A parallel aVLSI system emulating neuronal circuits of early vision

Tetsuya Yagi & Kazuhiro Shimonomura
Department of Electronic Engineering, Graduate School of Engineering, Osaka University
Yamada-oka 2-1, Suita, Osaka 565-0871 Japan
yagi@ele.eng.osaka-u.ac.jp

Abstract - We have developed a vision system inspired by the hierarchically arranged parallel neuronal network of the brain. The system consists of a silicon retina and an FPGA (Field Programmable Gate Array). The image is filtered by a Laplacian-Gaussian-like receptive field of the silicon retina, and then it is transferred to the FPGA. The orientation selection chip selectively aggregates multiple pixels of the silicon retina, mimicking the feed-forward model proposed by Hubel and Wiesel. The present system carries out the convolution of the even- or odd-type Gabor-like filter with input image in real-time.

I. INTRODUCTION

The brain computes image with quite different algorithm and architecture from those of the conventional digital image processing system. In the mammal, visual information is transmitted in parallel mainly to the primary visual cortex, or V1, via the lateral geniculate nucleus (LGN) after pre-processed by the retina. In the visual system of the brain, the image is perceived promptly and stably using a compact and power consuming hardware. One of the reasons for such a high computational performance of the brain can be attributed to its hierarchically arranged network architecture. Therefore, it is interesting and important from engineering perspectives to develop an image processing system inspired by the architecture of the brain. On this background, we are designing a novel image processing system using analog very large integrated circuit (aVLSI) technology.

II. SILICON RETINA

The vertebrate retina is one of the few tissues of the central nervous system in which electrical properties and structural organization of neurons are well correlated. Five principal cell types of neurons have been identified in the retina ([1] for outlines). Fig.1 is a schematic illustration showing the gross structure of the vertebrate retina. In Fig., the bottom side corresponds to the frontal surface of the retina from which the light comes through the optical apparatus of the eye (arrows). The light passes through the transparent retina to reach the photoreceptor array. The light-sensitive pigment catches photons and triggers a chemical reaction cascade, which transduces light into a voltage response. The voltage signal is transmitted to the second order neurons, the horizontal cell and the bipolar cell. Bipolar cells transmit the outputs of the outer retinal circuits to amacrine cells and ganglion cells. The bipolar cell exhibits the center-surround antagonistic receptive field. Interplexiform cells (IP cells) are located at the amacrine cell layer and provide feedback pathways to the OPL. Inspired by the unique architecture the retinal circuit, the neuromorphic silicon retinas, novel analog very large integrated (aVLSI) chips for real-time image processing, have been fabricated ([2], [3], [4] for outlines). Some silicon retinas mimic the edge-enhancement effect by the concentric center-surround receptive field found in the retinal circuit [5], [6], [7], [8], [9], [10], [11] and some mimic the motion detection by the transient-type voltage response in the retinal circuit [12], [13], [14], [15], [16], [17]. Recently, Boahen et al. have fabricated a silicon retina which incorporates the transient and the sustained responses in a single chip[18], [19]. The outputs of the chip mimic the spike responses of four types of ganglion cell in the primate retina. This chip is very useful to study the computational essence of the retinal neuronal circuit. However, it is not designed for engineering applications. In the previous study, a silicon retina which can provide both sustained and transient responses with analog voltage outputs was fabricated in our laboratory [20]. The outputs of the chip are offset-suppressed analog responses with the aid of sample/hold circuits embedded in each pixel circuit to compensate for uncontrollable mismatches of transistor characteristics.

III. HIERARCHICAL ARCHITECTURE INSPIRED BY THE PRIMARY VISUAL CORTEX

One of the most distinct differences between the LGN neuron and the V1 neuron is the receptive field organization. LGN neurons have concentrically arranged antagonistic receptive fields as those of retinal neurons but V1 neurons have elongated ones. Among those V1

