A Novel Analog CMOS Cellular Neural Network for Biologically-Inspired Walking Robot

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***Abstract*— We propose a novel analog CMOS circuit that implements a class of cellular neural networks (CNNs) for biologically-inspired walking robots. Recently, a class of autonomous CNNs, so-called a reaction-diffusion (RD) CNN, has applied to locomotion control in robotics. We have introduced a novel RD-CNN, and implemented it as an analog CMOS circuit by using multiple-input floating-gate (MIFG) MOS FETs. As a result, the circuit can operate in voltage-mode. From the results on computer simulations, we have shown that the circuit has capability to generate stable rhythmic patterns for locomotion control in a quadruped walking robot.**

I. Introduction

Biologically inspired approaches have succeeded in motion control in robotics. Biological systems have been evolved to optimize themselves under selective pressures for a long time. Therefore, it is expected that biological findings provide us good ideas for design and control methods in robotics.

Central pattern generator (CPG) is the biological neural network that can produce a rhythmic movement for locomotion of animals, such as walking, running, swimming and flying [1]. The rhythmic movement produced by CPG induces a coordination of physical parts. Since the degree of freedom relevant to locomotion is very high, this coordination is necessary for stable locomotion. Therefore, CPG can be said to play the central role in locomotion of animals.

During the past decade, based on the CPG framework, many researchers have developed locomotion controllers for legged walking robots [2]-[4]. Such controllers have the advantages in i) reduction of the amount of calculation required for motion control because of needless of complicated planning to generate motion trajectory, and ii) high adaptation to an unexpected disturbance as a result of a CPG interacting with environments through sensory information.

Recently, Arena *et al.* have proposed a reaction-diffusion cellular neural network (RD-CNN) as a CPG controller for a legged walking robot [9]. The RD-CNN is a class of autonomous CNNs that can generate various spatial-temporal patterns automatically, and therefore it is very suitable for a CPG controller to generate rhythmic motion patterns for multiple-legged walking robots.

In the present paper, we propose an analog CMOS circuit that implements a novel RD-CNN for locomotion control in a quadruped walking robot. In the past CNN-based CPG controllers have been already implemented in hardware [10]-[11]. In particular, Braciforte *et al.* developed an analog chip having good programmability [11]. In their circuit, the components called cells interacts with each other thorough current. Therefore, there are several problems as follows: i) many current amplifiers are needed, and thus they occupy a large area on a chip, ii) it is difficult to operate stably without tuning of the bias currents because of the irregularity in current thorough the current amplifiers, and iii) the circuit consumes high amount of power in operation. Hence, we introduce a novel RD-CNN, and implemented it as analog CMOS circuit by using multiple-input floating-gate (MIFG) MOS FETs. In the circuit, we represent state variables of the cells and interactions terms between the cells as the voltages instead of current. As a result, it is expected that the circuit can operate stably. By using SPICE, we confirmed the desirable of the operation of the circuit as CPG controller.

II. A CNN-based CPG Controller

In this section, we propose a class of RD-CNNs as a CPG controller for a quadruped walking robot.

A. Central Pattern Generator

Firstly, we briefly review biological principles of locomotion of animals. Animal locomotion, such as walking, running, swimming and flying, is based on the rhythmic movements generated by CPG. One role of CPG in locomotion of animals is controlling of each limb. As a result of interaction with CPGs that actuate muscles at each joints of the limbs, rhythmic movements of each limb are stabilized. Another one is interlimb coordination. CPGs that control each of the limbs are synchronized via coordinating interneurons between the CPGs, and then interlimb coordination is achieved. Since the degree of freedom of physical parts relevant to locomotion is very high, the rhythmic coordination of physical parts is necessary for stable locomotion.

In vertebrates, different patterns of interlimb coordination, called ”gaits”, can be observed. For instance, horses have several gaits, such as walk, trot and gallop. These gaits are characterized by phase relationship in limb movements during locomotion. In other words, a gait is considered as phase-locked oscillation of CPGs that control each of the limbs.

B. A RD-CNN for CPG Controller

In the previous works, a great number of CPG models have been proposed [5]-[7]. Most of these have been constructed from sets of coupled nonlinear oscillators, where each oscillator controls each joint of limbs.

