

Research Article

# Snake Robot Controlled by Biomimetic CPGs

Damien Blanchard<sup>1</sup>, Kazuyuki Aihara<sup>2</sup>, Timothée Levi<sup>2\*</sup>

<sup>1</sup>GEII Department, IUT Bordeaux, University of Bordeaux, Talence 33400 France

<sup>2</sup>Institute of Industrial Science (IIS), The University of Tokyo, Meguro-ku, Tokyo 153-8505, Japan

## ARTICLE INFO

### Article History

Received 14 October 2018

Accepted 18 December 2018

### Keywords

Snake robot  
 CPG  
 biomimetic  
 spiking neural network  
 locomotion

## ABSTRACT

The design of biomimetic robot is one popular research. To achieve this goal, the reproduction of animal locomotion is mandatory. Animal locomotion is created by the activities of Central Pattern Generator (CPG). 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 field programmable gate array. We designed one unsupervised snake robot using this network of CPG. It is composed of one head wagon followed by seven slave wagons. Infrared sensors are also embedded in the head wagon. This robot can reproduce the locomotion of one snake.

© 2019 The Authors. Published by Atlantis Press SARL.

This is an open access article distributed under the CC BY-NC 4.0 license (<http://creativecommons.org/licenses/by-nc/4.0/>).

## 1. INTRODUCTION

The design of biomimetic robot is one popular research. To achieve this goal, the reproduction of animal locomotion is mandatory. Animal locomotion is created by the activities of Central Pattern Generator (CPG) that produces alternating bursts [1]. Most rhythmic movements are programmed by CPG networks [2]. CPGs are neural networks capable of producing rhythmic patterned outputs without sensory input. CPGs in animal locomotion have been studied such as swimming in salamander [3] or lamprey [4], and heart-beat system in leech [5,6].

Usually in robotic field, CPGs are designed 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 a leech [6]. This simple network uses eight excitatory neurons with 12 inhibitory synapses, making it an ideal

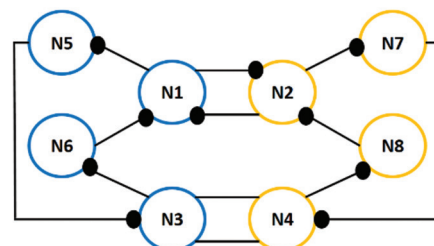
candidate for our applications. This neural network model has been designed by Hill et al. [6] and described in Figure 1.

### 2.2. Simplification of the Model

To design this CPG (Figure 1), Hill's neural network diagram [6] was used.

The network designed by Hill uses the Hodgkin–Huxley (HH) model [9] and complex equations for synapses. Our first work was to simplify this model by applying Izhikevich neurons [10] instead of HH model. Using the short-term synaptic plasticity [11] and the Izhikevich Regular Spiking neurons, the activity of Hill's model was reproduced.

Even though the model was simplified, the same behavior and characteristics as the biological CPGs was successfully reproduced. The important point is to allow a variability in the characteristics

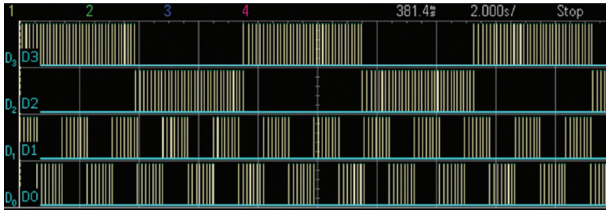


**Figure 1** Diagram of the Segmental Oscillator of the Heartbeat of the Leech. The modelling is from Hill et al. [6]. N1–N2 and N3–N4 are two elemental oscillators. N1, N3, N5, and N6 are controlling the left part (blue), N2, N4, N7, and N8, the right part (orange). The 12 black dots represents inhibitory synapses with short-term plasticity. All neurons are excitatory ones.

\*Corresponding author. Email: [levi@sat.t.u-tokyo.ac.jp](mailto:levi@sat.t.u-tokyo.ac.jp)

**Table 1** | Utilization of the resources for the implementation of biomimetic CPGs in CMOD A7-A35 board

Kintex-7	Utilization	Available	Percentage
LUT	7786	20,800	37.43
FF	3299	41,600	7.93
BRAM	50	50	100
DSP	40	90	44.44



**Figure 2** | Two different CPGs with different period (1.8 and 7.8 s). The output are from the scope.

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 [0.3 and 35 s].

