An Analog Integrated Circuit for Motion Detection

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1 Introduction
The recognition of motion and shape is an essential function in biological vision systems. The visual image is divided into each brightness in massively parallel photoreceptor cells and is preprocessed in following cells in retina. Then the preprocessed information is processed via two routes of motion recognition and shape recognition in brain. Finally, they are aggregated. The real time detection of motion, which needs the high speed in processing, should be done in hardware since it leads to wide practical applications.

The hardware should be implemented in analog integrated circuits which have the capability of the large-scale integration of neurons, as in biological systems. The optical flow, which represents the information of motion, has been studied in the research field of computer vision[1]. The optical flow chip has been tried to be realized by J. Kramer et al[2]. We have tried to simplify the fundamental analog integrated circuit for motion detection combining biological systems with a simplified algorithm of the optical flow. The results of SPICE simulation of the one dimensional network showed that it can detect the direction and speed of motion and that expand into the two dimensional network.

2 Model and Algorithm of Motion Detection
The optical flow in the two dimensional plane is represented with a following equation[1]
\[
\frac{\partial f}{\partial x}u + \frac{\partial f}{\partial y}v + \frac{\partial f}{\partial t} = 0, 
\]
where \( f \) is the intensity at a position \((x, y)\) and \( t \) the time. It was found that equation (1) can be simplified by assumption:
\[
\lambda(u_{i+1,j} + u_{i-1,j} + u_{i+1,j+1} + u_{i,j-1} - 4u_{i,j}) - f_x(i,j)f_t(i,j) = 0, \]  \( \lambda \) is the constant, and \( i \) and \( j \) the positions in \( x \) and \( y \) directions, respectively. For the second term \( f_xf_t \) in eqs. (2) and (3) change the sign depending on the direction of motion. Their absolute values are proportional to the velocity of motion. The first term in eqs. (2) and (3) means spatial smoothing.

For the one dimensional motion the optical flow is simplified as follows.
\[
-\lambda(u_{i-1} + u_{i+1} - 2u_i) + f_xf_t = 0. \]  (4)

The correlation model of motion detection[3] for the one dimensional space is shown in Fig. 1(a). Each cell has a direct output and two delayed outputs with a time constant \( \tau \) being connected with neighboring cells. The connection to the right-hand side is excitatory and to the left-hand side is inhibitory.

The target of light spot moves toward the \( x \) direction with the velocity \( s \). It passes the \((i-1)\)th cell at time \( t \) and the \( i \)th cell at \((t+dt)\). When \( \tau \) is equal to \( dt \), the output \( I_{out} \) is the highest since the delayed output from the \((i-1)\)th cell coincides with the direct output. When \( \tau \) is shorter or longer than \( dt \), the output \( I_{out} \) is low since the correlation of the direct output to the delayed output is small. Then the absolute value of output \( I_{out} \) is varied depending on the correlation, as shown in Figs 1(b) and (c). Since the output cell receives inhibitory and excitatory synaptic connections from the neighboring cells, the sign of the output \( I_{out} \) is changed when the direction of motion is changed.

3 Circuit and Network for Motion Detection
The circuit of the \( i \)th cell of the model in Fig. 1(a) is shown in Fig. 2, which is called a velocity sensing circuit(VSC). The input \( I_{in,i} \) produces the source current \( I_{s,i} \) of a differential pair. The delayed outputs \( D_{out,i-1} \) and \( D_{out,i+1} \) from the neighboring cells are received as \( V_{in,i-1} \) and \( V_{in,i+1} \) respectively. They divide the source cur-
Fig. 1. The correlation model. (a) network structure; (b) input signals; (c) outputs of the ith cell.

Fig. 2. Velocity sensing circuit (VSC).

Fig. 3. One dimensional VSC network.

Fig. 4. Time response of the ith VSC.

The one dimensional network is constructed by connecting VSCs, as shown in Fig. 3. The nodes of outputs are connected with a pass transistor. A following equation is obtained around the ith node,

\[ -G(V_{i-1} + V_{i+1} - 2V_i) + I_{out,i} = 0, \]  

where \( V_i \) is the potential at the ith node and \( G \) the conductance of the pass transistor. Equation (5) has the same formula as eq. (4) of the optical flow. Thus, the potential at the ith node \( V_i \) represents the local velocity at the position \( i \).

The response of the ith VSC is shown in Fig. 4, where \( G = 0 \). When an image moves to the right-hand side, a positive output current \( I_{out,i} \) is obtained, as shown in Fig. 4(a). A negative output current \( I_{out,i} \) is obtained when an image moves to the left-hand side, as shown in Fig. 4(b).
4 Simulation Results

A primitive network was evaluated by SPICE simulation. The input current $I_{in,i}$ was applied during the period when a light spot is located in the area of VSC with the length $L$. No input current was applied when the light spot is located in the spacing $d$ between VSCs.

The results of SPICE simulation are shown in Fig. 5 for a primitive network with $L = 100\mu m$, $d = 10\mu m$ and $C = 50pF$. The output current $I_{out,i}$ was approximately proportional to the speed of light spot in the range between + and - maximum values $s_0$. The sign of the output current was changed when the direction of motion was changed. The absolute value of $s_0$ means the highest speed measurable. It is increased when $C$ is reduced and $d$ is increased.

The layout pattern of a test chip is shown in Fig. 6, which is going to be fabricated at Electron Device Research Center in our university. A photodiode generates an input current $I_{in,i}$. The capacitance $C$ is formed with a pn junction. Thus, the maximum speed $s_0$ can be controlled by varying the bias voltage applied to the pn junction.

5 Motion Detection System

In a biological motion detection system as in monkey, the edge of target in an image is detected at the primary visual cortex V1 through a retina. Then the orientation and speed are detected in the middle temporal area MT. Silicon retina forms the edge of target in an image[4], [5]. The orientation of the edge could be detected in a self-organized network as the orientation columns in V1[6]. The motion field in the two dimensional space could be formed by arranging the one dimensional networks in Fig. 3 to $x$ and $y$ axes. Thus, the orientation and speed of motion could be detected when a network is formed as the orientation and speed columns in MT.

6 Conclusion

It was clarified in motion detection that the analog network based on a biological system works in a similar manner to a simplified algorithm of the optical flow. The proposed network is constructed by combining simple fundamental circuits called VSC. The direction and speed of motion can be detected with the network. The network is expandable for large scale integration. A motion detection system for the two dimensional space was proposed based on biological systems.
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References