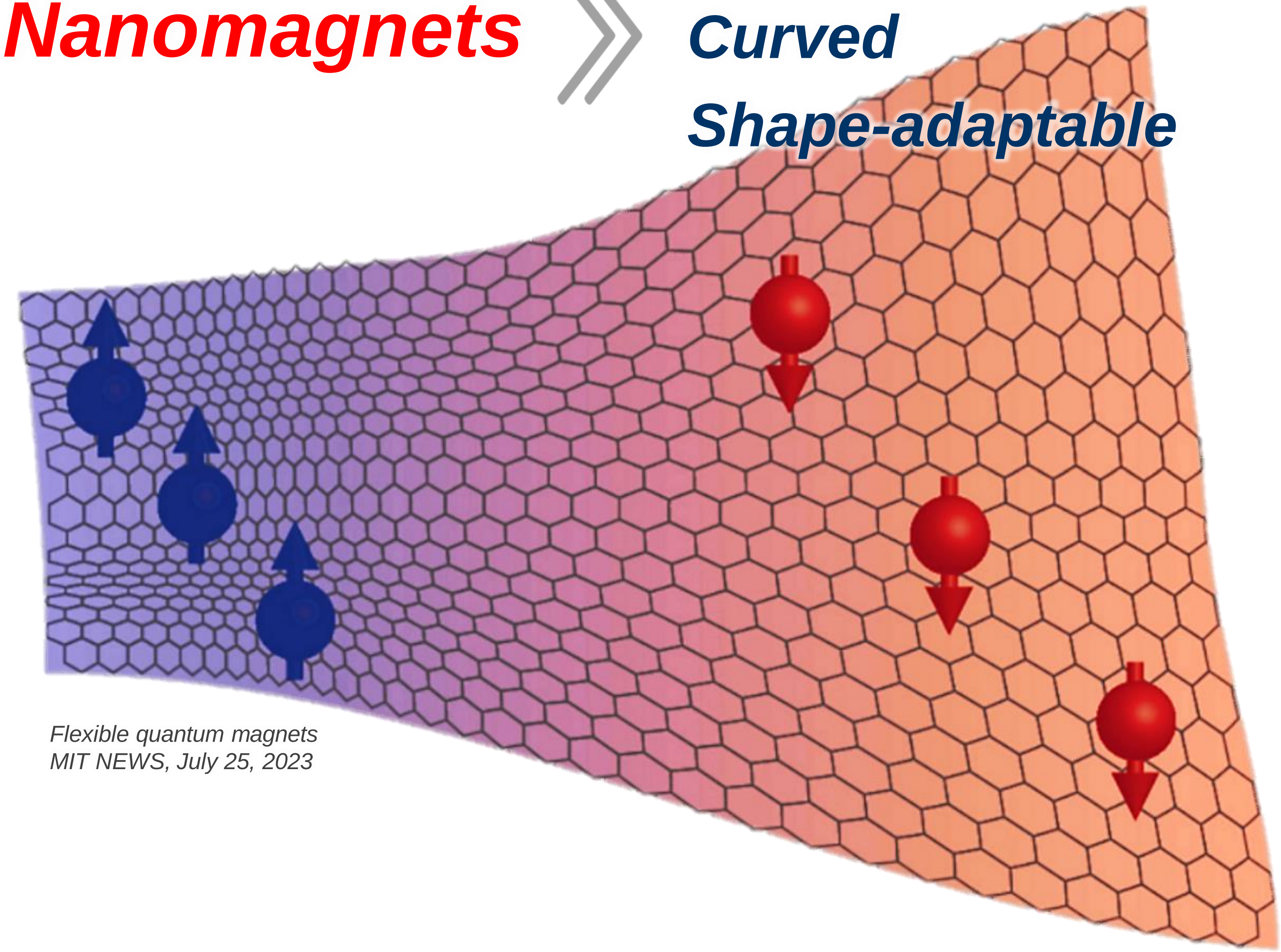

N
S


A
1 km
N
NE
E
SE
S
SW
W
NW
0
20
40
60
80
100
120
140
160
180
200
220
240
260
280
300
320
340


Magnetism
Eletrical circuits
Signal transfer
Magnetostriction
Miniature magnetism
Permanent Magnets
Infomation storage
Power conversion
Automative electronics
Medical
Magnetic field

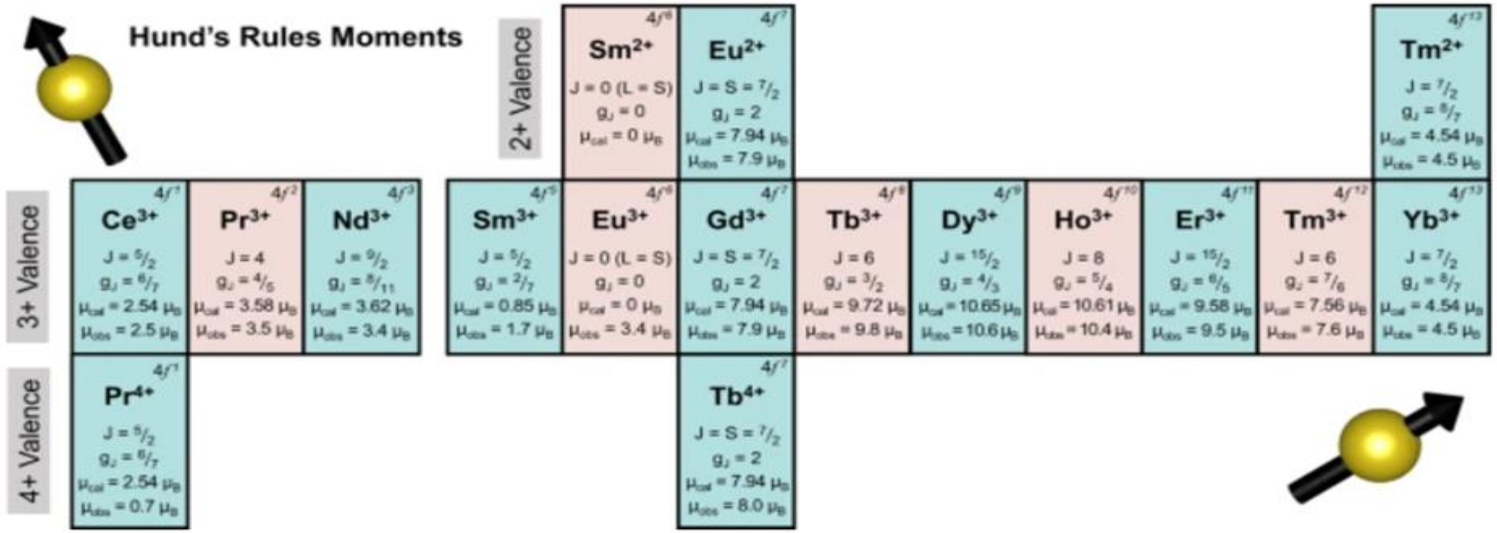

Charging 85%

Nanomagnets

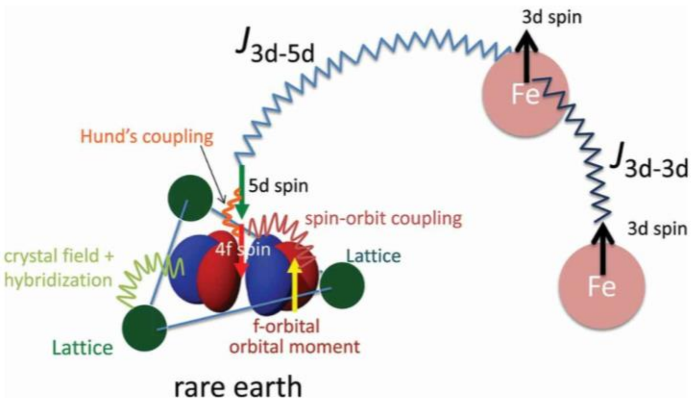


Flexible quantum magnets
MIT NEWS, July 25, 2023

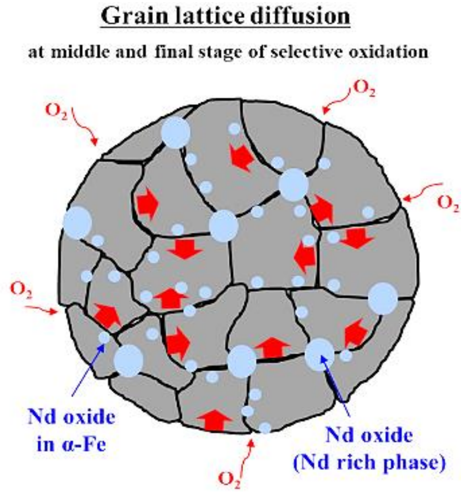
Lightweight
Curved
Shape-adaptable



Hund's Rules Moments
2+ Valence
3+ Valence
4+ Valence
Sm²⁺ 4f⁶ J = 0 (L = S) gJ = 0 μcal = 0 μB
Eu²⁺ 4f⁷ J = S = 7/2 gJ = 2 μcal = 7.94 μB μobs = 7.9 μB
Tm²⁺ 4f¹³ J = 7/2 gJ = 8/7 μcal = 4.54 μB μobs = 4.5 μB
Ce³⁺ 4f¹ J = 5/2 gJ = 6/7 μcal = 2.54 μB μobs = 2.5 μB
Pr³⁺ 4f² J = 4 gJ = 4/5 μcal = 3.58 μB μobs = 3.5 μB
Nd³⁺ 4f³ J = 9/2 gJ = 8/11 μcal = 3.62 μB μobs = 3.4 μB
Sm³⁺ 4f⁵ J = 5/2 gJ = 2/7 μcal = 0.85 μB μobs = 1.7 μB
Eu³⁺ 4f⁶ J = 0 (L = S) gJ = 0 μcal = 0 μB μobs = 3.4 μB
Gd³⁺ 4f⁷ J = S = 7/2 gJ = 2 μcal = 7.94 μB μobs = 7.9 μB
Tb³⁺ 4f⁸ J = 6 gJ = 3/2 μcal = 9.72 μB μobs = 9.8 μB
Dy³⁺ 4f⁹ J = 15/2 gJ = 4/3 μcal = 10.65 μB μobs = 10.6 μB
Ho³⁺ 4f¹⁰ J = 8 gJ = 5/4 μcal = 10.61 μB μobs = 10.4 μB
Er³⁺ 4f¹¹ J = 15/2 gJ = 6/5 μcal = 9.58 μB μobs = 9.5 μB
Tm³⁺ 4f¹² J = 6 gJ = 7/6 μcal = 7.56 μB μobs = 7.6 μB
Yb³⁺ 4f¹³ J = 7/2 gJ = 8/7 μcal = 4.54 μB μobs = 4.5 μB
Pr⁴⁺ 4f¹ J = 5/2 gJ = 6/7 μcal = 2.54 μB μobs = 0.7 μB
Tb⁴⁺ 4f⁷ J = S = 7/2 gJ = 2 μcal = 7.94 μB μobs = 8.0 μB