### 2.3. Implementation in Digital Neuromorphic System

Biomimetic CPGs [12–15] are implemented in a digital platform: CMOD A7-A35 Xilinx Artix-7 Field Programmable Gate Array (FPGA). The neural network implementation architecture operates on a single computation core. This real-time digital system requires few resources and low power consumption [16–19]. Table 1 summarizes the stated resources and Figure 2 describes two CPGs with different periods.

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 seven wagons (like spinal cord) and one locomotive (mimics the brain).

Biomimetic CPGs will control the different motors of the wagons. As the output of the FPGA board is 3.3 V with low current, a power driver for the motors and a VHDL module for converting the CPGs to Pulse Width Modulation (PWM) to control motor speed needs to be added. The PWM frequency should be between 100 Hz and 200 kHz. The duty cycle of the PWM controls the speed of the motor. Pololu\_DRV8835 was used for the power

driver. Motors are DG01D with a 0.8 kg.cm couple and a no load speed of 90 rpm. Figure 3 shows the 3D structure of the wagons.

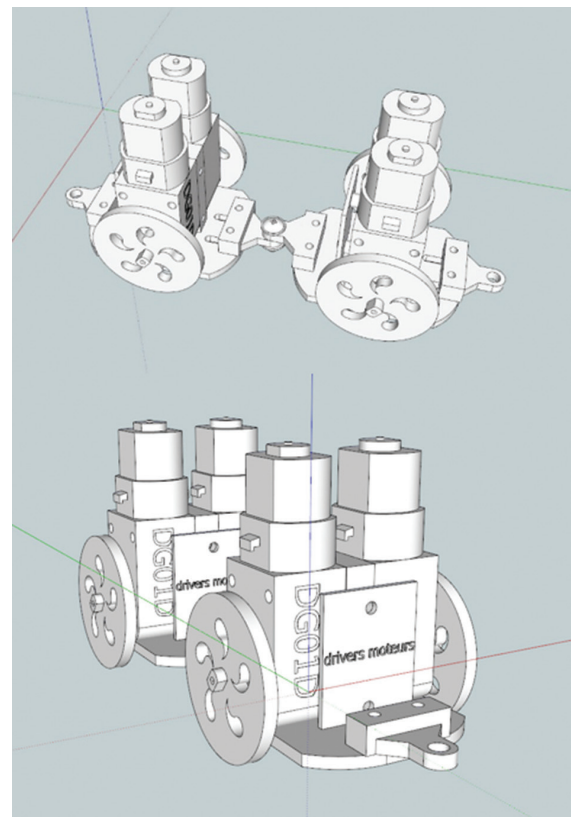
All the distance between the different wagons and the possible movement angle can be tuned with mechanical structure. Figure 4 shows how the tuning is possible with the orange screws.

The design of electrical connection and components for the locomotive and for the wagon is described in Figure 5.

The locomotive system has three 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.

## 4. RESULTS

Height CPGs were implemented (one for the locomotive and seven 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



**Figure 3** | 3D view of the wagon design.



**Figure 4** | The orange screw allows the tuning of distance of the different wagons but also the angle for the movement.

like we can find in animal locomotion [20]. Figure 6 describes this CPG network and the forward locomotion [19].

The final snake robot is 59 cm long and works with real-time biomimetic CPGs and mimics the snake locomotion. Figure 7 shows the final snake robot picture.

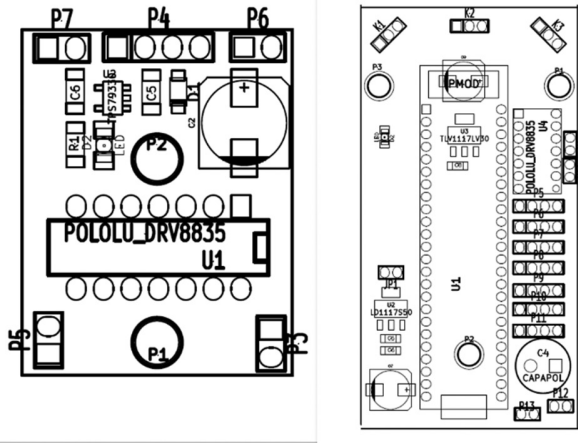


Figure 5 | On the left, the electrical circuit of the wagon. On the right, the electrical circuit of the locomotive with the FPGA board.

