Design of Rehabilitation Control Method for Lower Extremity Exoskeleton

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Keywords: Exoskeleton, Sliding mode variable structure compensation control, CPG, Gait planning.

Abstract. In order to obtain rehabilitation of lower extremity exoskeleton robot, control method and gait trajectory are studied and designed. In the control method, the variable structure compensation control method is adopted according to the characteristics of the driving component, and the control results are verified by simulation. As for the gait path planning, we use the CPG oscillator model to generate the oscillatory curve and adjust the angle of the joint by parameter adjustment. Finally, the simulation proves the feasibility of the control method and gait planning, which lays the foundation for the further design and optimization of the lower extremity exoskeleton.

Introduction

Exoskeleton robot is a wearable artificial intelligence bionic equipment which combines sensing, control, information, fusion, mobile computing technology, and can be applied to military, medical, rehabilitation, fire rescue and other fields [1-2]. Most foreign classic exoskeleton products such as BLEEX [3], HULC [4], XOS [5], eLEGS [6] use hydraulic components to drive, mainly for the reason that under the condition of equal output power, the hydraulic system has the characteristics of small size, light weight, low inertia and good dynamic performance. So, this article uses asymmetric valve hydraulic cylinder as the original drive. Classical PID control theory is difficult to overcome the robust problem [7], which in most cases cannot get a satisfactory control effect. Although the sliding mode control method is particularly suitable for the asymmetric hydraulic cylinder trajectory tracking system, it can significantly improve the dynamic precision and robustness of the system [8]. However, in the process of designing a sliding mode controller, it is necessary to obtain the equivalent control amount related to the current system parameters, which is very difficult for the complex hydraulic system. So this paper uses a combination of the two methods of variable structure compensation PID control method to achieve non symmetric valve controlled cylinder trajectory tracking system.

Based on the tracking system, the key problem of trajectory planning is rehabilitation exoskeleton robot movement. The trajectory of the exoskeleton is the trajectory of the human body, or we can say the gait path planning. The traditional method is based on the model of the trajectory planning method, which has made a wide range of applications. But it walks unnatural and consumes high energy. In recent years, the central pattern generator (CPG) based on the motion control principle is relatively wide. With the development of biology and neuroscience, some new research results provide new ideas for the research of robot, especially after the emergence of CPG, the control of rhythmic movement stability and adaptability to the environment has attracted a lot of attention robot [9]. This paper proposes a CPG shock model to generate the exoskeleton robot gait.

Control Method

The design of the traditional sliding mode variable structure controller usually consists of two parts, one is the effective control quantity which is used to ensure that the system state converges and can be stabilized in the sliding surface motion. The other part is the discontinuous control term to compensate the disturbance so that the system state can approach the sliding surface. As exoskeleton is worn on human body, it is difficult to obtain accurate model and parameters. Therefore, it is difficult to determine the equivalent control quantity that depends heavily on the system model and
parameters, and the control performance is difficult to guarantee. In this paper, the main drive of lower extremity exoskeleton is asymmetric valve controlled hydraulic cylinder. The variable structure PID control method is used to control the hip and knee joint. In this method, the sliding surface is designed by the system state equation, and the variable structure term is introduced to compensate the PID control link to improve the robustness of the system. And the method of obtaining equivalent control quantity in traditional synovial variable structure control is avoided, so the design of control is simplified greatly, and the demand of system parameter is reduced.

The reasonable setting of the PID control can be achieved without disturbing the stability of the system and make the error converge to a small level. So in order to ensure the control performance, the reasonable setting of the PID control is regarded as the approximate equivalent control. On this basis, nonlinear compensation is added to suppress the influence of system parameters change and external disturbances so as to improve the robust characteristics of the system. Finally, a block diagram of variable structure compensation PID control method shown in Figure 1 is obtained.

Variable structure compensation PID control is constituted by PID control and variable structure compensation. Among them, the design of variable structure is referenced to the sliding mode variable structure control method. Firstly, set system error:

\[ e = e_1 \] (1)

first order derivative of error

\[ \dot{e} = e_2 \] (2)

second derivative

\[ \ddot{e} = e_3 \] (3)

then the sliding surface equation is:

\[ s = \lambda_1 e_1 + \lambda_2 e_2 + e_3 \] (4)

\( \lambda_1 \) and \( \lambda_2 \) are constant values greater than zero.

Then the variable gain compensation control is obtained with the compensation gain of \( h \). \( \text{sign}(s) \) is sign function. Therefore, the discontinuous control quantity is:

\[ u_c = h \text{sign}(s) \] (5)

![Figure 1. Block diagram of variable structure compensation PID control method.](image)

In the PID control part of the design, considering that the integral sliding surface is not included in the equation while PD control can meet the control requirements in industrial applications, PD control can be used in the variable structure compensation PID controller design to simplify the derivation process of the stability analysis. Thus, the variable structure compensation PID control can be expressed as:
\[ u = -(K_p e_1 + K_d e_2) - h \text{sign}(s) \] 

(6)

It is necessary to point out that the definition of the error in the state equation is the difference between the actual trajectory and the desired trajectory, so the control volumes are all negative.

