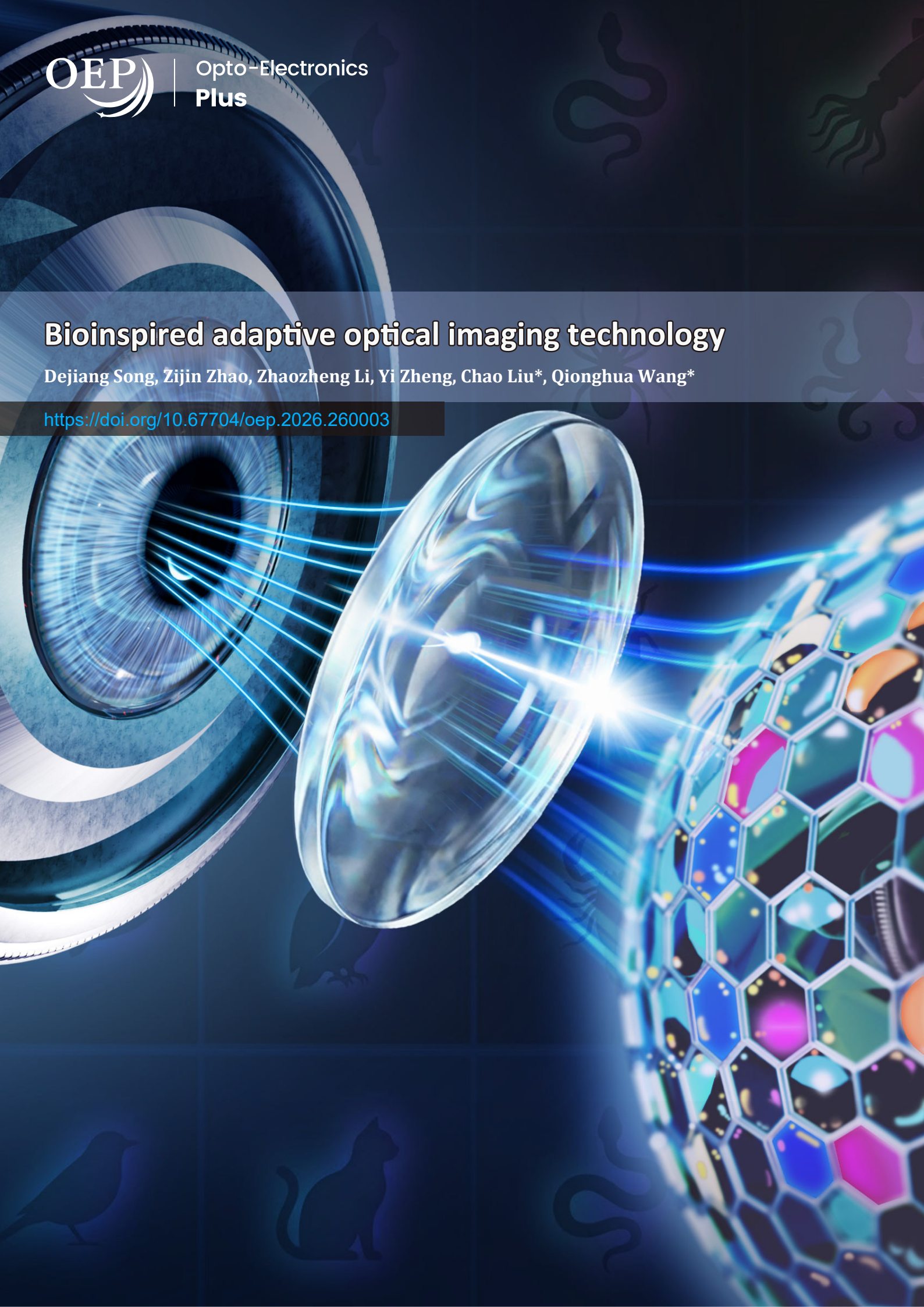


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Bioinspired adaptive optical imaging technology

Dejiang Song¹, Zijin Zhao², Zhaozheng Li², Yi Zheng², Chao Liu^{1,2*} and Qionghua Wang^{1,2*}

Abstract: Bioinspired adaptive optical imaging technology draws inspiration from nature's visual systems to overcome the limitations of conventional static optics. By emulating adaptive mechanisms like the human eye's accommodation and pupil response or the compound eye's wide field of view, this field enables imaging systems that dynamically tune key parameters such as focal length, aperture, and field of view. This review systematically examines two primary research thrusts: human-eye-inspired adaptive imaging using tunable lenses and apertures, and compound-eye-inspired systems for wide-field and multi-scale imaging. This review also explores adaptive technologies inspired by other biological models, such as polarization and spectral vision. Despite progress, challenges in integration, reliability, and multi-parameter control persist. Future advancement hinges on co-designing novel materials, adaptive device architectures, and intelligent processing to transition from passive biomimicry to actively intelligent imaging systems for applications ranging from robotics to biomedicine.

Keywords: bioinspired vision; adaptive optics; compound eye imaging; biomimetic imaging

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1 Introduction

Optical imaging technology stands as an indispensable sensing tool for modern scientific exploration, industrial inspection, medical diagnosis, and daily life^{1–3}. However, most conventional imaging systems are based on static, rigid optical designs, with their performance parameters, such as focal length, field of view (FOV), numerical aperture, and spectral response fixed during manufacturing. When confronted with the complexity and dynamism of real-world environments, the imaging quality, robustness, and adaptability of these systems are often significantly challenged. To transcend these inherent constraints, researchers are increasingly turning to nature, a repository of elegant solutions refined over billions of years of evolution, which has given rise to a stunning diversity of superior visual systems^{4–11}.

Against this backdrop, bioinspired vision has flourished into a vibrant and highly interdisciplinary frontier of research. It integrates knowledge from optical engineering, biophysics, materials science, micro/nanofabrication, computer vision, and neuroscience, aiming to decode the physical structures, information processing mechanisms, and behav-

ioral strategies of biological visual systems and translate their core principles into advanced artificial devices and systems. The goal is not merely to mimic form but to replicate and even surpass specific functions of the prototypes. For instance, liquid tunable focus lenses that mimic the accommodative mechanism of the human crystalline lens address the drawbacks of bulky and slow mechanical lens movements in traditional optics, offering revolutionary compact and silent solutions for smartphone cameras¹², medical endoscopes^{13–15}, and wearable devices¹⁶. Curved microlens array imaging systems inspired by insect compound eyes can achieve ultra-large FOV imaging exceeding 180°, providing novel visual perception paradigms for drone obstacle avoidance, panoramic surveillance, and micro robotics. Meanwhile, multi-channel polarization imaging sensors inspired by mantis shrimp (Stomatopod) vision can simultaneously capture a scene's intensity, spectral, and polarization information, opening unprecedented perceptual dimensions for material identification, underwater detection, and biomedical analysis. These remarkable achievements demonstrate that bioinspired vision is not a simplistic conceptual mimicry but a viable technological

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pathway toward imaging systems with high performance, low power consumption, high environmental adaptability, and novel functionalities. The synergistic integration of biomimetics and optics has already catalyzed a series of groundbreaking imaging principles and devices.

Within this broad spectrum, bioinspired adaptive optical imaging technology represents a critical and dynamic subfield. It refers to systems capable of dynamically adjusting their key optical or optoelectronic parameters such as focal length, aperture, spectral response according to changing task requirements or environmental conditions. This mimics the real-time adaptability observed in biological visual systems. Its core value lies in enhancing the comprehensive performance and operational robustness of imaging systems in dynamic scenarios through intelligent, hardware-level reconfiguration, moving beyond the limitations of purely post-processing algorithmic compensation. Compared to traditional static imaging, bioinspired adaptive imaging offers significant advantages, including extended depth of field, consistent performance under variable lighting, enhanced information acquisition capabilities, and the potential for more compact and power-efficient architectures.

Current research is advancing along several distinct yet complementary trajectories, largely mirroring biological prototypes. The first major thrust focuses on bioinspired human-eye adaptive imaging technology. This direction aims to emulate the camera-style vision of mammals, particularly the human eye's accommodative lens and adaptive iris^{17–19}. The second dominant thrust comprises bioinspired compound-eye adaptive imaging technology²⁰. Inspired by

the apposition or superposition compound eyes of arthropods, these systems target large FOV or panoramic imaging, high temporal resolution for motion perception, and unique imaging modalities. Furthermore, adaptive technologies derived from other specialized biological models, such as the foveated vision of raptors, the polarization vision of cephalopods, or the spectral expansion in mantis shrimp constitute important and emerging complementary pathways¹⁰.

Despite these fruitful achievements, the field continues to face multifaceted challenges²¹. Different bioinspired technology pathways require further optimization in terms of integration density, response speed, actuation energy consumption, and seamless compatibility with standard electronic readout systems. A paramount, systems-level challenge lies in achieving a tighter co-design and synergy between novel materials, adaptive device architectures, freeform optical design, and embedded information processing algorithms. This integration is essential to realize a fundamental leap from passive biomimicry of form to active intelligence in function, which is the key to widespread practical application.

This review aims to provide a systematic exposition of the underlying principles, significant recent advances, and emerging trends in bioinspired adaptive optical imaging technology. It will commence with an overview of biological visual diversity and its core inspirations for adaptive imaging. This review concentrates on two major, well-established research thrusts: bioinspired human-eye adaptive imaging technology and bioinspired compound-eye adaptive imaging technology, as shown in Fig. 1.

