ARTICLE IN PRESS
JID: NEUCOM [m5G;December 2, 2017;10:59]

Neurocomputing 000 (2017) 1–12

Contents lists available at ScienceDirect

Neurocomputing

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

Dynamically stable walk control of biped humanoid on uneven and inclined terrain

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ARTICLE INFO

Article history:
Received 20 January 2017
Revised 17 July 2017
Accepted 19 August 2017
Available online xxx

Keywords:
Bipedal walk control
Neural network controller
Uneven terrain

ABSTRACT

This paper contributes to the literature on energy efficient gaits on unknown terrains for humanoid robots, the locomotion system of which has anthropomorphic characteristics. In this work, we firstly present an energy efficient gait for humanoid robots. The main feature of the new gait is the absence of an area of support. The stiffness-free foot can rotate freely around the ankle joint. This feature makes the gait suited for uneven terrains. We then present a group of neural network controllers to regulate the sagittal and lateral motion of the robot's gait in the presence of an unknown terrain. The resulting gait evaluated on an Aldebaran Nao robot, (1) reduces the energy consumption by 41% on a flat ground compared to the conventional Aldebaran gait, (2) can handle small disruptions caused by an uneven terrain, and (3) looks more like a human gait. A video showing the gait in the simulator is available.

1. Introduction

Bipedal walking for humanoid robots is one of the most interesting challenges in robotics. In the papers [1–3], we have investigated the possibility of creating a dynamically stable and energy efficient gait without an area of support. Here, the absence of an area of support means that the ankle joint can move freely while the foot is on the ground. In the sagittal direction the robot's Center of Mass (CoM) is falling forward till the foot of the swing leg touches the ground. In the lateral direction, the robot balances above the stance foot in the single support phase, and falls towards the new stance foot in the double support phase. The falling towards the new stance foot is stopped by putting a force on the new stance leg. The resulting gait[1] was subsequently evaluated on a real Nao robot. The stability of the gait is validated on a flat ground but not on an uneven terrain. Since there is no feedback in the controller, the robot cannot adjust the gait parameters to compensate for the uneven floor. In this paper, we improve the gait's stability on an uneven terrain by introducing feedback in the controller.

Our contributions are as follows: First, we integrate the previous insights to develop a simple new gait with less energy consumption for omni-directional biped walking. This gait exhibits robust dynamically stable behavior on a flat floor. Second, we demonstrate that feed-forward neural network controllers can be used to enhance the stability control for the locomotion on an uneven terrain. The simple framework opens the door to developing wider sets of bipedal skill, and is applicable to other types of humanoid robots.

The remainder of this paper is organized as follows. In the next section, we will give a brief overview of existing research about kinematics models for humanoid robots, stability criteria and various approaches to obtain energy efficient bipedal walking. Section 3 briefly describes the new gait that we developed and presented in [1]. We used the Inverted Pendulum Model (IPM) to investigate the energy consumption in the sagittal plane. Subsequently, we extended the model to the lateral plane and describe a gait controller with multiple parameters for a 3D full-body humanoid robot. The controller can achieve a stable gait on a physical robot in the real world after we optimize its parameters through Policy Gradient Reinforcement Learning (PGRL). Section 4 introduces our work on the neural network controller to enhance the gait's stability on an uneven terrain. Section 5 describes the implementation of proposed methods in the simulator and on a Nao robot. The results are demonstrated in this section as well. Section 6 concludes this paper. We provide a brief summary of the results and outline the future research.

2. Related work

2.1. Models of bipedal walking

Humanoid robots have complex bodies with irregular shape and mass distribution. Therefore, it is advantageous to obtain an

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[1] A video of the new gait at: https://project.dke.maastrichtuniversity.nl/robotlab/?attachment_id=153.

https://doi.org/10.1016/j.neucom.2017.08.077
0925-2312/

Please cite this article as: Z. Sun, N. Roos, Dynamically stable walk control of biped humanoid on uneven and inclined terrain, Neurocomputing (2017), https://doi.org/10.1016/j.neucom.2017.08.077

elemental representation of the robot's dynamics. Ideal features of a model are simplicity, and both a conceptually and mathematically accurate representation of the dynamics of the real system. The main approaches employed to model the kinematics of humanoid robots are based on the Inverted Pendulum Model (IPM) ([4]), which involves a simplification compared to the body of the robot. The IPM represents the whole body of the robot as a point mass located at the center of mass (CoM) of the actual robot. The point mass is linked to the base of the robot by a telescopic massless leg. Restraining the movements of the CoM to a horizontal plane allows to simplify the motion equation of the IPM. The resulting model is known as the Linear Inverted Pendulum Model (LIPM), which [5] proposed to describe humanoid robot locomotion. The LIPM provides an efficient means to represent the kinematic behavior of the robot and it is therefore a popular tool to understand and manipulate the balance of a humanoid robot. With the LIPM and zero moment point (ZMP) stability criteria [6], institutes/companies have successfully built biped robots that can walk with various gaits adapting to different walking situations (e.g. [7–10]).

