Oscillator Networks for Image Segmentation and their Circuits using Pulse Modulation Methods

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ABSTRACT

This paper proposes a modified model of the oscillator network, LEGION, suitable for VLSI implementation. The model performs gray-level real image segmentation using nonlinear analog dynamics. Because of the limited calculation precision in VLSI implementation, it is important to estimate the calculation precision required for proper operations in the modified model. By using numerical simulation, the necessary precision is estimated to be 5 bits. A new circuit technique using pulse-width/pulse-phase modulation (PWM/PPM) methods is proposed for implementing nonlinear dynamics. A nonlinear oscillator circuit, which is the most important part of LEGION, is proposed by using this technique. The basic operation of this circuit is confirmed by circuit simulation.

KEYWORDS: oscillator networks, pulse modulation, nonlinear function

1. INTRODUCTION

Recently, many reports demonstrate that nonlinear analog dynamics plays an important role in neural information processing. Chaotic neural networks[1] and nonlinear oscillator networks[2] are typical examples. However, conventional neural hardware (VLSI implementation of neural networks) hardly implements such nonlinear dynamics. Typical models implemented in conventional neural chips are backpropagation networks and Boltzmann machines. The backpropagation networks are layer-type feed-forward networks and have no dynamics. Boltzmann machines have symmetrical connections. Thus their dynamics always leads to fixed-point steady states, and chaotic behavior or oscillation is never observed.

Circuit architectures in conventional neural chips are classified as digital or analog. Digital approaches have high calculation precision and controllability, but cannot implement analog dynamics exactly. Analog approaches are obviously suitable for realizing analog dynamical systems, but the calculation precision is affected by various non-idealities in circuit components. Moreover, it is not easy in analog approaches to generate arbitrary nonlinear, non-monotone transfer functions.

We have already proposed a new circuit technique generating arbitrary nonlinear functions by using a pulse-width modulation method[3]. We have also demonstrated that discrete-time, continuous-state nonlinear dynamical systems can be constructed by using this method[4]. However, the previously proposed technique requires plural reference waveforms corresponding to the inverse function of the expected nonlinear transfer function and plural comparators whose number is equal to the number of monotone intervals. These requirements increase power consumption and circuit complexity.

In this paper, we propose a new circuit technique for implementing nonlinear dynamics. Then, we describe a preliminary study for VLSI implementation of nonlinear oscillator networks, including the estimation of the calculation precision necessary for the proper operation. Finally, we propose a nonlinear oscillator circuit based on our new circuit technique.

2. PULSE MODULATION METHODS FOR NONLINEAR DYNAMICAL SYSTEMS

From the viewpoint of information representation, the pulse-width modulation (PWM) method is one approach toward achieving time-domain information processing using pulse signals. Another approach is the pulse-phase modulation (PPM) method, where the information is included in the pulse arising time.

A PWM approach has been proposed as an analog-digital merged circuit architecture[5]. This PWM approach is suitable for large-scale integration of analog processing circuits because it matches the scaling trend in Si CMOS technology and leads to low voltage operation. This approach also achieves lower power consumption operation than traditional digital circuits because one data is represented by only one state transition. The PPM approach also has the same advantages. However, it requires a reference signal (clock) defining the start time for measuring the phase, whereas a PWM signal includes all of the information in itself. PWM signals are therefore suitable for signal transmission, whereas PPM methods can effectively be used in local circuits.

We propose a new circuit technique using PWM/PPM methods that can implement arbitrary nonlinear dynamics. As an example, a third-order nonlinear function generator is shown in Fig. 1. The input voltage is linearly transformed into a PWM signal (a pulse with a width of T) by one comparator, and then the PWM signal is linearly transformed into phase T of the pulse with a width of Δt (PPM signal). The PPM signal switches a current source modulated by a nonlinear non-monotone waveform $f(t)$. The current source supplies charges equal to $f(T)\Delta t$ to a serially connected capacitor C. As a result, the voltage of the capacitor node is nonlinearly modulated; the voltage change is $f(T)\Delta t/C$. If the output voltage is fed back to the input, this circuit can implement discrete-time dynamics. This is an approximate solution of the corresponding differential equation if the voltage change is very small. Thus, we can easily obtain nonlinearly modulated voltages and PWM/PPM signals following arbitrary nonlinear dynamics.

