Bioinspired Imaging: Discovery, Emulation, and Future Prospects

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I. INTRODUCTION

Should research and development efforts in imaging technology pay special attention to biology for inspiration? An affirmative answer would have to contend with the obvious technical ascendancy of modern medical imaging systems, such as computer-assisted tomography, or magnetic resonance imagery, not to mention the pace of innovation in the ubiquitous cell phone camera, none of which can be called "bioinspired." Laser-based devices, such as two-photon microscopy, have revolutionized imaging in neurobiology, but owe their fundamentals to discoveries in physics. Satellite imaging systems commonly exploit hyperspectral approaches, which run counter to almost anything found in biology.

This Special Issue on Bioinspired Imaging highlights progress and continuing efforts in the domain of vision and biological optics.

On the other side of the ledger, discoveries in biological research continually bring to light an astonishing array of specialized sensory systems that animals use to scan the natural environment, or to control their own visibility. Even seemingly unrelated work in molecular genetics can have unpredictable extensions into imaging technology. To cite one salient example, the discovery of how to use microbial opsin genes to genetically sensitize neurons to infrared light has led to what the journal *Science* has called an "Insight of the Decade" [1]. Its subsequent use in optogenetic imaging earned the title, "Breakthrough of the Year," according to the journal *Nature Methods* in 2010. Optogenetics combines laser technology with newly developed techniques for the control of fluorescence in light-sensitive proteins. It enables high spatial and temporal resolution in imaging live neural tissue, as well as selective optical control of neural activity [2].

Because transformative developments often arise where they are least expected, it would be rash to speculate about where, in the fast-changing arena of biological research, the next insight or breakthrough will be found with high potential for "bioinspired" or "bioenabled" advances in imaging technology. (We do not pretend that these are pure categories.) Nonetheless, it is difficult to ignore the growing general interest in the potential for biological insights to transform various technical endeavors. The past few decades attest to the growth of academic disciplines and research specialties such as biomedical engineering, robotics, neuromorphic systems design, biomaterials, and biofabrication, all of which express confidence in the transformative role of biology as a key partner for interdisciplinary progress. The wide scope of these activities can be seen in various

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conferences and workshops, such as the annual National Science Foundation (NSF)-supported Neuromorphic Engineering Workshop, founded in pursuit of Carver Mead's original vision [3], and in new journals and books such as the multivolume series being published by CRC Press, and by Springer.

The narrower backdrop for several papers in this Proceedings of the IEEE is a focus on how animals make use of sensory information. The biological world crafts remarkable solutions to an amazing range of sensing and imaging problems. We find these capabilities intriguing for their stark contrast with human experience. We cannot easily guess how a fish parses its neighborhood using electroreception, nor even readily imagine that it does. We have intuitive difficulty with the idea that a magnetic sense might be combined with photoreception, yet this now seems a strong hypothesis in the case of some long-distance navigators. Polarized light is especially useful for many animals that are equipped to decipher the natural world's Stokes vectors, but how they do it remains largely a mystery. Biological systems that process visual information are as varied and unpredictably complex as their long histories of evolutionary development. If there is one constant reminder in the wide range of new work on biological sensory systems, it is that our familiar, human capabilities—our Aristotelian five senses—prepare us little to anticipate what a study of other sensory systems could reveal.

This Special Issue on Bioinspired Imaging highlights progress and continuing efforts in the domain of vision and biological optics. We present a selection of papers tied together only by their prospects and provocations for technical innovation. All have a link to biology, though the prominence of that connection was not our only consideration in inviting authors to write for this Proceedings volume. Given the breadth of our topic, we sought a wide array of viewpoints. Although the term "breakthrough" is apt for some of this work, many important and useful ideas for the technical community derive equally from steady, incremental efforts. Several papers presented here are prime examples for the benefits of long-term collaboration across multiple disciplines. Indeed, we deliberately sought authors whose work exemplified constructive synergy at the interface between biology and engineering.