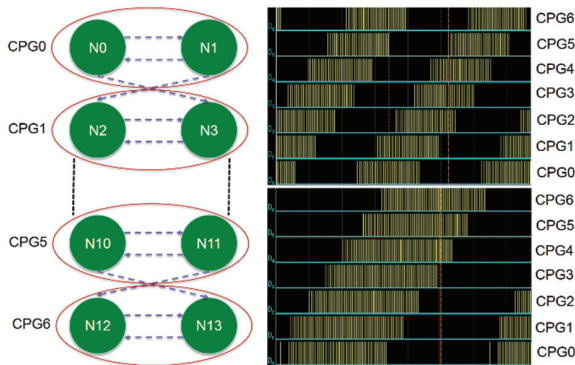


Figure 6 | Forward locomotion [19] with two examples of speed using a chain of 7 CPGs for the seven wagons. Time axis is 1 s by division. Signal are the left neuron (N0, N2, N4, N6, N8, N10 and N12) of each CPG.



Figure 7 | Picture of the snake robot with the locomotive and the seven wagons.

## 5. 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 to biological animals. It can also be used in bio-hybrid robotics (biomimetic CPGs can be replaced by *in vitro* cell culture). We previously showed that our system can be connected to biological neurons [22,23]. Another advantage is that the 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 [25,26].

## ACKNOWLEDGMENT

Authors thank Social Cooperation Program for Brain-Morphic AI to Resolve Social Issues, IIS, University of Tokyo.

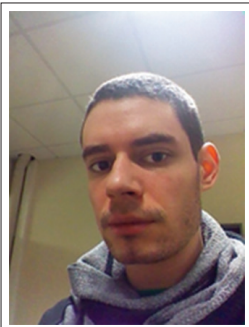
## REFERENCES

- [1] T. Graham 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, *J. Physiol.* 48 (1914), 18–46.
- [2] E. Marder, D. Bucher, Central pattern generators and the control of rhythmic movements, *Curr Biol.* 11 (2001), R986–R996.
- [3] A.J. Ijspeert, A. Crespi, D. Ryczko, J. Cabelguen, From swimming to walking with a salamander robot driven by a spinal cord model, *Science* 315 (2007), 1416–1420.
- [4] A.H. Cohen, G.B. Ermentrout, T. Kiemel, N. Kopell, K.A. Sigvardt, T.L. Williams, Modelling of intersegmental coordination in the lamprey central pattern generator for locomotion, *Trends Neurosci.* 15 (1992), 434–438.
- [5] G.S. Cymbalyuk, Q. Gaudry, M.A. Masino, R.L. Calabrese, Bursting in leech heart interneurons: cell-autonomous and network-based mechanisms, *J. Neurosci.* 22 (2002), 10580–10592.
- [6] A.A. Hill, J. Lu, M.A. Masino, O.H. Olsen, R.L. Calabrese, A model of a segmental oscillator in the leech heartbeat neuronal network, *J Comput Neurosci.* 10 (2001), 281–302.
- [7] S. Amari, Characteristic of the random nets of analog neuron-like elements, *IEEE Transactions on Systems, Man, and Cybernetics*, IEEE, 1972, pp. 643–657.
- [8] B. van der Pol, J. van der Mark, The heartbeat considered as a relaxation oscillation, and an electrical model of the heart, *Phil. Mag.* 6 (1928), 763–775.
- [9] A.L. Hodgkin, A.F. Huxley, A quantitative description of membrane current and its application to conduction and excitation in nerve, *J. Physiol.* 117 (1952), 500–544.
- [10] E.M. Izhikevich, Simple model of spiking neurons, *IEEE Transactions on Neural Networks*, IEEE, 2003, pp. 1569–1572.
- [11] E.M. Izhikevich, G.M. Edelman, Large-scale model of mammalian thalamocortical systems, *Proc. Natl. Acad. Sci.* 105 (2008), 3593–3598.
- [12] J.H. Barron-Zambrano, C. Torres-Huitzil, FPGA implementation of a configurable neuromorphic CPG-based locomotion controller, *Neural Netw.* 45 (2013), 50–61.
- [13] C. Li, R. Lowe, T. Ziemke, Humanoids learning to walk: a natural CPG-actor-critic architecture, *Front Neurobot.* 7 (2013), 5.

