Robot dynamic trajectory tracking control algorithm based on steady-state closed-loop learning

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Abstract. In order to improve the stability control ability of flexible lower limb exoskeleton robot, a dynamic trajectory tracking control algorithm of flexible lower limb exoskeleton robot based on steady-state closed-loop learning is proposed. Gyroscope and rangefinder are used as information sensors of flexible lower limb exoskeleton robot to collect position information of flexible lower limb exoskeleton robot, fuse collected positioning information of flexible lower limb exoskeleton robot, fuse physical information and measure parameters of flexible lower limb exoskeleton robot by using dynamic information measurement method, and obtain mapping feature set of Cartesian space according to trajectory components of flexible lower limb exoskeleton robot. The pose information of the flexible lower limb exoskeleton robot is obtained through the forward kinematics, and the information is enhanced according to the spatial position information. The steady-state closed-loop learning method is adopted to realize the adaptive learning of the robot dynamic trajectory tracking control. The simulation results show that this method is adaptive to the dynamic trajectory tracking control of the robot, and the positioning control ability of the robot is strong.

1. Introduction
With the development of intelligent flexible lower limb exoskeleton robot technology, it is necessary to use artificial intelligence control method to design the positioning of flexible lower limb exoskeleton robot, so as to improve the stability control ability of robot. In the process of building equipment inspection, the output stability of flexible lower limb exoskeleton robot is not good, and its target positioning and environmental adaptability are not strong. It is necessary to combine environmental parameter fusion with robot attitude stability adjustment model. The positioning control model of flexible lower limb exoskeleton robot is established to improve the output stability of flexible lower limb exoskeleton robot, and the related research on positioning method of flexible lower limb exoskeleton robot has attracted great attention[1].

Intelligent positioning control of flexible lower limb exoskeleton robot is realized by optimizing the robot's environmental parameters and self-adaptive control. According to the visual imaging and parameter characteristics of flexible lower limb exoskeleton robot, combined with the method of environmental parameter fusion, the output stability control of robot is realized. At present, the methods of stability control and location detection of flexible lower limb exoskeleton robot mainly include PID control method, visual feature detection method, fuzzy parameter control method and spatial feature matching method, etc. In the computer vision environment, the visual target image point matching of flexible lower limb exoskeleton robot is studied to realize visual tracking and location recognition, but the traditional methods for dynamic trajectory tracking control of flexible
lower limb exoskeleton robot have poor adaptability and low accuracy [2]. In this paper, a dynamic trajectory tracking control method of flexible lower limb exoskeleton robot based on steady-state closed-loop learning is proposed. Firstly, the position information of flexible lower limb exoskeleton robot is collected, and then the robot's own structural parameters and physical parameters are combined to carry out feature matching, and a feature matching model of the robot's environmental parameters and control parameters is established. Finally, the simulation test analysis is carried out, and the validity conclusion is obtained.

2. Flexible lower limb exoskeleton motion information sampling and robot pose information extraction

2.1. Motion information acquisition of flexible lower limb exoskeleton

In order to realize the dynamic trajectory tracking control of the flexible lower limb exoskeleton robot, the fusion sensing recognition technology is adopted to collect the attitude and position parameter information of the flexible lower limb exoskeleton robot, and the motion information distribution characteristic quantity of the flexible lower limb exoskeleton robot is analyzed [3]. Combined with the adaptive parameter optimization method, the robot's equipment information and component information are collected by using sensors such as gyroscopes, and the robot's motion information recognition ability is improved. Using gyroscopes and rangefinders to collect information, the attitude characteristic quantity of the flexible lower limb exoskeleton robot is expressed as follows:

\[
S_{\gamma,(n)}(f) = \frac{T_B}{(NT_C)}X(f)\sum_{n=0}^{N-1} \sin^2\left(\pi T_B \left(f - \frac{1}{NT_C}\right)\right)
\]

Wherein

\[
\left|X(f)\right|^2 = T_C^2 N \sin^2\left(\pi T_C f\right) \left|X_{\text{code}}(f)\right|^2
\]

\[
X_{\text{code}}(f) = \frac{1}{\sqrt{N}} \sum_{n=0}^{N-1} x_n \exp(-j2\pi fnT_c)
\]

