BIOMIMETICS

Avian eye–inspired artificial vision takes a step forward

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Bioinspiration from avian eyes allows development of artificial vision systems with foveated and multispectral imaging.

For most animals on Earth, eyes are one of their most vital sensory organs. For humans, our ability to see a rich and colorful environment stems from our visual system's capability to optically perceive and image the surrounding environment. Similarly, artificial vision systems play a pivotal role in robotics, allowing them to detect and identify their surrounding objects efficiently. Thanks to the technological advances in artificial vision systems, mobile robots—such as uncrewed aerial vehicles, humanoid robots, and autonomous vehicles—have been improving rapidly in recent years, holding promising potential to increasingly influence our lifestyles with their enhanced capabilities (*1*). However, grand challenges still remain and need to be addressed to fully unlock capabilities of robotic vision. For instance, conventional imaging devices consist of complex, bulky optical systems and inefficient data processing modules, which may not be sufficient to meet the dynamic, high-performance, and miniaturization requirements of robot vision systems (*2*). How can we effectively address these challenges?

Turning to natural vision systems, which have evolved over hundreds of millions of years, we can find a variety of animal eyes that are well adapted to diverse environmental conditions. These biological eyes mostly surpass conventional artificial imaging systems in both performance and simplicity, thereby offering rich inspiration for technological advancements. Over the past two decades, there have been many artificial vision systems developed that mimic the remarkable architecture of animal eyes, particularly chambered or compound eyes (*3*). For instance, the human eye, with its single chamber in a spherical shape that efficiently captures light to form images, has inspired the development of artificial vision systems for high-quality, low-distortion imaging using just a single lens (*4*). Otherwise, the compound eyes of insects, made up of thousands of ommatidia, provide a wide field of view and nearly infinite depth of field, influencing the design of artificial vision systems that surpass traditional cameras in these aspects (*5*). In addition, the fascinating eye architectures of a few other creatures—such as the monocentric lens structure of fish eyes, ellipsoidal eye structure of fiddler crabs, and strongly curved eye structure found in extinct trilobites—have also inspired investigation of artificial vision systems (*6*, *7*). Despite these important advances, the remarkable perception and imaging capabilities of birds—pinpoint accuracy in focusing on distant objects, highly sensitive detection of moving targets, and multispectral imaging—remain underexplored. Notably, these attributes are essential to mobile robotics, especially uncrewed aerial systems.

In their recent paper, Park *et al.* (*8*) demonstrated an avian eye–inspired perovskite artificial vision system for foveated and multispectral imaging. This system, which mimics both the structural and functional features of avian eyes (Fig. 1A), was constructed with an artificial fovea and vertically stacked perovskite photodetector arrays. Remarkably, this system was sensitive to a variety of spectral ranges, facilitating the detection of both visible [red, green, blue (RGB)] and ultraviolet (UV) light and eliminating the need for color filters. It could also provide a magnified focusing view akin to foveated imaging found in nature, thereby offering an enhanced ability to detect distant objects.

The artificial fovea reported by Park *et al.* (*8*) was developed by replicating the natural fovea of avian eyes. Strategically designed with a Gaussian profile, it achieved continuous magnification without blind spots or image overlap. This elaborate design not only enhances the practicality and reliability of the artificial fovea but also facilitates its seamless integration with existing optical systems, marking a notable step forward in foveal imaging technology. Moreover, by mimicking the avian vision's geometric foveal slope, the artificial fovea could focus on objects across different distances, with a central region for distant focus and a peripheral area for closer observation (Fig. 1B). As a consequence, this artificial fovea substantially enhanced motion detection capability by more than 3.6-fold and increased the object detection confidence score from 0.39 to 0.76.

Multispectral imaging represents another attractive feature of avian vision systems. To achieve this capability, conventional imaging devices usually exploit filters to capture RGB colors, but this method can sometimes introduce artifacts such as moiré patterns and jaggies (*9*). Although numerical algorithms can reduce these artifacts, the need to categorize the pixel array into different colors limits the pixel density. To circumvent this issue, Park and colleagues (*8*) have proposed the architecture of vertically stacked arrays of R, G, B, and UV perovskite photodetectors to allow selective absorption of specific wavelengths of light without color filters (Fig. 1C). This multispectral imaging technique enabled precise color matching between the reconstructed images and the original colors captured by iPhone 14 cameras.