As explained above, our new techniques use only one comparator for the voltage-pulse conversion and one reference waveform, and do not require plural inverse function wave-

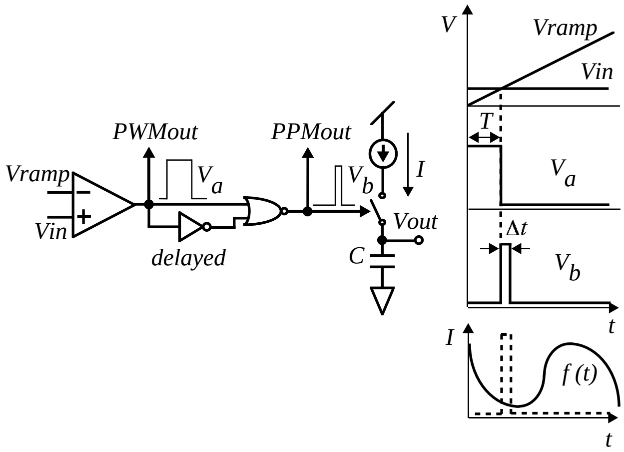

Figure 1: Third-order nonlinear function generator circuit

forms as in the previous approach. Therefore, the new circuits achieve less power consumption and much simpler circuit configuration, including the control system, compared with previous circuits. The simple configuration also leads to higher calculation precision.

3. OSCILLATOR NETWORK FOR IMAGE SEGMENTATION

3.1. Model Description

The segmentation of a visual image into a set of coherent patterns is a fundamental task, and recently, the importance of its role increases because the technology of single-object recognition has become increasingly advanced. The *locally excitatory, globally inhibitory oscillator networks (LEGION)* proposed by D. L. Wang and D. Terman[2, 6] are a practical model for image segmentation using a nonlinear oscillator system. The image segmentation using oscillator networks has some advantages when compared with other models. VLSI implementation of the nonlinear oscillator system is essential for real-time image (or moving picture) recognition because such a system requires a highly parallel operation.

Schematics of the LEGION model are shown in Fig. 2. This model consists of a large number of oscillators, each of which correspond to each image pixel, and the global inhibitor. Each oscillator is connected to the neighboring oscillators and the global inhibitor, which is a suitable structure for VLSI implementation from the viewpoint of interconnection complexity.

Let us explain the LEGION model dynamics. The original LEGION model for gray-level real image segmentation is described not by analog dynamics, but by software language. Therefore, we modified the model which is capable of segmenting gray-level real image with nonlinear dynamics. The dynamics of the i-th oscillator is represented by the following equations:

$$\frac{dx_i}{dt} = 3x_i - x_i^3 + 2 + \rho - y_i + \alpha H(CP_i) + H_2(S_i), \quad (1)$$

$$\frac{dy_i}{dt} = \varepsilon[\gamma(1 + \tanh(x_i/\beta)) - y_i], \quad (2)$$

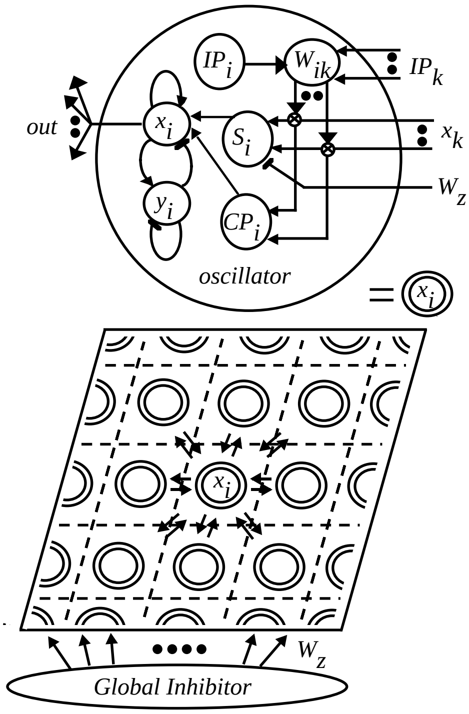

Figure 2: Oscillator network model (LEGION)