**CPG Gait**

What the CPG model adopted in this paper is the Mastuoka oscillator model. Using two Mastuoka oscillators to form a simple CPG network, and each oscillator is composed of two mutually inhibited neurons, as is shown in Figure 2.

![Figure 2. Schematic diagram of CPG network model.](image)

Using modified CPG model \(^{[10]}\) can avoid the zero-dead zone caused by the movement of stagnation. The specific differential equations are:

\[
\begin{align*}
\tau_i u_i &= -u_i + bv_i + ay_i + \sum_{j=1}^{n} w_{ij} y_j + u_0 + \text{Feed}_i \\
\tau'_i y_i &= -y_i + y_j \\
y_i &= f(u_i) \\
f(u_i) &= \max(0, u_i) \\
y_i &= y_{fi} - y_{ei} \\
i &= 1, 2, \ldots, n
\end{align*}
\] 

(7)

\(\tau_i\) and \(\tau'_i\) are rise time constant of oscillator and time constant of adaptation. Subscript \(i, f\) respectively represent the \(i\)th oscillator, flexor and extensor neurons. \(w_{ij}\) is the connect weight for oscillator \(j\) to \(i\), \(a\) is the mutual inhibitory coefficient between cells, \(b\) is a self-inhibitory coefficient of cell adaptation, \(u_0\) is constant excitation input, \(\text{Feed}_i\) is feedback item.

The interference immunity of CPG is determined by its insensitivity to initial values. After introducing proper feedback and adding proper reflection mechanism, when the robot is disturbed, the reflex mechanism will act, and the control force or angle of control will have a sudden adjustment to produce a jump. The traditional control of this transition takes a period of feedback to eliminate, or even cannot be eliminated, resulting in movement instability. While the CPG is not sensitive to the initial value, after receiving the jump, it will soon destroy the jump and restore its stable oscillation state. So, robot with CPG control has certain anti-interference \(^{[11]}\).

When adjusting the oscillator parameters, the oscillator's angular frequency and amplitude have the following approximate relationship with the CPG model parameters \(^{[12]}\):

\[
\omega_n \approx \frac{1}{\tau'} \sqrt{(\tau + \tau')b - \alpha u} 
\] 

(8)
\[ A = \frac{u_0}{2} \left( \frac{\tau + \tau'}{\tau a} - 1 + \frac{2}{\pi} (a + b) \sin^{-1}\left( \frac{\tau + \tau'}{\tau a} \right) \right) \]  

Under certain constraints, the desired CPG vibration cycle and amplitude can be obtained by adjusting the parameters of the CPG model, thus satisfying the gait requirements of the lower extremity exoskeleton.

**Simulation Experiment**

In MATLAB/SIMULINK, a variable structure compensation structure PID control model of lower extremity exoskeleton position tracking system, is constructed as shown in Figure 3.

![Figure 3. SIMULINK model of variable structure compensation PID control of lower extremity exoskeleton.](image)

Simulation results given in Figure 4 shows the dynamic tracking effect of sinusoidal signals with frequency 1Hz. It can be seen that the tracking effect maintains a quite good consistency when the asymmetric valve-controlled hydraulic cylinder piston rod is extended and contracted during the movement of the exoskeleton. Comparing the error between the tracking error and the PID control result, as shown in Figure 5, it can be seen that the variable structure compensation PID error is smaller and has higher control precision and better robustness.

![Figure 4. Simulation results.](image)  
![Figure 5. Comparison of error curve.](image)

The simulation model of the CPG oscillator is built in MATLAB/SIMULINK, as is shown in Figure 6.

According to the relationship between amplitude, period and parameter, adjust the parameters to optimize the output curve of the oscillator and compare it with the actual walking ankle angle, as is shown in Figure 7. It can be seen that the results are basically consistent with the changes of ankle angle when walking, thus can be used as the gait trajectory of the lower extremity exoskeleton.
The simulation process does not add feedback items \((Feed_i=0)\), since in order to make the reflex mechanism really play a regulatory role, the feedback item needs a lot of experiments and analysis whose form is also quite complex. However, this does not affect the generality and correctness of the proposed gait generation method.

**Summary**

In this paper, the control method of the lower extremity exoskeleton and the planning of the gait trajectory are mainly designed. For the control method, the variable structure compensation control method is adopted according to the characteristics of the driving component, and the control results are verified by simulation. In the planning of the gait trajectory, the oscillation curve generated by the CPG oscillator model is used as the angle of the joint change based on the relationship between the amplitude period and the coefficient. Finally, MATLAB Simulation is used to verify the feasibility of the proposed control method and gait planning, which lays a foundation for further design and optimization of rehabilitation lower extremity exoskeleton.

**References**