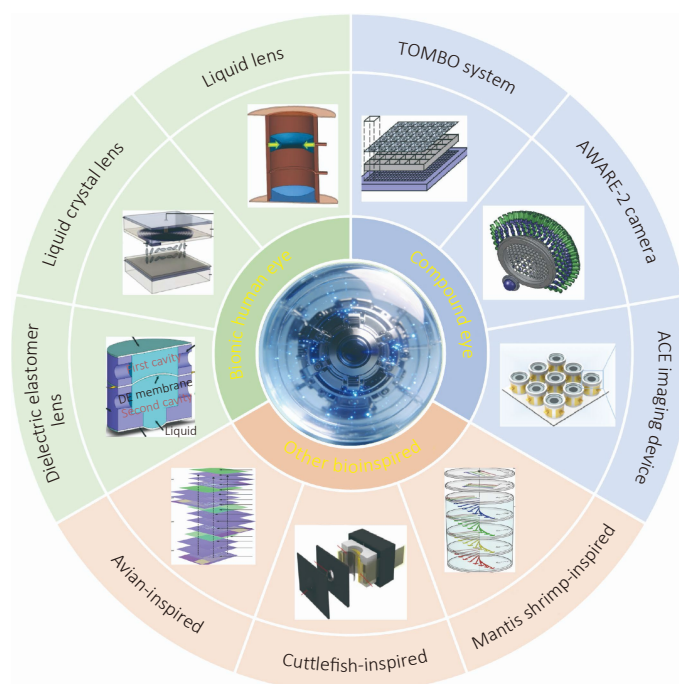


Fig. 1 | Several types of bioinspired adaptive optical imaging technology

The former section provides an in-depth analysis of tunable apertures and variable focus lenses that emulate the human pupil and crystalline lens. These sections cover mainstream technological pathways including electrowetting effect, liquid crystals, dielectric elastomers, and light-driven actuation, along with their integrated applications¹⁶. The latter section analyzes curved array imaging systems inspired by insect compound eyes, examining their unique advantages and implementation strategies for FOV expansion, depth-of-field enhancement, motion perception, and dynamic beam steering via optical phased arrays. Furthermore, the review offers perspectives on adaptive technologies inspired by other specialized biological models. Finally, the review summarizes the core scientific challenges and key technological bottlenecks currently confronting the field. We posit that through sustained learning from biological prototypes coupled with engineering innovation, bioinspired adaptive optical imaging technology is poised to instigate transformative advances in next-generation visual perception systems.

2 Principles and advances in bioinspired adaptive optical imaging technology

Through billions of years of evolution in response to complex and dynamic living environments, organisms in nature have developed highly specialized visual systems, which serve as a continuous source of inspiration for artificial imaging technologies. Examples span from the human eye with its precise accommodative capability, to the ultra-wide field-of-view of insect compound eyes, and further include feline vision adapted for low-light conditions, avian optics for long-distance acuity, and piscine visual systems optimized for underwater environments. The biomimicry of these biological visual mechanisms has catalyzed the development of diverse bioinspired imaging approaches.

Among these, bioinspired adaptive imaging technology stands out, which is capable of dynamically adjusting optical or optoelectronic parameters according to environmental conditions and task requirements. Its prominence is attributed to the substantial improvements it offers in system performance and robustness under dynamic imaging scenarios. Current research is predominantly concentrated on two well-defined directions, each grounded in canonical biological models and exhibiting significant application potential. The first focuses on adaptive technologies emulating the camera-style vision of mammals, particularly the human eye, with the goal of achieving rapid focusing and aberration correction under high-resolution conditions. The second direction involves adaptive systems inspired by the compound eye vision of arthropods, targeting large FOV imaging, high motion sensitivity, and distinctive imaging modalities. In addition, adaptive technologies derived from other specialized biological visual functions, such as polar-

ization perception and spectral expansion, serve as important complementary pathways.

Accordingly, this review is structured around three core thematic areas: bioinspired human-eye adaptive imaging technology, bioinspired compound-eye adaptive imaging technology, and other bioinspired adaptive imaging technologies. We systematically examine their underlying biological principles, technical implementations, current challenges, and prospective development trends.

2.1 Bionic human eye adaptive imaging technology

2.1.1 Fundamental principles of bionic human eye adaptive imaging

Adaptive regulation mechanisms of the human eye The human eye's excellent visual performance is attributed to two core adaptive regulation mechanisms: pupil aperture adjustment and crystalline lens focusing. The pupil, located at the center of the iris, regulates the amount of incoming light through contraction and dilation. In bright environments, the iris sphincter muscle contracts, reducing the pupil diameter to as small as 2 mm to avoid retinal damage from excessive light. In dark environments, the iris dilator muscle relaxes, increasing the pupil diameter to approximately 8 mm to enhance light collection. This dynamic adjustment of the pupil aperture enables the human eye to maintain clear vision over a wide range of light intensities²².

The crystalline lens, a biconvex transparent elastic body, achieves focal length adjustment through changes in curvature, a process known as accommodation. When viewing distant objects, the ciliary muscle relaxes, and the crystalline lens assumes a flatter shape with a longer focal length. When focusing on near objects, the ciliary muscle contracts, reducing the tension on the lens capsule and allowing the crystalline lens to become more convex, thereby shortening the focal length. This accommodation mechanism enables the human eye to achieve clear imaging of objects at different distances, with a focal length adjustment range corresponding to a diopter change of approximately 10–14 D²³.

Bionic simulation principles To replicate the human eye's adaptive regulation capabilities, bionic imaging systems need to simulate the pupil's aperture control and the crystalline lens's focal length adjustment through engineered optical components and regulation mechanisms.

For pupil aperture simulation, the key is to develop adjustable diaphragms that can dynamically change the light-passing area. Common regulation mechanisms include electrowetting-on-dielectric (EWOD), microfluidic control, and MEMS (micro-electro-mechanical systems) actuation. The EWOD effect, which modulates the contact angle between a liquid and a solid surface by applying an electric field to alter surface tension, has become a mainstream approach for liquid iris design due to its fast response, low power consumption, and simple structure. As demonstrated in the adaptive liquid iris based on electrowetting, two

immiscible liquids (conductive and insulating) are encapsulated in a transparent chamber, and the liquid-liquid interface shape is adjusted by an electric field to regulate the effective aperture²⁴.

For crystalline lens simulation, the core is to develop tunable focus lenses that can dynamically change their curvature or refractive index. The regulation mechanisms mainly include EWOD-driven curvature change, liquid volume adjustment, liquid crystal molecular orientation control, and dielectric elastomer deformation. These mechanisms mimic the ciliary muscle's role in adjusting the crystalline lens's curvature, enabling continuous focal length tuning. For example, EWOD-based liquid lenses adjust the curvature of the liquid-liquid interface through surface tension modulation, while dielectric elastomer lenses utilize the electroactive deformation of polymer films to alter the lens surface curvature. Liquid crystal lenses, on the other hand, achieve refractive index modulation by controlling the orientation of liquid crystal molecules through an electric field, thereby changing the focal length²⁵.

2.1.2 Related research on bionic tunable human eye imaging systems

Liquid lenses One of the core objectives of bioinspired human-eye imaging is to achieve rapid, precise, and mechanically fatigue-free focal length adjustment akin to the human eye. However, traditional mechanical zoom methods that rely on moving solid lens groups face fundamental limitations in terms of size, response speed, and energy consumption. This challenge has spurred the exploration of revolutionary zoom technologies, among which tunable liquid lenses stand out due to their unique non-mechanical actuation principles, emerging as a key enabling technology for realizing bioinspired adaptive optical systems²⁶.

The earliest research on tunable liquid lenses dates back to 1963²⁷. Tulis proposed a technique utilizing acoustic pres-

sure oscillations to control droplet shape. The droplet deforms during actuation, achieving beam focusing functionality, which can be regarded as the prototype of liquid lenses. The core of tunable liquid lenses lies in their non-mechanical actuation mechanism, which directly determines the lens's response speed, power consumption, reliability, and integration potential. Over the following two decades, researchers extensively studied tunable liquid lenses and proposed various types, such as electrowetting liquid lenses, dielectrophoretic liquid lenses, and electrostatic liquid lenses²⁶.

Electrowetting technology is currently the most mature and commercially advanced solution. Its working principle involves applying a voltage to change the contact angle between a conductive liquid and an insulating solid wall, thereby driving the deformation of a droplet or a liquid-liquid interface. This technology offers relatively fast response speeds, typically at the millisecond level, allows for larger optical apertures, and operates at relatively low driving voltages, as shown in Fig. 2.

Dielectrophoretic actuation utilizes non-uniform electric fields to exert force on neutral but polarizable media, causing their displacement or deformation. Typically, dielectrophoretic lenses employ electrodes to apply a non-uniform electric field, attracting liquid with a higher dielectric constant to regions of higher electric field strength. This squeezes and alters the curvature of the optical interface. Its greatest advantage is that the driven liquid itself is insulating, avoiding electrochemical effects possible in electrowetting, and theoretically offers longer lifespan and lower hysteresis. However, its driving voltage is usually higher, optical design is more complex, and it demands high precision in electrode structure.