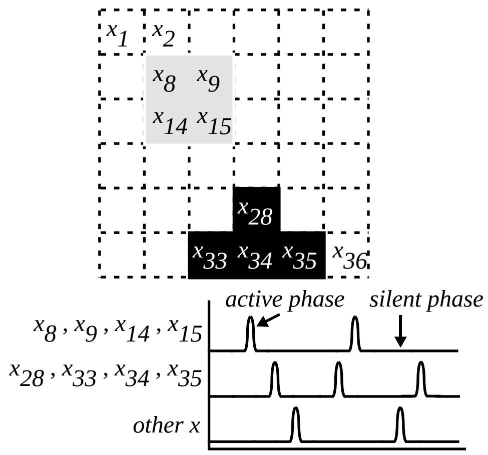

Figure 3: Oscillator network state

where ρ, α, ε, γ and β are constants, CP_i is a variable determined by the image data, S_i is a coupling term described below, and $H(x)$ and $H_2(x)$ are defined as $H(x) = 1$, $H_2(x) = 1$ if $x \geq 0$ and $H(x) = 0$, $H_2(x) = -1$ if $x < 0$. This dynamics produces synchronous and asynchronous states (these include active and silent phases) between oscillators as shown in Fig. 3. A region oscillating synchronously is extracted as a coherent pattern. An oscillator is determined to belong to an oscillation region or not according to whether $H_2(S_i)$ is positive or negative in Eq.(1). S_i and CP_i are represented by the following equations:

$$S_i = \sum_{k \in N_i} W_{ik} H(x_k - \theta_x) - W_z H(z - \theta_z), \quad (3)$$

$$W_{ik} = \frac{imax}{(1 + |IP_i - IP_k|)}, \quad (4)$$

$$\frac{dz}{dt} = \phi(\sigma - z), \quad (5)$$

$$CP_i = H(\sum_{k \in N_i} W_{ik} - \theta_p), \quad (6)$$

where W_{ik} is the connection weight from oscillator k to i, IP_i is the image intensity at pixel i, $imax$ is the maximum intensity value (256 for 8bit data), N_i is the neighborhood of i, z is a variable representing the global inhibitor state, and $\sigma = 1$ if $x_i \geq \theta_{xz}$ for at least one oscillator i, and $\sigma = 0$ otherwise. W_z, θ_x, θ_z, ϕ, θ_p and θ_{xz} are constants.

The dynamics for segmentation is as follows: When pixel i and k belong to a coherent pattern, W_{ik} becomes large because $|IP_i - IP_k|$ is small. Oscillators i and k oscillate synchronously because $H_2(S_i)$ in Eq. (1) becomes 1. On the other hand, oscillators i and k oscillate asynchronously when they belong to neighboring different coherent patterns because W_{ik} becomes small. In this way, regions corresponding to neighboring different patterns are separated from each other.

However, the behavior of oscillators belonging to coherent patterns apart from each other is not defined by only W_{ik}, so it is possible that plural coherent regions are extracted. We have to make such oscillators oscillate asynchronously with each other. This is attained by the global inhibitor, whose effect is expressed by the second term $-W_z H(z - \theta_z)$ in Eq. (3). When the activation level of at least one oscillator exceeds the threshold θ_{xz}, σ becomes 1, and z exceeds the threshold θ_z. As a result, all oscillators in the network are inhibited. Coherent blocks which cannot endure inhibition by the global inhibitor fall into the silent phase. Oscillators that can stay in the active phase are those of which the excitation at the start time is stronger than the inhibition. In this way, oscillators belonging to different coherent patterns oscillate asynchronously. Thus, image segmentation is achieved in the time domain. In this model, because a larger W_z leads to more detailed segmentation, it is important to set W_z at the proper value for the input image.

