Snake robot controlled by biomimetic CPGs

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Abstract

Locomotion is one of the most basic abilities in animals. Neurobiologists have established that locomotion results from the activity of half-center oscillators that provides alternation of bursts. Central Pattern Generators (CPGs) are neural networks capable of producing rhythmic patterned outputs without rhythmic sensory or central input. We propose a network of several biomimetic CPGs using biomimetic neuron model and synaptic plasticity. This network is implemented on a FPGA (Field Programmable Gate Array). We designed one unsupervised snake robot using this network of CPG. It is composed of one head wagon and 7 slave wagon. Infrared sensors are also embedded in the head wagon. This robot can reproduce the locomotion of one snake. The hardware robot is also described in this paper.

Keywords: snake robot, CPG, biomimetic, spiking neural network, locomotion.

1. Introduction

Locomotion is one of the most basic abilities of animals. Neurobiologists have established that locomotion is created by Central Pattern Generator (CPG) activity that produces alternating bursts[1]. Most rhythmic movements are programmed by CPG (Central Pattern Generator) networks[2]. CPGs are neural networks capable of producing rhythmic patterned outputs without sensory input. CPGs can be found in animal locomotion such as swimming in salamander[3], and lamprey[4], as well as the cardiac pulsation system of the leech[5, 6].

Usually, in the field of robotics, CPGs are made using simple neuron models[7] or simple oscillators[8], which are not biological time scales and which are considered as bio-inspired systems rather than biomimetic systems. These models provide sinusoidal oscillations and cannot reproduce biomimetic CPGs which have variability in performance. As our aim is to replicate biological behavior, we developed biomimetic CPGs using digital neuromorphic system.

2. Biomimetic CPGs in digital neuromorphic system

2.1. *CPG neural network*

The biomimetic CPG is based on the neural network system that controls the heartbeat of the leech[6]. This network is simple. It just only uses 8 excitatory neurons with 12 inhibitory synapses, making it an ideal candidate for our applications.

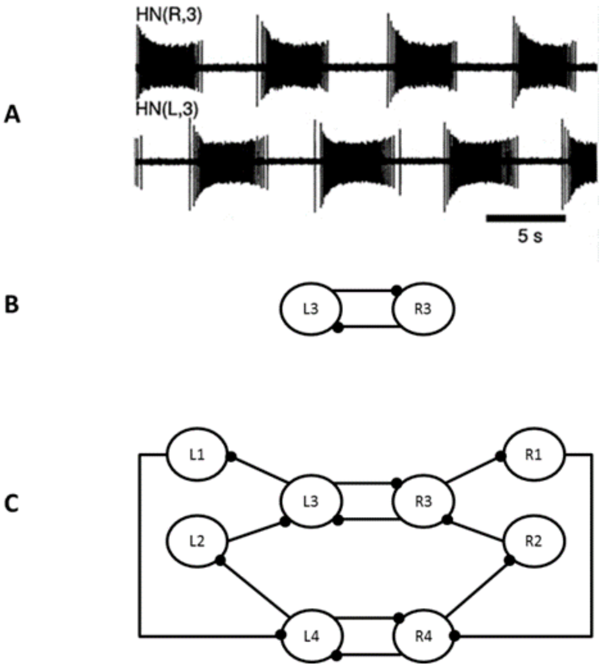

Fig. 1. Electrical activity of the neural system of the Heartbeat of the Leech. Neurons are represented by circles. Inhibitory synapses are represented by black dots. A: Electrical Activity from the Leech [HILL 2003]. B: Diagram of an Elemental Oscillator of the Heart of the Leech. C: Diagram of the Segmental Oscillator of the Heart of the Leech.

2.2. *Simplification of the model*

To design this CPG (Segmental Oscillator in Figure 1.C C), we use Hill's neural network diagram[6].
The network designed by Hill uses the Hodgkin-Huxley model[9] and complex equations for synapses. A first work was to simplify this model and use Izhikevich neurons[10]. Using the short-term synaptic plasticity[11] and the Izhikevich Regular Spiking neurons, we reproduced the activity of Hill's model.

