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Biomimetic snake locomotion using Central Pattern Generators network and bio-hybrid robot perspective

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Abstract: Neurological disorders affect millions globally and necessitate advanced treatments, especially with an aging population. Brain Machine Interfaces (BMIs) and neuroprostheses show promise in addressing disabilities by mimicking biological dynamics through biomimetic Spiking Neural Networks (SNNs). Central Pattern Generators (CPGs) are small neural networks that, emulated through biomimetic networks, can replicate specific locomotion patterns. Our proposal involves a real-time implementation of a biomimetic SNN on FPGA, utilizing biomimetic models for neurons, synaptic receptors and synaptic plasticity. The system, integrated into a snake-like mobile robot where the neuronal activity is responsible for its locomotion, offers a versatile platform to study spinal cord injuries. Lastly, we present a preliminary closed-loop experiment involving bidirectional interaction between the artificial neural network and biological neuronal cells, paving the way for bio-hybrid robots and insights into neural population functioning.

Keywords: Biomimetic neural network, CPG, snake robot, closed-loop, FPGA, real-time.

1. INTRODUCTION

The ability to move is fundamental for animals, and neurobiologists have determined that Central Pattern Generator (CPG) activity, generating alternating bursts, is responsible for locomotion [1-4]. CPG networks, neural networks capable of producing rhythmic patterned outputs without sensory input, play a crucial role in programming most rhythmic movements. Examples of CPGs in animal locomotion include swimming in salamanders and lampreys, as well as the cardiac pulsation system in leeches [5, 6]. In the realm of robotics, CPGs are typically constructed using simple neuron models or oscillators that operate on non-biological time scales, representing bio-inspired rather than biomimetic systems [7-10]. These models generate sinusoidal oscillations and lack the variability found in biomimetic CPGs. To create a biomimetic CPGs, our team firstly developed a first version using Izhikevich neuron model [11, 12]. Going further, we incorporate a more biologically coherent model such as the Hodgkin-Huxley (HH) [13] model to allow a more accurate modeling of the neural network, hence better suiting the aim of creating an artificial biomimetic spinal cord model.

Multi-legged robots require Central Pattern Generators (CPGs) to facilitate movement and coordinate their actions. In current research, an Amari-Hopfield CPG or basic CPG models, such as the Van der Pol, are often employed, characterized as non-linear oscillators generating sinusoidal oscillations that lack biomimicry [14, 15]. In our pursuit of a more biomimetic approach, we have developed biomimetic CPGs [11, 12]. These CPGs aim to replicate animal locomotion, mirroring movements like swimming in *Xenopus*, salamanders, and lampreys, as well as the heartbeat system

in leeches [10, 16]. We then developed network of CPGs to reproduce different patterns of locomotion like forward one. We designed one snake robot with different wagons which reproduce the spinal cord.

This system finds practical application in robotics, contributing to the development of robots that exhibit smoother and more closely aligned behaviors with biological animals. Moreover, it holds promise in the sphere of bio-hybrid robotics, involving both living and artificial components, as demonstrated by its ability to interface with biological neurons [17]. An additional benefit lies in its capacity for real-time simulation, enabling the modeling of various CPG topologies and the exploration of different hypotheses and treatment protocols for biomedical applications, such as those related to spinal cord injury [18, 19]. A bio-hybrid experiments is presented in the last section to describe the bidirectional communication between biological network and the biomimetic CPGs.

2. BIOMIMETIC CPGS

We proposed a network of several cascaded CPGs using biomimetic models for neurons, synapses and the short-term plasticity. The network is designed in order to induce a forward snake-like motion.

2.1. CPG neural network

Herein, the structure of our CPGs has been simplified to only two neurons compared to our previous CPG neural network [12]. The neurons are connected to each other with inhibitory synapses which implement short-term plasticity. Fig. 1 illustrates the structure of one CPG.

† Jérémy Cheslet is the presenter of this paper.

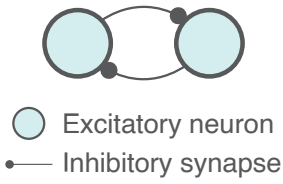


Fig. 1. Schematics of a single CPGs composed of 2 neurons, coupled with each other with inhibitory synapses.