Electrostatic actuation, also known as electrostatic force or electrode polarization force actuation, operates on the principle of generating Maxwell stress between the liquid

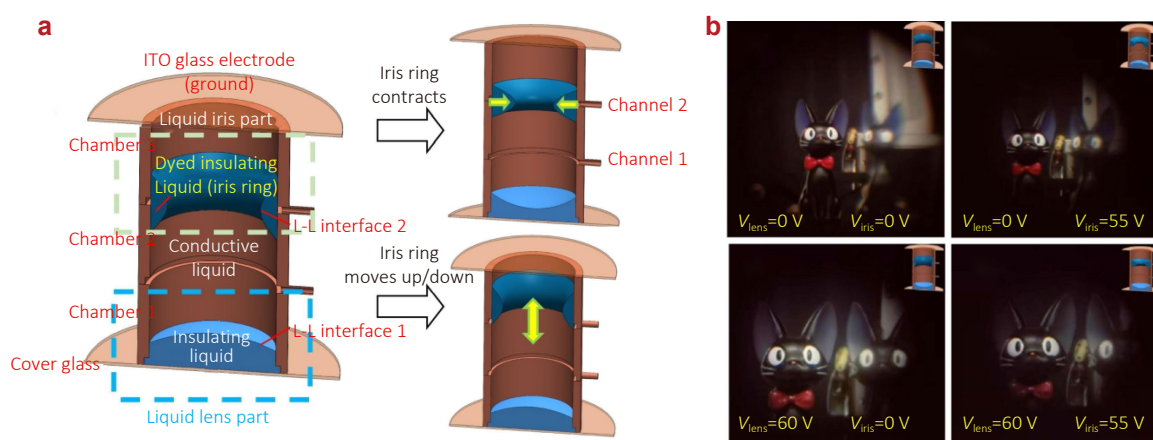


Fig. 2 | (a) Schematic diagram of structure and working principle of the ELL-LI (electrowetting liquid lens integrating adaptive liquid iris). (b) Experimental results of imaging depth of field under different applied voltages on the liquid lens part and liquid iris part. Figure reproduced with permission from: ref. ¹⁹, Elsevier Ltd.

and an electrode by applying an electric field, directly compressing the liquid interface to induce deformation. A common design uses a conductive liquid as one electrode, forming an electric field with another solid annular electrode, deforming the conductive liquid film via electrostatic force. This technology can have a very simple structure and potentially extremely fast response speeds. Its main limitations are the typically high required driving voltage and potentially limited deformation range and control linearity.

Liquid crystal lenses Liquid crystal (LC) lenses represent a critical class of electrically tunable optical elements. Their core principle lies in dynamically controlling the spatial distribution of the refractive index via an external field to achieve continuous focal length adjustment. By replacing traditional solid lenses, LC lenses overcome the inherent limitation of a fixed focal length, enabling compact, lightweight, and programmable optical systems without the need for mechanical moving parts. This capability establishes their importance in applications such as adaptive imaging, augmented reality (AR) displays, and optical communication, as shown in Fig. 3²⁸.

A fundamental advancement in this field is the development of electrically tunable LC lenses for AR projection, whose focal plane can be shifted electronically to superimpose virtual images at varying depths. Subsequent research has focused on improving optical performance and simplifying the structure. For instance, utilizing a 90° twisted nematic liquid crystal cell to replace traditional polarizers enhances light efficiency and simplifies the lens configuration²⁹. Further innovations include polarization-independent designs based on a microdomain twisted structure, as well as lenses capable of radial focus tuning using ultrasonic excitation³⁰.

Traditional LC lenses achieve focal length tunability by controlling the rotation angle of the liquid crystal molecules. Liu et al.³¹ designed and fabricated a tunable planar liquid crystal Alvarez lens whose focal length can be adjusted through the lateral displacement of two planar liquid crystal phase plates driven by a dielectric elastomer actuator (DEA). This tunable planar liquid crystal Alvarez lens was fabri-

cated using maskless laser direct writing technology. It enables the focusing of virtual images of objects at different depths in real world environments.

Concurrently, substantial research efforts have been dedicated to improving response speed for real time applications. Methods such as employing polymer-stabilized blue-phase liquid crystals, dual-frequency liquid crystal driving, and optimized alignment layers have achieved switching times ranging from microseconds to milliseconds, thereby enabling fast 2D/3D switchable displays and optical switches^{32–34}. Furthermore, integrating LC lenses into AR near-eye display devices has realized multi-focal plane functionality, effectively alleviating the vergence accommodation conflict.

Dielectric elastomer lenses Dielectric elastomer (DE) lenses utilize the electroactive deformation of dielectric elastomer films to adjust the lens curvature, simulating the human eye's crystalline lens accommodation. These lenses offer advantages such as large deformation, fast response, and low power consumption, making them suitable for high-performance adaptive imaging systems, as shown in Fig. 4³⁵. While liquid lenses and liquid crystal lenses offer distinct benefits such as low driving voltage and no mechanical moving parts, dielectric elastomer lenses provide unique advantages like large deformation and fast response. A detailed comparison of these three lens types is summarized in Table 1.

The core structure of a dielectric elastomer (DE) lens typically includes a DE membrane, flexible electrodes, and a transparent liquid or elastomeric medium. When a voltage is applied to the electrodes, the DE membrane undergoes area expansion and thickness reduction due to electrostatic forces, thereby altering the lens curvature and focal length. Carpi et al.³⁶ used an annular dielectric elastomer to drive an elastomeric lens, achieving a 26.4% change in focal length under a driving voltage of 3.5 kV. Niklaus et al.³⁷ separated the dielectric elastomer from the lens membrane, realizing a focal length tuning range of 4–8 mm for a liquid lens under a driving voltage of 1.7 kV. Cheng et al.³⁸ developed a

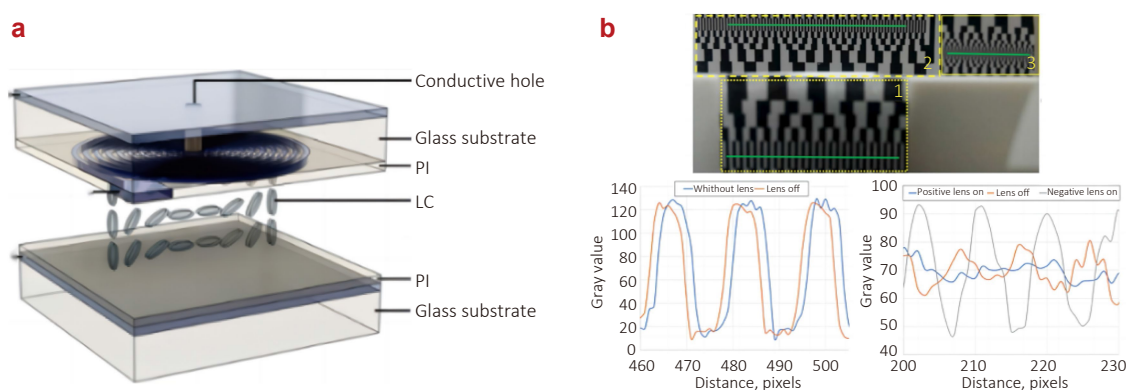


Fig. 3 | (a) Schematic presentation of tunable liquid crystal lens. (b) Preliminary quantitative analysis of image quality. Figure reproduced with permission from: ref.²⁸, Optica Publishing Group.

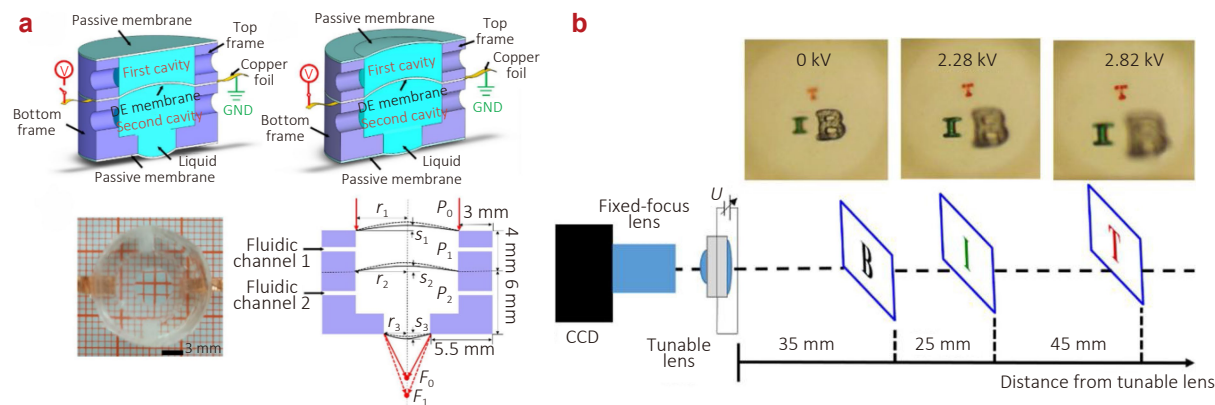


Fig. 4 | (a) Architecture of the tunable lens using dielectric elastomer. (b) Demonstration of adaptive focusing by viewing three letters placed at different distances from the tunable lens. Figure reproduced with permission from: ref.³⁵, Optica Publishing Group.

Table 1 | Comparison of key performance metrics for bioinspired adaptive imaging lenses.

Lens type	Response time	Driving voltage	Aperture size	Key advantages	Main Limitations
Liquid lens	Millisecond level	Low (typically 10–100 V)	Several millimeters	Simple structure, low power consumption, wide tunable focus range, fast response	Complex liquid encapsulation, gravity effects
Liquid C crystal lens	Milliseconds to hundreds of milliseconds	Low(a few volts to tens of volts)	Several millimeters to centimeter scale	No mechanical moving parts, array-compatible, good optical uniformity	Polarization dependence, response speed limited by liquid crystal viscosity
Dielectric elastomer lens	Sub-millisecond to millisecond level	High (typically hundreds of volts to several kV)	Several millimeters to centimeter scale	Large deformation, potential for integrated actuation and sensing, material flexibility	High driving voltage, stringent insulation and packaging requirements

dielectric elastomer lens with independent driving and optical chambers, achieving a diopter range of 15.13–22.80 D under a driving voltage of 1 kV. Zhang et al.³⁹ designed a human-eye-inspired zoom lens using an annular DE actuator. The soft lens, employing a DEA with carbon grease electrodes, achieved a maximum focal length change of 44.7% (190 mm→105 mm) under a voltage of 4.5 kV. Such adaptive lenses offer advantages like simple fabrication, low cost, and ease of operation, holding significant potential for applications in the biomedical field.