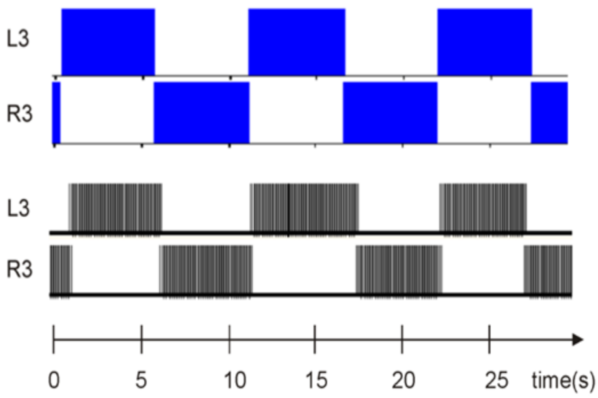

Fig. 2. Comparison of CPG activity between Hill's model (in blue) and our model (in black)

Even though we have simplified the model, we are able to reproduce the same behavior and characteristics as the biological CPGs. The important point is to allow a variability in the characteristics of the CPGs. Percentages of variability can be controlled by adjusting the parameters of short-term synaptic plasticity.
By changing the parameters of the inhibitory synapses, it is possible to obtain different periods and cyclic ratios. This is very important especially for closed-loop experiments and to reproduce locomotion activities for robotics. A single parameter pair manages the modification of the period and of the duty cycle. The possible period interval in seconds is quite wide [0.3s; 35s].

2.3. *Implementation in digital neuromorphic system*

Biomimetic CPGs[12, 13, 14, 15] are implemented in a digital platform: CMOD A7-A35 Xilinx Artix-7 FPGA (Field Programmable Gate Array). The neural network implementation architecture operates on a single computation core. This digital system works in real-time, requires few resources and is low power consumption[16, 17, 18, 19]. Table 1 summarizes the resources.

Table 1. Utilization of the resources for the implementation of biomimetic CPGs

Kintex-7	Utilization	Available	Percentage
LUT	7786	20800	**37.43**
FF	3299	41600	**7.93**
BRAM	50	50	**100**
DSP	40	90	**44.44**

Figure 3 describes the CMOD A7 FPGA board where CPGs with different period are implemented.

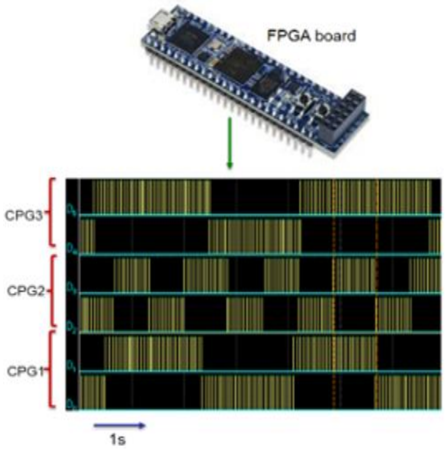

Fig. 3. Three different CPGs with different period (1,7s, 3,6s and 5s). The output are from the scope.

As we implemented the biomimetic CPGs in the FPGA board, we design the structure of the snake robot which embedded the FPGA board.

3. Snake robot

3.1. *Design*

The snake robots is composed of 7 wagons (like spinal cord) and 1 locomotive (mimics the brain).

Biomimetic CPGs will control the different motors of the wagons. As the output of the FPGA board is 3.3V with low current, we need to add a power driver for the motors and one VHDL module for converting the CPGs to PWM (Pulse Width Modulation) to control motor speed. The PWM frequency should be between 100 Hz and 200 kHz. The duty cycle of the PWM controls the speed of the motor. We use a Pololu_DRV8835 for the power driver. Motors are DG01D with a 0.8 kg.cm couple and a no load speed of 90 rpm.

