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Disturbance Estimation based Robust Center of Mass Tracking Control of Humanoid Robot

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Abstract: This paper presents a novel design based on disturbance estimation and rejection for robust balance and walking control of humanoid robot. A state-feedback control (SFC) law is designed for trajectory tracking of the center of mass (CoM) of a 3−D linear inverted pendulum model (3D-LIPM) of humanoid robot. To achieve robustness i.e. to cancle the effects of disturbance, the control law is augmented with the Uncertainty and Disturbance Estimator (UDE) based estimate of the disturbance. Next, stability of the close loop system is analysed. The effectiveness of the UDE augmented state feedback controller in estimating the disturbances as well as tracking is validated through the simulations.

Keywords: robust control, uncertainty and disturbance estimation, UDE, humanoid robot.

1. INTRODUCTION

Balance and walking control of humanoid robots is an active area of research due to challenges like more number of degrees of freedom, non-linear dynamics as well as coupling. To design balance and walking control algorithms for biped humanoid robots, several simplified dynamic models have been proposed in the literature. Inverted pendulum model represents one such simplified and computationally efficient model that has been widely used Hemami (1977) in the literature. As the dynamics of inverted pendulum is nonlinear, it has been later modified by constraining the CoM height to the horizontal plane resulting in a Linear Inverted Pendulum Model (LIPM) Kajita (1991). In Kajita et al. (2001), the authors have extended the LIPM model and proposed a 3D Linear Inverted Pendulum Model (3D-LIPM) for the generation of real time walking patterns. Use of 3-D LIPM model for the design of stabilizing controller using preview control with zero moment point (ZMP) feedback can be found in Kajita et al. (2003). In Kajita et al. (2014), a ZMP tracking control as well as improved preview control for stabilization based on the simplified model is discussed.

Humanoid robots interact with the environment and thus the interaction forces need to be controlled to stabilize the robot. Apart from the interaction forces, push-recovery and recovery from fall are the more challenging areas of research in balance and control of the robots. In these scenarios, external forces act on the robot causing degradation in the performance of the overall system. To address these issues, a stabilizing controller based on a capture point (CP) dynamics using natural dynamics of the linear inverted pendulum (LIP) is used to derive the CP trajectory of the bipedal robot Pratt et al. (2006), here LIP model is used for design of the CP tracking controller. The concept of capture point is extended to N-step capturability based control by Pratt et al. (2012) and the proposed algorithm was tested using M2V2 bipedal robot. The disturbance adapting gaits using capture point feedback for generating the online CoM pattern is proposed in Kim et al. (2023) wherein the CoM trajectory is tracked by implementing the implicit ZMP-CoM relation. Hu et al. (2023) presented an overview of the biped gait control methods like model based gait, stability criterion based gaits and learning strategy based gaits wherein various inverted pendulum models have also been discussed. Iqbal et al. (2023) presented the analysis and stabilization of aperiodic trajectories of a hybrid-linear inverted pendulum (H-LIPM) walking on a vertically moving surface. In Choi et al. (2007), authors have used simplified rolling sphere model for generating ZMP/CoM based walking pattern and proposed the posture/walking controller wherein the stabilizing control is composed of a ZMP as well as CoM tracking control. Overall scheme was tested on *Mahru I* humanoid robot demonstrating robustness against disturbances due to the contact forces/moments acting during landing phase of the leg. Further, the scheme was experimentally tested with the dancing robot arms.

Performance of the control system affected by external disturbances can be recovered by estimating their effect and negating it by modifying the nominal controller with the estimated disturbance. As the legged robots are usually affected by external disturbances, disturbance rejection becomes an important aspect of the design of a control system. In literature, various methods have appeared for the design of robust control based on disturbance estima-

