An Analog CMOS Circuit for Locomotion Control in Quadruped Walking Robot

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Abstract

We propose an analog CMOS circuit for developing a biologically-inspired locomotion controller for a quadruped walking robot. The proposed circuit is based on the biological neural network, called *the central pattern generator* (CPG), that can generate rhythmic movements for locomotion of animals, such as walking, running, swimming, and flying. We constructed a CPG model from the Wilson-Cowan neural oscillators, and implement it as analog integrated circuit that can perform parallel processing essentially. Furthermore, we fabricated a test chip in standard CMOS technology. By experiments on the test chip, we have shown that the proposed circuit has capability to generate stable rhythmic patterns for locomotion control in a quadruped walking robot.

1 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 generate rhythmic movements for locomotion of animals, such as walking, running, swimming, and flying [1]. The rhythmic movement generated by CPG induces a coordination of physical parts. Since the degree of freedom of physical parts relevant 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.

In recent years, many researchers have developed CPG-based locomotion controllers for legged walking robots [2]-[3]. Such controllers have following advantages: 1) CPG can generate motion patterns without the complicated planning of the motion trajectory, and 2) the amount of calculation required for locomotion control is reduced as a result of a coordination of physical parts induced by CPG.

In the present paper, focusing on such advantages, we propose an analog CMOS circuit for developing a CPG-based controller for a quadruped walking robot. In the past a number of CPG-based controllers have been proposed, however, most of these have been implemented in software on digital microprocessors. Since the digital microprocessor can only sequential processing, it is difficult to perform multi-task operation during locomotion. Hence, we propose a hardware implementation of a CPG-based locomotion controller for a legged robot. In particular, our controller is designed as an analog integrated circuit that can perform parallel processing essentially. Furthermore, we fabricated a prototype chip in standard CMOS technology. By experiments, we confirmed the desirable of the operation of the circuit as a CPG-based controller.

2 CPG-based Locomotion Controller

In this section, we propose a biologically-inspired locomotion controller for a quadruped walking robot.

2.1 Biological Background of Locomotion Control

Firstly, let us briefly review the biological background of locomotion of animals. Animal locomotion, such as walking, running, swimming and flying, is based on the rhythmic movements generated by CPG. A CPG consists of sets of neural oscillators situated in ganglion or spinal cord. Induced by inputs from command neurons, a CPG generates a rhythmic pattern of neural activity unconsciously and automatically. As a result of such a rhythmic pattern activating the motor neurons, the rhythmic movements of animals occur [1].

One role of CPG in locomotion of animals is to control of each individual limb. As a result of interaction with CPG neurons that actuate muscles at each joints of the limb, rhythmic movements of each limb are stabilized. Another one is cooperation between the limbs, i.e., *interlimb coordination*. CPGs that control each of the limbs are synchronized via coordinating interneurons between the CPGs, and thus the interlimb coordination is achieved. Since the degree of freedom of physical parts relevant to locomotion is very high, the coordination of the physical parts is necessary for stable locomotion. The rhythmic movements generated by CPG induces this coordination. Therefore, CPG plays significant roles in locomotion of animals.

In vertebrates, different patterns of interlimb coordination, called the gaits, can be observed. For instance, horses has 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. Figures 1(a)-(c) show the phase diagrams of the typical walking patterns of mammals. Here, gray and white boxes represent the stance phases and swing phases, LF, LH, RF and RH represent left forelimb, left hindlimb, right forelimb and right hindlimb, respectively.

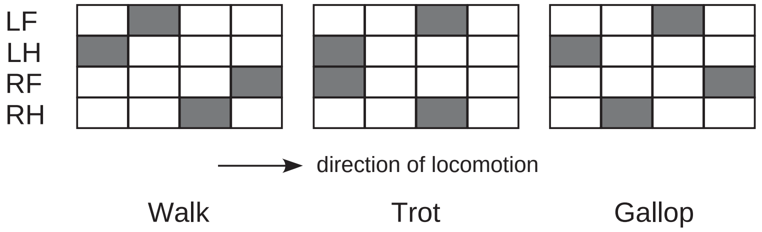


Figure 1: Phase diagrams of the typical locomotion patterns of animals.

2.2 CPG Model for Locomotion Controller

In the previous works, a great number of CPG models have been proposed [4]-[6]. Most of CPG models are constructed using a set of coupled nonlinear ocillators, where each oscillator controls each joint of the limb. In the present paper, we constructed a CPG model from the Wilson-Cowan neural oscillator [7] that can easily implemented on silicon chips [8]. The dynamics of the CPG model is given by the following equations:

$$\dot{v}_i^1 = -v_j^1 + f(\sum_j A_{i,j} v_j^1 - \sum_j B_{i,j} v_j^2 + S_i^1) \tag{1}$$

$$\dot{v}_i^2 = -v_j^2 + f(\sum_j C_{i,j} v_j^1 - \sum_j D_{i,j} v_j^2 + S_i^2). \tag{2}$$

where v_i^1 and v_i^2 represent the activities of i-th group of excitatory and inhibitory neurons, S_i^1 and S_i^v are the external inputs, and the parameters A_j through D_j represent the coupling strength between the groups of neurons. The transfer function $f_\mu(x)$ is given by the hyperbolic tangent and μ is its gain control parameter. Depending on these parameters, the CPG model shows various behaviors, such as phase-locked oscillation.