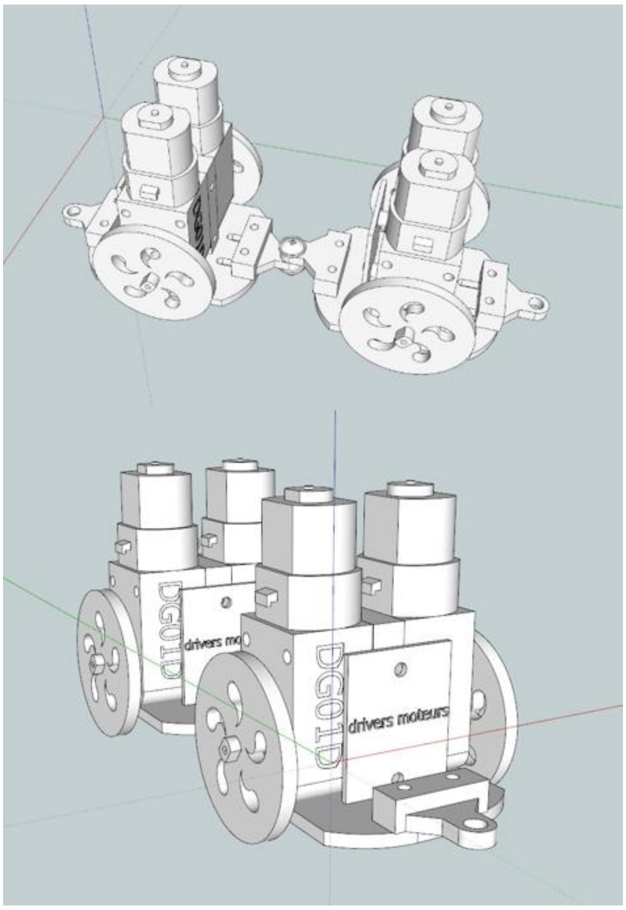

Fig. 4. 3D view of the wagon design

All the distance between the different wagons and the possible movement angle can be tuned thanks to mechanical structure. Figure 5 shows how the tuning is possible.

Fig. 5. The orange screw allows the tuning of distance of the different wagons but also the angle for the movement.

The design of electrical connection and components for the locomotive and for the wagon is described in figure 6.

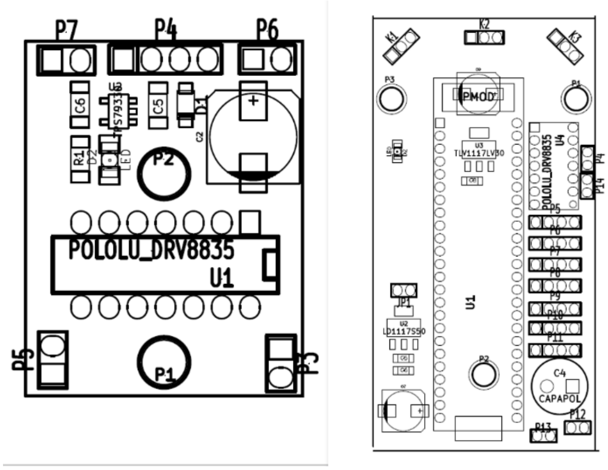

Fig. 6. On the left, the electrical circuit of the wagon. On the right, the electrical circuit of the locomotive with the FPGA board.

The locomotive system has 3 IR sensors for detecting the different obstacles and then send stimulus to CPGs for modifying duty cycle and period. The tuning of the duty cycle allows the movement and the tuning of period allows the speed or the stop of the robot.

3.2. *Results*

Height CPGs were implemented (one for the locomotive and 7 for the wagons). Enable input are connected to each wagon to choose which ones are working for simulating a lesion of the spinal cord.

The CPGs are connected for allowing forward locomotion like we can find in animal locomotion[20]. Fig. 7 describes this CPG network and the forward locomotion.

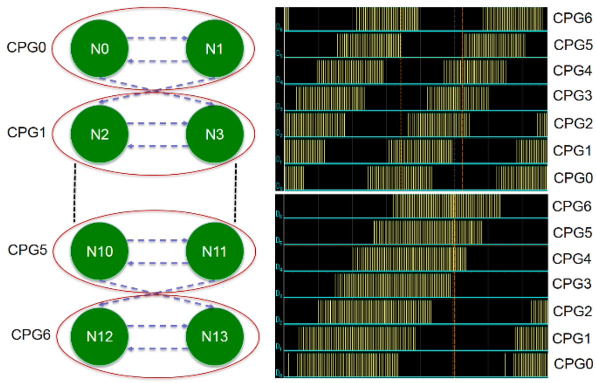

Fig. 7. Forward locomotion with two examples of speed using a chain of 7 CPGs for the 7 wagons. Time axis is one second by division. Signal are the left neuron (N0, N2, N4, N6, N8, N10 and N12) of each CPG.

The final snake robot is 67 cm long and works with real-time biomimetic CPGs and mimics the snake locomotion. Figure 8 shows the final snake robot picture.

Fig. 8. Picture of the snake robot with the locomotive and the 7 wagons.

4. Conclusion

This article describes the design of a snake robot. This robot is controlled by real-time network of biomimetic CPGs. This system can be used in robotic applications[21] for a closer behavior of biological animals. It can also be used in bio-hybrid robotics (biomimetic CPGs can be replaced by in vitro cell culture). We show previously that our system can be connected to biological neurons[22,23]. Another advantage is that real-time systems can simulate multiple CPG topologies and simulate different hypothesis and protocol treatments for biomedical applications such as spinal cord injury[24] and neuroprosthetics[25].