2.2. Energy consumption

The dynamic model is not the only factor to be considered. The energy consumption of a gait is an important issue. Various approaches have been proposed to reduce the energy consumption of a gait. One of these approaches is passive-dynamic walking where the robot's dynamics are designed to enable a robot to walk down slight slopes without control input, except for the gravitational force. The paper of [11] explained this well. Kuo A. et al. [12] believed that passive-dynamic walkers have three primary flaws: (1) they can only walk down slopes, (2) their gaits are restricted by their dynamics, and (3) they are sensitive to perturbations. Realizing these limitations, researchers [13] have sought to improve passive-dynamic walker by adding actuators.

A second approach to obtain energy efficient bipedal walking is through the application of mechanical compliances. In the work of [13] and [14], springs were added across the hip, thigh, knee and ankle simultaneously. Yang T. et al.[15] exploited parallel knee compliance on the robot ERNIE and discussed how soft/stiff springs affect the energy efficiency at different walking speeds. Jerry P. et al.[16] described the implementation of series-elastic actuation on Spring Flamingo (a MIT's planar bipedal walking robot) to enable the control of the ground reaction forces during walking. In the commercial platform used in our experiments, such hardware modifications are not possible.

A third approach to improve the energy-efficiency of bipedal walking is by designing gaits that minimize the energy cost. The most common means of design is to use parametric optimization of the parameters that specify the gait of the robot. For example, Chevallereau et al. [17] used parametric optimization to design fourth degree polynomial functions that give the joint motions over a step as functions of time. Unlike the previous example, in the work of [18] cubic splines connected at points uniformly distributed along the motion time are used to generate complete optimal steps, including a double support phase.

Parametric optimization methods are also implemented to optimize the walking gait on humanoid Nao robots. In the work of [19], the proposed method models the omni-directional motion as the combination of a set of periodic signals. The parameters controlling the characteristics of the signals are encoded into genes and evolutionary learning is used to learn an optimal set of parameters. The Nao humanoid robot is used as the test platform. Abdolmaleki et al. [20] augmented the 3D inverted pendulum with a spring model and use policy search to optimize the parameters of the walking engines on Nao robots. Shahbazi et al. [21] introduced a two-stage learning algorithm for Central Pattern Generator (CPG) of Nao robot's bipedal walking.

2.3. Stability control on uneven terrains

A biped robot with a primal walk controller is capable of walking on flat surfaces. However, it has the defect that its stability may not be guaranteed on uneven terrains. A slight irregularity or an undulation of the ground can undermine the balance of the robot. This defect makes the biped robot less practical in real (outdoor) environments where the ideal flat ground is rare.

A number of researchers have proposed solutions for the stability control problem of biped robot on uneven surfaces [22–27]. In the work of Yi [28], these solutions are divided into three categories:

1. Analyze the ground surface using external sensors such as a laser range finder or a camera [29–31]. The robustness of those methods rely on the measurement accuracy of the sensors. Since the position where the sensor is mounted, is usually above the robot's chest, this kind of solutions is not applicable for a wide range of humanoid robots.
2. Use specialized hardware to ensure the stability of walking on an uneven terrain. Sano et al. [24] introduce a new foot with four passive joints, each of which is equipped with a spring and a sensor, to achieve stable biped walking. Wang et al. [32] enable stable dynamic walking on an uneven terrain using a walking model with mechanically compliant ankles. Kang et al. [25] have developed a new biped foot mechanism capable of making a large support polygon on an uneven terrain using three or four spikes.
3. Gain terrain-adaptive skills using a feedback controller [33–36]. In these approaches, a feedback controller tunes the gait parameters to realize stable walking on uneven terrains. Yi et al. [28] proposed a method using foot measurements and an on-line learning algorithm, to estimate the surface gradient. This information is used to modify the robot locomotion and control parameters.

Our proposed work uses feedback control. However, it does not estimate the gradient of the slope, but adapts the torque in the knee of the stance leg, and, in the double support phase, also the torque in the knee of the swing leg based on the position of the center of mass (CoM), its speed and its acceleration. Another difference is that our feedback controller does not use a stability criterion such as the zero-moment point (ZPM).

3. Our gait

This section briefly describes our new gait presented in [1–3]. We first analyzed the gait without an area of support using an IPM with telescopic legs. Then we designed a controller which implements the gait on a real Nao robot.

3.1. Kinematics model in sagittal direction

The IPM with telescopic legs allows the length of the virtual support leg to vary during a step. We proposed the leg-length policy $\delta : [-\frac{\pi}{2}, \frac{\pi}{2}] \to [0, 1]$ that determines how much the virtual support leg will be shortened as function of the angle between stance leg with vertical axis. The shortening of the stance leg is realized by bending the knee joint, see the right side of Fig. 1.

To identify the leg-length policy that minimizes the energy consumption of a robot, we make use of the fact that the robot has to bend the knee in order to shorten the leg. The knee torque is the main factor determining the energy consumption [1]. Fig. 3 shows the optimal leg-length policy $\delta(\alpha)$ as a function of the angle α