Although DE lenses currently require relatively high driving voltages, posing risks of electric shock, tissue damage, and dielectric breakdown when directly applied in in vivo or contact-based biomedical scenarios, ongoing advances in materials science, particularly the development of high-permittivity elastomer composites and ultra-thin film technologies, have progressively reduced the required driving voltage. Future research efforts will focus on establishing reliable safety barriers between kilovolt-level voltages and biological tissue tolerance, while further exploring the synthesis and application of intrinsically safe low-voltage-driven materials.

2.2 Adaptive imaging in bio-inspired compound eye systems

2.2.1 Fundamental principles and driving forces

The insect compound eye represents a quintessential multi-

aperture visual perception system composed of a large number of structurally and functionally quasi-independent ommatidia. Compared with conventional single-aperture imaging systems, compound eyes naturally exhibit several advantageous characteristics, including an ultra-FOV, strong tolerance to optical aberrations, and intrinsic parallel information acquisition capability. Owing to these features, compound eyes have long served as a major source of inspiration for the development of bio-inspired imaging systems.

Nevertheless, natural insect compound eyes are predominantly fixed-focus systems with structurally immutable configurations. Key imaging parameters, including focal length, angular sampling distribution, and spectral response, are largely determined through evolutionary processes and remain rigid once formed. While such hard-wired designs are sufficient for specific ecological niches, they inherently limit the adaptability of compound eyes when confronted with complex and dynamically changing visual environments. This constraint becomes particularly evident when translating biological compound-eye concepts into artificial imaging systems intended for engineering applications.

Early research on artificial compound eyes primarily focused on leveraging multi-channel parallel imaging to achieve ultra-wide FOV coverage. By arranging a large number of fixed-focus sub-apertures on planar or curved substrates, these systems aimed to overcome the space–bandwidth product limitation of conventional single-aperture imaging architectures^{40–42}. In this stage, the dominant

design objective was to "see wide", and significant progress was made in achieving compact, wide-angle imaging through multi-aperture configurations.

However, as application demands gradually evolved toward "seeing clearly", "seeing far", and "seeing flexibly", the limitations of fixed-focus compound-eye imaging systems became increasingly apparent. Although compound eyes inherently excel in wide FOV coverage and parallel information acquisition, most existing artificial implementations rely on rigid geometries and fixed optical parameters. Consequently, achieving a flexible trade-off among resolution, FOV coverage, and system complexity remains challenging. In dynamic imaging scenarios involving variable working distances, target scales, or illumination conditions, fixed-focus compound-eye systems often exhibit limited adaptability^{43–46}.

To compensate for such limitations, conventional approaches typically increase the number of ommatidia or employ higher-resolution sensors, which inevitably leads to a sharp rise in system complexity, data bandwidth, and computational burden. These trade-offs not only restrict real-time performance but also undermine the intrinsic advantages of compound eye architectures in compactness and efficiency. As a result, the lack of imaging adaptability has emerged as a key bottleneck hindering the broader deployment of compound-eye imaging systems in complex environments.

Against this background, adaptive imaging concepts have gradually been introduced into bioinspired compound eye research. Rather than relying solely on fixed geometrical arrangements, adaptive compound-eye imaging systems seek to dynamically regulate imaging parameters such as focal length, magnification, FOV, and imaging scale in response to changing scene requirements. This paradigm shift marks a transition from static bio-inspired replication toward functional and intelligent bio-inspired imaging.

Accordingly, compound-eye imaging research has progressively evolved from fixed-focus multi-aperture designs to architectures that incorporate tunability and

adaptive control. This evolution has given rise to several representative technical routes, including fixed-focus multi-aperture compound eyes, fixed-focus multi-scale compound eyes, and adaptive zoom compound-eye imaging systems. Together, these approaches form the foundation of modern bio-inspired adaptive compound-eye imaging research.

2.2.2 Related work on bio-inspired adaptive compound eyes

Fixed-focus multi-aperture compound-eye imaging

Fixed-focus multi-aperture compound-eye imaging represents one of the earliest and most representative paradigms in artificial compound-eye research. The core idea is to exploit a large number of sub-apertures operating in parallel to achieve wide-angle scene acquisition. These systems typically emulate the structural organization of insect compound eyes by arranging fixed-focus microlenses on planar or curved substrates, thereby breaking through the FOV and space bandwidth product limitations of conventional single-aperture imaging systems^{47–48}.

A seminal example is the TOMBO architecture proposed by Tanida et al., which realized a compact compound-eye imaging system through a microlens array combined with computational reconstruction, as shown in Fig. 5⁴⁹. Subsequent studies introduced curved compound eye geometries to further enhance FOV coverage. Jeong et al. reported a biologically inspired artificial compound eye with a hemispherical microlens array, while Song et al. demonstrated an arthropod-eye-inspired digital camera system^{50–51}. These works marked important milestones in structural biomimicry and parallel imaging.

With advances in freeform optical design and micro/nanofabrication technologies, increasingly compact and sophisticated fixed-focus multi-aperture compound-eye systems have been developed. Such systems have found applications in wide-area surveillance, target localization, and light-field acquisition. For instance, Zhang et al. constructed a biomimetic multispectral curved compound-eye camera by integrating a fixed-focus curved microlens

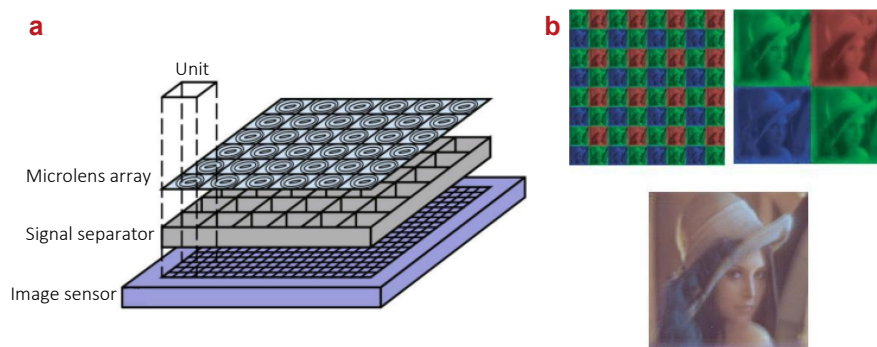


Fig. 5 | (a) Schematic structure of the TOMBO microlens array. (b) Experimental result of color imaging with the color separation by units. Figure reproduced with permission from: ref.⁴⁹, Optica Publishing Group.

array with relay optics, enabling real-time multispectral imaging over an ultra-large FOV approaching one hundred degrees⁵².

Despite these advances, the fixed focal length and immutable imaging parameters of individual ommatidia fundamentally limit the adaptability of fixed focus multi-aperture compound-eye systems. When imaging distance or resolution requirements vary, these systems typically rely on increasing the number of sub-apertures or sensor resolution to compensate for performance degradation. Such strategies significantly increase system complexity and data throughput, thereby constraining scalability and real-time performance.

Fixed-focus multi-scale compound-eye imaging To better balance wide FOV coverage and high-resolution imaging, fixed focus multi-scale compound eye imaging architectures have been proposed. These systems generally adopt hierarchical optical configurations, combining a primary objective lens with a compound eye sub-aperture array. Through coordinated operation of multiple imaging scales, global scene awareness and localized high-resolution observation can be simultaneously achieved.

Bioinspired multi-scale compound eye imaging technology was pioneered by Brady et al.⁴⁸, with the AWARE-2 multi-scale, wide-field, gigapixel compound eye camera system, published in 2012, representing one of the most representative achievements (as shown in Fig. 6). Building upon this foundation, Brady's team subsequently developed the AWARE-10 and AWARE-40 systems. The AWARE-10 architecture comprises a large spherical objective lens coupled with 382 micro-cameras, each integrated with a 14-megapixel sensor. This configuration achieves a field of view of $100^\circ \times 60^\circ$ and an instantaneous angular resolution of up to $26.3 \mu\text{rad}$, enabling ship identification with 70% accuracy at distances ranging from 4 km to 6 km. In contrast, the AWARE-40 system replaces the concentric spherical objective with a front-end collection lens designed based on a symmetric double-Gauss architecture, which then cooperates with 262 micro-cameras to form the final image. This system achieves a field of view of 36° , an instantaneous angular resolution of up to $10 \mu\text{rad}$, and a total pixel count of 2.4 billion.

In 2020, Huang et al. systematically modeled and analyzed monocentric fixed-focus multi-scale optical systems. By introducing multiple levels of sub-imaging units, they demonstrated that system resolution could be effectively enhanced without sacrificing wide FOV coverage, and compared the aberration performance of different multi-scale configurations⁵³. In such architectures, the primary imaging channel captures coarse global information, while the compound eye sub-aperture array provides spatially non-uniform resolution enhancement in regions of interest.

This concept of non-uniform resolution allocation has been widely explored in applications such as light-field imaging, microscopy, and multi-scale target perception⁵⁴. By distributing spatial resolution according to task requirements, fixed focus multi-scale compound-eye systems partially alleviate the inherent trade-off between resolution and FOV. In addition to hierarchical optical designs, alternative approaches have been proposed to improve multi-scale imaging performance by optimizing the spatial arrangement of sub-apertures. For example, irregular lens array designs have been introduced to enhance sampling coverage and imaging quality across different working distances⁵⁵.

Nevertheless, despite incorporating scale hierarchy, fixed-focus multi-scale compound-eye systems remain constrained by immutable optical parameters. The working distance and magnification of each imaging scale are fixed once fabricated, rendering these systems incapable of dynamically adapting to changes in observation distance or target scale. Consequently, their adaptability remains fundamentally limited.

Adaptive zoom compound-eye imaging Building upon fixed-focus multi-aperture and multi-scale compound-eye paradigms, adaptive zoom compound eye imaging systems introduce tunable optical elements to enable dynamic regulation of imaging parameters. By incorporating adaptive components at either the ommatidium level or the system level, these approaches significantly enhance imaging flexibility while preserving the parallel and wide-angle advantages of compound eye architectures.

