



Robust and Adaptive Control of an Exoskeleton Robot For Tracking Modified Desired Trajectory Based on Zero Moment Point Stability Theory

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ABSTRACT: The Creation of reference trajectories and the ability to track them in the presence of disturbances and uncertainties are important issues in investigating the exoskeleton performance. One of the methods of trajectory planning is the central pattern generation algorithm. This algorithm will behave in a limit cycle and the temporal disturbances have quickly removed the system and created harmonious trajectories. In this paper, for the creation of reference trajectories of each joint, a combination of seven modified Hopfield oscillators is used which provides the ability to change the frequency and domain of walking. Online modification of robot joint reference trajectories is done by using the feedback error signal between desired zero momentum point and zero momentum point of the robot at any moment. In order to cope with the disturbances and uncertainty with the uncertain domain and achieve maximum efficiency in tracking robot reference trajectories, an adaptive dynamic fast terminal sliding mode controller is used due to the elimination of chattering phenomena, and finite-time convergence. Also, by moving the Upper link the maximum stability of the robot based on the zero momentum point criterion is guaranteed. To achieve maximum performance, controller parameters, oscillator coefficients, and connections between them are optimized. Finally, the performance of the proposed method is compared with a sliding mode controller. The results demonstrate the superiority of the proposed method.

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1. INTRODUCTION

Exoskeletons are used for augmentation and rehabilitation purposes [1]. A basic locomotor pattern of many walker robots is produced by Central Pattern Generator (CPG). Central Pattern Generator is a neural circuit that can produce various motion patterns, like walking, breathing, chewing, flying, and swimming [2]. If feedback signals are exerted, CPG can produce flexible motions in unknown environments[2].

A variety of oscillators are used for CPG modeling. Hopfield Oscillator is one of the most eminent oscillators [3]. This oscillator is developed by adding some terms to match the actual phase and amplitude of motion specifically for motion generation in the realm of walking robots [4]. In the CPG method, Fourier decomposition is the governing theory for the combination of several oscillators to learn a desired periodic signal with oscillatory input[5].

In this paper, reference trajectories are generated online by combining seven Hopfield oscillators which frequencies and amplitudes are adjustable according to the input signal. To achieve the maximum level of zero moment point criterion stability [6], at each time step reference trajectories of robot joints are modified based on error signal between the position of the desired and real zero moment points.

Due to the advantages of Sliding Mode Control (SMC),

various sliding-based controllers have been proposed such as dynamic sliding mode control [7]. In this method, adding an additional dynamic to the sliding surface improves the closed-loop response and robustness.

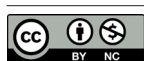
2. PROBLEM STATEMENT

Reference trajectories of robot joints are generated online by combining seven Hopfield oscillators so that frequencies and amplitudes are adjustable according to the input signal. This approach results in stable rhythmic locomotion of the robot. In the next step, an Adaptive dynamic sliding mode control scheme with a fast terminal sliding manifold is applied to track the reference trajectories. To achieve the maximum level of Zero Moment Point (ZMP)-based stability at each time step, reference trajectories are modified based on the error signal between the position of the desired and real zero moment points.

To reach a harmonious motion between the robot and the user, in this paper a 7-DOF mechanism is chosen that its joints are placed on the user's hip, knee, and ankle joints. The dynamic model of the exoskeleton lower limb can be expressed as:

$$\tau = M(q)\ddot{q} + C(q, \dot{q}) + G(q) + \tau_d + J^T F_i \quad (1)$$

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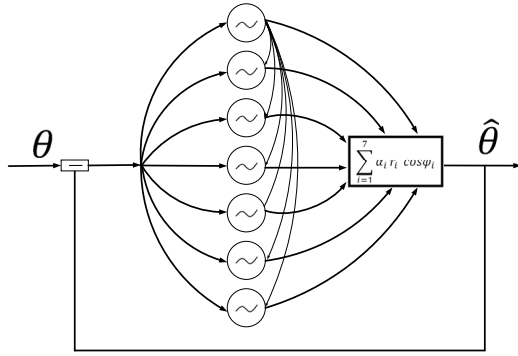


Fig. 1. The combination of the oscillators for each CPG

Where τ and τ_d represent actuator and disturbance torques, and M , C , and G are inertia, Coriolis and centrifugal, and gravity matrices, respectively. Also F_i and J are interaction force and Jacobian matrix, respectively.

3. DESIRED GAIT PATTERN GENERATION

T online determination of desired joint trajectories. seven modified Hopfield oscillators are combined such that the generated trajectories give the opportunity to adjust the amplitude and frequency of the motion according to the input signal. A modified Hopfield oscillator is defined as [8]:

$$\begin{aligned}
 \dot{r}_i &= \rho(\sqrt{\mu} - r_i^2)r_i + \epsilon F(t) \cos \varphi_i \\
 \dot{\varphi}_0 &= \omega_0 - \frac{\epsilon}{r_0} F(t) \sin \varphi \\
 \dot{\varphi}_i &= \omega_i - \frac{\epsilon}{r_i} F(t) \sin \varphi + h, \forall i > 0 \\
 h &= [Z_i \sin(R_i - \varphi_{i,\Delta} - \varphi_i)] \\
 \dot{\omega}_i &= -\epsilon F(t) \sin \varphi_i \\
 \dot{\alpha}_i &= \eta F(t) \cos \varphi_i r_i \\
 \dot{\varphi}_{i,\Delta} &= \epsilon_i \sin(R_i - \varphi_{i,\Delta} - \varphi_i), \forall i > 0 \\
 R_i &= \frac{\omega_i}{\omega_0} \varphi_0 \\
 F(t) &= \theta - \hat{\theta} \\
 \hat{\theta} &= \sum_{i=0}^N \arccos \varphi
 \end{aligned} \tag{2}$$

where, r and φ are radius and phase of the system, respectively. ρ shows the power of attraction of the limit cycle. It can be shown that $\sqrt{\mu}$ corresponds to the radius of this limit cycle. ω represents the frequency of the oscillation. ϵ , ϵ_i , and Z_i are constant parameters. The term h joins the output of all oscillators to the first one and φ_0 is the output phase of the first oscillator. The combination of the oscillators for each CPG is shown in Fig. 1.

