TECHVIEW: ROBOTIC VISION

Neuromorphic Vision Sensors

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Animal sensory systems are essential both to survival and competition. They, and their analogs in robots, must not only convert inputs into internal representations, itself a task of staggering complexity, they must do so efficiently if they are to act rapidly on the sensory input. The challenge for developing robotic sensory systems is therefore twofold: to recreate the flexibility, sophistication, and adaptability of animal systems, and to do so with computational efficiency and elegance.

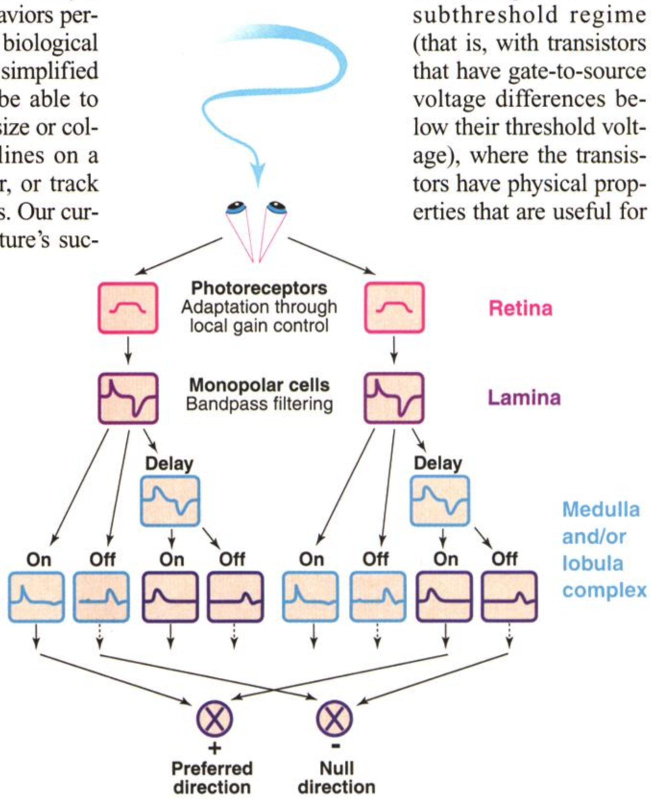
Neuromorphic sensors are specialized sensory processing functions implemented by analog electronic circuits that are inspired by biological systems. We believe that these circuits are particularly good candidates for the construction of artificial sensory systems that attempt to emulate biological vision. Vision is one of the most useful sensory modalities but comes at high cost. The real-time processing of the continuous, high-dimensional input signals provided by vision sensors is challenging both in terms of the computational power required and the sophisticated algorithms required to extract behaviorally relevant information.

Digital vision sensors. Robotic vision sensory systems have been implemented using conventional Complementary Metal-Oxide Silicon (CMOS) imagers or charge-coupled device (CCD) cameras, interfaced to digital processing systems that execute machine vision algorithms on general-purpose serial or coarsely parallel architectures. Using these methods, significant progress has been made on vision problems such as three-dimensional (3D) scene reconstruction, object recognition, texture analysis and synthesis, and tracking (*1*, *2*). The sophistication of real-time, vision-driven motor control (visuo-motor) processing systems is also improving. For example, autonomous vehicles have been developed that can drive on freeways at speeds of up to 130 km/h while avoiding collisions, following lanes, and even automatically overtaking slower vehicles (*3*, *4*). However, these conventional digital machine vision systems tend to have excessive power consumption, size, and cost for useful robotic applications. Furthermore, with few exceptions, their performance falls well short of robust real-world functionality.

Learning from nature's example. Nature has evolved many fine solutions for vision processing. Insects such as flies, bees, or crickets, as well as birds and higher animals, rely mainly on visual cues to navigate safely in their environment, avoiding obstacles, approaching objects, triggering escape or landing responses, and performing tasks such as visual homing and foraging. Insects are particularly challenging for robotic systems: They achieve their performance with a nervous system that has less than a million neurons and weighs only about 0.1 mg.

Current robots can achieve only a very limited set of the behaviors performed so effortlessly by biological systems, and then only in simplified environments; they may be able to avoid obstacles of a fixed size or color, follow high-contrast lines on a uniform background floor, or track targets with specific shapes. Our current inability to match nature's success arises partly from the fact that current robots are unable to quickly, easily, and cheaply exploit the many different cues provided by visual information. Another reason is our slow progress in understanding how these cues can be combined dynamically to steer appropriate behavior. These limitations suggest that instead of using a single powerful (but bulky and expensive) general-purpose machine vision system, we should explore the use of multiple special-purpose (compact and cheap) vision sensors, such as direction-of-motion sensors, velocity sensors, and looming or tracking sensors, to preprocess the sensory input. Each of these "perceptive sensors" would reduce their high-dimensional sensory input into a low-dimensional output that encodes information relevant, for example, for pilotage and navigation.