One representative class of adaptive compound eye systems integrates liquid lenses or variable curvature

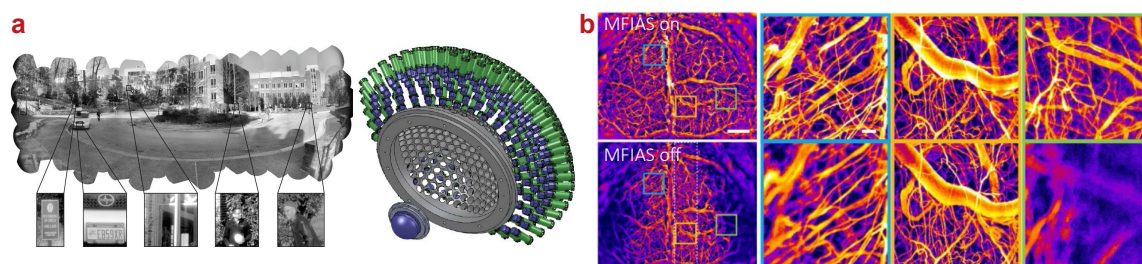


Fig. 6 | (a) System architecture of the AWARE-2 camera. (b) Traffic circle capture using AWARE-2. Figure reproduced with permission from: ref.⁴⁸, Springer Nature.

interfaces at the ommatidium level. Zhu et al. demonstrated early tunable-focus microlens arrays fabricated on curved substrates, where thermally responsive hydrogel actuators were employed to modulate interface curvature and achieve continuous focal tuning under wide-FOV conditions⁵⁶. Mishra et al. further developed optofluidic microlenses capable of independently tuning focal length and aspheric aberrations through coordinated electrostatic and hydraulic actuation, providing a versatile platform for high performance adaptive ommatidia⁵⁷.

Subsequently, stimulus responsive materials have been explored to realize environmentally adaptive compound eye systems. Ma et al. reported a smart compound-eye imaging system based on protein materials, where reversible structural deformation induced by environmental pH enabled dynamic modulation of both focal length and FOV⁵⁸. In parallel, electrowetting-based liquid lenses have emerged as a promising solution for electrically driven adaptive compound-eye imaging. Zhao et al. designed and simulated an electrowetting liquid-lens-based compound eye, achieving continuous focal tuning of individual ommatidia through voltage control⁵⁹. More recently, Zheng et al. proposed an adaptive compound eye imaging device based on an electrowetting liquid aperture with adjustable shape, enabling dynamic control over both aperture geometry and focal properties while maintaining wide-FOV imaging performance, as shown in Fig. 7⁶⁰.

Beyond ommatidium-level adaptation, system-level approaches have also been explored. By incorporating tunable relay optics or zoomable primary imaging chains, compound-eye systems can achieve continuous adjustment of overall magnification and working distance, partially mitigating mismatches between curved image surfaces and planar sensors^{61–62}. Collectively, adaptive zoom compound eye imaging technologies represent a crucial step toward intelligent, scene-aware bio-inspired imaging systems.

In addition to the artificial apposition and superposition optics discussed above, the unique visual mechanisms of

insects and marine organisms have inspired a range of advanced imaging functionalities. For instance, the compound eyes of dragonflies possess specialized neural processing pathways that enable exceptionally fast motion detection and tracking, inspiring the development of high-speed vision systems for collision avoidance in drones and autonomous vehicles. Similarly, the mantis shrimp features up to 16 different photoreceptor types, enabling unparalleled polarization and multispectral sensitivity. This has led to innovations in compact polarization imaging sensors for underwater exploration and biomedical diagnostics, as detailed further in Section 2.3.4. Furthermore, the compound eyes of lobsters, which utilize a reflective optic design based on square facets, demonstrate remarkable light collection efficiency in low-light environments. This mechanism has inspired the development of lobster-eye X-ray telescopes and wide-angle surveillance systems that require high sensitivity. Collectively, these biological paradigms demonstrate that beyond merely mimicking the eye shape, replicating the neural computation and optical physics of these species can drive breakthroughs in motion detection, polarization imaging, and low-light adaptation.

2.3 Other bioinspired adaptive imaging technologies

Beyond conventional human-eye-inspired accommodation mechanisms and insect-inspired compound-eye architectures, a rapidly growing body of research has explored adaptive imaging strategies inspired by a diverse range of non-human biological systems. In natural environments, many organisms have evolved highly specialized visual mechanisms to cope with extreme or dynamically varying conditions, including low-light habitats, underwater scattering media, large temperature gradients, strong illumination contrast, and spectrally complex surroundings. These organisms, such as birds, snakes, cephalopods, crustaceans, aquatic species, and various soft-bodied biological systems, often rely on unconventional sensing principles that extend

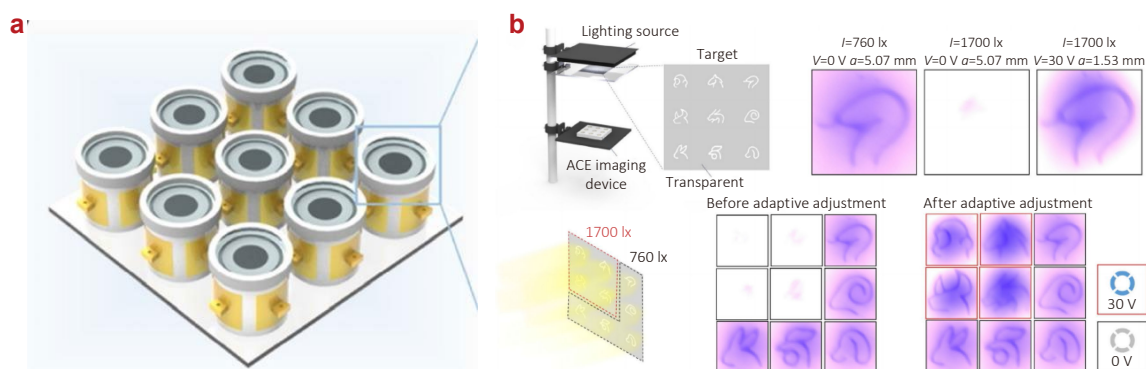


Fig. 7 | (a) Structural principle of a zoomable adaptive compound-eye imaging system based on an electrowetting liquid aperture. (b) Imaging performance of a zoomable adaptive compound-eye system in complex and non-uniform illumination scenarios. Figure reproduced with permission from: ref.⁶⁰.

beyond classical refractive image formation. Their visual performance emerges from adaptive spectral filtering, thermal radiation perception, polarization sensitivity, dynamic aperture modulation, soft-tissue deformation, and multi-modal information fusion.

In recent years, advances in optoelectronic materials, micro- and nanofabrication, metasurface optics, perovskite photodetectors, soft-matter engineering, and integrated sensing architectures have enabled researchers to translate these biological strategies into artificial imaging systems. As a result, a new class of bioinspired adaptive optical imaging technologies has emerged, characterized by tunability, reconfigurability, and strong environmental adaptability. Compared with conventional cameras, these systems significantly expand the functional boundaries of artificial vision, enabling robust imaging under complex illumination, multispectral environments, and dynamically changing scenes. This section reviews representative progress in such non-ocular bioinspired adaptive imaging technologies, organized according to biological archetypes, with emphasis on their underlying adaptive mechanisms and imaging functionalities.

2.3.1 Avian-inspired and feline-inspired adaptive optical imaging systems

Bird vision is widely recognized for its exceptional spatial acuity, rapid visual processing, and advanced spectral sensitivity. Many bird species, particularly raptors and migratory birds, possess a highly developed foveated retinal architecture in which photoreceptor density exhibits a pronounced

spatial gradient. This configuration allows birds to maintain wide-field situational awareness while achieving extremely high spatial resolution within the central visual field. In addition, avian retinas contain oil droplets embedded within cone photoreceptors, which function as natural spectral filters that enhance wavelength selectivity and color discrimination⁶³.

Inspired by these biological features, avian-inspired artificial imaging systems have focused on foveated imaging, spatially graded spectral responsivity, and multispectral adaptation. A representative example is the avian eye-inspired perovskite artificial vision system reported by Park⁶⁴, as shown in Fig. 8, which leverages the tunable bandgap, high absorption coefficient, and processability of halide perovskites. By engineering spatial gradients in material composition and device responsivity, the artificial retina exhibits a foveation-like response, where central pixels provide enhanced spatial resolution and spectral selectivity, while peripheral regions prioritize wide-field perception. This strategy mirrors the biological trade-off between resolution and field of view in avian vision.

