Anthropomorphic robot modelling with virtual height inverted pendulum approach in Simulink: step length and robot height influence on walking stability.

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Abstract

Humanoid stable walking is a complex task due the high number of degrees of freedom, system nonlinearity and relatively small size of robot footprint. Biped robots tend to fall down as walking speed increases or when the terrain conditions change. This paper presents dynamically stable walking modelling of Russian humanoid AR-601M in Simulink environment with virtual height inverted pendulum model (VHIPM), an effective and simple trajectory generation method based on inverted pendulum model (IPM). This algorithm adjusts height of the center of mass in IPM model to reduce ZMP error and guarantees stable locomotion up to some critical speed. We investigate influence of the step length and step period on walking stability. Maximum torque values in leg joints are estimated in order to verify if such trajectories are attainable by robot motors. We demonstrate that the robot model is capable to achieve significant walking speeds on flat surfaces using this method.

Keywords: bipedal robot, dynamic stability, Simulink, AR-601M robot

1. Introduction

Humanoid robot design and locomotion are currently among of the most exciting and challenging research topics in robotics. Over the last decades, a number of successful approaches for stable bipedal robot walking have been developed.[1] The multi-functionality and high flexibility of anthropomorphic design, abilities of a humanoid robot to replace a human in various practical operations and human-robot interaction scenarios provide good motivation for such research activities.

To ensure walking stability, the majority of modern humanoid robots employ analytical methods, which are based on locomotion dynamics and usually apply some particular stability constraints. One of the most common stability constraints is the Zero Moment Point (ZMP).[2] In order to simplify equations deriving, ZMP criteria could be applied for walking reference trajectory generation together with a simplified robot model, such as Linear Inverted Pendulum Model (LIPM).[3] However, LIPM model does not consider full body dynamics. This causes ZMP errors, which may become critical for a given walking speed. To deal with this problem, the authors in Ref. 4 suggested a novel simplified robot model which was called a Virtual Height Inverted Pendulum Model (VHIPM): the authors experimentally demonstrated[4] that the ZMP error could be significantly reduced by varying the height of Center of Mass (CoM) in LIPM model.

This paper suggests the VHIPM application for modeling of Russian anthropomorphic robot AR-601M in MATLAB/Simulink environment. We find maximal speed of AR-601M stable walking and next calculate torques in the robot joints to provide such locomotion. The rest of the paper is organized as following. Section 2 presents the robot and its Simulink model. Section 3 describes the process of walking trajectory generation, followed by simulation results within Section 4. Finally, we conclude in Section 5.

2. The Biped Model

We have constructed 41 degrees of freedom (DoF) model of AR-601M robot; however, only 12 joints (6 DoF in each pedipulator) are active during the robot locomotion. Three joint axes are in the hip, two joints are at the ankle and one in the knee. Mass and size parameters of the robot pedipulators are given in Table 1. Total mass of the robot is 65 kg. Figure 1 demonstrates the robot simulation in MATLAB/Simulink environment.

Table 1. Mass and size parameters of the pedipulators.

Link	Size parameters (mm)	Mass (kg)
Thigh	Length : 280	7.5
Shank	Length : 280	6.9
Foot	L×W×H: 254×160×106	3.2

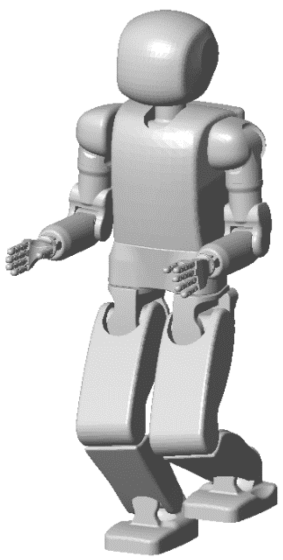

Fig. 1. A snapshot from animation window in MATLAB/Simulink environment

Complete 3-D simulation of multibody dynamics was performed using variable step period implicit solver (ODE 23t*) of MATLAB SimMechanics Toolbox. We modelled the robot feet ground contact with nonlinear spring-damper method[5], where normal and friction forces are calculated according to Eq. (1) – Eq. (2) respectively:

$$F_n = k_n z + b_n z\dot{z} \quad (1)$$
$$F_t = b_t z\dot{x}, \quad F_t \leq \mu F_n \quad (2)$$

where k_n, b_n, b_t and μ are contact force parameters. The details of the contact model can be found in Ref. 6 which presents the previous work of the authors.