4. ADAPTIVE DYNAMIC SLIDING MODE CONTROL ON THE BASIS OF FAST TERMINAL SLIDING MANIFOLD

An adaptive dynamic sliding mode control scheme with a fast terminal sliding manifold has been proposed in this section. Modified sliding manifold is defined as:

$$\begin{aligned}
 v &= s + \lambda \int_0^t s(\tau) d\tau \\
 s_i &= \dot{e}_i + \alpha e_i + \beta |e_i|^{\gamma} \text{sgn}(e_i)
 \end{aligned} \tag{3}$$

where, α , β , and γ are positive constants. e_i is tracking error of the i^{th} joint. λ is a positive constant. To extract the control law, the time derivative of the sliding manifold is equalized to zero.

$$\begin{aligned}
 \dot{v} &= \dot{s} + s = \ddot{e} + (\gamma \beta |e|^{\gamma-1} + \lambda + \alpha) \dot{e} \\
 &+ \lambda \alpha e + \lambda \beta |e|^{\gamma} \text{sgn}(e)
 \end{aligned} \tag{4}$$

$$\begin{aligned}
 u &= M \ddot{q}_d + C \dot{q} + G + D - M (\gamma \beta |e|^{\gamma-1} + \lambda + \alpha) \dot{e} \\
 &+ \lambda \alpha e + \lambda \beta |e|^{\gamma} \text{sgn}(e)
 \end{aligned} \tag{5}$$

$$D = \tau_d + J^T F_i$$

In order to guard against uncertainties and disturbances, an adaptive control law is added to the law defined in Eq. (5), which results in,

$$\dot{\psi} = \eta |v| \tag{6}$$

5. RESULTS AND DISCUSSION

In this paper, white noise with 20 percent amplitude of the control signal is applied to each joint, and 20% uncertainties in parameters are applied. To investigate the performance of the controller, ZMP and the desired trajectory of the upper limb joint for adaptive dynamic sliding mode control and sliding mode control are illustrated in Figs. 2 and 3, respectively.

As is shown in Figs. 9 and 10, the ZMP trajectory produced by the Adaptive Dynamic Sliding Mode Control is closer to the desired one despite small upper limb joint movement altitude.

6. CONCLUSION

In this paper, the performance of the proposed method has been compared with CPG based- SMC. The results show that the proposed scheme outperforms the others in tracking the desired joint trajectories, convergence rate, interacting forces between humans and the robot, control effort, motion stability based on ZMP criterion, as well as robustness against disturbances, uncertainties, and faults.

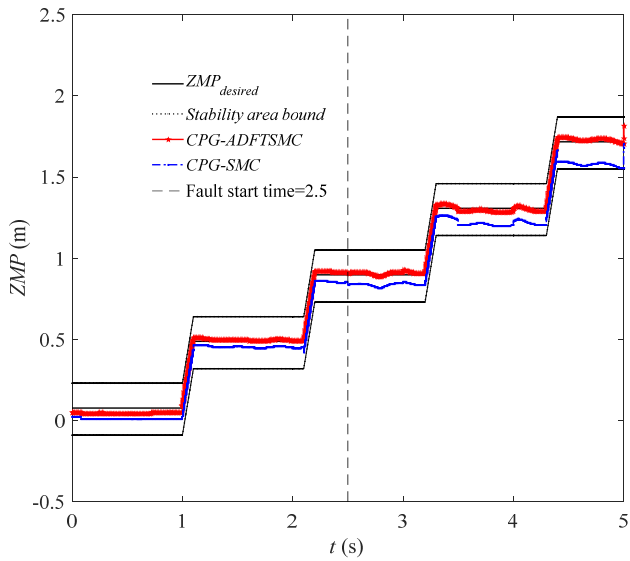


Fig. 2. ZMP position

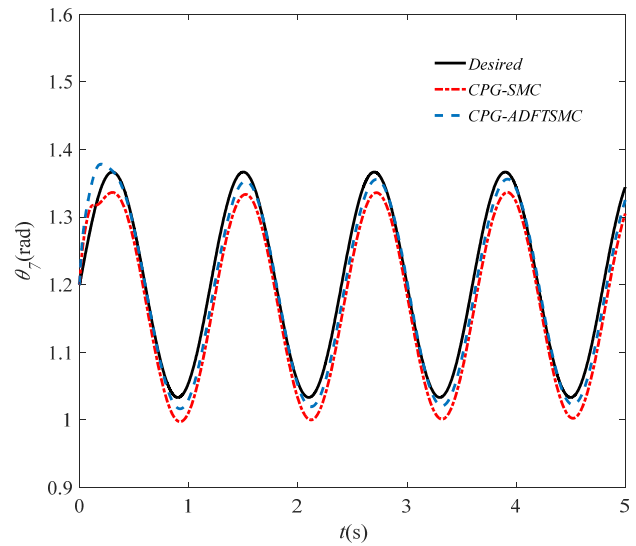


Fig. 3. The trajectory for the upper limb joint

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