The 20th U.S.- Korea Forum on Nanotechnology

Energy-efficient Systems for Artificial Intelligence and Quantum & Neuromorphic Applications

Bioinspired Vision Systems for Intelligent Robotics

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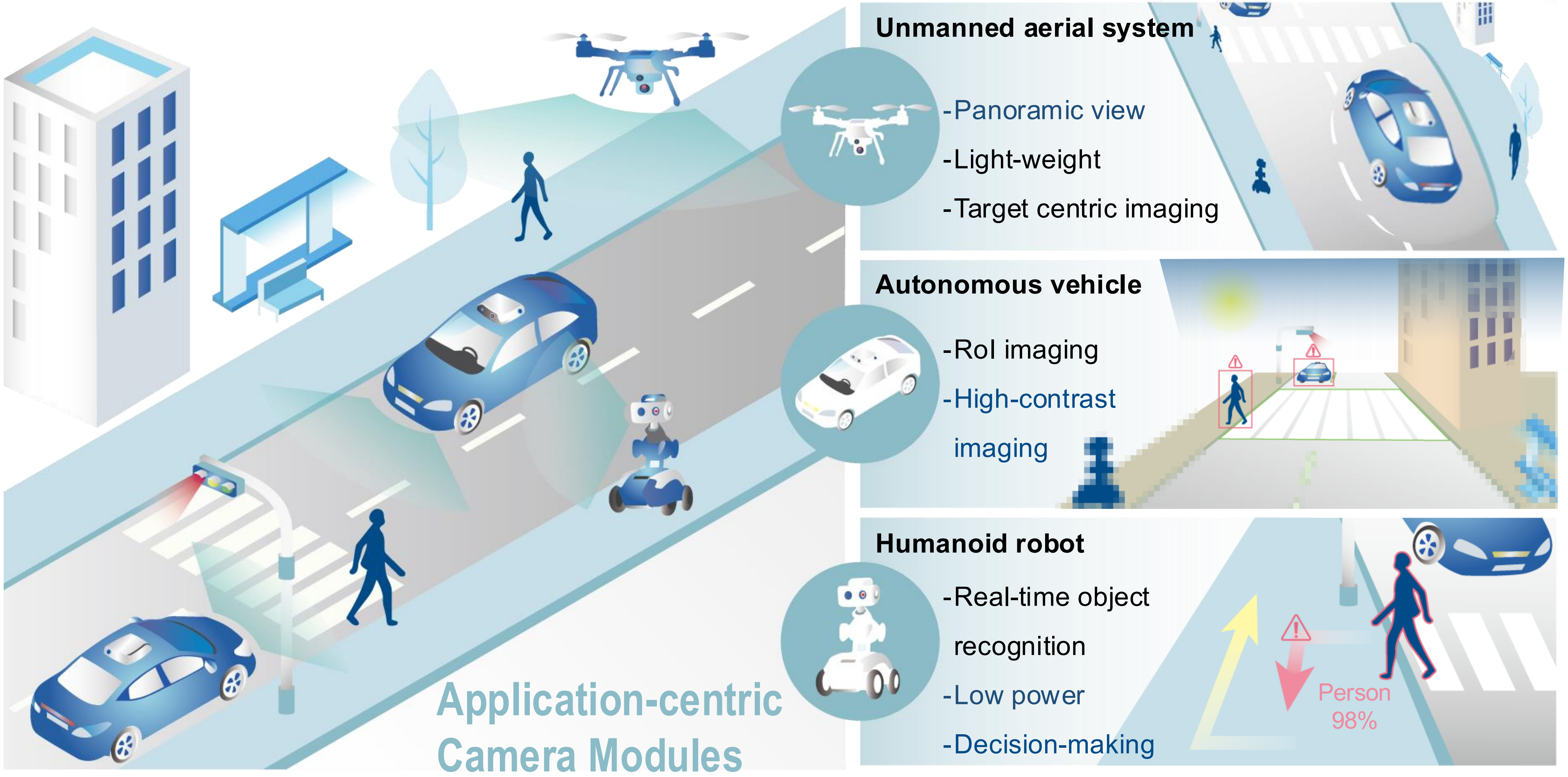
KAIST Korea Advanced Institute of Science and Technology

Daily Life Applications for Intelligent Robots

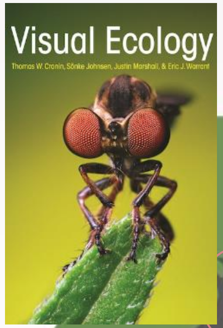


C. Choi et al., Nanomaterial-Based Artificial Vision Systems, **ACS Nano** 18, 1241 (2024)

Biological Eyes in Animal Kingdom

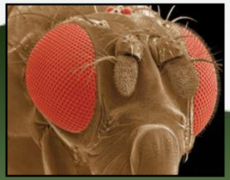
‘Visual Ecology’

Eye variations have originated from their habitats!



Avian eye

- High visual acuity
- **Zooming (Foveated imaging)**



Insect eye

- **Wide field of view**
- High motion sensitivity

Human eye

- **High visual acuity (R, G, B)**
- Adaptability, high dynamic range

Spider eye

- Stacked retina
- **Depth sensing**

Feline eye

- Vertical slit-like pupil
- **Camouflage breaking**

Cephalopod eye

- W-shaped pupil
- **High-contrast imaging**

Herbivore eye

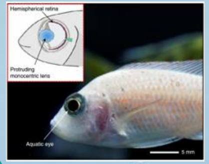
- Horizontal slit-like pupil
- Panoramic imaging
- Adaptive optic module

Crab eye

- **Amphibious vision**
- Panoramic imaging

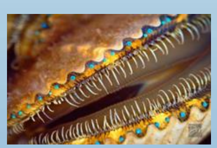
Crustacean eye

- **Multispectral imaging**
- Polarization vision



Fish eye

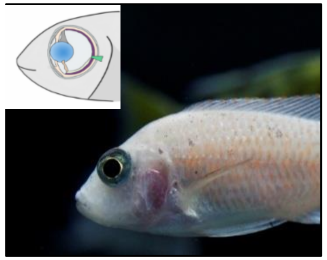
- GRIN ball lens
- **Wide field of view**



C. Choi et al., **Adv. Mater** 36, 2412252 (2024)

Bioinspired Artificial Eyes

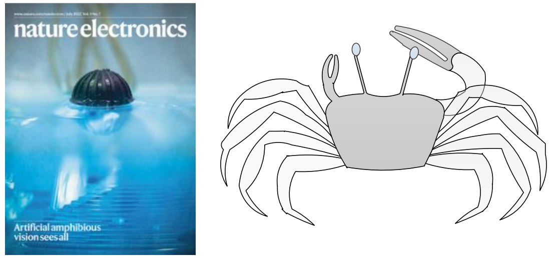
Fish Eye Cameras



- -Wide-field of view (~120-160 deg.)
- -Minimum optical aberration

Nat. Electron. *3, 546 (2020)*

Crab Eye Cameras



- -Panoramic imaging
- -Amphibious imaging (flat optics)

Nat. Electron. *5, 452 (2022)*

Cuttlefish Eye Cameras

- -Pol.-sensitive photoreceptors
- -High-contrast, high-resolution IMG

Sci. Robot. *8, ade4698 (2023)*

Avian Eye Cameras

- -Wide spectrum of light (vis. and UV)
- -High-res., magnified image at center

Sci. Robot. *9, adek6903 (2024)*

Goat Eye Cameras

- -Horizontal wide FoV
- -Configurational In-sensor computing

Nat. Commun. *15, 6021 (2024)*

Feline Eye Cameras

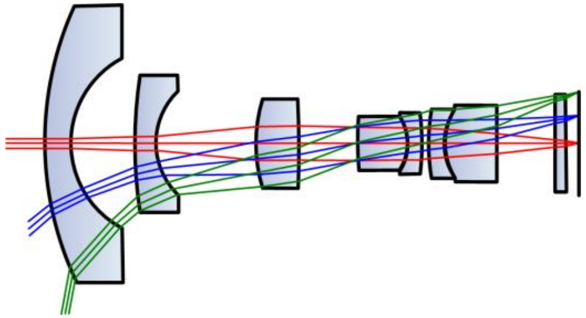
- -Highly sensitive focus on the target object (removal of background noise)

Sci. Adv. *10, eadp2809 (2024)*

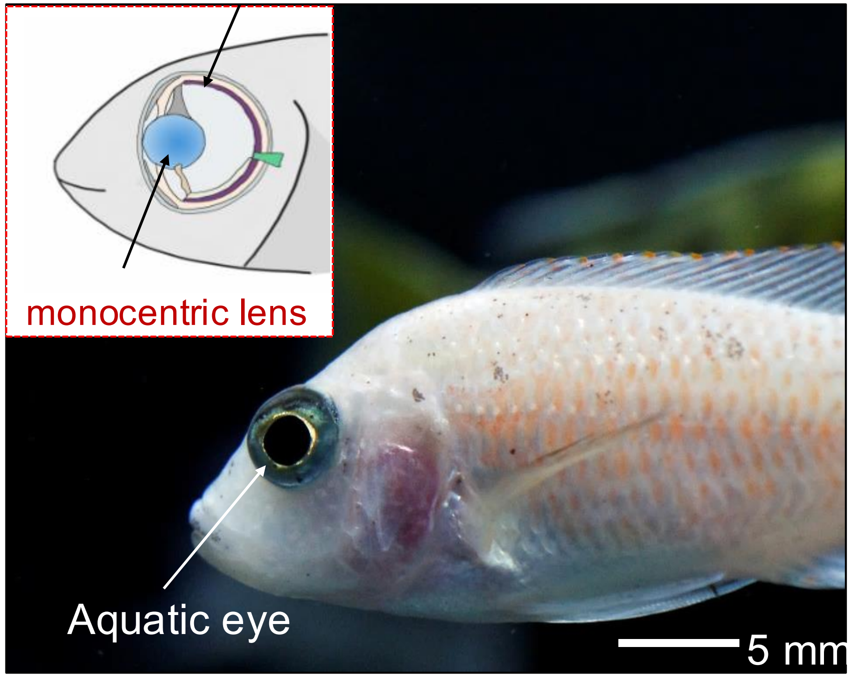
Key Challenges:
(Application-specific) Co-design of optics components and imaging pixels

Fish Eye Geometry

Fisheye lens (conventional)

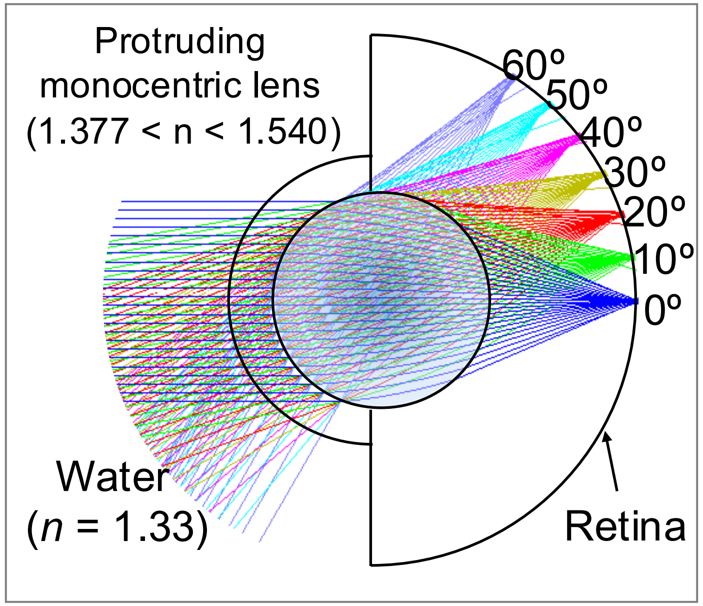


7~13 bulk lens combination
Heavy, high cost
high precision alignment



Wide-Field of view (~120 – 160 degree)
Ultra-slim design
Minimum optical aberrations