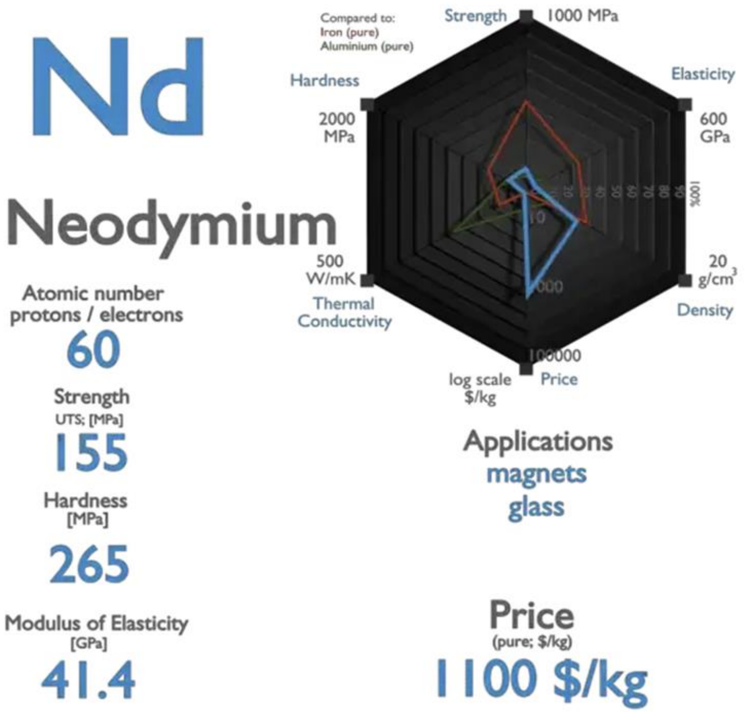


3d spin
J3d-5d
Fe
Hund's coupling
5d spin
J3d-3d
spin-orbit coupling
3d spin
crystal field + hybridization
4f spin
Lattice
Fe
Lattice
f-orbital
orbital moment
rare earth

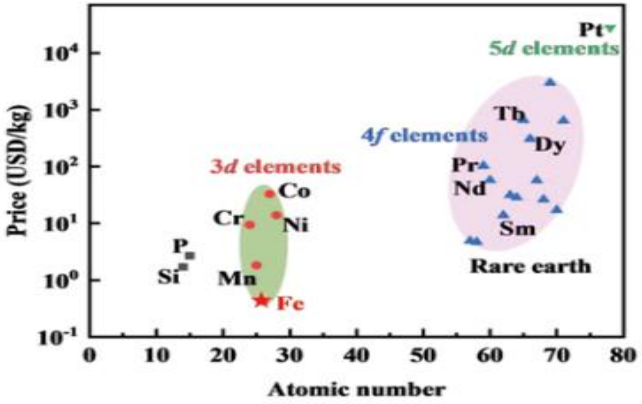


Grain lattice diffusion
at middle and final stage of selective oxidation
O2
O2
O2
O2
O2
Nd oxide in α-Fe
Nd oxide (Nd rich phase)

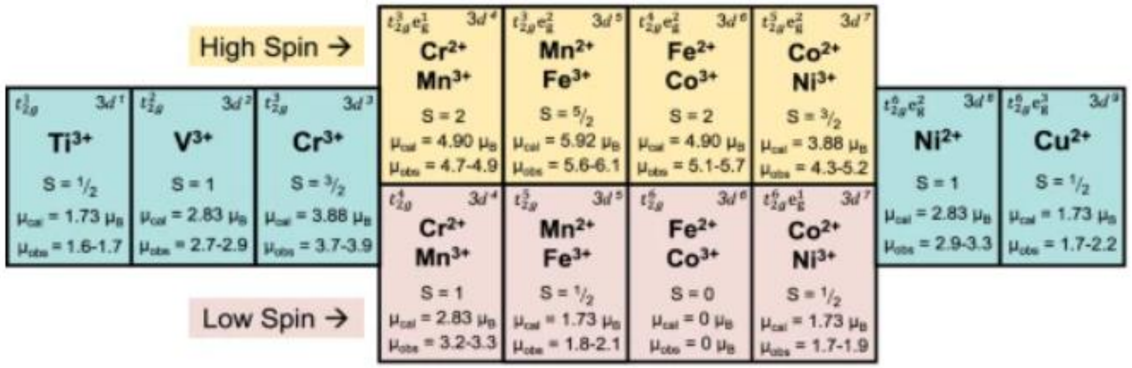
Ferrite magnet
Neodymium magnet

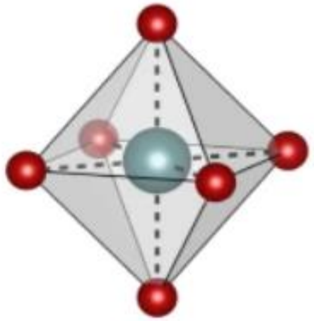


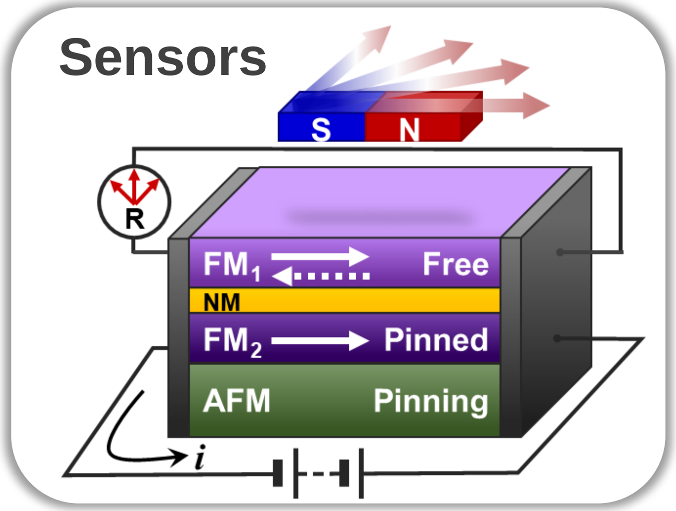
Nd
Neodymium
Atomic number protons / electrons
60
Strength UTS; [MPa]
155
Hardness [MPa]
265
Modulus of Elasticity [GPa]
41.4
Compared to: Iron (pure) Aluminium (pure)
Strength
1000 MPa
Elasticity
600 GPa
Hardness
2000 MPa
500 W/mK
Thermal Conductivity
20 g/cm3
Density
log scale $/kg
Price
Applications
magnets
glass
Price (pure; $/kg)
1100 $/kg



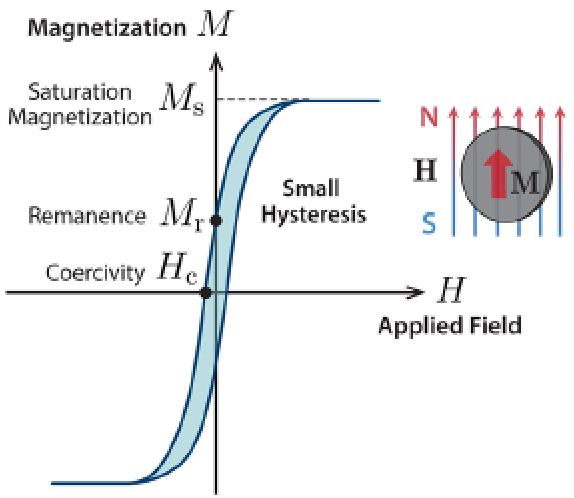
Price (USD/kg)
Atomic number
5d elements
4f elements
3d elements
Pt
Tb
Dy
Pr
Nd
Sm
Rare earth
Co
Cr
Ni
Mn
Fe
P
Si



