Biomimetic CPGs for robotic applications

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Abstract: Locomotion is one of the most basic abilities of animals. Neurobiologists have established that locomotion results from the activity of half-center oscillators that provides alternating bursts. Most rhythmic movements are programmed by central pattern-generating (CPG) networks consisting of neural oscillators. A biomimetic system mimics the nature for simulating the living behavior and/or replaces it (rebuilding the living part). We propose a network of hundreds biomimetic CPGs using biomimetic neuron model and synapses. This network is implemented in an FPGA (Field Programmable Gate Array). This article is decomposed into two parts: the description, the implementation and results of the biomimetic network of CPGs, and the architecture and advantages of robots including our biomimetic CPGs.

Keywords: Central Patter Generators, Spiking neural networks, biomimetic, robotic.

1 INTRODUCTION

Locomotion is one of the most basic abilities of animals. Neurobiologists have established that locomotion results from the activity of half-center oscillators that provides alternating bursts. The first half-center oscillator was proposed by Brown [1] in 1914. Pools of interneurons control flexor and extensor motor neurons with reciprocal inhibitory connections. Most rhythmic movements are programmed by central pattern-generating networks consisting of neural oscillators (Marder [2]). Central Pattern Generators (CPGs) are neural networks capable of producing rhythmic patterned outputs without rhythmic sensory or central input. CPGs underlie the production of most rhythmic motor patterns and have been extensively studied as models of neural network function (Hooper [3]). Half-center oscillators control various animal locomotion like swimming in xenopus, salamander (Ijspeert [4]), and lamprey (Cohen [5]), as well as leech heartbeat system (Cymbalyuk [6], Hill [7]).

Usually, in robotic field, the CPGs are made using simple neuron-models, are not in biological time scale and were more bio-inspired than biomimetic. A bio-inspired system is inspired by nature for dealing with engineering task (neural network for pattern recognition, data mining, etc.). A biomimetic system mimics the nature for simulating the living behavior and/or replaces it (rebuilding the living part. While multi-legged robots need CPG to move or coordinate their movements, researchers implement an Amari-Hopfield CPG (Amari [8]) or basic CPGs like Van der Pol ones (Van der Pol [9]), modeled as non-linear oscillators. Those models provide sinusoidal oscillations that are not biomimetic. To be closer to the nature, we developed biomimetic CPGs.

This article is decomposed into two parts: the description and results of the biomimetic network of CPGs, and the architecture and advantages of robots including our biomimetic CPGs.

2 DESIGN OF BIOMIMETIC CPGs

We propose a network of hundreds biomimetic CPGs using biomimetic neuron and synapse models. This network is implemented in an FPGA (Field Programmable Gate Array). The network implementation architecture operates on a single computation core. This digital system works in real-time, requires few resources and is low power consumption. It is important points for robotic applications. The implementation of this network of CPGs is validated by comparing it with biological data of leech heartbeat neural network. These CPGs could reproduce biological activity of CPG neural networks in terms of period but also in terms of variation of duty cycle and period of bursting.

2.1 Model of the Leech Heartbeat system

Our CPG is based on the Leech heartbeat neural network system (Hill [7]). This network is simple; just 8 excitatory neurons with inhibitive synapses are needed, making it an ideal candidate system for elucidating the various biomechanisms governing CPG behaviors and for robotic applications. Fig. 1 describes the diagram of the CPG.

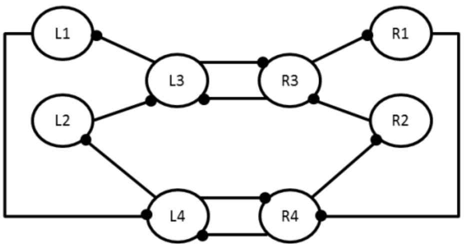

Fig. 1. A diagram of the CPG in the leech heartbeat system, including two elemental oscillators, L3/R3 and L4/R4, and two pairs of coordination neurons, L1/R1 and L2/R2

2.2 Neuron model

In designing a Spiking Neural Network (SNN), the first step is the choice of a biologically realistic model. Indeed, a mathematical model based differential equations is capable of reproducing a behavior quite similar to that of a biological cell. The choice of model was based on two criteria: the family of neurons able to be reproduced and the number of equations. These criteria were used to compare several models, including the Leaky Integrate and Fire model (LIF) (Indiveri [10]), the Hodgkin-Huxley model (HH) (Hodkin-Huxley [11]), and the Izhikevich model (IZH) (Izhikevic [12]).