In which, \(T_C\) is the oscillator parameter optimized by two sensors, \(T_B\) is the track output parameter, and \(N\) is the sampling frequency number representing the flexible lower limb exoskeleton robot. By using the non-rigid characteristic analysis method, the corresponding moving centroid distribution of the robot is obtained as follows:

\[
PG_{ab} = 10\log_{10} N - 10\log_{10} \left(\sin c\left(\pi f_T T_c\right)\right) - 10\log_{10} \left(\left|X_{\text{code}}(f)\right|^2\right) - 10\log_{10} \left(\sum_{f_i} \sin c\left(2\pi f_i \left(f - \frac{1}{NT_C}\right)\right)\right)^2
\]

According to the above analysis, combined with the robot walking vibration suppression method, the offset component of the flexible lower limb exoskeleton robot is calculated as \(1/NT_C\) Hz, and the modified DH parameter method is used to carry out position parameter correction and information fusion, and the parameter correction equation is obtained as follows:

\[
r(t) = s(t) + j(t)
\]

Wherein, \(s(t)\) is the deviation correction control component of the flexible lower limb exoskeleton robot, and the ranging code \(j(t)\) is obtained. The collected positioning information of the flexible lower limb exoskeleton robot is fused by using the dynamic information measurement method, and given the movement track distribution of the end, the characteristic components of the positioning information are as follows:
According to the above analysis, the position information of the flexible lower limb exoskeleton robot is collected, and the motion information fusion and adaptive control are carried out by combining the parameter fusion technology[4-6].

2.2. Robot pose information extraction and environment map planning

According to the trajectory component of the flexible lower limb exoskeleton robot, when the mapping feature set of Cartesian space is satisfied $f_j = f_0$, multi-parameter fusion is carried out according to the pose information of the robot, and the dynamic distribution expression becomes:

$$ J_1(nT_b) = \sqrt{\frac{2}{S}} \frac{1}{T_b} \int_{nT_b}^{(n+1)T_b} J_1(t) \, dt = \frac{2J\sqrt{J}}{ST_B} \sum_{i=(n-1)/N}^{nN-1} c_i \int_{t_i}^{t_{i+1}} \cos \varphi_i \, dt = \frac{2J}{SN} \cos \varphi_j \sum_{i=(n-1)/N}^{nN-1} c_i $$

The inverse kinematics model of the flexible lower limb exoskeleton robot is obtained, and the minimum characteristics of the new position in the drag line are as follows:

$$ \Delta E = -\eta \left[ \left( \frac{\partial E}{\partial \theta} \right)^2 + \left( \frac{\partial E}{\partial b} \right)^2 \right] $$

Let the set of desirable points of the flexible lower limb exoskeleton robot on the 180° meridian trajectory satisfy the convergence, and get $d_1, d_2, \ldots, d_q$ under the constraint convergence condition. If $C_\phi(x') = 0$, different trajectory tracking task sets are obtained to satisfy:

$$ Y(P, Q, \beta) = Y\left[ \text{red} (P, Q, \beta), Q, \beta \right] $$

The pose information of the flexible lower limb exoskeleton robot is obtained by forward kinematics, which is expressed as:

$$ J_1(nT_b) = \frac{2J\sqrt{J}}{SN} \cos \varphi_j \sum_{i=0}^{N-1} c_i $$

According to the information collection results of the flexible lower limb exoskeleton robot information sensor, the environment map planning of the flexible lower limb exoskeleton robot positioning is carried out[7], as shown in Figure 1.

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**Figure 1** Environment map planning of flexible lower limb exoskeleton robot
3. Optimization of robot dynamic trajectory tracking control