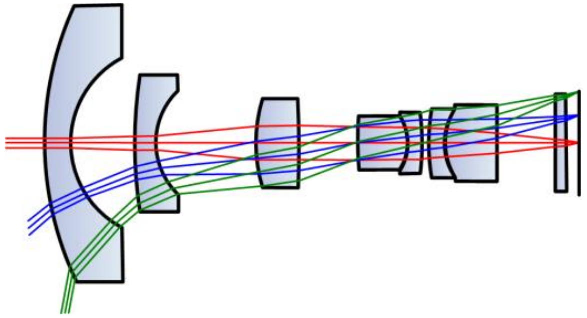
Rainbow trout's eye



M. S. Kim et al., Nat. Electron. 3, 546 (2020)

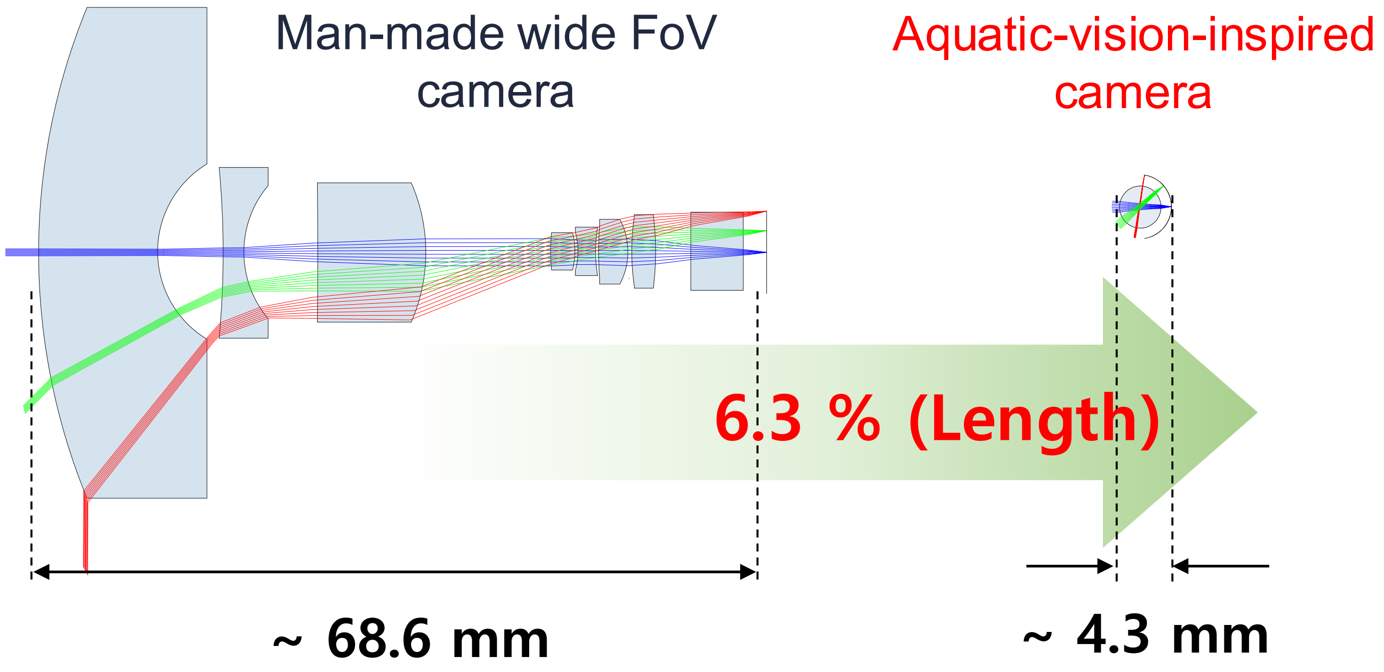
Fish Eye Geometry

Fisheye lens (conventional)



7~13 bulk lens combination
Heavy, high cost
high precision alignment

Ray-tracing simulation



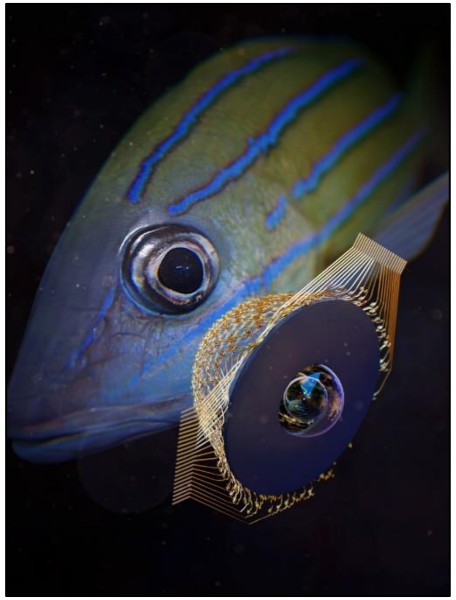
Wide-Field of view (~120 – 160 degree)
Ultra-slim design
Minimum optical aberrations

Miniaturized size (~6%)
Facile accommodation

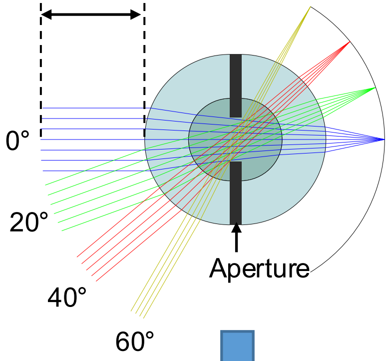
M. S. Kim et al., Nat. Electron. 3, 546 (2020)

Fish-Eye-Cameras

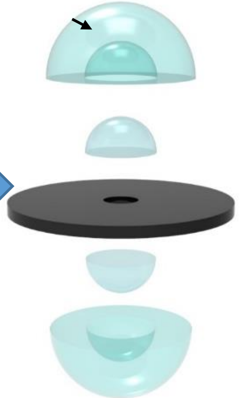
Observation

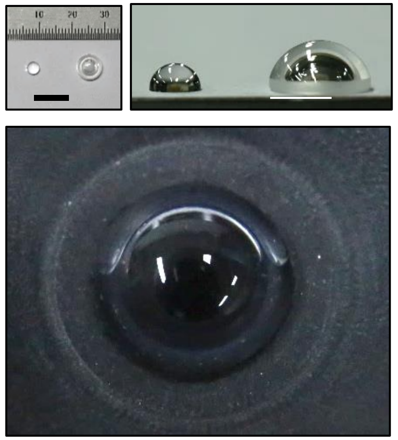


Design optimization



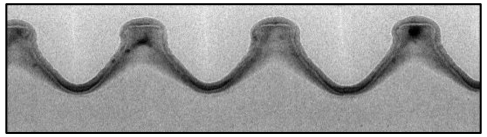
Lens/aperture integration



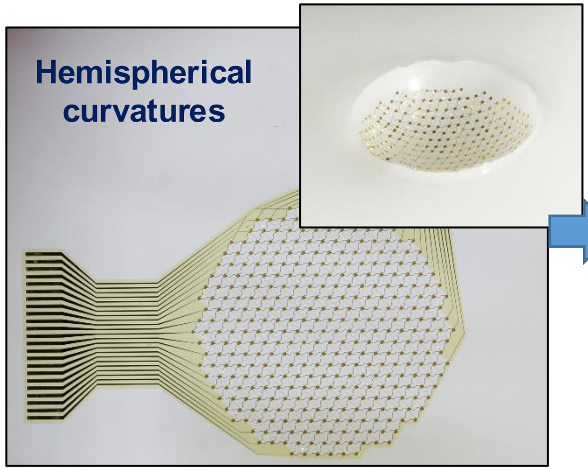


1. **Wide field of view (> 120º)**
2. **Ultra-slim design (8 → 1)**
3. **Minimum optical aberration**
4. **Facile accommodation**
5. **Miniaturized size (6.3%)**

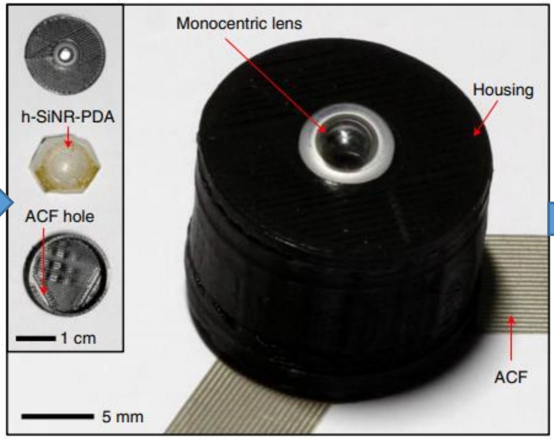
Nanophotonic structures (for enhancing Abs. Eff.)



