

Walking on Different Slopes for NAO Humanoid Robot for an Open Loop Design

Dr. Bhavin C. Shah

Assistant Professor, Electronics & Telecommunications Department,
Atharva College Of Engineering, Malad-Marve Road, Charkop Naka, Malad (West),
Mumbai-400095, India
mr.bhavin@hotmail.com

Abstract— Dynamic gait planning for humanoid robots encounters difficulties such as stability, speed, and smoothness. In most of previous studies, joints' trajectories are calculated in 3D Cartesian space, then, introducing boundary conditions and using polynomials, the first and second derivatives of the motion are ensured to be continuous. Then, the stability of the motion is guaranteed using Zero Moment Point (ZMP) stability criterion. In this study, a trajectory planner is presented using the semi-ellipse equations of the motion; the continuity of the derivatives is preserved. Stabilization of motion is attained through using ZMP criterion and 3d inverted pendulum equations in three slope conditions. The effectiveness of the proposed approach is investigated using Webots software. Implementing proposed approach, smoothness, stability, and convenient speed (rather than 17 cm/s in flat condition) are achieved.

I. INTRODUCTION

Exciting challenge of the locomotion of the humanoid robots attracts many researchers [16]. Nonetheless, because of dynamical complexity, passive degree of freedom, changeability of kinematic structure, and repeatability of motion, humanoid robot locomotion is far from human locomotion. The well-known approach of Vukobratovic [19], called Zero Moment Point (ZMP), is one of the earliest and finest approaches to encounter the problem of biped robot locomotion. This approach was derived from the dynamical analysis of robot motion viewpoint. The term of ZMP refers to a point on the ground where the resultant moment caused by robot gravity and robot body inertia is vanishing [17]. This approach guarantees the dynamical balance of biped robot while the ZMP is located in the polygon that is formed by the feet on the ground, called support polygon [3],[4] The first ZMP-based 12-DOF biped robot, driven by hydraulic actuators, is developed by [1]. The linear inverted pendulum mode (LIPM) is introduced in [8] to calculate the COG trajectory analytically. In this method, the LIPM is used to generate the COG trajectory for a single support phase. Incorporating the ZMP based and the LIPM techniques, a novel walking pattern generation with arbitrary foot placements is proposed in [7]. Using the preview control approach of the ZMP, the exact multi body dynamics were calculated based on simple inverted pendulum method. The motion control of biped robots is investigated in [20]. Describing gait synthesis of biped locomotion as an optimization problem with the constraint,

[7] proposed a dynamically stable gait planning in slope surface. Furthermore, based on dynamic walking algorithm in [9], a several online controllers were used to deal with uneven and inclined ground by [10].

The concept of the ZMP is implemented on various famous robots as NAO provided by French company Aldebaran Robotics. Kulk and Welsh [11]. improved the speed, robustness, and efficiency through allowing the robot to settle into more natural gait by means of modifying the low-level positional controller. Using a simple inverted pendulum model, an implementation of omnidirectional walking is proposed in [15] in which a preview controller is applied to generate dynamically balanced center of mass trajectories. Incorporating a feedback controller with an online generated feet pattern to assure an stable gait, Czarnetzki, et al. [1] proposed a novel observer-based control system to achieve reactive motion generation for dynamic biped walking. Graf, et al. [4] present a COM-based closed- loop gait for the NAO robot, the torso pose of the robot is the underlying idea of the active balancing used in their approach. In this paper, a trajectory planning approach is proposed for NAO humanoid robot based on ZMP criterion using carttable model. The performance of the proposed approach is investigated in different slope conditions using Webots simulation environment.

II. METHODOLOGY

A. Robot Model:

Robot and its surrounding environment are simulated in Webots software which is able to simulate robots with industrial qualities in dynamical and physical aspect of view [12]. NAO is an autonomous, programmable and medium sized humanoid robot [3] that is developed by a French company, Aldebaran Robotics, in 2004 (as shown in Fig. 1). Sony's dog robot AIBO has been replaced by NAO in the RoboCup Standard Platform League (SPL) since 2008. The NAO RoboCup edition has 21 DOFs while the academic edition of it possesses 25 DOFs. The height and the weight of NAO are 58cm and 4.3kg, respectively.