Whether we expect a technical innovation to come from incremental study or from sudden insight, we are accustomed to the idea that biosystems can provide clues to innovation. Indeed, there are abundant examples where natural systems, in specific contexts, can outperform human inventions. A bat's morphing wing enables maneuvers that are still impossible for any airborne device. A tiny parasitic fly, whose acoustic receptor is as small as a pencil point, can localize sound sources with a precision equivalent to widely spaced microphones [4]. In the optical domain, animals have developed infrared sensing without need for special cooling. Three beetle species, each relying on its own, distinct sensing mechanism, can detect infrared signals over distances large enough to challenge our best technical devices [5]. And a lowly, bottom-dwelling aquatic animal, the stomatopod crustacean, offers, in its photoreceptors, a unique optical plan for an achromatic quarter-wave retarder [6], [7].

Research into examples such as these rarely confirms anyone's first guess about how these various sensing behaviors are enabled. Surprises are the rule, not the exception. Such examples also remind us that sources of bioinspiration are not confined to any single research area. In a living world bursting with variety and complexity, there is no formula for finding the most useful ideas for technical invention. Famously, they can arise even from errors or inattention in the laboratory. We might also contend that the most important part of "bioinspired" is the inspiration. Charles S. "Doc" Draper's invention of the inertial guidance system for ships and airplanes illustrates this point. The device has long been thought to emulate a neural system in the mammalian inner ear, the three semicircular canals, which were assumed to register accelerative forces in all three (x, y, z) directions. Only recently has it come to light that the human sense of spatial orientation normally relies on a default setting, 1g, rather than a continuous sensory measurement of the gravitoinertial force component in the z-direction. [8]. Incomplete knowledge of the biological system, in this case, was no impediment to Draper's inventive genius.

As Guest Editors for this Special Proceedings Issue, we tried deliberately to select representative work that explores biological foundations as well as work that provokes, proposes, or demonstrates bioinspired technical emulations. We are deeply grateful to the authors, especially for their effort to make their topics accessible to a broad technical audience, and to expose, whenever possible, their ideas for new transformative directions in their research. Papers in this volume reflect an intentionally expansive construal of the term "bioinspired." The only commonality among them may be the linkage they exhibit between the study of how a natural system operates, and an attempt to derive from biology an idea, or a process of possible use within the broad domain of sensing and representing the optical environment.

II. NATURAL SYSTEMS DIVERGE FROM ENGINEERING PRACTICE

Much current interest in natural biological systems stems from a realization that what often underpins their ecological success is a form of neural information processing that bears little resemblance to standard engineering practice, but endows the animal with robust, fault-tolerant capacities: "In stark contrast to human engineered information processing and computation devices, biological neural systems rely on a large number of relatively simple, slow, and noisy processing elements and obtain performance and robustness from a massively parallel principle of operation and a high level of redundancy where the failure of single elements usually does not induce any observable system performance degradation'' (Posch *et al.*, in this issue). There are ongoing projects to emulate such features in general-purpose computing hardware [9].

Also, few biosensors can measure absolute physical magnitudes: Commonly, they are tuned only to changes or to rates of change. As input variations decline, so does their responsiveness—or, to use the terms of some of our authors, biosensing tends to be "event driven." Orthogonal filtering architectures, so prevalent in engineering practice, are the exception, because each organism's requirements for sensing must answer to its primary modes of action [10]. Some biosensors embrace noise and redundancy, rather than suppress them. Although textbooks segregate their chapters on distinct sensory modalities, such as photoreception, mechanoreception, chemoreception, etc., there is growing evidence that many of the smallest animal brains immediately integrate, or fuse distinct channels of information. Moths, for example, apparently mix receptor inputs for odor concentration, wind velocity, and optic flow to guide their plume-tracking flight. Whether they do this to develop an image or some other representation of their environment, we can only speculate. A moth may not need to engage in imaging, as we understand the term in the context of human perception, but if it does, the image it makes may not be purely visual.

