# Neural controllers for adaptive locomotion in Biorobotics: from models to circuits

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***Abstract*—Neural oscillators are the basic blocks for the implementation of bio-inspired locomotion control systems. The FitzHugh-Nagumo neuron is a paradigmatic example of how rich behaviors, typical of biological neurons, can be obtained using simplified models. Introducing a piecewise-linear approximation of the neuron nonlinearity, it is possible to perform a nullcline-based control strategy that modulates the oscillation characteristics depending on the robot needs and synchronizes the different units devoted to control the multiple degrees of freedoms present in the robotic system. The proposed architecture represents a useful alternative for adaptive CPG control, allowing flexibility and simplicity in the generation of multiple gaits. Furthermore, the application of this method can be extended to a hardware level integrating the neural control system with the motor dynamics to create an embodied model of a neuron. Both analog and digital implementation can be easily developed, and an application to a 2 DoFs biped robot is presented.**

## I. Neural locomotion control

The use of neural controllers is very impactful in bio-inspired robotics. In fact, oscillators have been widely employed for a variety of applications regarding the implementation of steady stable and synchronised gaits for various forms of legged robots hexapods [1]. Additionally, it has been shown how oscillations are deeply related to motion rhythms generation and maintenance from a biological perspective, where the concept of Central Pattern Generator (CPG) is adopted [2], [3]. CPGs are made up of coupled oscillators which generate locomotion patterns and each gait is uniquely identified by the relative phase displacements among the oscillators. When multiple oscillators have to be considered, developing a network, the possibility to use reduced-order models without loosing in behavioral complexity is envisaged. Our research group has been involved for many years in the design and implementation of nonlinear, neural-like oscillators working as locomotion controllers for bio-inspired, mainly legged prototypes. The first design of a neuron model suitable for implementing a slow-fast dynamics controlling locomotion dates back to 1999 [4]. The research for highly adaptive motion controllers was found to rely both on synaptic learning and on intrinsic plasticity within the single neural structure. One of the most important issues, in this sense, is the possibility to modulate the time spent in the spiking regime (i.e. in average over the threshold) and the remainder recovery time. In the last few years our attention was focussed on the FitzHugh-Nagumo neuron (FHNs) neuron models, which, by themselves, provide an easier second-order representation of the more complex Hodgkin-Huxley (HH) model [5]. As well as other forms of oscillators, the classical FHN model is characterized by the presence of a cubic-shaped nullcline. A further simplification was introduced by McKean [6], through the cubic approximation by means of a piecewise-linear (PWL) function.

We have been deepening the analysis of the FhN neuron model, coming to the conclusion that oscillation period is closely related to the nullclines configuration in the phase plane. Consequently, it is possible to assess both phase and time requirements, such as the oscillation period, through nullclines manipulation. On the other hand, handling with smooth nullclines such as the original cubic one is not simple. Thus, PWL framework can provide an easier way to both simplify a nonlinear model and control its behaviour, considering the whole system as a mosaic of affine dynamical systems. Additionally, these PWL-shaped systems facilitate the implementation in hardware, as shown in [7].

Several solutions for phase-shift synchronisation have been proposed, even for PWL-based systems [8]. The aim of our strategy is to control the dynamics of networked PWL-shaped FHNs (P-FHNs) through their nullclines [9], relying on computing the oscillation period of all the nodes in a master-slave configuration relating their period to a suitable nullcline slope. This approach involves both continuous variables, such as the state variables and discrete events that trigger the nullcline adaptation. The PWL framework makes the approach particularly simple since it allows to reshape the dynamics of the system in precise ranges only through the modulation of specific branches of system nullclines. Phase locking control in a network of P-FHNs was recently analysed and applied for locomotion patterns generation in legged robots in various simulated configurations[9] .