B. Gait Planning:

Humanoid robot movement control is initiated with generating the joints' trajectories. The trajectory delivers the corresponding desired position at each instant time;

therefore, it commonly stated as a parametric time function. For determining this function, other implementation issues, such as time discretization, time derivatives, etc., should be considered. Trajectory planning of humanoid robots could be executed in joint space (directly designating the joint angles time evolution) or Cartesian space (designating the end effector position and orientation). The former planning procedure contributes the fast and simple solution by means of avoiding inverse kinematics problem in which indirect control of the end effector pose results in difficult collision avoiding. While in Cartesian space planning, external environment geometric constraints could be met more directly although inverse kinematics problem must be solved. In order to generate trajectories in Cartesian space, two stability criteria exist: static stability and dynamic stability. In static stability, neglecting the robot dynamics, the center of gravity (CoG) is considered as stability criterion. This assumption leads to restrict the applicability of this approach for slow motions of the robots. Consequently, most researchers applied dynamic stability in their studies. Center of pressure (CoP), Zero Moment Point (ZMP) [14], and Foot Rotator Indicator (FRI) [2] are the most common dynamic criteria. The ZMP criterion is adapted to synthesis humanoid gait. The underlying idea of the ZMP criterion states that while the ZMP is located in support polygon, the dynamically balanced walking of humanoid robot is guaranteed.

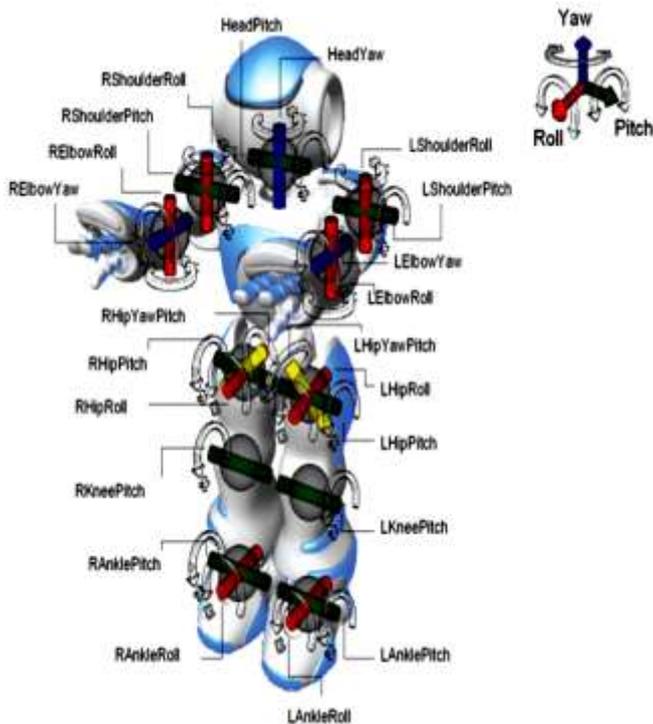


Fig. 1: NAO robot kinematic structure

The leg joints motions are determined using foot trajectories and inverse kinematics of the robot. So, being ZMP a function of joint's position, velocity, and acceleration results

in determining the feasible joint positions which satisfies the prescribed reference ZMP in the ZMP based walking trajectory generation. The prescribed reference ZMP will be satisfied by the support foot motion whereas the swing foot motion will be designed independently from the ZMP equations in the Cartesian space. Support leg and swing leg are considered as two manipulators in the gait generation. Consequently, the humanoid gait generation could be viewed as manipulator trajectory generation. In walking phases (double support and single support), the hip is the base frame and the ankle is the end effector for each foot. Fig. 2 depicts swing and support states of legs in base frames, respectively. The double support phase of the walking cycle is crucial due to its effect on increasing the stability of walking and reducing the impact between the swing leg and the ground although it is only about 20 percent of walking cycle [5].

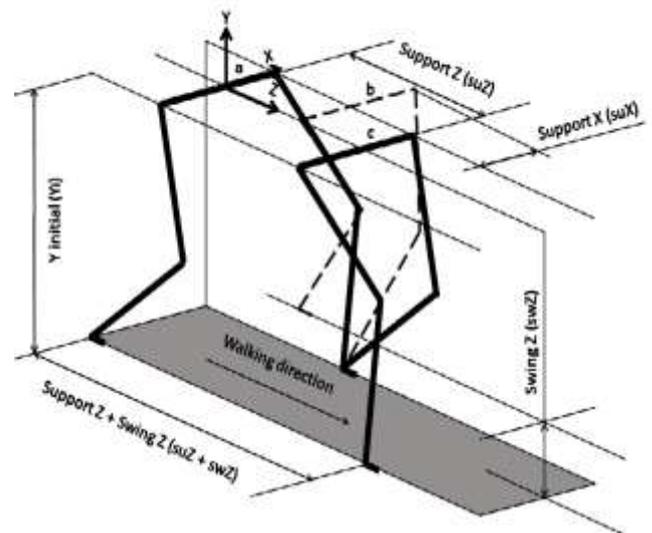


Fig. 2: Swing and support legs states in a step. Conditions a, b, and c, illustrate three states of double support, middle of single support, and double support phases.