An intriguing aspect of the sensory integration that weaves together distinct neural inputs is that it proceeds despite the desynchronized time scales of various receptor mechanisms. Typically, the signals from photoreceptors are neurological laggards, highly dependent on the level of illumination, while signals from mechanoreceptors, e.g., from an insect's antennas, or from strain receptors in its wing, race ahead. In vertebrates, sensory processing time depends also on the number of synapses from the periphery to central hubs. Fast inputs can be delayed to allow a time window to overlap with slow inputs. Even the dual visual systems of many insects, such as flies, locusts, or hawkmoths, operate on different time scales: signals from the polarization-sensitive ocelli are conveyed much more rapidly than signals from the spectrally sensitive compound eye [11]. Yet, cross-modal information fusion clearly poses no flight control problems for these insects. They apparently have no need for a Kalman filter [12].

Such striking differences between how animals use sensors, and how conventional engineering systems use them, motivates interest in modeling the information flow, not just at a photoreceptor, or at its lens, but through the ensuing computations behind the lens. For example, the compound eyes of fast-moving insects lack resolving power, facet by facet, but these animals can gain effective spatial acuity via a temporal analysis of moving scenes. For slow-moving animals, e.g., under water, visual performance may depend more on having optical components of the right size, relative to the absorption and scattering of light in the external medium [13]. In most biological eyes, signals produced in adjacent photoreceptors are highly correlated, so the standard engineering goal of isolating the readouts from neighboring pixels at the focal plane of a camera would not be as "bioinspired" as working with less isolation among pixel elements [14]. In any case, tradeoffs in spatio–temporal resolution also can be expected to reflect an animal's unique behavioral requirements, such as its ability to find its way in dim or bright illumination, detect small or large prey, hide or break camouflage. Just as engineering use dictates engineering design, a deep understanding of biological sensory mechanisms requires knowledge of the ecological circumstances in which they are used.

This insight about how biological mechanisms accommodate to ecological requirements was more eloquently stated in Rüdiger Wehner's classic paper (1987) about how sensory systems have evolved to "solve particular problems posed by the idiosyncracies of the environment in which they operate." He advised neurobiologists to ". . .adopt the attitude of the engineer, who is concerned not so much with analyzing the world than with designing a system that fulfills a particular purpose" [15]. A recent book, *Visual Ecology* (2014) by some of the authors in this special issue, exemplifies how a deeply informed commitment to understand an organism's behavioral circumstances can unlock the operational principles it uses to solve problems of detection, identification, and navigation [16].

In an important respect, these principles converge upon an energetics requirement that also constrains many engineering designs. Just as battery power limits what an electromechanical system can do, neural efficiency in a sensorimotor system is evidently a priority when an organism's metabolic costs are taken into account [17]. Computational efficiency has long been recognized as a governing feature of neural processing, whether for sensing objects in a natural environment or for the muscular guidance and control needed to move within the environment [18]. Indeed, given the massive flux of inputs to any visual system, it is difficult to imagine how it could work at all without relying on sparse coding of some kind [19]. Although few papers in this special issue touch upon the question, there is much current interest in the details of exactly how biological sensory systems achieve a sparse representation of objects and natural scenes. The development of mathematical theory for sparse representations, and its application to image processing, e.g., in computer vision, has been surveyed in several other IEEE publications, and is not a topic of this special issue. Yet these formal developments reinforce the idea of cross-disciplinary convergence, where evolutionary adaptations to limit metabolic costs are recognized as biological antecedents of the sparse coding formulas.

III. OVERVIEW OF THE PAPERS IN THIS ISSUE

If readers are surprised at the variety of topics in this special issue, we will have accomplished one of our goals, which is to illustrate the increasingly diverse array of biological insights for problems of imaging. Useful ideas for these problems do not always stem from the study of creatures known to make visual images. Indeed, the extent to which animals actually rely on image making is a largely unsolved and very difficult problem. Except in the case of our own mental images, the problem admits no access to direct evidence [20]. Instead, as we have remarked above, a "biological advantage" often can be found in neural information processing, or in biophysical phenomena associated with nonvisual, or even nonsensory systems.