(Hill [7]) used the HH to reproduce the leech heartbeat system with eight neurons (Fig. 1). The HH model reproduces all types of neurons with good accuracy (spike timing and shape). Its main drawbacks are the large number of parameters and the equations required. In the heartbeat network, the main focus is on excitatory neurons, like regular-spiking neurons (RS). The HH model required 32 parameters for an RS and 26 for a fast-spiking neuron (FS) (Grassia [13]). Furthermore, simulating an RS neuron required four ionic channels (dynamics of potassium and sodium ions, leak current, and slow potassium). In contrast, LIF only involves two equations but is only capable of simulating a few types of neurons.

The IZH represents a good solution, as it is based on two equations and is capable of reproducing many different families of neurons by changing four parameters. Furthermore, according to (Izhikevic [12]), this model is resource-frugal, a key advantage when the aim is to design a large CPG network embedded in the same board. The IZH model depends on four parameters, a,b,c and d which make it possible to reproduce the spiking and bursting behavior of specific types of cortical neurons. From a mathematical standpoint, the model is described by a two-dimensional system of ordinary differential equations (Izhikevic [12]):

$$\frac{dv}{dt} = 0.04v^2 + 5v + 140 - u + I_{Izh} \qquad (1)$$

$$\frac{du}{dt} = a(bv - u) \qquad (2)$$

with the after-spike resetting conditions:

$$if \quad v \geq 30mV \Rightarrow \begin{cases} v \leftarrow c \\ u \leftarrow u + d \end{cases} \qquad (3)$$

2.3 Synapse model

A network is defined by a group of neurons and a group of synapses. Once the neuron model had been chosen, it was obviously necessary to choose a synapse model. Like the neuron model, this model had to be biomimetic but frugal in its use of resources. As the synaptic behavior described in (Hill [7]) requires too many resources to be implemented on FPGA, the method chosen to fit overall biological behavior was activity-dependent depression (Tabak [14]). Activity-dependent depression of synapses is another biological phenomenon consisting of reducing a synaptic weight after a spike. The synaptic current is included into I_{Izh} in (1).

2.4 Network topology

The architecture was based on three main blocks: the neuron implemented (or neuron computation core), a synapse, and the RAM. The connectivity between those blocks is shown in Fig. 2.

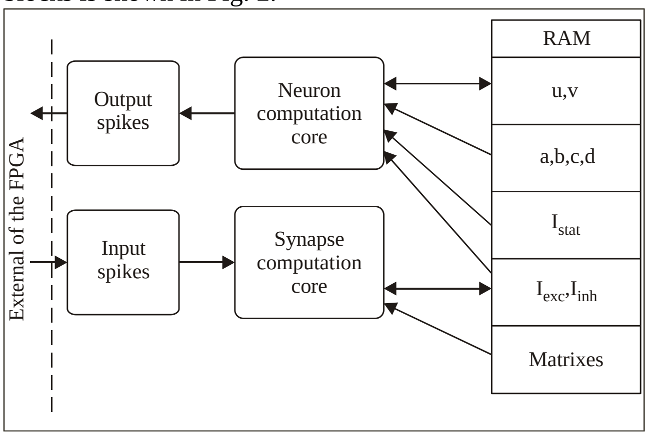

Fig. 2. Global architecture of the spiking neural network

So far, the neuron computation core can update the state ('u' and 'v' variables) of each neuron. In the digital network, the role of the synapse is to update all synaptic currents and weights related to the activity of all neurons, so the synapse block exhibits two behaviors (spiking or not). The I_{Izh} current is divided into 3 currents: I_{stat}, I_{exc} and I_{inh}. I_{stat} is a constant current that have originally the neuron, I_{exc} and I_{inh} are respectively the excitatory synaptic current and the inhibitory one. These 2 currents describe if there is an excitation or inhibition to apply at the neuron.

2.5 Implementation and results

We implement a network of 240 CPGs into a Spartan 6 digital board. This number will allow us several robotic applications like the simulation of Salamander which requires 40 CPGs which we will describe later. Table 1 describes the resources needed for the implementation of the network into a Spartan 6 digital board.

Table 1. Resources needed for our CPG network on a Spartan 6 digital board

Resources	Total available	Used for one CPG	Used for 240 CPGs
Slice FF's	184304	1,093 (0.6%)	1,459 (0.8%)
Slice LUT	92152	1,037 (1.2%)	1,756 (1.9%)
Multiplier	180	10 (5.6%)	10 (5.6%)
Total RAM	4824 kb	9 kb (0.2%)	765 kb (16%)

To validate our CPG into FPGA, we compare it first with the model described in (Hill [7]). We compare the period, the duty cycle of the burst and also the frequency of the 8 neurons.

