Neural Networks 21 (2008) 667–681

Contents lists available at ScienceDirect

Neural Networks

journal homepage: www.elsevier.com/locate/neunet

2008 Special Issue

Towards a general neural controller for quadrupedal locomotion

Christophe Maufroy [a,*], Hiroshi Kimura [b], Kunikatsu Takase [a]

[a] *Graduate School of Information Systems, University of Electro-Communications, Tokyo, Japan*

[b] *Graduate School of Science and Technology, Kyoto Institute of Technology, Kyoto, Japan*

ARTICLE INFO

Article history:
Received 11 August 2007
Received in revised form
7 March 2008
Accepted 7 March 2008

Keywords:
Quadruped
Neural controller
CPG
Rhythmic motion
Posture
Computational simulation

ABSTRACT

Our study aims at the design and implementation of a general controller for quadruped locomotion, allowing the robot to use the whole range of quadrupedal gaits (i.e. from low speed walking to fast running). A general legged locomotion controller must integrate both posture control and rhythmic motion control and have the ability to shift continuously from one control method to the other according to locomotion speed. We are developing such a general quadrupedal locomotion controller by using a neural model involving a CPG (Central Pattern Generator) utilizing ground reaction force sensory feedback. We used a biologically faithful musculoskeletal model with a spine and hind legs, and computationally simulated stable stepping motion at various speeds using the neuro-mechanical system combining the neural controller and the musculoskeletal model. We compared the changes of the most important locomotion characteristics (stepping period, duty ratio and support length) according to speed in our simulations with the data on real cat walking. We found similar tendencies for all of them. In particular, the swing period was approximately constant while the stance period decreased with speed, resulting in a decreasing stepping period and duty ratio. Moreover, the support length increased with speed due to the posterior extreme position that shifted progressively caudally, while the anterior extreme position was approximately constant. This indicates that we succeeded in reproducing to some extent the motion of a cat from the kinematical point of view, even though we used a 2D bipedal model. We expect that such computational models will become essential tools for legged locomotion neuroscience in the future.

1. Introduction

Control methods for legged locomotion are generally classified into ZMP[1]-based methods (Takanishi, Takeya, Karaki, & Kato, 1990; Yoneda, Iiyama, & Hirose, 1994) and limit-cycle-based methods (Miura & Shimoyama, 1984). When we consider legged locomotion from the point of view of the *Froude number*[2] (*Fr*) (Alexander, 1984), we can point out the following (Fukuoka, Kimura, & Cohen, 2003):

- at low *Fr* (low speed), since gravity is dominant, posture control using sensory information such as ground reaction force information (like the center of pressure COP or the ZMP) and/or vestibular information is more important.
- at high *Fr* (high speed), since inertial force is dominant, rhythmic motion control to construct a limit cycle is more important.

Consequently, a general legged locomotion controller must integrate both posture control and rhythmic motion control and have the ability to shift continuously from one control method to the other according to locomotion speed. However, to the authors' best knowledge, implementation of such a controller has never been reported.

On the other hand, the nervous system of legged animals, through its interaction with the body (i.e. the musculoskeletal system), is a wonderful example of a controller which possesses such an ability. In order to understand the underlying principles supporting this ability, there have been up until now several computational simulation studies of a neuro-mechanical system combining a neural model and a musculoskeletal model based on the knowledge about neuroscience of the locomotion of vertebrates (Ijspeert, 2001; Miyakoshi, Taga, Kuniyoshi, & Nagakubo, 1998; Ogihara & Yamazaki, 2001; Ogihara, Aoi, Sugimoto, Nakatsukasa, & Tsuchiya, 2006; Taga, 1995; Taga, Yamaguchi, & Shimizu, 1991; Tomita & Yano, 2003). However, the neural model and/or the musculoskeletal model in these studies were much abstracted or simplified.

* Corresponding author.
E-mail addresses: chris@kimura.is.uec.ac.jp (C. Maufroy), kimura@mech.kit.ac.jp (H. Kimura), takase@is.uec.ac.jp (K. Takase).

[1] ZMP (Zero Moment Point) is the point with respect to which dynamic reaction force at the contact of the foot with the ground does not produce any moment. It can be seen as the extension of the projection of the center of gravity on the ground, including inertial forces and so on.

[2] $Fr = v/\sqrt{gL}$ (where v is the forward speed, g the acceleration due to gravity and L the leg length).

0893-6080/$ – see front matter © 2008 Elsevier Ltd. All rights reserved.
doi:10.1016/j.neunet.2008.03.010

On the other hand, a few computational simulation studies of a neuro-mechanical system using neural and musculoskeletal models more faithful to the knowledge about neurophysiology of the locomotion of lampreys (Ekeberg, 1993) and cats (Ekeberg & Pearson, 2005; Wadden & Ekeberg, 1998; Yakovenko, Gritsenko, & Prochazka, 2004) were also carried out. Although the models for legged locomotion used in these former studies were limited to 2D and included only the hind legs (Ekeberg & Pearson, 2005; Yakovenko et al., 2004), it is expected that such computational models will become essential tools for legged locomotion neuroscience when 3D quadrupedal locomotion will be successfully simulated in the future.

