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Optimized 3D stable walking of a bipedal robot with line-shaped massless feet and sagittal underactuation

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HIGHLIGHTS

- We propose a 3D robot model with massless line feet and a corresponding contact model.
- We obtain 3D stable walking with one degree of underactuation using a previous 2D method.
- We generate walking trajectories and optimize them to reduce the energy cost.
- The optimized gaits with smooth energy cost curves are obtained from 0.2 m/s to 1.5 m/s.

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ABSTRACT

This paper seeks to provide a method for optimizing 3D bipedal walking with satisfactory energy efficiency, provable stability and one degree of underactuation. Following the studies of the planar biped RABBIT, we propose a 3D robot with massless line feet which serve as sagittal rotation axes when lying flat on the ground. Using this configuration and the control method based on virtual constraints and feedback linearization, the walking stability can be verified by the restricted scalar Poincaré map of the zero dynamics of the system, and periodic gaits can be obtained analytically as in the case of planar bipeds with point feet. A line-foot contact model is adopted to ensure one degree of underactuation. Unlike most published contact models of bipedal walking, this model also prevents possible yaw movements of the feet on the ground. In addition, we adopt an output function named "symmetry outputs" with the desired outputs parameterized by Bézier coefficients and postural parameters, and the gait optimization is performed using a SQP algorithm. According to the results obtained from a bipedal model with a height of 1.5 m and a weight of 39 kg, the optimization program is capable of calculating stable periodic gaits with a speed between 0.2 m/s and 1.5 m/s.

1. Introduction

Unlike industrial robots, humanoid robots have to adopt biped gaits; accordingly, the question of how to lower their energy consumption to the level of their human counterparts is essential for maturing the technology. In pursuance of this goal, many researchers have been motivated to study optimized periodic gaits, however there are still many questions left unanswered, especially for 3D bipedal robots.

Early efforts in the optimization of bipedal gaits usually define each gait as functions of time and then search optimized gaits purely in the sense of dynamics with no consideration for control laws or proofs of stability [1–3]. In the meanwhile, there are widespread attempts of ZMP control strategies such as the Linear Inverted Pendulum Model adopted in the Robot HRP-4 [4,5]. This model later evolved into more complicated models such as the Inverted Pendulum with Flywheel and the idea of the capture point [6,7]. Nevertheless, gaits designed using these methods generally do not take impacts into account, and the ZMP condition itself is not sufficient for the asymptotic stability of a periodic walking motion [8].

Nearly two decades ago, a planar bipedal robot named "RABBIT" was built in Grenoble, which originated the concept of virtual constraints and the hybrid zero dynamics in the study of underactuated planar bipedal locomotion [9,8,10]. The feedback control laws based on these methods can produce walking motions with finite time stability while tracking reference trajectories

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defined as functions of robot state. A synthesis of these methods can be found in [11], and the recent application of the methods introducing the human outputs and the canonical walking function is published in [12]. Similar results considering ZMP regulation can also be found for planar bipedal robots with nontrivial feet [13]. One advantage of analyzing planar bipedal robots is that the restricted Poincaré map is a scalar with a closed-form expression, and the asymptotic orbital stability can be assessed analytically.

Although the achievements for planar bipeds seem promising, the efforts to extend these methods to 3D bipedal robots are still confronted with many difficulties. For a 3D bipedal robot with two degrees of underactuation, there are already some published results [14–16]. The recent attempts to physically realize an underactuated 3D bipedal robot is presented in [17]. However, with two or more degrees of underactuation, one has to use numeric simulation instead of direct integration to create hybrid invariant manifolds, and the resulting restricted Poincaré map is of dimension three or higher, meaning that the stability now depends on the calculation of the eigenvalues of the linearization of the restricted Poincaré map [18]. These difficulties might bring a negative effect on the performance of corresponding optimization programs. Another strategy to apply planar biped results to 3D bipedal robots involves the application of functional Routhian reduction [19,20]. The idea of this method is to decouple the sagittal and coronal dynamics of a 3D bipedal robot by shaping the Lagrangian of the robot system to satisfy the "almost-cyclic" requirement. Nevertheless, this method requires 3D bipedal robots to be fully actuated, which somehow counteracts the benefit in trying to find optimized gaits for underactuated planar bipedal robots. In addition, it is only possible to decouple coronal motion located at the stance ankle, thus greatly constraining the utility of the method when a 3D bipedal robot has more than one out-of-plane joints.