2.3 Hardware Implementation of a CPG-based Controller

We here describe a hardware implementation of the proposed CPG model. Firstly, we have designed a cell circuit that constitutes a part of the CPG model. This circuit consists of elementary analog CMOS circuits, the differential pair, the current mirror, and the RC circuit. Furthermore, we replace the MOS FETs comprising the differential pair with multiple-input floating-gate (MIFG) MOS FETs in order to realize summation of the voltages.

Figure 2(a) shows the schematic of the cell circuit. The circuit dynamics is represented by the following equations:

$$C\dot{V} = -\frac{V}{R} + I_\mu(V_{FG}^+ - V_{FG}^-) \tag{3}$$

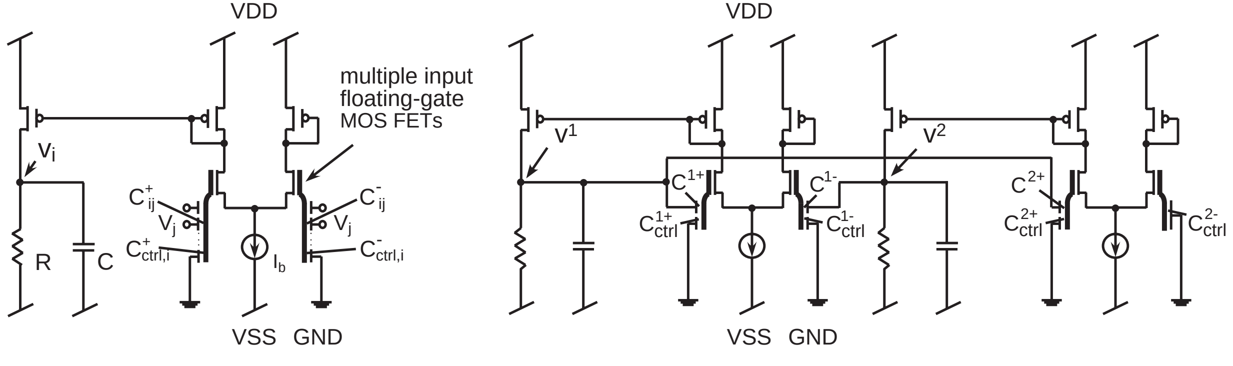
where V represents the voltage, C the capacitance, and R resistance value. $I_\mu(\cdot)$ represents the output current of the differential pair, V_{FG}^+ and V_{FG}^- are the floating-gate voltages of MIFG MOS FETs. Furthermore, we here assumed that the bias current of the differential pair I_b =-2VSS/R.

We constructed the oscillator circuit from two cell circuits (Fig.2(b)). In the circuit, each cell circuit interacts with each other via coupling capacitance.

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

$$C\dot{V}_i^1 = -\frac{V_i^1}{R} + I_\mu(\sum_{j,n} \frac{C_{i,j}^{1+,n}}{C_T} V_j^n - \sum_{j,n} \frac{C_{i,j}^{1-,n}}{C_T} V_j^n) \tag{4}$$

$$C\dot{V}_i^2 = -\frac{V_i^2}{R} + I_\mu(\sum_{j,n} \frac{C_{i,j}^{2+,n}}{C_T} V_j^n - \sum_{j,n} \frac{C_{i,j}^{2-,n}}{C_T} V_j^n) \tag{5}$$

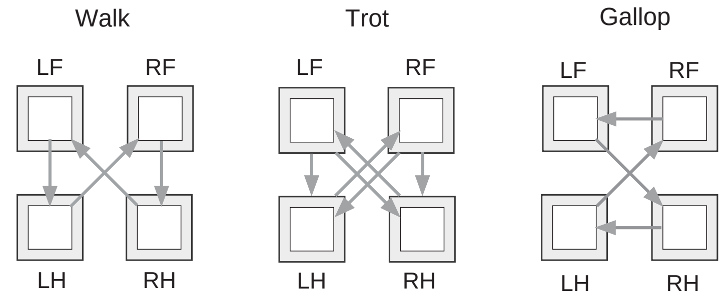


(a) (b)

Figure 2: The schematic of (a) the cell circuit and (b) the oscillator circuit.

where V_i^1 and V_i^2 represent the voltage of the i-th excitatory and inhibitory cell circuit, and $C_{i,j}^{m\pm,n}$ $(m, n = 1, 2)$ is the coupling capacitance value between the cell circuits. The total capacitance value of the floating gate C_T is given by $C_T = C_{GD} + C_{GS} + C_{GB} + \sum_i C_{i,j}^{m\pm,n} + C_{ctrl,i}^{m\pm,n}$, where $C_{ctrl,i,j}^{m\pm,n}$ is the capacitance of each of the control gates, which is added to control the total capacitance value of the floaring-gate. C_{GD}, C_{GS} and C_{GB} represent the parasitic capacitance value between the floating-gate and the drain, the source, and the bulk of the MIFG MOS FETs, respectively. The circuit shows various behaviors, such as oscillation, depending on value of the physical parameters.

