Implementation of Early Vision Model for Edge Extraction with Single-Electron Devices

Andrew Kilinga Kikombo[a], Alexandre Schmid[b], Tetsuya Asai[a], Yusuf Leblebici[b], and Yoshihito Amemiya[a]
[a] *Grad. Sch. of Information Science and Technology, Hokkaido University, Japan,* kikombo@sapiens-ei.eng.hokudai.ac.jp
[b] *Microelectronic Systems Laboratory, Swiss Federal Institute of Technology (EPFL), Switzerland*

We propose a possible circuit structure consisting of single-electron circuits that can extract edges in projected images. Electrical circuits that are designed by mimicking computational structures in living organisms—neuromorphic circuits, would provide an insight in developing even more efficient processors. In this work, based on a well studied model for edge detection in the vertebrate retina [1], we propose a single electron circuit performing the same function, and demonstrate its operation.

The vertebrate retina consists of massively interconnected neural cells in a hierarchical structure where edge detection is carried out mainly through three types of cells: (i) photoreceptors which transduce light into electrical signals, (ii) horizontal cells which receive inputs from the superjacent layer of photoreceptors, and produce spatially-averaged outputs in relation to the inputs, and (iii) bipolar cells that produce the difference in amplitudes between the outputs of photoreceptors and horizontal cells [1]. The schematic model is shown in Fig. 1(a). We assume that illuminated (or non-illuminated) photoreceptors produce low (or high) potentials (Fig. 1(b)-P). The outputs are spatially averaged by horizontal cells (Fig. 1(b)-H). The difference in amplitudes between photoreceptors and horizontal cells is obtained by subtracting "H"- from their corresponding "P"-values in bipolar cells. Therefore, the non-zero outputs of bipolar cells represent positions of edges in the input image (Fig. 1(b)-B).

Based on the retinal model above, we propose a neuromorphic architecture with single-electron oscillators [2]. A single-electron oscillator consists of a tunneling junction C_j, resistance R and a bias voltage source (see insets in Fig. 2). When a positively-biased (or negatively-biased) oscillator is illuminated, photo-induced electron tunneling in C_j occurs [3-4], which leads to voltage drop (or increase) at the node (● in Fig. 2) because of electron tunneling from the ground (or node) to the node (or ground). We refer to this as a firing event. Since the rate of electron tunneling is proportional to the intensity of incident light, the average firing rate of each oscillator would also correspond to the intensity of light input.

A unit pixel of the proposed edge extracting circuit is shown in Fig. 2. We implement a retinal photoreceptor (P) with a positively-biased oscillator that is triggered by external light inputs. Horizontal cells (H) are constructed by resistively-coupled single-electron oscillators (negative bias), to emulate extensive gap junctions in retinal cells. Subtractive functions in bipolar cells can qualitatively be imitated by neural excitation and shunting inhibition mechanisms. This is achieved through capacitive coupling between oscillators in the bipolar cell layer (B_x) [5]. An excitatory coupling is achieved by connecting a positively- (+) to a negatively- (-) biased oscillator. In the absence of an external input, the oscillator node takes a voltage value equivalent to the bias voltage. If tunneling occurs in the positive oscillator, this leads to a drop in the node potential of the coupled negative oscillator below its threshold, thus inducing it to tunnel. Shunting inhibitory coupling is realized by applying the same bias voltage to the two coupled oscillators. For example if the two are positively biased, tunneling in either of them leads to a drop in the node voltage of the other far below the threshold, thus restraining it from tunneling (inhibition) even in the presence of an external trigger input. With these excitatory and inhibitory configurations, we partly imitate subtractive functions of bipolar cells as follows. Let us assume that electron tunneling occurred in P_1 (Fig. 2). This induces tunneling in the B_{1l} oscillator to trigger a subsequent tunneling in B_{1l}-B_{3l} branch (excitatory). Simultaneously, tunneling in P_1 induces tunneling in H, which in turn induces B_2 to tunnel. This activates the inhibitory coupling between B_2 and B_{3l}. By so doing, B_2 restrains B_{3l} from tunneling, thus reducing its average firing rate. If the B_2 cells on both sides of B_{3l} tunnel, they would increase the inhibition effect on it, sufficiently reducing its average tunneling rate. Therefore if adjacent photoreceptors are illuminated, the average firing rates of corresponding output cells (O) would be extremely low in comparison with those at the edges. Through this process, the circuit can detect the edge position, i.e., positions where average firing rates of bipolar cells is high.

To confirm the basic operation, we constructed a one-dimensional array circuit consisting of 100 pixel circuits. Light input was incident upon photoreceptors from number 30 to 70. Light input was simulated by applying an external trigger input on photoreceptors. The response of each cell in the photoreceptor, horizontal and bipolar cell layers is shown in Fig. 3. The vertical axis is normalized with the highest average firing rate in the photoreceptor layer. As the figure shows, the average firing rate of the horizontal cells is lower than the corresponding photoreceptors. This is because of the resistive coupling in horizontal layer. The bipolar cells with a high firing rate correspond to the photoreceptors at the edges of the incident image. Thus the proposed single-electron structure can successfully perform as an edge detecting circuit.

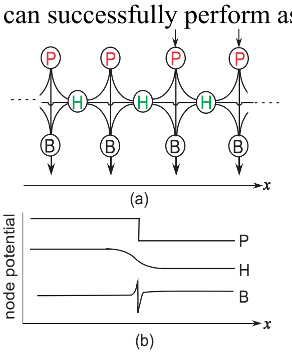

Fig. 1 Mechanism of edge detection in the vertebrate retina

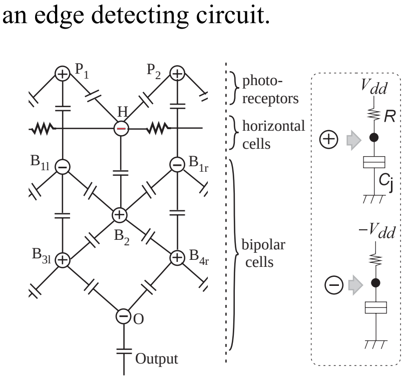

Fig. 2 Unit pixel of the edge detecting circuit

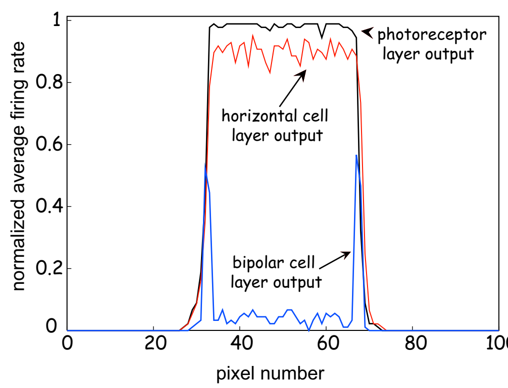

Fig. 3 Response characteristics of photoreceptor, horizontal and output (bipolar) cells. Temperature = 0 K.

References

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