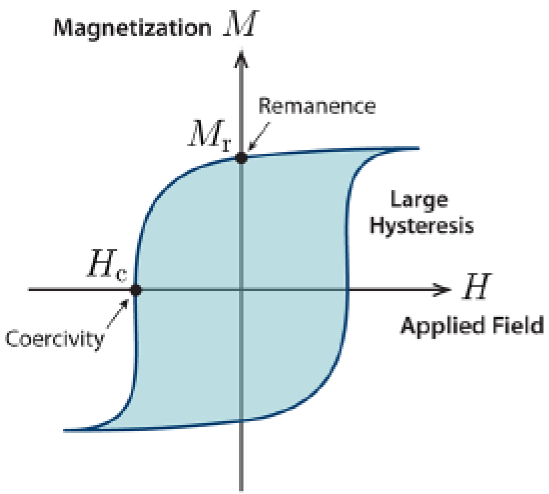


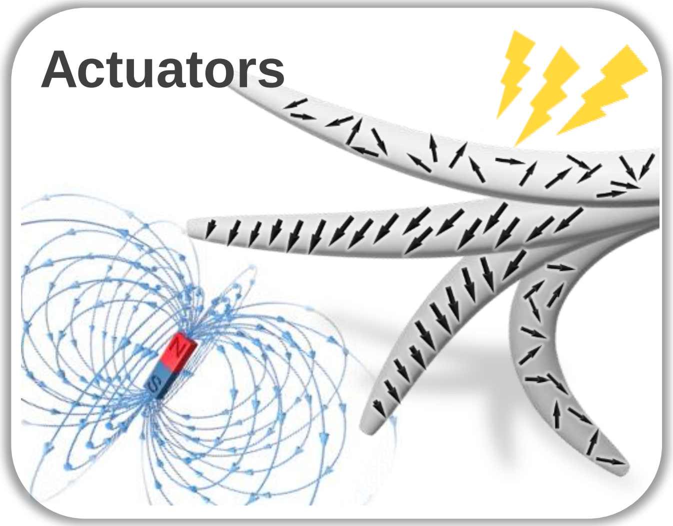


Soft-magnetic

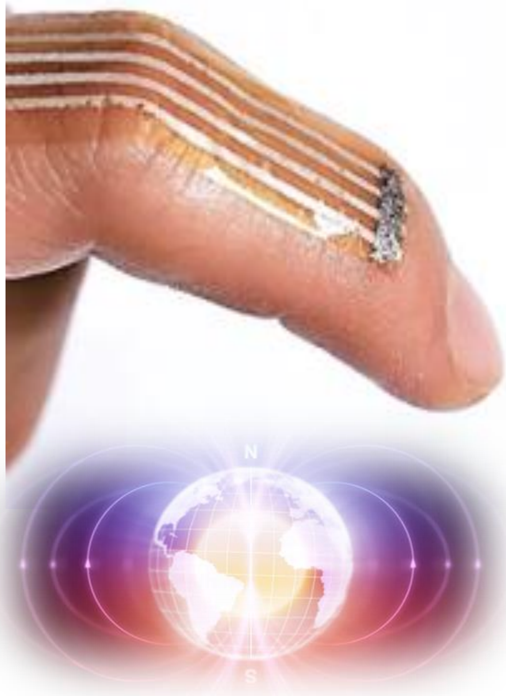


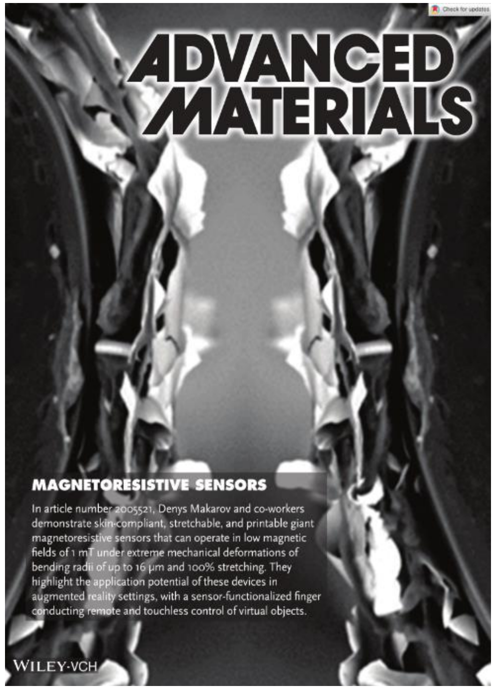
Hard-magnetic

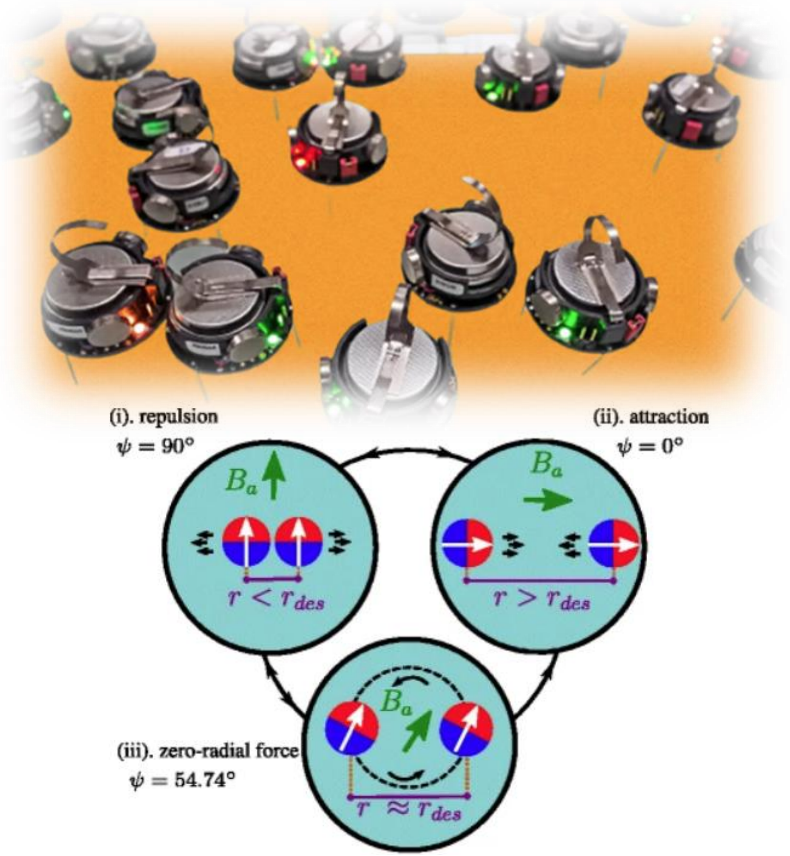




Ultra-Thin Nanomagnets for Highly Compliant Motion Sensors with Touchless Manner







Approaches for Flexible Magnetic-Field Sensors

Touchless gesture detection for interactive wearables

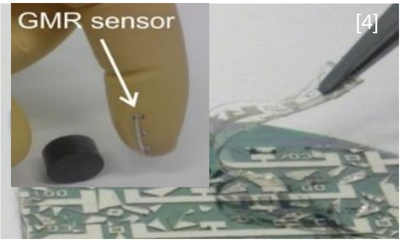
Wearables

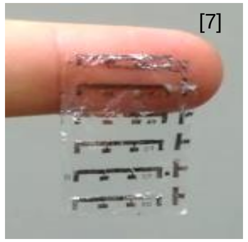
Soft robots

Virtual reality

Flexible magnetic-field sensors

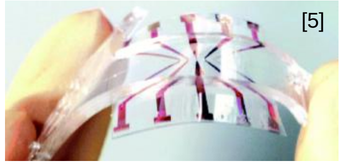
Bendable GMR sensors



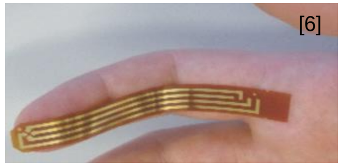


Ultra-thin and imperceptible GMR sensors

Flexible GMR sensors

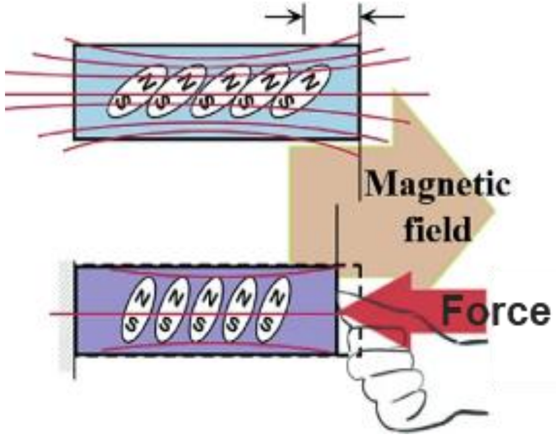


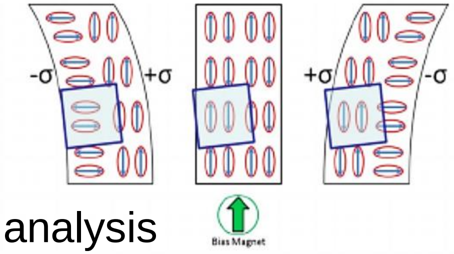
Wearable Hall sensors



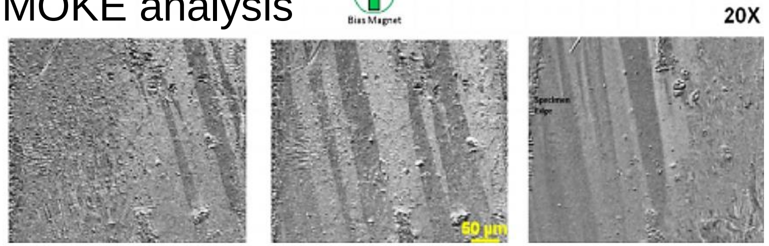
[1] *Mater. Horiz.* **2019**, *6*, 1138
[2] *Nat. Electron* **2018**, *1*, 589..
[3] *Adv. Mater.* **2008**, *20*, 3224.
[4] *Nano Lett.* **2011**, *11*, 2522.
[5] *Lab Chip* **2014**, *14*, 4050.
[6] *Adv. Mater.* **2015**, *27*, 1274.
[7] *Nat. Commun.* **2015**, *6*, 6080.

Inverse magnetostriction

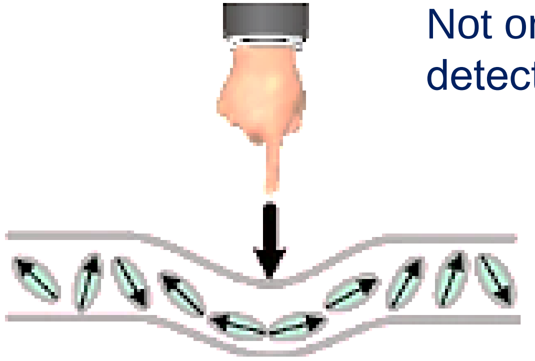




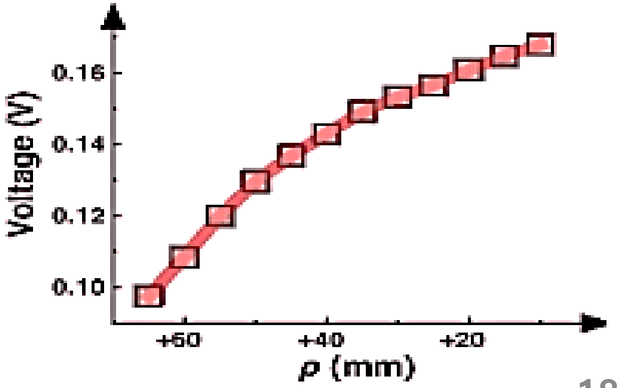
MOKE analysis



Magnetic domain change under strain!



Not only sense B field, but also detect the mechanical stimuli…



Motion artifacts reduce selectivity to B field!

