Virtual Spring Mass Damper based Posture Balance Controller for Humanoid Robots

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***Abstract*—In this paper, a posture balance controller for humanoid robot has been proposed. The humanoid robot is modeled as Linear Inverted Pendulum attached to a virtual spring mass damper (SMD) system. The additional virtual SMD system provides flexibility to directly control the center of mass (CoM) position in presence of the external push disturbance hence maintaining desired posture and balance. Approximate model parameters i.e, spring and damping constants have been identified using system identification technique. A state feedback controller has been designed which provides a reactive force cancellation against external push disturbance acting on the humanoid robot resulting in effective posture and stable balance. The efficacy of the presented controller is shown through numerical and multibody simulations based on NAO humanoid robot.**

Keywords—Linear Inverted Pendulum Model (LIPM), State Feedback Controller (SFC), Posture Balance Controller, NAO

I. INTRODUCTION

In the transformative journey of mobile robots that can work in human-centric environments, humanoid robots set a cornerstone to it. Humanoid offers high dexterity and mobility similar to humans to a great extent making them capable to work in environments designed for humans. Gait pattern generation and designing of control system for these fascinating machine becomes a major challenge due to nonlinearities and high degrees of freedom [1], [2]. The complexity involved with these machines has attracted many researchers towards this area.

Humanoid robot gait pattern generation and control based on LIPM model have been widely addressed in the literature [2]–[4]. Several other simplified models have also been studied in detail e.g. inverted pendulum (IP) model [5], nonlinear LIPM (NLIPM) [4], LIPM with flywheel [6], table-cart model [7], three-mass inverted pendulum model [8] and inverted pendulum with spring mass [9]. In real life scenario, maintaining stability while walking is a prime concern. Various stabilization controllers [10], [11], [7] have been proposed in the literature. In [12], a balance control combining offline pattern with real-time modification of the joint space trajectories has been proposed. Humanoid stabilization based on the linear inverted pendulum tracking based balance control is presented in [10]. Posture and walking control based on the zero moment point (ZMP) and center of mass (CoM) for

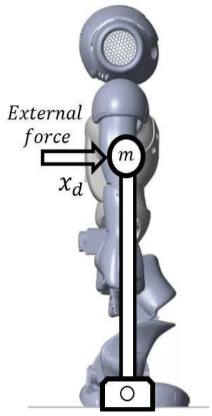

Fig. 1: Simplified LIPM modeling of NAO humanoid robot

humanoid robot has been presented in [7], wherein the authors have presented experimental results of the humanoid robot proving efficacy of the controller. Similarly, in [11], authors presented CoM+ZMP regulator based stabilization controller. A model predictive control based posture control handling the external disturbances acting on the humanoid robot has been proposed in [13]. In recent work capture point (CP) has attained attention of the researchers. Concept of the capture point for push recovery of humanoid robots has been proposed in [6]. Capture point based balance and walking control for humanoid robots have been proposed in [6], [14], [15]. In [16] the concept of the capture point has been extended to center of mass in nonlinear framework. A state feedback and observer based posture controller for biped robot has been proposed in [9].

The external disturbances like push disturbance as well as non-uniform distribution of the contact forces lead to posture instability in humanoid robots. One way to address this issue is to estimate the effect of the external disturbance and cancel the same [17]–[20]. In [21] and [22], the authors have proposed a robust CoM trajectory tracking controller for humanoid robot wherein the disturbance acting on the robot is estimated using an uncertainty and disturbance estimation (UDE) technique and cancelled through the controller.

Most of the existing literature enhances the humanoid disturbance handling capability by controlling CoM of the robot through ZMP control or CP based stepping strategy. In contrast, this work aims to enhance humanoid disturbance handling capability by adding a virtual system to the LIPM representation. This additional virtual system provides flexibility of directly controlling the center of mass position of the humanoid robot in presence of external push disturbance acting at the center of mass of the robot and hence maintaining the desired posture and balance. The controller provides a restoring torque in order to follow the desired trajectory. The proposed control law employs a state feedback controller for the desired trajectory tracking.

The paper is organized as follows: System modeling and identification is presented in Section II whereas Section III presents the proposed balance and walking control design based on the virtual system. The closed loop stability proof of the proposed controller has been discussed in Section IV. Section V presents numerical as well as multi-physics simulation results for *NAO* humanoid. Finally, Section VI concludes this work.