The model of a P-FHN is a second-order system whose state $\mathbf{x} = [x_1, x_2] = [V, I]$ is given by:

$$\begin{cases} \varepsilon \frac{dV}{d\tau} = I_0 - I - G(V) \\ \frac{dI}{d\tau} = \beta V - I - V_0 \end{cases} \tag{1}$$

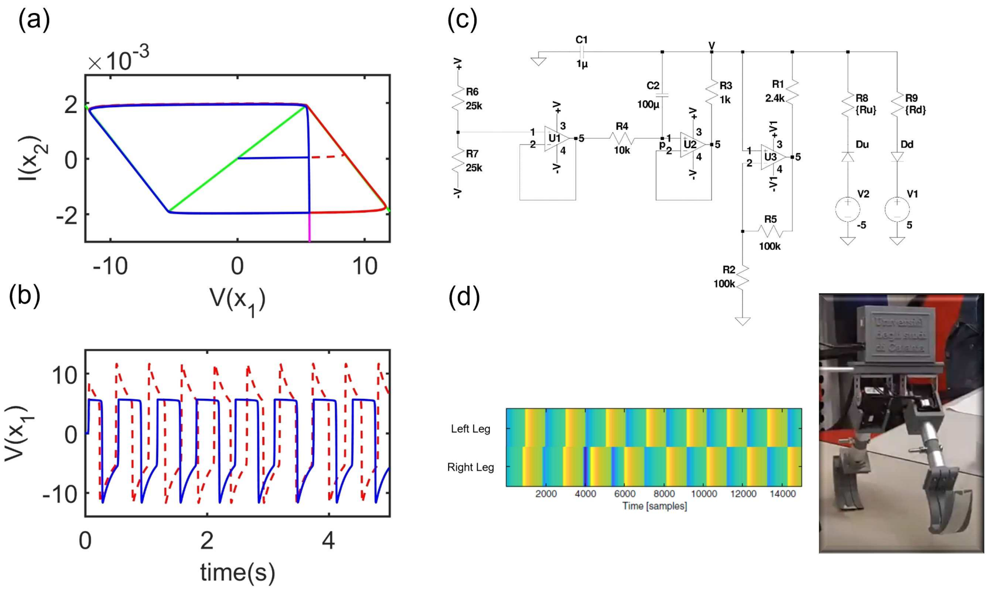


Figure 1: (a) Examples of nullcline manipulation through the external slope change. (b) The effect on the limit cycle is a change of the oscillation period and the possibility to modify the duty cycle if only one branch of the nullcline is modified as here reported. (c) Circuit model for the single adaptive neuron. (d) Stepping diagram and biped robot controlled through the proposed strategy.

where:

$$-G(V) = \begin{cases} 1 - V & if \quad V \geq \frac{1}{s+1} \\ sV & if \quad -\frac{1}{s+1} \leq V \leq \frac{1}{s+1} \\ -1 - V & if \quad V \leq -\frac{1}{s+1} \end{cases} \quad (2)$$

$\tau$, $\beta$, $I_0$, $V_0$ and $s$ are parameters related to the original circuit implementation as discussed in [7].

Additionally, the system parameters were designed to fulfil the constraints related to the existence of limit cycles [9].

The neural system can be easily implemented in hardware using analog discrete components; some results related to a circuit simulation are reported in Fig. 1 (a-b) where the control of the nullclines and the effect on the limit cycle are shown and in Fig. 1 (c) where the circuit implementation is reported.

The perspectives of this research activity are twofold: from the one hand P-FHN networked systems can be a useful alternative for adaptive CPG control, allowing flexibility and simplicity in the generation of multiple gaits [9]; from the other hand, the application of this method can be extended to a hardware level integrating the neural control system with the motor dynamics to create an embodied model of neuron. The key aspect is the exploitation of the body (the set of all the motors and sensors with their own properties) and how to embed it into a neural structure which has its dynamics too in order to create a bridge between the physical world and the neural processing. In our case the side advantage is that we can reduce the order of the neural system considering only the first equation in 1, including the motor dynamics to complete the system for the generation of non-linear oscillations. Preliminary results verified the suitability of the approach, developing the system through a micro-controller based platform interfaced with Dynamixel servo-motors. Fig. 1 (d) shows an example of master-slave synchronization of two motors with the nullcline-based control applied to a biped robot. This opens the way to new generations of adaptive embodied, closed loop locomotion controllers for legged robots.

## References


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