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An effective trajectory generation method for bipedal walking

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Abstract

This paper presents the virtual height inverted pendulum mode (VHIPM), which is a simple and effective trajectory generation method for the stable walking of biped robots. VHIPM, which is based on the inverted pendulum mode (IPM), can significantly reduce the zero moment point (ZMP) error by adjusting the height in the inverted pendulum. We show the relationship between VHIPM and other popular trajectory generation methods, and compare the ZMP errors in walking when trajectories are generated by various methods including VHIPM. We also investigate the sensitivity of the ZMP error in VHIPM to the step length, walking period and mass distribution of a robot. The simulation results show that VHIPM significantly reduces the ZMP errors compared to other methods under various circumstances.

Keywords: Biped robot; Walking motion; Zero moment point (ZMP); Inverted pendulum mode (IPM); Virtual height

1. Introduction

Humanoid robots have been a topic of great interest for a long time [1–12]. Since the introduction of P2 [1] and SDR-3X [2], greater interest has been drawn to humanoid robots. Among the various motions of a humanoid robot, the most basic and important motion is bipedal walking. Bipedal walking is probably the most appropriate way for robots to move around in a real environment. However, biped robots, which are complex nonlinear systems with many degrees of freedom, can fall down easily while walking due to its relatively small feet. Extensive researches have been conducted on bipedal walking, and now biped robots are capable of walking with a certain amount of stability. Yet, these biped robots still show a tendency for falling down as walking speed increases or when the mass distribution of the biped robot changes. Therefore, further studies need to be conducted on a trajectory generation method that is more robust to variations of walking speed and mass distribution of the biped robot.

Keeping the zero moment point (ZMP) of a biped robot inside a supporting foot can ensure that a biped robot can walk stably without falling down [14]. Several methods have been proposed to generate walking trajectories satisfying this condition.

The first method, which is called the multiple masses inverted pendulum mode (MMIPM) in [19], generates a walking trajectory by computing the ZMP equation of a robot model consisting of multiple point masses [17–19]. In MMIPM, it is important to choose a proper number of point masses, because it determines the complexity of the robot model and its modeling error. If there is a large number of point masses in a robot model, the modeling error can be small but the model becomes complex. Therefore, it takes a long time to generate a trajectory for walking motion by MMIPM, and it is not suitable for cases where there is a need to adjust the trajectory in real time.

The second method, which is called the inverted pendulum mode (IPM), generates walking motion from the dynamic equation of an inverted pendulum model with one mass at the center of gravity (CoG) [20–23]. IPM is simple and useful for robots with a heavy upper body, light legs and especially prismatic knee joints. However, robots actuated by electric motors usually have heavy legs and revolute knee joints. These differences can result in a large ZMP error. Although this ZMP error can be reduced by using the two masses inverted pendulum mode (TMIPM) [19] or the gravity-compensated inverted pendulum mode (GCIPM) [24], these error reductions

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are relatively small. Therefore, in order to further reduce the ZMP error, feedback control is necessary.

In addition, a walking trajectory can be generated by using a robot model with an unactuated ankle joint. The trajectory generated by this method has a stable ZMP trajectory which is near the center of the supporting foot. Since this method is based on robot dynamics, it requires long computational time in generating the walking trajectory with small ZMP error as in MMIPM [25–27]. In order to resolve this computational difficulty, robot dynamics was learned by a neural network in [28]. Another way to generate walking trajectories is by utilizing the motion data of human walking [29]. This trajectory can be quite efficient and stable if the mass distribution and motion mechanism of a biped robot are similar to those of human being. However, robots are quite different from humans. In order to use the motion data of human walking in a robot model, the motion data needs to be parameterized so that it can be suitable for the robot model [30,31].

In this paper, we propose a simple and effective method based on IPM, which we will call the virtual height inverted pendulum mode (VHIPM). In VHIPM, the walking trajectory is generated from the inverted pendulum model with a virtual height which is adjusted depending on the walking speed and mass distribution of the robot. Because the ZMP trajectory is mainly determined by the CoG trajectory, it is possible to reduce the ZMP error by simply modifying the height of the CoG in the inverted pendulum. In order to verify this, we investigate the influence of the CoG trajectory on the ZMP trajectory. The results show that VHIPM reduces the ZMP error during walking.

VHIPM has several advantages compared to other methods. First, VHIPM is simple, so it is suitable for generating trajectories for bipedal walking in real time. If it can be generated in real time, a robot might not fall down even if it is walking on uneven ground or the walking speed changes. Second, VHIPM can be applied to various types of robots because VHIPM only considers the CoG movement like IPM, and the ZMP error in VHIPM is much smaller than the ZMP error in IPM. Another advantage of VHIPM is that it is easy to solve the inverse kinematics problem for generating joint trajectories from the walking motion in Cartesian space.

This paper is organized as follows: Section 2 introduces a biped robot model and walking motion for bipedal walking. Section 3 describes VHIPM and determines the values of necessary parameters in VHIPM by simulation. In Section 4, we simulate the walking motions which are generated by various methods including VHIPM and compare the simulation results. Finally, conclusions follow in Section 5.

2. Robot model and walking motion

2.1. Robot model

Despite the fact that a human body is composed of numerous parts and has many degrees of freedom (DoFs), a human-like motion can be simply described by a model with 17 segments and 30 DoFs [32,33]. If we focus on only the leg motion, we can model the upper body as one segment, and the model has 8 segments and 17 DoFs [34]. Moreover, if the transverse plane motion is not considered, the model shall have 8 segments and 12 DoFs as shown in Fig. 1. In the figure, the positive direction of the x-axis corresponds to the robot's forward movement, the positive direction of the y-axis corresponds to the robot's movement to its left, and the positive direction of the z-axis is the opposite direction of gravity. In this model, the upper mass (m_8) is located at the end of the link l_8 and each of the other masses is located in the middle of its corresponding link. The parameters of the robot model were set as in [35] and are summarized in Table 1. The foot length and width are 200 mm and 80 mm respectively. Let (x_s, y_s, z_s) denote the position of

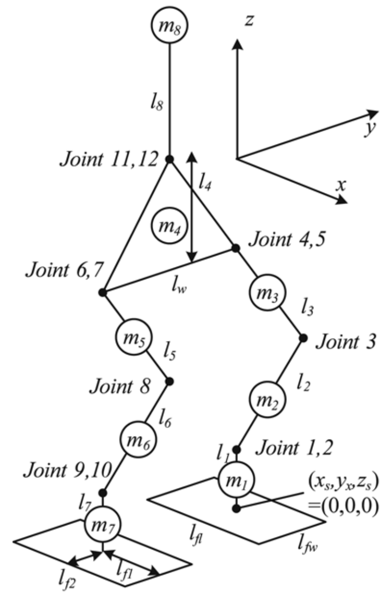

Fig. 1. 3D robot model with 8 segments and 12 DoFs.

Table 1
Parameters of the biped robot [35]

Parameter	Value
m_1	3.3 kg
m_2	5.7 kg
m_3	10.0 kg
m_4	13.0 kg
m_5	10.0 kg
m_6	5.7 kg
m_7	3.3 kg
m_8	30.0 kg
l_1	100 mm
l_2	300 mm
l_3	300 mm
l_4	100 mm
l_5	300 mm
l_6	300 mm
l_7	100 mm
l_8	250 mm
l_w	150 mm
l_{fl}	200 mm
l_{fw}	80 mm
l_{f1}	100 mm
l_{f2}	40 mm