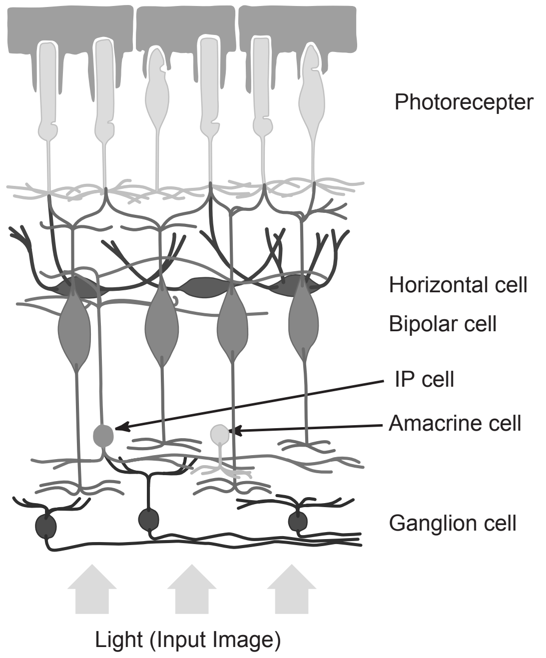


Fig. 1. Structure of the vertebrate outer retinal circuit.

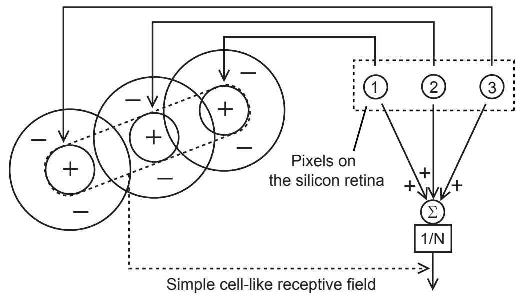


Fig. 2. A model to obtain an orientation selective receptive field based on the feed-forward model proposed by Hubel and Wiesel. N is the number of aggregated pixels.

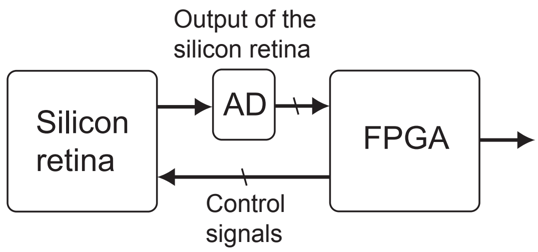


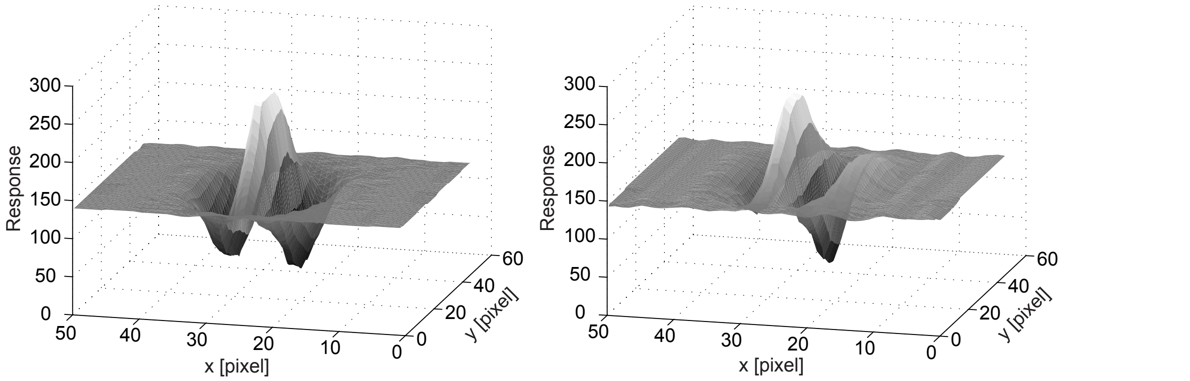
Fig. 3. Block diagram of the vision system which consists of a silicon retina and an FPGA.

neurons, the simple cell exhibits adjacent on- and off-area and therefore optimally responds to a specifically oriented light or dark bar.

