ANALOG CMOS IMPLEMENTATION OF A NEUROMORPHIC OSCILLATOR WITH CURRENT-MODE LOW-PASS FILTERS

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ABSTRACT

We propose an analog current-mode subthreshold CMOS circuit implementing a neuromorphic oscillator. Our circuit is based on the half-center oscillator model proposed by Matsuoka, well known as a building block for constructing a neuromorphic robot locomotion controller. We modified the Matsuoka's oscillator to be suitable for analog curent-mode implementation, and designed it as an analog integrated circuit with current-mode low-pass filters. Through experimental results on a fabricated chip, we confirmed that the circuit generates a stable oscillation and the amplitude and frequency of the oscillation can be controlled by tuning bias currents over a wide range.

1. INTRODUCTION

Locomotor behavior of animals, such as walking, running, flying, and swimming, is generated by the central nervous system, called the central pattern generator (CPG) [1]. A CPG consists of sets of neural oscillators, situated in the ganglion or the spinal cord. Induced by inputs from higher level, a CPG generates rhythmic neural activity activating muscles in the absence of any sensory inputs, resulting in locomotor behavior of animals. While not necessary for generating rhythmic activity, sensory inputs regulate such rhythmic activity over a wide range [1]. As a result, CPG adapts locomotor behavior to unpredictable environments.

During the past decade, many researchers have applied the functions of CPG to locomotion control in robotics [4]-[6]. Taga *et al.* have used a CPG model, based on the neural oscillator model proposed by Matsuoka [3], in simulating for biped locomotion [4]. Kimura *et al.* developed a CPG controller for quadruped locomotion on rough terrain [6]. From engineering point of view, these works show that CPG has high adaptability to unpredictable environments.

In neuromorphic engineering, many CPG chips have been proposed [7]-[12]. As a CPG chip, it is desirable to control the amplitude and frequency of the oscillation over a wide range because a neuromorphic oscillator with high control-

lability is required for constructing a CPG-based controller capable of adapting to a given environment.

The aim of this work is to implement a neuromorphic oscillator capable of controlling the amplitude and frequency of oscillation. We designed and fabricated an analog current-mode neural oscillator, based on the half-center oscillator model proposed by Matsuoka. As a result, the proposed circuit generates a stable oscillation, and the amplitude and frequency of the oscillation can be controlled by tuning bias currents over a wide range.

2. THE HALF-CENTER OSCILLATOR MODEL

Brown proposed the concept of the half-center oscillator to account for the alternating rhythmic activity in the flexor and extensor motoneuron during walking in cat [2]. A half-center oscillator consists of two neurons, a flexor half-center and an extensor half-center, with reciprocal inhibition as shown in Fig. 1. The half-centers alternatively activate flexor and extensor muscles in the absence of pacemaker cells. Each half-center has dynamical properties such as self inhibition, fatigue or adaptation. The flexor half-center activates the flexor muscles and suppresses the extensor half-center via synaptic inhibition in the flexion phase, in turn, due to the self-inhibition and adaptation, transition from the flexion phase to extension phase occurs.
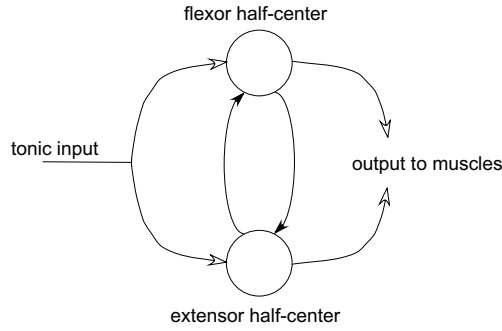
Matsuoka proposed a half-center oscillator model that consists of two-neurons, described by the following system equations [3]:

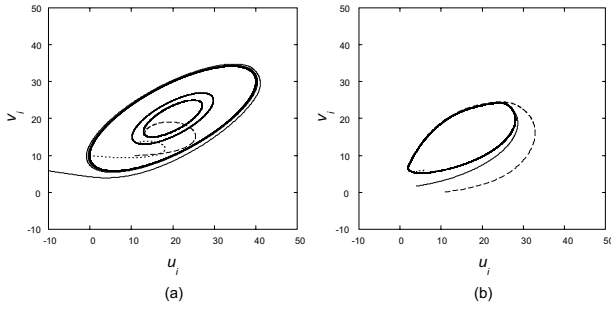$$\tau_u \frac{du_i}{dt} = -u_i + s - \beta v_i - w_{ij}f(u_j) \qquad (1)$$

$$\tau_v \frac{dv_i}{dt} = -v_i + f(u_i) \qquad (2)$$

$$f(x) = \max(0, x) \qquad (3)$$

where u_i represents the inner state of the i-th neuron, v_i an adaptation variable of the neuron ($i = 1, 2$), s a tonic input, w_{ij} a synaptic strength between the i-th and j-th neuron, β

Fig. 1. Schematic of the half-center oscillator. Black and white arrows represent inhibitory and excitatory synapses.

Fig. 2. Phase-plane portraits of (a) the Matsuoka model and (b) the proposed model. There exists multiple steady states for same parameter values in the Matsuoka model.

the adaptation effectiveness, τ_u a time constant of the self-inhibition, and τ_v a time constant of the adaptation effect. This model generates limit-cycle oscillations depending on these parameters. The stability and properties of this model are analyzed in [3]. The amplitude of the oscillation is proportional to a tonic input, and the frequency and shape of the oscillation can be controlled by tuning the ratio of time constants. Utilizing such properties, this model has been fluently used in robotics [4]-[6]. Taga *et al.* have used it in simulating for biped locomotion. Williamson has applied it to control robot arm movements [5]. Kimura *et al.* applied it to control a quadruped robot on rough terrain [6].

Despite these advantages, a problem is that this model has multiple solutions for a same parameter set, as it is shown in Fig. 2. This occurs when we determine a parameter set to make all variables positive. To avoid this problem, we modified the Matsuoka model as follows:
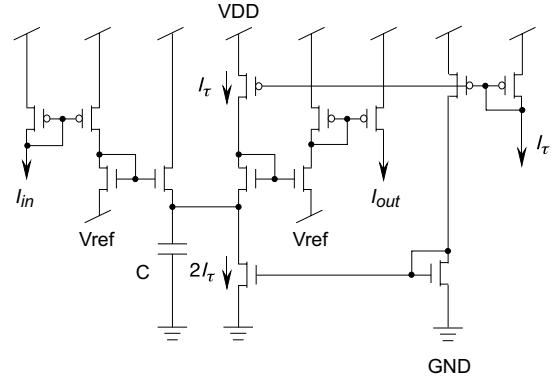
$$\tau_u \frac{du_i}{dt} = -u_i + f(s - \beta v_i - w_{ij}u_j) \tag{4}$$

$$\tau_v \frac{dv_i}{dt} = -v_i + f(u_i) \tag{5}$$

where all variables and parameters are same as in (1)-(2). As a result, we can obtain a limit-cycle solution such that all variables are positive, and thus this model is suitable to
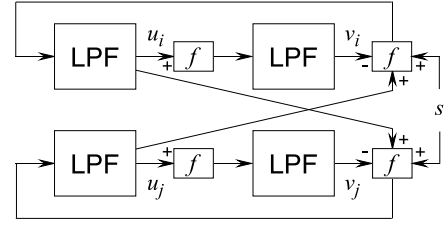
Fig. 3. Block diagram of the proposed model, where LPF represents a low-pass filter and f the nonlinear function.

Fig. 4. Schematic of current-mode low-pass filter.

implement as an analog current-mode circuit that uses unidirectional currents.

3. CIRCUIT ARCHITECTURE

We here describes analog current-mode implementation of the half-center oscillator model described in the previous section.