Approaches for Flexible Magnetic-Field Sensors

Touchless gesture detection for interactive wearables

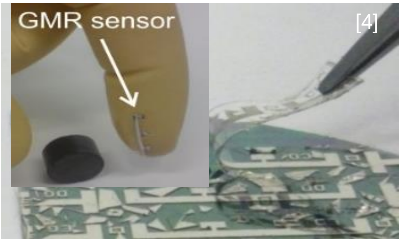
Wearables

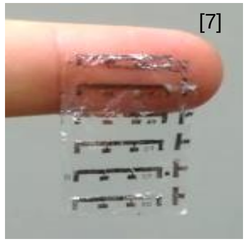
Soft robots

Virtual reality

Flexible magnetic-field sensors

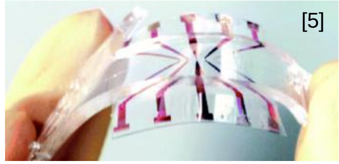
Bendable GMR sensors



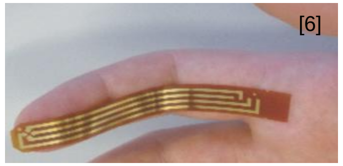


Ultra-thin and imperceptible GMR sensors

Flexible GMR sensors

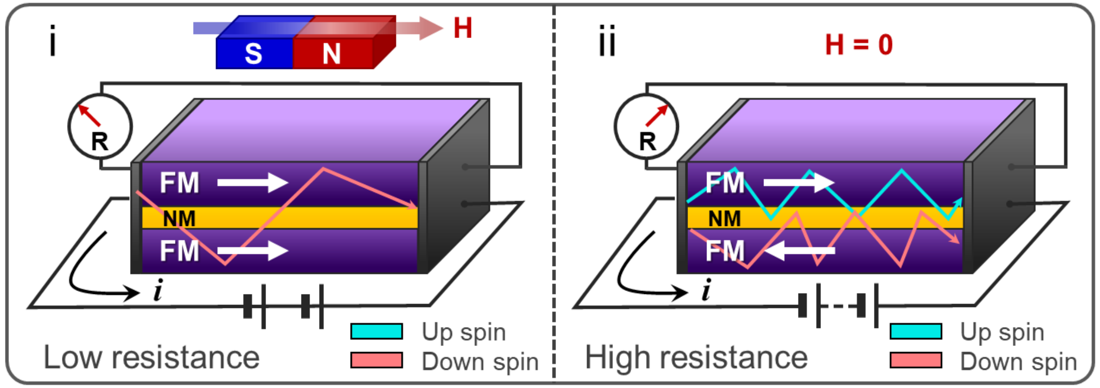


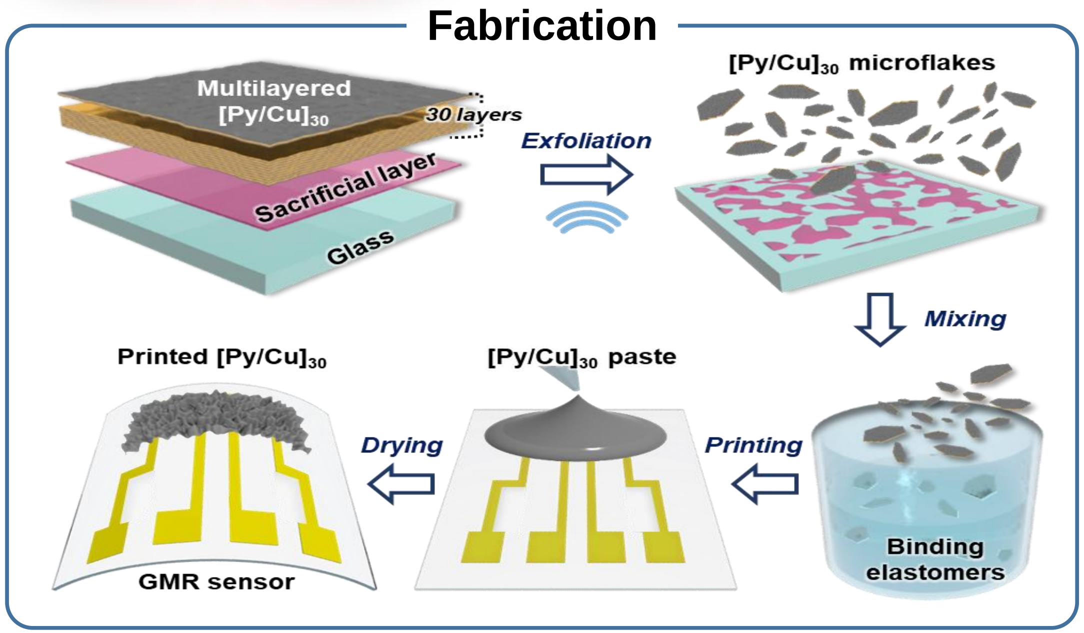
Wearable Hall sensors



Printed GMR sensor for on-skin electronics

Giant magnetoresistance





[1] *Mater. Horiz.* **2019**, *6*, 1138
[2] *Nat. Electron* **2018**, *1*, 589..
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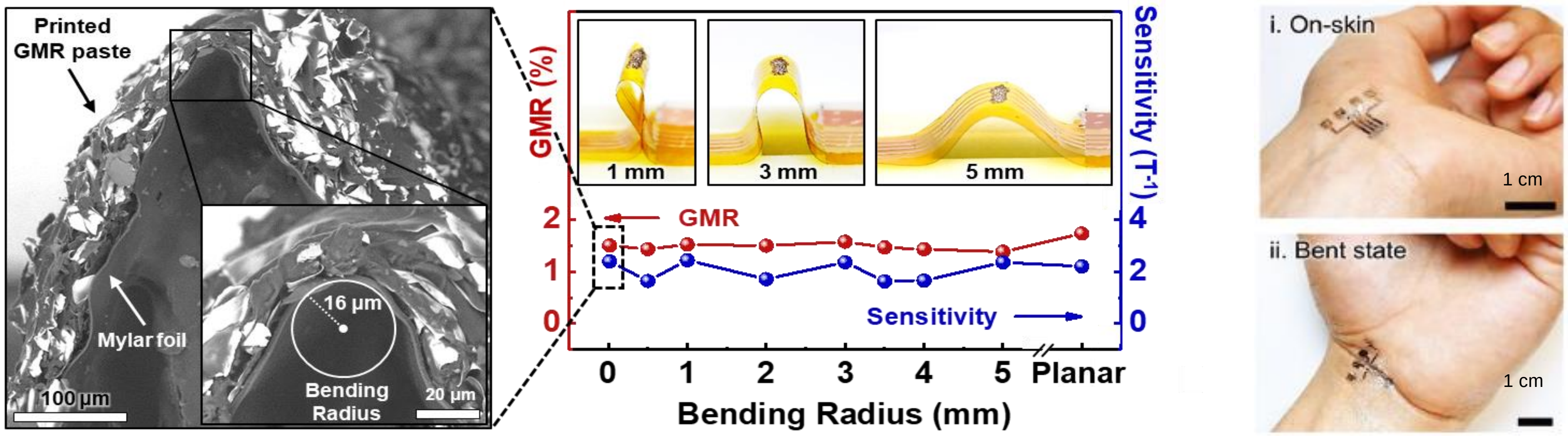
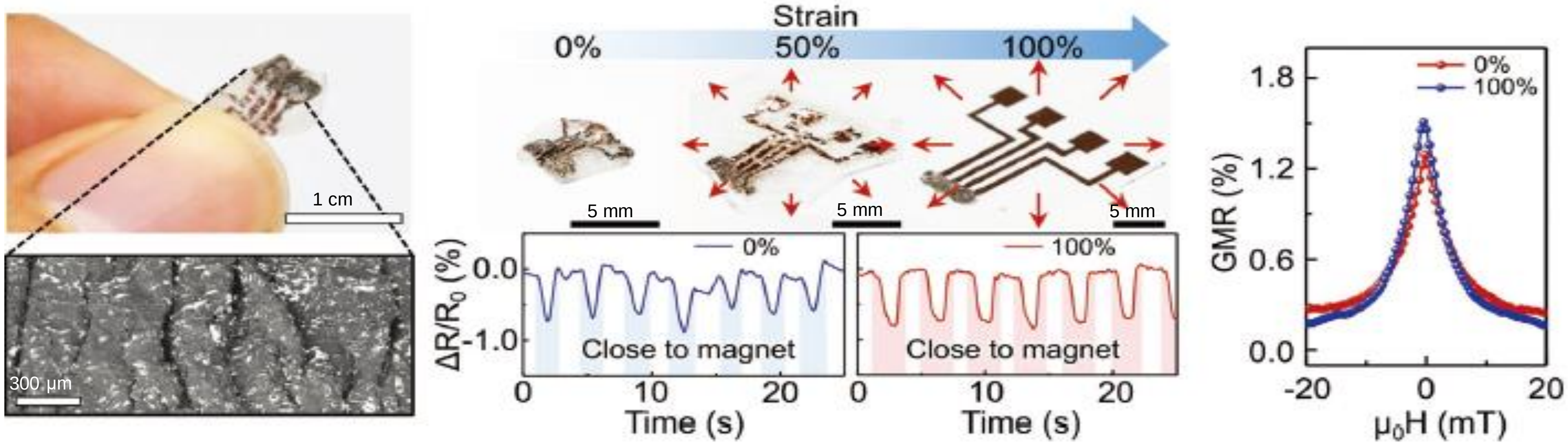
[5] *Lab Chip* **2014**, *14*, 4050.
[6] *Adv. Mater.* **2015**, *27*, 1274.
[7] *Nat. Commun.* **2015**, *6*, 6080.

