Real-Time Emulation of Neural Images in the Outer Retinal Circuit

Jun HASEGAWA and Tetsuya YAGI
Division of Electrical, Electronic and Information Engineering, Graduate School of Engineering, Osaka University

Abstract: We describe a novel real-time system that emulates the architecture and functionality of the vertebrate retina. This system reconstructs the neural images formed by the retinal neurons in real time by using a combination of analog and digital systems consisting of a neuromorphic silicon retina chip, a field-programmable gate array, and a digital computer. While the silicon retina carries out the spatial filtering of input images instantaneously, using the embedded resistive networks that emulate the receptive field structure of the outer retinal neurons, the digital computer carries out the temporal filtering of the spatially filtered images to emulate the dynamic properties of the outer retinal circuits. The emulations of the neural image, including 128 × 128 bipolar cells, are carried out at a frame rate of 62.5 Hz. The emulation of the response to the Hermann grid and a spot of light and an annulus of light has demonstrated that the system responds as expected by previous physiological and psychophysical observations. Furthermore, the emulated dynamics of neural images in response to natural scenes revealed the complex nature of retinal neuron activity. We have concluded that the system reflects the spatiotemporal responses of bipolar cells in the vertebrate retina. The proposed emulation system is expected to aid in understanding the visual computation in the retina and the brain.

Key words: retina, neuromorphic silicon retina, real-time emulation, neural image, receptive field.

The retina is where the first stage of visual information processing in the nervous system of the brain takes place [1]. Most cells there respond to light exhibiting slow graded potential changes. Retinal neuronal circuits have been described by analog electric circuits in previous studies [2–4]. In physiological experiments, the spatiotemporal properties of cell response to light, namely, the receptive field properties, in the retinal circuits have been investigated using simple visual stimuli, e.g., spots of light or annuli of light. Most of the analog circuit models were contrived from these physiological experiments. On the other hand, the visual function of the retinal cells cannot be obviously inferred from these models, since the input images under natural conditions are highly complex. To understand and infer the visual functions of the retinal neurons, the response of these models to natural scenes must be studied in real time. However, the image computation of natural scenes by using a conventional digital computer system that operates through sequential algorithms involves high computational costs.

In the distal retinal, photoreceptors, horizontal cells, and bipolar cells constitute neuronal circuits to filter input images spatiotemporally with their electrical properties. Under light-adapted conditions, the cone photoreceptors convert light into graded voltage signals. The voltage signals are transmitted to the second-order neurons, the horizontal and bipolar cells. It is well known that neighboring horizontal cells are tightly coupled electrically by the gap junctions [5], typical electrical synapses, to form a neuronal synecytium. Because of this electrical coupling, the electric signals transmitted to the horizontal cells spread laterally along the synecytium, and the horizontal cells exhibit a wide receptive field [3]. The neighboring cone photoreceptors are also coupled, but weakly, by the gap junctions, assumed to be useful for reducing noise in the photoreceptor cells [2]. The bipolar cell exhibits the center-surround antagonistic receptive field [6]. The origin of the receptive field center is the cone photoreceptors. The origin of the receptive field surround is the horizontal cell synecytium [7, 8]. These receptive fields of the retinal neurons are designed to adapt to the structure of natural scenes [9] and must be expressed with a large 2-dimensional digital mask. Therefore a parallel architecture of computation similar to the spatiotemporal filtering in retinal circuits is necessary for real-time emulation.

The neuromorphic silicon retina is an analog very large scale integrated (aVLSI) electronic circuit that emulates the structure and the image computations of the retinal circuits ([10–12] for outlines). Several types of neuromorphic silicon retinas have been fabricated previously to emulate the center-surround receptive field organization of the outer retinal circuits [13–17]. These silicon
retinas emulate spatial properties of the receptive fields of the outer retinal neurons constituting a neuronal synaptium using resistive networks efficiently, and they are good candidates for real-time emulation of the responses of outer retinal neurons. However, it is difficult to implement temporal properties of graded responses with the aVLSI circuit.

