Robotics and Autonomous Systems 75 (2016) 297–309

Contents lists available at ScienceDirect

Robotics and Autonomous Systems

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

Active balance of humanoids with foot positioning compensation and non-parametric adaptation[☆]

Chengju Liu [a], Tao Xu [a], Danwei Wang [b], Qijun Chen [a,*]

[a] School of Electronics and Information Engineering, Tongji University, Shanghai, China
[b] School of Electrical and Electronic Engineering, Nanyang Technological University, Singapore

HIGHLIGHTS

- A novel adaptive non-parametric foot positioning compensation approach is proposed.
- A CIPM taking into account of supporting area to CoM acceleration is used.
- A non-parametric regression model based on extended Gaussian Process is used for online FPC.
- A real-time & sample-efficient local adaptation method is proposed for the non-parametric model.

ARTICLE INFO

Article history:
Received 21 April 2014
Received in revised form
23 January 2015
Accepted 16 September 2015
Available online 30 September 2015

Keywords:
Humanoid walking
Active balance
Foot positioning compensation
Gaussian process

ABSTRACT

To maintain human-like active balance for a humanoid robot, this paper proposes a novel adaptive non-parametric foot positioning compensation approach that can modify predefined step position and step duration online with sensor feedback. A constrained inverted pendulum model taking into account of supporting area to CoM acceleration is used to generate offline training samples with constrained nonlinear optimization programming. To speed up real-time computation and make online model adjustable, a non-parametric regression model based on extended Gaussian Process model is applied for online foot positioning compensation. In addition, a real-time and sample-efficient local adaptation algorithm is proposed for the non-parametric model to enable online adaptation of foot positioning compensation on a humanoid system. Simulation and experiments on a full-body humanoid robot validate the effectiveness of the proposed method.

1. Introduction

Robust locomotion is fundamental for a humanoid robot to maneuver in an unstructured and undetermined human environment. Currently, humanoid walking is commonly realized by planning the Center of Mass (CoM) trajectories so that the resultant Zero Moment Point (ZMP) [1] trajectory follows a desired ZMP trajectory, which is normally determined by predefined foot positioning [2–4]. For real time implementation, a humanoid robot was represented by a mass-concentrated model and a simplified dynamics model is generally used [5].

However, these control methods can realize humanoids walking under ideal environment instead of complex real world, where balanced walking of a humanoid robot requires dynamic stability. To achieve this objective, strategies have been proposed to compensate for nonzero variations in momentum [6] or regulate CoM directly through sensory feedback control [7]. These approaches actually imitate the instantaneous reactive balance strategies of human beings, but their performances are significantly limited. The supporting feet of a humanoid robot forms a supporting polygon on the ground. Because the humanoid robot's foot can only push the ground, the forces available to control the CoM is limited by the area of this supporting polygon once the foot steps are determined. And this supporting area constraint makes the robot unable to adjust its controllability freely to large disturbances.

Besides the instantaneous reactive balance strategies, dynamics adjustable foot positioning is also an effective strategy for active balance. Experience such as taking several steps to recover from a

---

[☆] This work was supported in part by the National Natural Science Foundation of China (Grant No. 61203344, 61573260, 91120308), and the Fundamental Research Funds for the Central Universities (0800219309), the Basic Research Project of Shanghai Science and Technology Commission (Grant No. 12JC1408800).

[*] Corresponding author. Tel.: +86 02169589338; fax: +86 02169589241.
E-mail addresses: liuchengju@tongji.edu.cn (C. Liu), xu.tao.dragon@gmail.com (T. Xu), EDWWANG@ntu.edu.sg (D. Wang), qjchen@tongji.edu.cn (Q. Chen).

http://dx.doi.org/10.1016/j.robot.2015.09.016
0921-8890/

stumble is a good illustration. Biomechanically motivated studies in [8] indicate that dynamic balance is realized more often than not on adjustable subsequent steps to ensure complete recovery and this foot positioning strategy is the key to balance recovery. On the other hand, the effectiveness of dynamic adjustable foot positioning can be explained as follows: the modification of foot positioning changes the available force region to control the CoM, hence appropriate foot positioning may provide corresponding forces to regulate the CoM trajectory as desired.

In this paper, a Foot Positioning Compensator (FPC) is proposed to dynamically adjust the foot positioning of a humanoid robot according to the real-time state of this robot's CoM. To take into account the constraint of limited supporting area of a real humanoid robot, a Constrained Inverted Pendulum Model (CIPM) is used to apply the available acceleration of CoM to determine the future state of CoM over control command. A Constraint Nonlinear Optimization Programming (CNOP) scheme [9] is used to find optimal FPC output from CoM state based on CIPM dynamics. Due to its computational complexity, this searching-based CNOP scheme is only applied offline to generate training samples for online FPC model.

