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Gait transition and modulation in a quadruped robot: A brainstem-like modulation approach

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ABSTRACT

In this article, we propose a bio-inspired architecture for a quadruped robot that is able to initiate/stop locomotion; generate different gaits, and to easily select and switch between the different gaits according to the speed and/or the behavioral context. This improves the robot stability and smoothness while locomoting.

We apply nonlinear oscillators to model Central Pattern Generators (CPGs). These generate the rhythmic locomotor movements for a quadruped robot. The generated trajectories are modulated by a tonic signal, that encodes the required activity and/or modulation. This drive signal strength is mapped onto sets of CPG parameters. By increasing the drive signal, locomotion can be elicited and velocity increased while switching to the appropriate gaits. This drive signal can be specified according to sensory information or set *a priori*.

The system is implemented in a simulated and real AIBO robot. Results demonstrate the adequacy of the architecture to generate and modulate the required coordinated trajectories according to a velocity increase; and to smoothly and easily switch among the different motor behaviors.

1. Introduction

The ability to traverse a wide variety of terrains while locomoting is basically a requirement for performing useful tasks in our human centric world. However, legged locomotion is a complex problem that involves behavioral diversity. A common factor to these behaviors are the notions of trajectory generation and modulation. These are of utmost importance in robotics and animal control since trajectories have to be modified on-line in several circumstances, such as gait adaptation to speed change, obstacle avoidance, goal motion, or when dealing with external perturbations.

In this article we address some of the issues directly related to these two notions, considering the generation of different types of gaits and the easy switch between them in quadruped robots. Specifically, we address the topic of smooth gait transitions in a quadruped robot. We propose an open-loop controller architecture that must be able to generate different motor behaviors for a robotic quadruped, namely locomotion initiation, smooth gait generation and switching according to speed change and to stop locomotion. It takes its inspiration from biology [1–4] where a low dimensional tonic input from higher centers is used to control speed and direction of locomotion. This tonic command is used to modulate the parameters of CPGs in the lower level, modeled by non-linear oscillators, and thereby affecting gait in a smooth manner.

We believe that in order to devise flexible, adaptive, relevant locomotor models it is imperative to integrate concepts of the vertebrate locomotor generator structure organization, function, components and flexibility. However, our perspective is an engineering one and abstractions are done such that the proposed models are well suited for robots.

The present work extends ideas presented in [5–7] for the generation of other behaviors, namely in drumming and in switching between crawling and reaching. Herein, we further explore this idea for the generation and switching among other motor behaviors, continuing our previous work [8]. We propose an architecture structured in two functional hierarchical layers according to their level of abstraction.

The lower layer addresses the role of the spinal cord and generates the motor patterns by networks of Central Pattern Generators (CPGs). Based on previous work [8–10], we apply (oscillator-based) differential equations to model a network of four coupled unit-CPGs. These systems are solved using numerical integration and sent to the lower level PIDs of the joints.

The second layer models very basically the brainstem command centers for initiating, regulating and stopping CPG activity and therefore initiate locomotion, switch among gaits and stop the locomotion. This layer receives a modulatory signal and uses a piecewise continuous function to modulate the CPG parameters

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(frequency, amplitude and relative phases) according to the signal strength. By sending these at the right timing to the lower layer, it results in the modulation of the generated trajectories and thus in different motor behaviors.

Nature has provided solutions to the locomotion of animals which may, in some sense, represent an optimum, since it has evolved through millions of years. For instance, quadruped walking animals such as horses or cats change their gait to be suited to their walking speed. However, at all walking speeds the onset of swing in a foreleg occurs just after the onset of stance in the ipsilateral hind leg [1]. These facts are very important to realize smooth motor patterns.

In robotics, in order to achieve smooth walking from low speed to high speed, these gaits should be similarly switched continuously. This can be easily achieved by applying the wave gait rule [11,12], i.e., the interlimb phase relationships should follow the value of the duty factor for a changing speed. This rule improves the stability of the locomotion and maximizes the stability margin [11,12] because the support of the body smoothly changes from three-point support (walk) to two-point support (trot) [13,12,11].

In this article, we explore the idea of taking into account the speed change when switching from a walk to a trot gait, by continuously changing the duty factor and the interlimb phase relationships. These two factors fully characterize a gait and herein directly specify the CPG parameters of the locomotion controller. Because the resultant motor patterns are modulated according to modulation of the CPG parameters, this is easily and straightforwardly achieved using our formulation, and is one of our controller's main advantages.