In the present study, we have developed a novel system consisting of a silicon retina and a digital computer to reconstruct the spatiotemporal receptive field of the outer retinal neurons on the basis of physiological experiments. The aim of this study is to emulate the dynamic neural images produced by bipolar cells in response to natural scenes in real time.

**METHODS**

**System setup.** The system consists of a silicon retina, a field-programmable gate array (FPGA), an Ethernet interface (ASPECTUS, Neuralimage Co., Ltd.), and a digital computer. Figure 1 shows the setup of the system. The silicon retina is controlled by the timing signals sent from the FPGA circuits. The silicon retina receives visual inputs through an optical lens. Then image frames from the silicon retina are transmitted to the data-read part of the FPGA circuits. The FPGA transmits the image frames to the digital computer through the Ethernet interface. All these processes are carried out at a frame rate of 62.5 Hz.

**Silicon retina.** An original model of the silicon retina has been fabricated previously [17]. Since the architecture of the silicon retina has been described elsewhere [17], it is described only briefly here. The circuit has been designed on the basis of the model of the outer retinal circuit [4]. The neuronal synaptium in the retina is known to be modeled by a resistive network [2–4, 18]. In the circuit, the photosensor array is arranged together with two layers of resistive networks and differential amplifiers. The voltage outputs from the photosensors are fed to these networks, one of which has a small length constant and the other a large one. The former represents the cone photoreceptor synaptium and the latter a horizontal cell synaptium. The network circuit reaches a stable state instantaneously with a short delay caused by the parasitic capacitances of the analog circuits. This instantaneous distribution of voltage emulates the spatial filtering carried out in a neuronal synaptium with a high computational efficiency. The differential amplifiers take the difference between the voltages at the corresponding nodes of two resistive networks to reproduce the center-surround receptive field of bipolar cells. The silicon retina has 128 × 128 pixels and was implemented in a 1 poly 3 metal 0.25 µm analog complementary metal-oxide semiconductor image sensor (CIS) technology. The die size is 12.5 × 12.5 mm². The pixel area is 87 × 87 µm². The photodiode area is 8 × 8 µm². A single pixel consists of a photosensor circuit, namely, the active pixel sensor (APS), two layers of the resistive networks, and two sample-and-hold differential amplifiers. Each pixel is connected to four neighboring pixels through metal-oxide semiconductor (MOS) resistors forming the resistive network that emulates the neuronal synaptium of the photoreceptor and of the horizontal cell (the originally fabricated chip has hexagonal connections; refer to [17] for details). The sample-and-hold differential amplifiers embedded in each pixel circuit calculate the difference between the output from the photoreceptor resistive network and the horizontal cell resistive network, emulating the center-surround antagonistic receptive field of the bipolar cell.

The APS generates photo-induced voltage changes that are linear to the luminance, as shown in Fig. 2. The sensitivity curve shown in Fig. 2 has been measured by using a liquid crystal display (LCD). The output voltage is obtained through an 8-bit analog-to-digital (AD) converter. The range of the AD converter is from 1.60 to 2.83 V. At high luminance, the output voltage is saturated because of the limited range of the AD converter. All the experiments reported in this paper have been conducted...
at a luminance of less than 100 cd/m^2 to ensure the linearity of the APS.

**Reconstruction of neural image.** The outer retinal cells respond to light exhibiting slow graded potential changes. This implies that the input images to the retina basically are temporally low-pass filtered by the outer retinal circuits. It is difficult, however, to implement the dynamic properties in aVLSI circuits. Here such dynamic properties are emulated by using a digital computer. We have calculated the weighted sum of the image frames obtained by the silicon retina to emulate the spatiotemporal property of the bipolar cell.

Figure 3 shows a schematic diagram of the reconstruction of the neural image of the bipolar cells. The silicon retina shown at the top-left corner in Fig. 3 receives an input image and filters it spatially with the analog circuits so that the output of silicon retina exhibits center-surround antagonistic spatial property, as mentioned earlier. The filtered image is then sent to the digital computer, shown at the bottom-left corner in Fig. 3, through the Ethernet interface. A software program installed in the digital computer calculates the weighted sum of the image frames so that the system emulates the spatiotemporal properties of bipolar cells.