Printable Giant Magnetoresistive Sensors

Need for highly compliant GMR sensors

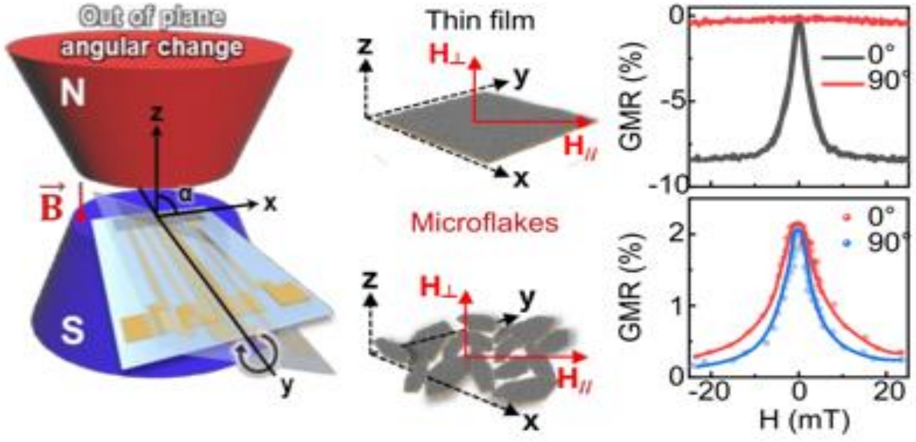


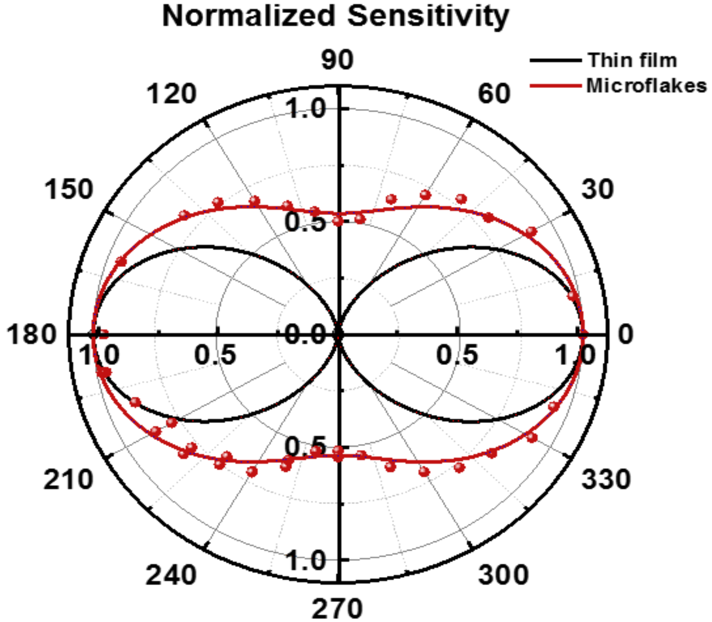
Stretchable & excellent mechanical stability



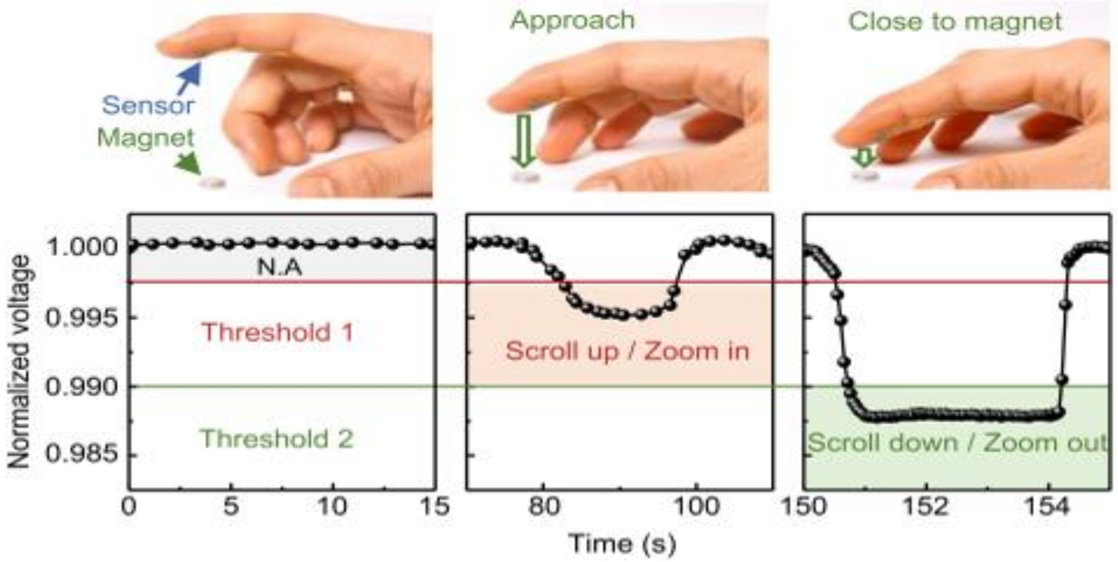
On-Skin Electronics for Human-Machine Interaction