II. System Modelling and Identification

A. System Modelling

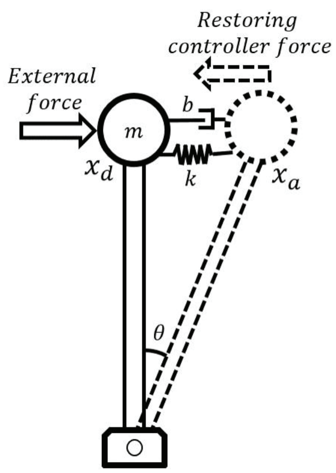

Fig. 2: Simplified LIPM with virtual spring-mass-damper of NAO humanoid robot

In this work, NAO humanoid robot has been modeled as a simplified Linear Inverted Pendulum (LIPM) model [1]–[4] as shown in Figs. 1 and 2. The LIPM model uses the following assumptions:

- Robot's center of mass corresponds to a point mass
- Center of Mass (CoM) height is constant
- Pendulum's base joint is torque free

Above assumptions simplify the model e.g. first and second assumption decouple the system dynamics in sagittal and transverse plane in terms of the state variables x and y. The overall analysis is carried out only for sagittal plane which is a vertical plane that divide the humanoid body into left and right sections. The external forces and disturbances are applied to the point mass of the LIPM model as shown in Fig. 2. The LIPM is then attached to the translational virtual spring-mass-damper (SMD) system and becomes basis of the proposed controller design. Next, considering only the SMD system, the equation of motion is written as

$$m\ddot{x} + b\dot{x} + kx = u \tag{1}$$

where u is the applied force, m is the mass and b and k are the damping and spring constants respectively. Rearranging (1) as,

$$\ddot{x} = \frac{u}{m} - \frac{b}{m}\dot{x} - \frac{k}{m}x \tag{2}$$

Hence, (2) can be written in state space form as,

$$\begin{bmatrix} \dot{x} \\ \ddot{x} \end{bmatrix} = \begin{bmatrix} 0 & 1 \\ -\frac{k}{m} & -\frac{b}{m} \end{bmatrix} \begin{bmatrix} x \\ \dot{x} \end{bmatrix} + \begin{bmatrix} 0 \\ \frac{1}{m} \end{bmatrix} u$$

$$y = [1\ 0] \begin{bmatrix} x \\ \dot{x} \end{bmatrix} \tag{3}$$

B. System Identification

To identify the system parameters i.e., damping and spring constants, system identification technique has been used. The standing NAO humanoid robot modeled as a multi-physics system is discussed in Section V-B is pushed slightly in positive x-direction at $t = 1$ sec. The free vibration response of CoM of robot in sagittal plane is shown in Fig. 3.

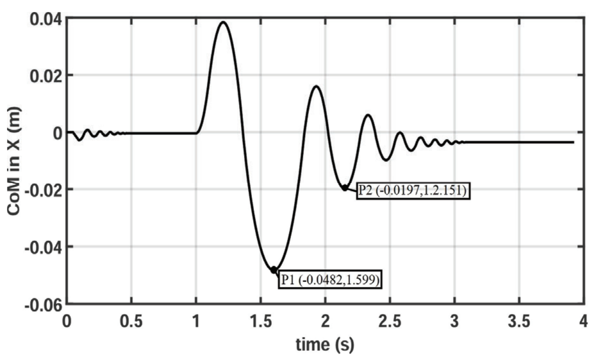

Fig. 3: Vibration response of CoM of robot in sagittal plane

The analytic solution of a second order system represented by (1) is given by

$$x(t) = Ae^{-\xi\omega_n t}\sin(\omega_d t + \varphi) \quad (4)$$

where

$$\omega_d = \omega_n\sqrt{1-\xi^2}$$

$$\omega_n = \sqrt{\frac{k}{m}}$$

$$\xi = \frac{b}{2m\omega_n}$$

From Fig. 3, it can be seen that the two peaks P_1 and P_2 have the magnitude −0.0482 m and −0.0197 m at the time