- [14] E. Donati, F. Corradi, C. Stefanini, G. Indiveri, A spiking implementation of the lamprey's central pattern generator in neuromorphic VLSI, 2014 IEEE Biomedical Circuits and Systems Conference (BioCAS) Proceedings, IEEE, Lausanne, Switzerland, 2014, pp. 512–515.
- [15] C. Qi, W. Jiang, S. Yang, Y. Qin, B. Deng, W. Xile, A real-time FPGA implementation of a biologically inspired central pattern generator network, *Neurocomputing* 244 (2017), 63–80.
- [16] M. Ambroise, T. Levi, S. Joucla, B. Yvert, S. Saïghi, Real-time biomimetic central pattern generators in an FPGA for hybrid experiments, *Front Neurosci.* 7 (2013), 215.
- [17] M. Ambroise, T. Levi, Y. Bornat, S. Saïghi, Biorealistic spiking neural network on FPGA, 2013 47th Annual Conference on Information Sciences and Systems (CISS), IEEE, Baltimore, MD, USA, 2013, pp. 1–6.
- [18] F. Grassia, T. Kohno, T. Levi, Digital hardware implementation of a stochastic two-dimensional neuron model, *J. Physiol. Paris* 110 (2016), 409–416.
- [19] T. Levi, Y. Guo, K. Aihara, T. Kohno, Study of real-time biomimetic CPG on FPGA: behavior and evolution, *J. Robot. Netw. Artif. Life* 4 (2018), 299–302.
- [20] T. Matsuo, T. Yokoyama, D. Ueno, K. Ishii, Biomimetic motion control system based on a CPG for an amphibious multi-link mobile robot, *J. Bionic Eng.* 5 (2008), 91–97.
- [21] T. Levi, T. Nanami, A. Tange, K. Aihara, T. Kohno, Development and applications of biomimetic neuronal networks toward brain-morphic artificial intelligence, *IEEE Transactions on Circuits and Systems II: Express Briefs*, IEEE, 2018, pp. 577–581.
- [22] S. Joucla, M. Ambroise, T. Levi, T. Lafon, P. Chauvet, S. Saïghi, et al., Generation of locomotor-like activity in the isolated rat spinal cord using intraspinal electrical microstimulation driven by a digital neuromorphic CPG, *Front Neurosci.* 10 (2016), 67.
- [23] M. Ambroise, S. Buccelli, F. Grassia, A. Pirog, Y. Bornat, M. Chiappalone, et al., Biomimetic neural network for modifying biological dynamics during hybrid experiments, *J. Artif. Life Robot.* 22 (2017), 398–403.
- [24] M. Capogrosso, T. Milekovic, D. Borton, F. Wagner, E.M. Moraud, J.B. Mignardot, et al., A brain–spine interface alleviating gait deficits after spinal cord injury in primates, *Nature* 539 (2016), 284–288.
- [25] T. Levi, P. Bonifazi, P. Massobrio, M. Chiappalone, Editorial: Closed-loop systems for next-generation neuroprostheses, *Front. Neurosci.* 12 (2018), 26.
- [26] S. Buccelli, Y. Bornat, I. Colombi, M. Ambroise, L. Martines, V. Pasquale, et al., A neuroprosthetic system to restore neuronal communication in modular networks, *bioRxiv* 2019.

## Authors Introduction

### Mr. Damien Blanchard



He obtained a 2-year technical degree in electrical engineering and computer sciences at Bordeaux Institute of Technology in 2007. From 2008 to today, he is working as electrical designer at IUT Bordeaux at Univ. of Bordeaux, France.

### Dr. Timothée Levi



He received the PhD degree in Electronics at Univ. of Bordeaux in 2007. From October 2009 to today, he is an Associate Professor at IMS lab., Univ. Of Bordeaux, France. During this period, from September 2013 to August 2015, he was a Visiting Research Fellow at University of Tokyo, Japan. From April 2017, He is Project Associate Professor at The University of Tokyo. His research

interest deals with neuromorphic engineering which aims at designing and using integrated circuits which components and architecture are neuro-mimetic for bio-hybrid experiments.

### Prof. Kazuyuki Aihara



He received a B.E. degree in electrical engineering and PhD degree in electronic engineering from the University of Tokyo, Japan, in 1977 and 1982, respectively. He led the ERATO (Exploratory Research for Advanced Technology) Aihara Complexity Modelling project by JST (Japan Science and Technology

Agency) from 2003 to 2008 and the FIRST Innovative Mathematical Modelling project by JSPS (Japan Society for the Promotion of Science) through the FIRST (Funding Program for World-Leading Innovative R&D Science and Technology) program from 2010 to 2014 by CSTP (Council for Science and Technology Policy). He is studying mathematical theory for modelling complex systems and its wide-ranging transdisciplinary applications in science and technology from the viewpoint of mathematical engineering and chaos engineering. On the applications side, he is working to bridge neuroscientific and clinical studies and next-generation AI by mathematical modeling and analyses of brain dynamics to realize neurointelligence.