3. Walking Trajectory Generation

Robot locomotion could be considered as a repetition of a single step motion[7]. We calculated walking trajectory under the following assumptions, which are widely applied in experimental approaches for biped walking[8]:

(i) The swing foot is parallel to the ground

(ii) The upper body is always kept upright

(iii) CoM of the robot model is moving at the constant height

(iv) The swing foot is moving in a cycloid trajectory and its coordinates can be described with the following equations:

$$y(t) = -S\cos(\tfrac{\pi t}{T}) \quad (3)$$
$$z(t) = 0.5H\,(1 - \cos(\tfrac{2\pi t}{T})) \quad (4)$$
$$x(t) = x_0 \quad (5)$$

where S is a single step length, H is a step height, T is a step period, x_0 is a distance between two feet in x direction. In Ref. 4 authors showed that equations for CoM trajectory can be expressed as:

$$\ddot{x}_{CoM} - \frac{g}{\alpha z_{CoM}} x_{CoM} = 0 \quad (6)$$

$$\ddot{y}_{CoM} - \frac{g}{\beta z_{CoM}} y_{CoM} = 0 \quad (7)$$

where coefficients α and β are found experimentally to reduce ZMP error. Therefore, we have following trajectories for CoM point of the robot:

$$x(t) = C_1 e^{-w_1 t} + C_2 e^{w_1 t},\ w_1 = \sqrt{\frac{g}{\alpha z_{CoM}}} \quad (8)$$
$$y(t) = D_1 e^{-w_2 t} + D_2 e^{w_2 t},\ w_2 = \sqrt{\frac{g}{\beta z_{CoM}}} \quad (9)$$

where C_1, C_2, D_1 and D_2 coefficients are found from initial and final values of CoM coordinates. After we define translational and rotational coordinates for the body and the swing foot, the joint angle trajectories are obtained from inverse kinematics problem solution.

Such trajectory assumes that robot has initial velocity. To move robot from resting state we first calculate trajectory with a short step length and then gradually increase it (to maximal value) until ZMP errors become critical and the robot falls down.

4. Simulation Results

This section considers a walking trajectory which is described with the listed in Table 2 parameters.

Table 2. Simulation parameters

Parameter	Value
Step height	0.1 m
Step period	0.5 sec
CoM height	0.75 m
Step length	0.1 m – max. value

First, we estimated maximal speed of the robot model that could be achieved using LIPM method. We define robot's walking trial as "stable" if the robot successfully executes a sequence of 100 steps. After each stable walking trial we increase step length by 0.05 m and verify robot's walking again. The process of step increase was repeated until the robot failed to execute a successful stable walking trial.

Simulations demonstrated that maximum step length at which the robot could perform stable walking is 0.95 m, which corresponds to 0.95 m/s walking speed. CoM forward velocity value is shown in Fig 2.

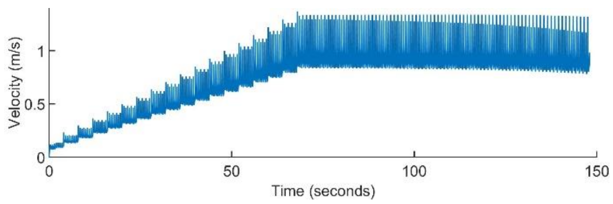

Fig. 2. Robot velocity in LIPM method

Figures 3-4 demonstrate ZMP coordinates for a step of 0.95 m length. Support foot center corresponds to (0,0) coordinate. According to the calculated values, we have approximately 2.5 cm error for X coordinate and 10 cm error for Y coordinate just after a single step.

Next, we vary α and β coefficients in Eq. (6) and (7) around 1 in order to minimize ZMP errors. Figures 5-6 show the dependence of maximal error of ZMP coordinate on α for x-coordinate and on β for y-coordinate. It was empirically detected that for x-coordinate optimal value of coefficient α is equal to 1, for y-coordinate optimal β should lie within [0.7, 0.8] interval. Walking simulation with these coefficients showed that such optimization of trajectories allows to increase maximal step length from 0.95 m to 1.1 m and to achieve a maximal speed of 1.1 m/s accordingly while keeping stable walking for at least 100 sequential steps.

