Robotics and Autonomous Systems 95 (2017) 52–63

Contents lists available at ScienceDirect

Robotics and Autonomous Systems

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

Optimized humanoid walking with soft soles

Giovanni De Magistris [a,b,*,1], Adrien Pajon [b,1], Sylvain Miossec [c], Abderrahmane Kheddar [a,b]

[a] CNRS-AIST Joint Robotics Laboratory (JRL), UMI3218/RL, Japan
[b] CNRS-University of Montpellier, LIRMM, Interactive Digital Human, France
[c] PRISME Laboratory, University of Orléans, Bourges 18020, France

HIGHLIGHTS

- We investigate adding outer soft soles to the feet of humanoid robots.
- New control framework using a deformation estimator.
- New walking pattern generator based on a minimization of the energy consumption.
- HRP-4's humanoid robot experiments to find an optimized walking gait.

ARTICLE INFO

Keywords:
Compliant soles
Deformation estimator
Walking pattern generator
Humanoid robots
Optimized walking gait

ABSTRACT

In order to control more efficiently the feet–ground interaction of humanoid robots during walking, we investigate adding outer soft (i.e. compliant) soles to the feet. The deformation subsequent to the contact of the soles with the ground is taken into account using a new walking pattern generator and deformation estimator. This novel humanoid walking approach ensures that the desired zero moment point for stability requirement is fulfilled. We validate our new controller using the HRP-4 humanoid robot performing walking experiments with and without the estimator. Also, to test the robustness of our approach and to obtain low-energy walking, we performed different walking motions.

1. Introduction

Gaited or non-gaited walking is generated by alternating phases of contact creation and breaking with the environment [1]. With rigid links and without shock absorbing mechanism, impact forces with the ground must be thresholded through contact transitions with nearly zero speed. This considerably limits the walking dynamics. Therefore, compliant mechanisms are used in humanoid robotics to absorb shocks at impacts and prohibit their propagation along the entire structure that results in non-desirable vibrations and eventually unstable behaviors. One common solution is to add flexible mechanisms at the robot ankles [2,3] that also protect the feet embedded force sensors. Unfortunately, such compliant mechanisms also act as passive joints whose deformations are hardly measurable [4]. In this way, the robot attitude is difficult to control, especially in complex maneuvers [5]. Another solution is to add the compliance between the foot and ground contact, see early work by [6]. In fact, humanoid robots have generally a thin rubber sole attached under each robot foot. Due to the thinness of this sole, the impact shocks are mainly absorbed by the ankle flexibility.

Alternatively, we favor removing the ankle flexibilities and investigate the use of thick soft soles under each foot of a humanoid robot (see Fig. 1). These soles not only absorb the impacts due to contact transitions, they also cast ground unevenness resulting in a relative increase of the contact surface. During walking, the compliance of these soles depends on the contact area variations. Also, since the compliance is put outside, it can be decoupled from the rigid dynamics. In order to generate balanced robot movements and directly control the contact with the environment, we developed a new Walking Pattern Generator (WPG) and deformation estimator. We validate our new methods for walking with compliant soles performing different experiments on HRP-4.

2. Problem formulation

In most simplified model-based planning and control, the ankle flexibility and the sole compliance are not modeled. They are left as 'perturbations' or 'uncertainties' to be tackled by the closed-loop controller. Therefore, controllers have to compensate for the errors

* Corresponding author at: CNRS-AIST Joint Robotics Laboratory (JRL), UMI3218/RL, Japan
E-mail addresses: giova.dema85@gmail.com (G. De Magistris), adrien.pajon@gmail.com (A. Pajon).
1 Co-first author.

http://dx.doi.org/10.1016/j.robot.2017.05.006
0921-8890/

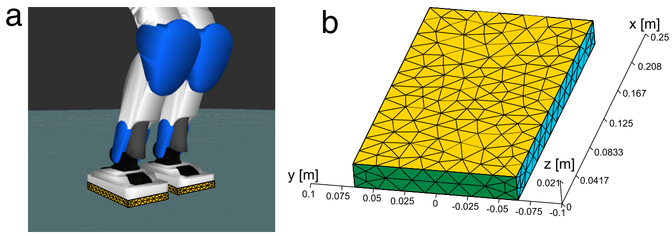


Fig. 1. (a) Rectangular parallelepiped soles mounted on HRP-4's feet; (b) meshed sole with 1494 tetrahedron elements.

in the attitude (i.e. free-floating orientation and position) due to the deformations of the flexible parts. In our control framework, we consider the model of the deformation that results from the contact of the soft sole with the ground using the Finite Element Model (FEM) and the mechanical laws of compliant contacts.