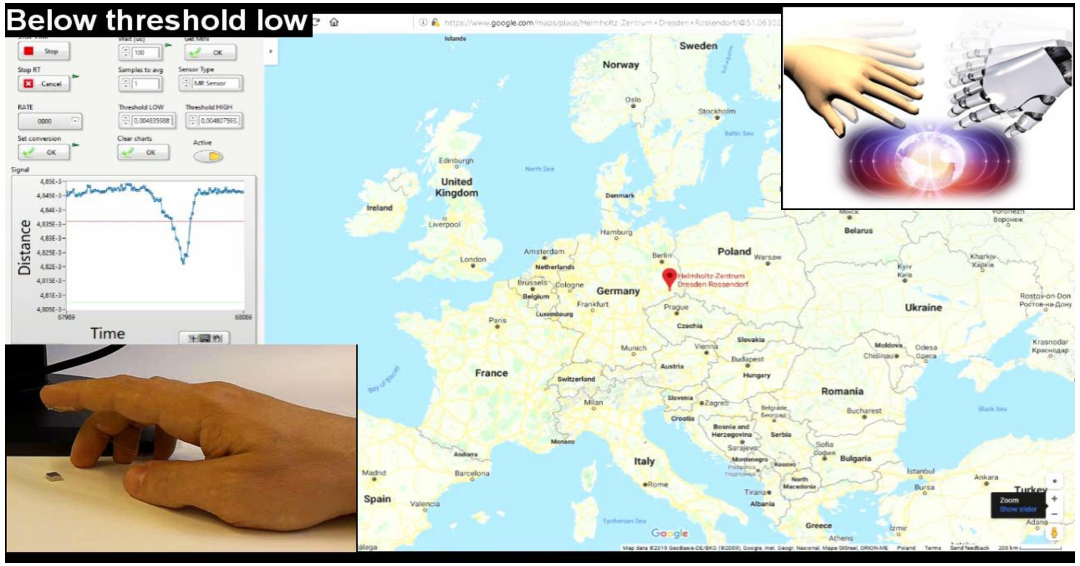
Omnidirectional magnetic field sensing



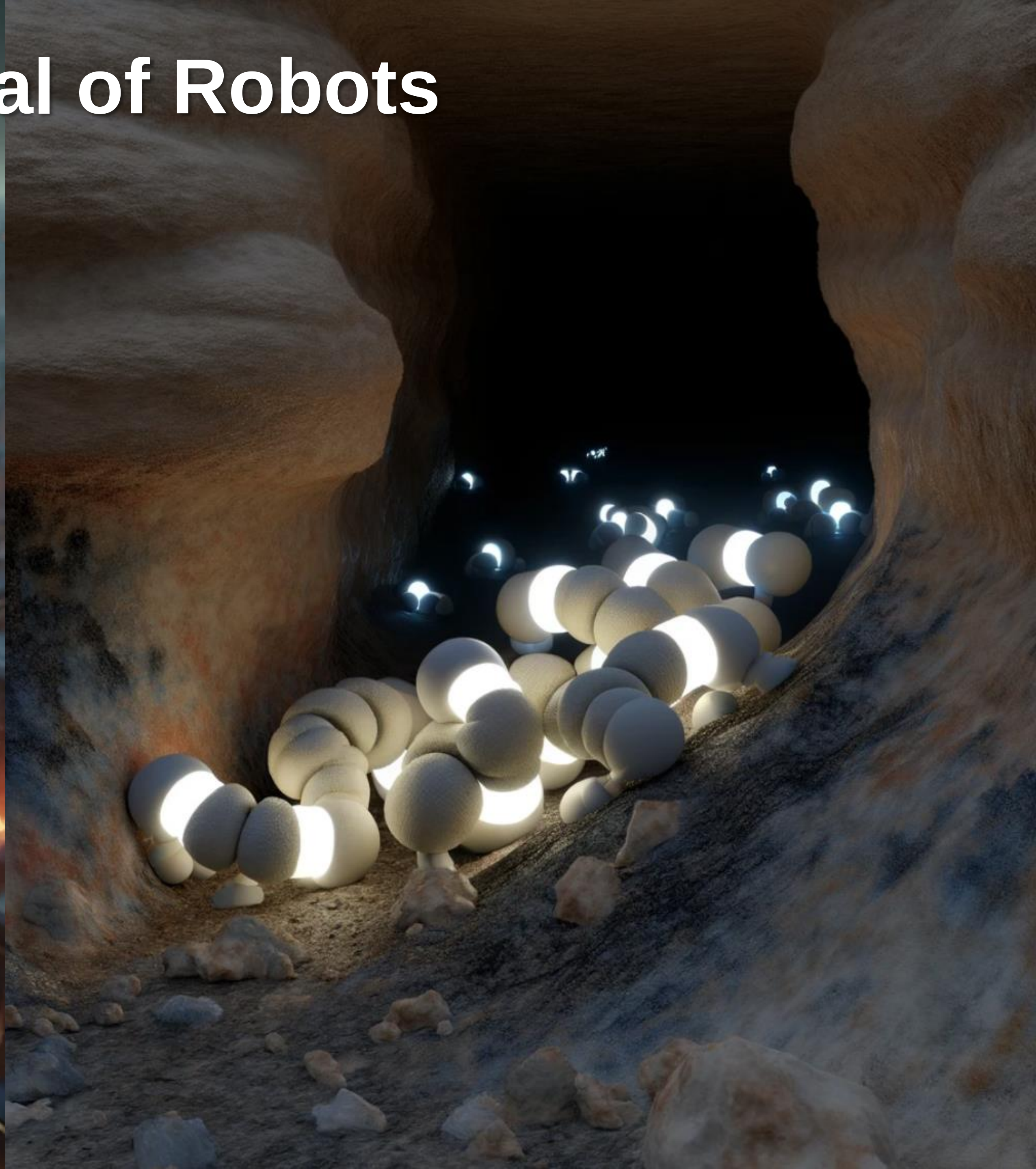


Remote control of objects



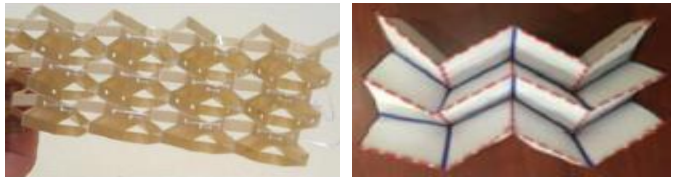


Ultimate Goal of Robots

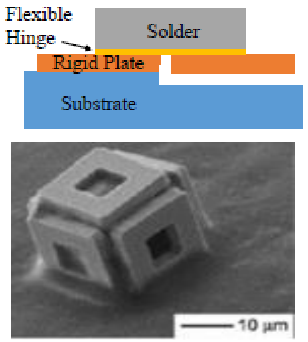


Reconfigurable Hingeless Magnetic Origami

Designs for shape-morphing soft actuators

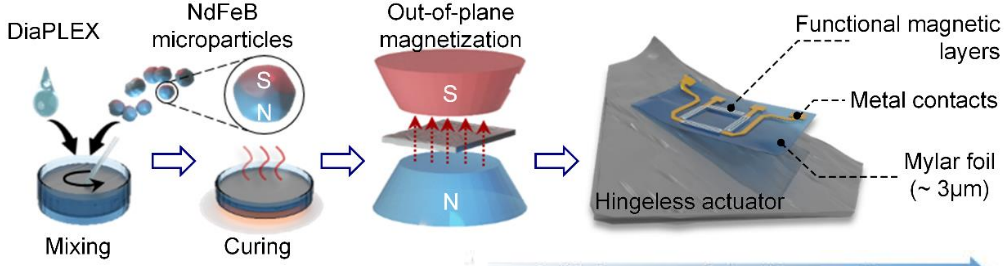


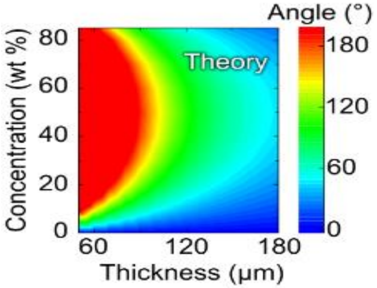
Adv. Intell. Syst. **2019**, *1*, 1900059.

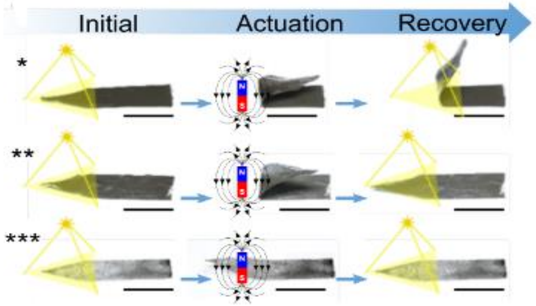


Issue **Requirement of predefined parameters and hinges**

Foldable and hingeless magnetic origami





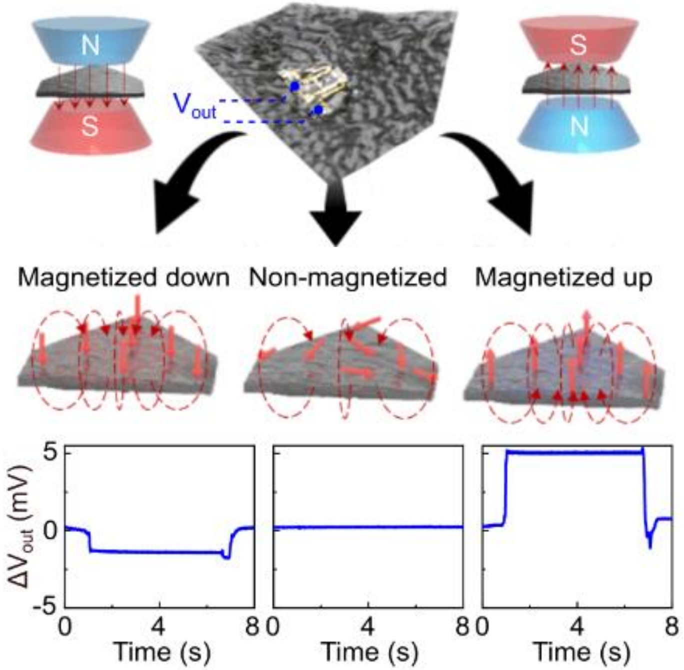


→ **180º folding** actuation **w/o hinge** & predefined shape
→ **Reconfigurable** actuation **by guiding light & B-field**

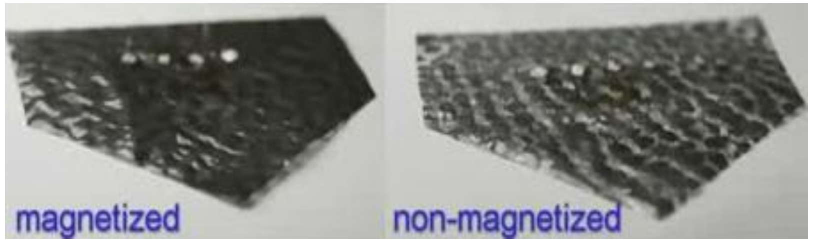
Self-awareness and response

Biological origami

Supervising origami by integrated magnetic-field sensors



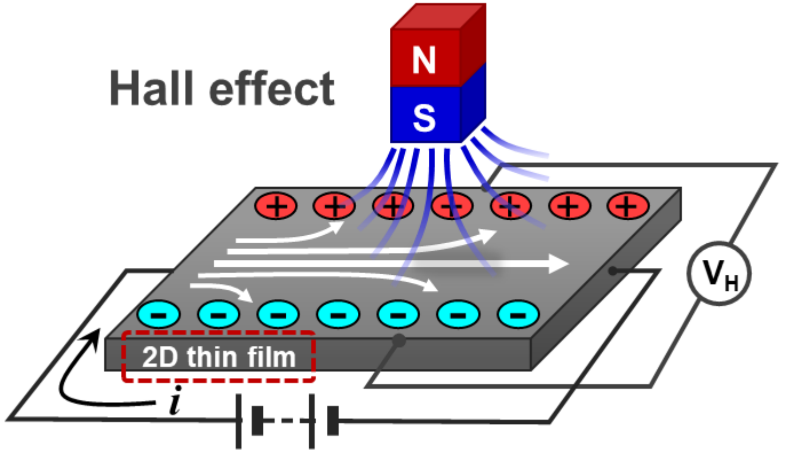
→ Sensing capability of small magnetic field to **be aware magnetized state and actuating parts**

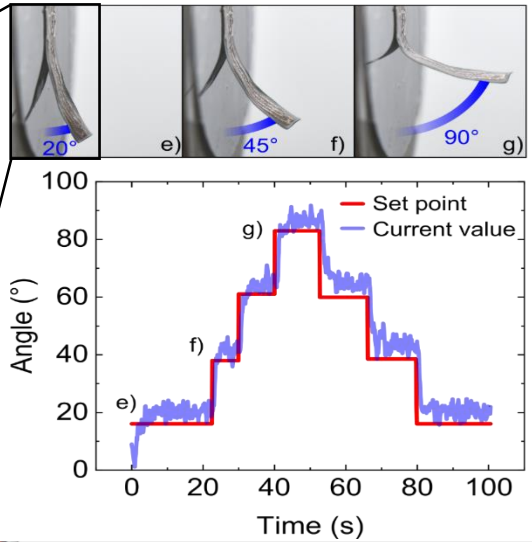


Magnetic Origami Capable of Lifting

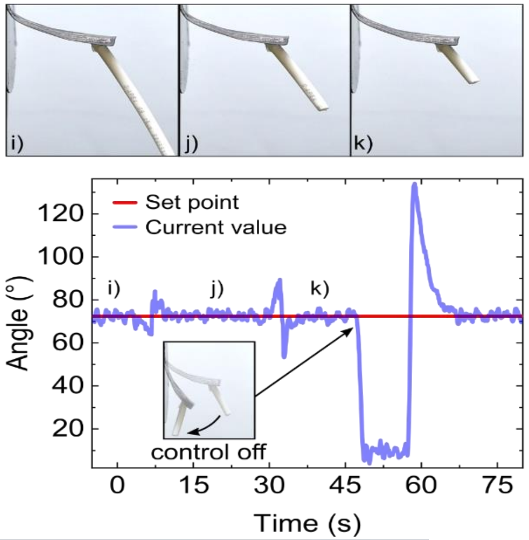
Supervising actuation for lifting up and down

