Biologically inspired neural controllers for motor control in a quadruped robot.

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Abstract

This paper presents biologically inspired neural controllers for generating motor patterns in a quadruped robot. Sets of artificial neural networks are presented which provide 1) pattern generation and gait control, allowing continuous passage from walking to trotting to galloping, 2) control of sitting and lying down behaviors, and 3) control of scratching. The neural controllers consist of sets of oscillators composed of leaky-integrator neurons, which control pairs of flexor-extensor muscles attached to each joint. The networks receive sensory feedback proportional to the contraction of simulated muscles and to joint flexion. Similarly to what is observed in cats, locomotion can be initiated by either applying tonic (i.e. non-oscillating) input to the locomotion network or by sensory feedback from extending the legs. The networks are implemented in a quadruped robot. It is shown that computation can be carried out in real time and that the networks can generate the above mentioned motor behaviors.

1 Introduction

A large amount of literature has been devoted to the understanding of the neural mechanisms at the basis of locomotion in vertebrates. Neural networks in the spinal cord have been shown to produce rhythmic patterns which, when connected to muscles, can generate the animal's locomotor pattern. Such a built-in spinal circuit is known as a *central pattern generator* (CPG) [8, 21]. The presence of CPGs has been demonstrated in many vertebrates such as fish, amphibians [21], cats [19], and possibly in humans [6]. To the exception of the lamprey [12] and the Xenopus embryo [18], the exact connectivity of the CPGs in most vertebrates has not been deciphered yet.

One way to a better understanding of the functioning of existing or potential locomotor circuits is to simulate them, as networks of Huxley-Hodgkin type of neurons [17, 1], or networks of leaky-integrator neurons [11, 22], for instance. Of special interest are simulations which include a mechanical simulation of the body to be controlled [9, 15, 14], as the inherent dynamics of the body is at least as important as the neural activity for shaping a locomotor gait. In a step further, an interesting approach is to embed the simulated neural controllers into a physical robot [2, 7, 16].

In this paper, we present a model of neural controllers for the control of locomotion and other motor patterns in a dog-like quadruped robot. The article gives a special emphasizes to how the motor patterns can be modulated by a control signal (the tonic input) for modifying the frequency and the phases of the gaits.

2 The controller

The locomotor gaits are generated by sets of coupled oscillators, one oscillator for each degree-of-liberty (DOF) of the legs joints. Following the robot's structure (see section 3), each leg has two DOF at the hip and one at the knee. The torque of a DOF is determined by a pair of simulated extensor-flexor muscles which receive signals from one oscillator. An oscillator is composed of four interneurons and two motor neurons.

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The oscillators are composed of neuron units, modeled as *leaky-integrators* [13]. According to this model, the mean membrane potential m_i of a neuron N_i is governed by the equation:

$$\tau_i \cdot dm_i/dt = -m_i + \sum w_{i,j} x_j$$

where $x_j = (1 + e^{(m_j + b_j)})^{-1}$ represents the neuron's short-term average firing frequency, b_j is the neuron's bias, τ_i is a time constant associated with the passive properties of the neuron's membrane, and $w_{i,j}$ is the synaptic weight of a connection from neuron N_j to neuron N_i.