Such foveated imaging architectures are particularly advantageous for scenarios involving fast motion or long-distance observation, where maintaining uniform high resolution across the entire field of view is inefficient and unnecessary. By dynamically allocating sensing resources, avian-inspired adaptive imagers reduce data redundancy while preserving task-relevant information. Moreover, the inherent spectral tunability of perovskite materials enables real-time adaptation of spectral response under changing

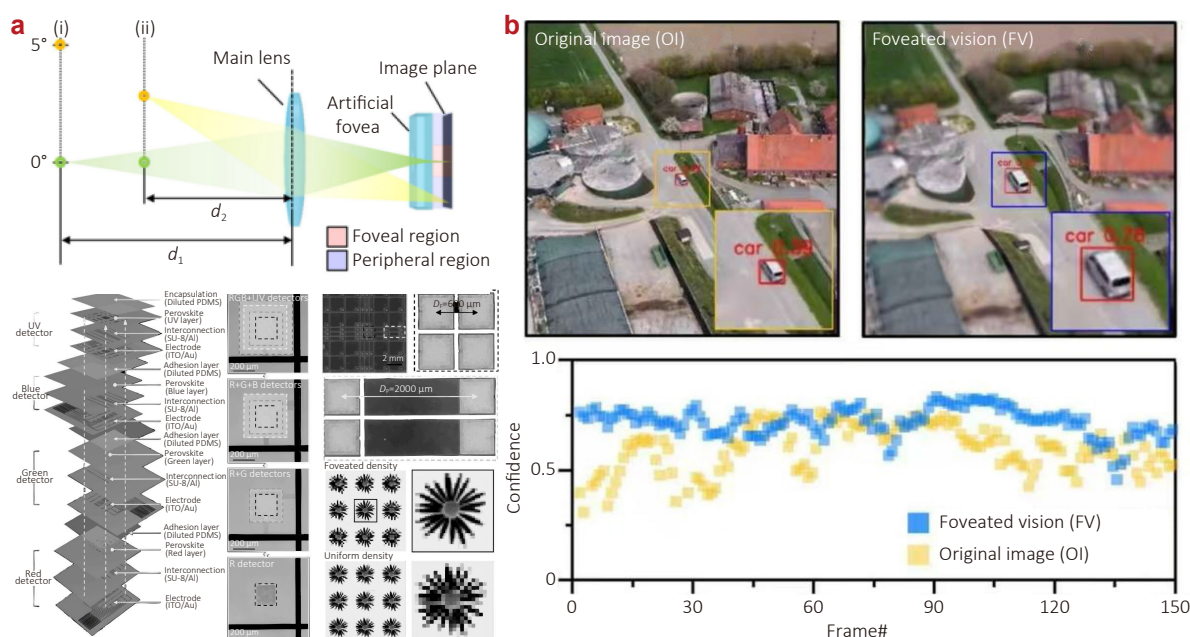


Fig. 8 | (a) Avian eye-inspired perovskite artificial vision system, comprising two parts: the artificial fovea and the vertically stacked perovskite photodetector arrays. (b) Simulation results based on YOLO v5 and scatter plot of confidence for foveated vision and original image during 150 frames. Figure reproduced with permission from: ref.⁶⁴, AAAS.

illumination conditions, analogous to the spectral filtering function of avian oil droplets.

In parallel, feline-inspired imaging systems have drawn inspiration from the cat eye's remarkable low light sensitivity. Cats possess a reflective layer known as the tapetum lucidum, which enhances photon reuse by reflecting unabsorbed light back toward the photoreceptor layer. Kim⁶⁵ translated this principle into a feline eye-inspired artificial vision system by integrating controlled reflective structures beneath the photodetector array. This design enhances signal strength under low-light conditions without saturating bright regions, thereby improving contrast and camouflage-breaking capability. Together, avian- and feline-inspired systems illustrate how spatial resolution distribution and illumination adaptation can be biologically co-optimized in artificial imaging platforms.

2.3.2 Snake-inspired thermal and multispectral imaging systems

Snakes, particularly pit vipers and related species, possess a unique sensory organ known as the pit organ, which enables detection of mid- to long-wavelength infrared radiation emitted by warm objects. Unlike conventional image-forming eyes, pit organs function as thermal sensors that map spatial temperature distributions, allowing snakes to localize prey even in complete darkness⁶⁶. This form of perception represents a fundamentally different sensory modality that complements visible-light vision.

Snake-inspired artificial imaging systems have therefore focused on extending spectral sensitivity beyond the visible range through thermal sensing and multispectral fusion. A key technological approach involves infrared-to-visible upconversion, in which long-wavelength infrared radiation is converted into shorter-wavelength photons detectable by silicon-based image sensors. Mu⁶⁷ demonstrated a snakes-inspired artificial vision system by integrating infrared upconversion materials directly with CMOS sensors, enabling visualization of thermal information using conventio-

nal imaging hardware. This strategy avoids the need for bulky or cryogenically cooled infrared detectors, significantly reducing system size and complexity, as shown in Fig. 9.

Beyond standalone thermal imaging, several studies have explored the fusion of infrared and visible-light information to enhance scene understanding. Such multispectral fusion enables simultaneous acquisition of temperature distributions, object contours, and visible textures, providing richer environmental information than either modality alone. This approach closely parallels the complementary roles of pit organs and eyes in snakes, which together support robust perception across a wide range of lighting conditions. Snake-inspired thermal imaging systems have shown strong potential for applications in night vision, surveillance, medical diagnostics, search-and-rescue operations, and environmental monitoring^{67–68}.

2.3.3 Cephalopod-inspired and arthropod-inspired illumination-adaptive imaging

Cephalopods, including cuttlefish, squids, and octopuses, exhibit some of the most unusual visual adaptations in the animal kingdom. One of their most distinctive features is the presence of non-circular pupil geometries, such as W-shaped or U-shaped apertures. These pupil shapes allow cephalopods to dynamically regulate the spatial distribution of incoming light, equalize brightness across the visual field, and reduce chromatic aberrations under highly non-uniform illumination⁶⁹.

Cephalopod-inspired artificial imaging systems seek to replicate these functions through dynamic aperture modulation and illumination-adaptive optics. Kim⁷⁰ reported a cuttlefish eye-inspired artificial vision system that employs programmable optical modulation to redistribute luminance across the image plane, enabling high-quality imaging under uneven illumination. The critical advantage of the bio-inspired W-shaped pupil is compellingly demonstrated in Fig. 10⁷⁰. Under a challenging, vertically uneven illumination condition (inset), the system with a conventional

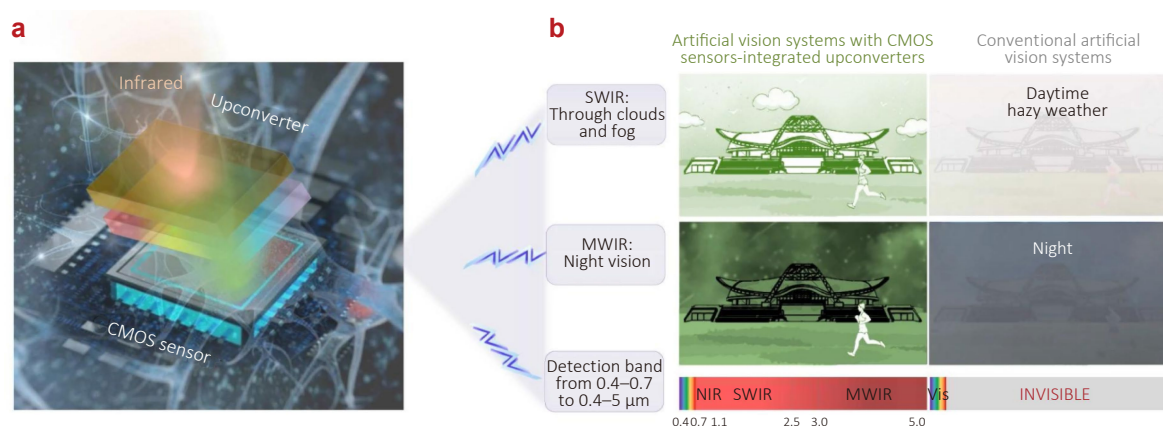


Fig. 9 | (a) Artificial vision systems for ultra-high-resolution infrared imaging. (b) Imaging comparison diagram of artificial vision systems with CMOS sensors-integrated upconverters and conventional ones. Figure reproduced with permission from: ref.⁶⁷, AAAS.

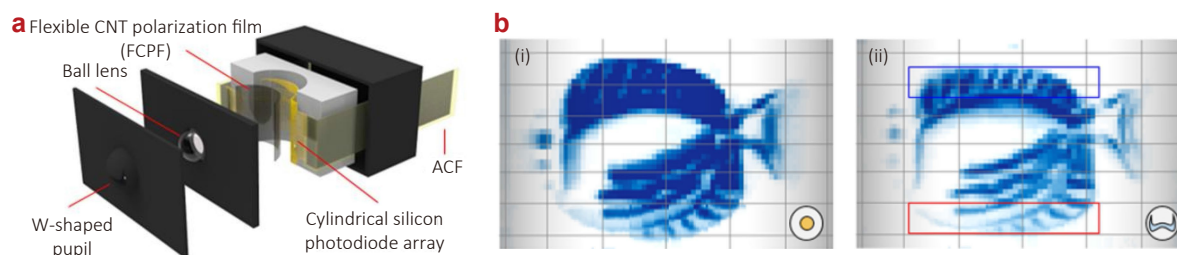


Fig. 10 | (a) All components of the cuttlefish eye-inspired artificial vision system. (b) The imaging results of the fish-shaped object by this system under vertically uneven illumination. Figure reproduced with permission from: ref.⁷⁰, AAAS.

circular pupil yields an image with a strong, obscuring brightness gradient. In stark contrast, when switched to the W-shaped pupil mode, the same system produces a dramatically improved image where the luminance is effectively equalized, revealing clear and consistent detail across the entire fish-shaped object. Magnified views further confirm the recovery of fine features in both bright and dark regions. This active, optical-level compensation allows the system to achieve robust performance in high-dynamic-range environments without relying solely on post-processing algorithms.

Arthropods, particularly jumping spiders, provide additional inspiration for illumination- and depth-adaptive imaging. Jumping spiders possess multilayered retinas that encode depth information through wavelength-dependent defocus. Guo⁷¹ translated this mechanism into a spider-inspired metalens depth sensor, in which wavelength-dependent focal shifts enable single-shot depth reconstruction without mechanical scanning. Similarly, insect stereopsis-inspired systems have demonstrated multifunctional imaging capabilities by exploiting angular and spectral diversity at the optical level⁷².

Together, cephalopod-inspired and arthropod-inspired systems demonstrate that illumination adaptation and depth perception can be achieved through unconventional optical geometries and bioinspired encoding strategies, offering alternatives to traditional exposure control and multi-frame imaging techniques.