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References

1. T. Brown, On the nature of the fundamental activity of the nervous centres; together with an analysis of the conditioning of rhythmic activity in progression and a theory of the evolution of function in the nervous system. Journal of Physiology, 48, 18-46, 1914
2. E. Marder and D. Bucher, Central pattern generators and the control of rhythmic movements. Current Biology 11, 986-996, 2001
3. A. Ijspeert, A. Crespi, D. Ryczko, J. Cabelguen, From swimming to walking with a salamander robot driven by a spinal cord model. Science, 315, 1416-1420, 2007

4. AH. Cohen et al., Modelling of intersegmental coordination in the lamprey central pattern generator for locomotion. Trends in Neuroscience. 15, 434–438, 1992
5. GS. Cymbalyuk, Q. Gaudry, MA. Masino, R.L. Calabrese, Bursting in Leech Heart Interneurons: Cell-Autonomous and Network-Based Mechanisms. J. Neuroscience, 22, 10580-10592, 2002
6. AA. Hill, J. Lu, MA. Masino, OH Olsen, RL Calabrese, A model of a segmental oscillator in the leech heartbeat neuronal network, J Comput Neurosci., 10, 281-302, 2001
7. S. Amari, Characteristic of the random nets of analog neuron-like elements, IEEE Trans. on System, Man and Cybernetics, 2, 643-657, 1972
8. B. Van Der Pol, The heartbeat considered as a relaxation oscillation, and an electrical model of the heart. Philosophical Magazine, 6, 763–775, 1928
9. AL. Hodgkin, AF. Huxley, A quantitative description of membrane current and its applications to conduction and excitation in nerve, The Journal of Physiology, 117, 500-544, 1952
10. E.M. Izhikevich, Simple model of spiking neurons. IEEE Transactions on Neural Networks, 14, 1569- 1572, 2003
11. E.M. Izhikevich and G. Edelman, Large-scale model of mammalian thalamocortical systems, Proceedings of the National Academy of Sciences of the United States of America, 105, 3593-3598, 2008
12. J.H. Barron-Zambrano and C. Torres-Huitzil, FPGA implementation of a configurable neuromorphic CPG-based locomotion controller, Neural Netw.45, 50–61, 2013.
13. C. Li, R. Lowe, T. Ziemke, Humanoids Learning to Walk : a Natural CPG-Actor-Critic Architecture, Frontiers in Neurorobotics, 7:5, 2013
14. E. Donati, F. Corradi, C. Stefanini, G. Indiveri, A spiking implementation of the lamprey's Central Pattern Generator in neuromorphic VLSI, IEEE BioCAS 2014,2014
15. C. Qi et al., A real-time FPGA implementation of a biologically inspired central pattern generator network, Neurocomputing, 244, 63-80, 2017
16. M. Ambroise, T. Levi, S. Joucla, B. Yvert, S. Saïghi, Real-time biomimetic Central Pattern Generators in an FPGA for hybrid experiments. Frontiers in Neuroscience, 7, 215, 2013
17. M. Ambroise, T. Levi, Y. Bornat, S. Saïghi, Biorealistic spiking neural network on FPGA, 47th Annual Conference on Information Sciences and Systems CISS, 1-6, 2013
18. F. Grassia, T. kohno, T. Levi, Digital hardware implementation of a stochastic two-dimensional neuron model, Journal of Physiology Paris, 110:4, 409-416, 2016
19. T. Levi, Y. Guo, K. Aihara, T. Kohno, Study of real-time biomimetic CPG on FPGA: behavior and evolution, JRNAL, 4:4, 299:302, 2018
20. T. Matsuo, T. Yokoyama, D. Ueno, K. Ishii, Biomimetic Motion Control System Based on a CPG for an Amphibious Multi-Link Mobile Robot, Journal of Bionic Engineering, 91-97, 2008
21. T. Levi, T. Nanami, A. Tange, K. Aihara, T. Kohno, Development and Applications of Biomimetic Neuronal Networks Toward BrainMorphic Artificial Intelligence, IEEE Transactions on Circuits and Systems II, 65:5, 577-581, 2018
22. S. Joucla et al.,, Generation of locomotor-like activity in the isolated rat spinal cord using intraspinal electrical microstimulation driven by a digital neuromorphic CPG, Frontiers in neuroscience, 10, 2016
23. T. Levi et al., Biomimetic neural network for modifying biological dynamics during hybrid experiments, Journal on Artificial Life and Robotics, May 2017
24. M. Capogrosso et al., A brain–spine interface alleviating gait deficits after spinal cord injury in primates, Nature, 539, 284-288, November 2016
25. T. Levi, P. Bonifazi, P. Massobrio, M. Chiappalone, Closed-loop systems for next-generation neuroprostheses, Frontiers in Neuroscience, 12-26, 2018