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Image Segmentation/Extraction Using Nonlinear Cellular Networks and Their VLSI Implementation Using Pulse-Modulation Techniques

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SUMMARY This paper proposes a new method for image segmentation and extraction using nonlinear cellular networks. Flexible segmentation of complicated natural scene images is achieved by using resistive-fuse networks, and each segmented regions is extracted by nonlinear oscillator networks. We also propose a nonlinear cellular network circuit implementing both resistive-fuse and oscillator dynamics by using pulse-modulation techniques. The basic operation of the nonlinear network circuit is confirmed by SPICE simulation. Moreover, the 10×10-pixel image segmentation and extraction are demonstrated by high-speed circuit simulation.

key words: *resistive-fuse network, oscillator network, image segmentation, image extraction, pulse modulation circuit*

1. Introduction

In order to recognize a natural scene image that includes several objects, we should segment the image into several recognition target objects, such as human faces, and extract them one by one. Although there exist some image segmentation algorithms [1], [2], a new segmentation technique using a neural network model has recently been proposed. The model is called *locally excitatory, globally inhibitory oscillator networks* (*LEGION*) [3]–[5], which is suitable for pixel-parallel operation.

We have already proposed a modified LEGION model suitable for VLSI implementation and its VLSI circuit based on pulse-modulation techniques [6], [7]. However, the oscillator network segments an image into many small pieces, such as a mouth, a nose and eyes in a human face, while we should extract the whole face region for face recognition. Thus, it is difficult to achieve effective object extraction only by using the oscillator network.

For this purpose, we use the resistive-fuse network, which is a well-known image segmentation processing model that preserves image edges and eliminates noise [8]. It can achieve flexible segmentation depending on an object size. The resistive-fuse network model can be implemented by our pulse-modulation techniques because it is one of the pixel-parallel nonlinear dynamical systems.

The resistive-fuse network, however, cannot extract each segmented region automatically. Therefore, in this paper, we propose a new segmentation/extraction method combining the resistive-fuse and oscillator networks. We also propose a VLSI circuit implementing the resistive-fuse and oscillator networks. Since we can share most circuit components for both network implementations, very few additional parts are required, and the circuit area is nearly equal to that of the original oscillator network circuit that we have already proposed [7].

This paper is organized as follows. In Sect. 2, we briefly review the resistive-fuse and nonlinear oscillator network models, and clarify their essential mechanisms. Numerical simulation results of image segmentation and extraction are also shown. In Sect. 3, we propose the nonlinear cellular network circuit implementing the resistive-fuse and oscillator networks using a pulse modulation approach. In Sect. 4, basic operations of the proposed circuit in the resistive-fuse and oscillator network modes are confirmed by circuit simulation. Segmentation/extraction processing of a 2-D image is also demonstrated. Finally, the conclusion is given in Sect. 5.

2. Nonlinear Cellular Networks for Image Segmentation and Extraction

2.1 Resistive-Fuse Networks for Image Segmentation

Figure 1 shows a schematic circuit diagram of the original resistive-fuse network. In this model, each pixel node consists of a voltage source V_{Ii}, which corresponds to an input image data at pixel i, and a resistor with conductance σ. Each pixel node is connected to the nearest neighbors with the resistive-fuse elements. For simplicity, the number of neighboring connections of

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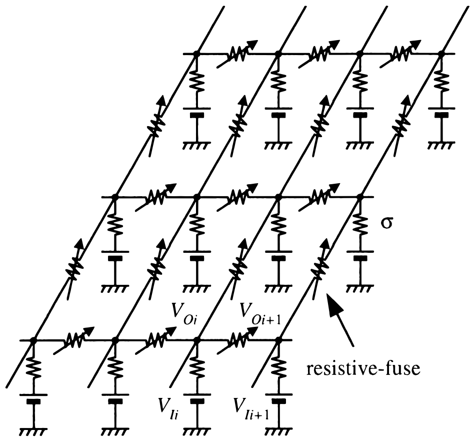


Fig. 1 Schematic circuit diagram of original resistive-fuse network model.