In the oscillatory mode, the circuit generates various rhythmic patterns depending on its coupling structure. Figure 3(a)-(c) show the network structures that generate rhythmic patterns corresponding to the locomotion patterns, such as walk, trot and gallop, respectively.

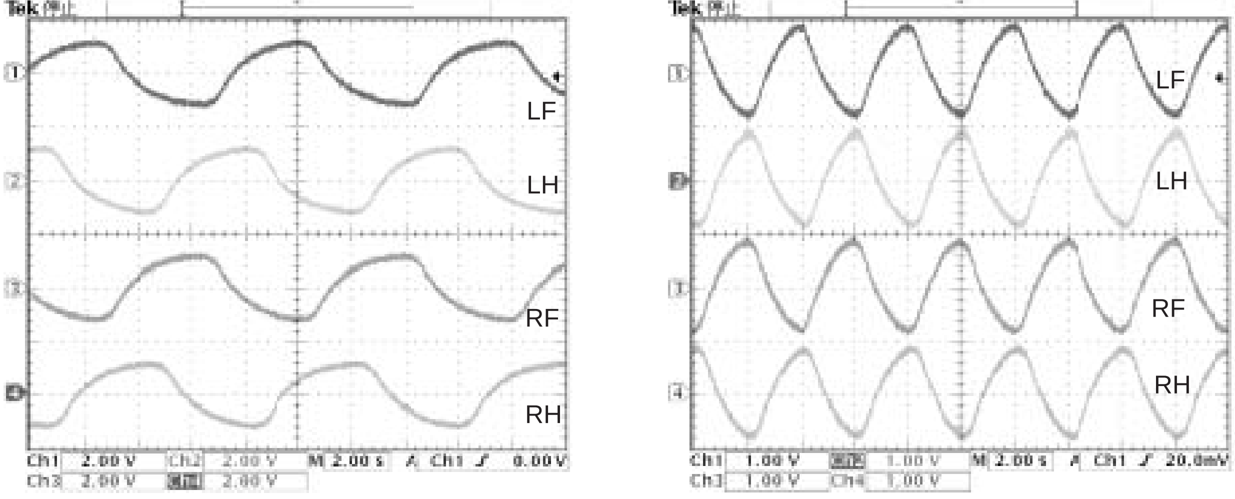


(a) (b) (c)

Figure 3: Coupling structures of the CPG circuit. (a) Walk mode. (b) Trot mode. (c) Gallop mode.

3 Experimental Results

By experiments on a test chip, we confirmed the desirable operation of the proposed circuit as a CPG-based controller. The test chip is fabricated by MOSIS AMIS 1.5-μm CMOS technology. In the following experiments, we set common parameters as follows:



(a) (b)

Figure 4: Experimental results on a fabricated test chip.

the capacitance $C = 1.0\ \mu\text{F}$, the resistance $R = 1.0\ \text{M}\Omega$, the bias current $I_b = 3\mu\text{A}$ and the rate of the capacitance of the coupling capacitors:

$$C_{i,i}^{1+,1} = C_{i,i}^{1-,2} = 0.5,\ C_{i,i}^{2+,1} = 0.3, C_T = 1.0\ \text{pF}$$

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

We confirmed the generation of rhythmic patterns in the circuit. Two examples of rhythmic patterns of voltage values V_i^1 in the circuit are shown in Figs. 4(a)-(b). It is shown that each rhythmic pattern corresponds to typical locomotion patterns, such as walk and trot. Here, we assumed that $V_{LF}^1, V_{LH}^1, V_{RF}^1$ and V_{RH}^1 drive the joint of each of the limbs.

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

$$C_{LF,RH}^{1-,2} = C_{RF,LH}^{1-,2} = C_{LH,LF}^{1-,2} = C_{RH,RF}^{1-,2} = 0.1\ \text{pF} \tag{6}$$

and the others were set at 0 F.

In the trot mode (Fig. 4(b)), we set the coupling capacitance as:

$$\begin{aligned} C_{LF,RH}^{1-,2} &= C_{RF,LH}^{1-,2} = C_{LH,RF}^{1-,2} = C_{RH,LF}^{1-,2} = 0.1\ \text{pF} \\ C_{LH,LF}^{2-,2} &= C_{RH,RF}^{2-,2} = 0.2\ \text{pF} \end{aligned} \tag{7}$$

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.

4 Summary

We propose an analog CMOS circuit that implements a CPG-based locomotion controller for a quadruped walking robot. We constructed a CPG model from the Wilson-Cowan neural oscillators, and designed it as an analog CMOS circuit that can perform parallel processing essentially. Furthermore, we fabricated a test chip in standard CMOS technology. From the experimental results, we have shown that our CPG circuit has capability to generate rhythmic patterns for locomotion control in quadruped walking robots. In our future work, we are going to incorporate it into a micro walking robot.

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