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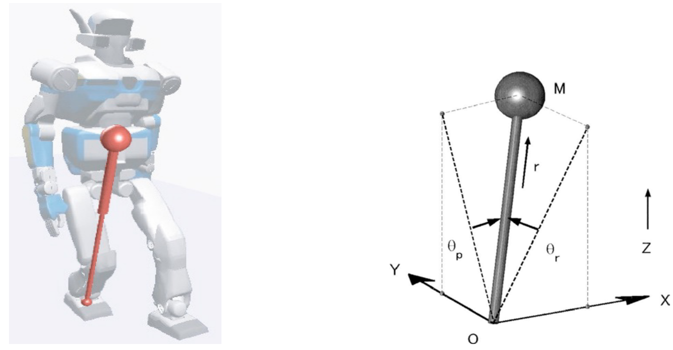
tion and cancellation approach. For example, a time-delay control (TDC) technique is proposed in Toumi (1990) wherein a nominal controller is augmented with a function which estimates the unmeasurable external disturbance with the help of information in the recent past. Similarly, a sliding mode based disturbance observer by Hall (2006) is used to estimate the disturbances and to robustufy the controller. The problem of obtaining estimate of the disturbance as well as system states simultaneously has been addressed in extended state observer (ESO) framework Han (2009); Wang (2003). Following the similar approach as that of TDC, while addressing the drawbacks associated with it, an Uncertainty and Disturbance Estimator (UDE) approach has been proposed in Zhong (2004) wherein the disturbance is estimated using an appropriate filter. Further, the effectiveness of the proposed approach over time-delay control has been demonstrated. Subsequently, various applications of UDE for practical systems as well as it's extensions have been reported in the literature. For example, a robust feedback linearization based control is designed for control of the robot manipulator using UDE based controller-observer structure is presented in Kolhe et al. (2013). Performance improvement of UDE scheme by employing $\alpha-$filter has been proposed by Chandar (2014).

Design of balance and walking control with uncertainties and external disturbances acting on the system is a challenging task, to address this issue various robust control strategies have appeared in literature. A hybrid observer based disturbance rejection scheme has been proposed in Morlando (2022) wherein a momentum-based observer for estimating external moment acting about CoM of the quadruped and an acceleration-based observer for estimating external force at CoM of the robot is proposed. An active disturbance rejection based humanoid stable walking with the help of ESO estimated external disturbance has been proposed in Soto et al. (2016) wherein the natural response of the $3-$D LIPM model in presence of external disturbance is restored with the help of ESO estimated disturbance. However closed loop performance of the control system for trajectory tracking is not demonstrated and also ESO estimated disturbance is injected through control channel only when external disturbance is acting on the system. A higher order ESO has been designed for disturbance as well as state estimation and servo based trajectory tracking control of a biped robot Fonseca et al. (2016). The stability of the closed loop system is analysed using Lyapunov approach and results of the scheme are compared with a high-order sliding-mode observer based controller demonstrating the performance superiority of the scheme. It is important to note that in Fonseca et al. (2016), a robust joint space trajectory traking controller using disturbance estimation is proposed, however, the outer walking and stabilization control loop has not been robustified in the work.

In this paper, a UDE based robust CoM trajectory tracking controller for the robot using $3-$D LIPM model of the humanoid robot is proposed. The main idea of the proposed technique is to estimate and cancel the disturbances affecting its performance. This is accomplished by designing an UDE which provides the estimate of the external disturbances and augmenting a state feedback controller with the estimate. Closed loop stability of the proposed design is analysed and efficacy of the scheme is demonstrated through simulations.



(a) (b)

Fig. 1. (a) Humanoid robot; (b) 3-D inverted pendulum represented as a walking robot Kajita et al. (2001)

The paper is organized as follows. The $3-$D LIPM model for the humanoid robot is described in Section 2 whereas section 3 presents the proposed robust state feedback control design. Results of the closed-loop stability analysis are discussed in section 4. Simulation results of the proposed UDE based robust controller and its comparison with the state feedback controller are presented in section 5 and, section 6 concludes this work.

2. PROBLEM FORMULATION

Walking of the legged robots is classified in two categories, first, static walking where, the projected CoM of the robot lies within the support polygon, next in case of dynamic walking, projected CoM leaves the support polygon for certain period of the walking cycle Kajita et al. (2014). The dynamic walk of the humanoid robot is realised with whole body balance which is unstable in nature Kajita et al. (2014). As discussed previously, to achieve dynamic walking, CoM trajectory need to be controlled dexterously. In literature, the problem is dealt in a great detail by designing stable gaits of humnoid robot assuring dynamic walking. The desired CoM position planning was initially proposed by Takanishi et al. (1990). Kajita et al. (2003) have proposed a preview control of ZMP alongwith the CoM feedback. In Choi et al. (2007) authors have designed CoM controller for dynamic walking of the robot. It is imperative to note that, by use of CoM feedback, walking pattern of the robot can be generated for dynamic walking. This work deals with the CoM trajectory tracking controller design for the $3-$D LIPM model of the *Johnny* humanoid wherein the control objective is CoM of 3-D LIPM model track the desired CoM trajectory in presence of the external disturbances.