This special Proceedings volume does not attempt to capture the entire research landscape related to imaging. Among several topics not represented here are bat-inspired ultrasonic acoustic imaging [21], obstacle avoidance based upon electroreception [22], emulations of the honey bee's wide field of view lens system [23], artificial compound eye microlenses [24], adaptive 3-D camouflage in cephalopods [25], and bioinspired nanoarchitectures for infrared imaging [26]. Of course, our desire for a wider survey had to respect the space available.

A word about the selection process for these papers: All were specifically invited. Those presented here survived an independent, multistage review. We sought authors who had deep experience at the nexus of biology and engineering, and who had a point of view, or a perspective to communicate, that we deemed to be of interest to a broad technical community. We are pleased that several authors took the opportunity to share the writing task with colleagues, especially with rising young scientists with complementary skills.

Papers in this special issue are grouped roughly into four clusters. The first describes extraordinary light-sensing capabilities in several species, and presents cutting-edge technology derived from research on these visual systems.

- The ability to see at night ought to be abysmally poor in the Central American bee, *Megalopta genalis*, because its apposition compound eyes do not combine photons from many directions. Yet, in defiance of its apparently inadequate lens system, this insect navigates superbly under dark forest cover. This Lund University, Lund, Sweden, research, led by Eric Warrant, explains the adaptations that enable *Megalopta* to be a highly competent night flyer, including amplification at the photoreceptor response and neural circuits that boost spatio–temporal summation and suppress noise. The authors use limitations in the detection reliability of nocturnal eyes as a starting point to demonstrate a method for enhanced night-vision video, with preserved color.
- Many animals can detect and discriminate the polarization properties of light. This research, led by Nicholas Roberts at the University of Bristol, Bristol, U.K., draws lessons for optical processing based on models of polarization information sensing in four species: fiddler crabs, cuttlefish, octopus, and mantis shrimp. An important theme of these models is their departure from current imaging technology. The authors demonstrate why polarization processing in animal vision should not be construed in the same terms common to engineering analysis, and they outline opportunities for new approaches.
- Taking a strong cue from the information compression found in the first neural layers of the retina, Milin Zhang and her colleagues highlight a monolithic CMOS polarization image sensor with on-focal-plane processing. Based at the University of Pennsylvania, Philadelphia, PA, USA, this design relies on a unique current-mode approach to promote high-speed readout regardless of light intensity. The authors discuss alternative approaches to polarization-based imaging, the advantages over polarization-blind imaging, and the key parameters for image construction from such devices. The paper details circuit architecture for polarization feature extraction, using a nanowire filter layout at the heart of the detector. The authors show examples of live-cell polarization imaging.
- Viktor Gruev and colleagues detail a CMOS-based imager to emulate biological sensing capabilities in both polarization and spectral regimes. Based at Washington University in St. Louis, St. Louis, MO, USA, this effort takes specific inspiration from eye designs in nature where optical information is processed at the focal plane. The authors show how to boost optical performance and how to facilitate visual interpretation of polarization information. The paper highlights biomedical areas where their work has been used or holds promise, including neural activity recording and tumor detection.

Each paper in the next group exhibits a distinctive foray into the question of how visual information can be conveyed by spiking neurons from the retina.

- Christoph Posch and colleagues recount the history and development of efforts to devise neuromorphic vision sensors. The authors survey the stark contrasts between the kinds of components available to biological and engineering systems. They outline new technical ideas to reach a higher benchmark for neuromorphic emulation. The need for emulation, the authors point out, stems from multiple deficiencies in state-of-the art systems, which tend to be frame based and unrelated to the dynamics of visual scenes. The authors show how a more biologically informed approach could outperform current imaging technology.
- Here, Ryad Benosman and colleagues introduce a method to do event-based filtering of spatio–temporal signals, with a goal to lower the computational cost of visual processing. A data-sampling rate that continually adapts to event frequencies mimics the sparse coding feature of many biological systems, and can be more efficient than a rate based upon only the maximum or average expected frequency. Linear and nonlinear filtering techniques are described. The authors, affiliated with the Pierre and Marie Curie University, Paris, France, report implementations and experiments to compare event-based processing with frame-based methods.
- The high dimensionality of visual scenes poses a special problem. The paper by Aurel Lazar and Yiyin Zhou takes up the dual challenge of modeling the neural code and devising an efficient inversion technique to decode (reconstruct) natural scenes. The authors, based at Columbia University, New York, NY, USA, review the history of work on this problem, and demonstrate how natural scenes can be represented as multidimensional spike trains. Using their prior formal results, they offer an elegant solution to the decoding problem and provide video examples of high-quality reconstructions.

