Impedance Synovial Control for Lower Limb Rehabilitation Exoskeleton System

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Abstract. It is very important to improve the working stability and wearing comfort for the lower limb exoskeleton system, so as to increase the rehabilitation effect of patients with lower limb injuries. However, due to the complex structure of the lower limb exoskeleton, there are uncertain disturbances in the system. Traditional control methods cannot meet the requirements of dynamic response and robustness, since there are still many shortcomings in the safety and compliance of the lower limb exoskeleton for rehabilitation wearing. In this paper, an impedance synovial control strategy for the exoskeleton of the lower limbs is proposed. The safety of contact force is considered, and the impedance controller is combined with the improved integral terminal synovial controller (ITSMC) to reduce system's errors, and to ensure system's rapidity. The proposed method reduces the impedance trajectory tracking error by 90% to the conventional linear synovial control (LSMC). The stability is analyzed by a Lyapunov function. The simulation results show that the combination of the synovial controller and impedance controller has superior performances, and the entire system has a good trajectory tracking effect.

Keywords: Lower-Limb Exoskeleton, Impedance control, Synovial control, Trajectory tracking.

1 Introduction

With the development of society, the number of patients with impaired limb caused by disease, aging, traffic accidents etc. is increasing. Relying on traditional equipment and medical personnel for physical rehabilitation training is inefficient [1]. The exoskeleton robot is a wearable robot, and has been applied in many fields such as military, medical, and industrial. It is mainly divided into two functions: improving personal athletic ability and helping patients with physical disabilities to recover [2-3].

With the development of robot technology, a variety of advanced control methods have been proposed to improve the control performance of exoskeleton at home and abroad. In [4], Wang et al. proposed a periodic event-trigger sliding mode control method. They performed the wearer's motion prediction under the GA-BP neural network,and the proposed method made the system's error convergence in the finite time. For trajectory control of multi-joint exoskeleton, In [5], Rafael Pérez-San Lázaro et al. combined high-order synovial control algorithm with adaptive control to design a second-order super-twisting synovial controller. The system's error is reduced under the adaptive control. The chattering problem caused by the synovial control is also decreased.

In order to achieve precise position control and compliance control of the lower limb rehabilitation exoskeleton, we study an impedance synovial control strategy. An impedance controller with external feedback is used to obtain the impedance control trajectory and external contact force, so as to improve the dynamic relationship between force and position. Then the inner loop synovial position controller is used to adjust the joint trajectory tracking, which improves the accuracy of the system's position control.The proposed method can improve the safety and stability when patients wear lower limb exoskeleton for rehabilitation exercise, and achieve efficient rehabilitation exercise.

Rest of paper is organized as follows. Section 2 describes the dynamics model of the lower limb exoskeleton. Section 3 proposes a composite control structure composed of impedance controller and synovial controller, and analyzes the stability of the system. Numerical simulations are performed in Section 4. Conclusions are given in the last part.

2 Dynamical Model Of Lower Limb Exoskeleton

According to the Lagrange dynamics equation, the joint space dynamics model of the lower limb exoskeleton robot can be expressed as follows:

$$M(q)\ddot{q}+C(q,\dot{q})\dot{q}+G(q)=\tau \,, \tag{1}$$

where, $q\in R^n$ is the rotation angle vector of the joint. $M(q)\in R^{n\times n}$ is an inertia matrix. $C(q,\dot{q})\in R^{n\times n}$ is the matrix of combination of centrifugal force and Coriolis force. $G(q)\in R^{n\times n}$ is the gravitational matrix. $\tau\in R^n$ is torque vector, and n is the degree of freedom.

Since the impedance control is implemented in the Cartesian coordinate system, it is necessary to obtain the dynamics equation in the Cartesian coordinate system through the angular dynamics equation.

Let x be the position vector of the exoskeleton joint of the lower limb. Then the following equation about relationship between robot ' s angle and position can be obtained as follows:

$$\dot{x}=J\left(q\right)\dot{q}\,, \tag{2}$$

where $J(q)$ is the Jacobian matrix.

In the state of static equilibrium, the relationship between the torque and force of the lower limb exoskeleton joint is as follows:

$$\tau = J^T\left(q\right)F_x\,, \tag{3}$$

where $J^T(q)$ is the Jacobian matrix.