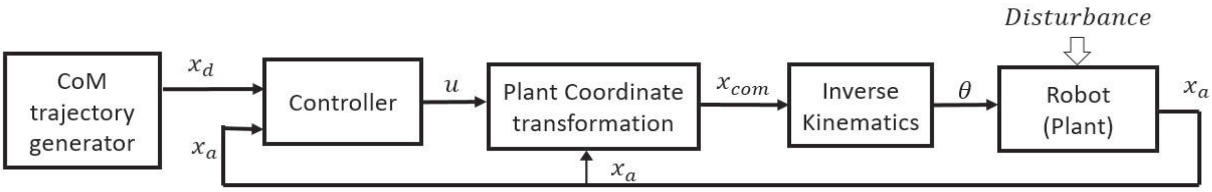

Fig. 4: Block schematic of the proposed control scheme

instants t_1 = 1.599 sec and t_2 = 2.151 sec respectively. Using the peak values, logarithmic decrement is calculated as

$$\delta = \ln\frac{|x_1|}{|x_2|} \quad (5)$$

Using logarithmic decrement from (5), one can find the damping ratio of the virtual system of (1) as,

$$\xi = \frac{\delta}{\sqrt{(2\pi)^2+\delta^2}} \quad (6)$$

Using (6), the damped natural frequency of (1) is calculated as,

$$\omega_d = \frac{2\pi}{T_d} \quad (7)$$

The undamped natural frequency is given by (8) below,

$$\omega_d = \omega_n\sqrt{1-\xi^2} \quad (8)$$

Considering approximate mass of the NAO humanoid robot as 6 *kg* and substituting these values in (4), one gets

$$k = m\omega_n^2 = 809.0947\ N/m$$

$$b = 2m\xi\omega_n = 19.6429\ Ns/m$$

The LIPM with virtual spring-mass-damper of (1) is used for robust balance controller design as discussed in the next section.

III. Controller Design

The main idea in controller design is to exert a restoring force on CoM of the robot against the external disturbance forces as shown in Fig. 2. The restoring force in (1) becomes the control input. The block diagram of the overall closed loop system has been shown in Fig. 4. Considering the plant dynamics of (2) and denoting x_d and x_a is the desired CoM and actual CoM position respectively, the control law is obtained as,

$$u = mv + b\dot{x}_a + kx_a \quad (9)$$

where,

$$v = \ddot{x}_d + K_d(\dot{x}_d - \dot{x}_a) + K_p(x_d - x_a) \quad (10)$$

where, K_p and K_d are gains of the controller (10).

IV. Close Loop Stability Analysis

This section presents the closed loop stability of the overall system. Substituting the control law (9) in the plant dynamics represented by (1), we get,

$$m\ddot{x}_a + b\dot{x}_a + kx_a = mv + b\dot{x}_a + kx_a \quad (11)$$

Rearranging and solving (11), we get,

$$\ddot{e} + K_d\dot{e} + K_p e = 0 \quad (12)$$

where, e is CoM tracking error i.e, $(x_d - x_a)$ Taking Laplace transform of (12), we get,

$$(s^2 + K_d s + K_p)E(s) = 0 \quad (13)$$

If one choose, $K_p > 0$ and $K_d > 0$, it can be assured that the poles of the characteristic equation (13) are on left half of the s-plane. From (12), one can conclude that the error dynamics of (13) is asymptotically stable assuring error convergence.

V. Simulation Results

In this experiment, Aldebran's NAO humanoid robot has been considered for simulation purpose. The approximate model parameters have been identified and discussed in section II-B. The proposed controller is initially verified through numerical simulations and then implemented and verified through multibody simulation for two cases. In the first case, the robot is standing and is subjected to external push. While in the second case, the controller performance is tested during walking.

A. Numerical Simulation

The NAO robot [23], [24] has been modeled as LIPM model with mass, $m = 6\, kg$ and length, $l = 0.32\, m$. The gains of the controller (9) and (10) are found out by considering the time constant of the controller as, $t_c = 0.15$ s, the resulting gain values are $K_p = 711.11$ and $K_d = 53.33$. The desired posture in this case is standing posture hence the desired CoM is at zero. The model is subjected to a sinusoidal disturbance of magnitude $0.05 \sin(t)\, m$ acting at the center of mass of the LIPM in x-direction. Figs. 5 and 6 show controller performance in trajectory tracking with and without the controller respectively. Fig.7 shows a comparative restoring controller force with time and its effect on the CoM position.

B. Multibody Simulation: Standing Case

Next the controller of (9) and (10) has been implemented for NAO multibody simulation subjected to the same disturbance as presented in the case of numerical simulation. In contrast to Fig. 8, Fig. 9 shows the performance of the controller in suppressing the disturbance acting on CoM and stabilizing the humanoid robot. Fig 10 shows a comparative restoring controller force with time and its effect on the CoM position. Fig. 11 show snippet of NAO standing multibody simulation. It is observed that in absence of stabilizing controller if the disturbance is increased to $0.07m$, the robot falls whereas the robot with proposed controller withstand the external disturbance.