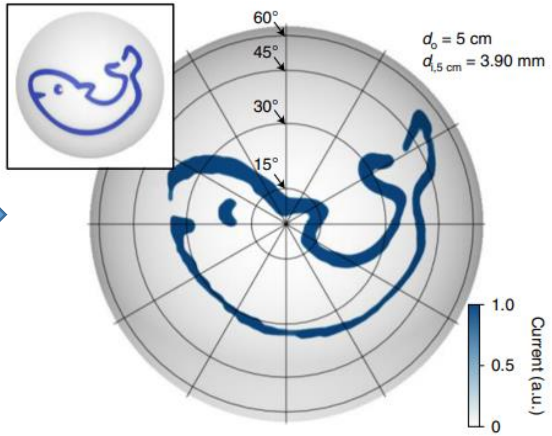
Flexible image-sensors



Integration

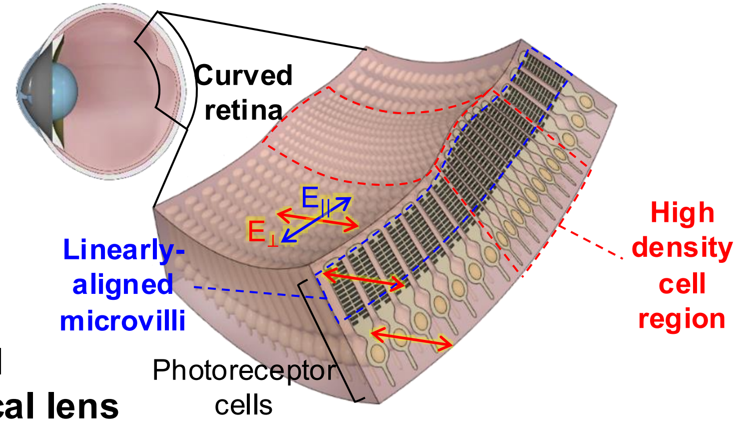


Imaging result

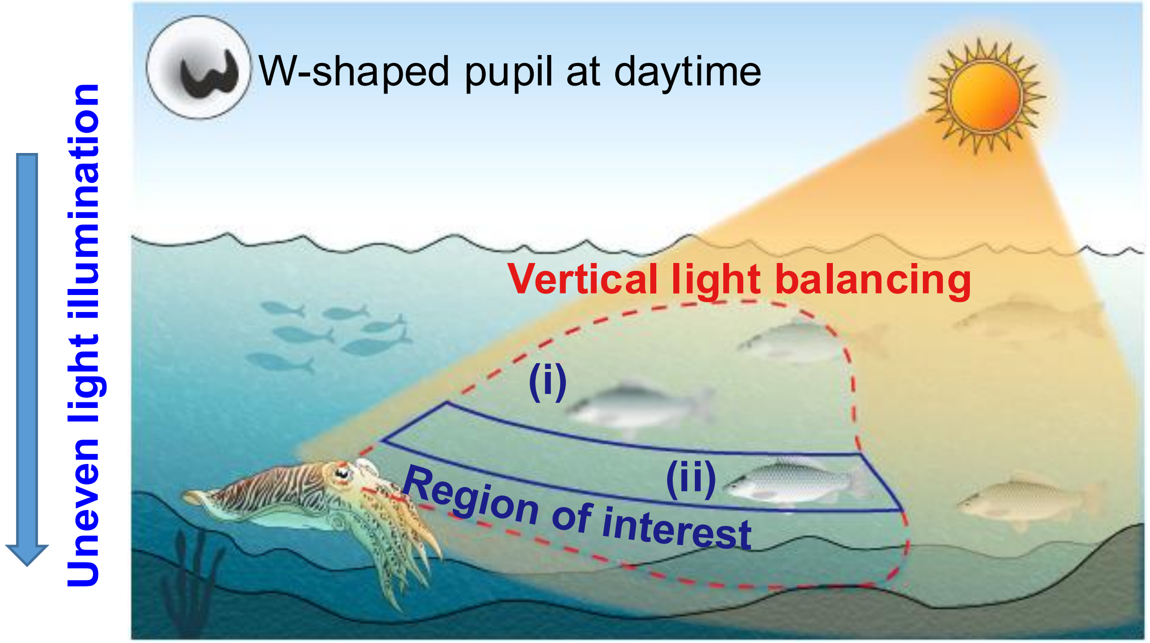


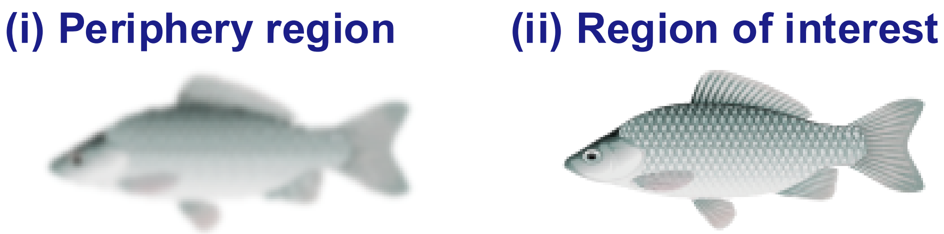
M. S. Kim et al., Nat. Electron. 3, 546 (2020)

Cuttlefish eyes



- **W-shape pupil**
- **Single spherical lens**
- **Curved retina**
- **High-density belt-like photoreceptor region**
- **Polarization-sensitive photoreceptors**





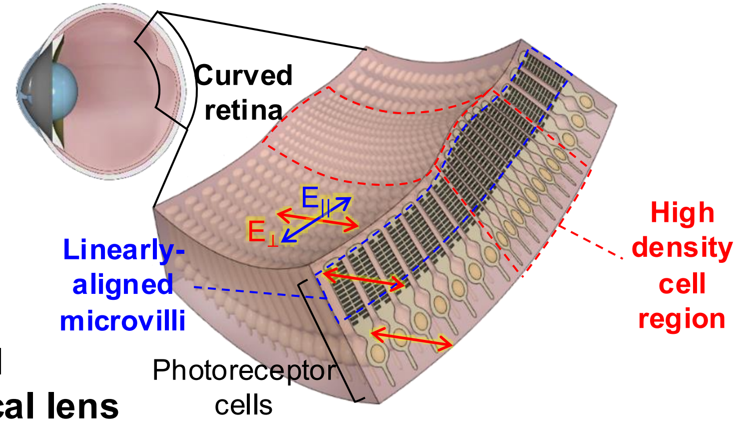
- W-shape pupil acts as a sun-shape to **balance the light intensity**
- High-density cell region **enhance the image resolution** in the region of interest

M. S. Kim et al., Science Robotics 8, ade4698 (2023)
https://www.youtube.com/watch?v=GDwOi7HpHtQ

L. M. Mathger et al, Vision Res. 83, 19 (2013)

Cuttlefish eyes

W-shaped pupil (daytime)



- **W-shape pupil**
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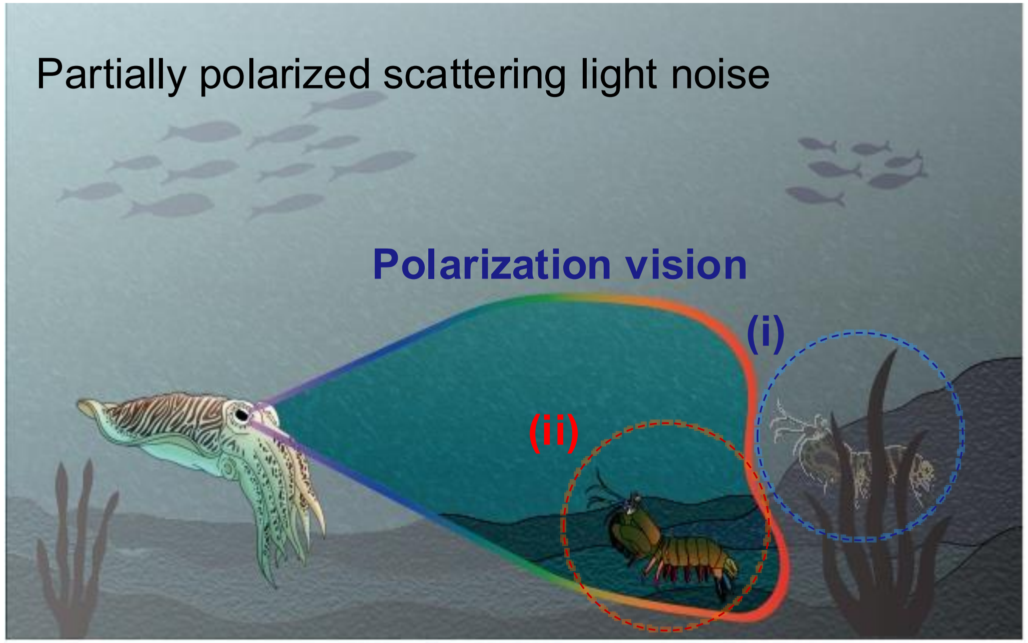


(i)

(ii)

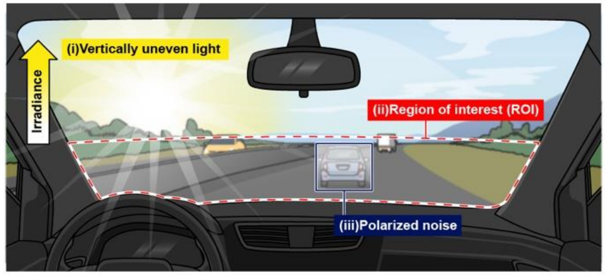
- Linearly aligned microvilli acts as **a linear polarizer**
- To effectively recognize camouflaged prey by extracting polarized light and filtering our randomly polarized background noise, leading to **enhanced visual contrast**

M. S. Kim et al., Science Robotics 8, ade4698 (2023)
https://www.youtube.com/watch?v=GDwOi7HpHtQ

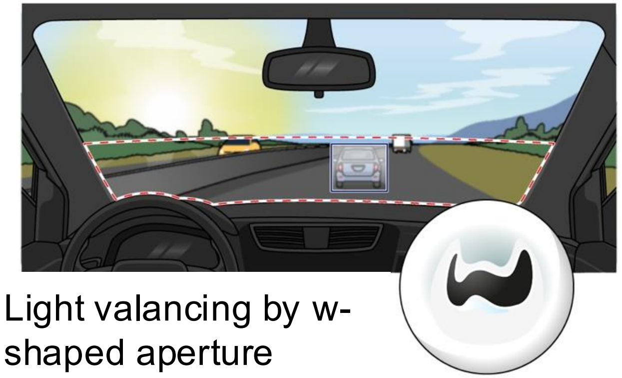
L. M. Mathger et al, Vision Res. 83, 19 (2013)

Potential applications

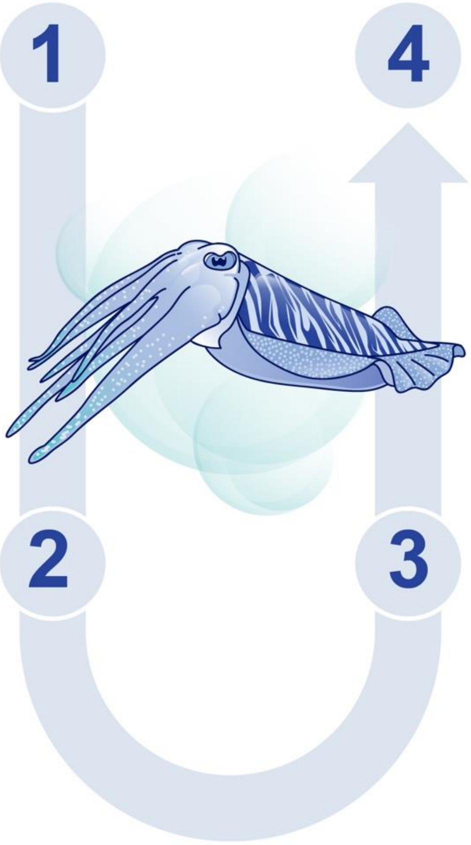
Camera for autonomous vehicles – High-contrast imaging

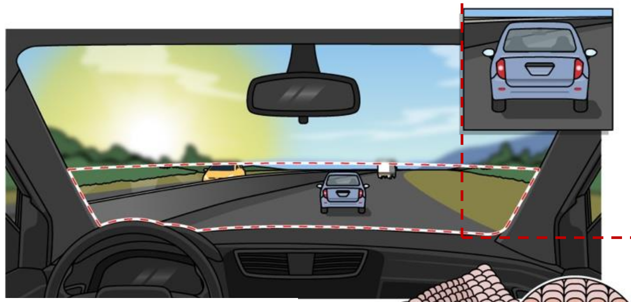


- Vertically uneven light conditions
- Strong light reflection (from object)