2.3.4 Crustacean and mantis shrimp-inspired polarization and multispectral imaging

Among marine organisms, crustaceans are renowned for possessing one of the most complex visual systems known. Mantis shrimp eyes contain numerous spectral channels and exhibit extraordinary sensitivity to both linear and circular polarization. This capability allows them to detect subtle optical signatures in underwater environments, where scattering and polarization effects strongly influence visual perception⁷³.

Inspired by these biological systems, mantis shrimp-inspired artificial imaging technologies have focused on polarization-sensitive and multispectral detection. Altaqui⁷⁴ demonstrated a polarization and spectrum sensitive organic

photodetector by vertically stacking anisotropic absorbing layers with distinct optical responses. This architecture enables simultaneous acquisition of spectral and polarization information at the pixel level without bulky external optics. Figure 11⁷⁴ vividly demonstrates the ability of such a system's structure to perform combined spectral and polarization imaging.

Such systems enable high dimensional optical sensing, in which intensity, wavelength, and polarization state are encoded within a single exposure. This approach enhances contrast, enables material discrimination, and reduces system complexity. The biological analogy lies in the mantis shrimp's ability to extract complex optical information with minimal neural computation, suggesting that hardware-level encoding can simplify downstream processing. Polarization-sensitive bioinspired imaging systems are particularly promising for underwater exploration, remote sensing, biomedical imaging, and machine vision.

2.3.5 Soft-bodied organism-inspired optofluidic and deformable optical systems

Many biological organisms rely on soft tissues and fluidic structures to modulate their optical properties. Examples include red blood cells, soft ocular tissues, and deformable membranes, whose curvature, thickness, and refractive index can change continuously in response to environmental stimuli. These mechanisms have inspired a class of optofluidic and soft-material-based adaptive optical systems.

One of the earliest demonstrations is the red-blood-cell-based adaptive microlens reported by Miccio⁷⁵, which exploits the biconcave geometry and membrane elasticity of red blood cells to achieve tunable focusing through osmotic or mechanical stimulation. Unlike conventional mechanically actuated lenses, this approach offers smooth, continuous focal tuning, intrinsic shock resistance, and extremely low energy consumption.

Building upon this concept, researchers have developed adaptive lenses based on hydrogels, elastomers, and photoresponsive polymers. Zheng reported a bioinspired photoresponsive soft robotic lens capable of reversible curvature modulation under optical stimulation⁷⁶. In parallel, electronically tunable perovskite-based curved image sensors have demonstrated focus adjustment without

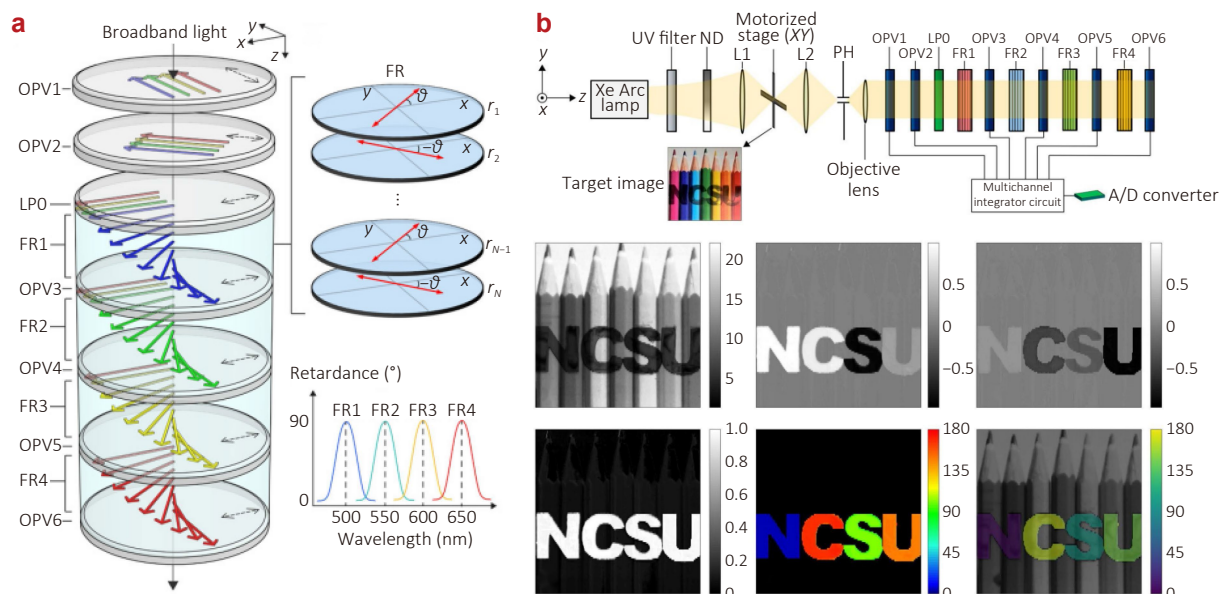


Fig. 11 | (a) Structure of the SIMPOL sensor. (b) SIMPOL imaging setup and polarization imaging. Figure reproduced with permission from: ref.⁷⁴, AAAS.

mechanical motion⁷⁷. These soft and material-driven adaptive optics are particularly attractive for wearable imaging devices, bio-integrated sensors, soft robotics, and curved imaging surfaces.

In summary, bioinspired adaptive imaging technologies have expanded far beyond traditional eye-mimetic paradigms by drawing inspiration from a wide range of non-human biological systems. Avian- and feline-inspired foveated and low-light imaging, snake-inspired thermal perception, cephalopod-inspired dynamic aperture control, mantis shrimp-inspired polarization and multispectral sensing, and soft-bodied organism-inspired deformable optics collectively demonstrate the immense potential of biological strategies for advancing artificial vision. By integrating adaptive functionality at the material, device, and system levels, these technologies enable imaging capabilities that are difficult or impossible to achieve using conventional optical designs. As biological insight continues to merge with emerging photonic and optoelectronic technologies, bioinspired adaptive imaging systems are poised to play a central role in next-generation intelligent vision platforms.

3 Future perspectives

Bioinspired adaptive optical imaging technology, spanning systems inspired by the human eye, compound eyes, and other specialized biological visual models, has demonstrated remarkable functional diversity and potential. However, as the field transitions from proof-of-concept demonstrations toward practical, high-performance applications, several convergent limitations and profound challenges have emerged, defining the critical frontiers for future research and development.

3.1 Limitations of current bioinspired adaptive optical imaging technology

Despite the diverse biomimetic inspirations, current adaptive optical imaging technologies face a convergent set of fundamental limitations that hinder their transition from laboratory prototypes to robust, deployable systems. A primary and pervasive constraint is the limited multi-parameter adaptability at the basic functional unit level, whether it is an ommatidium or a synthetic pupil-lens system. Most existing implementations excel in tuning a single parameter, such as focal length via liquid or liquid crystal lenses, or aperture size via electrowetting iris devices. However, they lack the capability for synergistic, real-time coordination between focus, aperture geometry, and dynamic aberration correction. This deficiency restricts a system's overall adaptability under real-world conditions featuring complex depth variations, non-uniform illumination, and high-contrast scenes, as it cannot holistically optimize the optical path like its biological counterparts^{78–80}.

At the system integration level, significant bottlenecks arise in scalability, consistency, and reliability. Translating a single, high-performance adaptive optical element into a functional array proves extremely challenging. Fabricating and integrating tens to hundreds of these elements, especially on curved substrates, introduces performance variability. This leads to inter-channel non-uniformity, optical crosstalk, and degraded image fidelity. Furthermore, systems that employ soft materials, optofluidic elements, or delicate microstructures are plagued by long-term reliability issues. Material degradation under thermal cycling, prolonged illumination, or environmental exposure, along with phenomena like fluid evaporation in liquid lenses, dielectric

breakdown, or mechanical fatigue in elastomers, causes optical performance drift and compromises operational stability, posing a major obstacle to practical, long-term deployment^{81–82}.

Underlying many device-level limitations are unresolved physical and material trade-offs. A fundamental tension exists between adaptive response speed and power consumption. While technologies like electrowetting offer millisecond-scale responses, this speed is often insufficient for high-speed perception tasks and comes with the cost of continuous electrical driving, which exacerbates power consumption and limits autonomous operation^{19,83}. Similarly, achieving a large optical tuning range frequently conflicts with desires for low operating voltage, large aperture size, or compact form factor. Consequently, many systems must rely heavily on complex backend computational algorithms to calibrate non-uniformities, correct aberrations, and reconstruct images. This dependence on post-processing negates the inherent advantages of bio-inspired architectures, such as parallel processing, true real-time performance, and system simplicity, ultimately creating a processing bottleneck.

3.2 Challenges of bio-inspired adaptive optical imaging technology

Addressing the current limitations demands coordinated advances across multiple disciplines, presenting a series of interconnected and formidable challenges. The foremost paradigm shift required is the transition from centralized, globally controlled systems to intelligent, distributed, and locally adaptive architectures. The future vision involves imaging arrays where individual pixels or ommatidia can independently sense local visual information, such as light intensity, contrast, or spectral content, and dynamically adjust their optical parameters through integrated, low-power actuation. Realizing this demands breakthroughs in on-chip control electronics, efficient closed-loop feedback mechanisms, and algorithms that can manage distributed autonomy without introducing instability or excessive computational overhead. Closely linked is the challenge of hardware and algorithm co-design, specifically moving towards "in-sensor" or near-sensor computing. The goal is to design optoelectronic materials and device architectures whose native response performs initial signal processing at the point of detection, drastically reducing data throughput and power consumption and reducing the reliance on bulky backend processing.

Expanding the functional boundaries of adaptation itself constitutes another critical challenge. While current research focuses on intensity and focal adjustment, the next frontier involves mimicking the spectral and multimodal adaptability found in nature. This includes developing systems that can dynamically adjust their spectral responsivity across a broad range for different environments, and creating truly

multifunctional platforms that seamlessly combine imaging, ranging, and motion detection within a single integrated system. Achieving such advanced functionalities in a compact, fast, and energy-efficient manner requires pioneering work in novel active materials, such as dynamically tunable metamaterials or nanostructures, and their seamless integration with adaptive optical elements⁸⁴. The core technical hurdle here is developing optoelectronic materials that combine broad, tunable spectral responsivity with environmental stability, low noise, and fabrication compatibility.