The trajectories must have 1st-order and 2nd-order derivative continuities. The 1st-order derivative continuity implies the joint smooth velocity, while the 2nd-order derivative continuity guarantees the joint smooth acceleration or torque. Besides, it can be proved that the 1th-order and 2nd-order derivative continuities in Cartesian space can guarantee the 1th-order and 2nd-order derivative continuities in joint space and vice versa, because the transformation from one space to another is a one-to-one mapping. In other words, any trajectory generation in Cartesian space has to convert to joint space to control each joint. Because of considering overall dynamics of the robot, Vukobratovic proposed ZMP equations suffer from complexity and intensive computations [17]. Kajita simplified the ZMP equations by introducing a cart-table model based on the ZMP and the inverted pendulum approach [7]. The 2-D cart-table model is illustrated in Fig.

3. As shown in Fig. 3, the robot is assumed to be a point mass, and the center of mass (COM) height is considered to be constant in the forward movement of the robot.

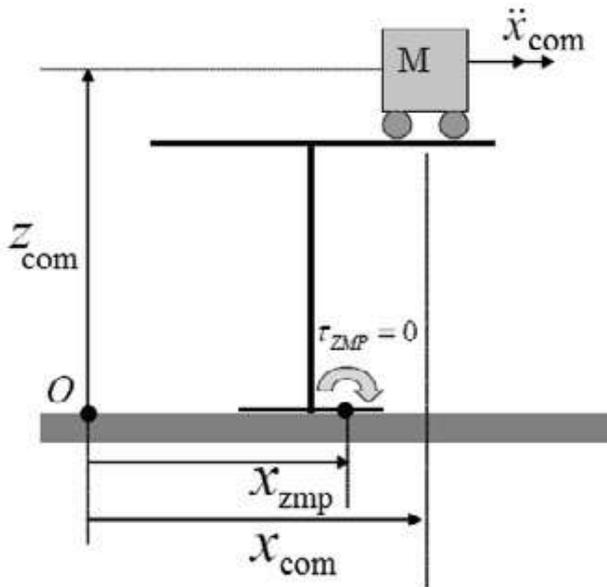


Fig. 3: Kajita's cart-table model

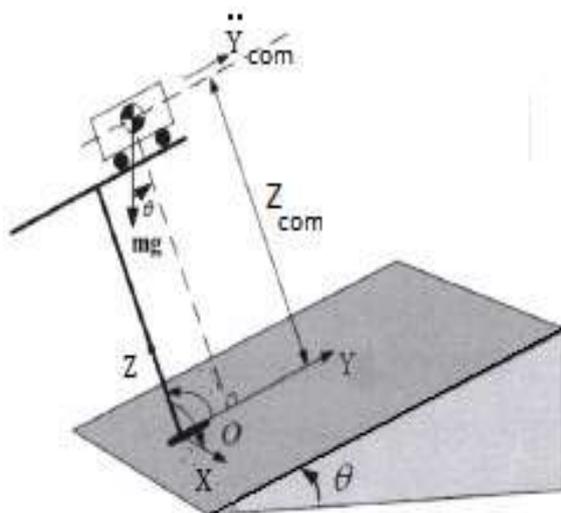


Fig. 4: Cart-table model in slope condition

In case of flat terrain, the 3-D model has been simplified into two separated 2-D models, whereas in case of slope terrain, the variable height of COM causes difficulties in decoupling the frontal and sagittal motion. In [6], a new frame is attached to the slope and assumed that the slope has constant height (as shown in Fig. 4). Obviously, the COM is translating in parallel manner with respect to the slope.

III. SIMULATION RESULTS

In this section, the results of the proposed trajectory planner are discussed through simulations on NAO robot using

Webots robotics simulator. The Webots simulator is based on ODE (open dynamic engine), an open source physics engine for simulating 3-D rigid body dynamics [13]. The simulations are executed on a 2.4 GHz core Duo 2 machine with the 3 GB of physical memory and 3 MB of cache memory.