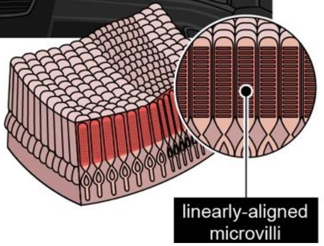
- Light valancing by w-shaped aperture



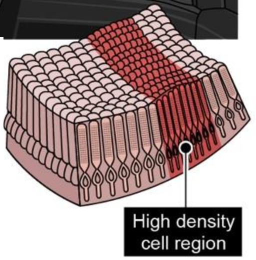


Recognize Target Object without any post image processing

- High-contrast imaging with polarizer-integrated sensors



- High-resolution imaging only in the target ROI

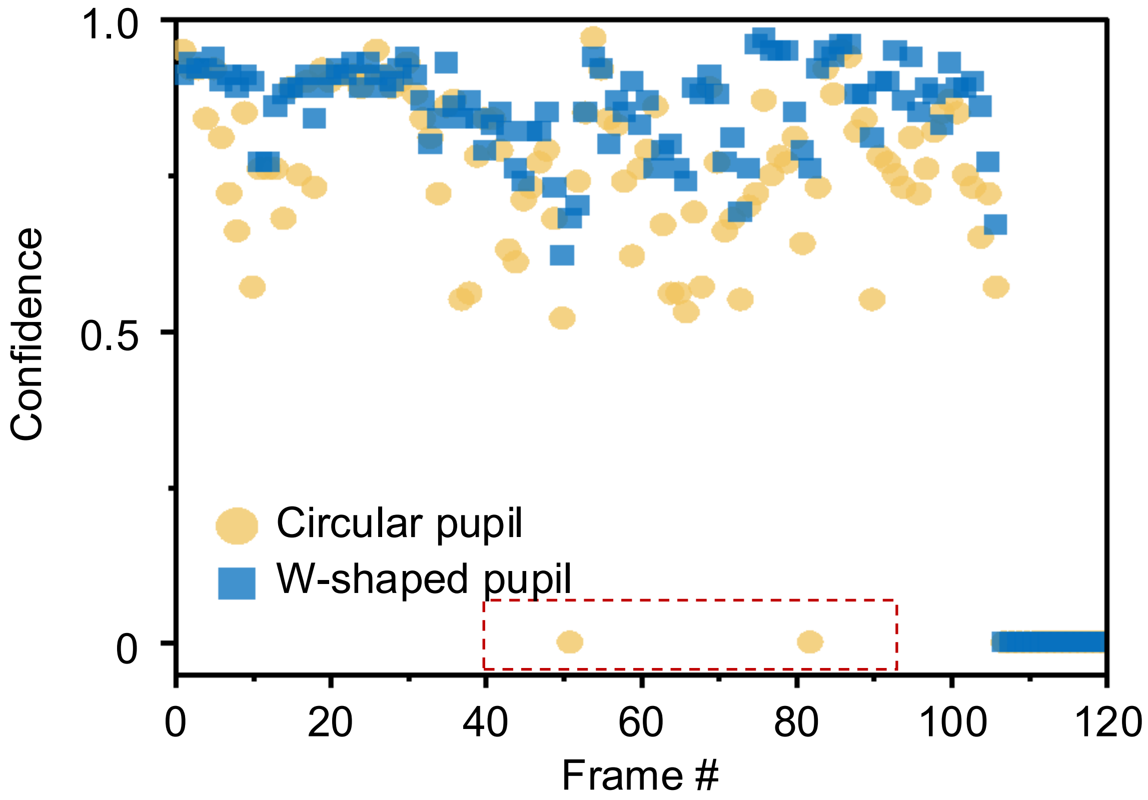


M. S. Kim et al., Science Robotics 8, ade4698 (2023)

Cuttlefish-eye-inspired cameras

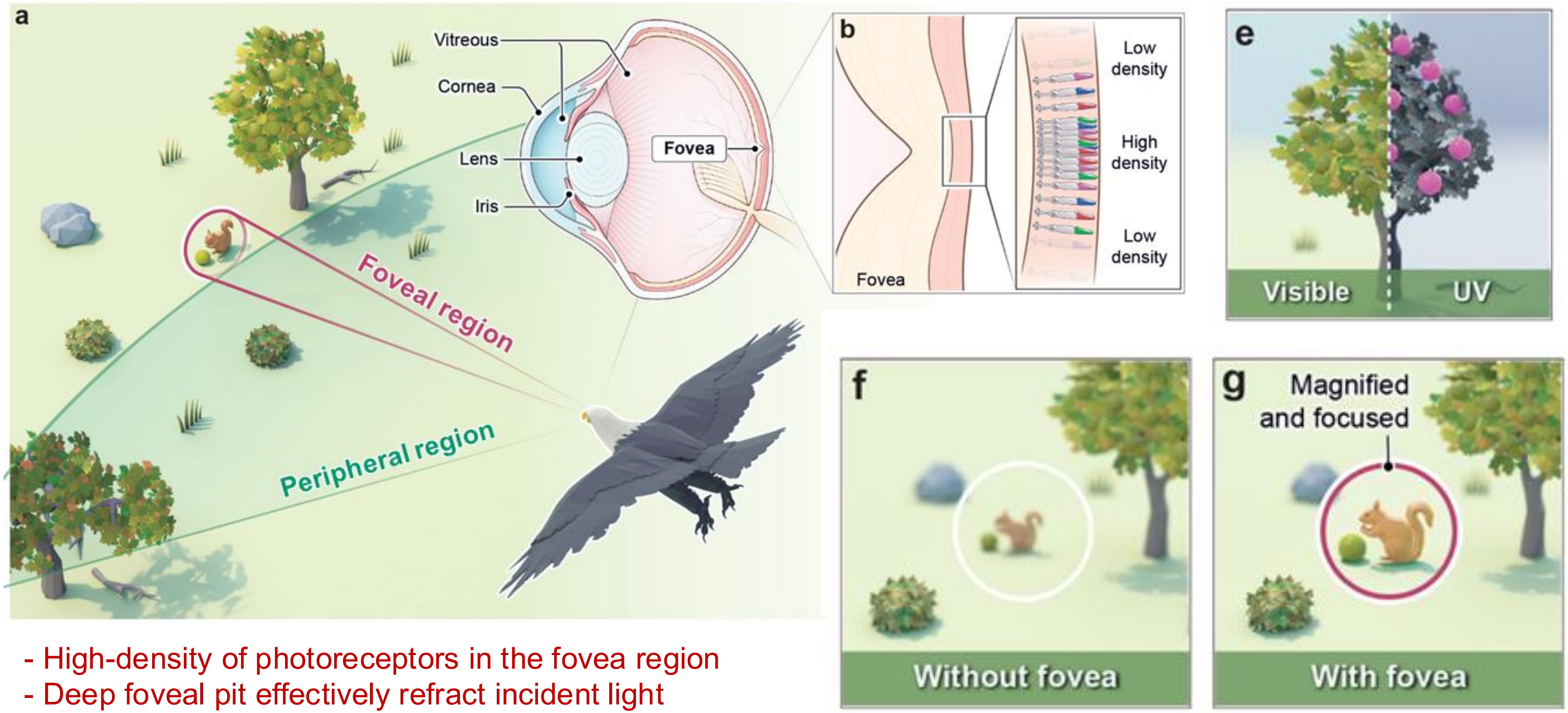
Object tracking
(under uneven illumination conditions)

Confidence plot vs. frame rate



M. S. Kim et al., Science Robotics 8, ade4698 (2023)

Avian Eyes

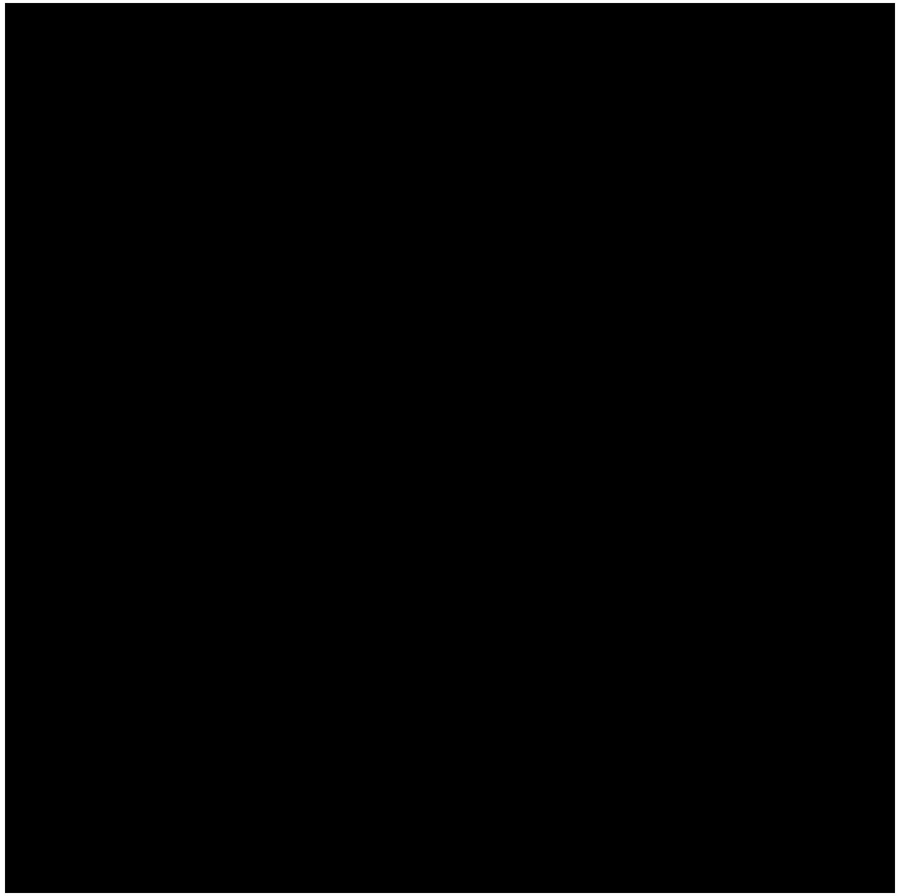


- High-density of photoreceptors in the fovea region
- Deep foveal pit effectively refract incident light
- Wide spectrum of light (visible and UV)

J. Park et al., Science Robotics 9, adek6903 (2024)

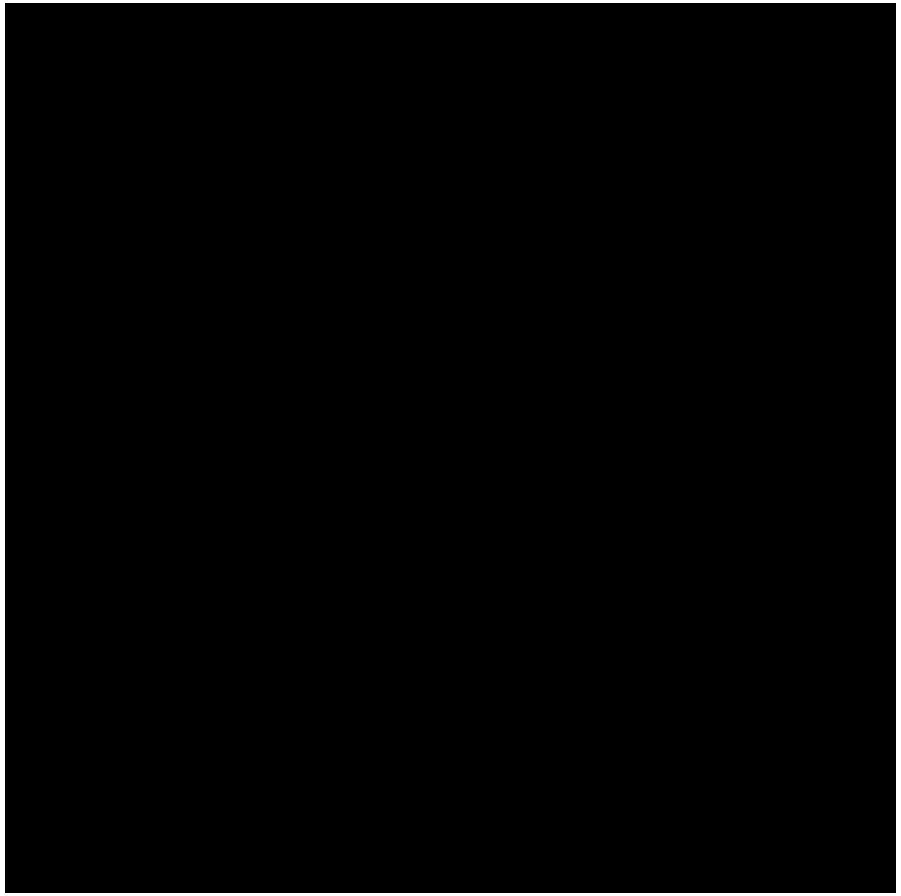
Artificial Avian Eye Cameras

Object detection



Confidence score : 0.39 (original), 0.76 (foveated)