The weighted sum is calculated as follows. The image frames acquired sequentially from the silicon retina are stored in the memory. A temporal filter is implemented as the lookup table containing floating-point numbers. The bipolar cell response, B(x, y, t), can be calculated from the input image, A(x, y, i) and a lookup table, f(i) as

\[
B(x, y, i) = \sum_{j=1}^{N} f(j) A(x, y, i - j)
\]

Here \(x\) and \(y\) indicate the position of a pixel, \(i\) indicates the frame index, and \(N\) indicates the length of the lookup table.

**Temporal filter.** In a previous study using intracellular recordings, the response of a single cone photoreceptor to a diffuse flash of low intensity has been expressed [19] as

\[
f(t) = Ce^{-\phi t} (1 - e^{-\phi t})^{n-1}
\]

where \(t\) is the time in seconds, \(\phi\) and \(n\) are constants \((n = 6, \phi = 16.7 \text{ s}^{-1})\), and \(C\) is a normalization constant expressed as

\[
C = \left[ \int_0^\infty e^{-\phi t} (1 - e^{-\phi t})^{n-1} dt \right]^{-1}
\]

Here \(f(t)\) is regarded as the impulse response of a cone photoreceptor. We used the above equation for the temporal weighting function of the outer retinal neurons. Ashmore and Copenhagen had shown that the bipolar cells in a light-adapted turtle retina follow almost the same time course as the cone photoreceptors [20]. Further, horizontal cells had also been confirmed to exhibit very similar temporal response curves [18]. We assumed that cone photoreceptors, horizontal cells, and bipolar cells give rise to the same temporal response curves defined by equation (2).

Figure 4 shows the impulse response curve of the model outer retinal neurons to be implemented in the emulated system. The solid line indicates the temporal filter expressed by equation (2), and the open circles indicate the sampled points used for the lookup table in equation (1). The sampling rate, 62.5 Hz, is sufficient to express the
The impulse response of model outer retinal cells. The solid curve indicates the temporal filter expressed by equation (2), and the open circles indicate the sampling points for the lookup table, the temporal filter. The sampling interval is 16 ms, and the number of sampling points is 33.

Time course of the impulse response because its cutoff frequency is 2.1 Hz. The number of sampling points, N, is 33.

Presentation of images. We emulated the neural image of the outer retinal cells in response to static and dynamic visual inputs. The static visual inputs include a slit of light and a Hermann grid [21]. The dynamic visual inputs include small/large spots of light, annuli of light, and natural scenes. These visual inputs were presented on an LCD placed in front of the silicon retina with a distance of 50 cm, except for the natural scene, which was directly presented to the silicon retina. The silicon retina is placed behind a lens using a diaphragm assembly (the maximum f number is 1.4).

The width of the slit was set at 0.75 pixel on the silicon retina. The width of white gridlines in the Hermann grid was set at 5.85 pixels on the silicon retina, and the pitch of the gridlines was set at 23.4. The diameter of the small spot formed on the silicon retina was 1.8 pixels. The annulus formed on the silicon retina had an inner diameter of 1.8 pixels and an outer diameter of 29.4. The diameter of the large spot on the silicon retina was 29.4 pixels. The diameter of the small spot was chosen to cover the center area of the receptive field. The size of annulus was chosen to cover only the surrounding area. The size of the large spot was chosen to cover both the center area and the surrounding area. The images were presented for 0.5 s each at 1 s intervals. The center position of the flash was carefully adjusted at the central pixel in the photosensor array of the silicon retina.

The emulation of the bipolar cell responses to natural scenes was carried out under indoor illumination conditions (518 lx). The diaphragm was adjusted (f number set at 2.0) to limit the input luminance level within the linear range of the photosensor. In this demonstration, a hand was moving downward in the visual field of the silicon retina camera at a distance of 80 cm. The camera lens was focused on the hand.

