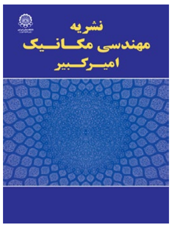

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# Optimal Adaptive Super-Twisting Sliding Mode Control of an Lower Limb Exoskeleton

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**ABSTRACT:** Disturbance and bounded uncertainty are the most important factors which can be degrade efficient performance of the lower limb exoskeleton. While sliding mode control is a robust control approach against such disturbances, however, by applying the boundary layer in spite of chattering phenomenon, robust performance becomes feeble. In order to overcome this drawback, high order sliding mode algorithms like supper twisting has been proposed in which, chattering phenomenon is mitigated by eliminating the boundary layer. In this paper, an adaptive supper twisting sliding mode control is proposed for a lower limb exoskeleton robot in which the sliding variable and its derivative tend to zero continuously in presence of the disturbance and bounded uncertainty. In addition, the desired trajectory of the upper limb is determined so that in each moment the stability of the robot is guaranteed based on zero momentum point criterion. To achieve maximum stability and minimum error in tracking of the desired trajectories, the controller parameters and the upper limb desired trajectory parameters are optimized using the Harmony Search algorithm. Robot is modeled in ADAMS and then control inputs are applied to the Adams model. Finally, Performance of two controllers is compared. Simulation results reveal the effectiveness of the proposed controller rather than the optimal sliding mode controller.

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## 1- Introduction

Wearable robotic systems (Exoskeletons) are devices that are generally similar to the human body or part of the human body and have harmonious behavior with the movements of the human body. Exoskeletons are applied to enhance the performance, ability and potency of healthy human or as a rehabilitation device. Conformity with the human body and also control strategies which are used in exoskeletons, has immense impacts on the performance of these means [1].

In this paper, first of all, the desired trajectories are designed based on reference [2]. Next, dynamic model of the robot is extracted using Lagrange method. In order to control the position of the robot joints and reduce the interacting force between the robot and the user, Sliding Mode Control (SMC) and adaptive robust nonlinear model predictive control are carried out. To guard against disturbances in result of interacting force between human body and robot, the value of the force is calculated in each time and applied to the robot as a compensatory torque [3]. The desired trajectory of upper limb joint is determined in such a way as to ensure robust stability based on the zero moment point.

## 2- Methodology

The understudied model in this paper is a lower limb exoskeleton robot containing seven links and five active joints for the hip, knee and ankle of the left and right legs.

By extracting the kinematic equations and using the Lagrange method, the dynamic model of the robot is as follows [4]:

$$\tau = M(\theta)\theta'' + C(\theta,\theta') + G(\theta) + \tau_d \tag{1}$$

where is the torque vector of the actuators, $M(\theta)$ is the inertia moment matrix, $C(\theta,\theta')$ is the centrifugal and gyroscopic effects matrix, $G(\theta)$ is the vector of gravitational forces and $\tau_d$ is the disturbance torque.

The design of the path is carried out in two stages: one and two supports. Schematic of the method is presented in Fig. 1.

where $\theta_s$, $\theta_e$ are the start and termination angles of double support phase, $D$ is the one step length, $D_1$ is the longitudinal distance of hip joint at the beginning of the single support phase, $D_2$ is the longitudinal distance of hip joint at the end of the single support phase, and $D_3$ is the longitudinal distance of hip joint at the end of the double support phase.

## 3- Controller Design

In this section, an adaptive-gain super-twisting sliding mode control is designed. By defining sliding surface and some mathematic simplifications, the sliding mode control law is as follows

$$\begin{aligned}\tau(t) &= C(\theta,\theta') + G(\theta) + M(q_d{}'' - \lambda(q' - q_d{}')) \\ &\quad + \tau_d - K\ \mathrm{sign}(S)\end{aligned} \tag{2}$$

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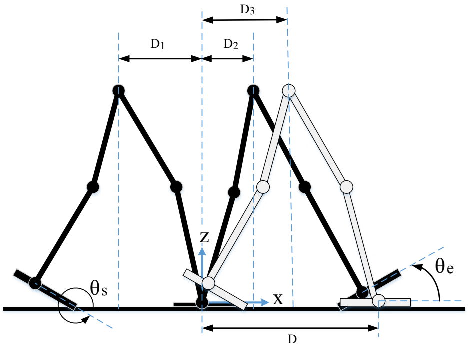