Ultimately, perhaps the most pressing practical challenge lies in overcoming the manufacturing and integration hurdles for scalability. For these bio-inspired technologies to move beyond proof-of-concept demonstrations, scalable, high-yield, and cost-effective fabrication processes must be developed. This is particularly acute for creating high-density, heterogeneously integrated systems on curved substrates, which involve the precise assembly of adaptive optical elements, transparent electrodes, driving circuits, and sensors without compromising geometric or optical precision. Similarly, for soft and optofluidic systems, the challenge of reliable encapsulation and packaging to ensure long-term robustness against environmental variability remains largely unsolved. Concurrently, there is a need to establish universal design and control paradigms that can manage the inherent complexities, such as material hysteresis, non-linear responses, and dynamic coupling between optical and mechanical domains, to ensure predictable, reproducible, and large-scale system performance. Only by making synergistic progress on these device-, material-, and system-level challenges can bio-inspired adaptive imaging fully realize its potential for intelligent perception in complex, dynamic environments.

3.3 Perspective of bioinspired adaptive optical imaging technology

Bioinspired adaptive optical imaging technology has entered a critical stage of transition from proof-of-concept demonstrations toward system-level integration and practical deployment. While substantial progress has been achieved in mimicking biological strategies, such as spectral adaptation, multimodal perception, and morphology-driven optical tuning, current systems still face limitations in scalability, stability, and integration density⁸⁵. From a broader perspective, future advances in this field will increasingly rely on synergistic developments across optical design, functional materials, device architectures, and computational paradigms, rather than isolated imitation of individual biological features, as illustrated in Fig. 12.

3.3.1 Metasurface-enabled integration and functional densification

One of the most promising technological pathways for

advancing bioinspired adaptive optical imaging lies in the adoption of metasurface-based optical components. Metasurfaces provide unprecedented control over optical wavefronts within subwavelength thicknesses, enabling compact realization of functions that traditionally require bulky refractive or diffractive optics⁸⁴. Such capability is especially valuable for bioinspired systems that demand simultaneous control over multiple optical degrees of freedom, such as wavelength, polarization, phase, and angular response.

In the context of biologically inspired imaging, metasurfaces offer a natural platform for implementing spatially varying optical responses analogous to avian foveated vision, cephalopod-inspired luminance redistribution, and crustacean polarization sensitivity, while maintaining compact form factors and high integrability. Moreover, reconfigurable metasurfaces incorporating phase-change materials, electro-optic modulation, or flexible substrates are expected to enable dynamic optical adaptation without mechanical motion⁸⁶. Such developments can significantly enhance system robustness while reducing alignment complexity and overall instrument form factor.

3.3.2 Advanced optoelectronic materials and heterogeneous integration

Material innovation remains a fundamental driver of progress in bioinspired adaptive imaging. Emerging optoelectronic materials can offer tunable spectral responsivity, high sensitivity, and compatibility with unconventional form factors⁸⁵. These properties are particularly well suited for replicating graded spectral sensitivity observed in avian and feline visual systems, as well as the broadband and polarization-sensitive detection found in aquatic and crustacean species.

Looking ahead, heterogeneous integration strategies that combine multiple material systems within a single sensing platform are expected to play an increasingly important role. Vertical stacking or lateral integration of photodetectors with complementary spectral, polarization, or temporal responses can enable compact multimodal imaging without reliance on external optical assemblies. Such material-level integration also helps mitigate alignment tolerances and improves system stability for real-world deployment.

3.3.3 Transition from mechanical actuation to electronic and material-driven adaptation

Another defining trend in the evolution of bioinspired adaptive optical imaging is the gradual replacement of mechanically actuated components with electronically or materially driven adaptive mechanisms. In biological systems, optical adaptation is typically achieved through tissue deformation, refractive index modulation, or neural control rather than discrete mechanical motion. Translating these principles into artificial systems enables faster response times, lower power consumption, and enhanced durability.

Electronic focusing through carrier redistribution, electrically tunable refractive indices, or phase-transition-based modulation offers a pathway toward inertia-free focal adjustment⁸⁵. Meanwhile, optofluidic and soft-material-based optics inspired by red blood cells and soft-bodied organisms provide continuous and reversible shape modulation with minimal energy input. These approaches are particularly attractive for applications requiring long-term operation, miniaturization, or deployment in mechanically demanding environments.

3.3.4 Convergence of adaptive optics and neuromorphic vision architectures

From a system-level perspective, the long-term trajectory of bioinspired adaptive optical imaging extends beyond optical adaptation alone toward the integration of sensing and computation. Biological vision systems perform substantial preprocessing at the photoreceptor level, enabling efficient extraction of relevant features before higher-level neural processing. Inspired by this paradigm, emerging artificial systems increasingly emphasize in-sensor adaptation and neuromorphic architectures, which integrate memory, computation, and sensing functions to reduce data redundancy and energy consumption.

By embedding adaptive responsivity, temporal dynamics, and selective sensitivity directly into photodetector arrays, future bioinspired imaging systems can reduce data transmission bottlenecks and enhance real-time perception while operating efficiently in complex environments. This convergence of adaptive optics with neuromorphic processing supports a fundamental shift from passive imaging toward intelligent, context-aware sensing units capable of operating efficiently in autonomous systems, robotics, biomedical imaging, and environmental monitoring.

In summary, the perspective of bioinspired adaptive optical imaging technology is shaped by a clear movement toward high integration, material-structure co-design, and sensor-level intelligence. Advances in metasurfaces, functional optoelectronic materials, soft adaptive optics, and neuromorphic integration collectively provide the technological foundation for next-generation bioinspired vision systems. As these elements continue to mature and converge, bioinspired adaptive imaging is expected to play an increasingly central role in applications ranging from autonomous systems and robotics to biomedical imaging and environmental sensing.

4 Conclusions

Bioinspired adaptive optical imaging represents a transformative paradigm, shifting from static, rigid designs to dynamic, environmentally responsive systems. As this review has detailed, significant progress has been achieved along two major fronts: human-eye-inspired systems that

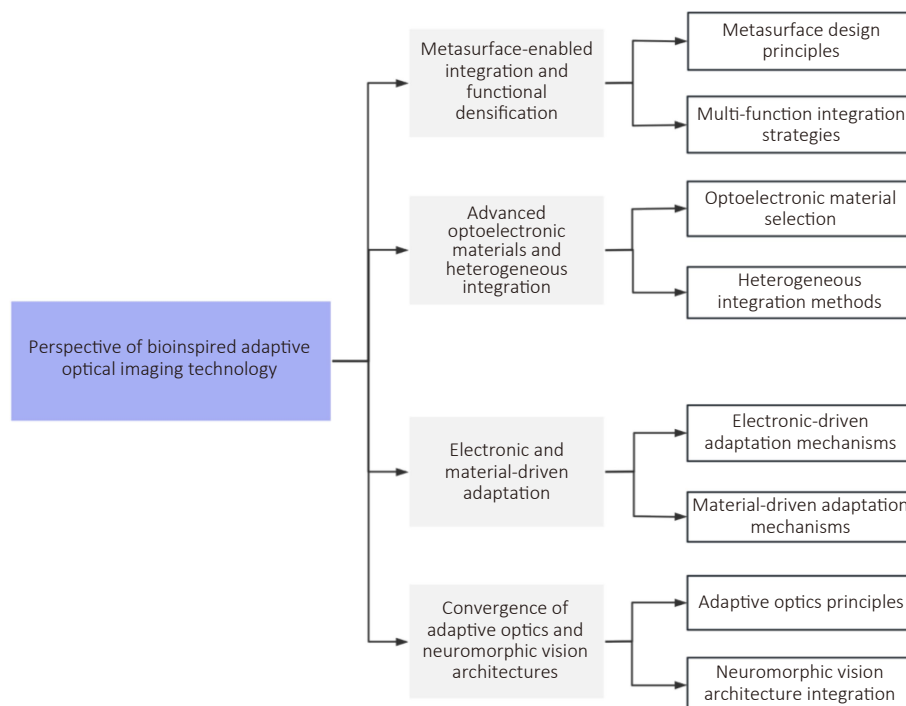


Fig. 12 | Perspective of bioinspired adaptive optical imaging technology.

replicate accommodation and pupil control for high-resolution focusing, and compound-eye-inspired architectures that deliver ultra-wide fields of view with emergent adaptive zoom capabilities. Complementary advances, drawing inspiration from avian, feline, snake, cephalopod, and mantis shrimp vision, have further expanded the functional repertoire to include foveated imaging, low-light enhancement, thermal perception, polarization sensitivity, and multispectral adaptation. However, the path toward robust, deployable systems is hindered by convergent limitations. These include the restricted multi-parameter adaptability of fundamental units, scalability and reliability challenges in array integration, and unresolved trade-offs between response speed, power consumption, and tuning range. Overcoming these barriers necessitates a fundamental shift toward distributed, intelligent architectures with local sensor-level adaptation and a tighter co-design of hardware and algorithms.

In conclusion, through sustained interdisciplinary synergy, bioinspired adaptive optical imaging is poised to catalyze next-generation visual systems. These systems will offer unparalleled adaptability, efficiency, and functionality, finding indispensable roles in autonomous robotics, advanced biomedical diagnostics, wearable technology, and beyond.

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Author contributions

C.L., and Q.H.W conceived the idea and guided the project. D.J.S., Z.J.Z., Y.Z., and Z.Z.L. wrote and edited the article.

Competing interests

The authors declare no competing financial interests.



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