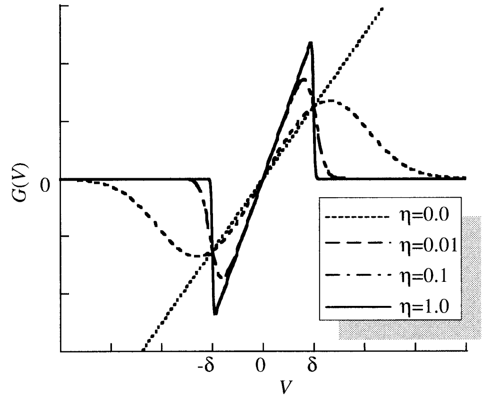


Fig. 2 Voltage-current characteristic of resistive-fuse.

each pixel node is four in Fig. 1, but we assume eight neighborhoods in this paper.

The resistive-fuse network reaches a steady state so as to minimize the total power consumption E, which is given by

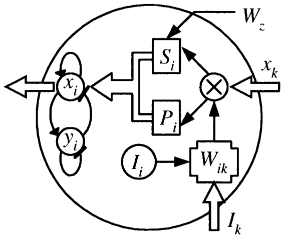
$$E = \sum_i \sum_{k \in n_i} \int_0^{V_{Oi}-V_{Ok}} G(V)dV + \frac{\sigma}{2} \sum_i (V_{Oi} - V_{Ii})^2, \qquad (1)$$

where, V_{Oi}, which represents the processing result (output), is a node voltage at pixel i: n_i is the neighborhood of i: $G(\cdot)$ is the voltage-current characteristic of a resistive-fuse shown in Fig. 2, and is given by

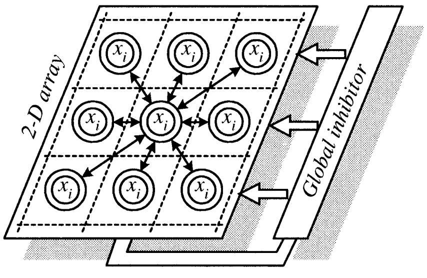
$$G(V) = \left[\frac{1}{1 + \exp(2\eta(V^2 - \delta^2))}\right] \frac{V}{R}, \qquad (2)$$

where, η, δ and R are constants. The variable η determines the characteristic of the resistive-fuse; i.e., it is a linear resistor if $\eta = 0$ and a resistive-fuse if $\eta = 1$.

From Eqs. (1) and (2), the resistive-fuse network behavior when $\eta = 1$ is as follows: If the absolute potential difference between neighboring pixels $|V_{Oi} - V_{Ok}|$ is smaller than the threshold value δ, the network behaves as a simple linear resistive network, and image smoothing is performed. On the other hand, if $|V_{Oi} - V_{Ok}| \geq \delta$, the pixel nodes are disconnected each other, and such pixels are recognized as an image edge.



(a) oscillator x_i



(b) oscillator network

Fig. 3 Oscillator network model.

In order to obtain the steady state of the resistive-fuse network, we use the steepest descent method:

$$V_{Oi}(t+1) = V_{Oi}(t) - \nu \frac{\partial E}{\partial V_{Oi}(t)},$$

$$\frac{\partial E}{\partial V_{Oi}(t)} = \sum_i \sum_{k \in n_i} G(V_{Oi}(t) - V_{Ok}(t)) + \sigma \sum_i (V_{Oi}(t) - V_{Ii}), \qquad (3)$$

where ν is a constant. Equation (3) just represents the updating process based on Kirchhoff's current law at each node. This process can be implemented by using our pulse-modulation circuit described in the next section.

If η is fixed at unity during the updating process, undesirable segmentation may be performed because the resistive-fuse network state is trapped at a local minimum. In order to achieve desirable segmentation, η should gradually be changed from 0 to 1 during the updating process.