2.2. Neuron, synapse and short-term plasticity models

In this work, the existing Izhikevich model [20] was substituted with a more biologically coherent that is the HH model. Indeed, the HH neuron model describes the evolution of the neuron membrane potential through the description of ionic channels. While exhibiting the highest degree of biological coherence among the considered models, the HH model is concurrently the most computationally intensive. Consequently, we adopted the Pospichil model featuring six ionic channels: potassium, sodium, leakage, slow potassium, L-type calcium and T-type calcium [21]. Details about the hardware implementation can be found in [22].

As for the intra-CPG synapses, we implemented inhibitory synapses with a similar plasticity to the spike mediated short-term plasticity (STP) described in [5]. With this, when both neuron are stimulated, they will bursts alternatively and produce a rhythmic patterned oscillation. The period of oscillation can then be modified by tweaking the different parameters of the biomimetic models, *i.e.* meaningful parameters.

2.3. Cascaded CPGs network

The entire network comprises several cascaded CPGs interconnected by forward excitatory synapses. The objective is to maintain the rhythmic patterns of the CPGs while introducing phases differences between them. Each neuron within the network is considered as a motor neuron of the robot it will operate: upon neuronal bursting, the associated motor is powered. Fig. 2 illustrates the network and shows the spiking activity of the HH CPG that governs the robot, along with a schematic representation of the network within the robot.

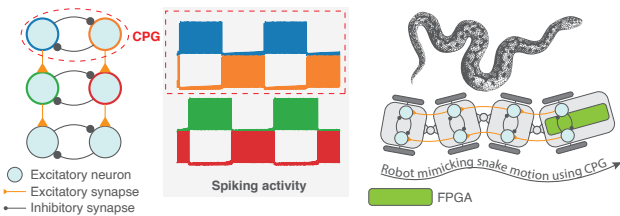


Fig. 2. The network composed of cascaded CPGs is reproducing snake motion. CPGs are interconnected by excitatory synapses introducing delay in the rhythmic patterns which generate the forward locomotion.

To maintain biomimicry, we selected AMPA and NMDA synapses from [23] to model our excitatory biomimetic synapses between CPGs. Both AMPA and NMDA synapses have been implemented and their principal distinction lies in their excitatory strength, as detailed in [22]. The ability to transition between these synaptic receptors enables the mod-

ulation of the dephasing among CPGs, impacting the snaking shape of the locomotion.

Incorporating a more biologically coherent model such as the HH model allows a more accurate modeling of the neural network, hence better suiting the aim of creating an artificial biomimetic spinal cord model.

3. HARDWARE IMPLEMENTATION AND PHYSICAL ROBOT

3.1. Implementation on digital neuromorphic system

The network is implemented on CMOD A7-35T FPGA (Field Programmable Gate Array) board. The design works in real-time and requires few resources which leads to a low power implementation. Table 1 presents the resources taken for a 50 CPGs network in CMOD A7-35T FPGA board.

Table 1. Utilization of the resources for the implementation of 50 CPGs on CMOD A7-35T board.

	Utilization	Available	Percentage
LUT	9416	20800	45%
FF	5395	41600	13%
DSP	49	90	54%
BRAM	0	50	0%

3.2. Design of the robot

The robot consists of a primary unit, referred to as the locomotive, followed by several identical units known as wagons. The locomotive bears essential components, including the FPGA board, batteries and the power management unit. Each individual car comprises a pair of wheels along with their respective motors, driven by a dedicated driver module. All wagons are interconnected to the locomotive through wiring for the transmission of power and control signals. The structural components of the cars are manufactured using a combination of 3D printing and laser-cut wood. Additional details regarding the robot's design and development can be found in [12]. Fig. 3 shows a picture of the snake robot.



Fig. 3. Picture of the snake robot with the locomotive and 7 wagons. Wires linking the locomotive to wagons are know shown.

4. PRELIMINARY EXPERIMENT

As a preliminary experiment to the development of neuro-prostheses, a biohybrid experiments in a closed-loop fashion was conducted to explore the interaction between an artificial model of spinal cord embodied by the snake robot and

human cerebral organoids as a brain model. In other words, it aims to mimic artificially the interaction between the brain and spinal cord. This prototype experiment was conducted once as a proof of feasibility. The experimental setup is illustrated in Fig. 4.