Motion detection

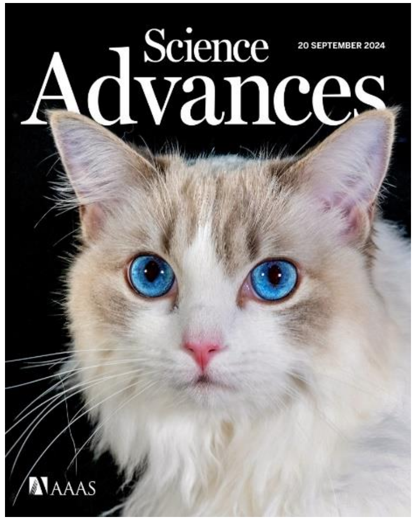


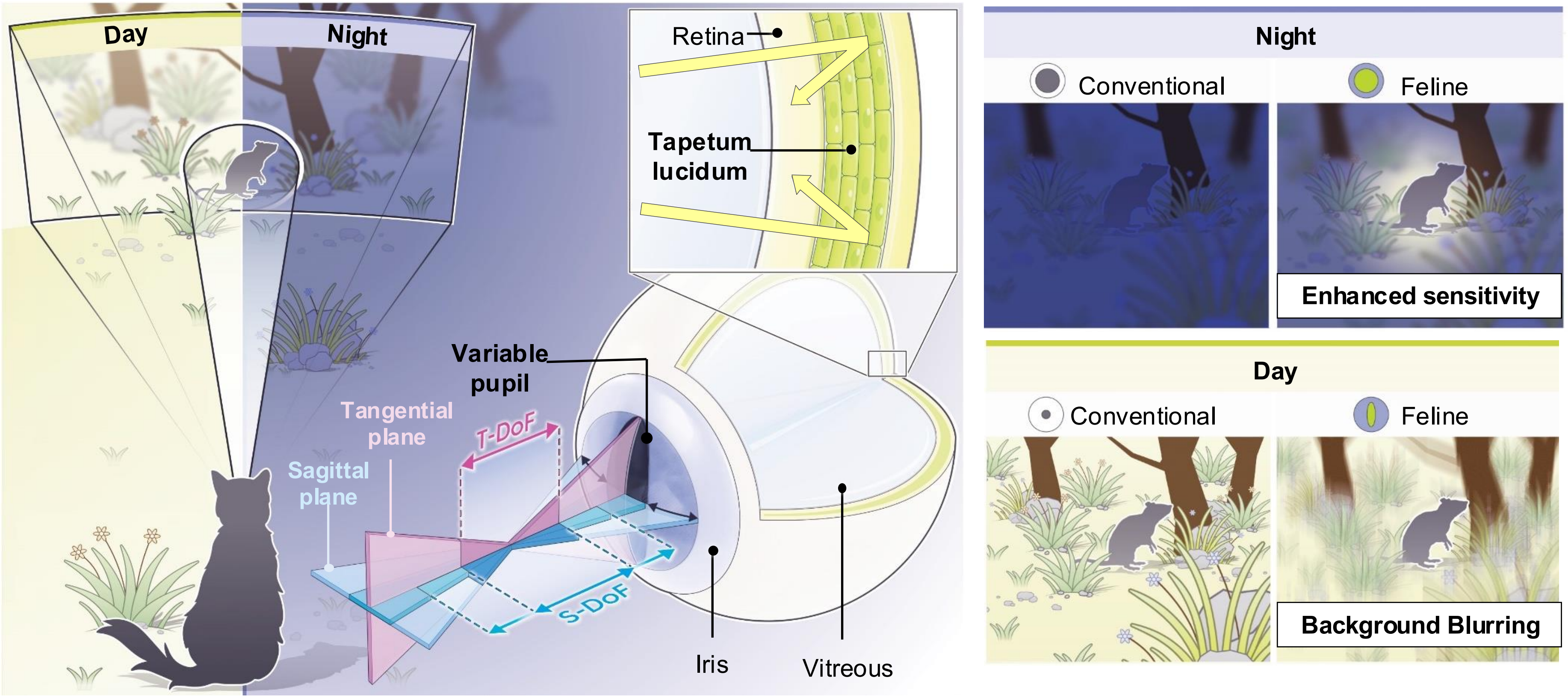
YOLO V5

Enhanced capability for motion detection by more than 3.6-fold

J. Park et al., Science Robotics 9, adek6903 (2024)

Feline Eye

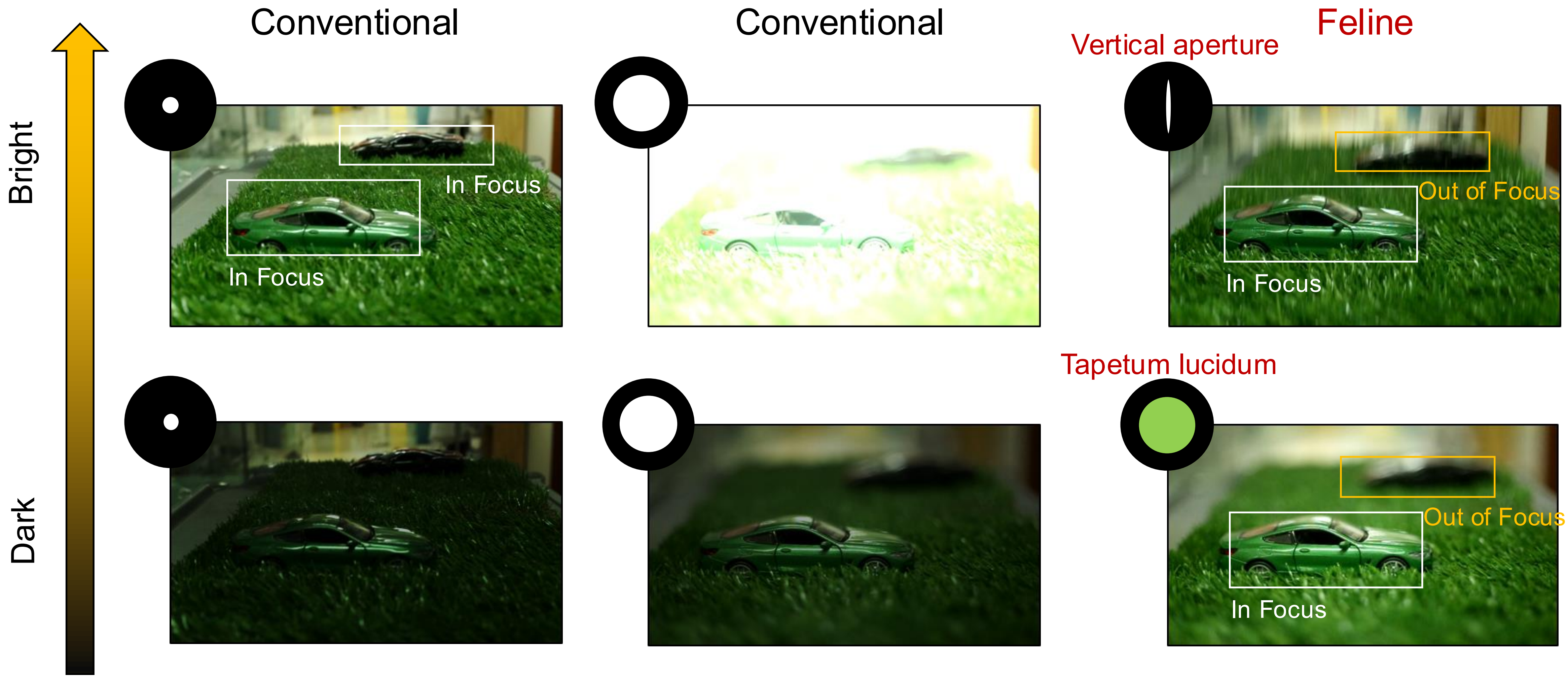




- At nighttime, tapetum lucidum reflects the incident light (passing through the retina back to the retina) : Enhanced sensitivity
- At daytime, vertical pupil provides asymmetric depth of focus (DoF) : High-definition focus on the target object.

M. S. Kim et al., Science Advances 10, eadp2809 (2024)

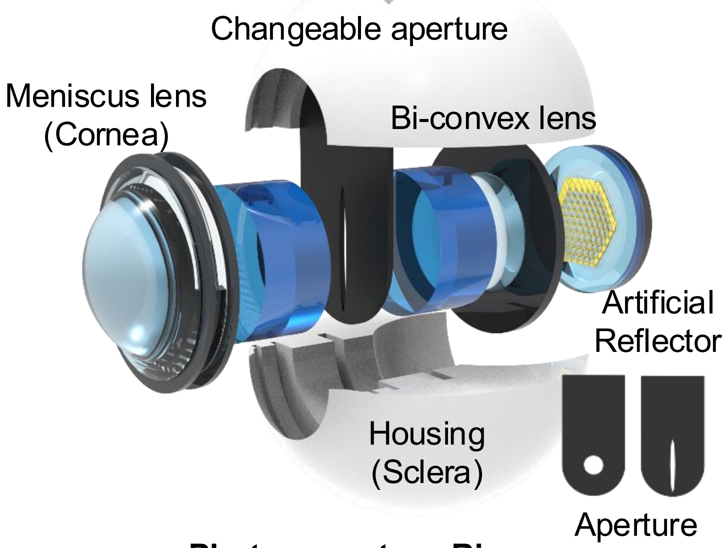
Feline Eye



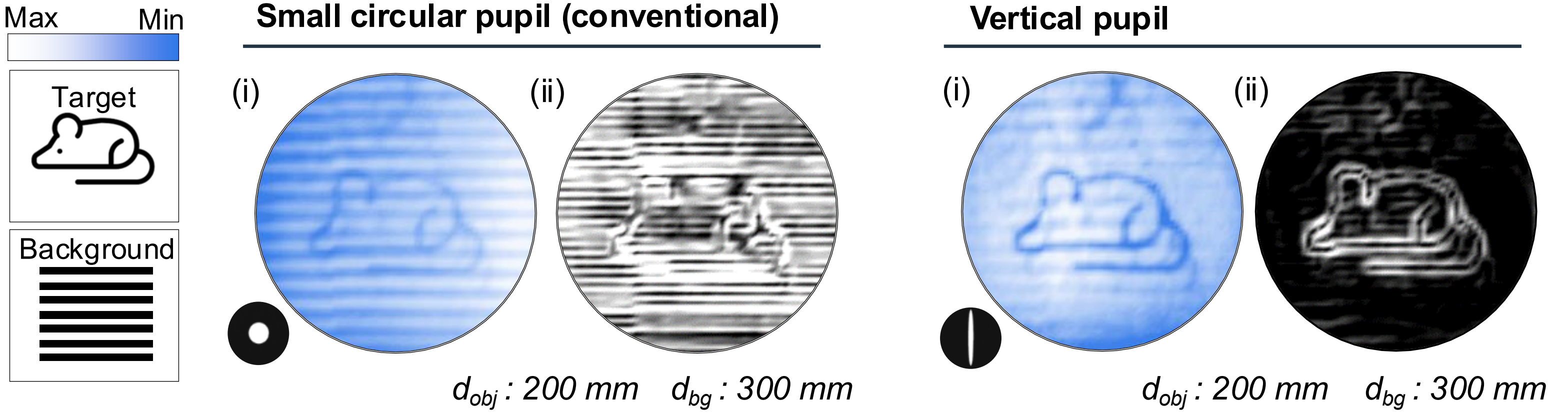
M. S. Kim et al., Science Advances 10, eadp2809 (2024)