3.1. Design of control algorithm

The collected positioning information of flexible lower limb exoskeleton robot is fused, the physical information fusion and parameter measurement of flexible lower limb exoskeleton robot are carried out by using dynamic information measurement method[8], and a 4×4 block combination model is used for visual tracking of flexible lower limb exoskeleton robot, and the distribution function of visual characteristics of flexible lower limb exoskeleton robot is obtained as follows:

\[ p\left(y_{n_i} \mid x_{n_i}, \theta, \beta\right) \propto p\left(y_{n_i} \mid x_{n_i}, \theta\right)p\left(y_{n_i} \mid \beta\right) \]

\[ \propto \prod_{i=1}^{k} \alpha_i \frac{1}{\sqrt{2\pi\sigma_i^2}} \exp\left\{-\frac{(x_i - \mu_i)^2}{2\sigma_i^2}\right\} \frac{1}{Z(\beta)} \exp\left\{-\sum_{i=1}^{c} V_i(y, \beta)\right\} \]

\[ = \prod_{i=1}^{k} \frac{\alpha_i}{Z(\beta)\sqrt{2\pi\sigma_i^2}} \exp\left\{-\frac{1}{2\sigma_i^2} \sum_{i=1}^{k} (x_i - \mu_i)^2 + \sum_{i=1}^{c} V_i(y, \beta)\right\} \]

The spatial information planning model of the flexible lower limb exoskeleton robot is established in the 4×4 sub-block area, and the information is enhanced according to the spatial position information, and the positioning control constraint function of the flexible lower limb exoskeleton robot is obtained in the 3×3 sub-block as follows:

\[ p(x_{n_i}, y_{n_i} \mid \Theta) = \prod_{i=1}^{k} \prod_{i=1}^{k} \alpha_i g(x_i, y_i \mid \mu_i, \sigma_i^2) \]

In the formula, \( w_3 \) represents the environmental constraint parameters of 3×3 block area and gray feature set, \( x_y \in w_3 \) represents the spatial state distribution set of robot retreat area, \( y_y \) represents the gradient minimum of flexible lower limb exoskeleton robot, and \( \alpha_i \) represents the fuzzy parameter rule set \( \Theta \), which is expressed as follows:

\[ \Theta = \left\{ \alpha_1, \alpha_2, \ldots, \alpha_k; \mu_1, \mu_2, \ldots, \mu_k; \sigma_1^2, \sigma_2^2, \ldots, \sigma_k^2 \right\} \]

Wherein, \( \mu_i, \sigma_i^2 \) represents the mean and variance of fitness of flexible lower limb exoskeleton robot. According to the above analysis, combined with the robot's own structural parameters and physical parameters, the feature matching model of the robot's environmental parameters and control parameters is established, and the position tracking information of the flexible lower limb exoskeleton robot is extracted to improve the positioning ability[9].

3.2. Parameter fusion and estimation optimization

Physical information fusion and parameter measurement of flexible lower limb exoskeleton robot are carried out by using dynamic information measurement method, and feature matching is carried out by combining the robot's own structural parameters and physical parameters, and a feature matching model of robot's environmental parameters and control parameters is established[10]. The modified feature components of dynamic positioning matrix of flexible lower limb exoskeleton robot are obtained as follows:

\[ (C_i/N_i)_{eff} = \frac{1}{(C_i/N_i) + \frac{C_i/C_r}{QR_c}} \]

Calculate the inverse kinematics distribution, and obtain the parameter output gain of dynamic positioning as follows:

\[ Q = \frac{\int_{-\infty}^{\infty} \left| H_k(f) \right|^2 G_c(f) df}{\int_{-\infty}^{\infty} \left| H_k(f) \right|^2 G_c(f) G_c(f) df} \]

According to the end-following kinematics analysis method, the pose is corrected, and the joint
variables of the flexible lower limb exoskeleton robot are expressed as follows:

$$s(t) = \frac{S}{\sqrt{2}} d(t)c(t)\cos(2\pi f_s t) + \frac{S}{\sqrt{2}} d(t)c(t)\sin(2\pi f_s t)$$

(17)

$$j(t) = \sqrt{2J} \cos\left(2\pi f_s t + \phi_j\right)$$

(18)

The dynamic trajectory tracking control of the robot is carried out by using the end-following motion adjustment method, and the adaptive control law is expressed as follows:

$$P_{\eta}(k) = \sum_{j=1}^{n_h(k)} (j_j(k)-j_i(k))\eta_j(k)$$

(19)

Wherein

$$j \in N_i(k), N_i(k) = \left\{ \| x_j(k) - x_i(k) \| < r_d(k) \right\}$$

(20)