2.1 Mathematical Model

Equations of motion of a 3-D inverted pendulum with point mass and a massless leg modelled as a prismatic joint as shown in Fig. 1-b Kajita et al. (2001) are reproduced in (1) for the sake of completeness.

$$m\begin{pmatrix} 0 & -rC_r & -rC_rS_r/D \\ rC_p & 0 & -rC_pS_p/D \\ S_p & -S_r & D \end{pmatrix}\begin{pmatrix} \ddot{x} \\ \ddot{y} \\ \ddot{z} \end{pmatrix} = \begin{pmatrix} \tau_x \\ \tau_y \\ f \end{pmatrix} - mg\begin{pmatrix} -rC_rS_r \\ -rC_pS_p \\ D \end{pmatrix} \quad (1)$$

Here, $S_r = \sin\theta_r$, $S_p = \sin\theta_p$, $C_r = \cos\theta_r$, $C_p = \cos\theta_p$ and $D = \sqrt{1 - S_r^2 - S_p^2}$, m is mass of the pendulum, g

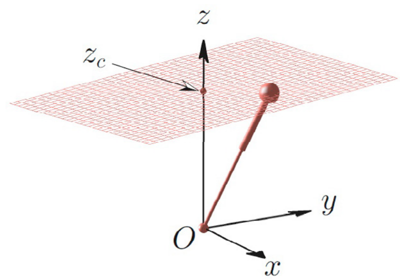


Fig. 2. Simplified 3−D LIP with CoM moving on constraint plane Kajita et al. (2014)

is gravity acceleration, (x, y, z) is position of the CoM, and (τ_r, τ_p, f) are the pendulum torque and force corresponding to the state variables (θ_r, θ_p, r). For complete derivation and details of symbols reader is advised to go through Kajita et al. (2001). As stated earlier, owing to the complexity of the problem, humanoid walking robot in 3D space has been frequently studied by considering simplified models. The class of motion which is simple for walking is to constraint the height of the center of mass of the pendulum Kajita et al. (2001). Let us introduce a constraint plane $z = k_x x + k_y y + z_c$, where k_x, k_y are the slopes and z_c is the height of the constraint plane as shown in Fig. 2 Kajita et al. (2014). By using above constraint and performing few mathematical simplifications as given in Kajita et al. (2001, 2014), the dynamics of the 3−D LIPM is obtained as

$$\ddot{x} = \frac{g}{z_c} x + \frac{1}{m z_c} u_x \tag{2}$$

$$\ddot{y} = \frac{g}{z_c} y - \frac{1}{m z_c} u_y \tag{3}$$

where $(u_x, u_y) = (\tau_r, \tau_p)$ are the torques about the x and y-axis respectively. The simplified robot/pendulum with constraint height is considered as a linear inverted pendulum as shown in Fig. 2. Here the center of mass of the robot is attached to a mass-less prismatic joint which rotates freely about a pivot O as shown in Fig. 2. The pivot point represents the ankle joint of the support leg of the robot. Since the dynamics of the 3−D LIPM is decoupled in terms of state variables (x, y) as well as input u_x and u_y, the disturbance estimation as well as control design for only the dynamics of LIPM in x plane is considered for the further analysis. The control design for y plane has also been carried out, however the details have been omitted here to save the space. Now, Consider

$$u_{ax} = -\frac{g}{z_c} x_1 \tag{4}$$

Defining $b = \frac{1}{m z_c}$, (2) can be written as,

$$\ddot{x} = -u_{ax} + b u_x \tag{5}$$

Above model has been used for control design and analysis in subsequent sections.

