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Biped locomotion control with evolved adaptive center-crossing continuous time recurrent neural networks

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ABSTRACT

We used center-crossing continuous time recurrent neural networks as central pattern generator controllers in biped robots, together with an adaptive methodology to improve the ability of the recurrent neural networks to produce rhythmic activation behaviors. The parameters of the recurrent networks are adapted or modified in run-time to reach the center-crossing condition, so the nodes get close to the most sensitive region to their input. This facilitates the evolution of the networks that act as central pattern generators to control biped structures. The robustness of the adaptive networks to produce rhythmic activation patterns was checked as well as the improvements and possibilities this adaptation may add.

1. Introduction

Central pattern generators (CPGs) are pulsating collections of neurons in the spine that can produce rhythmic patterns of neural activity without receiving rhythmic inputs. They can be building blocks for the animals' locomotion neural circuits [11], as well as for other rhythmic activities (such as breathing or chewing). Büschges states that it is well established that "locomotor patterns result from the interaction between central pattern generating networks in the nervous system, local feedback from sensory neurons about movements and forces generated in the locomotor organs, and coordinating signals from neighboring segments or appendages" [4].

The work of Ijspeert [11] reviews different alternatives to define CPGs. Here we focus on the control of biped robots. Bipedal walking is a difficult task due to its highly unstable dynamic behavior [7]. Legged locomotion is characterized by cyclic activity of the limbs, and the defining feature of CPGs is a high degree of recurrence, which greatly biases the dynamics of the system toward cyclic activation patterns [22].

As McHale and Husbands [19] pointed out, although the characteristic equations associated with a specific network are a compact description of the network, we are as yet unable to predict from these equations the dynamic characteristics of the network when it is embodied in an environmental agent. Evolutionary robotics provides an alternative to the hand design of robot controllers, especially for autonomous robots acting in uncertain and noisy domains. Artificial evolution is used to automate the design procedure of these controllers, changing the focus from deciding how adaptive behaviors are to be generated to deciding what behaviors are generated [9,21]. Within this methodology, we used an adapted genetic algorithm to automatically obtain the neural controllers that will act as CPGs in the control of biped structures and for locomotion behaviors, where such controllers will use run-time adaptation of their parameters.

As indicated by Aoi and Tsuchiya [1], steady walking of a biped robot implies a stable limit cycle in the state space of the robot so, in the design of a locomotion control system, there are three problems associated with achieving a stable limit cycle: the design of the motion of each limb, interlimb coordination, and posture control. In addition to these problems, when environmental conditions change or disturbances are added to the robot, there is the added problem of obtaining robust walking. The aim of the adaptive methodology presented here is to solve these problems.

This paper is organized as follows. In Section 2 we summarize previous works on the control of biped robots, focusing on those using continuous time recurrent neural networks as controllers. In Section 3 we describe the center-crossing condition in such type of recurrent networks, which facilitates the design of neural oscillators. In Section 4 we explain the adaptive methodology developed, which starts from such center-crossing condition and which enables to easily obtain rhythmic oscillators for the biped locomotion behavior. Sections 5 and 6 describe the methods used, that is, the software simulation environment, the robot designs, and the evolutionary algorithm used. Section 7 exposes the results, describing with examples the potentials of our adaptive controllers. Finally, Section 8 indicates the conclusions and intended future work.

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2. Previous work

Several models have been used to implement CPGs, including vector maps, systems of coupled oscillators and connectionist models [11]. As Ijspeert [11] indicates, with the neural models, the focus was on how rhythmic activity is generated by the network properties. Along this line, Beer [2] introduced the model of continuous time recurrent neural networks (CTRNN), one of the most used to represent CPGs. As Beer indicates, "CTRNNs is a class of neural models that is simple but dynamically universal" [3]. In [3] the author performed a study of the global parameter space structure of CTRNNs, estimating the probability of encountering different kinds of dynamic behaviors in CTRNN parameter space regions.

The work of McHale and Husbands [19] presents a comparative study of four types of neural networks to synthesize bipedal control systems: the conventional CTRNN [2], the center-crossing CTRNN [16] (explained in the next section), the plastic neural network (PNN) [8] and the GasNet developed by the authors. The PNNs incorporated run-time learning through Hebbian rules and GasNets were inspired by the action of nitric oxide as a neuromodulator. The authors' interest was to evolve networks capable of achieving locomotion with a simulated biped. Of the 14 distinct networks tested (variants of those types), CTRNNs were shown to have advantages in most of the cases. Continuous time recurrent neural networks were able to attain higher average fitness, although GasNets obtained the highest fitness peak with cyclic locomotion.