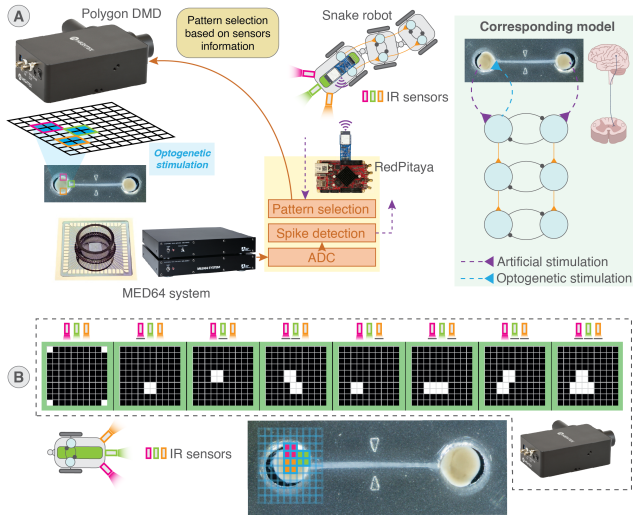


Fig. 4. Closed-loop biohybrid experiment. **(A)** Closed loop interaction between biological connected cortical organoids and artificial CPG as a model of brain to spinal cord interaction. Three IR sensors located at the front of the robot (purple, green and orange rectangles) trigger localized optogenetic stimulation on the left organoids. **(B)** Sequence of DMD patterns selected based on information of the infrared sensors. The pattern was projected on the left organoid.

4.1. Setup

Starting from the biological network, the spiking activity from left and right organoids stimulates the first CPG of the snake robot. MEA signals are recorded by the AlphaMED64 system and forwarded to an FPGA (RedPitaya STEMLab125-1) that performed digitalization and threshold based spike detection.

Spiking information is then sent through Wi-Fi to the snake robot. The CPG is configured on the snake robot to provide a stimulation based on the spike activity of the biological culture received *via* the Wi-Fi module (PMOD ESP32).

Sensory feedback is introduced through optogenetic stimulation of the left organoid triggered accordingly to the infrared sensors present in the front of the robot. The information of each sensor is mapped as a square area for each sensor as illustrated in Fig. 4B.

The optogenetic stimulation is performed using a DMD and made possible by a genetic alteration of the organoids. The sequence of illumination patterns was designed using Polygon software provided by the manufacturer of the DMD.

On reception of the information of sensors, the RedPitaya selects the corresponding pattern on the DMD. The selection of the pattern is done using the trigger in input that allows to switch patterns from pulses (see Fig. 4A). Hence, the appro-

prate number of pulses were sent based on IR sensor information to select the matching pattern.

The cortical organoids used in this experiment were cultivated using the procedure described in [24, 25].

The connected organoids were plated on MEA and infected with Channelrhodopsin-2 to allow optogenetic stimulation. More specifically, 1 μ l of AAV-CAG-hCHR2-tdTomato (VectorBuilder Inc.) was added to the culture media at day 60 experiment for optogenetic interventions as in [26]. The infection rate was confirmed through imaging at day 100 as depicted in Fig. 5A.

The activity of the organoids was recorded using the AlphaMED64 system and checked regularly to ensure that the cultures were still alive, active and shown spiking activity as presented at day 92 in Fig. 5B. The experiment was performed at day 110.

