A Neuromorphic Circuit for Motion Detection with Single-electron Devices based on Correlation Neural Networks

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Nano-electronic devices are projected as promising candidates for future electronic LSI platforms with specific applications in parallel analog information processing. As one of the *more-than*-Moore candidates, single(few)-electron devices have been extensively studied, because they inherently operate with extreme low power dissipation and thus are viewed as promising functional devices for low-power applications. At present, most of the research has primarily focused on device fabrication techniques. However, one key issue to tackle is on how to incorporate such devices in future LSI systems. That is, it is necessary to come up with new architectures that could accommodate new device concepts, and also address draw backs facing nano-electronic devices. The present conventional architectures won't be able to fully cater for low fault-tolerance and non-uniformity among individual units in nano-electronic circuits.

One way of achieving this goal is to learn from biological (neuronal) systems. Despite the fact that neurons are highly susceptible to environmental interferences, they nevertheless effectively carry out information processing. By obtaining hints from such systems, we could create robust and efficient LSIs especially for parallel information processes. In this work, toward realizing *neuromorphic* image processors with nano-electronic devices, we propose a basic circuit consisting of single-electronic devices and demonstrate that it can detect motion in incident images.

Motion detection is one of the essential tasks in first levels of visual information processing carried out in the retina. Living organisms, in particular, insects utilize motion detection to avoid collision and in motion perception. The proposed circuit is based on the correlation motion scheme [1]. In this model, motion detection is carried out by comparing signals from a photoreceptor to delayed signals from adjacent photoreceptors. This is illustrated in Fig. 1(a). The photoreceptors (P_i s) transduce light inputs (a light spot moving from the left (P_1) to the right (P_2) at nominal velocity v) into electrical signals. The signals are fed to the corresponding correlators and also to the neighboring pixels through delayers. For example, let's consider pixel 2. Photoreceptor P_2 receives light inputs to produce electrical signals corresponding to the light intensity. Output signals of P_2 are fed to the underlying correlator C_2 and also to the adjacent correlator C_3 through delayer circuit d_2. Similarly, correlator C_2 receives a delayed signal from adjacent photoreceptor P_1 through d_1. The output of C_2 is given by the product of these two signals (P_2 and d_1). In other words, C_2 calculates the correlation value between P_2 and d_1. As illustrated in Fig. 1(b), if the two signals overlap, i.e., if the time the light spot takes to move from P_1 to P_2 ($\equiv t_{12}$) is equivalent to the delay time (τ), the correlator (C_2) gives the maximum output. This would be referred to as the maximum detectable velocity (v_{max}). Otherwise, if the velocity is lower (or higher) than the maximum velocity, the correlator gives a monotonously increasing (or decreasing) output (Fig. 1(c)).

The conceptual schematic model is shown in Fig. 1(d). Photoreceptor P_{i+1} produces an excitatory signal toward correlator C_{i+1}, and interneuron I_i. At the same time, P_i sends the excitatory signal to delayer D_i. The delayer in turn produces an inhibitory signal toward interneuron I_i. The interneuron I_i produces an inhibitory signal toward correlator C_{i+1}. The correlator gives a zero output at a maximum value of the inhibitory signal I_i. The output then gradually increases as the inhibitory signal decreases. Thus the correlator qualitatively imitates multiplication function by producing an output corresponding to the difference in magnitude of the excitatory signals from P_{i+1} and inhibitory signals from I_i (delayed signals from P_i). The additional excitatory coupling between P_{i+1} and I_i prevents the correlator from responding to stationary light spots by constantly inhibiting C_{i+1} through I_i.

To realize the proposed motion detecting circuit, we employ single-electron oscillators [2]. A single-electron oscillator, (see inset in Fig. 2(a)) consists of a tunneling junction Cj, resistance R and a bias voltage source. When a negatively-biased (or positively-biased) oscillator is illuminated, *photo-induced* electron tunneling [3 - 4] in C_j occurs, which leads to voltage increase (or drop) at the node (●) because of electron tunneling from the node (or ground) to the ground (or node).

The retinal photoreceptor is implemented with a negatively biased single-electron oscillator. We assume that the number of tunneling events is proportional to the intensity of illuminated light; high intensities would produce high firing rates and vice versa. The delayer is realized with capacitively coupled single-electron oscillators, forming a delay transmission line. Fig. 2(a) shows the basic configuration of the delayer. Let us assume that electron tunneling occurred in P_i. This triggers a signal flow toward underlying oscillator $D_{1,j}$. Electron tunneling in P_i leads to node voltage increase in $D_{1,i}$ above its threshold thus inducing it to tunnel. Likewise tunneling in $D_{1,i}$ reduces the node voltage of $D_{2,i}$ below the threshold inducing it to tunnel [5]. Therefore signals emanating from the photoreceptors propagate through a series of positively and negatively biased oscillators, with a time delay at each stage caused by stochastic nature of electron tunneling. Fig. 2(b) shows circuit construction of the conceptual schematic model shown in Fig. 1(d). Suppose that a light spot is moving from the left to the right. This triggers photoreceptors to tunnel. The delayer circuit delays signals flowing from photoreceptor P_i toward $D_{2,i}$ as explained above. As explained in Fig. 1(d), the correlator is inhibited by the delayer output. Propagation of tunneling events in a transmission line consisting of capacitively coupled positively- and negatively-biased oscillators can be inhibited by inserting a unipolar pair of oscillators [5]. This is realized by capacitively connecting the delayer to the correlator circuit with a unipolar pair of negatively biased oscillators (see solid box in Fig. 2(b)). On the other hand, tunneling in P_{i+1} induces tunneling in B_{i+1} which in turn induces C_{i+1} to tunnel. Because C_{i+1} and $D_{3,i}$ make an unipolar pair, tunneling in $D_{3,i}$ inhibits tunneling in C_{i+1}. Therefore the tunneling rate of C_{i+1} increases as the inhibition signal from $D_{3,i}$ decreases. The additional $D_{3,i+1}$ connection between P_{i+1} and $D_{3,i}$ prevents the correlator from responding to stationary images.