Recently, Arena *et al.* have proposed a class of RD-CNNs as artificial CPG model to control locomotion in a hexapod walking robot [9]. Their model is described by the following equations:

$$\dot{x}^1_{i,j} = -x^1_{i,j} + (1 + \mu + \epsilon)y^1_{i,j} - sy^2_{i,j} + S^1_{i,j} \tag{1}$$

$$\dot{x}^2_{i,j} = -x^2_{i,j} + sy^1_{i,j} + (1 + \mu - \epsilon)y^2_{i,j} + S^2_{i,j} \tag{2}$$

with

$$S^1_{i,j} = D_1(y^1_{i-1,j}+y^1_{i+1,j}+y^1_{i,j-1}+y^1_{i,j+1}-4y^1_{i,j}) + I^1_{i,j} \tag{3}$$

$$S^2_{i,j} = D_2(y^2_{i-1,j}+y^2_{i+1,j}+y^2_{i,j-1}+y^2_{i,j+1}-4y^2_{i,j}) + I^2_{i,j} \tag{4}$$

where $x^n_{i,j}$ is a state variable, $I^n_{i,j}$ a bias constant $(n = 1, 2)$, (i, j) a grid point of the cell, μ, ϵ and s the coupling parameters, D_n a diffusive coefficient, and an output $y^n_{i,j} = f(x^n_{i,j})$ a nonlinear function, which is usually given by the piecewise linear function.

Originally, their model has been proposed as the RD-CNN for simulator of reaction-diffusion partial differential equations [9]. The RD-CNN is one of the most significant classes of autonomous CNNs [8]. Since the model can produce various spatial temporal patterns automatically, it is suitable for artificial CPGs in generating various rhythmic patterns for locomotion control in multiple-legged robots.

Let us introduce a novel RD-CNN, which is suitable for constructing an analog CMOS circuit that works on voltage-mode. Firstly, we rewrite (1)-(4) as follows:

$$\dot{x}^1_{i,j} = -x^1_{i,j} + \sum_{k,l} A_{i,j;k,l}y^1_{k,l} - \sum_{k,l} B_{i,j;k,l}y^2_{k,l} + I^1_{i,j} \tag{5}$$

$$\dot{x}^2_{i,j} = -x^2_{i,j} + \sum_{k,l} C_{i,j;k,l}y^1_{k,l} - \sum_{k,l} D_{i,j;k,l}y^2_{k,l} + I^2_{i,j} \tag{6}$$

where (k, l) is a grid point in neighborhood of a point (i, j), and $A_{i,j;k,l}, B_{i,j;k,l}, C_{i,j;k,l}$ and $D_{i,j;k,l}$ coupling coefficients. The above formalism is naturally extended to include the cross diffusion terms. Furthermore, we rewrite the equations above in terms of a new state variable $v^n_{i,j}$ as follows:

$$\dot{v}^1_{i,j} = -v^1_{i,j} + f(\sum_{k,l} A_{i,j;k,l}v^1_{k,l} - \sum_{k,l} B_{i,j;k,l}v^2_{k,l} + I^1_{i,j}) \tag{7}$$

$$\dot{v}^2_{i,j} = -v^2_{i,j} + f(\sum_{k,l} C_{i,j;k,l}v^1_{k,l} - \sum_{k,l} D_{i,j;k,l}v^2_{k,l} + I^2_{i,j}). \tag{8}$$

The equations can be derived from (5) and (6) by the following transformation:

$$x^1_{i,j} = \sum_{k,l} A_{i,j;k,l}v^1_{k,l} - \sum_{k,l} B_{i,j;k,l}v^2_{k,l} + I^1_{i,j} \tag{9}$$

$$x^2_{i,j} = \sum_{k,l} C_{i,j;k,l}v^1_{k,l} - \sum_{k,l} D_{i,j;k,l}v^2_{k,l} + I^2_{i,j}. \tag{10}$$

The transformation above is an Affine, and its inverse transformation is also an Affine. Therefore, (5)-(6) and (7)-(8) are dynamically equivalent. In case of $f(x) = \tanh(x)$, similarly, the above transformation can be checked. As shown in the following section in detail, the transformation is useful for analog chip implementation rather than a mathematical problem. We are going to consider the RD-CNN given by (7)-(8) as a CPG model for constructing a CPG controller.

III. Circuitry Architecture

We here propose an analog CMOS circuit that implements a CPG controller based on the proposed RD-CNN. First, a cell circuit that constitutes a part of the proposed RD-CNN is described, and then the architecture of the CPG controller.

A. Cell Circuit

We have designed a cell circuit that constitutes a part of the proposed RD-CNN (Fig. 1(a)). This circuit consists of analog elementary circuits, differential pair, current mirror, RC circuit and current source.