According to formulas (1), (2), (3), and considering the modeling error and disturbance d, the model is established as follows:

$$M_x(q)\ddot{x} + C_x(q,\dot{q})\dot{x} + G_x(q) + \Delta(q,\dot{q},\ddot{q}) = F_x\ , \tag{4}$$

where, $M_x(q) = J^{-T}(q)M(q)J^{-1}(q)$, $C_x(q,\dot{q}) = J^{-T}(q)(C(q,\dot{q}) - M(q)J^{-1}(q)\dot{J}(q))J^{-1}(q)$ $G_x(q) = J^{-T}(q)G(q)$,$\|\Delta(q,\dot{q},\ddot{q})\| \le \eta$.

3 Impedance Model And Design Of Synovial Controller

3.1 Establishment Of Impedance Model

According to the relationship between force and position error, the dynamics model of impedance control is described as follows:

$$M_{\mathrm{m}}\left(\ddot{x}_r - \ddot{x}\right) + B_{\mathrm{m}}\left(\dot{x}_r - \dot{x}\right) + K_{\mathrm{m}}\left(x_r - x\right) = F_e\,, \tag{5}$$

where, M_m , B_m , K_m are the inertia, damping and stiffness parameter matrices in the impedance model. F_{e} is the contact force between the end of the single-leg two-link exoskeleton and the external environment. x is the actual position trajectory. x_r is the ideal position trajectory, and $x(0) = x_{\mathrm{r}}(0)$.

In the impedance model, the target of impedance control is that the actual position trajectory x to track the desired impedance trajectory x_d . Let $x = x_d$, the impedance model is expressed as follows:

$$M_m\ddot{x}_d + B_m\dot{x}_d + K_m x_d = -F_e + M_m\ddot{x}_r + B_m\dot{x}_r + K_m x_r\ , \tag{6}$$

where, $x_d(0) = x_{\mathrm{r}}(0), \dot{x}_d(0) = \dot{x}_r(0)$.

Considering the contact resistance of the external environment, the dynamics model (4) can be transformed as follows：

$$M_x(q)\ddot{x} + C_x(q,\dot{q})\dot{x} + G_x(q) + \Delta(q,\dot{q},\ddot{q}) + F_{\mathrm{e}} = F_x\,, \tag{7}$$

3.2 Design Of Synovial Controller

Based on the impedance model of (6), the impedance control trajectory is supposed to be equal to the ideal trajectory in the workspace. Define the position error as follows:

$$\mathrm{e(t)} = x_d(t) - x(t)\,, \tag{8}$$

Since disturbances existing in the system, for better finite-time tracking effect, and eliminating steady-state errors, the synovial function is designed as follows:

$$S = \dot{e} + \int_0^t K_1 sig^{\alpha_1}(\dot{e}) + K_2 sig^{\alpha_2}(e)dt\,, \tag{9}$$

where $\mathrm{sig}^r(\xi)=[|\xi_1|^r\, sign(\xi_1),\ldots,|\xi_n|^r\, sign(\xi_n)]^T$, $0<\alpha_2<1$, $\alpha_1=2\alpha_2/(\alpha_2+1)$, and K_1 and K_2 are two positive definite diagonal matrices. Derivative the equation (9) with respect to time. We may get the following equation:

$$\dot{S} = \ddot{e} + K_1 sig^{\alpha_1}(\dot{e}) + K_2 sig^{\alpha_2}(e) , \tag{10}$$

In order to ensure the system reaching the synovial surface in the finite time, the isokinetic approach rate we use is as follows:

$$\dot{S} = -\eta\, \mathrm{sgn}(s) , \tag{11}$$

where, $\eta > 0$. The general switching function is sign(x). Compared with the sign(x), the hyperbolic tangent function is a relatively smooth switching function. Therefore, we apply this function as the switching function of the approach rate. The improved approach rate function is as follows:

$$\dot{S} = -\eta \tanh(\frac{s}{\varepsilon}) , \tag{12}$$

where ε is the steepness of the switching function. The steepness of the curve can be adjusted by the ε to achieve better control effect.