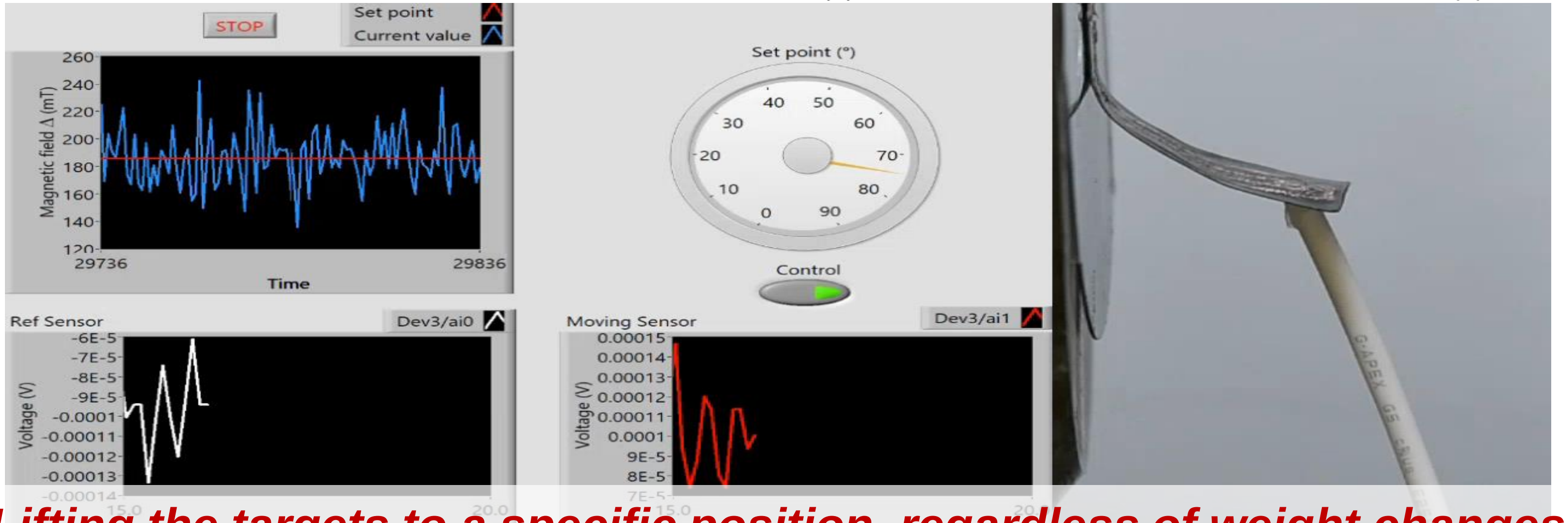
Out-of-plane magnetic field sensing





Controllable actuation

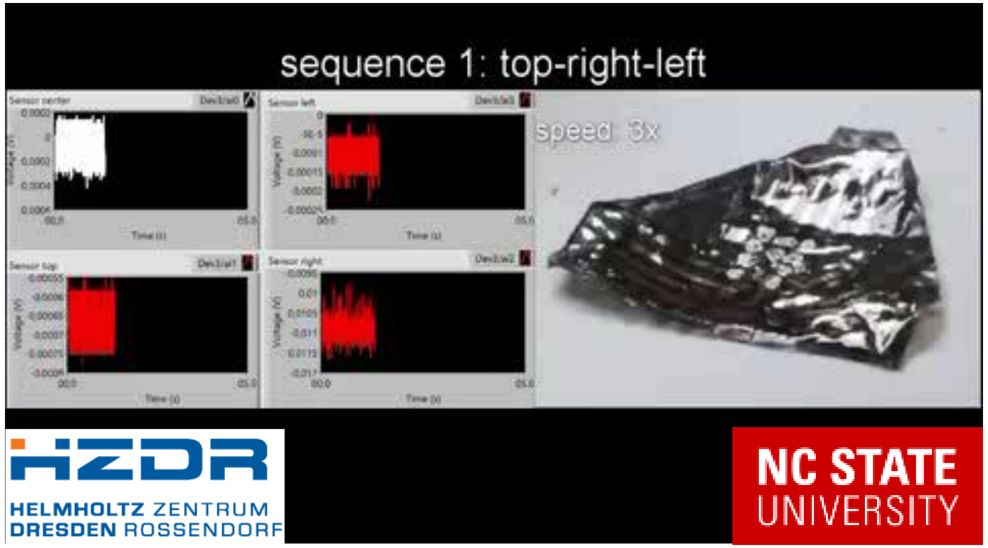


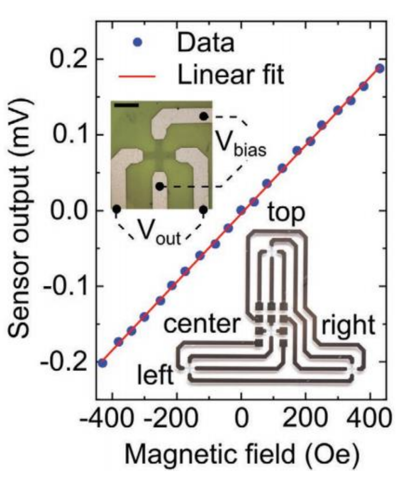


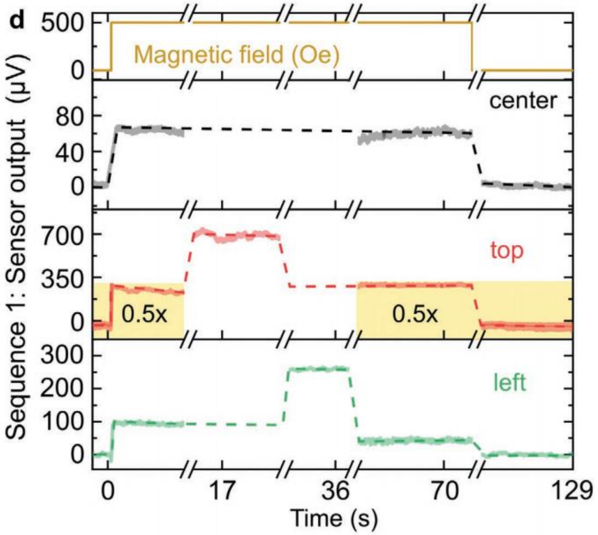
Lifting the targets to a specific position, regardless of weight changes

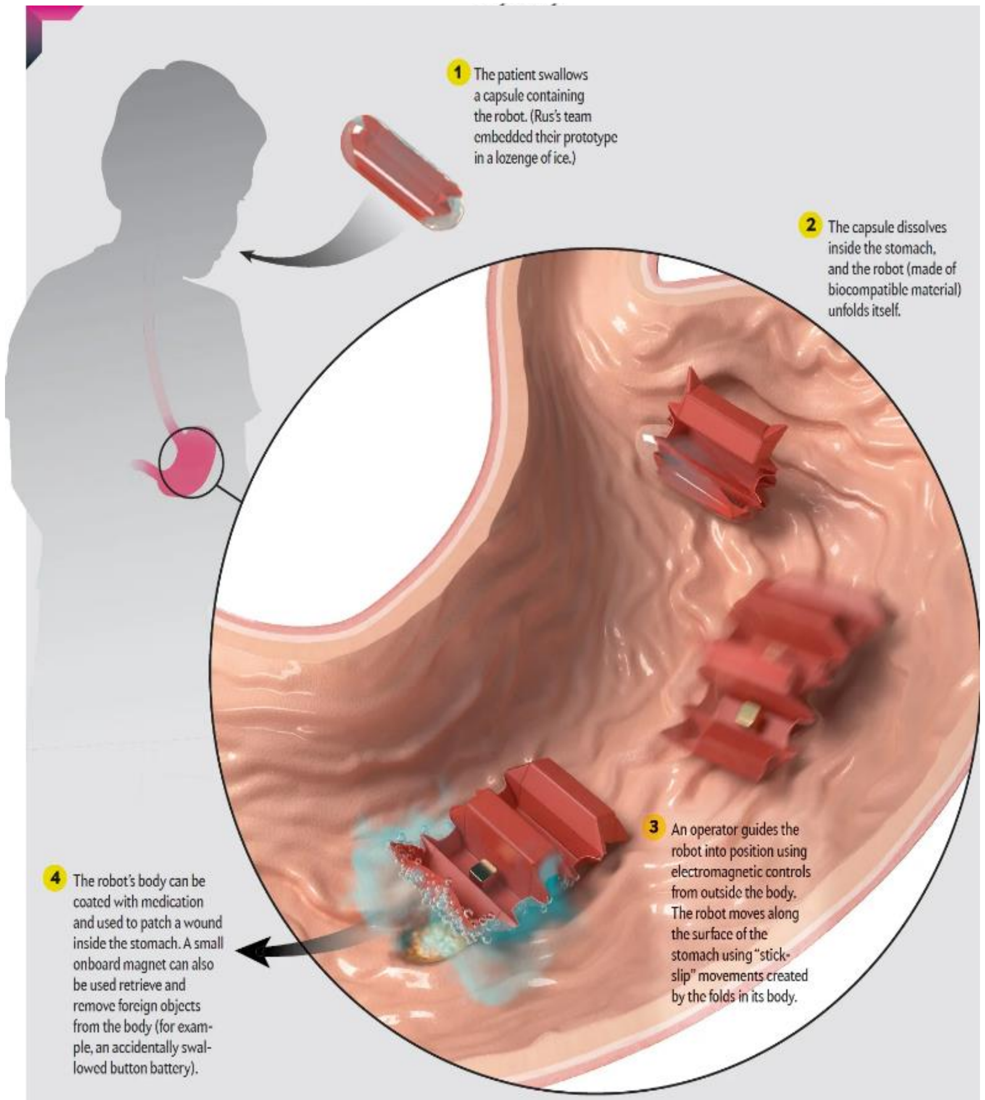
Magnetic Origami Capable of Self Shape-Morphing

