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Multiple chaotic central pattern generators with learning for legged locomotion and malfunction compensation

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ABSTRACT

An originally chaotic system can be controlled into various periodic dynamics. When it is implemented into a legged robot's locomotion control as a central pattern generator (CPG), sophisticated gait patterns arise so that the robot can perform various walking behaviors. However, such a single chaotic CPG controller has difficulties dealing with leg malfunction. Specifically, in the scenarios presented here, its movement permanently deviates from the desired trajectory. To address this problem, we extend the single chaotic CPG to multiple CPGs with learning. The learning mechanism is based on a simulated annealing algorithm. In a normal situation, the CPGs synchronize and their dynamics are identical. With leg malfunction or disability, the CPGs lose synchronization leading to independent dynamics. In this case, the learning mechanism is applied to automatically adjust the remaining legs' oscillation frequencies so that the robot adapts its locomotion to deal with the malfunction. As a consequence, the trajectory produced by the multiple chaotic CPGs resembles the original trajectory far better than the one produced by only a single CPG. The performance of the system is evaluated first in a physical simulation of a quadruped as well as a hexapod robot and finally in a real six-legged walking machine called AMOSII. The experimental results presented here reveal that using multiple CPGs with learning is an effective approach for adaptive locomotion generation where, for instance, different body parts have to perform independent movements for malfunction compensation.

1. Introduction

Humans, mammals, insects, and other arthropods employ legs for movement. Common to all of them is that their walking pattern usually shows a high level of proficiency adapted to the different terrains of their natural habitat. Legged robots, on the other hand, have not yet achieved this level of performance.

Optimized biomechanics and (neural) control create these efficient and often very elegant walking patterns in animals and some robots have copied this strategy with varying levels of success. Many reports have demonstrated gait generations in animals which are achieved through oscillations originating from the spinal cord (vertebrate) or from different ganglions

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(invertebrate) [18,9]. This is known as the concept of central pattern generators (CPGs) and has been applied to different types of legged robots, such as bipedal robots [52,2,1], quadruped robots [24,38], hexapod robots [3,4,34,35] and in our previous works [42,51,46]. Bio-inspired amphibious robots [44,33,11] and snake-like robots [10] also employed this kind of control strategy. Further details on CPG-based locomotion control have been reviewed in [32].

CPG-based locomotion is directly inspired by the way animals control their movement. It has many advantages, such as distributed control, the ability to deal with redundancies, and fast control loops. It also allows modulation of locomotion by simple control signals [32,39]. When applied to robot control, we do not need to know the precise mechanical model of a robot. We can also easily integrate sensory information and adjust the control signal due to the simple structure of a CPG. Therefore, CPG-based control has already become an effective approach to perform legged locomotion in robots.

However, there are several problems yet to be solved. Although previous CPG-based algorithms can generate sophisticated gait patterns and deal with irregularities of the terrain to some extent [39], the problem of leg malfunction compensation in CPG-based control is still a challenging task. A troubling control problem can arise from the fact that the main controller usually contains CPGs which always control all legs with identical frequency [30]. If a robot suffers from leg failures, the other – still functioning – legs cannot immediately tune their oscillations appropriately. In contrast, insects can adjust the frequency of each leg individually [5,49]. If their legs are malfunctioning or disabled, they can still perform proper locomotion by changing the oscillation frequencies of the legs independently. Such a phenomenon also appears in mammals. For example, a cat can walk with the hind legs over a treadmill belt while the fore legs rest on a stationary platform [48] even after spinal cord injury. This indicates that the cat can independently adjust each leg's movement to achieve stable locomotion.

Traditional robotic methods for compensating leg malfunction are complicated [56,37]. They are mostly based on kinematics or dynamics models [23]. Robots usually have to detect where a malfunction happens, then replan the gait pattern and choose another proper foot contact point. For different legs, the different foot trajectories are recalculated using inverse kinematics. Hence, all situations have to be considered and, as such, the procedure is computationally intensive.

In contrast to the traditional control methods, we develop a CPG-based control strategy not only to generate multiple gaits but also to deal with leg malfunction. Inspired by multiple oscillators found in the neural system of insects [5,16,15], we extend our previously proposed chaotic CPG controller [51] to multiple CPGs, according to the number of legs of the robot. The CPGs can be synchronized or desynchronized to produce uniform or non-uniform patterns, respectively. If all CPGs are synchronized, the neural outputs are the same. If they are desynchronized, the neural outputs can oscillate at different frequencies. Thus, if some joints are disabled, other legs can change their oscillation frequencies independently. A simulated annealing (SA) based approach [20,6] is applied to our robots in order to learn a suitable combination of leg oscillation frequencies, allowing leg malfunction compensation to be achieved automatically. Furthermore, the applications to a hexapod robot and a quadruped robot demonstrate the effectiveness of our proposed algorithm and its generalization properties. To verify our algorithm in a real world application, our hexapod robot AMOSII is employed to evaluate the control strategy and learning. The proposed methods allow AMOSII to perform multiple gaits and to adapt its locomotion in case of disabled legs. Therefore, the main contribution of this paper is a novel control strategy relying on multiple chaotic CPGs with an additional automatic learning mechanism for leg malfunction compensation.

This article is structured as follows. Section 2 presents the overall control algorithm where the chaotic CPG is briefly introduced as a single oscillator. After which, we show how to design multiple CPGs and also state how the multiple CPGs synchronize and desynchronize with each other. Section 3 introduces the learning algorithm (simulated annealing) and the principle of selecting a suitable combination of leg oscillation frequencies for malfunction compensation. Section 4 demonstrates the implementation of the proposed multiple CPGs and the learning strategy on simulated hexapod and quadruped robots. Section 5 introduces our real hexapod walking platform – AMOSII. The learning results obtained from simulation are applied to the robot and the effectiveness of the results is successfully verified. Section 6 discusses the results, and finally in Section 7 we present our conclusion.

2. Multiple chaotic central pattern generators and synchronization mechanism

Our multiple CPGs-based locomotion controller is derived from the chaotic CPG controller, introduced in [51]. First, we describe a single CPG oscillator and then show how it can be extended to multiple CPGs. The synchronization and desynchronization mechanisms are also presented. The multiple CPGs generate either different periodic patterns independently, or they become synchronized and generate the same pattern. Here, they will be synchronized for basic locomotion generation and desynchronized for malfunction compensation.

2.1. Single chaotic CPG

The chaos control CPG unit is shown in Fig. 1. In this figure, x_1 and x_2 indicate the neurons that generate the oscillation, while c_1 and c_2 are the control inputs depending only on the period p with a control strength μ. $w_{11},\ w_{12},\ w_{21}$ represent the synaptic weights and θ_1 and θ_2 indicate the biases. Dynamics of the chaos control CPG can be exploited to generate complex patterns for legged robots, like chaotic leg motion and different walking patterns (multiple gaits). To achieve different