Research on control algorithm of the upper limb rehabilitation robot based on PI hysteresis compensation

Wang Zhiming¹, Ye Wangwei²*, Gong Sijia³, Hua Qi⁴

¹,²,³,⁴ School of Mechatronic Engineering and Automation, Shanghai University, Shanghai, Baoshan Qu, 200436, China
*Corresponding author’s e-mail: 15990078160@163.com

Abstract. The upper limb rehabilitation robot is used to assist patients with upper limb hemiplegia for rehabilitation training. During the passive rehabilitation training of the patient, the trajectory of the rehabilitation training must be as smooth as possible, so that the patient will not feel discomfort when pulling the affected limb. The passive control algorithm of the existing upper limb rehabilitation robot is not ideal for the lag processing of the system. This paper designs a passive control algorithm based on PI hysteresis compensation. The hysteresis effect of the system can be greatly reduced by introducing the hysteresis compensation term $u_c$. Experimental results show that the algorithm can effectively eliminate the hysteresis effect of the system.

1. Introduction
The Upper limb rehabilitation robot is used for rehabilitation training of upper limb hemiplegia patients [1]. The exoskeleton of the upper limb rehabilitation robot is the core part of the whole system, and the design of motion control strategy directly affects the dynamic characteristics of the robot, and further affects the feasibility and effect of rehabilitation training for patients [2]. Due to the synchronous belt transmission at the elbow joint, the upper limb rehabilitation robot studied in this paper inevitably suffers from hysteresis. Hysteresis will affect the response speed of the system, cause the rehabilitation trajectory to lag, and affect the system stability. This paper requires to design a passive control algorithm for the upper limb rehabilitation robot which can effectively solve the hysteresis effect of the system.

2. Structural model of upper limb rehabilitation robot
The structure model of the 5-DOF upper limb rehabilitation robot is shown in Figure 1. All parts and assemblies are completed by 3D graphics software SOLIDWORKS. It has five degrees of freedom, all of which are rotating joints, mainly for adduction/abduction movement of the upper limb shoulder joint, flexion/extension movement, internal/external rotation movement, flexion/extension of the elbow joint, flexion/extension of the wrist joint motion.

The 5-DOF upper limb rehabilitation robot in this design consists of five servo motors, in which the flexion and extension motion of the elbow joint and the power transmission of the internal and external rotation of the shoulder joint are driven by synchronous belt. For the synchronous belt drive, hysteresis is a relatively easy situation. Compared with other joints that directly use servo drive, if the traditional control algorithm is adopted in the control, the real-time difference of joint response will often be caused, resulting in motion instability and system error. Therefore, the problem of time delay must be considered when controlling the two joints driven by belt drive.
3. Passive control algorithm for PI hysteresis compensation

Passive training is the basic mode of patients' early rehabilitation training, in which the robot drives the patient's affected limb to move in a small range [3]. The role of the robot is to smoothly pull the patient along the trajectory in advance. In the research process of motion control system of the upper limb rehabilitation robot, the classical PI/PD control method is the most used by researchers [4]. Because the model of upper limb rehabilitation robot is complex and difficult to obtain, and the classical PI/PD control technology has the characteristics of dynamic characteristics adjustable. PI/PD control method can achieve satisfactory control effect by adjusting the system parameters.

3.1 Analysis of hysteresis problem

Hysteresis is a special kind of nonlinearity, its output not only depends on the input at the current time, but also depends on the historical state of the input. Due to the existence of hysteresis, the system often presents defects such as poor control accuracy, oscillation, and even instability [5]. The traditional control becomes powerless, especially when the hysteresis is unknown, the control of such uncertain factors is more difficult, so various effective control approaches are needed to eliminate the influence of hysteresis.

In order to deal with the dynamic system with hysteresis, the hysteresis is first modelled. The Preisach model [6], KP model and PI model are common models. In view of the control problem of hysteresis system, the main method is to build its inverse model to compensate on the basis of hysteresis modelling. In this paper, the hysteresis compensation is introduced in the traditional PI control algorithm and the trajectory tracking effect of joints is studied.

3.2 PI hysteresis compensation control algorithm

In the process of motion rehabilitation of the upper limb rehabilitation robot, the energy transferred by the motor to the corresponding joint will be partially lost, which will lead to a certain deviation between the actual joint movement offset and the ideal position offset of the actual motor output.