It should be noted that the conceptual circuit responds to light spots moving from the left to the right only. Therefore we designed a bi-directional motion detection circuit shown in Fig. 2(c). We employed an additional transmission line between P_{i+1} and C_i. This produces delayed signals toward correlator C_i, for light spots moving from the right to the left.

The operation of the proposed motion detection circuit was investigated though Monte-Carlo based computer simulations with a one-dimensional array construction consisting of 100 pixels. In the simulations, instead of light inputs, we applied trigger voltages of 2.5 mV to photoreceptors P_is in Fig. 2(c). All the coupling capacitances were set to 2 aF, whereas tunneling junction capacitance C_j was set to 10 aF. Figure 3 shows simulation results of velocity response curve evaluated at zero temperature. The vertical axis shows maximum firing rate of the 50*th* correlator circuit against velocity of projected image. The proposed circuit can detect motion in images with a maximum detectable velocity of 10 pixels/ns. This would correspond to a maximum velocity of 1 km/s if adjacent photoreceptors were fabricated at a pitch of 100 nm. Furthermore, the maximum detectable velocity of this circuit can be tuned by adjusting delay-time τ along the delay transmission line. This could be achieved by increasing (or decreasing) the number of oscillators to increase (or decrease) the value of maximum detectable velocity.

References:

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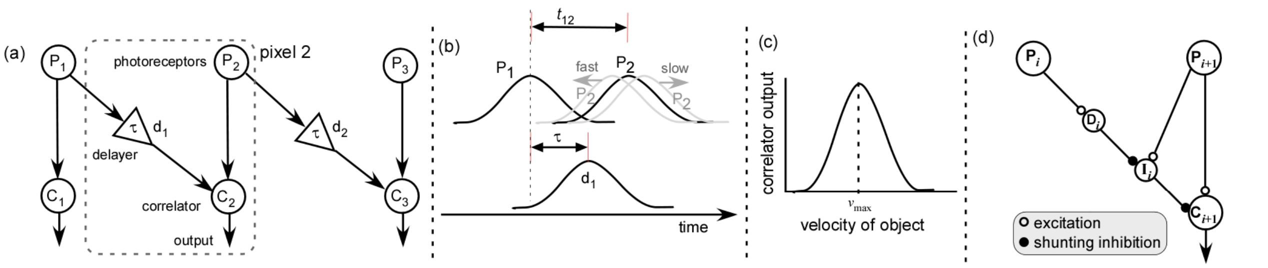

Fig. 1 (a) Correlation model for motion detection consisting of photoreceptors (P), delayers (D) and correlators (C). (b),(c) Operation of the correlation model. (d) Conceptual schematic model with single-electron devices. The photoreceptors produce an excitatory signal toward the delayer and correlator circuits.The correlators receive excitatory signals generated from corresponding photoreceptors and inhibitory signals from adjacent photoreceptors through delayer circuits.

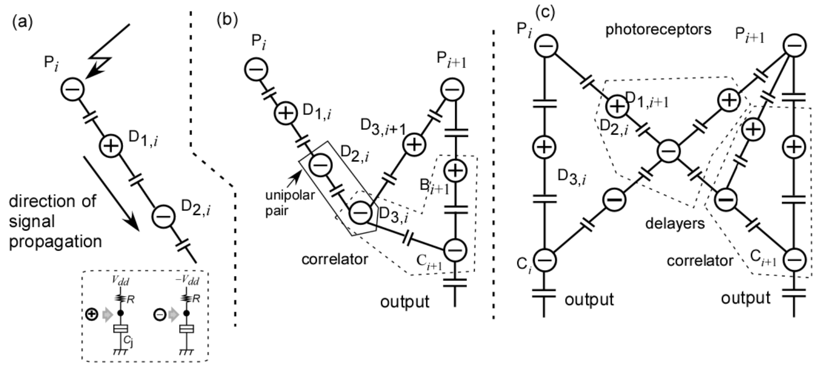

Fig. 2 (a) Signal propagation through oscillators in the delayer circuits. (b) Operation of the correlator circuit. (c) unit pixel for bidirectional motion detecting circuit.

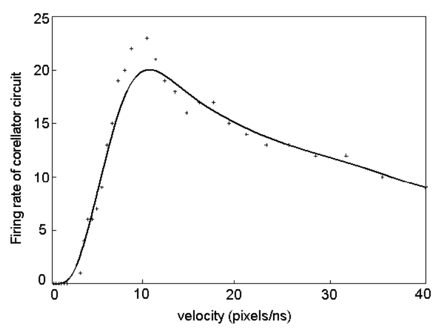

Fig. 3 Motion detection with a 100 pixel array construction. Vertical axis shows maximum firing rate of the 50*th* correlator against velocity of projected image.