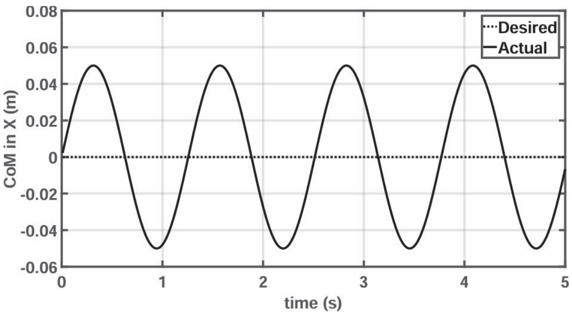

Fig. 5: Desired vs Actual CoM position without controller

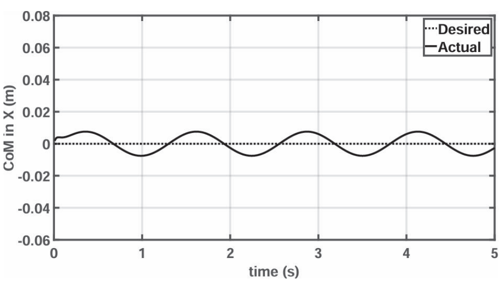

Fig. 6: Desired vs Actual CoM position with the controller

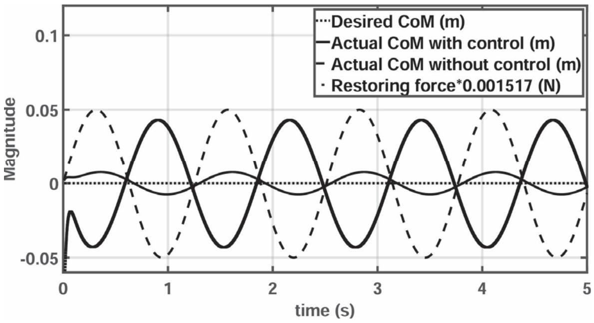

Fig. 7: Controller restoring force and its effect on CoM position

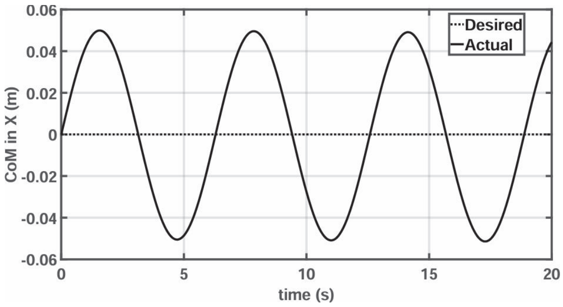

Fig. 8: Desired vs Actual CoM position without controller (Multibody Simulation)

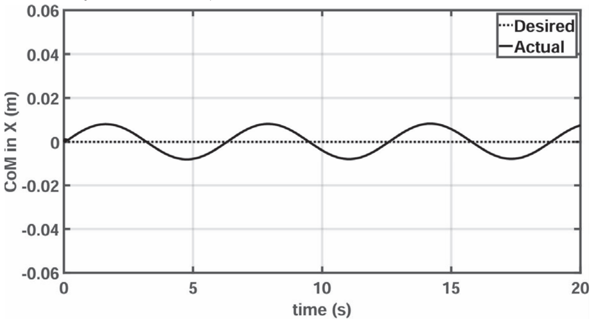

Fig. 9: Desired vs Actual CoM position with the controller (Multibody Simulation)

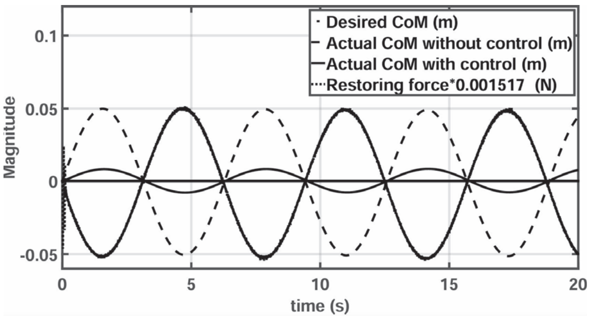

Fig. 10: Controller restoring force and its effect on CoM position (Multibody Simulation)