RESULTS

Static response to slit of light
The neural images formed by the silicon retina in response to a slit of light are shown in Fig. 5. The slit of light is presented on the LCD. The emulated neural images formed by the cone photoreceptors, the horizontal cells and the bipolar cells are shown in Fig. 5, A–C, respectively. As shown in the panels in Fig. 5, the slit image formed by the horizontal cells is blurred, indicating a tight lateral electrical coupling in the resistive network. The cone photoreceptors also blur the input image slightly, indicating the loose lateral electrical coupling. The one-dimensional response distribution profiles of the images are shown in Fig. 5, D–F. The abscissas represent the pixel positions, and the ordinates the response amplitudes of the system. The spatial profile of the amplitude distribution decays exponentially as the distance from the slit increases in Fig. 5, D and E, which is in agreement with the continuous sheet model of neuronal syncytium [3]. When the syncytium is regarded as a continuous sheet, the spatial distribution of the electrical signal along it is expressed by the exponential function in response to a slit of light [3]. The emulated bipolar cell response (Fig. 5F) is reconstructed as the difference of two exponential curves and exhibits the center-surround receptive field.

Static response to Hermann grid
The Hermann grid [21] was presented to the emulation system (Fig. 6). The Hermann grid (Fig. 6A) is a spatial pattern causing illusions in which illusory dark spots are perceived at the intersections of white grids. The image is displayed on the LCD. The response of the system reached a stable state within 0.5 s after the image was displayed. Figure 6B is the emulated neural image of the bipolar cells. Dark spots were observed at the intersections of white grids, similar to the human perception. The voltage distributions along the rows indicated by the solid and dotted lines in Fig. 6B are plotted in Fig. 6C. Hollows (indicated by the black arrows) are observed at the intersections in the response profile along a white grid (solid line). The areas within the dark squares (dotted line) also show spatial modifications (indicated by the white arrows). These modifications are caused by the center-surround antagonistic receptive fields of the bipolar cells. The illusory dark spots at the intersections of white gridlines are caused by superimposed inhibitory surrounds of four contiguous areas around the intersections.
Real-Time Emulation of Neural Images

Fig. 6. Response to Hermann grid image. The original Hermann grid image (A) causes an illusion, and dark spots are perceived at the intersections of the white grids. The emulated neural image of the image formed by the bipolar cells is shown in B, where the dark spots are perceived as similar to the human perception of the image shown in A. The response profiles along 2 rows (indicated by the solid and dotted lines in B) are shown in C.

Fig. 5. Static response to illuminated slit. The emulated neural images are shown in A–C. The dimension of the image is 128 × 128 pixels. The one-dimensional voltage distribution profiles of the images are shown in D–F. The abscissas represent the horizontal positions, and the ordinates represent the responses (arbitrary unit). A and D show the responses of the photoreceptors; B and E show the responses of the horizontal cells; and C and F show the responses of the bipolar cells, which emulate the center-surround antagonistic receptive fields of the bipolar cells.
Dynamic response to spot of light

Figure 7 shows the emulated responses of an individual bipolar cell at the spot of light and the annulus of light. The white background indicates that the lights are switched on, and the dark background indicates that the lights are switched off. The small spot of light evoked a positive response, and the annulus of light evoked a negative response. These responses were distorted at the onset and offset of light as a result of the temporal filtering. The large spot caused almost no response in the emulated bipolar cell, which implies that the responses of the center and surrounding areas are well balanced at any given time.

Dynamic neural image to natural scene

Figure 8 illustrates the dynamic neural image emulated in real time using the system. The speed of a moving hand was 5.0 cm/s for Fig. 8, A–C, and 41.2 cm/s for Fig. 8, D–F. Figure 8, A and B, show snapshots of the emulated neural image of the bipolar cells. As shown in the panels in Fig. 8, the image of the moving hand as well as the static background was captured, though the details of the hand were slightly blurred because of its motion. The time courses of the responses of pixels marked with symbols (filled circle, open circle, and cross) are plotted in Fig. 8C. The arrows indicate the time at which Fig. 8, A and B, was obtained. These time courses predict the intracellular voltage changes in the bipolar cells located at the corresponding sites when the retina is focused at the scene.