Feline Eye Cameras

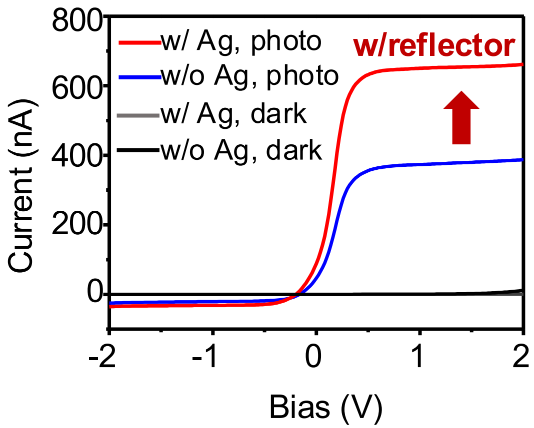
Feline-eye-inspired Cameras

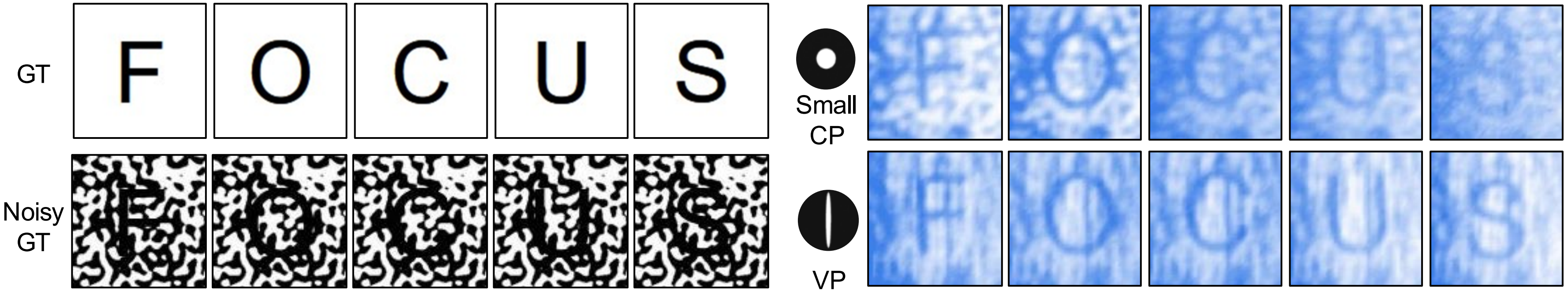


Imaging characteristics

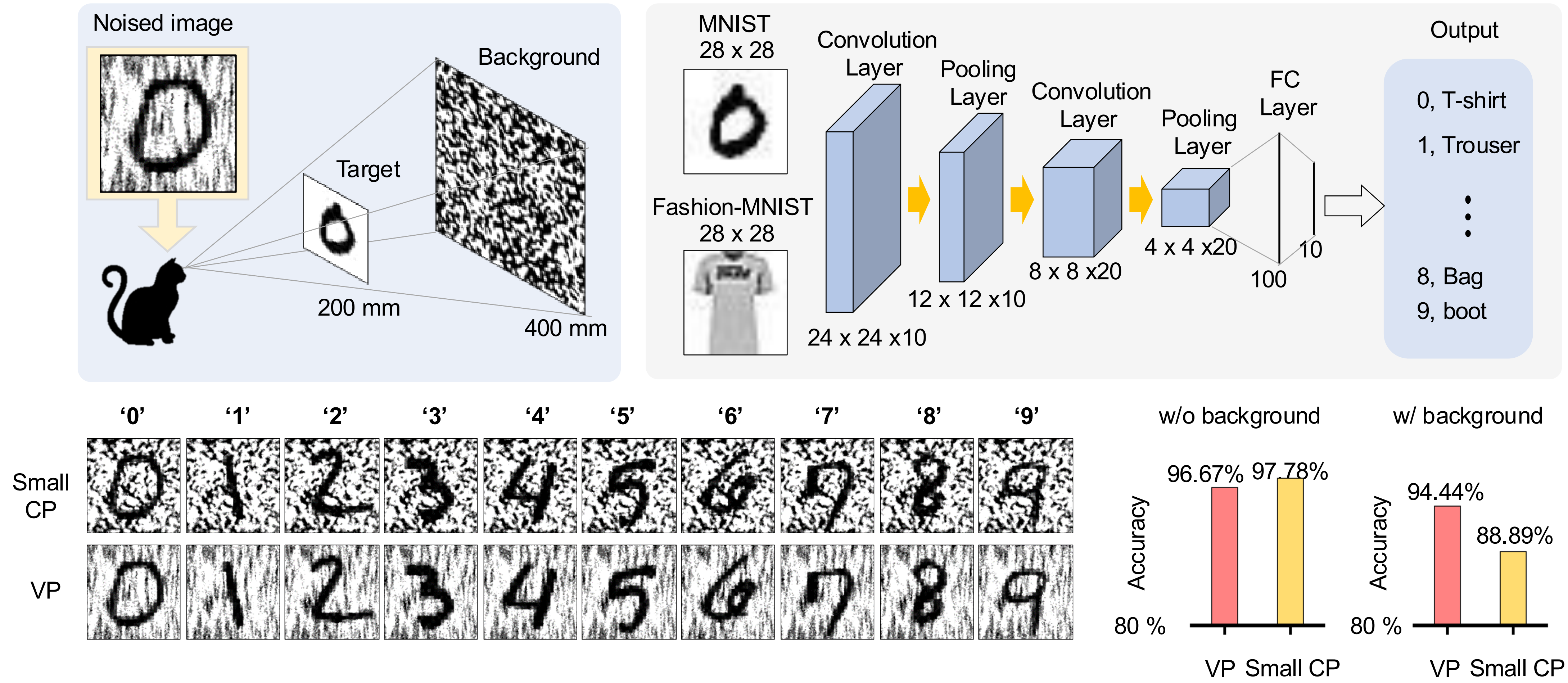


Photocurrent vs. Bias



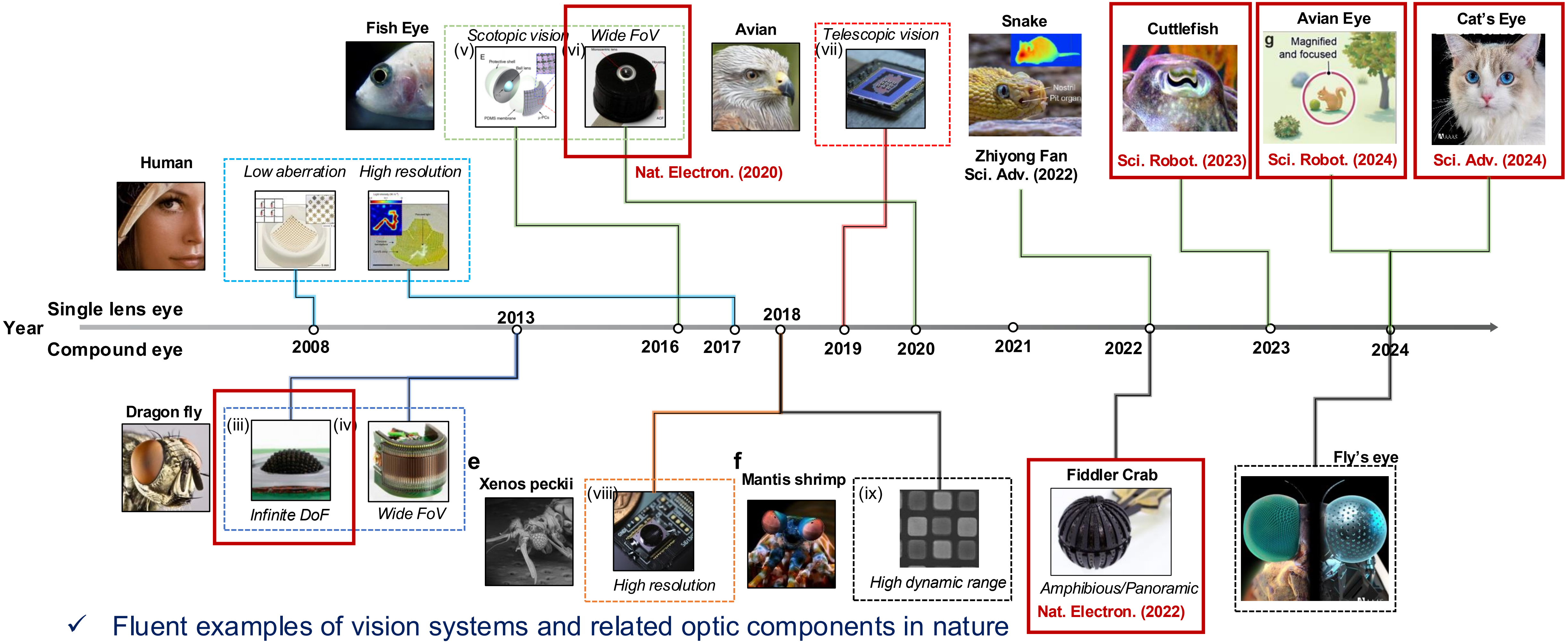


Feline Eye Cameras



M. S. Kim et al., Science Advances 10, eadp2809 (2024)

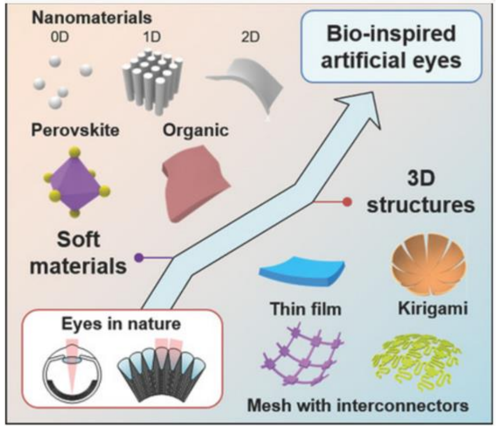
Summary



- ✓ Fluent examples of vision systems and related optic components in nature
- ✓ Much room for improvements in optical and electrical characteristics
- ✓ 'Beyond biology'