Although the CIPM takes into account supporting area constraints, substantial model errors still exist for a real full-body humanoid robot. Factors such as the multi-body dynamics and other mechanical effects (links elasticity, gear backlash, uncertain ground friction etc.) cannot be sufficiently modeled. It therefore makes sense for a humanoid robot to autonomously learn its real dynamics and adapt its compensator accordingly in a real environment. On this point, an adjustable non-parametric regression model is applied online to represent the mapping from CoM state to FPC output. To adapt the online FPC model fast and efficiently, a sample-efficient online local adaptation algorithm is also proposed for the non-parametric model.

The rest of this paper is organized as follows. Section 2 reviews works related to humanoid disturbance rejection using foot positioning adjustment. Section 3 presents a constrained inverted pendulum model for a humanoid robot. Section 4 introduces a FPC strategy. Section 5 develops a non-parametric FPC model and Section 6 an adaptation method. Section 7 presents both simulation and experimental results to show the performance of the proposed FPC strategy. Section 8 provides the conclusions.

2. Related work

Recently, increasing attention is directed to applying adjustable foot positioning for disturbance rejection in humanoid robot walking. For a standing robot to resist unexpected impact, a Maximal Constraint Positively Invariant (CPI) Sets method [10] is proposed to determine whether a robot needs to take a step to recover from disturbance. The prediction is based on the Linear Inverted Pendulum Model (LIPM) [5] and the consideration of the supporting area constraint, but the stride of the compensation step is simply determined as a ratio of the ZMP tracking error and the ratio is determined by experimental experience.

Capture Point (CP) [11] stands for the location where a pushed humanoid robot should step on to recover by only one step. The determination of CP is derived from the LIPM dynamics and an orbital energy equation. A flywheel strategy of the upper body is further applied to enlarge Capture Region (CR). Because of the limitation that the distance between the supporting foot and its CP can be too far for one step to reach, multiple-step approach is later explored by some other researchers [12–14]. However, the performances of these methods were validated under simulated environment only and there is no discussion on how this approach can be applied in a continuous walking humanoid robot.

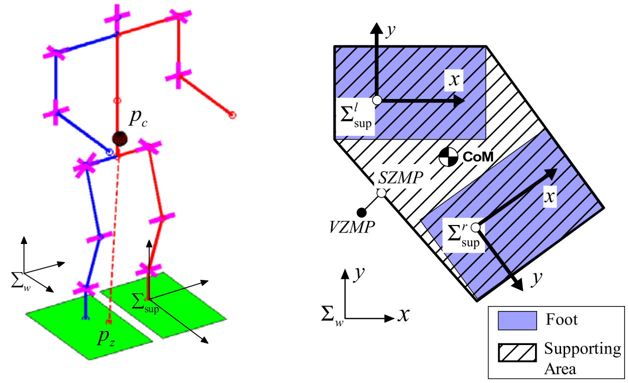

Fig. 1. Coordinate Systems of the humanoid robot (left); Foot supporting polygon and the convex hull clip (right). The strict ZMP [22] is the clipped result of virtual ZMP (VZMP) [23], which is directly computed by the LIPM model.

For disturbance rejection of continuous walking, Wieber et al. [15,16] proposed an online walking gait generation approach with both adjustable foot positioning and step duration based on the Linear Model Predictive Control scheme. However, only simulated experiments were developed and no supporting area constraint was considered. Based on the preview control scheme [17], Nishiwaki et al. [18] proposed strategies to adjust future foot positioning and ZMP trajectory. Several typical experiments were developed on a real full-body humanoid robot to validate the effectiveness of their methods. Similar works also include foot positioning adjustment based on Feasible Region [19] and avoidance behavior from external forces for a human-carrying biped [20]. These approaches show some preliminary results of disturbance rejection for humanoid walking. However, these developments are based on simplified inverted pendulum model solely.

Recently, some basic concepts are described and the idea of FPC based on non-parametric regression model is illustrated by a couple of experimental results in [21]. This paper provides rigorous development of the proposed adaptive FPC in [21]. In addition, the non-parametric adaptation algorithm is extended to address batch instances and its difference from other online learning methods is compared using several numeric experiments. Comparison experiments with other FPC approaches are used to address the added value of the proposed method over other previous works.

3. Constrained inverted pendulum model

3.1. Coordinate systems

A typical full-body humanoid robot is illustrated in Fig. 1. Two coordinate systems are used: the first one is the world coordinate system $\sum_w$, with its origin on the ground and its x, y axis formed a plane parallel to the ground; the second one is called the supporting coordinate system $\sum_{\text{sup}}$, which is attached on the supporting foot. Its origin is the origin point of the supporting foot with its x axis pointing in the forward direction of the supporting foot, and y axis to the outside.

3.2. Linear inverted pendulum model

The dynamics of a humanoid robot can be approximated as a linear inverted pendulum with its mass concentrated at CoM and supported at ZMP (Fig. 2). In this model, the robot's leg is assumed as a weightless scalable limb and its kinematics constraints are not considered. When not considering the constraint of the limited area of supporting polygon and neglecting the vertical moment of