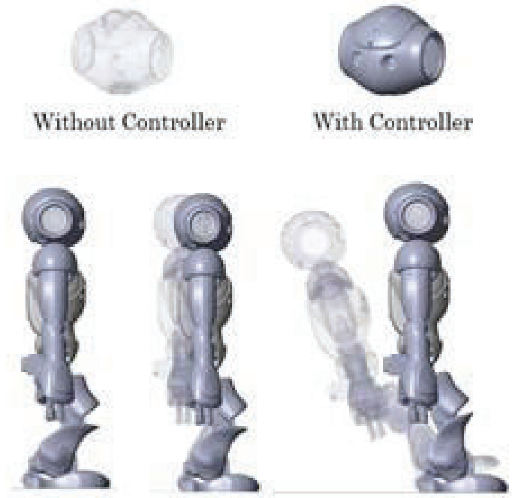

Fig. 11: Controller performance in terms of CoM position

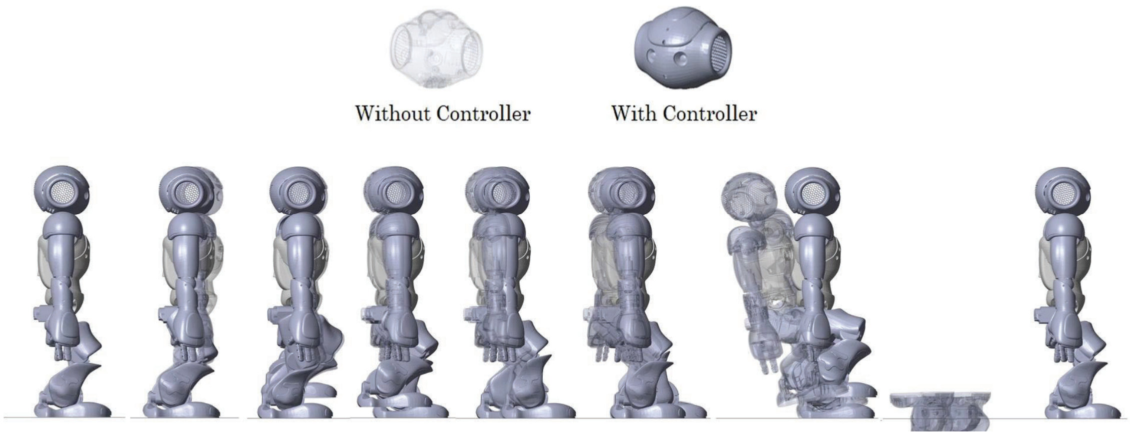

Fig. 12: Snippets of NAO walking in presence of external disturbance

C. Multibody Simulation: Walking Case

The proposed controller has been implemented over NAO multibody simulation while walking. In this case the sinusoidally varying disturbance of magnitude $0.06\,m$ has been applied. Fig. 13 and 14 shows CoM positions in x, y directions. Fig 12 shows snippet of NAO multibody simulation while walking. It can be seen, the humanoid robot is able to walk in presence of external disturbance with the proposed controller.

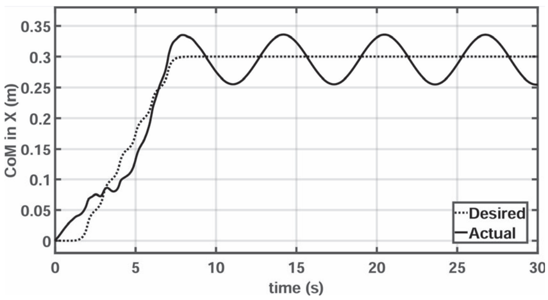

Fig. 13: CoM position of NAO in X direction

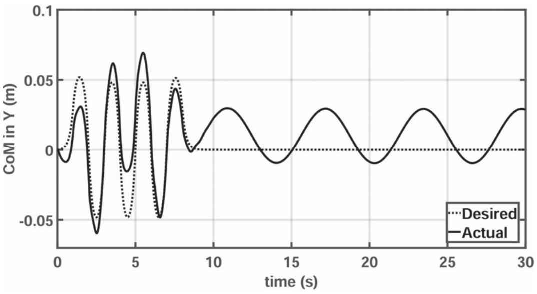

Fig. 14: CoM position of NAO in *Y* direction

VI. CONCLUSION

In this work, a spring-mass-damper based posture balance controller has been presented. The humanoid robot is initially modeled as a linear inverted pendulum with attached virtual spring-mass-damper system. A second order state feedback controller has been designed. The efficacy of the presented controller is shown using numerical and multibody simulation on Aldebran's NAO humanoid robot. The presented posture balance control is effective in handling external push and disturbances.

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