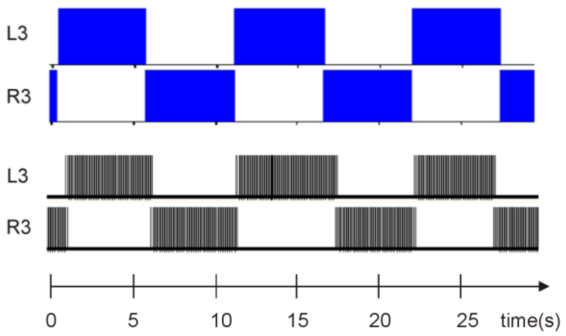

Fig. 3. Comparison between CPG bursting activity in the complex model simulated by scilab, as described in (Hill [7]) and our digital CPG presented above thanks to a logic analyzer. L3/R3 is the couple of neurons (elemental oscillator) described in Fig. 1. The time scale is the same.

In this case (Fig. 3), the activity of one neuron inhibits the second neuron. Due to activity-dependent depression and the GABA effect, the inhibition ends and lets the second neuron fire again. In both cases (biological modeling system and digital system), the bursting activity was similar in terms of period (12s) and duty cycle (55%), thus validating our digital CPG.

Modifying the I_{stat} included into I_{Izh} (1), we could modify the period of the bursting activity. This point is really important because we could in real-time modifying the frequency of the locomotion activity tuning only one parameter.

We described the network of biomimetic CPGs that we designed. Now we will describe the possible applications of these networks and why the biomimetic part is important.

3 ROBOTIC APPLICATIONS

In the second part, as this CPG network is likely to be useful for mimicking the locomotion activity of various animals, we propose some possible robotic architecture using this network of CPGs.

3.1 Biomimetic animal robots

CPGs are really important for designing biomimetic animal locomotion. Usually, the CPGs are simple oscillators or bio-inspired ones. In our case, the biomimetic advantage of our network of CPGs is that the behavior is really the same as biological neural networks, with the variation of duty cycle and periods. The animal robots will then behave more like in the nature. For designing a salamander robot, it needs 20 CPGs with a frequency of walking from 0.6 to 1.2 Hz, and of swimming from 1.6 to 2.9 Hz [15]. Our system fits with these specifications, and we could also improve it using more CPGs as our network contains 240 CPGs. As the period of our CPG could be modified depending just one parameter, we could make a closed-loop between a sensor and the CPG.

3.2 Hybrid robots

One main advantage of our system is that it allows hybrid experiments. Then we could use our CPG as an artificial control unit, and the different actuators and sensors will be biological ones. We already made a hybrid experiment where our biomimetic CPG controls the locomotion through a rat spinal cord.

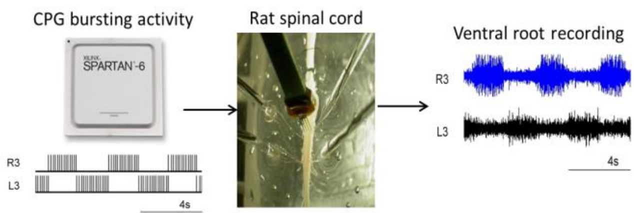

Fig. 4. The biomimetic CPG send its bursting activity to a rat spinal cord. The ventral root output of the spinal cord, which is directly sent to muscles, is the same than the CPG bursting activity.

3.2 Microfluidic robots

Currently, we are designing a microfluidic robot controlled by our CPG (Fig. 5). This robot is based on biomimetic control, actuator and sensor architecture that features highly modularized components and used few energy. It can conduct autonomous investigation and is less subject at pressure conditions. This main part of the robot is based on PDMS (Polydimethylsiloxane) microfluidic devices. The advantage of using our biomimetic CPG as control unit is that we could easily change the period and the duty cycle of the bursting activity. Furthermore, the FPGA power consumption is less than microprocessor one, that is important for the autonomy of the robot. As our control unit is biomimetic, the microfluidic robot will reproduce better the nature locomotion (variation of duty cycle and period) than simple electronic oscillators.

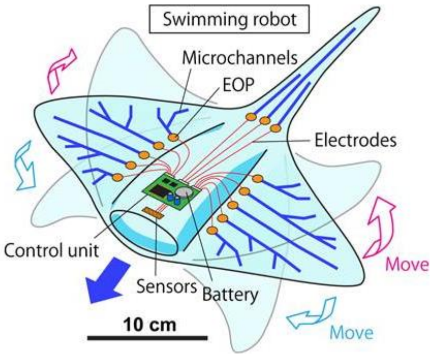

Fig. 5. Microfluidic robot using biomimetic CPGs as control unit

4 CONCLUSION

A network of biologically realistic CPGs was implemented with a minimum resource cost, while maintaining its biomimetic activity, as shown in the results section. The biomimetic part is important for robotic applications especially for animal robots and hybrid robots. The variation of period and duty cycle that we could observe in nature is possible with these CPGs. Future robotic applications using these CPGs are described.

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