In which, \( \eta_j(k) \) is the process function of the robot's end following movement, and the robot is positioned in a 6-degree-of-freedom space, and the positioning accuracy is as follows:

$$\eta_i(k) = \begin{bmatrix}
    c\theta & -s\theta & 0 & a_{\alpha_4} \\
    s\theta c\alpha_{\alpha_4} & c\theta c\alpha_{\alpha_4} & -s\alpha_{\alpha_4} & -d_s a_{\alpha_4} \\
    s\theta s\alpha_{\alpha_4} & c\theta s\alpha_{\alpha_4} & c\alpha_{\alpha_4} & d c\alpha_{\alpha_4} \\
    0 & 0 & 0 & 1
\end{bmatrix}$$

(21)

In which: \( s \) represents the adjacent constraint parameter and \( c \) represents the process variable, by adding a rotation error. To sum up, the dynamic positioning optimization is carried out according to the environmental perception information of the flexible lower limb exoskeleton site, and the adaptive control and posture dynamic adjustment in the process of robot positioning and detection are carried out in combination with the map space planning algorithm to realize the dynamic positioning and posture reliability control of the robot\[11,12\].

4. Simulation experiment and result analysis

In order to verify the application performance of this method in realizing the dynamic trajectory tracking control of flexible lower limb exoskeleton robot, the simulation experiment was carried out, and OpenCV was used for simulation test. The sensitivity coefficient of flexible lower limb exoskeleton robot for measuring environmental parameters was set to 0.34 mdps/digit, and the working environment temperature of the robot was -10°C–+50°C, which met the requirements of general building environment. The sampling time interval of flexible lower limb exoskeleton motion information was 0.45s, and the map of flexible lower limb exoskeleton robot was constructed.

| Table 1 Map Spatial Distribution of Flexible Lower Extremity Exoskeleton Robot |
|-------------------------------------------------|
| Map center | Measured positioning center | Error spacing |
|------------|-----------------------------|---------------|
| 1 | (-54,32) | (-4, 5) | 4.56 |
| 2 | (14.5,26.5) | (15,13.2) | 5.78 |
| 3 | (43, 45) | (24,156) | 5.54 |
| 4 | (13.5,36.5) | (14,145) | 5.52 |
| 5 | (14,-3.5) | (122,-45) | 6.44 |
| 6 | (24.1,15.6) | (34.6,14.4) | 5.16 |

According to the above parameter settings, the dynamic trajectory tracking control of the flexible lower limb exoskeleton robot is carried out, and the sampling results of the robot motion information are shown in Figure 2.
According to the sampling results in figure 2, the pose tracking information of the flexible lower limb exoskeleton robot is extracted, and the dynamic positioning optimization is carried out according to the environmental perception information of the flexible lower limb exoskeleton site, so as to realize the dynamic trajectory tracking control of the robot. The detection results are shown in figure 3.

Analysis of Figure 3 shows that this method can effectively realize the accurate positioning of flexible lower limb exoskeleton robot, and test the positioning accuracy. The comparison results are shown in Table 2. Analysis of Table 2 shows that this method has higher positioning accuracy for flexible lower limb exoskeleton robot.

Table 2 Comparison of positioning accuracy

| Iteration times | Reference [3] | Reference [4] | Reference [5] |
|----------------|---------------|---------------|---------------|
| 100            | 0.435         | 0.854         | 0.943         |
| 200            | 0.676         | 0.857         | 0.957         |
| 300            | 0.967         | 0.965         | 1             |

5. Conclusions
Combining environmental parameter fusion and robot attitude stability adjustment model, the positioning control model of flexible lower limb exoskeleton robot is established to improve the output stability of flexible lower limb exoskeleton robot. In this paper, a dynamic trajectory tracking control method of flexible lower limb exoskeleton robot based on steady closed-loop learning is proposed. Gyroscope and other sensor devices are used to collect the equipment information and component information of robot, and the frontal position information of flexible lower limb exoskeleton robot is obtained through forward kinematics. According to the spatial position information, the feature matching model of the robot's environmental parameters and control parameters is established, and the position tracking information of the flexible lower limb exoskeleton robot is extracted to realize the accurate positioning and detection of the robot. The research shows that the positioning accuracy of
the flexible lower limb exoskeleton robot by this method is higher and the control performance is better.

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