Future directions

Materials/mechanics

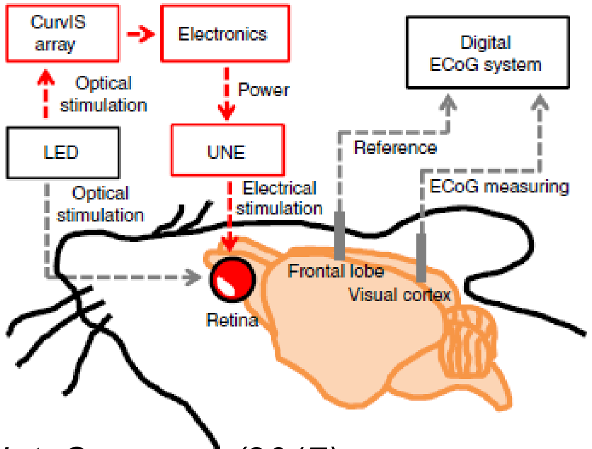


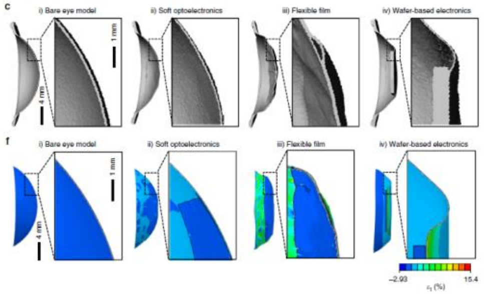
- Soft materials
- Graded index media
- Tunability
- 3D geometry

New findings, new designs

- Crustaceans' eye, Avians' eye, feline eye, herbivore, etc.
- Novel optic functions

Visual Prosthesis

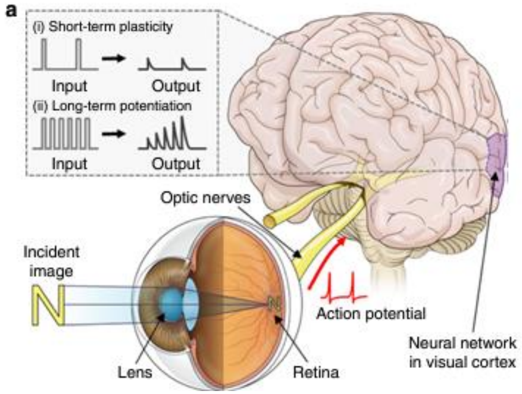


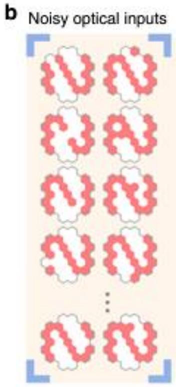


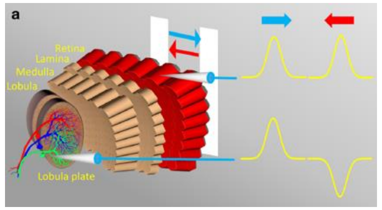
- Minimizing the mechanical stress in animal organs

Nat. Commun. (2017)

Combination with neuromorphic systems







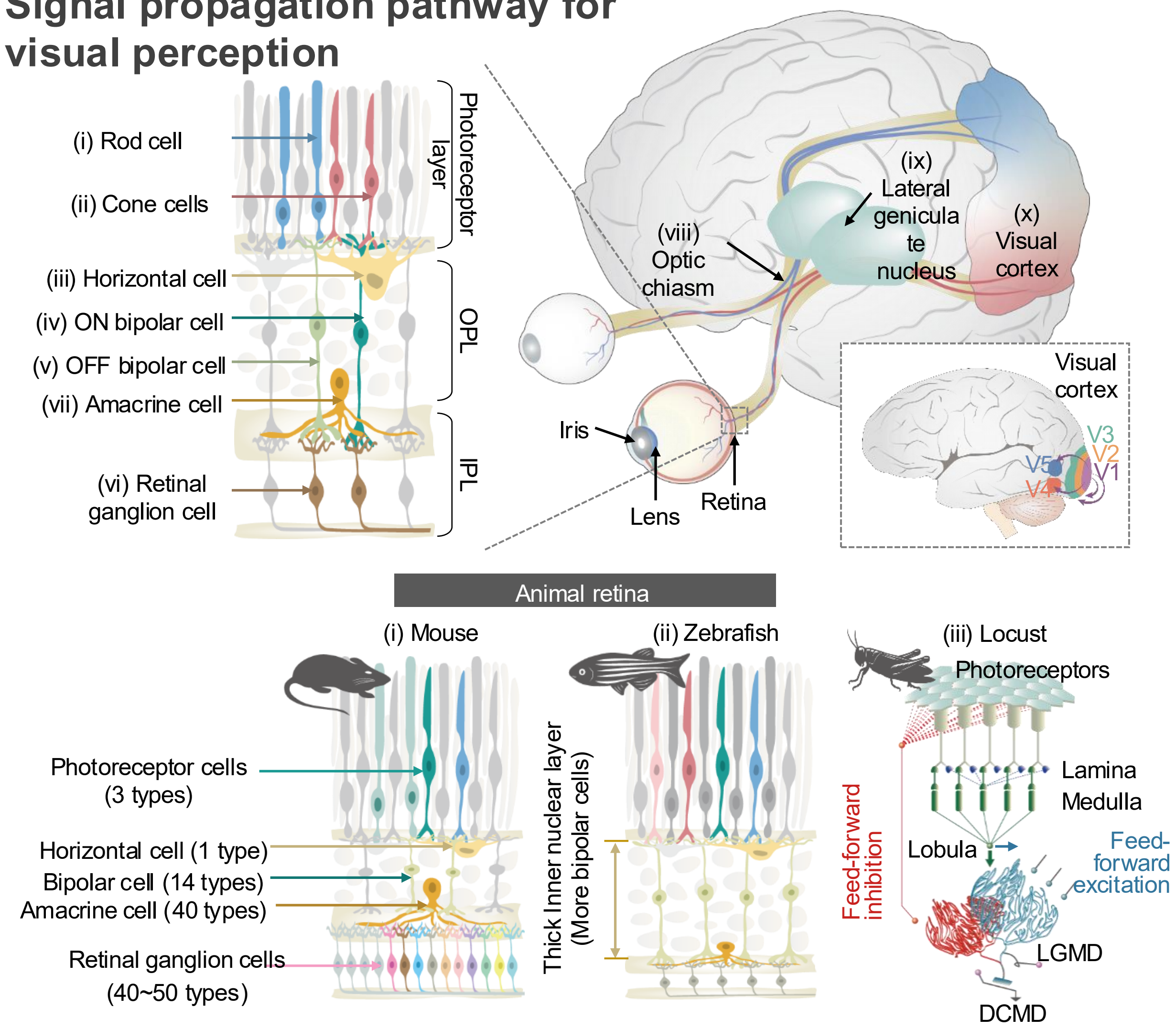
- Decision making
- Event camera

Nat. Commun. (2020), Nat. Commun. (2024)

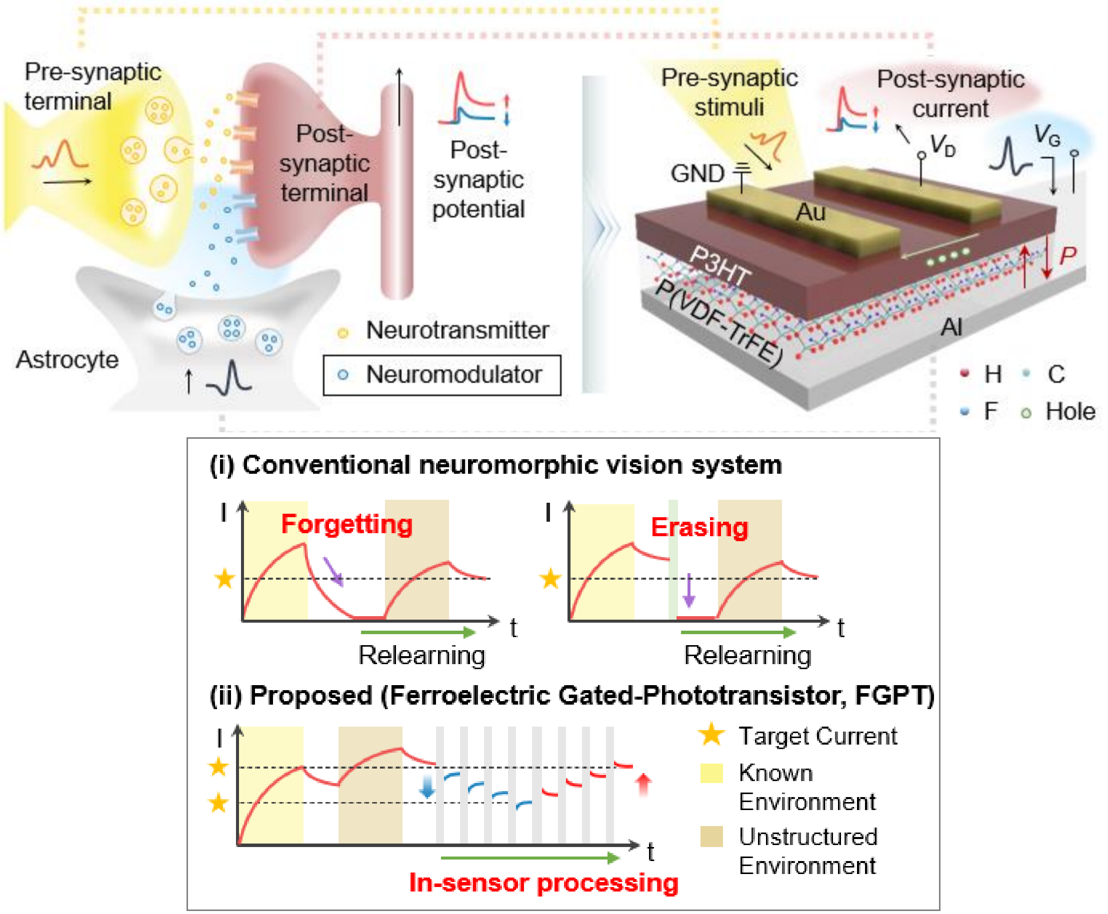
(Review) G. J. Lee et al., Adv. Funct. Mater. 28, 1705202 (2018)
(Review) M. S. Kim et al., Adv. Mater. Technol. 2100144 (2021)