Combining (7), (8), (9) and (12), the controller can be designed as follows:

$$\begin{aligned} F_x &= M_x(q)\ddot{x}_d + C_x(q,\dot{q})\dot{x} + G_x(q) + \Delta(q,\dot{q},\ddot{q}) + F_e \\ &\quad + K_1 M_x(q) sig^{\alpha_1}(\dot{e}) + K_2 M_x(q) sig^{\alpha_2}(e) + M_x(q)\eta \tanh(s/\varepsilon) \cdot \end{aligned} \tag{13}$$

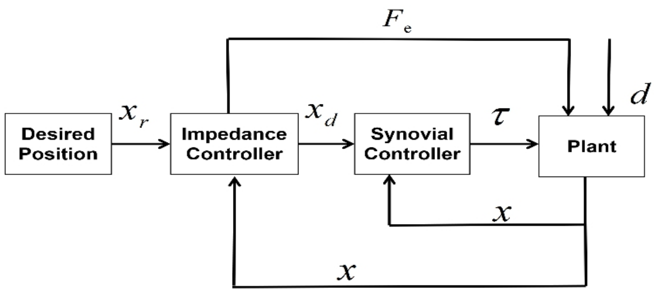

Fig. 1. The diagram of the controller.

3.3 Proof Of Stability

A Lyapunov function V is considered as follows:

$$V = \frac{1}{2}s^2 , \tag{14}$$

The derivative of V is as follows:

$$\dot{V} = \dot{s}s = -\eta s \tanh(\frac{s}{\varepsilon}) \le 0 , \tag{15}$$

4 Numerical Simulations And Discussions

In the numerical simulation, is calculated by formula (5), while is calculated by (6). The end of the single-leg two-link is in contact with the outer . There are the following two situations:

(1) When $x_1 \le 0$, there is no external contact force at the end of the single-leg two-link, that is, $F_e = [0 \quad 0]^T$.

(2) When $x_1 \ge 0$, there is external contact force at the end of the single-leg two-link, that is, $x_1 = 0$, $\dot{x}_1 = 0$, $\ddot{x}_1 = 0$. The damping parameters of the external contact are $M_m = diag[1.0]$, $B_m = diag[10]$, $K_m = diag[50]$.

Considering $\Delta(q, \dot{q}, \ddot{q}) = 1.0 \sin t$, and the controller gain in the synovial controller is selected as $K_1 = \begin{bmatrix} 75 & 0 \\ 0 & 130 \end{bmatrix}$, $K_2 = \begin{bmatrix} 110 & 0 \\ 0 & 161.1 \end{bmatrix}$, $\alpha_2 = 0.5$, $\alpha_1 = 0.67$, $\eta = 1.2$, $\varepsilon = 0.5$. Numerical simulations and results are displayed as follows.