The differential pair, which is the most fundamental components of the cell circuit, can approximate the sigmoidal funcion. When MOS transistors comprising the differential pair operate in their subthreshold region, the static response of the differential pair is given by:

$$I_\mu(V^+ - V^-) = I_b \frac{1 + \tanh(\mu(V^+ - V^-))}{2} \tag{11}$$

where I_μ represents the output current of the differential pair, V^+ and V^- the input voltages, I_b the bias current, $\mu = \kappa/2V_T$, V_T the thermal voltage and κ the electrostatic coefficient between the gate and channel. By subtracting a half of the bias current from the output current I_μ, the characteristic of the nonlinear function $f(x)$ is obtained.

Furthermore, we replace the MOS transistors that comprise the differential pair with MIFG MOS FETs [12] (Fig. 1(b)). As a result, the operation of weighted linear summation of voltages is realized. Generally, the floating-gate voltage of MIFG MOS FET is expressed by the following equations [12]:

$$V_{FG} = \frac{C_{GD}}{C_T}V_D + \frac{C_{GS}}{C_T}V_S + \frac{C_{GB}}{C_T}V_B + \frac{Q_0}{C_T} + \sum_l \frac{C_l}{C_T}V_l \tag{12}$$

where $C_T = C_{GD} + C_{GS} + C_{GB} + \sum_l C_l$ and V_l are the input gate voltages, C_l the capacitance values between each of the input gates and the floating-gate, and Q_0 represents any initial charge in the floating-gate. The floating-gate voltage is approximately expressed by:

$$V_{FG} \simeq \sum_l \frac{C_l}{C_T}V_l \tag{13}$$

where it is assumed that Q_0 is 0 and $C_{GD}, C_{GS}, C_{GB} \ll C_T$. Furthermore, the differential voltage between the floating-gates of the differential pair with MIFG MOS FETs is approximately expressed by the following equations:

$$V^+_{FG} - V^-_{FG} \simeq \sum_l \frac{C^+_l}{C_T}V^+_l - \sum_l \frac{C^-_l}{C_T}V^-_l \tag{14}$$

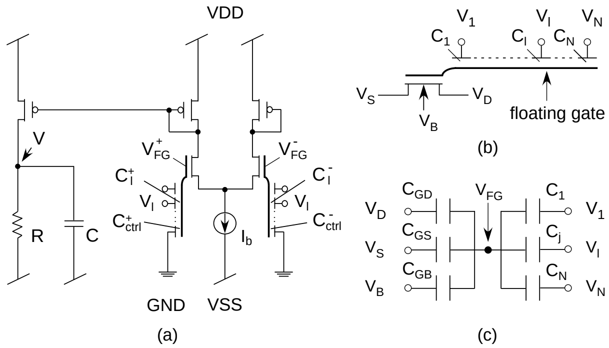

Fig. 1. Schematic of cell circuit.

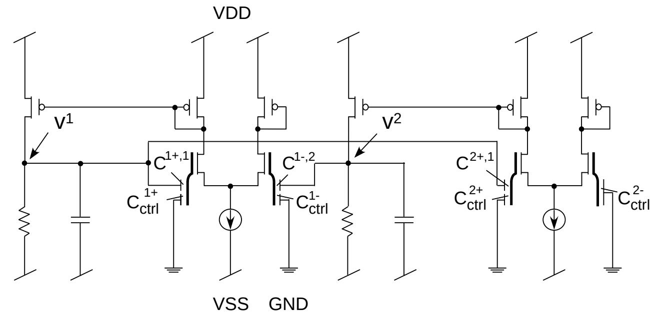

Fig. 2. Schematic of unit circuit.

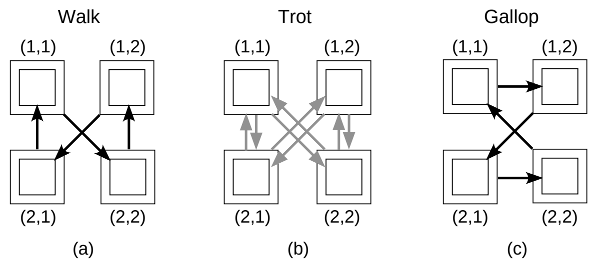

Fig. 3. Coupling configurations of network circuits. (a) Walk mode. (b) Trot mode. (c) Gallop mode.

where V_{FG}^{+} and V_{FG}^{-} is the floating-gate voltages, V_l^{+} and V_l^{-} the input gate voltages, C_l^{+} and C_l^{-} the capacitances between each of the input gates and the floating-gate.