3.2. Estimation of Calculation Precision

In order to implement this model in our PWM/PPM circuits, we changed the equations into difference ones by using the Euler's discretization, and transformed the variables so that the variable range was in the first quadrant because PWM/PPM signals are always positive. The modified dynamics is represented by the following equations instead of Eqs. (1) and (2):

$$\frac{x_i(t+1) - x_i(t)}{\Delta t} = -(x_i(t) - 1.2)^2(x_i(t) - 4.2) + \rho + \alpha H(CP_i) + H_2(S_i) - y_i(t), \quad (7)$$

$$\frac{y_i(t+1) - y_i(t)}{\Delta t} = \varepsilon[\gamma(1 + \tanh(x_i(t)/\beta - \delta)) - y_i(t)]. \quad (8)$$

We confirmed gray-level real image segmentation by numerical simulation using Eqs. (3) to (8), where $\alpha = 0.2, \rho = 0.02, \beta = 0.1, \gamma = 6.0, \Delta t = 0.15, \phi = 3.0, \delta = 20, \theta_{xz} = 0.1, \theta_x = 0.6, \theta_z = 0.1, \theta_p = 1000$, and $W_z = 75$. From the viewpoint of VLSI implementation, we have to estimate

Figure 4: Input image (gray-level image, 150×150 pixels)