Supervising sequence and order of actuation for customized folding process



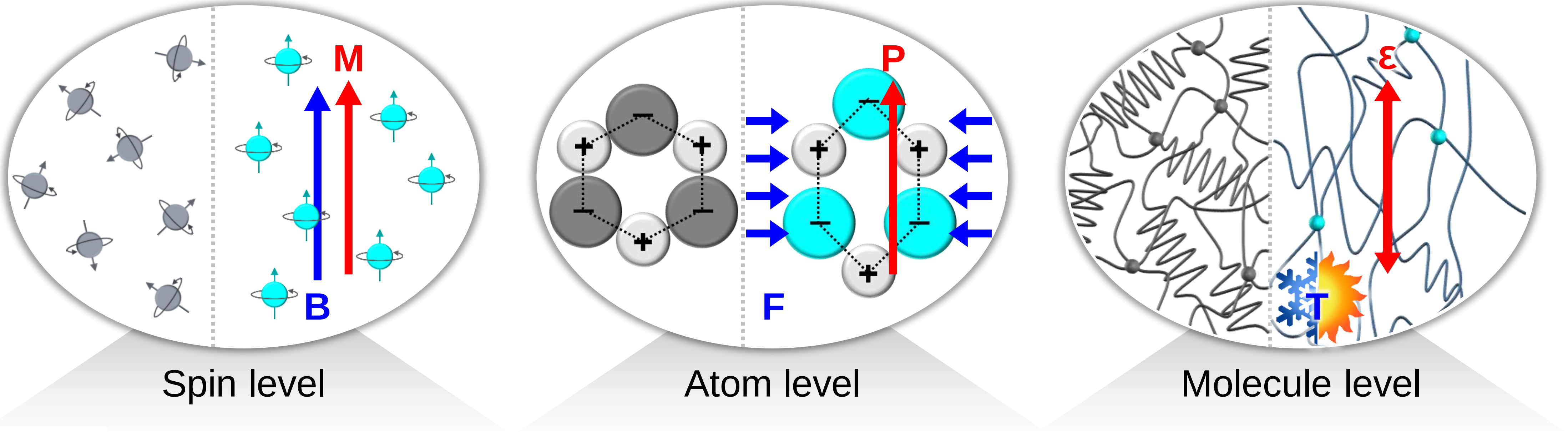


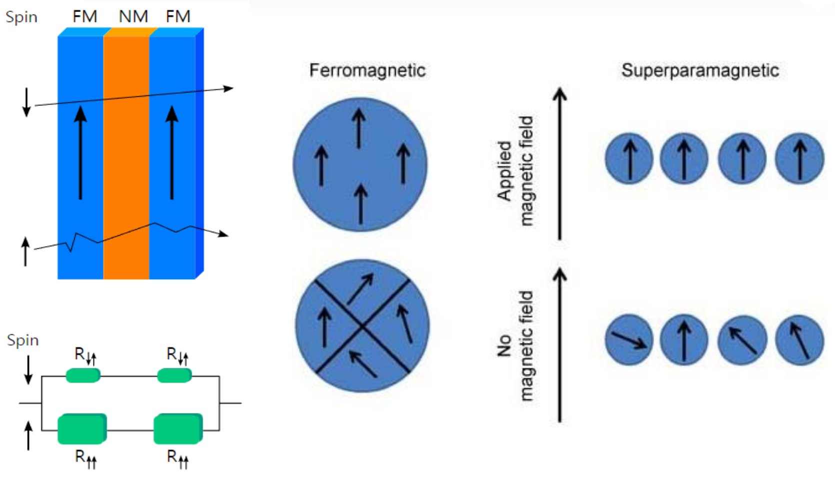




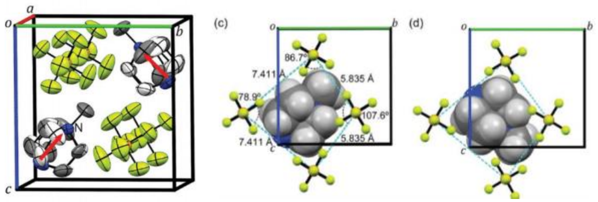
Stimuli-Responsive Intelligent Materials

Stimuli-Responsive Intelligent Materials on a Scale

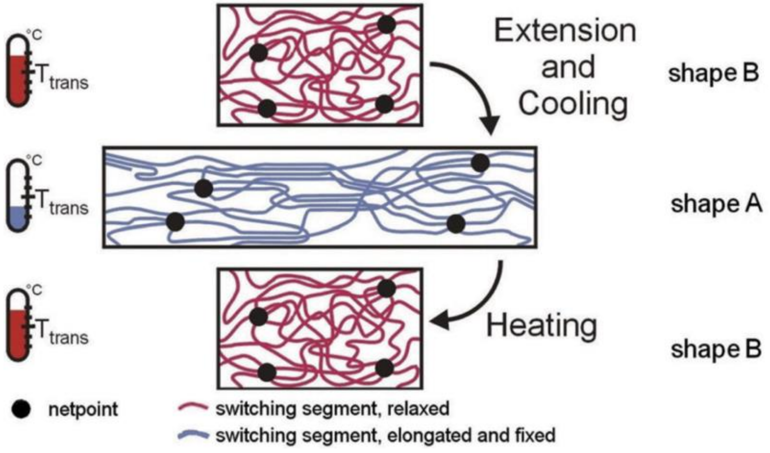




RTP at 300K

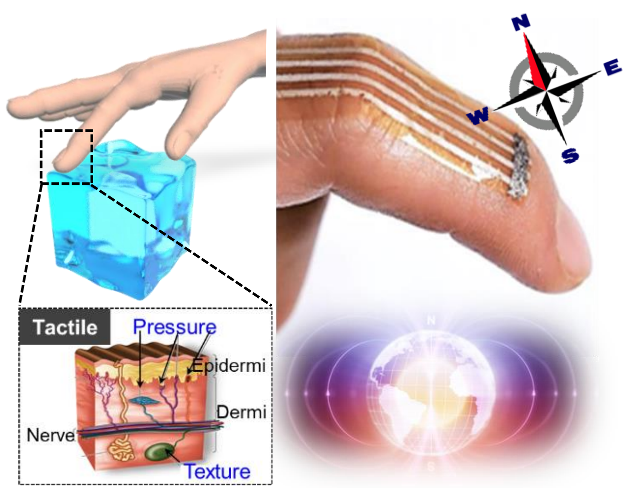


- Orthorhombic crystal system ($Pmc2_1$)
- Ferroelectric phase
- Spontaneous polarization (parallel to the c-axis)
- Distorted arrangement from cubic arrangement (anions)
- Different lengths of the three sides
- Methyl group → Large distortion → Large E_c (Coercive field)

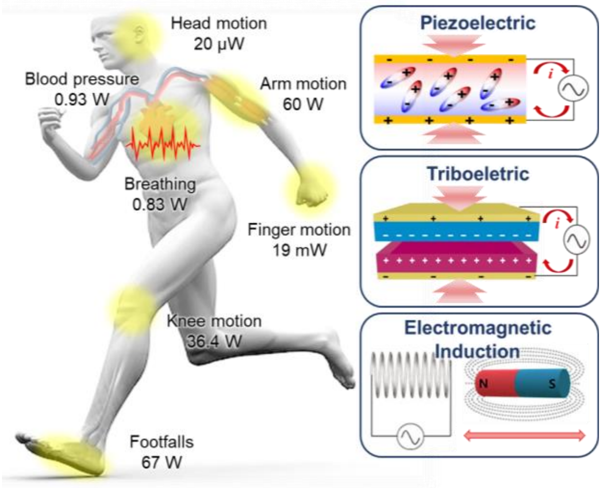


Perspective of Flexible Electronics and Soft Robotics

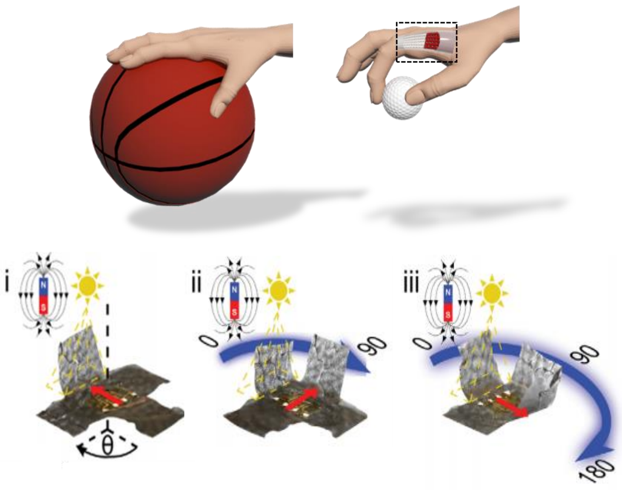
Next-Generation Flexible Electronics for Soft Robotics and Human Augmentation



Artificial Sensation
Proximity Sensors/Electronic Skins



Sustainable Operation
Energy Harvesting Devices



Artificial Motor
Soft Actuators

Applications

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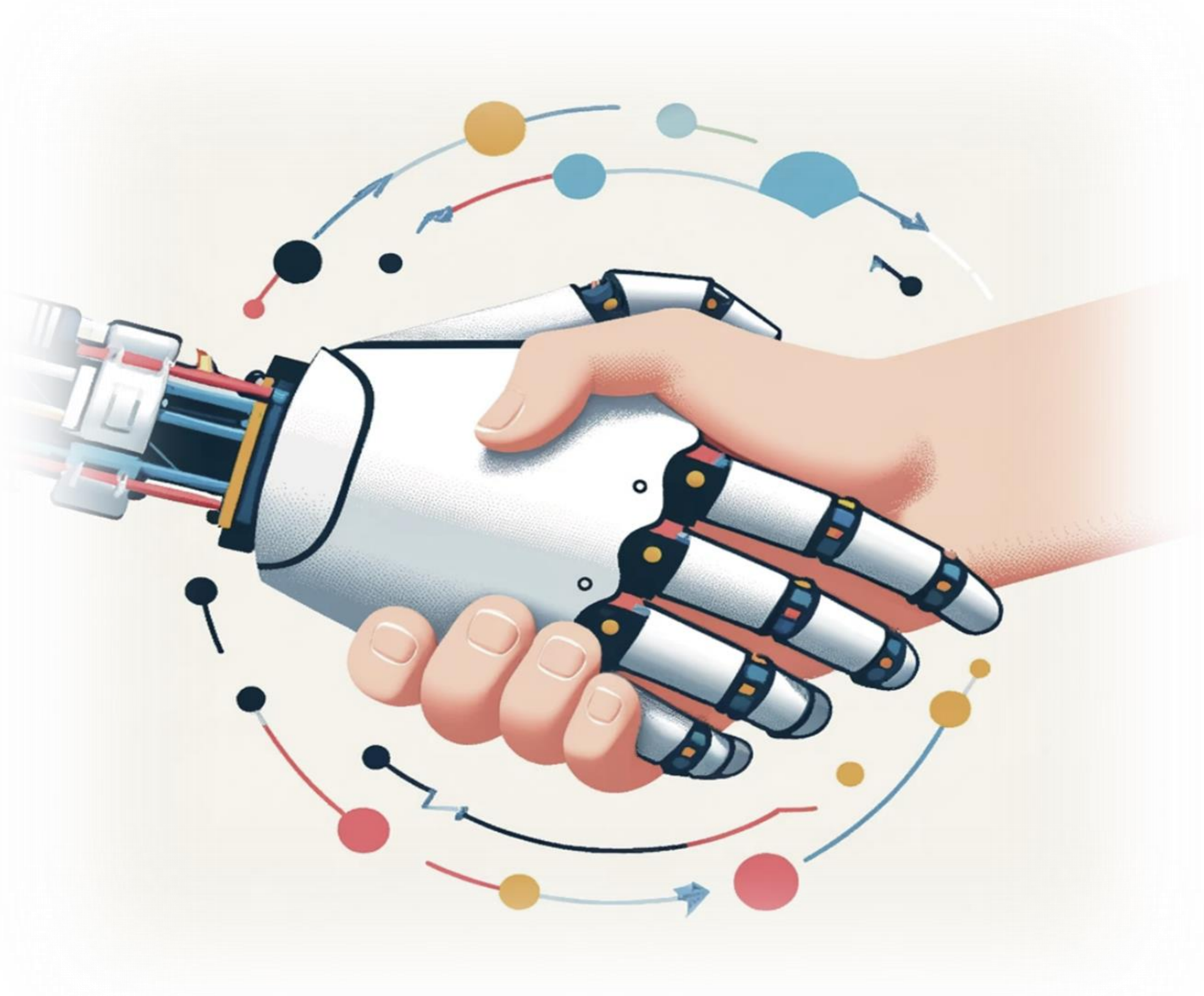

Thank you for your attention!