Fig. 1. Schematic of the phase changing

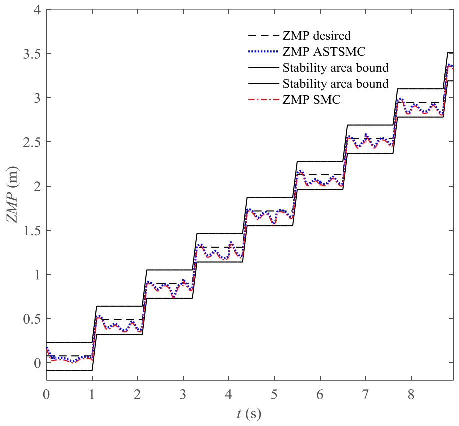

Fig. 3. Location of the ZMP

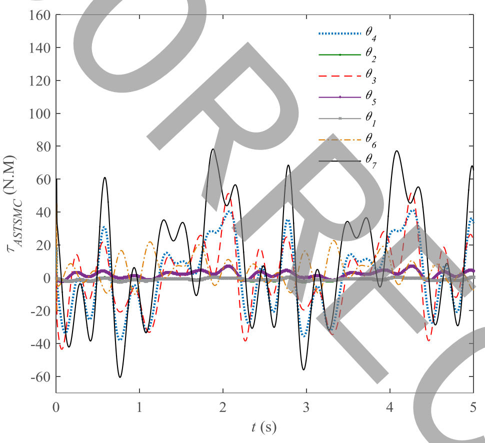

Fig. 2. Control signal of the proposed controller

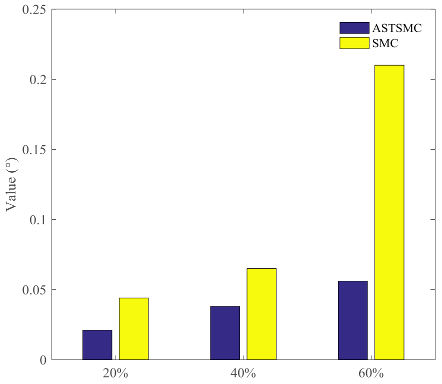

Fig. 4. RMS of tracking error in presence of different disturbances

To eliminate the chattering without reducing the robustness characteristics of the controller, the control command is modified as adaptive-gain super-twisting sliding mode control law [5].

$$\begin{aligned} &\tau_i(t) = \bar{\tau}_i(t) + \omega_i \\ &\omega_i = A_i\sqrt{|S_i|}\,\mathrm{sign}(S_i) + v_i \\ &v_i' = -\frac{\beta}{2}\mathrm{sign}(S_i) \end{aligned} \tag{3}$$

In Eq. (3), $\beta = 2\varepsilon A$ and also:

$$A_i' = \begin{cases} W_1\sqrt{\frac{\gamma_1}{2}}\mathrm{sign}(|S_i| - \mu) & A > a_m \\ \eta & A < a_m \end{cases} \tag{4}$$

where $W_1, \gamma_1, \varepsilon$, $\mu$ and $\eta$ are constant. Stability analysis can be addressed through Lyapanouv theory. Moreover, Zero Momentum Point (ZMP) is a point on the ground which sum of all the active forces moments is equal to zero. If the ZMP perch into the support polygon between the foot and the ground, stability of the biped robot is guaranteed [6]. Therefore, instability of the robot can be illustrated through monitoring the ZMP location. The ZMP in x-axis direction can be calculated as follows:

$$\begin{aligned} x_{ZMP} &= \frac{\sum_{i=1}^{n} m_i(z_i'' + g)x_i - \sum_{i=1}^{n} m_i x_i'' z_i - \sum_{i=1}^{n} I_{iy}\theta_{iy}''}{\sum_{i=1}^{n} m_i(z_i'' + g)} \\ y_{ZMP} &= \frac{\sum_{i=1}^{n} m_i(z_i'' + g)y_i - \sum_{i=1}^{n} m_i y_i'' z_i - \sum_{i=1}^{n} I_{ix}\theta_{ix}''}{\sum_{i=1}^{n} m_i(z_i'' + g)} \end{aligned} \tag{5}$$

In order to optimized controller parameters, an objective function considered as:

$$CF = \int |ZMP - ZMP_{desird}|^2 + \sum_{i=1}^{7}\int |e_i|^2 \tag{6}$$

where $ZMP_{desird}$ is the ZMP in SSP and DSP which is defined based on maximum stability value in each phase and is trajectory tracking error.

## 4- Simulation Results

In this section, simulations are performed. Fig. 1 presents the control signal for the controllers which is in the applicable range.

Additionally, the location of ZMP is depicted in Fig. 3, in which both controllers generate a stable motion for the robot using upper limb-angle. The ZMP trajectory produced by the Adaptive Super Twisting Sliding Mode Controller (ASTWSM) controller providing a wider stability margin.

Fig. 4 divulges the superiority of the proposed controller rather than conventional SMC in the presence of exogenous disturbance. Moreover, for 30 percent disturbance, both of the designed controllers have constant and similar performance.

## 5- Conclusion

This paper addressed a robust control of a lower limb exoskeleton. Effectiveness of the controller was observed against exogenous disturbances and uncertainties. Moreover, stability of the robot through ZMP and its location had less divergent with the optimal ZMP trajectory.

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