3. ROBUST STATE FEEDBACK CONTROL DESIGN

3.1 State Feedback Controller (SFC)

The objective of the control design is to track the CoM trajectory. Considering, states (x, y) and it's derivatives are available, a state feedback control (SFC) law for the plant of (5) is designed as

$$u_x = \frac{1}{b}(u_{ax} + \nu_x) \tag{6}$$

Applying (6) to the LIPM dynamics of (5) results in

$$\ddot{x} = \nu_x \tag{7}$$

where ν_x is the outer loop control and is defined as

$$\nu_x = \ddot{x}^\star + k_1(x^\star - x) + k_2(\dot{x}^\star - \dot{x}) \tag{8}$$

where the $[x^\star \quad \dot{x}^\star]^T$ represent the desired state vector. Applying the control (8) to the linear dynamics (7) results into the tracking error dynamics as follows,

$$\frac{d^2 e_x}{dt^2} + k_2 \frac{d e_x}{dt} + k_1 e_x = 0 \tag{9}$$

where $e_x(t) = x^\star(t) - x(t)$ represents the tracking error. The k_i are the control gains which are chosen to achieve the desired tracking response.

3.2 UDE based Robust State Feedback Controller

Consider the dynamics represented by (2). To account for the external disturbances, the dynamics of (2) can be rewritten as

$$\ddot{x} = -u_{ax} + b u_x + d_x \tag{10}$$

where d_x represents the external disturbances. In presence of the external disturbance d_x, the robust state feedback control resulting into the error dynamics as given by (9) can be obtained as

$$u_x = \frac{1}{b}(u_{ax} + \nu_x - d_x) \tag{11}$$

However, to implement the control of (11), one needs the value of d_x. To address this issue, a UDE technique proposed in Zhong (2004) is employed in this work. Application of UDE technique for robustification of controllers for different applications can be found in Talole (2011); Kolhe et al. (2013). Now, to address the issue of disturbance estimation, robust state feedback control takes the form as

$$u_x = \frac{1}{b}(u_{ax} + \nu_x + u_{dx}) \tag{12}$$

where u_{dx} cancels the external disturbances acting on the system and is given by

$$u_{dx} = -\hat{d}_x \tag{13}$$

The $\hat{d}_x$ is the estimate of the disturbance d_x. The controller (12) is designated as the robust state feedback controller (UDE+SFC) wherein the outer loop control, ν_x, is as given in (8). Substituting (12) in (10) leads to

$$\ddot{x} = u_{dx} + \nu_x + d_x \tag{14}$$

from where one gets

$$d_x = \ddot{x} - u_{dx} - \nu_x \tag{15}$$

In UDE based disturbance estimation technique, external disturbances is estimated by using an appropriate filter. In this work, a first order filter proposed in Zhong (2004) is used for this purpose. In view of the (15) and following the methodology given in Zhong (2004); Talole (2011), a first-order filter is chosen as

$$G_x(s) = \frac{1}{1 + \tau_x s} \tag{16}$$

with $\tau_x > 0$. The $\hat{d}_x$ i.e. the estimate of the external disturbance d_x using filter of (16) can be obtained by solving following equation, Zhong (2004)

$$d_x = \tau_x \dot{\hat{d}}_x + \hat{d}_x \tag{17}$$

Substituting, (13) and (17) in (15) one gets

$$\ddot{x} + \hat{d}_x - \nu_x = \tau_x \dot{\hat{d}}_x + \hat{d}_x \tag{18}$$

from where

$$\tau_x \dot{\hat{d}}_x = \ddot{x} - \nu_x \tag{19}$$

Now, integrating both the sides of (19), one gets

$$\hat{d}_x = \frac{1}{\tau_x}\dot{x} - \frac{1}{\tau_x}\int \nu_x dt \tag{20}$$

Substituting (4), (8) and (20) in (12) gives the UDE based robust state feedback controller using the filter of (16). The resulting controller is as follows

$$u_x = \frac{1}{b}\left[u_{ax} - \frac{1}{\tau_x}\dot{x} + \nu_x + \frac{1}{\tau_x}\int \nu_x dt\right] \tag{21}$$

It is imperative to note that, under the assumption of $\hat{d}_x \approx d_x$, applying UDE based robust state feedback control (21) to the dynamics of (10) results into the tracking error dynamics given by (9) thus cancelling the effects of the external disturbances.