However, as exposed in [16] with a statistical analysis, if we use an evolutionary method to obtain networks (CTRNNs) capable of producing rhythmic behavior, the probability that a random network population of a moderate size (100 individuals) contains one or more CTRNNs exhibiting pulse behavior is rather small. Furthermore, Reil and Husbands [22] evolved CTRNNs for a simulated biped. They showed that there is no need for proprioceptive information to control stable straight-line bipedal walking. They also reported that the fraction of evolutionary runs leading to stable walkers was only 10% (even allowing backward walking controllers). Moreover, the authors, in a second stage, provided the robot with two simulated ears and evolved controllers to approach a sound sensor so the robots could achieve directional walking. They experimented with incremental evolution, as the previously evolved weights were clamped and only the weights from the sensory unit were evolved.

Mathayomchan and Beer [16] additionally experimented with the inclusion of the so-called center-crossing networks. These networks can produce oscillatory behaviors in an easier way, since their nodes' parameters are tuned so that the neurons operate in the most sensitive region. When they generated 10,000 random center-crossing CPGs and 10,000 completely random CPGs, they found that 26.6% of the center-crossing circuits produced oscillations, while for random circuits only 1.2%. When they used an evolutionary algorithm to search for control oscillators of a simple biped robot, they demonstrated that relative to a random initial population, seeding an initial population of an evolutionary search with center-crossing networks improved both the frequency of pulse-circuits occurring in a population and the speed with which high fitness pulse-circuits evolved.

Vaughan et al. [24] used two symmetrical feed-forward continuous time neural networks to control the movements of the legs in a biped structure. The networks received as input, among others, accelerations in the three axes and different joint angles of the robot, together with a time signal provided by a CPG that regulated the walking gait. The goal of the authors with these networks was the control of passive walkers for efficiency: by using passive dynamics and compliant tendons the biped conserved energy while walking on a flat surface. Izquierdo and Buhrmann [13] synthesized single circuits that performed two different behaviors: orientation to sensory stimuli (chemotaxis) with a simulated Khepera and legged locomotion in a simulated one-legged insect walking agent. The authors' main interest was to demonstrate that small fully interconnected networks (CTRNNs) can solve the two tasks with the ability to switch between the behaviors from the interactions of the circuit's neural dynamics, its body and environment. The networks were used as reflexive pattern generators, where all the neurons received sensory perturbations: from the leg angle during walking and from the proximity to the food during chemotaxis.

Meyer et al. [20] used the leaky-integrator model of the CTRNNs for calculating the value of the nodes of their neural controllers [14]. Their work was more focused on the developmental process of the phenotype from the genotype and on the incremental evolution of behavior modules. For example, the authors presented examples of obstacle-avoidance and locomotion for a hexapod robot, in which a first module generated a straight-line locomotion behavior, and an additional controller, obtained in a second stage, modulated the leg movements secured by the first controller making it possible for the robot to turn in the presence of an obstacle and avoid it.

With other alternatives different from CTRNNs, the neural oscillator proposed by Matsuoka [18] was widely used to model the firing rate of two mutually inhibiting neurons, described by a set of differential equations. This model was used in robotic applications to achieve designated tasks involving rhythmic motion which requires interactions between the system and the environment. For example, Matsubara et al. [17] proposed a learning framework for a CPG-based biped locomotion controller using a policy gradient reinforcement learning method for a 5-link biped robot. Their CPG-based controller was composed of a neural oscillator model (Matsuoka's [18] model) and a sensory feedback controller which mapped the states of the robot to the input to the neural oscillator model. Matsuoka's oscillator model was also used by Endo et al. [6], applying two oscillators to control the leg movement of a 3D robot model. One oscillator controlled the position of both legs in vertical direction, while the other controlled the position of both legs along the forward direction. They also implemented it on the QRIO robot. However, it is difficult to determine the CPG parameter values in this oscillator model for various robots and environments, since there is no general design principle to determine the parameter values.

Hein et al. [10] used the discrete time dynamics of a two neuron network oscillator to generate a core oscillation for the control of the joints of a biped. An additional layer of weights connects this basic oscillator to the motor neurons which control the joints. They focused their work on the transfer of the evolved controllers obtained in their simulation to real robots. von Twickel and Pasemann [25] evolved neuromodules for single morphologically distinct legs of a simulated hexapod walking machine. They demonstrated how small reflex-oscillators, which rely on the sensorimotor loop and hysteresis effects, generate effective locomotion. An analysis of the controllers showed that sensory inputs and dynamic effects, like hysteresis, play a major role in the generation of walking patterns and for robust behavior under changing environmental conditions, where the controllers worked without a CPG. Previously, Wischmann and Pasemann [26] used a recurrent neural controller to enable a simulated walking device to walk on a flat surface with minimal energy consumption. The applied evolutionary algorithm fixed neither the size nor the structure of the recurrent network. Such controller network used sensory information, as a foot contact sensor provided information to the network.

Ishiguro et al. [12] focused their work on the neuromodulation of a neural circuit that controlled a biped robot. The modulation, through the diffusion of neuromodulators, allowed the dynamic