Available online at www.sciencedirect.com
ScienceDirect
Journal of Bionic Engineering 13 (2016) 572–584

Adaptive Walking Control of Biped Robots Using Online Trajectory Generation Method Based on Neural Oscillators

Chengju Liu[1], **Danwei Wang**[2], **Erik David Goodman**[3], **Qijun Chen**[1]

1. *School of Electronics and Information Engineering*, *Tongji University*, *Shanghai* 201804, *China*
2. *School of Electrical and Electronic Engineering*, *Nanyang Technological University*, *Manyang Avenue* 639798, *Singapore*
3. *BEACON Center for the Study of Evolution in Action*, *Michigan State University*, *East Lansing* 48824, *USA*

Abstract

This work concerns biped adaptive walking control on irregular terrains with online trajectory generation. A new trajectory generation method is proposed based on two neural networks. One oscillatory network is designed to generate foot trajectory, and another set of neural oscillators can generate the trajectory of Center of Mass (CoM) online. Using a motion engine, the characteristics of the workspace are mapped to the joint space. The entraining property of the neural oscillators is exploited for adaptive walking in the absence of a priori knowledge of walking conditions. Sensory feedback is applied to modify the generated trajectories online to improve the walking quality. Furthermore, a staged evolutionary algorithm is developed to tune system parameters to improve walking performance. The developed control strategy is tested using a humanoid robot on irregular terrains. The experiments verify the success of the presented strategy. The biped robot can walk on irregular terrains with varying slopes, unknown bumps and stairs through autonomous adjustment of its walking patterns.

Keywords: biped robot, adaptive walking, neural oscillator, trajectory generation, staged evolution algorithm

doi: 10.1016/S1672-6529(16)60329-3

1 Introduction

Biped locomotion control is fundamental for biped robots to work in unknown walking conditions. Many biped robots successfully utilize Zero Moment Point (ZMP) based locomotion control methods[1–6]. Most researches focus on walking stability of biped robots on flat terrain or on known uneven terrains. The trajectory-based methods are good for a robot to walk according to pre-designed trajectories while maintaining its balance. However, pre-designed trajectories are fixed and therefore, if terrain conditions change, pre-designed trajectories may fail. Although multiple trajectories for different terrains can be designed, and switching is possible while walking, they cannot cover all situations a robot might encounter.

For a biped robot walking on different terrains, like overcoming obstacle[7], it is necessary to adapt to walking terrains with adjustable workspace trajectories. As the complexity of walking conditions increases, the polynomial interpolation method becomes inefficient. The polynomial order becomes too high and its computation will be too demanding. To overcome this problem, Shih[1] proposed a strategy that uses cubic spline interpolation to plan foot trajectories. Huang *et al*.[2] formulated the constraints of foot motion parameters to produce different types of foot motion for various terrains. Park *et al*.[5] presented a gait trajectory generation method based on the combination of sinusoidal functions and 3rd-order polynomial functions to realize free gait biped walking. Based on ZMP, a gait synthesis technique was employed by Seven *et al*.[6]. The pitch angle reference for the foot sole plane was modified in real time using a fuzzy logic system to adapt to various walking slopes.

Human walking does not exhibit the characteristics of precise trajectory tracking. Biological researches show that the human walking is the consequence of the combination of inherent patterns and reflexes[8,9]. Researchers investigated bio-inspired control methods based on biomechanics of musculoskeletal system and motor neural networks[10,11]. Inspired by Central Pattern

Corresponding author: Qijun Chen
E-mail: qjchen@tongji.edu.cn

Generator (CPG), locomotion control methods have been proved workable[12–15]. CPG is a type of oscillator network that can produce rhythmic oscillatory signals endogenously. Through mutual inhibition of the neurons and entrainment with sensory feedback, the movement patterns of the network can be adjusted. The CPG-based motion control methods have been successfully used in swinging and crawling robots[16,17], as well as multi-legged robots[18,19]. For the control of biped locomotion[20–23], inspired by Taga's work[24,25], the walking control strategies are exploring in recent years.

The CPG-inspired motion control strategies are usually synthesized into joint-space control method and workspace control method. For the joint-space control methods, usually using one CPG unit to control one Degree of Freedom (DoF) of the robot, and the distributed oscillator network can generate complex coordinated multi-dimensional signals used as force or torque control to realize the coordinated motion. Due to the inherent instability of biped walking, the traditional joint space CPG control methods are not very feasible. For biped walking control, CPGs are usually used as supplements to other controllers.

For legged animals, the tips of the legs reflect gait patterns. Task space based study of animal walking mechanism can be an efficient way for CPG-inspired walking control of legged robots. Endo *et al.* [26], Ha *et al.*[27] and Aoi *et al.*[28] designed motion control strategies in the workspace space of biped robots. By using nonlinear oscillators to generate the nominal trajectories of the joints and the nominal trajectories are modified using feedback information that depend on the posture and motion of the biped robot to achieve robust walking[28]. To further develop the biped environmental adaptive walking capability, an online trajectory generation method should improve the dynamic stability and adaptability of any robot. That is, the generated trajectories should be modulated online according to the terrain conditions. In our previous work[29], using nonlinear oscillators, a CoM trajectory generator and a workspace trajectory modulator are designed. However, the pre-designed fixed foot trajectory limits the environmental adaptability. This paper aims to improve the walking adaptability on irregular terrain using neural oscillators. The adaptive foot trajectory and robust CoM trajectory can be generated online. In this paper, the following contributions are achieved:

(1) A new workspace trajectory generation method is presented based on a neural network consisted of four coupled nonlinear oscillators. The output signals of the neural network are transformed into the workspace trajectories for the two legs of a biped robot;

(2) A staged process is designed to evolve the parameters of the control system offline (using Webots platform). Firstly, numerical simulation is employed to analyze the effect of each parameter on the oscillatory output. Then, an NSGA-based method is used to realize the walking pattern evolution;

(3) Through the entrainment of the oscillators and the feedback signals of the biped robot, the generated CoM and foot trajectories can be modulated online according to the walking conditions to realize adaptive walking.

The motion engine will be used to realize the mapping from workspace to joint space (Ref. [30]). Thus, the adaptive joint control signals can drive all leg joints to realize the desired motion. The advantages of this proposed method are that it does not require prior information on the terrain conditions, nor does it rely on range sensor information for surface topology measurement. Both Webots simulations and real experiments are designed to demonstrate the efficiency of the presented control system. The rest of this paper is organized as follows: Section **2** introduces the design methods of the trajectory generators, the feedback path design and the parameter evolution of the control system. Section **3** describes the humanoid robot NAO and presents the simulation and experimental results of the various irregular terrain adaptive walking. The conclusion and discussion of this work and the future work are stated in Sections **4**.

2 Control system

For a biped robot to realize adaptive walking, the swing foot trajectory needs to be adjusted online to realize various walking patterns. In order to best improve the stability and adaptability, the modulation of swing foot trajectory and CoM trajectory should be combined. In the following sections, the trajectory generation methods are presented.

2.1 CPG-based trajectory generators

2.1.1 CPG model

A neural oscillator model evolved from