Analog Current-mode Implementation of Neuromorphic Oscillator for Robotic Locomotion

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Background: Recently, biologically-inspired approaches have succeeded in locomotion control in robotics [1]-[3]. Such approaches are based on the concept of the central pattern generators (CPGs) that are neural networks capable of generating oscillatory movements for locomotion of animals. From engineering point of view, a CPG can be described as a set of coupled nonlinear oscillators, each of which controls of each joints of the limb. In neuromorphic engineering, many researchers developed CPG chips (e.g. [2], [3]). As a building block for constructing a robot locomotion controller, it is desirable to control the oscillation over a wide range. We propose an analog current-mode neuromorphic oscillator circuit with high controllability of the amplitude and frequency of the oscillation.

Model: We propose a neuromorphic oscillator model based on the half-center oscillator model proposed by Matsuoka [4]. Our model consists of two neurons, a flexor half center and an extensor half-center, with reciprocal inhibition (**Fig. 1**). The model is represented as the following equations:

$$\tau_u \frac{du_i}{dt} = -u_i + f(s_i - \beta v_i - w u_j)$$

$$\tau_v \frac{dv_i}{dt} = -v_i + f(u_i), \quad (i, j = 1,2)$$

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

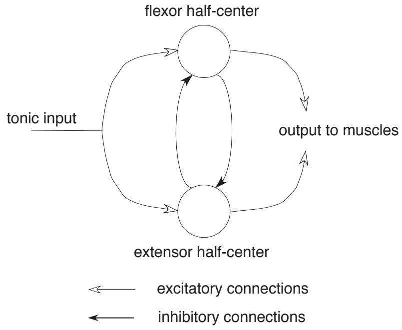

Figure 1: Schematic of neuromorphic oscillator model.

where u_i represents the inner state of the i-th neuron, v_i an adaptation of variable of the neuron, s_i a tonic input, w and synaptic strength between the i-th and the j-th neuron, β the adaptation effectiveness, τ_u a time constant of the self-inhibition, and τ_u a time constant of the adaptation effect. This model can generate an oscillatory pattern that alternatively activates flexor and extensor muscles. The amplitude of the oscillatory pattern is proportional to a tonic input, and the frequency and shape of the oscillatory pattern is determined by the ratio of the time constants. Such properties can be utilized to control the amplitude and frequency of the oscillation.

Circuit Implementation: We propose an analog current-mode implementation of the proposed model. The proposed circuit consists of four current-mode low-pass filters and half-wave rectifiers (**Fig. 2**). The current-mode low-pass filter (**Fig. 3**) operates in log-domain based on the dynamic translinear principle. [5]. The circuit dynamics is expressed the following equation:

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

where I_{in} represents the input current, I_{out} the output currents, I_τ the bias currents, C the capacitance, and U_T thermal voltage. The half-wave rectifier can be easily implemented with a current mirror. The dynamics of the oscillator circuit is expressed by the following equations:

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

$$\frac{CU_T}{I_\tau} \frac{dI_{v_i}}{dt} = -I_{v_i} + f(I_{u_i}), \quad (i, j = 1,2)$$

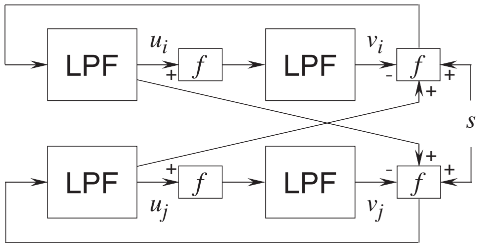

Figure 2: Schematic of oscillator circuit.

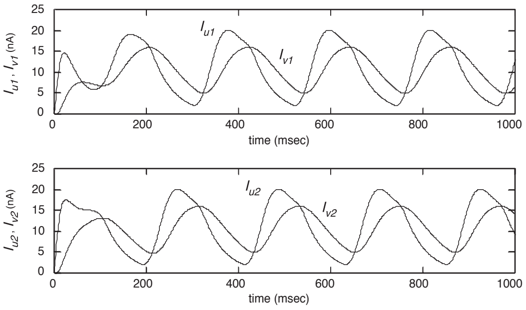

Figure 4: Waveforms of the output currents.

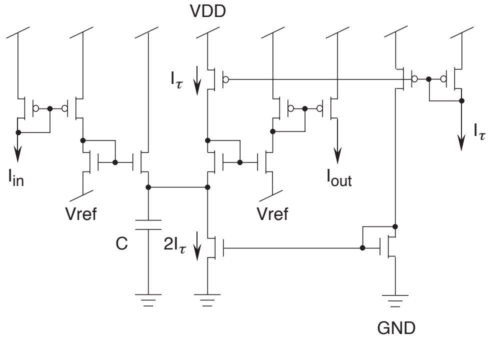

Figure 3: Schematic of current-mode low-pass filter.

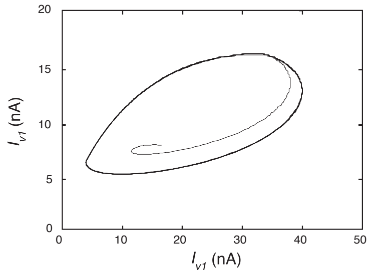

Figure 5: Phase-plane portrait of the output currents.

where I_{ui} the current that corresponds to the inner state of the i-th neuron, I_{vi} the currents that corresponds to an adaptation of variable of the neuron, and I_s the bias currents. The circuit can generate a stable oscillatory pattern autonomously. The amplitude of the oscillatory pattern can be controlled by I_s, and the time constant of the circuit can be controlled by tuning the bias current I_τ.

Simulation Results: We verified the operation of the proposed circuit with SPICE simulation. In the following simulations, we used MOSIS AMI 1.5-μm BSIM LEVEL 49 parameters. The circuit parameters were set at as follows: The capacitance C = 10 nF, the coupling parameters $\beta = 5$ and $w = 4$, the bias currents I_b = 10 nA and I_τ = 100 nA, and the supply voltages VDD = 1.5 V and Vref = 0.5 V. **Figure 4** shows the waveforms of the output currents I_{ui} and I_{vi}. **Figure 5** shows a closed $(I_{ui}\ ,\ I_{vi})$ phase plane portrait. These results show the stable oscillation of the circuit.

Conclusions: We have proposed an analog current-mode neuoromorphic oscillator for constructing a robot locomotion controller. The proposed circuit can generates oscillatory patterns and control the frequency and the amplitude of the oscillatory patterns over a wide range. 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, ultra low power consumption can be expected. Through SPICE simulations, we have confirmed that the circuit cane generate a stable oscillatory pattern. These characteristics of the proposed circuit are suitable for a building block for constructing a neuromorphic robot locomotion controller.

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