We developed a vision system to emulate the orientation selective response of the simple cell in the primary visual cortex. Convergence of the response of neurons having center-surround receptive field can produce an elongated orientation selective receptive field [21], which is known as the feed-forward model (Fig.2). Recent physiological studies suggest that the mechanism for generating the orientation selectivity is more complex. Although this model does not thoroughly explain all properties of a simple cell, the results of physiological experiments qualitatively support this idea. Therefore, we used a feed-forward connection as the basic structure to realize orientation selectivity. Fig.3 shows a block diagram of the vision system used in the present work. The system consists of a silicon retina, an AD converter and an FPGA (Xilinx XCV150). As shown in the Fig., the multiple pixels, located on a straight-line with preferred orientation, are averaged in the FPGA. The receptive field produced by this model is the even-type. The odd-type receptive fields can be obtained by combining neighboring even-type responses. Here, we used the silicon retina developed by Kameda et al.[20]. The spatial response of this silicon retina exhibits a Laplacian-Gaussian-like receptive field. The output of the silicon retina, obtained as analog voltage, is read out pixel by pixel, and converted to 8-bit digital signals. Subsequently, the digital signals are sent to the FPGA. The FPGA aggregates multiple pixels of the retina, mimicking the feed-forward model shown in Fig.2. The configured circuit can generate the response orienting at 0 deg, 60 deg and 120 deg.

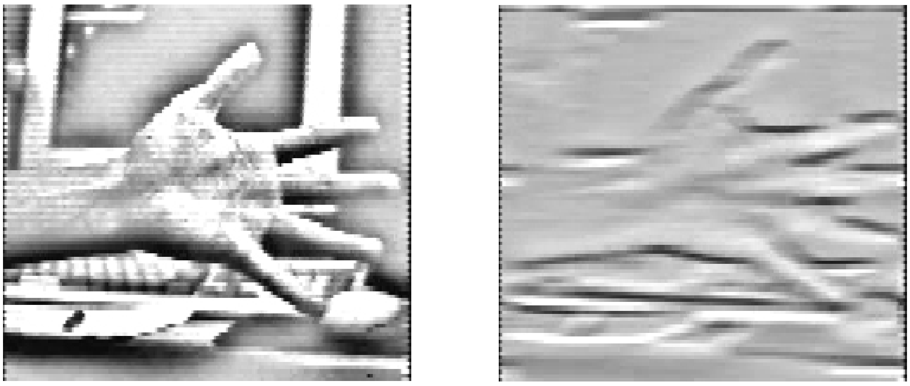
IV. IMAGE PROCESSING WITH THE SYSTEM

A white bar on black background was presented to the system. The orientation selective responses of the system are shown in Fig.4. The white bar is oriented at 0 deg. The preferred orientation of the system was also set to 0 deg. The resolution of the silicon retina used here was 40x46 pixels. (A) is the even-type response. (B) is the odd-type response generated by subtraction between two even-type responses. For each case, responses of 8 pixels are aggregated. The excited and inhibited sub-regions appear side by side alternately, similar to the elongated receptive field of simple cells in the primary visual cortex. Low noise responses are obtained because the noise compensation circuit is embedded in the silicon retina. The response of the system to a natural scene was examined under indoor illumination (0.18W/m2). Fig.5 shows the responses of the system to a hand in a laboratory scene. (A) is the output of the silicon retina. The edges in the image are enhanced with a Mach-band-like effect. (B) is the odd-type orientation selective output preferred to horizontal orientation. Only horizontal edges are enhanced, while others such as vertical edges of the monitor are blurred. It is notable that these computations are carried out in



(A) (B)

Fig. 4. Responses of the system to a slit pattern. (A) and (B) are even-type and odd-type response, respectively.



(A) (B)

Fig. 5. Response of the system to a hand. A is the output of the silicon retina, B is odd-type response preferred to 0 deg. orientation (horizontal orientation).

real-time (within the frame sampling time with NTSC) using a compact and low power hardware. The preliminary version of the present system has been applied to real-time image processing for autonomous robot [22], [23].

V. CONCLUSION

In this study, we have configured the vision system, which consists of a silicon retina and an FPGA. This system provides an orientation selective receptive field constructed by the hierarchical architecture based on the feed-forward model. The system can produce the orientation selective response to natural images in real-time under indoor illumination. To implement a large scale parallel vision system, we will design an analog VLSI chips which exhibit orientation selective receptive fields.

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