The development of avian eye–inspired artificial vision marks a notable step toward replicating the intricate capabilities of natural sight in robotics, holding promising applications in uncrewed aerial vehicles and autonomous driving. Rich opportunities still exist in this inspiring area of robotic vision. For instance, future studies could follow by integrating metalenses (*10*) for lighter systems with higher degrees of integration; enhancing multispectral capabilities by broadening the spectral range from UV to infrared and

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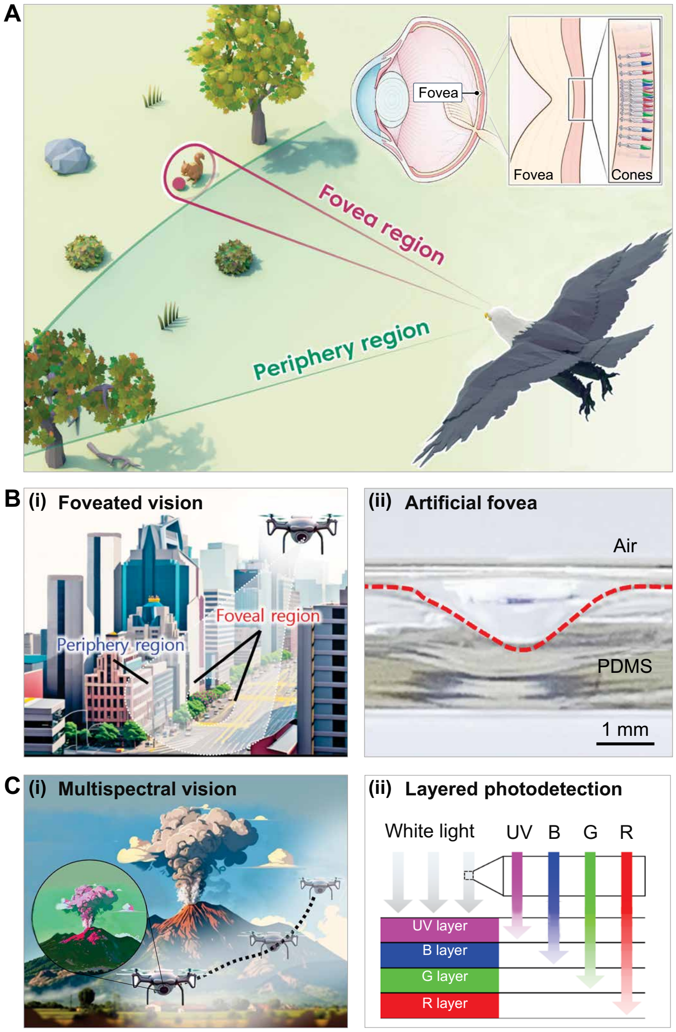

Fig. 1. Features of avian eyes and avian eye–inspired perovskite artificial vision. (**A**) Schematic illustration showing the visual ecology of birds and a magnified view of the deep fovea in the retina, where four types of cone cells are spaced at varying intervals beneath it. (**B**) Schematic and characteristics of the foveated vision of the artificial vision system: (i) schematic illustration showing the foveated vision of artificial vision system, where the image is magnified and focused in the foveal region, and the periphery region can also be perceived with low resolution; (ii) optical image of a cross-sectional view of the artificial fovea. (**C**) Schematic and characteristics of the multispectral vision of the artificial vision system: (i) schematic of the artificial vision system for uses in an uncrewed aerial vehicle and (ii) principle of vertically stacked perovskite photodetection devices enabling color detection without color filters.

beyond; combining features from various biological eyes to create electronic eyes with multifunctional capabilities; and improving the manufacturing process to achieve enhanced device stability and increased resolution. The quest for enhanced robotic vision not only promises to transform our interactions with machines but also to deepen our understanding of the natural mechanisms of vision.

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