2.2 Oscillator Networks for Object Extraction

We have already proposed a nonlinear oscillator network model for gray-level image extraction, which is suitable for pixel-parallel VLSI implementation. Figure 3 schematically shows the model. It consists of a 2-D array of oscillators, each of which corresponds to

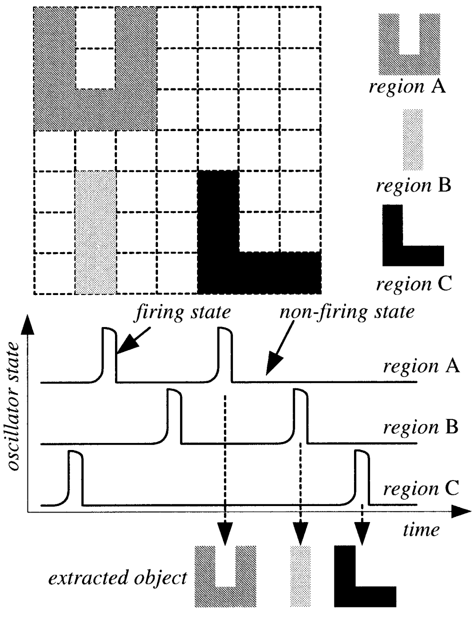


Fig. 4 Oscillator network states.

an image pixel, and the global inhibitor. Each oscillator is connected with the eight neighbors and the global inhibitor.

The dynamics of the i-th oscillator is described by the differential equations represented by two variables, x_i and y_i. In order to implement the oscillator network model using our pulse-modulation circuit, we changed them into difference ones, and are given by

$$\frac{x_i(t+1)-x_i(t)}{\Delta t} = -(x_i(t)-\zeta)^2(x_i(t)-\xi)+\rho + \alpha p_i + H_2(S_i) - y_i(t), \tag{4}$$

$$\frac{y_i(t+1)-y_i(t)}{\Delta t} = \varepsilon[\gamma(1+\tanh(x_i(t)/\beta-\lambda)) - y_i(t)]. \tag{5}$$

where ζ, ξ, ρ, α, ε, γ, β and λ are constants: $H_2(x) = 1$ $(x \geq 0)$ and $H_2(x) = -1$ $(x < 0)$. Each oscillator has a firing or non-firing state, and synchronous and asynchronous firing states between oscillators are produced as shown in Fig. 4. A region firing synchronously is extracted as a coherent pattern. Such cooperative behaviors are generated by p_i and S_i in Eq. (4), and are given by

$$p_i = H\left(\sum_{k \in N_i} W_{ik} - \theta_p\right), \tag{6}$$

$$W_{ik} = I_{max}/(1+|I_i - I_k|), \tag{7}$$

$$S_i = \sum_{k \in N_i} W_{ik} H(x_k - \theta_x) - W_z H(z - \theta_{xz}), \tag{8}$$

where θ_p, θ_x, θ_{xz} and W_z are constants: W_{ik} is the connection weight from oscillator k to i: N_i is the neighborhood of i: I_i is the intensity of pixel i, and I_{max} is the maximum intensity value: $H(x) = 1$ if $x \geq 0$ and $H(x) = 0$ if $x < 0$. The global inhibitor state z is given by

$$z = H\left(\sum H(x_i - \theta_z) - 1\right), \tag{9}$$

where θ_z is a constant.

The dynamics for extraction is as follows: *Leader* parameter p_i determines whether oscillator i can strongly fire or weakly fire. Coupling factor S_i determines whether oscillator i belongs to a firing region or not. When pixels i and k belong to the same coherent region, weight W_{ik} becomes large because $|I_i - I_k|$ is small. Because $H_2(S_i)$ in Eq. (4) becomes unity, oscillators i and k fire synchronously. On the other hand, when they belong to neighboring different coherent regions, they fire asynchronously because W_{ik} becomes small and $H_2(S_i) = 0$. Moreover, the other oscillators belonging to the other regions hardly fire because of the global inhibitor. Thus, coherent regions are extracted one by one.

2.3 Numerical Simulation Results

We performed numerical simulation of real image segmentation using Eqs. (2) and (3), where $\sigma = 1/120$, $R = 20$ and $\nu = 1$. The original and segmented images are shown in Figs. 5(a) and (d)–(g) with values of δ, respectively. During the updating, we changed the value of η in Eq. (2) from 0 to 1. Segmentation is successfully achieved as shown in Fig. 5(f), in which the regions corresponding to recognition objects such as human faces are smoothed, and their edge information is preserved.