Neuromorphic vision sensors. The neuromorphic approach to artificial perceptive sensors implements specialized sensory processing functions inspired by biological systems in analog electronic circuits. These circuits are parallel and asynchronous, and they respond in real time. Surprisingly useful results have been obtained in replicating insect visual homing and chemo- and phonotaxis strategies, using simple off-the-shelf analog components interfaced to robots (*5*, *6*). Small, dense sensory processing systems have also been developed using analog circuits fabricated with Very Large Scale Integration (VLSI) technology. Neuromorphic Analog VLSI (aVLSI) systems (*7*, *8*) are electronic circuits that explicitly implement biological-style processing on individual chips or systems composed of chips. These CMOS circuits operate in the subthreshold regime (that is, with transistors that have gate-to-source voltage differences below their threshold voltage), where the transistors have physical properties that are useful for



Architecture of aVLSI elementary motion detector modeled on the fly visual system. The input goes through a photoreceptor circuit with adaptive local gain control. The receptor output is then bandpass filtered by the monopolar cell's circuit. The output of this circuit splits into two pathways; in one pathway, the signal is delayed through a low-pass filter. ON and OFF transient signals are generated from the delayed and undelayed signals. Subsequently, the ON and OFF delayed signals in each pixel are correlated with the undelayed signals from the adjacent pixel. The final "+" output is sensitive to a stimulus moving in the preferred direction; the "-" output is sensitive to a stimulus moving in the null direction. The layers in the block diagram correspond to the processing layers in the fly anatomy. It is postulated that the circuitry for the delay block and the ON and OFF pathways are located in the medulla and/or the lobula complex.

CREDIT: ADAPTED FROM (19)

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emulating neurons and neural systems, such as thresholding, exponentiation, and amplification (*7*). These similarities with biology, and the increasing availability of CMOS VLSI technology at decreasing cost, make it a convenient medium for synthesizing neuromorphic sensors.

Emulating biological vision. Neuromorphic vision chips (*9*, *10*) process images directly at the focal plane level with circuits that implement hardware models of the first stages of visual processing in biological systems. In the retina, early visual processing is performed by receptors and neurons arranged in a manner that preserves the retinal topography with local interconnections. Neuromorphic circuits have a similar physical organization: photoreceptors, memory elements, and computational nodes share the same physical space on the silicon surface and are combined into local circuits that process, in real-time, different types of spatio-temporal computations on the continuous analog brightness signal.

The highly distributed nature of physical computation in these analog systems leads to efficient processing that would be computationally expensive on general-purpose digital machines. For example, like their biological counterparts, neuromorphic sensors such as the aVLSI retinae described above can operate over an input range covering many orders of magnitude, despite limited bandwidth. This extraordinary performance is achieved by a simple but densely parallel process that involves continually adapting local reference signals to the average signal statistics prevailing there (*11*).

Robots with neuromorphic sensors. Various aVLSI sensors are now being tested on simple robots. Synthetic modeling (*12*) using robots with conventional or mixed digital-analog sensory systems has already helped researchers to understand behaviors and neural control mechanisms of insects (*5*, *13–16*). Applying neuromorphic sensors to these types of robotic systems enables researchers to build models of increasing complexity and computational efficacy, without having to include workstations or digital signal processor (DSP) systems in the sensory-motor loop.

Motion cues provide a particularly rich source of information for navigation, and several types of aVLSI motion chips are being developed for the analysis of these cues (*17*). One interesting example of a neuromorphic motion sensor that simplifies motor control is based on the fly's visual system (*18*, *19*). Flies use visuo-motor control, based on the analysis of visual motion cues, for tasks such as target fixation, course stabilization, and tracking. The motion chip used in the Koala robot (K-Team, Lausanne, Switzerland) (see the figure on this page) is modeled on the wide-field direction-selective cells of the fly. The circuit on the chip combines the outputs of elementary motion detectors to form just two outputs, one indicating a preferred direction of motion in the field of view, the other the null direction (see the figure on the previous page). These low-dimensional outputs from both sensors are used by a simple motor control system on the robot to generate fixation and optomotor responses similar to those used by flies and achieve robust course stabilization. At the annual Telluride workshops on Neuromorphic Engineering, neuromorphic motion chips have even been interfaced to aerodynamic actuators for implementing optomotor responses on flying robots (*20*, *21*). Visual tracking, auditory localization, reactive maze solving, and locomotion control were also demonstrated.

Picture of a neuromorphic "Koala" robot. Focal plane motion detector chips are mounted behind lenses on two boards, which carry additional discrete electronic components such as the trim potentiometers that set parameter voltages. Each chip has 37 elementary motion detectors. The aggregated outputs of the elementary motion detectors in each motion chip drive the motor system of the robot, and so generate the fly-like behaviors (optomotor response and fixation response).

Autonomous navigation. One of the primary goals in this field is the design of autonomous robots that can navigate easily and safely through natural environments. A class of neuromorphic sensors being developed to achieve this goal is that of tracking sensors based on their absolute intensity (*22*, *23*), whereas others select targets based on their relative contrast (*24*, *25*). They have the common advantage of selectively reducing the amount of data that needs to be transmitted from the visual sensor to the motor control stages. The transmission of only relevant data saves communication bandwidth, simplifies control, and reduces response latency. All of these are important advantages in improving pilotage and navigation. As the number of sensory functions being implemented on aVLSI neuromorphic chips increases, more examples of autonomous robots that use these chips to navigate successfully in natural environments are being proposed (*18*, *19*, *25*).

The computational architecture, dense processing, small size, and low power consumption of neuromorphic sensors make them attractive for constructing artificial sensory systems that attempt to emulate biological processing. They also offer an attractive alternative to special-purpose digital signal processors, particularly for machine vision tasks on autonomous mobile robots that require only qualitative processing.

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26. We thank S.-C. Liu and A. Usseglio-Viretta for the figure, and S. Chambers for editorial advice. We acknowledge the contributions of our colleagues at the Institute of Neuroinformatics and the Telluride Workshop on Neuromorphic Engineering. Supported by the Swiss National Science Foundation Swiss Priority Programs and the Koerber Foundation.

CREDIT: A. USSEGLIO-VIRETTA