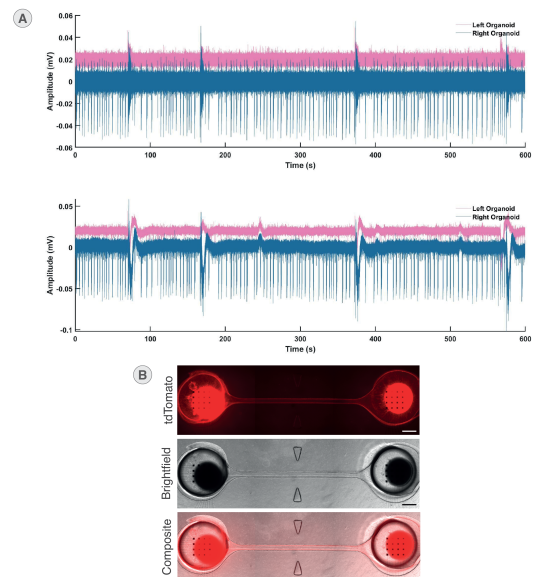


Fig. 5. Connected human cerebral organoids used in the closed-loop biohybrid experiment. **(A)** Connectoid organoids expression of ChR2 imaged at day 100. Infection and plating at day 60. Scale bar is 500 μ m. **(B)** Band pass filtered (top) and raw (bottom) electrical activity of left and right organoids on day 92 recording on MEA. Band pass filter has low-cut of 300 Hz and high-cut of 3 kHz.

4.2. Results

The feasibility of the system was demonstrated qualitatively by running the system for 10 minutes and filming the behavior of the robot as well as visualizing the stimulation triggers of the DMD and spiking activity of the cultures.

The Fig. 6 presents shots extracted from the video of the experiment that shows an example of optogenetic stimulation.

As the robot get closer to the obstacle, the IR sensor is set high and select the appropriate pattern to illuminate on the culture (Frames 2,3 in Fig. 6). When the robot moves

away, the sensors are low and the associated pattern is selected (Frames 4,5 in Fig. 6). While the experiment certainly cannot prove that the robot dodges the obstacle, it can be confirmed that the spiking activity of the CPG is modified by the spiking activity of the culture. Indeed, the robot does not move following a straight line in a snake-like motion but rather moves in a disorganized way because of the spiking activity of the culture.

In this setup, the latency between spike detection from the organoids and stimulation on the snake robot is between 5-10 ms and about the same from the CPG to the organoids that corresponds to Wi-Fi latency.

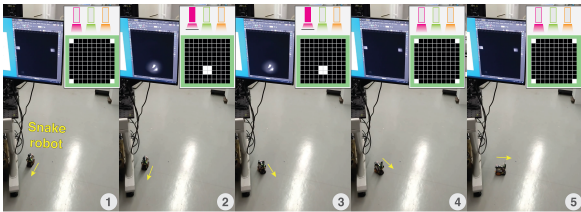


Fig. 6. Images extracted from the video of the biohybrid experiment conducted showing the trigger of the DMD stimulation based on IR sensors. The illumination of the corresponding pattern on the DMD is selected based on the information of the infrared sensors. The illuminated pattern is visualized on the interface provided by the software controlling the DMD. Only the first wagon was used in this experiment to facilitate the movement as space was limited.

4.3. Validation

Although promising, the experiment conducted shows multiple limitations as it was thought as a prototype. Indeed, it focuses more on the feasibility than on the reliability so as validations were kept to a minimum.

The next step would be to conduct complex validations of the system to estimate the reliability of the experiment and to design a protocol that would allow to assess the efficacy of the closed-loop.

Nonetheless, this complex experiment requires a considerable amount of preparation to cultivate the organoids as well as to prepare the setup. Additionally, cross-disciplinary skills are mandatory to ensure the good operation of the experiments as electronics and biology are deeply intricate. Moreover, the effects of the electrical stimulation on human cerebral organoids is not yet completely identified [26], thus requiring additional studies.

To conclude, this experiment constitutes a preliminary work toward the realization of neuroprostheses and points out the challenges it involves. While a significant amount of points needs to be validated and clarified, it has been demonstrated that biohybrid closed-loop interaction remains feasible.

5. CONCLUSION

This article presents the implementation of a real-time biomimetic neural network based on biological coherent models. Compare to previous implemented neural network

[11, 12], this version allows a more accurate modeling resulting in better modeling of spinal cord model. Finally, the final experimental setup demonstrates the feasibility of biohybrid closed-loop experiment between biological neurons and artificial biomimetic CPGs through the medium of a snake robot. This preliminary work constitutes a first step in experimenting different network topologies to simulate different hypothesis and protocol treatments for biomedical applications such as spinal cord injury and neuroprosthetics [27-29].

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