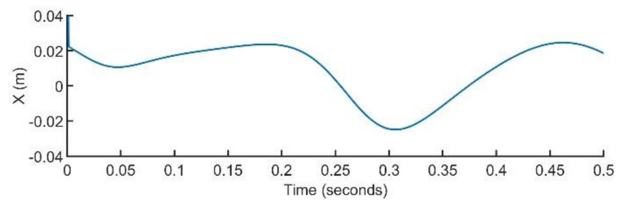

Fig. 3. ZMP x coordinate

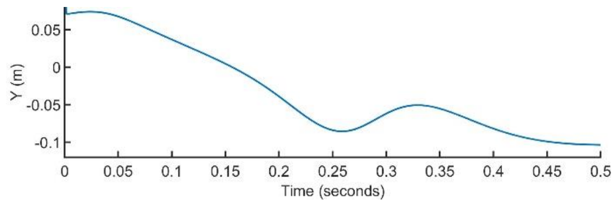

Fig. 4. ZMP y coordinate

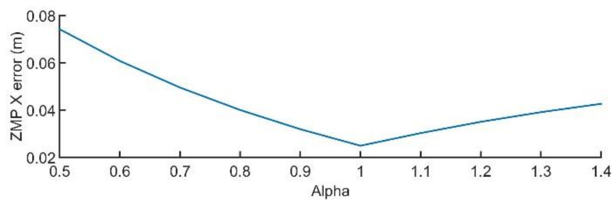

Fig. 5. Dependence of ZMP x coordinate error on alpha

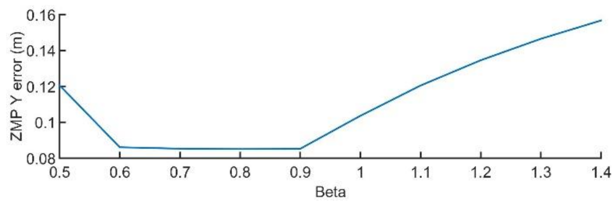

Fig. 6. Dependence of ZMP y coordinate error on beta

Finally, we estimated the peak torque value in ankle and knee joints that the robot motors should generate in order to afford the robot locomotion according to the calculated trajectory. Figures 7 and 8 show the calculated torque values for the ankle and the knee joints respectively.

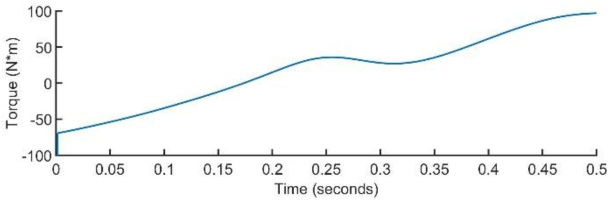

Fig. 7. Torque value in ankle joint

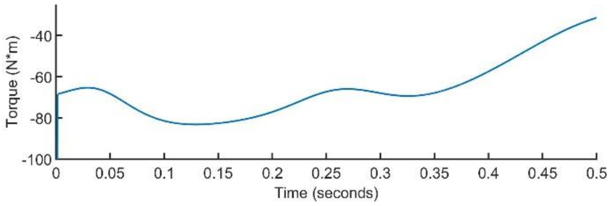

Fig. 8. Torque value in knee joint

The maximal value is approximately 100 N*m for the ankle and 80 N*m for the knee joint. With regard to the technical specifications of real AR601-M robot, its motors can generate maximal values of 50 N*m for the knee and 20 N*m for the ankle joint. Unfortunately, this means that such high maximal speeds could not be achieved for the real robot. Therefore, we are limited to use trajectories with lower maximum speed, which are dynamically stable according to simulations.

5. Conclusions

This paper presents a biped walking robot AR601-M trajectory reference generation algorithm based on ZMP approach with Linear Inverted Pendulum Model (LIPM) and Virtual Height Inverted Pendulum Model (VHIPM) methods. Simulations in MATLAB/Simulink environment indicated significantly better performance of VHIPM method when compared with LIPM method. We investigated in depth the influence of the step length and step period on walking stability. In general, proper coefficients selection with a help of simulation for each particular robot model affords to achieve maximal walking speed for stable locomotion. The resulting torque values in the knee and the ankle joints could be calculated for such maximal walking speed and next verified against the technical capabilities of the real robot joint motors. Unfortunately, in our case the maximal speed of stable locomotion that was successfully demonstrated in the flat surface walking simulation turned out to be unfeasible for AR601-M robot due to the limited capabilities of its joint motors. However, the knowledge of the theoretically possible speed within a simulation and the robot motors specifications give a good hint for the real achievable speed. As a part of our future work, we are going to implement the presented in this paper algorithms on AR601-M robot and verify that it could perform stable locomotion and achieve the calculated through simulations peak walking speed.

6. Acknowledgements

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