Future directions : Bio-inspired in-sensor computing

Signal propagation pathway for visual perception



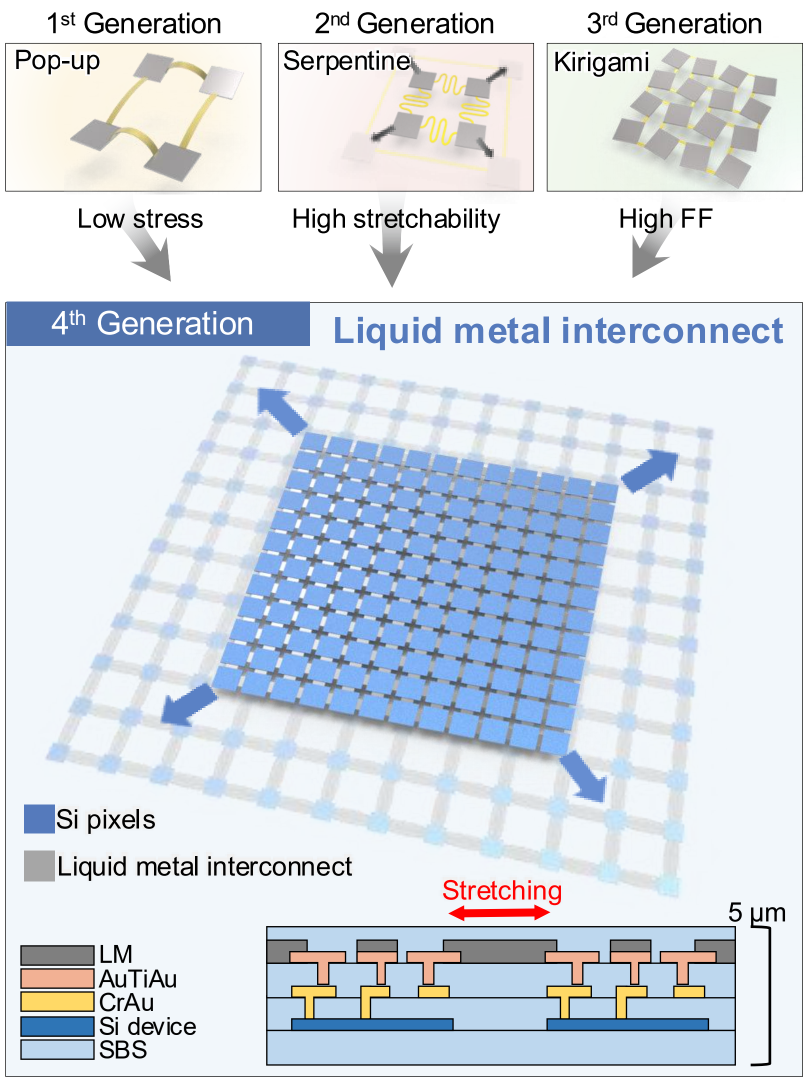
Tripartite Synapse-Inspired System (example)



Y. Lee et al., ***Adv. Mater.*** *37, 2503475 (2025)*

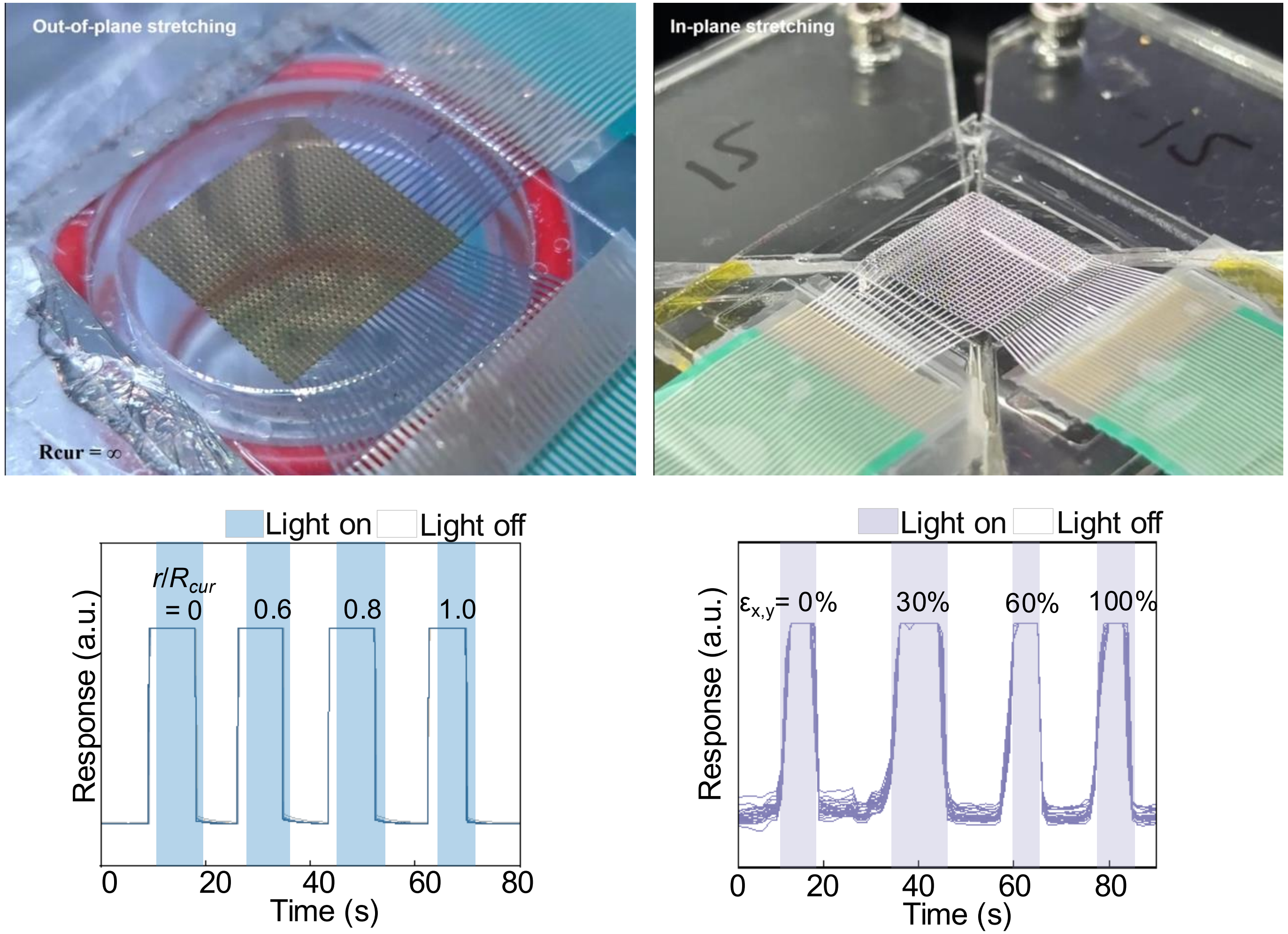
C. Choi et al., **Adv. Mater** 36, 2412252 (2024)

Stretchable Image Sensors for Robotic Vision



(i) Out-of-plane stretching

(ii) In-plane stretching

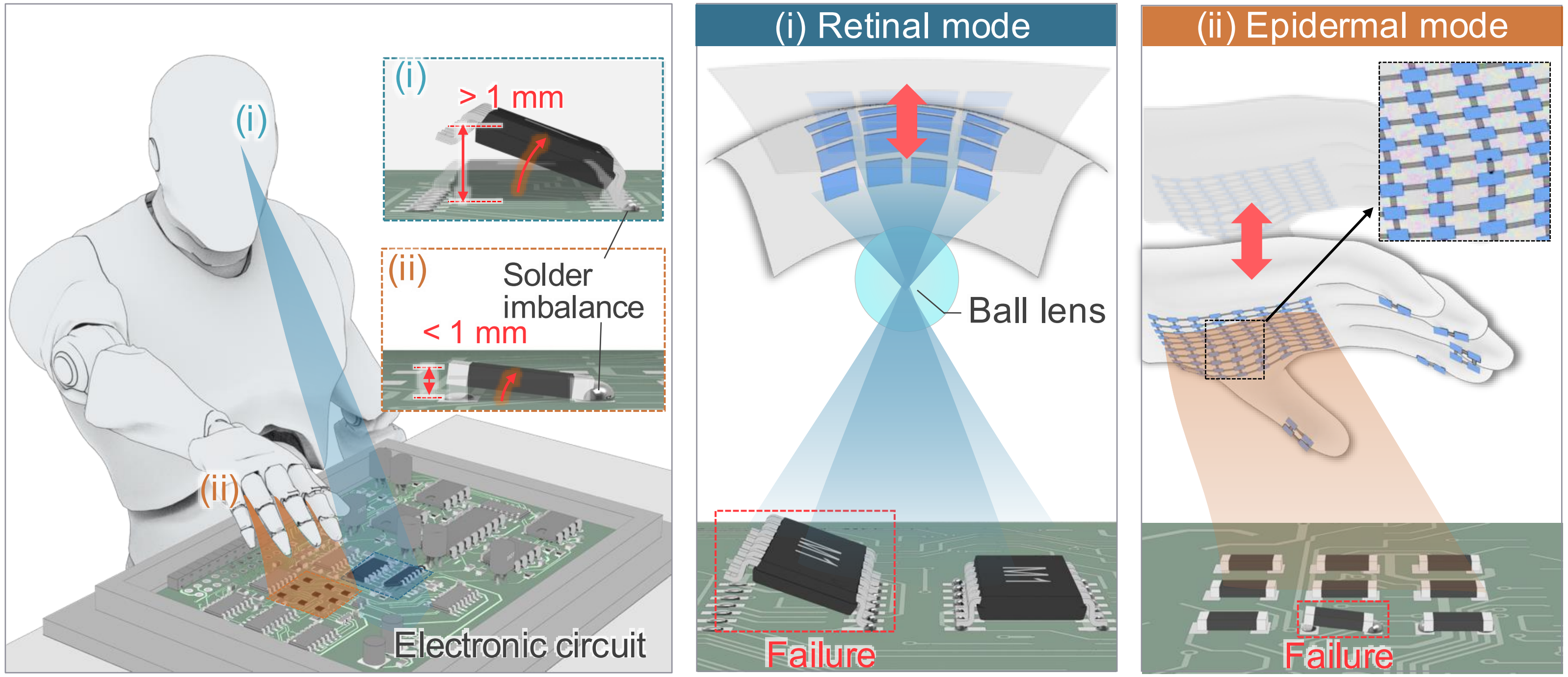


- Stable operation under two mechanical deformation modes

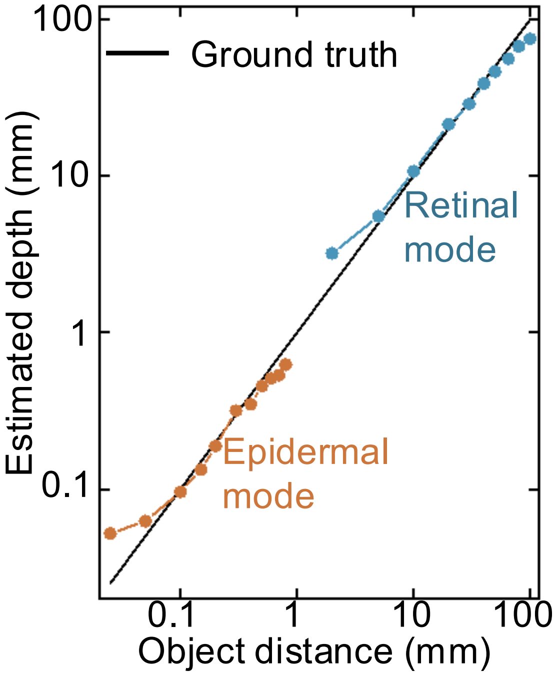
*C. Park et al., **Nat. Mater.** (2026)*

Hierarchical robotic vision for depth perception

Multi-scale depth perception



Complementary depth range



(i) Retinal mode: Wide-view imaging (> 80°) and macro-scale depth mapping (5-70 mm) via curvature and focal-length modulation

(ii) Epidermal mode: Lens-free, near-contact imaging and micro-scale depth mapping (0.1-0.6mm) via object-to-sensor distance modulation

*C. Park et al., **Nat. Mater.** (2026)*

Thank you for your attention!

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