In regard to the scene in which a hand was moving fast at 41.2 cm/s, the image of the hand was totally blurred and almost invisible, and the background was seen through the blurred hand (Fig. 8, D and E), clearly indicating the low-pass filtering dynamics of the emulated outer retinal neurons. The time courses of the responses are plotted in Fig. 8F. This behavior might be suitable for the sustained channel response to perceive a stationary image robustly without obstruction by objects moving at high speeds.

The wave patterns shown in Fig. 8, C and F, reflect the spatial luminance patterns of the hand. The three sampling positions, i.e., top, center, and bottom, exhibit similar wave patterns with temporal shifts according to the speed of the moving hand. Although the spatial pattern of the hand moving at low speeds was reflected in the temporal wave pattern in detail (Fig. 8C), the details of pattern were lost at high speeds (Fig. 8 F).

DISCUSSION

We have demonstrated the real-time emulation of the neural image of the bipolar cells. The image has been emulated by using a combination of analog and digital systems consisting of a neuromorphic silicon retina, an FPGA, and a digital computer. The neuromorphic silicon retina carries out the spatial filtering of the input images instantaneously using the embedded resistive networks that mimic the receptive field structure of the outer retinal neurons. The digital part of the system, namely, the FPGA circuits and digital computer, carry out the temporal filtering of the output images from the silicon retina.

Real-time computation of neural images for natural scenes

The real-time emulation of neural images based on physiological experiments is important for studying the functional significance of the visual neuronal circuits, since it provides a variety of more realistic experimental environments. Simple visual stimuli have been used in physiological experiments; however, natural scenes are composed of various spatiotemporal frequencies. The spatiotemporal receptive field of the retina is highly...
adapted to the structure of natural scenes [9] and does not match the digital image processing techniques, such as the digital mask operation. For example, the receptive field of horizontal cells is known to be expressed by the Bessel function [22] when the retina is illuminated with a spot of light, indicating that the horizontal cell receptive field covers a large area of the retinal surface. Thus a large 2-dimensional digital mask is necessary to express such a wide receptive field. Indeed, the size of the mask must be larger than $40 \times 40$ pixels to reconstruct the receptive field of the bipolar cells emulated in this study (Fig. 5).
Predicting neural response to natural scenes

The present system can be used for various purposes. For example, it provides a useful simulation environment for verifying and developing the physiological models of the retina. The emulated outputs of the individual bipolar cells shown in Fig. 8, C and F, can be compared with intracellular recordings of the physiological experiments in which the same natural scenes used in the emulations are given. Because the neuronal responses to neural scenes cannot be easily predicted from the receptive field measured by simple stimuli in the intracellular recordings, even in regard to linear models, the emulation results with the present system provide a good reference for the intracellular recordings.

Furthermore, the result of emulation can be compared directly with that of psychophysical experiments. The system can perceive the same visual environment designed for human subjects in psychophysical experiments, as demonstrated in Fig. 8. The psychophysical experiments carried out by de Lange [23] and Kelly [24] have revealed that the human visual system also exhibits its low-pass temporal filtering. If the model parameters are determined on the basis of the physiological data of the primate retina, a quantitative comparison of the psychophysical data with the emulation results from this study might be possible.

For a more-realistic emulation

The emulated responses of the bipolar cell in response to the small spot of light and an annulus of light were similar to the responses of the on-center bipolar cells of the goldfish retina [6]. The large spot of light, however, did not induce apparent responses in the system, which is not always the result in the intracellular recordings of bipolar cells. The intracellular recordings of the bipolar cells tend to show weak transient responses at the onset and offset of the light. These transient responses, however, can be emulated through several minor changes in the control signals for the silicon retina, e.g., including a time lag between the center response and the surround response. The FPGA circuits and digital computer enable flexible and versatile computations with their highly programmable characteristics. Although we have emulated images using a linear model of the outer retinal neurons as the simplest system, the system can deal with some kinds of nonlinear properties, such as synaptic delay, rectifications, and a logarithmic input-output relation.

The present system is able to reconstruct a dynamic neural image of the outer retinal circuits, which give rise to graded potential change. The ganglion cells and some kinds of amacrine cells in the retina, however, are known to respond to light with action potentials, as cortical neurons. The present system is unable to reproduce the action potentials. In this regard, the neural images calculated for these spike-generating neurons represent an averaged spike frequency for a time window corresponding to the frame-sampling time of the system. Moreover, the system can emulate not only the neural images of retinal neurons, but also those of cortical neurons.