4. STABILITY ANALYSIS

As is obvious from (2) and (3), the dynamics of the 3−D LIP is decoupled and hence stability analysis for LIP only in x-plane is presented. Now, defining $x_1 = x$, and $x_2 = \dot{x}$, the dynamics of (2) in presence of external disturbance d_x shown in (10) can be written in a state space form as

$$\begin{aligned} \dot{x}_1 &= x_2 \\ \dot{x}_2 &= ax_1 + bu_x + d_x \\ Y &= x_1 \end{aligned} \tag{22}$$

Now, defining the system state vector as $X_p = [x_1 \ x_2]^T$, (22) can be written as

$$\begin{aligned} \dot{X}_p &= A_p x_p + B_p u_x + B_d d_x \\ Y_p &= C_p x_p \end{aligned} \tag{23}$$

where

$$A_p = \begin{bmatrix} 0 & 1 \\ a & 0 \end{bmatrix}; B_p = \begin{bmatrix} 0 \\ b \end{bmatrix}; B_d = \begin{bmatrix} 0 \\ 1 \end{bmatrix}; C_p = [1 \ \ 0]; A_o = \begin{bmatrix} 0 & 0 \\ -a & 0 \end{bmatrix}$$

The UDE+SFC controller (12) using $u_{dx} = -\hat{d}_x$ and $a = \frac{g}{z_c}$ is re-written as

$$u_x = \frac{1}{b}(-ax + \ddot{x}^\star + k_1(x^\star - x) + k_2(\dot{x}^\star - \dot{x}) - \hat{d}_x) \tag{24}$$

Denoting the reference state vector $R_x = [x^\star \ \dot{x}^\star]^T$ and the gain vector as, $K_p = [m_1 \ m_2]$ with the elements as $m_1 = \frac{k_1+a}{b}$, $m_2 = \frac{k_2}{b}$, the controller (24) is re-written as

$$u_x = -K_p X_p + K_p R_x + K_R R_x - \frac{1}{b}\hat{d}_x + \frac{1}{b}\ddot{x}^\star \tag{25}$$

where $K_R = [-\frac{a}{b} \ 0]$. It can be shown that the reference state vector dynamics, $\dot{R}_x$, can be written as

$$\dot{R}_x = A_p R_x + A_o R_x + B_d \ddot{x}^\star \tag{26}$$

With A_o defined above, now defining the state vector tracking error, $e_{cx} = R_x - X_p$ and using (23), (25) and (26) and carrying out few simplifications, we get the following state tracking error dynamics

$$\dot{e}_{cx} = (A_p - B_p K_p)e_{cx} - B_d \tilde{d}_x \tag{27}$$

Table 1. Simulation parameters for 3−D LIP

Parameter	Definition	Value
m	mass of the robot	4.39964kg
z_c	Constrained height of CoM	0.35289m
g	Gravity acceleration	$9.81m/s^2$
t_{s_x}, t_{s_y}	Desired settling times	0.01s
ζ_x, ζ_y	damping ratios	1
τ_x, τ_y	filter time constants	0.005s
$[x(0), y(0)]$	Initial position	[0.151;0.05]m
$[\dot{x}(0), \dot{y}(0)]$	Initial velocity	[-0.467;0.467]m/s

where $\tilde{d}_x = d_x - \hat{d}_x$ is the disturbance estimation error. Now, the disturbance estimation error dynamics is obtained by subtracting (17) from $\tau_x \dot{d}_x$

$$\tau_x \dot{d}_x - d_x = \tau_x \dot{d}_x - \tau_x \dot{\hat{d}}_x - \hat{d}_x \tag{28}$$

Rearranging (28) we get

$$\dot{\tilde{d}}_x = -\frac{1}{\tau_x}\tilde{d}_x + \dot{d}_x \tag{29}$$

Combining (27) and (29) yields the following closed loop error dynamics

$$\begin{bmatrix} \dot{e}_{cx} \\ \dot{\tilde{d}}_x \end{bmatrix} = \begin{bmatrix} (A_p - B_p K_p) & -B_d \\ 0 & -\frac{1}{\tau_x} \end{bmatrix} \begin{bmatrix} e_{cx} \\ \tilde{d}_x \end{bmatrix} + \begin{bmatrix} 0 \\ 1 \end{bmatrix} \dot{d}_x \tag{30}$$