The work presented here seeks to find a compromise solution that does not require numerical simulation to determine the stability of underactuated 3D bipedal robots. The compromise is achieved by using massless line feet different from point feet proposed in [14]. When lying flat on the ground, the line feet work as underactuated rotation axes. In this way, we can attain a scalar restricted Poincaré map for our 3D bipedal robot similar to the one of a planar biped, and thus enlarge the range of applications of the method from [10] to cover 3D bipedal walking scenarios. In order to avoid the complications arising from the swing foot control, we model the feet of our robot idealistically as two massless bodies with zero rotor inertia at the ankle joints. In this way, we can define a impact model with line contact and propose the contact constraints including a ZMP constraint and friction constraints assuming that the stance foot contacts the ground only at two points. These constraints can even prevent possible yaw movements of the stance line foot, which is unfortunately neglected in many previous publications [14,15,18]. In addition, we also adopt the symmetry outputs of planar bipeds defined in [21] to facilitate the geometric interpretation of robot movement in the sagittal plane. By running optimization at different walking speeds, we are able to gather optimized stable walking data for the proposed robot model.

The main contribution of this paper is: (1) the extension of the control method from [10] for 2D bipedal walking to 3D scenarios; and (2) the impact model and contact model for 3D bipedal robots with massless line feet.

The paper is organized as follows. Section 2 delineates the robot model treated here with an emphasis on its impact model and contact model. Section 3 presents the controlled outputs and extends the HZD-based feedback design for 3D bipedal robots. Section 4 summarizes the details of the optimization program including the parameterization of walking trajectories, the definition of the criterion and constraints, and the optimization realization. Section 5 provides the optimized walking data with a speed ranging from 0.2 m/s to 1.5 m/s. The paper is concluded in Section 6 with a discussion of the result and our future work.

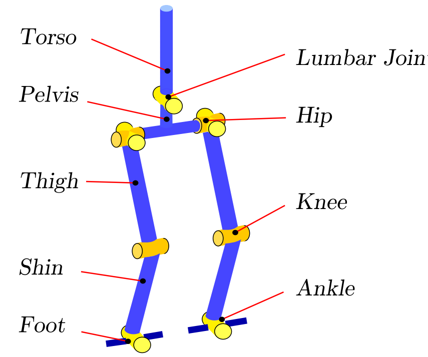

Fig. 1. Robot model configuration and definitions of joints and links.

Table 1
Model parameters for the 8-link 3D biped.

Link parameters	Thigh (f)	Shin (t)	Pelvis (p)	Torso (T)
Mass, m_* (kg)	3.936	2.227	7.882	18.793
Length, l_* (m)	0.403	0.403	0.089	0.605
Inertia, I_{*x} (m^2 kg)	0.054	0.030	0.060	0.486
Inertia, I_{*y} (m^2 kg)	0.054	0.030	0.040	0.418
Inertia, I_{*z} (m^2 kg)	0	0	0.059	0.145
CoM, p_* (m)	0.174	0.174	0	0.219

2. Robot model

2.1. Robot description and hypotheses

As depicted in Fig. 1, the 3D bipedal robot is modeled as a tree structure with two identical legs and a torso all connected to a single pelvis. It contains eight links: a torso, a pelvis, two thighs, two shins and two line-shaped massless feet. The robot model is strictly symmetric about the sagittal plane with the ankle joints locating in the center of the line feet. There are seven joints on the robot with each hip joint having two degrees of freedom (DOF) and the other joints all having one degree of freedom. The robot ankles only serve as pivots of coronal movements, and thus no yaw motion is permitted. The robot studied has a total mass of 39 kg and a total height of 1.5 m. The length of line foot l_{foot} is 0.15 m, the distance between two hips is 0.152 m, and the motor rotor inertia expressed on the joint side is 0.8 kg m^2 for all the actuated joints except the ankle joint. The rest of the model parameters are calculated from proportional virtual anthropomorphic structures automatically generated using the total mass and the total height [22,23]. These parameters are listed in Table 1. Among them, the CoMs (Center of Mass) of the thighs are measured in reference to the hips, the CoMs of the shins are located by their distances from the knees, the CoM of the pelvis is positioned by its vertical distance from the hip axis, and the CoM of the torso is defined by its distance from the lumbar joint. Due to the symmetries of the bodies, the matrices of inertia of all the links can be considered diagonal, which can be written as $\mathbf{I}_* = diag(I_{*x}, I_{*y}, I_{*z})$.

The line foot proposed here can serve as an underactuated pivot of sagittal movement while leaving the ankle joints handle the coronal movement. With this configuration, we can enumerate hypotheses for a class of 3D bipeds. It is important to note that the hypotheses in [11] are similar but they are only suitable for planar bipedal robots.