Inspired by these computational simulation studies of neuro-mechanical systems, many studies about robot locomotion control using a neural model have been carried out (Aoi & Tsuchiya, 2005; Berns, Ilg, Deck, Albiez, & Dillmann, 1999; Fukuoka et al., 2003; Lewis, Etienne-Cummings, Hartmann, Xu, & Cohen, 2003; Kimura, Akiyama, & Sakurama, 1999; Kimura, Fukuoka, & Cohen, 2007; Nakanishi et al., 2004; Tsujita, Tsuchiya, & Onat, 2003) and, in some cases, resulted in predictions that were supported by biological data (Ijspeert, Crespi, Ryczko, & Cabelguen, 2007). However again the neural model and the musculoskeletal model in these studies were also much abstracted or simplified. In the future, if neurophysiologically faithful neuro-musculoskeletal models can be applied to robots, robots will turn out to be valuable tools for locomotion neuroscience as well, because physical simulations of locomotion including computationally hard to simulate phenomena (like collisions, fluid dynamics, dynamics of deformable surface and so on) will then become available.

In this general context, we pursue the following two goals which we believe to be complementary. The first one is related to robotics and consists in developing a general quadrupedal controller for robots in order to achieve:

- high locomotion ability from low speed walking to high speed running, involving autonomous gait transitions according to the change of speed (Shik, Orlovsky, & Severin, 1966), and
- high locomotion adaptability on irregular terrain.

As, in order to fulfill this goal, we decide to take inspiration about how such functions are achieved in animals, we are naturally led to formulating the second goal, related to physiology and neuroscience, which is to:

- propose a new quadrupedal locomotion controller using a neural model faithful to some extent to the knowledge about neurophysiology of the locomotion of cats, and
- develop both a computational model (based on biologically faithful musculoskeletal data) and a physical model (i.e. a robot) as potentially useful tools for quadrupedal locomotion neuroscience.

In this article, as the first stage of our computational simulation studies, we extended and improved the NPG architecture proposed by Wadden and Ekeberg (1998) in order to use it with the musculoskeletal model proposed by Ekeberg and Pearson (2005), and simulated stepping motions using a two hind leg model. By doing this, we obtained the original results of being able to induce autonomous speed and stepping pattern modulations according to the change of a single tonic input (modeling the input from the upper neural system), while using that biomorphic musculoskeletal model. Moreover, similar trends of the variation of the main characteristics of the stepping patterns with speed could be observed in our simulation results and in the biological data on real cat walking.

Section 2 presents the general framework in which our study takes place. An overview of the musculoskeletal system and the neural controller is given in the following section. Section 4 details the neuronal models that we used in our controller and its implementation. Results of our computational simulations using this model are presented in Section 5 and discussed in Section 6. We finally conclude in Section 7.

2. Background

2.1. Motivations

In former studies (Fukuoka et al., 2003; Kimura et al., 1999, 2007), we realized adaptive walking on irregular terrain using the mammal-like quadruped robot "Tekken". Our approach until now has been to use a control system based on the CPG (Central Pattern Generator) paradigm, associated with a set of reflexes. However, we were not able to realize stable low speed walking with low stepping frequency, mainly due to the lack of leg loading sensory feedback to the CPG for posture control. This is in agreement with the results of studies (Deliagina and Orlovsky (2002) for example) pointing out that this kind of sensory feedback is vital for postural control in four-legged mammals. Moreover, it has been recently demonstrated in simulation studies that the information about the load supported by the legs is also crucial for leg coordination during walking (Ekeberg & Pearson, 2005) and that this kind of sensory feedback could be used to stabilize bouncing and running gaits (Geyer, Seyfarth, & Blickhan, 2003). Due to the importance of the role that it plays at various locomotion speeds, leg loading sensory feedback is probably the main sensory information that a general controller for legged locomotion should rely on.

Including our former studies, nonlinear oscillators have been broadly used as CPG models to generate rhythmic motions. However, as supported by the experience gained in our former studies, it seems to be difficult to properly integrate posture control and rhythmic motion control using such an oscillator-type CPG. Therefore, we decided to develop a more sensor-dependent CPG model, following the arguments by Cruse (2002) that:

- *A central rhythm generator implying a "world model" in the form of a central oscillator could even cause the behavior to deteriorate in unpredictable situations.*
- *Local rules exploiting feedback loops and the mechanical properties of the body can produce the basic rhythm and can sufficiently explain a considerable part of the coordination.*

Using such an architecture, while generating the self-excited physical oscillation as a result of local feedback (Ono, Furuichi, & Takahasi, 2004; Poulakakis, Smith, & Buehler, 2006), we might be able to integrate sensor-dependent posture control and sensor-driven rhythmic motion control, hence realizing locomotion both at low and high speeds using the same control system.

In the next section, we introduce related studies on sensor-dependent neural controllers and biologically faithful musculoskeletal models for legged locomotion.

2.2. Related studies

As a physical simulation of a neural controller of invertebrates, Espenschied, Quinn, Beer, and Chiel (1996) constructed the gait pattern generator proposed by Cruse (1990) referring to a stick insect. They also employed the swaying, stepping, elevator and searching reflexes observed by Pearson and Franklin (1984) in a stick insect, and realized statically stable autonomous walking of a hexapod robot on a rough terrain. In their gait pattern generator, the stepping pattern generator of each leg receives only sensor information of the adjacent legs. When the leg motion is changed by reflexes, the phase differences between legs are autonomously adjusted through sensor information of the leg. Consequently, their neural system is more sensor dependent and more decentralized.

As a computational simulation of a neural controller of vertebrates, Wadden and Ekeberg (1998) designed and tested their original neural controller for the actuation of a single leg, made of two links and four muscle-like actuators. This neuro-mechanical