The proposed system is implemented and tested in both, a simulated environment and the real ERS-7 robot from Sony. The obtained results demonstrate the adequacy and feasibility of the proposed locomotor controller to generate the required coordinated trajectories for locomotion; to modulate the generated motor patterns according to a velocity increase; and to smoothly and easily switch among the different motor behaviors. Further, both the modulation and switching are elicited according to a unique modulatory drive signal, either given *a priori* or by sensory information.

Results also show that the stability margin decreases approximately linearly with the velocity increase, and that the switching among the gaits happens smoothly. If instead an abrupt transition between these gaits is applied, the system moves quickly into a trot, exhibiting a non-natural, messy and less stable behavior.

This article is structured as follows. We will first review recent work on quadruped locomotion using Central Pattern Generators and gait transition. Section 3 presents details of motor patterns and gait transition. Section 4 briefly introduces the proposed architecture; discussing the neural structures involved in the locomotion of vertebrates; the biological observations more pertinent to this work and the controller requirements. Section 5 describes the lower layer of the proposed architecture. The second layer is presented in Section 6 where the mechanism to encode movement specifications is described in detail. Section 7 presents the obtained results for several experiments. We conclude by presenting the conclusions and discussing some future directions for our work.

2. State-of-the-art

In this work, we address the problem of developing a controller architecture, modeled by nonlinear dynamical systems, inspired in the functional model of biological motor systems that can online generate and modulate different motor patterns (gaits) and select and switch between them according to the (sensed) speed and/or the behavioral context for a quadruped robot. We choose this task because it requires important features of movement control, notably timing, synchronization and accuracy and behavior integration. Experiments have been delineated such that these behaviors are integrated and their switch is elicited either by sensory information or *a priori*.

The design of the architecture takes into account experimental knowledge about how the nervous system deals with the control problem in a robust and flexible way [14,15,3,16–18]. It is partly inspired from the biological concepts of Central Pattern Generators (CPGs) [15], i.e., spinal-neural networks capable of autonomously producing coordinated rhythmic output signals; and by the concepts of force fields [19].

We have applied the dynamical systems theory for: (1) generating complex movements that smoothly superimpose and/or switch between discrete and rhythmic primitives; (2) easily control the switch between the possible movements; (3) DOFs coordination; and (4) modulate the movements according to given signals or possible feedback pathways.

The dynamical systems approach has proven to be successful in many robotic applications [20,14,21,5,22–24,9,25,8,7,26,27]. It offers multiple interesting features which apply well to model CPGs for robotic controllers, including: low computational cost; the intrinsic stability properties allow for feedback integration; intrinsic robustness against small perturbations; smooth trajectories modulated by simple parameter changes; provide for coupling/synchronization; and entrainment phenomena when coupled to mechanical systems.

Additionally, in the design of the architecture we have assumed that complex movements are constructed out of the combination of simpler motor primitives [14,19,16]. This modularity is also assumed in terms of behaviors [16]. In animals, different motor behaviors, designed to solve a variety of motor tasks, are stored as motor programs in the nervous system. Once activated, these are subject to parameterization that modulate the trajectories generated by the CPGs and produce different motor behaviors [19,3].

These two last assumptions enable movements to be generated in a modular fashion and are convenient for modeling purposes [21]. This allows: (1) to tackle the complexity inherent to the design of dynamical systems; (2) a fast response to stimuli; and (3) an easy switching between behaviors. Thus, it is well suited for fast adaptive behaviors because it turns a high dimensional trajectory generation problem into a simple selection between predefined behaviors. This is in fact an interesting way of making the encoding of multiple trajectories more compact [28].

The proposed architecture is organized onto hierarchical layers, similarly to the motor control systems involved in goal-directed locomotion in vertebrates [3]. This modularity between the layers enables us to achieve independence between them which is adequate for a real implementation of the architecture, from a computational perspective. Higher layers that require more computational power but with larger time scales can easily be implemented in external computers and communicate with the robot when needed [28].

Control approaches based on CPGs and nonlinear dynamical systems are widely used in robotics to achieve tasks which involve rhythmic motions such as biped and quadruped autonomous adaptive locomotion over irregular terrain [29,22], juggling [30], drumming [8], playing with a slinky toy and basis field approaches for limb movements [19]. Some of these works present a high degree of sensor-driven and/or learned autonomy.

Herein, we extend the ideas presented in [7] for a similar architecture towards the achievement of continuous gait transition using a CPG-based approach. We do not expect precise and exact motions, since the CPG approach is not intended for such a goal and in this work is open-loop and disregards physical