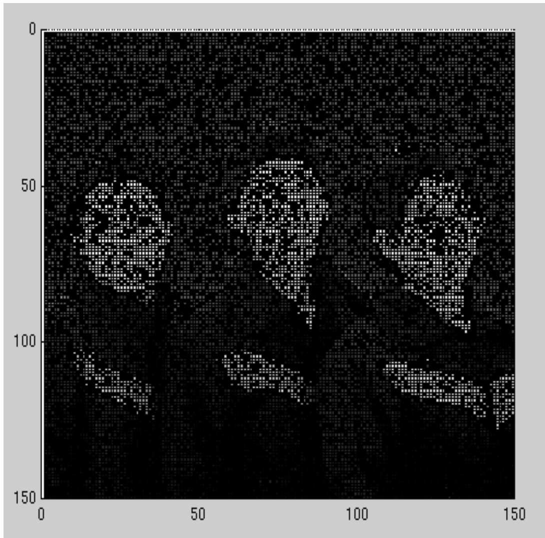

Figure 5: Image output for $N_{prec} = 4$

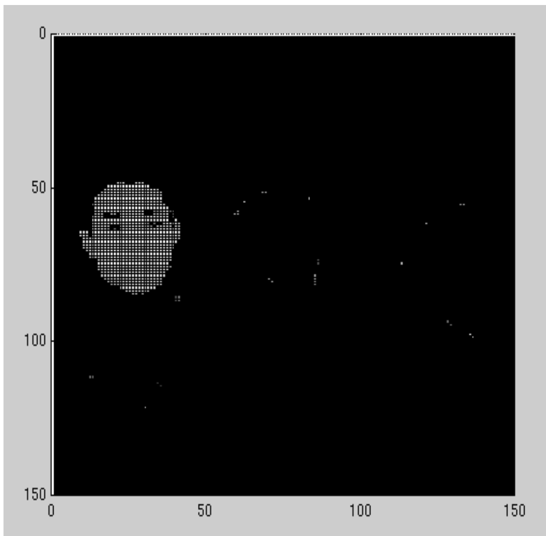

Figure 6: Image output for $N_{prec} = 5$

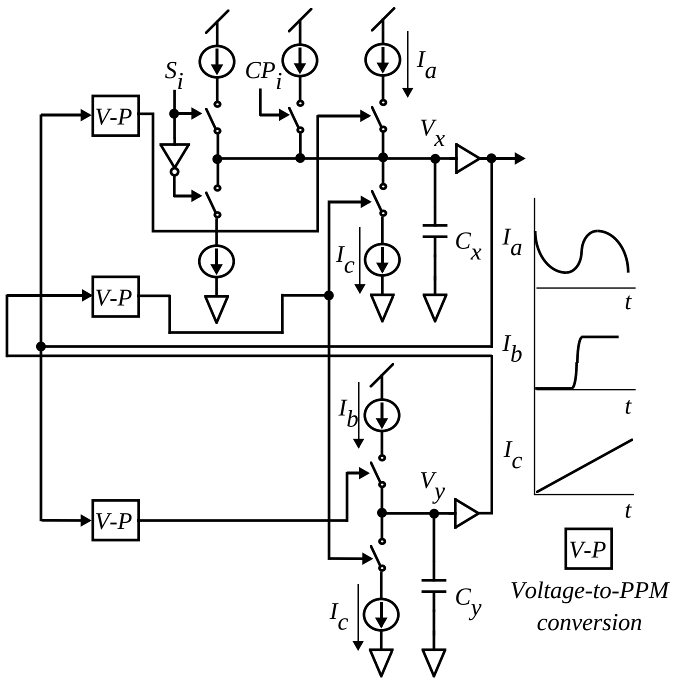

Figure 7: Oscillator circuit based on PPM method

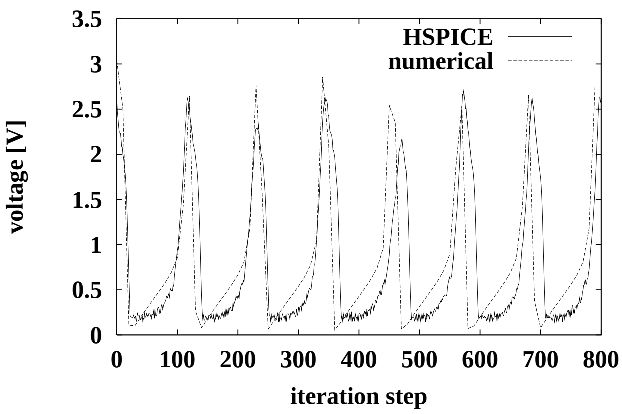

Figure 8: HSPICE simulation results of oscillator circuit

the calculation precision required for the proper operations. We performed simulation adding uniformly random numbers corresponding to noise in the calculation of CP_i, S_i, W_{ik}, z, $x_i(t)$ and $y_i(t)$. The calculation precision is expressed by bits: $N_{prec} \equiv \log_2(dmax/rmax)$, where $dmax$ and $rmax$ are the maximum amplitude of data and random numbers, respectively. The input image is shown in Fig. 4, and the simulation results are shown in Figs. 5 and 6.

The LEGION model fails to segment the image when $N_{prec} = 4$, but the segmentation is successful when $N_{prec} = 5$. Therefore, the calculation precision required for proper operations is more than 5 bits.

4. OSCILLATOR CIRCUIT BASED ON PWM/PPM METHOD

We propose a nonlinear oscillator circuit, which is the most important part of the LEGION model, by using our PWM/PPM method. A block diagram is shown in Fig. 7. This circuit implements the dynamics expressed by Eqs. (7) and (8). The values of x_i and y_i are represented by voltage V_x and V_y, and are stored as charges in capacitors C_x and C_y, respectively. The third-order and logistic function (tanh) of x_i in Eqs. (7) and (8) are generated by voltage-to-PPM converters and the nonlinearly modulated current sources explained in Sec.2. PPM signals switch current sources, and small charges corresponding to finite differences in Eqs. (7) and (8) are injected into or extracted from C_x and C_y in each time step.

Circuit simulation (HSPICE) of one oscillator circuit was performed, where S_i and CP_i were set at positive. The parameters of the device used were based on a 0.4 μm CMOS process, the supply voltage was 3.3 V, and the clock period was 1 μsec. The simulation result shown in Fig. 8 demonstrates the expected oscillation. Thus, it was confirmed that the proposed oscillator circuit correctly implements the nonlinear dynamics shown in Eqs. (1) and (2).

5. CONCLUSION

A preliminary study for VLSI implementation of the oscillator network model, LEGION, for image segmentation was described. First, we proposed a new circuit technique which can implement nonlinear dynamics based on a PWM/PPM method. Next, we modified the original LEGION model so that it can segment gray-level real images with nonlinear dynamics. We estimated the calculation precision required for proper operations in the modified model to be 5 bits by numerical simulation. Moreover, we proposed a nonlinear oscillator circuit based on our PWM/PPM method and confirmed the basic operation by circuit simulation.

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