After the output current of the differential pair with MIFG MOS FETs is reversed by current mirror, it is integrated by RC circuit. The circuit dynamics is represented as follows:

$$C\dot{V} = -\frac{V - \mathrm{VSS}}{R} + I_\mu(V_{FG}^{+} - V_{FG}^{-}) \quad (15)$$

$$= -\frac{V}{R} + \frac{\mathrm{VSS}}{R} + \frac{I_b}{2}\tanh(\mu(V_{FG}^{+} - V_{FG}^{-})) + \frac{I_b}{2} \quad (16)$$

where C is the capacitance and R the resistance. We set that substrate voltage $\mathrm{VSS} < 0$ for the purpose of setting the equilibrium voltage at 0. When we assumed that $\mathrm{VSS}/R + I_b/2 = 0$, the equations above are rewritten as follows:

$$C\dot{V} = -\frac{V}{R} + \frac{I_b}{2}\tanh(\mu(V_{FG}^{+} - V_{FG}^{-})) \quad (17)$$

$$\simeq -\frac{V}{R} + \frac{I_b}{2}\tanh(\mu(\sum_l \frac{C_l^{+}}{C_T}V_l^{+} - \sum_l \frac{C_l^{-}}{C_T}V_l^{-})) \quad (18)$$

$$= -\frac{V}{R} + \frac{I_b}{2}F_\mu(\sum_l C_l^{+}V_l^{+} - \sum_l C_l^{-}V_l^{-}) \quad (19)$$

where we have replaced $F_\mu(x) = \tanh(\mu x/C_T)$.

Furthermore, we constructed an unit circuit from two cell circuits. Figure 2 shows schematic of the unit circuit, where V^1 and V^2 represent the voltage of the first cell and the second cell, respectively. This unit circuit has reciprocal interactions via capacitive coupling. Depending on the capacitances of coupling capacitors, the unit circuit shows various behaviors, such as a limit-cycle oscillation.

B. Network Circuit

By combining the unit circuits, we constructed entire CPG network circuits. The network dynamics is given by the following equations:

$$C\dot{V}_{i,j}^{1} = -\frac{V_{i,j}^{1}}{R} + \frac{I_b}{2}F_\mu(\sum_{k,l,n} C_{i,j;k,l}^{1+,n}V_{k,l}^{n} - \sum_{k,l,n} C_{i,j;k,l}^{1-,n}V_{k,l}^{n}) \quad (20)$$

$$C\dot{V}_{i,j}^{2} = -\frac{V_{i,j}^{2}}{R} + \frac{I_b}{2}F_\mu(\sum_{k,l,n} C_{i,j;k,l}^{2+,n}V_{k,l}^{n} - \sum_{k,l,n} C_{i,j;k,l}^{2-,n}V_{k,l}^{2}) \quad (21)$$

where (k, l) is a grid point in neighborhood of unit (i, j), and $V_{i,j}^{1}$ and $V_{i,j}^{2}$ represent the voltaege of the first cell and the second cell, respectively. The total capacitance of the floating gate C_T is given by:

$$C_T = C_{GD} + C_{GS} + C_{GB} + \sum_{k,l,n} C_{i,j;k,l}^{m\pm,n} + C_{ctrl,i,j}^{m\pm} \quad (22)$$

where $C_{ctrl,i,j}^{m\pm}$ is the capacitance of each of the control gates, which is added to regulate the total capacitance of the floaring-gate. The network circuit also shows various behaviors, such as oscillation, depending on value of the physical parameters.

Depending on its coupling structure, the circuit generates various rhythmic patterns. Figure 3(a)-(c) show the network structures that generate rhythmic patterns corresponding to the locomotion patterns of animals, such as walk, trot and gallop, respectively. Here, the grid points $(1, 1), (1, 2), (2, 1)$ and $(2, 2)$ correspond to each of the limbs.

In the circuit, the weighted linear summation of inputs is implemented by the capacitive coupling. As a result, the interaction between the cells is expressed as voltages instead of currents. It should be noted that this interaction has high accuracy because of the relative accuracy of a capacitor array in silicon, and thus the total circuit would operate stably.

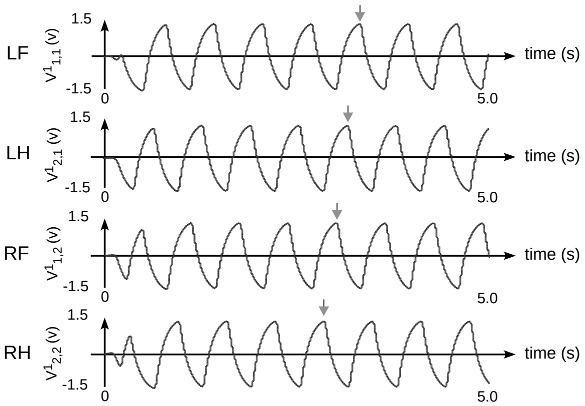

Fig. 4. Waveforms in network circuit (the walk mode).