We believe that the real-time emulation of the neuronal network models presented in this paper will aid in understanding the visual computation in the retina and the brain.

We thank K. Shimonomura, H. Okuno, K. Inoue, and T. Fehervari for their valuable comments on the manuscript.

REFERENCES

1. Dowling JE. The retina: an approachable part of the brain. Cambridge, Massachusetts: Belknap Press of Harvard University Press; 1987.
2. Lamb TD, Simon EJ. The relation between intercellular coupling and electrical noise in turtle photoreceptors. J Physiol. 1976;263:257-68.
3. Naka KI, Rushton WAH. The generation and spread of S-potentials in fish (Cyprinidae). J Physiol. 1976;192:437-61.
4. Yagi T, Onshima S, Funahashi Y. The role of retinal bipolar cell in early vision: an implication with analogue networks and regularization theory. Biol Cybern. 1997;77:163-71.
5. Kaneko A. Electrical connexions between horizontal cells in the dogfish retina. J Physiol. 1971;213:95-105.
6. Kaneko A. Physiological and morphological identification of horizontal, bipolar and amacrine cells in goldfish retina. J Physiol. 1970;207:623-33.
7. Marchal-Falsava P-L. Horizontal cells influence membrane potential of bipolar cells in the retina of the turtle. Nature. 1978;275:141-2.
8. Toyoda JI, Tonosaki K. Effect of polarization of horizontal cells on the on-centre bipolar cell of carp retina. Nature. 1978;270:399-400.
9. Field DJ. Relations between the statistics of natural images and the response properties of cortical cells. J Opt Soc Am A. 1987;4:2379-94.
10. Mead C. Analog VLSI and Neural Systems. Addison-Wesley; 1989.
11. Koch C, Li H, editors. Vision chips: implementing vision algorithms with analog VLSI circuits. IEEE Computer Society Press; 1995.
12. Most A. Vision Chips. Kluwer Academic Publishers; 1999.
13. Mead C, Mahowald MA. A silicon model of early visual processing. Neural Networks. 1985;1:191-7.
14. Boahen KA, Androue AG. A contrast sensitive silicon retina with reciprocal synapses. Advances in Neural Information Processing Systems. 1992:4764-72.
15. Liu S-C, Boahen K. Adaptive retina with center-surround receptive field. Advances in Neural Information Processing Systems. 1996;6:678-84.
16. Yagi T, Matsutomo T, Kobayashi H. Parallel analog image processing: solving regularization problems with architecture inspired by the vertebrate retinal circuit. In: Leondes CT, editor. Neural network systems techniques and applications. Academic Press; 1998. p. 201-85.
17. Kameda S, Yagi T. An analog VLSI chip emulating sustained and transient response channels of the vertebrate retina. IEEE Trans Neural Netw. 2005;14:1405-12.
18. Yagi T. Interaction between the somata and the axon terminal of retinal horizontal cells in Cyprinus carpio. J Physiol. 1986;375:121-35.
19. Beylor DA, Hodosi AL, Lamb TD. The electrical response of turtle cones to flashes and steps of light. J Physiol. 1974;242:685-727.
20. Ashmore JF, Copenhagen DR. An analysis of transmission from cones to hyperpolarizing bipolar cells in the retina of the turtle. J Physiol. 1983;340:569-97.
21. Spillmann L. The Hermann grid illusion: a tool for studying human perceptive field organization. Perception. 1994;23:691-708.
22. Lamb TD. Spatial properties of horizontal cell responses in the turtle retina. J Physiol. 1976;263:239-55.
23. de Lange H. Research into the dynamic nature of the human fovea-cortex systems with intermittent and modulated light. J. Attenuation characteristics with white and colored light. J Opt Soc Am. 1968;4:774-84.
24. Kelly DH. Visual responses to time-dependent stimuli. J. Amplitude sensitivity measurements. J Opt Soc Am. 1961;51:422-9.