The proposed model consists of four low-pass filters and nonlinear functions (Fig. 3). Thus, it can be implemented with current-mode low-pass filters and current mirrors. The current-mode low-pass filter (Fig. 4) operates in log-domain based on the dynamic translinear principle [14]. The circuit dynamics is expressed by the following equation:

$$\tau \frac{dI_{out}}{dt} = -I_{out} + I_{in} \tag{6}$$

where I_{in} is the input current, I_{out} the output current, and τ the time constant expressed by:

$$\tau = \frac{CU_T}{I_\tau} \tag{7}$$

where C the capacitance, U_T the thermal voltage, and I_τ the bias current. The nonlinear function defined by (3) can
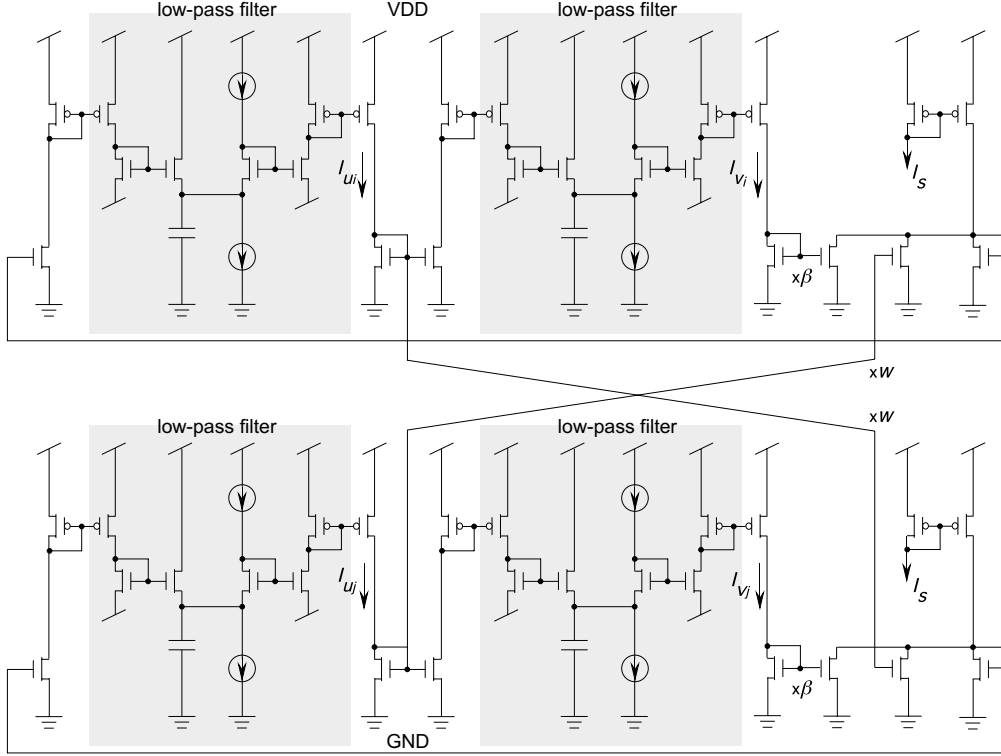
Fig. 5. Schematic of the oscillator circuit.

be easily implemented with current mirrors. We constructed a half-center oscillator circuit from current-mode low-pass filters and current mirrors, as shown in Fig. 5. The circuit dynamics is expressed by the following equations:

$$\tau \frac{dI_{u_i}}{dt} = -I_{u_i} + f(I_s - \beta I_{v_i} - w I_{u_j}) \quad (8)$$

$$\tau \frac{dI_{v_i}}{dt} = -I_{v_i} + f(I_{u_i}) \quad (9)$$

where I_{u_i} corresponds to the inner state of the i-th neuorn, I_{v_i} an adaptation variable of the neuron, I_s a tonic input, w_{ij} a synaptic strength between the i-th and j-th neuron, β the adaptation effectiveness, and τ a time constant. The parameters w_{ij} and β are determined by the aspect ratio of transistors comprising current mirrors. The time constant can be controlled by tuning the bias current I_τ. Depending on these circuit parameters, this circuit generates a stable limit-cycle oscillation.