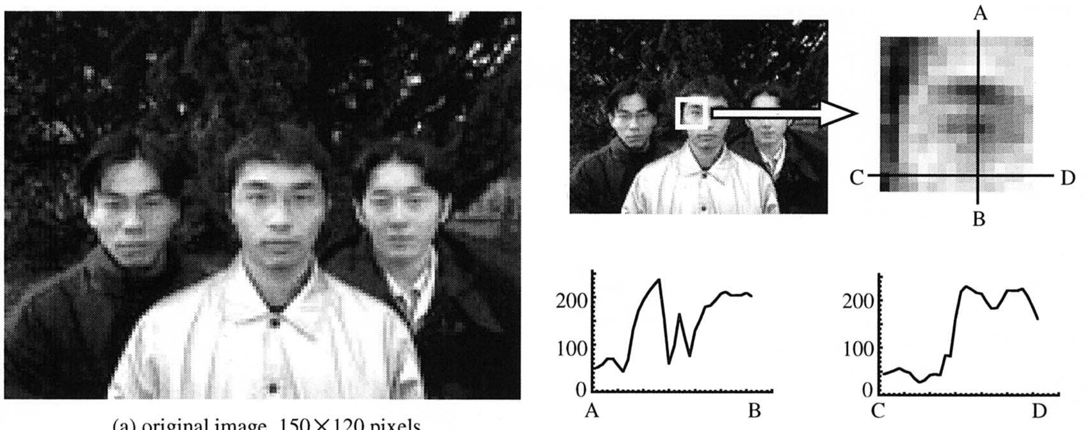
The numerical simulation results of object extraction using the oscillator network are shown in Fig. 6. Figures 5(a) and (f) are used as the input images of Figs. 6(a) and (b)–(d), respectively. In Fig. 6(a), although object extraction is achieved, the features of the human face are extracted separately. This result is not suitable for face recognition processing as described in Sect. 1. On the other hand, the whole face region, which includes all features, are extracted in Figs. 6(b) and (c).

Thus, the effective image segmentation and object extraction for real image recognition is achieved by using the resistive-fuse and oscillator networks.

3. A Nonlinear Cellular Network Circuit

3.1 Pulse Modulation Circuit Technique for Nonlinear Analog Dynamical Systems

The pulse modulation approaches, which include pulse-width modulation (PWM) and pulse-phase modulation



(a) original image 150×120 pixels
(b) pixel intensity at line A-B
(c) pixel intensity at line C-D

