[Short Note]

Design of Hardware-Based Biomimetic Neural Networks Exhibiting Oscillatory Burst Firing of Lamprey Nervous System

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Abstract

We designed hardware-based neural networks (HNNs) that resemble neural functions of the lamprey using electronic circuits. The lamprey has a relatively simple nervous system among vertebrates. In addition, the central pattern generator of the lamprey is better understood than that of other vertebrates. Hence, we designed the HNNs based on the known structure of the lamprey nervous system. The HNNs can generate burst firing that imitates two functions of lamprey. In one function, the left and right segments alternately generate oscillatory burst firing. In the other function, burst firing propagates from head to tail of the lamprey. Therefore, we achieved biomimetic HNNs that generate oscillatory activity from the lamprey nervous system.

Keywords: Hardware-Based Neural Networks, Robot, Lamprey, Biomimetics, Burst Firing

1. Introduction

In general, animals can move autonomously in their environments given their excellent motor control. In contrast, robot systems mostly controlled by computer programs cannot handle all unknown situations. Consequently, a human operator must control a robot system under complicated scenarios.

Mimicking animal behavior may allow to enhance robot control. Some studies on the somatic nervous system have been focused on the central pattern generator (CPG).[1, 2] The CPG comprises neural networks in the spinal cord and is thought to control movement patterns such as walking and swimming. As the nervous system of the lamprey is better understood than that of other vertebrates by its simplicity,[3, 4] its functions may be implemented in robotic systems.

Software or hardware-based models can be used to imitate the nervous system. Software models are more widely used because they are easy to design. For example, the AmphiBot robot uses software models[5] to implement a biomimetic CPG of the lamprey nervous system for movement control, achieving movements resembling those of a

lamprey. In small robots, hardware-based models can be implemented more easily than software models. However, hardware-based models are more costly and time consuming to design than software models. Therefore, few studies have addressed hardware-based models.

Although biomimetic hardware-based neural models of the nervous systems of different organisms have been studied,[6, 7] conventional networks have failed to realistically imitate their structure and function. In this study, we designed hardware-based neural networks (HNNs) that replicate the structure and functions of the lamprey CPGs. The designed HNNs generate periodic burst waveforms that imitate two lamprey functions. Simulation results confirm the output waveforms generated by the developed HNNs.

2. Biomimetic HNNs Imitating Lamprey Nervous System

A. HNN components

Figure 1 shows the circuit diagrams of a cell body model and a synapse model that constitute the basic HNN components. The cell body model is an oscillator circuit that

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Fig. 1. Circuit diagrams of cell body and synapse models.

imitates some neural functions (Fig. 1(a)) and can switch between the self-excitation mode and separately excited mode by changing the voltage of source V_A . The synaptic model is a circuit that performs the spatiotemporal sum of the outputs from the cell body model. Figures 1(b) and (c) show excitatory synaptic models that promote the oscillation of the corresponding output of a cell body model when the cell body model of the input oscillates. Figures 1(d) and (e) show inhibitory synaptic models that inhibit the oscillation of the corresponding output of a cell body model when the cell body model of the input oscillates. In addition, the HNNs include synaptic models that provide delay using integrator circuits (Figs. 1(c) and (d)), and synaptic models whose output decreases after a predefined time (Fig. 1(e)).

The voltage source for the self-excited oscillation is V_A , and that for the separately excited oscillation is V_{AS} . The circuit parameters are the following. Resistors: $R_{CL} = 3.3 \text{ k}\Omega$, $R_{CG} = 820 \text{ k}\Omega$, $R_{C1} = 18 \text{ k}\Omega$, $R_{C2} = 20 \text{ k}\Omega$, $R_{DE} = 39 \text{ k}\Omega$, $R_{DI} = 39 \text{ k}\Omega$, and $R_I = 47 \text{ k}\Omega$. Capacitors: $C_{CG} = 1 \text{ nF}$, $C_{CM} = 12 \text{ nF}$, $C_E = 100 \text{ nF}$, $C_{DE1} = 3.3 \text{ }\mu\text{F}$, $C_{DE2} = 1 \text{ pF}$, $C_{DI1} = C_{DI2} = C_{I1} = 10 \text{ }\mu\text{F}$, and $C_{I2} = 20 \text{ }\mu\text{F}$. Voltage sources: $V_A = 3.5 \text{ V}$, $V_{AS} = 3.45 \text{ V}$, $V_{DD} = 3.5 \text{ V}$, $V_{Eint} = 1.5 \text{ V}$, $V_{DEint} = 1.6 \text{ V}$, $V_{Dint} = 1.65 \text{ V}$, $V_{int} = 1.62 \text{ V}$. In addition, we used n-type MOSFETs (metal-oxide-semiconductor field-effect transistors) model SSM3K17FU and p-type MOSFETs model BSS83P for M_{I5} and model BSH203 for the other transistors.

B. HNN structures

Figure 2 shows the connection diagram of the HNNs to replicate the lamprey nervous system. We devised the

Fig. 2. Connection diagram of HNNs.

model structure by simplifying the lamprey CPG structure. The HNNs are bilaterally symmetric like the lamprey CPG. The inhibitory synaptic models reciprocally inhibit each other in opposite cell body models. The output of the mutually inhibiting synaptic models decreases after some time.

With the designed structure, the HNNs imitate the function of lateral inhibitory interneurons. In the reciprocally inhibitory cell body models, when one model oscillates, the other cannot oscillate. In addition, the models alternately exhibit oscillatory bursts. The cell body models are connected from head to tail by excitatory synaptic models that provide delay characteristics. Therefore, an oscillation of the cell body models (C_{L0} , C_{R0}) in the self-excitation mode propagates to the input of the other cell body models with a delay. Moreover, the cell body models are connected from tail to head by inhibitory synaptic models with delay to stabilize the lag period.

C. Simulation results

Figure 3 shows an example of the output waveforms from the HNNs. The output voltage of each cell body model, v_{Cout} , is shown in Fig. 1(a). These simulation results were obtained using PSpice (Cadence Design Systems). Figure 3(a) shows the output waveforms from C_{L1} and C_{R1} . Figure 3(b) shows the output waveforms from C_{L1} – C_{L4} . In Fig. 3(a), C_{L1} and C_{R1} alternately generate oscillatory bursts. The burst oscillation resembles the neural function of the lamprey in which the left and right segments alternately oscillate. In Fig. 3(b), the oscillatory bursts propagate with delays from C_{L1} to C_{L4} . These bursts resemble the neural function in which burst the oscillation propa-

Fig. 3. HNN output waveforms.

gates from head to tail of the lamprey. Therefore, the HNNs generate biomimetic oscillatory burst firing of functions from the lamprey CPG.

We plan to use shape-memory alloys as actuators for a lamprey-type robot. This alloy shrinks at high temperatures and expands at low temperatures. The output waveforms shown in Fig. 3 can be used to drive the actuator by heating the alloy during the oscillatory burst period and letting it radiate during the inactivity period. Therefore, by assembling as many actuators as circuits C_{LN} and C_{RN}, we expect the robot to generate snake-like movement.

3. Conclusion

We designed HNNs that imitate functions of the lamprey CPG. Specifically, the HNNs generate oscillatory bursts corresponding to two lamprey neural functions. In one function, the left and right segments alternately generate oscillatory bursts, and in the other function, the oscillatory burst propagates from head to tail. We verified the HNN output waveforms by simulations. We are currently constructing the HNNs using discrete circuits, and in future work, we will design a lamprey-type robot equipped with the proposed HNNs for actuation.

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