Suppose that the planned trajectory of the joint is $\theta^r$, and the actual trajectory of the joint is $\theta$, then error $e$ and error integral $n$ can be expressed as:

$$e = \theta^r - \theta$$

(1)
\[ n = \int_{0}^{t} (\theta^r(\tau) - \theta(\tau))d\tau \]  

(2)

The control of traditional PI controller is:

\[ u_m = K_p e + K_i n \]  

(3)

The hysteresis phenomenon mainly occurs at the joint motion commutator. In order to eliminate the time delay of the system, the time delay compensation term \( u_c \) is introduced on the basis of the original PI control law, as follows:

\[ u_c = K_c \frac{v^r}{q + (v^r)^2} \]  

(4)

Where, \( K_c \) is the time delay compensation coefficient, \( q \) is strictly positive real number, and \( v^r \) represents the speed of the joint. Therefore, the PI control law after introducing delay compensation is:

\[ u = u_c + u_m = K_p e + K_i n + K_c \frac{v^r}{q + (v^r)^2} \]  

(5)

The five joint positions and joint velocity expression symbols of the upper limb exoskeleton rehabilitation robot designed in this paper are shown in table 1.

| The joints                        | Joint position notation | joint velocity notation |
|-----------------------------------|-------------------------|------------------------|
| Flexion and extension of shoulder joint | \( \theta_1 \)          | \( v_1 \)              |
| The shoulder joint is extended    | \( \theta_2 \)          | \( v_2 \)              |
| Shoulder screw inside and outside| \( \theta_3 \)          | \( v_3 \)              |
| Elbow flexion and extension      | \( \theta_4 \)          | \( v_4 \)              |
| Wrist flexion and extension      | \( \theta_5 \)          | \( v_5 \)              |

By substituting each joint into the above equation, the PI delay compensation control law of each joint can be obtained as follows:

\[ u_1(k) = K_{p1}(\theta^r_1(k) - \theta_1(0)) + K_{i1}T \sum_{i=1}^{k} (\theta^r_1(i) - \theta_1(i)) + K_{c1} \frac{v^r_1(k)}{q + (v^r_1(k))^2} \]  

(6)

\[ u_2(k) = K_{p2}(\theta^r_2(k) - \theta_2(0)) + K_{i2}T \sum_{i=1}^{k} (\theta^r_2(i) - \theta_2(i)) + K_{c2} \frac{v^r_2(k)}{q + (v^r_2(k))^2} \]  

(7)

\[ u_3(k) = K_{p3}(\theta^r_3(k) - \theta_3(0)) + K_{i3}T \sum_{i=1}^{k} (\theta^r_3(i) - \theta_3(i)) + K_{c3} \frac{v^r_3(k)}{q + (v^r_3(k))^2} \]  

(8)

\[ u_4(k) = K_{p4}(\theta^r_4(k) - \theta_4(0)) + K_{i4}T \sum_{i=1}^{k} (\theta^r_4(i) - \theta_4(i)) + K_{c4} \frac{v^r_4(k)}{q + (v^r_4(k))^2} \]  

(9)

\[ u_5(k) = K_{p5}(\theta^r_5(k) - \theta_5(0)) + K_{i5}T \sum_{i=1}^{k} (\theta^r_5(i) - \theta_5(i)) + K_{c5} \frac{v^r_5(k)}{q + (v^r_5(k))^2} \]  

(10)

Where, \( T \) represents the sampling period of the system.

4. Experimental verification

In order to observe the robustness of the above PI time-delay compensation control algorithm, the elbow joint of the upper limb rehabilitation robot was selected as the experimental object. The actual angular position of the joint is read by an encoder mounted at the joint. The trajectory errors of traditional PI control algorithm and PI hysteresis compensation control algorithm were recorded respectively.
Figure 2 shows the trajectory error curve. By observing the error changes of the PI hysteresis compensation control curve in figure 3, it can be seen that the trajectory tracking effect is significantly better and the trajectory error is significantly smaller. The maximum error of trajectory tracking is 0.62° and the maximum error value is reduced by 66.1%, indicating that the PI hysteresis compensation algorithm can compensate for the system delay in time.

![Graph showing elbow position error](image)

Figure 2. Elbow position error

5. Conclusion
In the passive control strategy of the upper limb rehabilitation robot, the control algorithm of PI hysteresis compensation is proposed in this paper. The introduction of the time delay compensation term \( u_c \) significantly reduces the time delay effect of the system and makes the trajectory control smooth and stable.

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