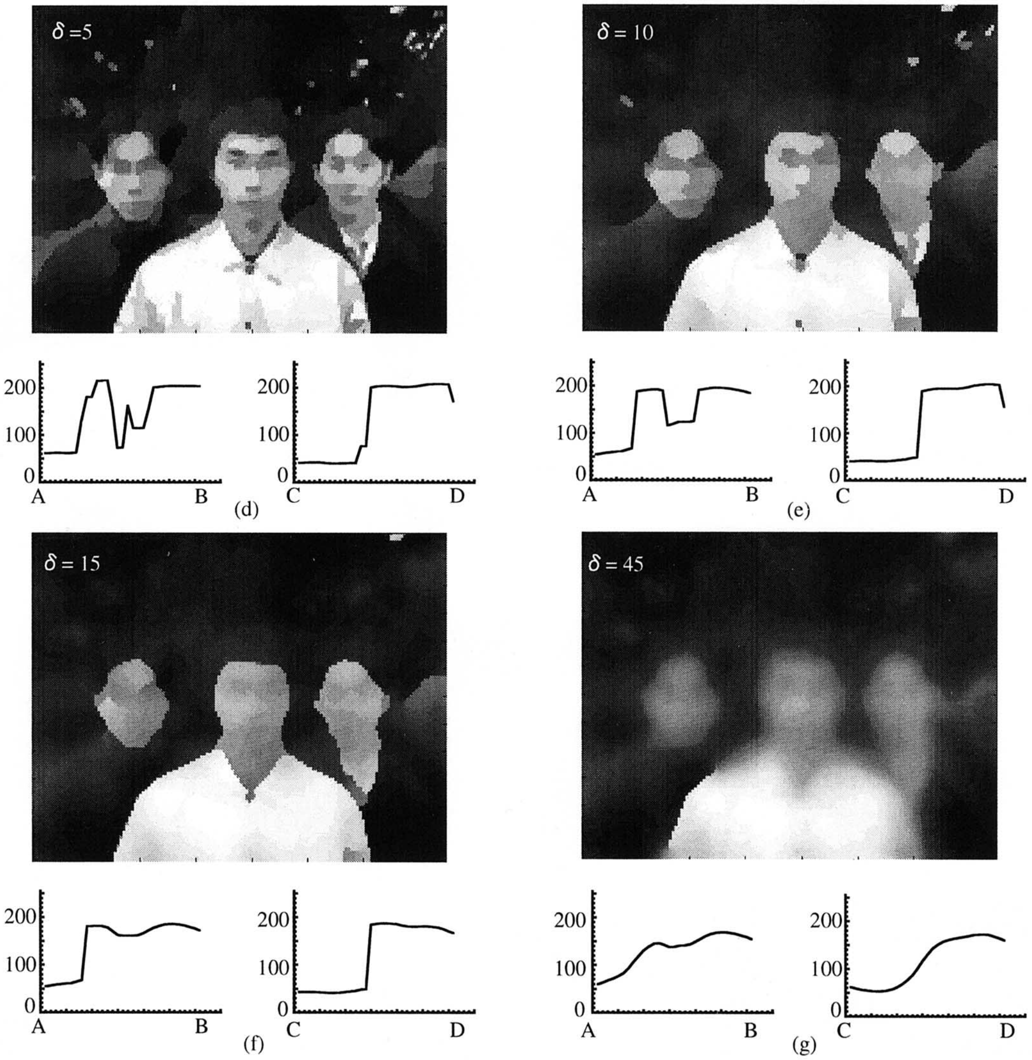


Fig. 5 Numerical simulation results of resistive-fuse network.

(PPM) methods, achieve time-domain analog information processing using pulse signals with a binary amplitude [9]. PWM/PPM circuits can implement arbitrary nonlinear dynamics as shown in Fig. 7 [10]. The input voltage V_{in} is linearly transformed into a PWM signal V_a and PPM signal V_b by comparing it with a linearly ramped signal V_{ramp}. By switching a current source that is modulated by nonlinear non-monotone waveform $f(t)$, the voltage of the capacitor node, V_{out}, is nonlinearly modulated. If the output voltage is fed