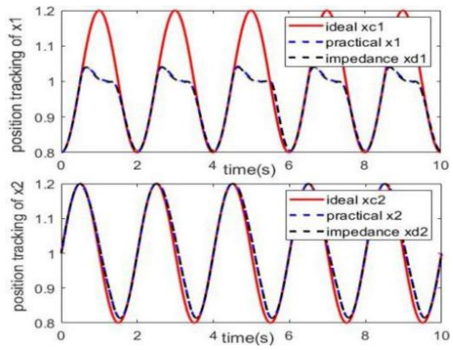

Fig. 2. The end joint node position tracking

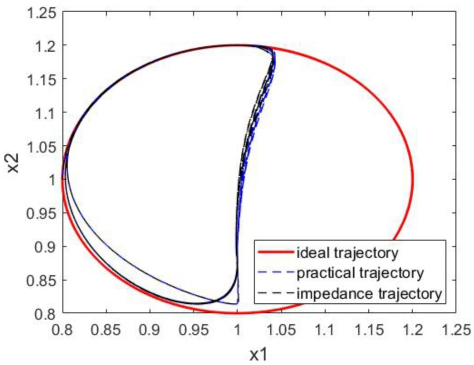

Fig. 3. The full trajectory tracking

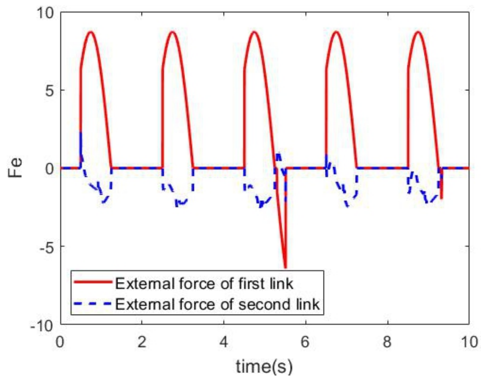

Fig. 4. External contact force

Figure2 shows the end joint node position tracking. Figure3 displays the full trajectory tracking. Figure4 shows the external contact force of the exoskeleton joint. Since the external contact force of the exoskeleton is at $x_1=1.0$, under the influence of impedance control, the position of the joint node rises briefly and then returns to $x_1=1.0$ .It can be seen from the Figure2 and Figure3 that the actual trajectory is not tracking the desired trajectory, but is tracking the impedance trajectory. The above three figures show the impedance control can well consider the influence of the external environment. Under the premise of ensuring stability, the joint can safely reach the target position.

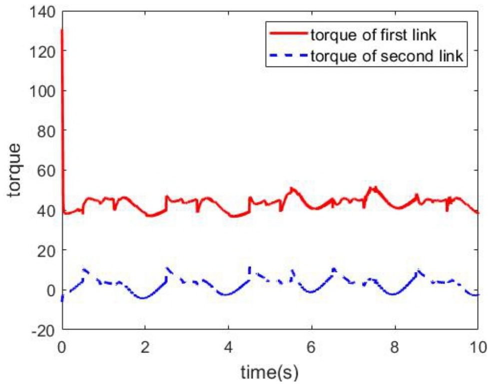

Fig. 5. Actual control torque

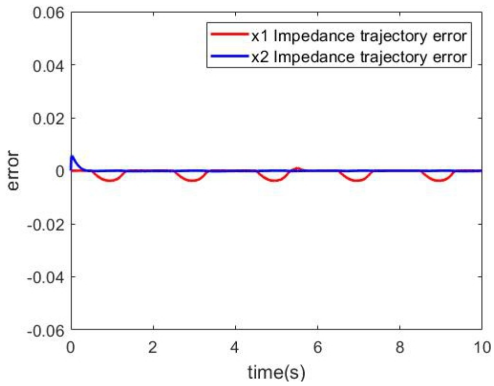

Fig. 6. ITSMC Impedance trajectory error

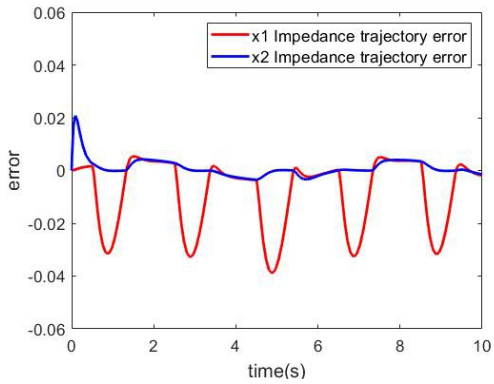

Fig. 7. LSMC Impedance trajectory error

Figure5 shows the actual control torque of the two links. Figure6 shows the impedance trajectory tracking error under the improved integral terminal synovial control (ITSMC). Figure7 shows the impedance trajectory tracking error under the general linear synovial control (LSMC). From the Figure6, we can see that the error is controlled in a very low range. Compared with the linear synovial control, the error is controlled under the improved integral terminal synovial control in a lower range. From the above three pictures, it is obvious that the designed controller makes the system stable and brings good anti-disturbances performance.

5 Conclusion

For the single-leg two-link lower limb exoskeleton system, considering its human-computer interaction force and its disturbances, an impedance synovial controller is proposed. The impedance controller is equivalent to adding feed-forward control to the control system. Under the approach rate based on the hyperbolic tangent function, the integral terminal synovial controller is designed to reduce disturbances and chattering so as to ensure the fast-tracking effect of the system. The simulation results show that the actual control trajectory is continuously adjusted by the synovial controller under the basis of impedance control, and the safe and compliant control is realized. In the future work, we will continue to improve the stability, safety and anti-disturbances ability of lower limb rehabilitation exoskeleton system.

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