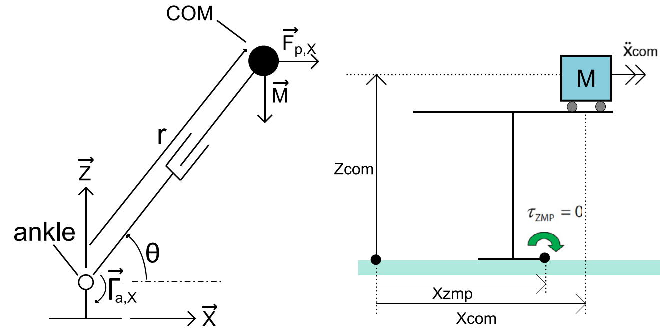
To control the humanoid robot attitude during walking, we use the multi-objective Quadratic Programming (QP) control scheme illustrated in Fig. 2. In particular, we developed a new WPG that is coupled with a sole deformation estimator to achieve good balance during walking. We also experimented the HRP-4's humanoid robot performances for different WPG.

In Section 3, we detail our new WPG; in Section 4 we illustrate how we can estimate the foot position and orientation taking into account the deformations; then in Section 5 we explain the QP for the whole-body control of the robot, which tracks the previously determined trajectories; in Section 6 we show how our WPG and the deformation estimator improve humanoid robot performances; finally, we conclude and explain the future works in Section 7.

3. Walking pattern generator

The Zero Moment Point (ZMP) and the ankle positions are directly linked (see later Eq. (33)). To obtain smooth right ankle and left ankle trajectories in the control framework of Fig. 2, we define the ZMP trajectories using a 5th order polynomial function. As will be explained in Section 3.3, the WPG developed in this paper calculates also smooth center of mass (COM) trajectories. This new WPG optimizes both single support phase (SSP) and double support phase (DSP) using a QP optimization.

Several works formulate the walking gait as an optimization problem [7–9]. They use an inverted pendulum model with a point mass to study feet convex-hull ZMP and not the whole ZMP trajectory of each foot. Therefore, the study of the DSP trajectory and force of each foot are not previously studied in the literature.



(a) Simplified robot model. (b) Cart-table model.

Fig. 3. Simplified robot model in sagittal plane at left and cart-table model at right.

For the remainder of the paper, we denote with subscript "1" the foot that leaves the floor at the end of DSP, and with subscript "2" the foot that comes in contact at the beginning of DSP.

3.1. Optimization criteria

We want to generate walking gaits that minimize the energy consumption E:

$$\min.(E). \tag{1}$$

From [9], the energy consumption that accounts for the motor and the gear models can be expressed as:

$$E = \sum_j \int_{t_i}^{t_f} (a_j\tau_j^2 + b_j\tau_j\dot{q}_j + c_j\dot{q}_j^2)dt \tag{2}$$

where τ_j is the force/torque, $\dot{q}_j$ is the joint j velocity, and a_j, b_j, c_j are the coefficients depending on joint j motor parameters and gear ratio.

Using the simplified robot model in Fig. 3a, Eq. (2) becomes:

$$E = \int_{t_i}^{t_f} (a_pF_p^2 + b_pF_p\dot{r} + c_p\dot{r}^2 + a_a\Gamma_a^2 + b_a\Gamma_a\dot{\theta} + c_a\dot{\theta}^2)dt \tag{3}$$

where subscript p denotes the prismatic joint and a the ankle joint, F_p is the prismatic force, $\dot{r}$ is the prismatic velocity, Γ_a is the ankle torque and $\dot{\theta}$ is the ankle velocity.

To obtain a quadratic problem ($\dot{r}$ and $\dot{\theta}$ are nonlinear functions of the ZMP and the COM), we keep only the force/torque terms (linear in terms of ZMP and COM parameters, see (13)). Therefore

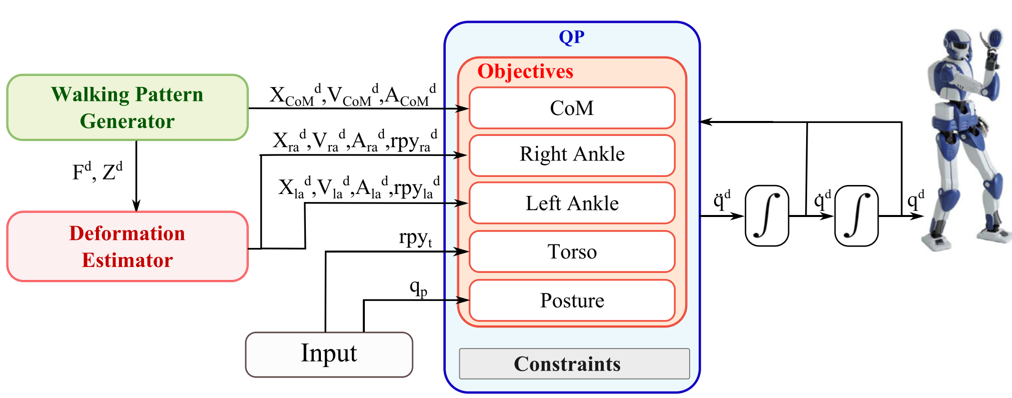


Fig. 2. Control scheme. The ankle reference trajectories change according to sole deformations.