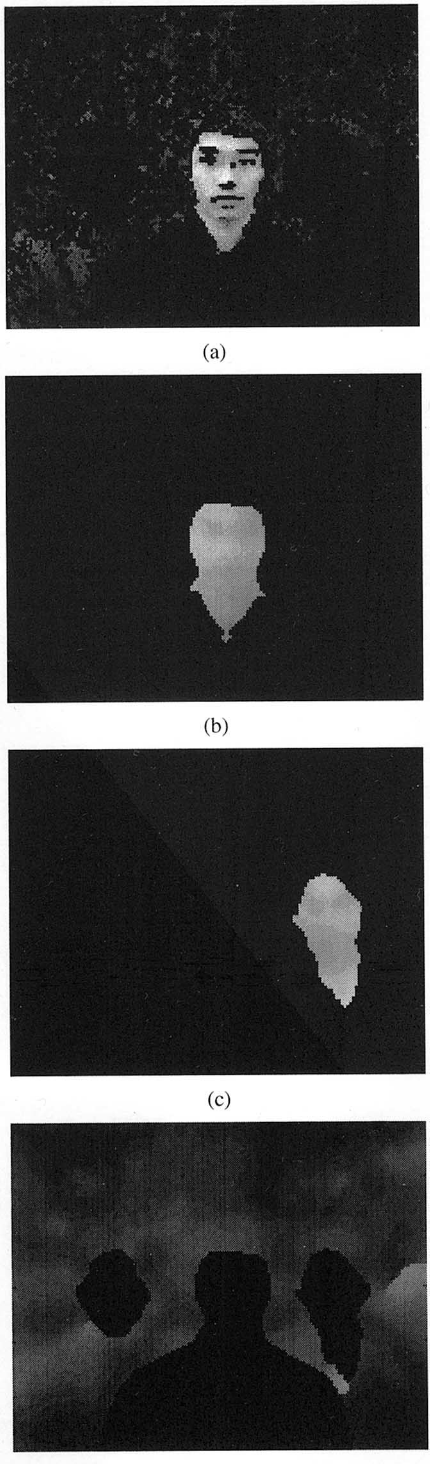

(a)
(b)
(c)
(d)

Fig. 6 Numerical simulation results of image segmentation and object extraction.

back to the input, this circuit can implement discrete-time dynamics.

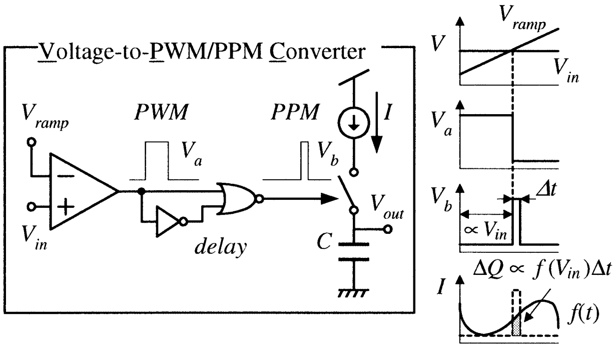


Fig. 7 Nonlinear transformation using pulse modulation.

3.2 Resistive-Fuse and Oscillator Operations

A pixel unit circuit for nonlinear cellular network implementing resistive-fuse and oscillator network dynamics is shown in Fig. 8, which is based on the oscillator circuit that we have already proposed [7]. This circuit has two modes: resistive-fuse and oscillator, and they are switched by SEL_1.

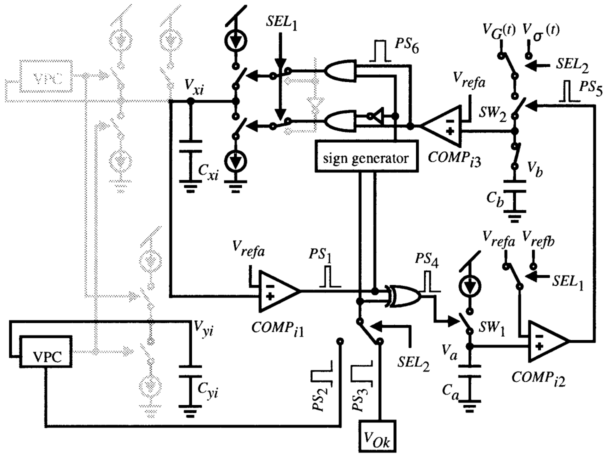
(1) Resistive-fuse Mode

The values of V_{Oi} and V_{Ii} are represented by voltage V_{xi} and V_{yi}, and are held at capacitors C_{xi} and C_{yi}, respectively. Voltage V_{xi} is linearly transformed into a PWM signal PS_1 with a pulse width of T_i by comparator $COMP_{i1}$. The pulse having a width of absolute difference value $|V_{Oi} - V_{Ok}|$ is generated by an XOR gate as a PWM signal PS_4 with a width of T_{ik0}. The pulse having a width of another absolute difference value $|V_{Oi} - V_{Ii}|$ is generated by switching signal SEL_2. The sign of $V_{Oi} - V_{Ok}$ is obtained by the sign generator. In order to synchronize the PWM signal with the nonlinear reference voltage, a pulse PS_4 is linearly transformed into a pulse PS_5 with a width of $T_{ik}(= T_{ik0})$. This pulse turns on SW_2 and capacitor C_1 holds the voltage $V_G(T_{ik})$, where V_G varies in the time-domain: $V_G(t) = G(t)$. Voltage $V_G(T_{ik})$ is linearly transformed into a pulse PS_6 with a width of $G(|V_{Oi} - V_{Ok}|)$. According as the sign signal, charges corresponding to the value $G(V_{Oi} - V_{Ok})$ are injected into or extracted from C_{xi} in each time step. Thus, the updating process expressed by Eq. (3) is performed.