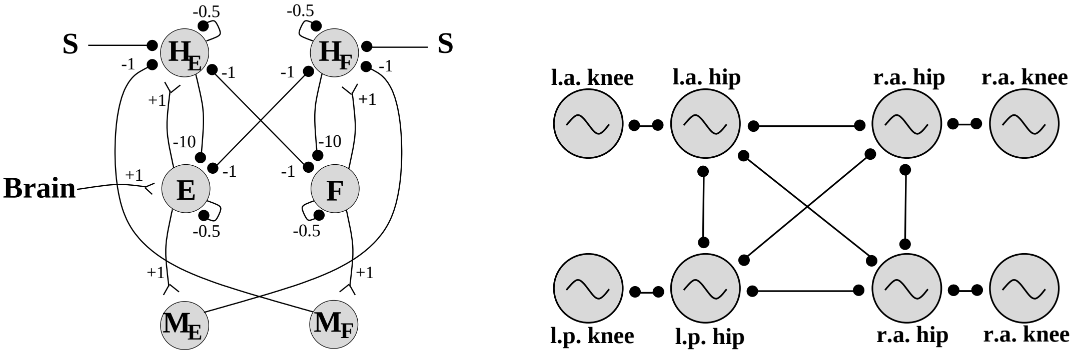

Figure 1: **Left:** Connectivity within one oscillator. B is the tonic input, M_E and M_F are the motoneurons for the extensor and flexor muscles resp., and E, F, H_E and $H - F$ are interneurons. The input connection from the brainstem is also shown.**Right:** Coupling among the hip and knee oscillators.

Figure 1 shows the connectivity within one oscillator and the coupling among the hip and knee oscillators. Each hip oscillator is coupled to all other hip oscillators and to one knee oscillator. One knee is coupled only with the corresponding hip oscillator. Each hip and knee oscillator can be activated independently, by sending input only to the relevant part of the limb. Because of the inter-coupling between the oscillators, the rest of the limb oscillators will be activated as well, but the activation will remain too weak to lead to oscillation of the other limbs. This property of the model allows us, for instance, to simulate scratching behavior of one posterior limb (simultaneous oscillation of hip and knee similar to that observed during walking [4]), by activating only the oscillators of the posterior left hip and knee.

Walking, trotting and galloping gaits as well as scratching behavior have been observed in spinalized[1] kittens [3]. This suggests that these motor behaviors are encoded in the spinal cord and could thus be modeled as a CPG. Our model is a potential, although simplified, model for such CPGs.

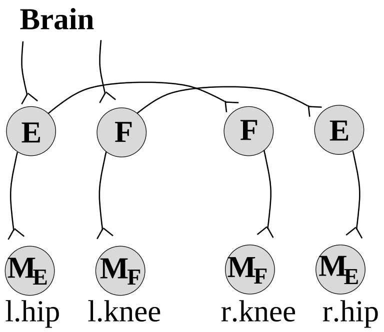

Figure 2: Circuitry for the lying down behavior.

In addition to the locomotor network, the neural controller includes a simple network of interconnections between the four legs for sitting and lying down behaviors (Figure 2). In order to make the sitting behavior

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[1] Spinalized relate to the state in which the animal has suffered a transection of the spinal cord.

smooth, we created an asymmetry between the muscle contraction of the left and right sides. Brain input starts first flexions of the posterior left leg and anterior right leg (hip and knee). A flexion of one leg consists of a contraction of the hip extensor and of the knee flexor. The neuron activity is propagated from the posterior left leg to the posterior right leg and from the anterior right leg to the posterior left leg, respectively. Anterior and posterior legs are not mutually interconnected. Figure 2 shows the connectivity for the posterior limbs. The network of the anterior limb has the opposite (left-right) connectivity.

3 The robot

We implemented the controller in a four-legged AIBO robot[10]. The robot has 3 degrees of freedom for the head, two for each hip, one for each knee and one for the tail. Its paws and toes (four per foot) are not motorized but are articulated, which gives the robot a better stability during walking. We implemented all patterns of locomotion, as well as the sitting and lying-down movements, and the scratching leg movements. Sensory feedback was generated using the motor potentiometer for measurement of joint angle and the internal computation of motor neurons activity for simulating muscle contraction.