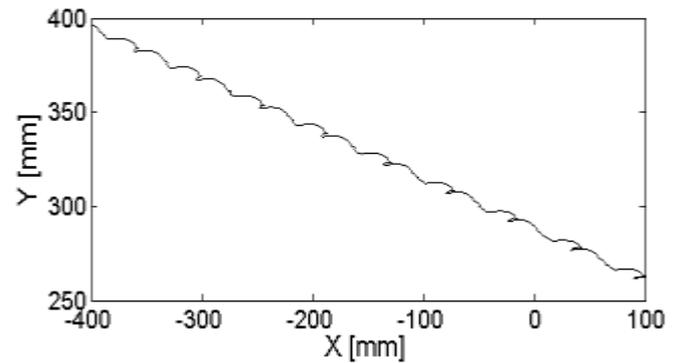


Fig. 5: CoM Height in negative slope condition

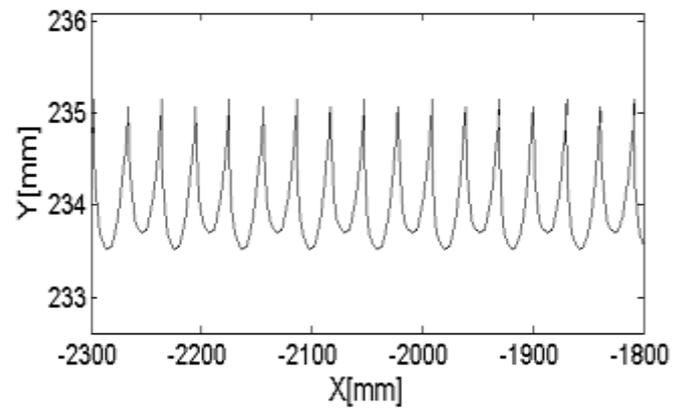


Fig. 6: CoM height in flat condition

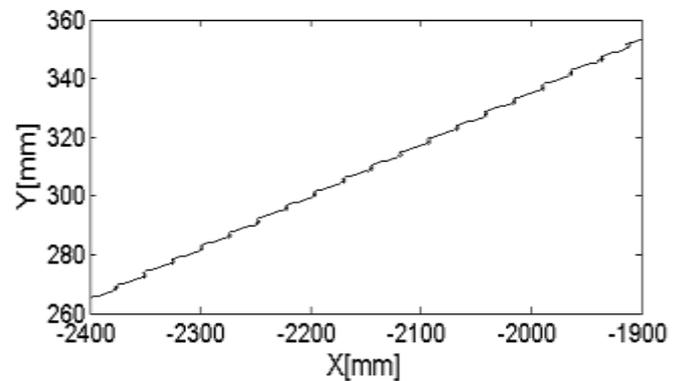


Fig. 7: CoM height in positive slope condition

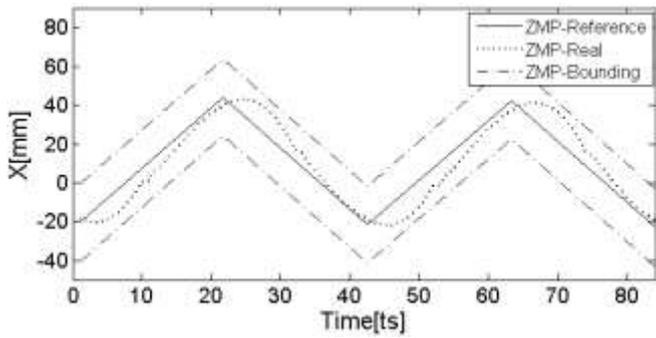


Fig. 8: x-direction ZMP in negative slope condition

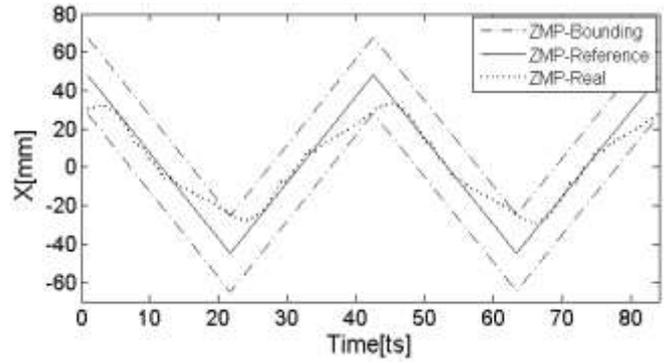


Fig. 12: x-direction ZMP in positive slope condition

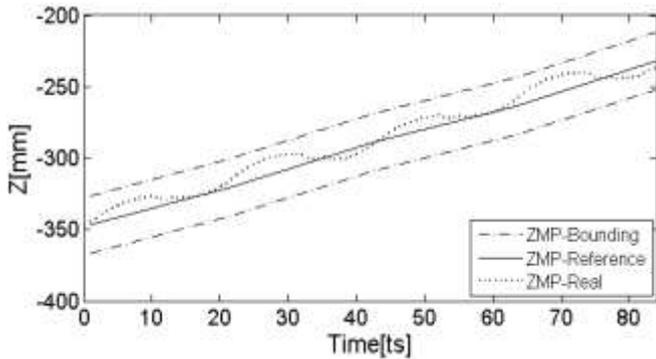


Fig. 9: z-direction ZMP in negative slope condition

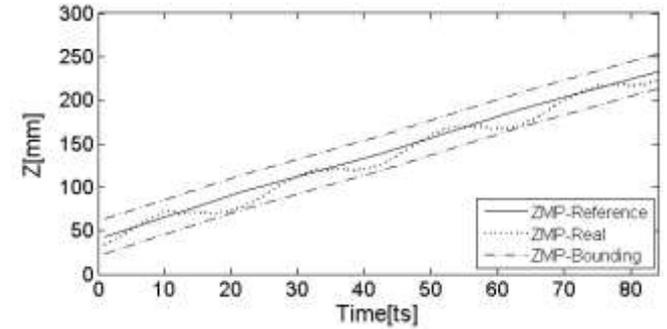


Fig. 13: z-direction ZMP in positive slope condition

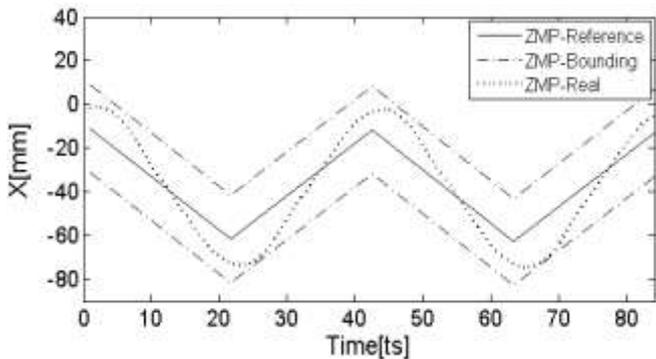


Fig. 10: x-direction ZMP in flat condition

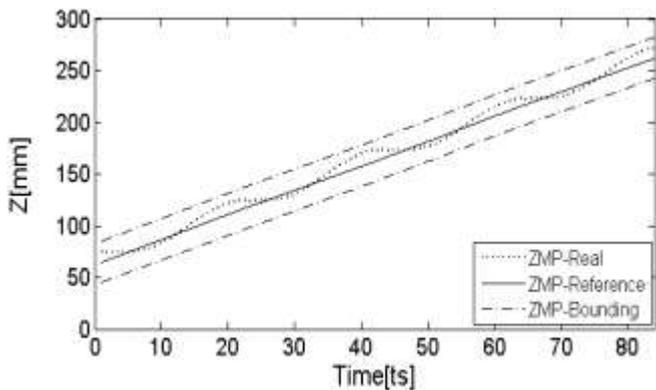


Fig. 11: z-direction ZMP in flat condition

IV. CONCLUSION

In this paper, a trajectory planner proposed to attain a dynamic walking for NAO humanoid robot in three slope conditions. Initially, ankle joint paths (in other words, equations of motion) are fully developed in all three conditions. Swing and support legs are considered two manipulators. Also, the path of each ankle is based on a semi-ellipse equation in the bases frames. The continuity of the first and second derivatives of motion is ensured by means of semi-ellipse path choice. Finally, using ZMP stability criterion and 3D inverted pendulum model, the generated paths are stabilized. The performance of the proposed approach is evaluated through simulation in Webots software. Results indicate that the desirable properties of dynamic stability, smooth motion, and satisfying speed are achieved in all three conditions.

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