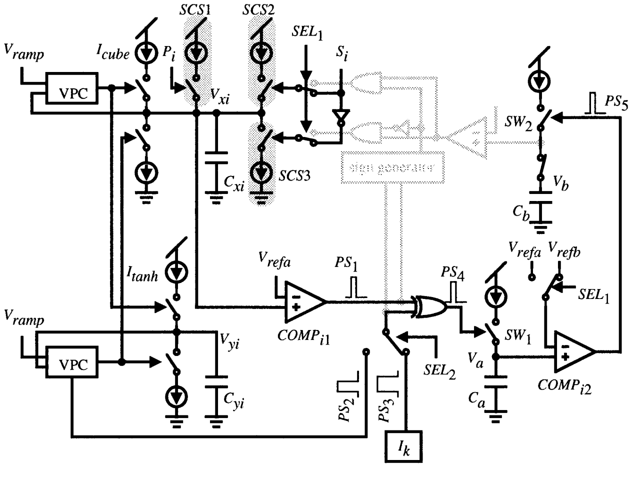
(2) Nonlinear Oscillator Mode

The values of x_i and y_i in the dynamics of an oscillator are represented by voltages V_{xi} and V_{yi}. The cubic and hyperbolic-tangent functions in Eqs. (4) and (5) are generated by converting from voltages into PPM signals in VPC and switching nonlinearly modulated current sources I_{cube}, I_{tanh} [7]. Charges corresponding to finite differences of x_i and y_i in Eqs. (4) and (5) are injected into or extracted from C_{xi} and C_{yi} in each time step.

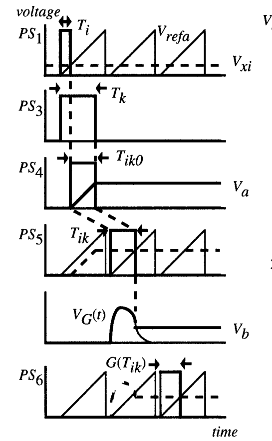
The connection weights expressed by Eq. (7) are



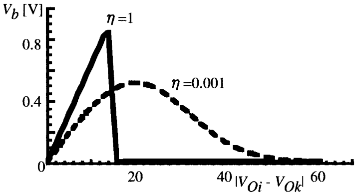
(a) the resistive-fuse mode



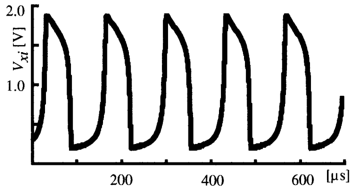
(b) the oscillator mode



(c) resistive-fuse timing chart



(d) HSPICE simulation result in the resistive-fuse mode



(e) HSPICE simulation result in the oscillator mode

Fig. 8 Pixel unit circuit for nonlinear cellular network circuit.

realized by using the circuit components implementing resistive-fuse transformation $V_G(\cdot)$. The pulse PS_4 corresponding to $|I_i - I_k|$ is generated and transformed into voltage V_a. By comparing V_a with reference signal voltage $V_{refb}(t)$ $(= I_{max}/t - 1)$, the pulse width T_{ik} of the signal PS_5 is given by $I_{max}/T_{ik} - 1 = V_a$, and this pulse is linearly transformed into voltage V_b. As a result, we obtain the voltage V_b corresponding to the connection weights W_{ik} in Eq. (7). A threshold function $H(\cdot)$ and summations used in Eqs. (6), (8) and (9) are generated by using a comparator $COMP_{i1}$ and switched current sources $SCS1$, $SCS2$, $SCS3$.

Thus, our proposed nonlinear cellular network circuit can implement both functions. Since we can share most circuit components for both network implementations, additional parts are very few, and the circuit area is nearly equal to that of the original oscillator network circuit. Therefore, as described in Ref. [7], the circuit area and power consumption for this circuit are estimated to be $150 \times 150\,\mu$m sq. and $150\,\mu$W at a power supply voltage of 5 V, respectively. We can integrate 100×100 pixels in a chip with power consumption of 1.5 W if the core chip area of 15×15 mm sq. is available.