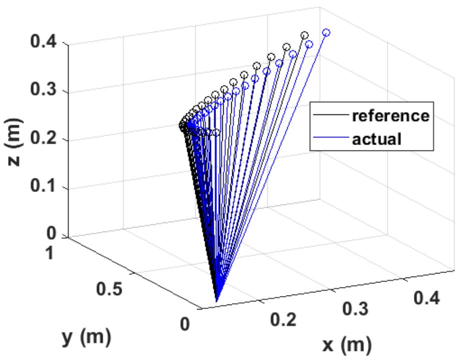
The eigenvalues of the system matrix of (30) are obtained by

$$|sI - (A_p - B_p K_p)||s - (-\frac{1}{\tau_x})| = 0 \tag{31}$$

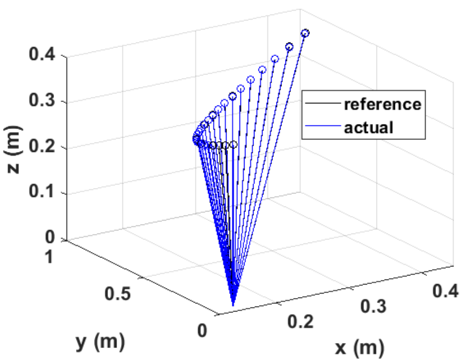
Noting that the pair $(A_p; B_p)$ is controllable, K_p comprising of controller gain, can be chosen to satisfy the tracking performance along with $\tau_x > 0$ to ensure stability for the error dynamics of (30). As the error dynamics is driven by $\dot{d}_x$, for bounded $|\dot{d}_x|$, bounded input-bounded output (BIBO) stability is assured. Lastly, if the rate of change of disturbance is small, i.e., if $\dot{d}_x \approx 0$, then the closed loop error dynamics is asymptotically stable Kolhe et al. (2013). From (29), it can be seen that the value of filter time constant, τ_x, affects the disturbance estimation accuracy. It is important to note that the disturbance estimation does not depend on the magnitude of the disturbance, but depend on the rate of change of the disturbance hence it needs to be continuous. To study the effect of noise further work needs to be carried out.

5. SIMULATIONS AND RESULTS

Numerical simulation results using the SFC as well as UDE+SFC control are presented to validate the proposed method. The simulation data for 3−D LIPM taken from Soto et al. (2016) is given in Table 1. The reference position trajectory is considered as natural response or zero input response of the 3−D LIPM with simulation data given in Table 1 as shown in Fig. 3. The external disturbance of the magnitude of $d_x = 200sin(4t)$ and $d_y = 200cos(4t)$ is introduced in the system represented by (10). The performance specifications for the LIPM trajectory tracking i.e. damping ratio and settling time are considered as given in Table 1. Next, the controller gains k_1 and k_2 required in (8) are chosen to satisfy these performance specifications. With this data, simulations are carried out to compare the performance of the proposed design of UDE+SFC control of (21) with the SFC controller of (6) discussed in section 3.1. The results of the trajectory



(a)



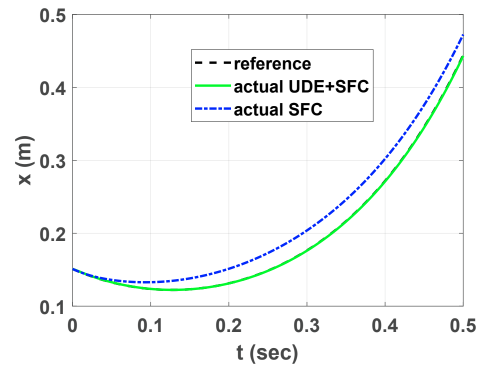
(b)