4 Results

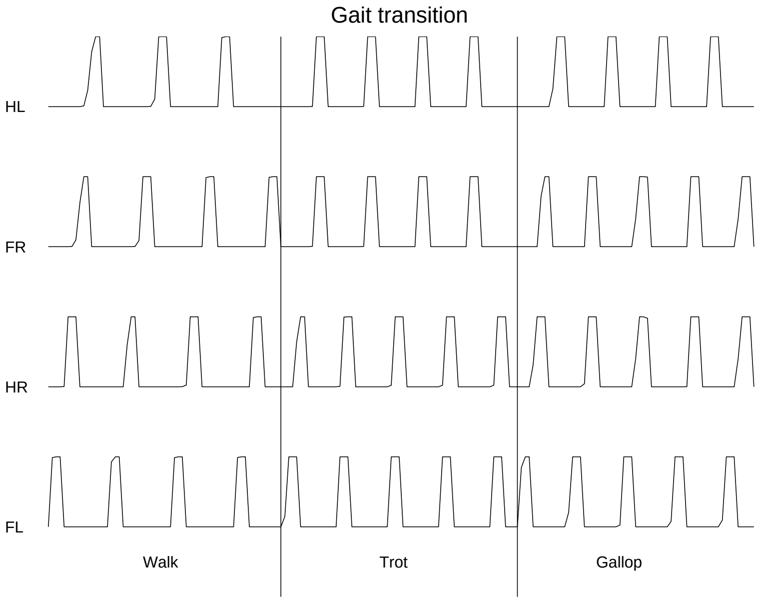

Figure 3: Transition from walking to trotting and then galloping gait following an increase of the tonic input from 1 to 1.4 and 1.6 respectively. The graph shows the hips motor neuron activity of anterior (H) and frontal (F), left (L) and right (R) limbs.

Locomotion Each of the three basic quadrupedal gaits (walk, trot and gallop, with phases of, respectively, [0.0,0.5,0.25,0.75], [0.0,0.5,0.0,0.5] and [0.0, 0.1,0.5, 0.6] between limbs numbered clockwisely from the front left foot) can be activated from rest position by activating each oscillator asynchronously, that is, by starting the tonic input to each oscillator with a phase delay corresponding to the required pattern. For instance, in order to generate the walking gait, tonic input is applied first to the oscillators of the frontal left leg (hip and knee), second to the oscillator of the posterior right leg, third to that of the frontal right leg and finally to that of the posterior left leg.

Similarly to what is observed in cats [5, 19, 20], transition from walk to trot and gallop is obtained by increasing the tonic input, when starting with the walking gait (as shown in figure 3). Increasing the level

Figure 4: The robot walking (top) and lying down (bottom).

of tonic input has the effect of increasing the oscillation frequency of the networks, as well as of shifting the phase between the hip oscillators.

The walking gait can also be initiated by activating the sensory feedback of all the four legs without applying any tonic input. Extending the legs, for instance, provides sensory feedback from joint angle sensors which, when connected to the locomotor interneurons as illustrated in Figure 1 (left), is sufficient to start the locomotor cycle.

Figure 4 (top) illustrates the walking gait as implemented in the robot, and Figure 4 (bottom) shows the lying down behavior. Because the robot's legs are not elastic, the robot could not gallop. The absence of elasticity also rendered the trotting gait too rigid and thus inefficient. That is, the robot looses much energy in slipping and thus progresses forward slowlier than when walking. In order to better watch the trotting and galloping gait, the robot was put on a shelf which sustained its body while leaving the legs free. The walking gait, however, proved to be an effective locomotion gait for the robot, with the right coordination between the oscillations in the different joints. Interestingly, providing asymmetrical tonic input between the left and the right side, enables the robot to turn slowly towards the direction with the less excitation. This is due to differences in the amplitude of the limb movements. Mpeg movies of the different walking and trotting gaits can be seen at http://www-robotics.usc.edu/ billard/dog-movies.html

5 Conclusion

This article presented the implementation of a neural controller for controlling the locomotion as well as the lying down behavior of a quadruped robot. The neural controller is implemented as a leaky-integrator neural network capable of producing the walking, trotting and galloping gaits observed in cat and dogs. The aim of the experiment was to effectively test the locomotor pattern generation by not only analysing the outputs of the simulated network, but also coupling it with a mechanical body for investigating the generated gaits and the effect of sensory feedback. Two phenomena observed in cats are reproduced: 1) modifying how tonic (i.e. non-oscillating) input is applied to the locomotor network leads to a switch from one gait to another, and 2) locomotor patterns can be initiated by sensory feedback.

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