4. EXPERIMENTAL RESULTS

We fabricated an experimental chip using a standard CMOS 1.5-μm process (MOSIS AMIS). We set the gate length of the transistor L=9.6 μm, the capacitance C=1 μF (off chip),

and the parameters β=5 and w_{ij}=4. The supply voltages were set at VDD=1.5 V and Vref=0.35 V.

We confirmed the rhythmic pattern generation in the oscillator circuit. Figure 6 shows the waveforms of measured currents I_{u_i} and I_{v_i}, where the bias currents were set at I_τ=100 nA and I_s=200 nA. The equilibrium currents of the circuit are calculated by solving the following equations:

$$\frac{dI_{u_i}}{dt} = \frac{dI_{v_i}}{dt} = 0, \ (i = 1, 2) \quad (10)$$

that yield:

$$I_{u_o} = I_s - \beta I_{v_o} - w_{ij} I_{u_o}, \ I_{v_o} = I_{u_o} \quad (11)$$

where I_{u_o} and I_{v_o} represent the equilibrium currents. Thus, the equilibrium currents become I_{u_o}=I_{v_o}=$I_s/10$. Figure 7 shows a closed (I_{u_i}, I_{v_i}) phase plane portrait. These results show the stable oscillation of the circuit.

The amplitude of the oscillation is proportional to the bias currents I_s because I_{u_i} and I_{v_i} are scaled by I_s. The frequency of the oscillation can be controlled by tuning the bias current I_τ over a wide range.

5. CONCLUSIONS

We have designed and fabricated an analog current-mode neuromorphic oscillator, based on the half-center oscilla-
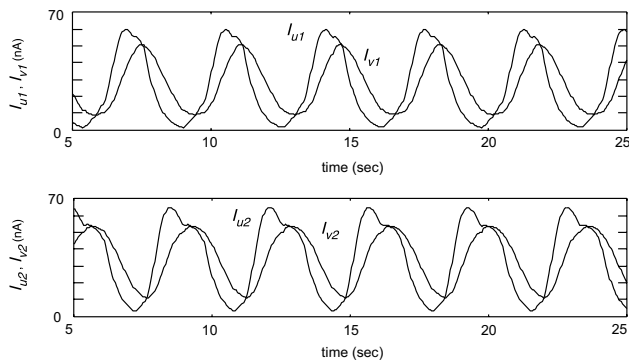
Fig. 6. Waveforms of currents in the experimental chip.

Fig. 7. Limit-cycle oscillation in (I_{u_1}, I_{v_1})-phase plane.

tor model proposed by Matsuoka. The circuit consists of four current-mode low-pass filters and several current mirrors that operate in their subthreshold region under the low-supply voltages. Thus, low power consumption can be expected. We have confirmed that the circuit generates a stable oscillation and the amplitude and frequency are controlled by tuning the bias currents. These characteristics of our neuromorphic oscillator are suitable for a building block for constructing a CPG controller. It is a further consideration to reduce the influence of the device mismatch on the circuit operation.

6. REFERENCES

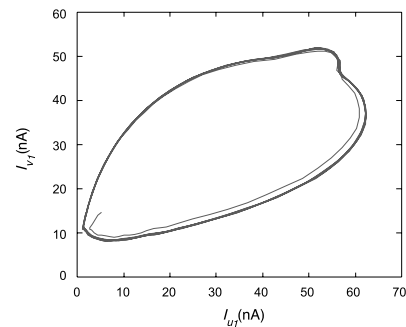[1] F. Delcomyn, *Foundations of Neurobiology*, New York: W. H. Freeman and Co., 1997.

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