Fig. 3. Trajectory tracking performance of LIP (a) SFC (b) UDE+SFC

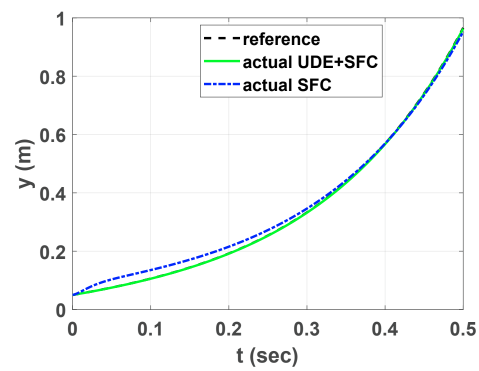
tracking of 3−D LIP are presented in Fig. 3. In Fig. 3(a), the trajectory tracking of SFC controller in presence of external disturbance is presented and it can be observed that the scheme has resulted in trajectory tracking error. However performance of the controller is restored with the help of proposed UDE+SFC controller as shown in Fig. 3(b). Results of position tracking of the walking primitive of the 3−D LIP in x, y plane are shown in Fig. 4. From Fig. 4(a) and (b), it can be noted that the position tracking for the SFC control in presence of external disturbance has resulted in tracking error, however the proposed UDE+SFC controller has offered satisfactory tracking performance. The time histories of the actual and estimated disturbances used in the robust UDE+SFC controller of (21) are shown in Fig. 5 from where it can be seen that the UDE estimator of (20) has estimated the disturbance quiet accurately. Performance comparison of SFC and UDE+SFC controller is also carried out based on root mean square error (eRMS) index of the output errors as Seshagiri (2000)

$$e_{RMS} = \sqrt{\sum_{j=1}^{N} \frac{(x_j^\star - x_j)^2}{N}} \tag{32}$$

where, N is the number of data samples, x_j is magnitude of output and $x_j^\star$ is the magnitude of reference both at jth sample. The number of samples used are $N = 500$ with time step of 0.001 s. The root mean square error index of the output errors for both the designs is presented in Table 2 from where it is observed that the value of eRMS for SFC controller is higher as compared to the UDE+SFC based design. Some more results are available but could not be included due to space constraints.

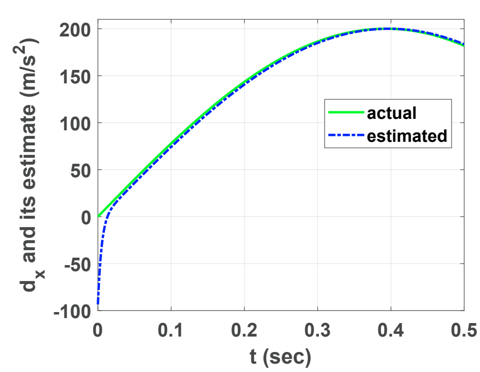


(a)

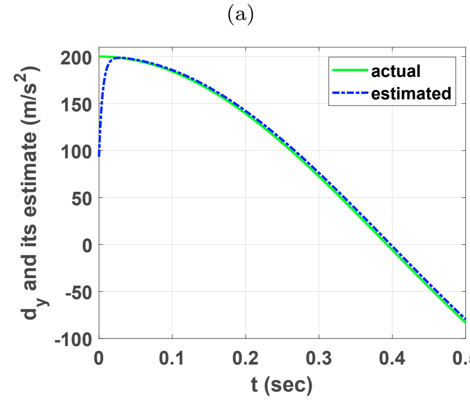


(b)

Fig. 4. Trajectory tracking of the walking primitive of SFC and UDE+SFC control (a) x plane (b) y plane



(a)



(b)

Fig. 5. Disturbance tracking performance of UDE+SFC control (a) d_x and it's estimate (b) d_y and it's estimate

Table 2. Comparative performance of SFC and UDE+SFC controller with eRMS index

Design	e_{RMS_x} (m)	e_{RMS_y} (m)
SFC	0.0227	0.0188
UDE+SFC	0.0004	0.0011

6. CONCLUSION

In this work, UDE based robust CoM trajectory tracking controller is designed for the humanoid robot. The important aspect of the proposed controller is, it does not need knowledge of the disturbance. Closed-loop stability of the overall system is analysed. Numerical simulation results of the proposed UDE augmented state feedback control for CoM trajectory tracking of a humanoid robot have also been presented. Proposed robust control offers better performance and robustness compared to the SFC control.

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