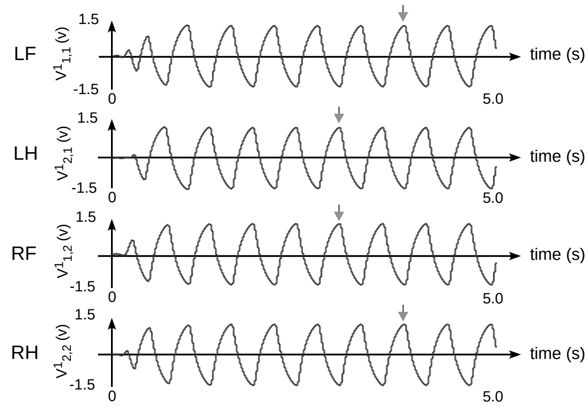

Fig. 5. Waveforms in network circuit (the trot mode).

IV. Results

By using SPICE, we confirmed the desirable operation of the proposed circuit as a CPG controller. In the following, we used HSPICE and MOSIS AMIS 1.5-μm CMOS device parameters, and then we set common parameters as follows: capacitance $C = 20$ pF, resistance $R = 6.0$ MΩ, the bias current $I_b = 500$ nA and coupling capacitances:

$$C^{1+,1}_{i,j;i,j} = C^{1-,2}_{i,j;i,j} = 0.5,\ C^{2+,1}_{i,j;i,j} = 0.3, C_T = 1.0 \text{ pF}$$

and the voltages $V_{DD} = 1.5$ V and $V_{SS} = -1.5$ V.

We confirmed that the circuit can generate stable rhythmic patterns that correspond to typical locomotion patterns of animals, such as walk, trot, and gallop. Two examples of the waveforms of voltages $V^1_{i,j}$ in the circuit are shown in Fig. 4 and 5. Here, we assumed that $V^1_{1,1}, V^1_{1,2}, V^1_{2,1}$ and $V^1_{2,2}$ drive the joint of each of the limbs, and grid points $(1,1)$,$(1,2)$,$(2,1)$ and $(2,2)$ correspond to left forelimb (LF), right forelimb (RF), left hindlimb (LH) and right hindlimb (RH), respectively.

In the walk mode (Fig. 4), we set coupling capacitances as:

$$C^{1+,2}_{1,1;2,1} = C^{1+,2}_{1,2;2,2} = C^{1+,2}_{2,1;1,2} = C^{1+,2}_{2,2;1,1} = 0.2 \text{ pF}$$

and the others were set at 0 F.

In the trot mode (Fig. 5), we set coupling capacitances as:

$$\begin{aligned} C^{1-,2}_{1,1;2,2} &= C^{1-,2}_{1,2;2,1} = C^{1-,2}_{2,1;1,2} = C^{1-,2}_{2,2;1,1} = 0.1 \text{ pF} \\ C^{2-,2}_{1,1;2,1} &= C^{2-,2}_{1,2;2,2} = C^{2-,2}_{2,1;1,1} = C^{2-}_{2,2;1,2} = 0.1 \text{ pF} \end{aligned}$$

and the others were set at 0 F.

In the gallop mode, we set coupling capacitances as:

$$C^{1+,2}_{1,1;2,2} = C^{1+,2}_{1,2;1,1} = C^{1+,2}_{2,1;1,2} = C^{1+,2}_{2,2;2,1} = 0.2 \text{ pF}$$

and the others were set at 0 F.

The results show that the proposed circuit has capability to generate rhythmic patterns corresponding to the typical locomotion patterns of animals.

V. Summary

We have proposed an analog CMOS circuit implementing a class of RD-CNNs for a CPG controller. In the previous works, CNN-based CPG controllers have been already implemented in hardware. Our work differs from these works in operation mode. Instead of currents, we represent state variables and interaction terms as voltages in the circuit by using multiple-input floating-gate MOS FETs. As a result, it is expected that the circuit can operate stably and reduce power consumption. From the results on circuit simulations, we have shown that the circuit has capability to generate various rhythmic patterns corresponding to vertebrate locomotion patterns. In our future work, we are going to incorporate it into a micro locomotor robot.

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