The following three papers discuss neuromorphic systems for tracking visual motion.

- Garrick Orchard and Ralph Etienne-Cummings review how motion sensing is understood in visual biology. The authors, from the Johns Hopkins University, Baltimore, MD, USA, and the National University of Singapore, Singapore, trace the historical development of models for motion detection and classification. Thirty four published approaches are compared. Most rely on a method of contrast or edge detection in the spatial or temporal domain. The authors discuss a new method using layers of spiking neurons, and suggest significant problems of neuromorphic design that still await solution.
- Francisco Barranco and colleagues continue the theme of the preceding paper with an investigation of how to emulate in a camera the visual information available in transient retinal responses and apply this emulation to detect visual motion. A new asynchronous neuromorphic vision sensor is described. Based at the University of Maryland, College Park, MD, USA, the authors explain why object contours pose a nontrivial problem for motion estimation, why solving it is vital, and how an event-based system fares in this regard, compared to other methods.
- In his paper, Patrick A. Shoemaker asks how to make neuromorphic analog models more useful to engineers. He notes that the history of analog VLSI modeling is replete with clever circuits unsuited for real-world applications. To illustrate, he takes a prominent motion-detection scheme, abstracted from research on insect vision, shows why it lacks utility, e.g., for autonomous guidance based upon optic flow, and then shows how it can be elaborated, consistent with recent biological evidence, to boost its functionality. An alternative class of analog models is introduced and tested. The author, who is with Tanner Research, Monrovia, CA, USA, shows why device imprecision poses a special problem. He demonstrates ways to evaluate sources of imprecision, and recommends steps to foster practical uses.

The final group includes two papers that offer very different insights on the nature of 3-D imaging, and one that surveys current developments and prospects for noise-enhanced information processing.

- What optical information is required to make a 3-D image, if the goal is to effectively mimic natural binocular viewing? Adrian Stern and his colleagues, based at Ben Gurion University, Beer-Sheva, Israel, and at the University of Connecticut, Storrs, CT, USA, take up this question of stereopsis in light of the severe constraints that human binocular viewing imposes. Their paper reviews the optical, physiological, and perceptual "boundary conditions" that must be taken into account. Their modeling approach defines an ideal stereoscopic light field for an optimal 3-D image. Using this model, the authors clarify key technical challenges and suggest ways to overcome them.

- This research, based at Purdue University, West Lafayette, IN, USA, adopts a theory of human visual perception to construct 3-D representations of natural scenes. The construction relies on discovering how human vision solves an inverse problem: Given a 2-D image at the retina, induce the correct layout of shapes and objects in external 3-D space that gave rise to it. Without bounding constraints, there are infinitely many solutions, so the problem is ill posed. The authors, Tadamasa Sawada, Yunfeng Li, and Zygmunt Pizlo, find these constraints in human perceptual analysis, sufficient for robotic 3-D constructions to match human vision. This paper presents new formal results and applies them to infer 3-D shapes from a camera image.
- Many biological systems, such as photoreceptors, operate in a noise-limited context. A physiologist who monitors a recording electrode may regard extraneous neural activity as "noise" because it hinders attempts to get a "clean" signal. From the point of view of the organism, on the other hand, endogenous noise may actually enhance some biological capabilities for information processing. In this paper, Hao Chen and his colleagues, Lav Varshney and Pramod Varshney, describe these phenomena, and review mathematical progress to achieve noise-enhanced outcomes in technical systems for detection, estimation, and imaging. They survey a broad panorama, from natural systems in physics and biology to applications for signal processing, with emphasis on image enhancement. They identify unsolved problems where further effort could bear fruit. ■

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