4. Circuit Simulation Results

4.1 Basic Operation of Both Networks

We performed circuit simulation (HSPICE) of the proposed circuit. The device parameters used were based on a $0.6\,\mu$m CMOS process, and the supply voltage was 5.0 V. As shown in Figs. 8(d) and (e), the expected resistive-fuse characteristic and oscillation were obtained.

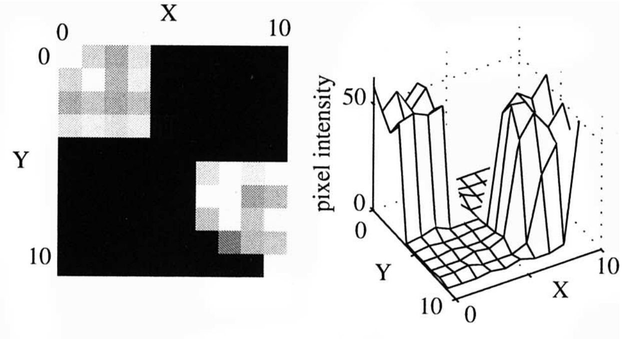
4.2 2-D Image Processing

Segmentation and extraction of a 10×10-pixel image are demonstrated in Fig. 9. These results were obtained by circuit simulation using PowerMill, a high-speed circuit simulator. In the resistive-fuse mode, the number of updating iterations was 30, and the operation time was $360\,\mu$s. As shown in Fig. 9(b), the input image is smoothed and its edge information is preserved. The object extraction is also achieved as shown in Fig. 9(c). The operation time was $500\,\mu$s, where the clock period was $1\,\mu$s. Thus, it was confirmed that the proposed circuit precisely implements the dynamics of resistive-fuse and oscillator networks.

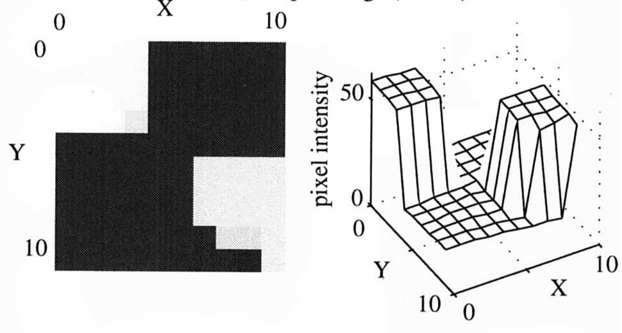
5. Conclusion

We proposed a new object extraction method using the resistive-fuse and oscillator networks. Flexible segmentation and individual object extraction are achieved by using both networks.

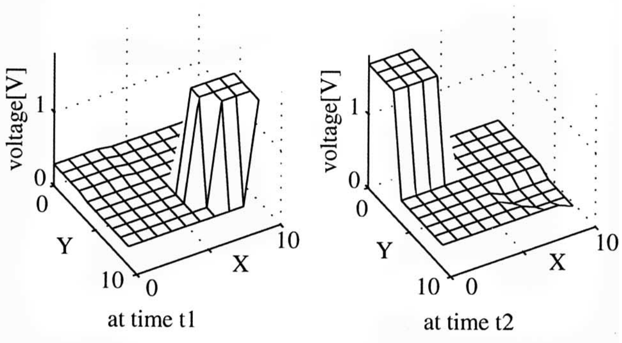
We also proposed a nonlinear cellular network circuit that can implement both functions of resistive-fuse and oscillator networks by using the same circuit components. By high-speed circuit simulation, segmentation and extraction of a 10×10-pixel image were demonstrated. From the circuit simulation results, we expect



(a) input image (10×10)



(b) circuit simulation result of image segmentation



at time t1

at time t2

(c) circuit simulation result of object extraction

Fig. 9 Circuit simulation results of 2-D networks.

to make the real-time image preprocessing LSI chip for a complex real scene recognition VLSI system.

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