

Deviation Correction Control of Biped Robot Walking Path Planning

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Abstract: The biped robot is disturbed by the bottom and the ground during walking, and the track error is generated. In the path planning of the robot, it needs for deviation tracking control, a method for controlling foot stability of biped robot is proposed based on centroid operation state compensation in this paper. The motion equation of the center of mass is constructed and the horizontal velocity of the center of mass is controlled by controlling the displacement of the center of mass in a single step period. According to the cycle characteristics of the robot walking system and the horizontal velocity of the robot centroid motion as the controlled object, the trajectory correction system model of the robot is constructed, and the position and pose of the robot end are obtained. The feedback controller is constructed to control the path offset compensation of the robot, and the biped robot path planning control is realized. The simulation results show that the trajectory correction control of biped robot with this method has strong ability of path planning and accurate track tracking, and it can accurately describe the dynamic characteristics of the robot's path. The tracking error is controlled in a lower range.

1. Introductions

With the development of artificial intelligence control technology, control technology of robot has made great progress. In the design of all kinds of robots, biped robots is referred as a typical, biped robots can effectively imitate human walking and other operations, it has a very good ability to adapt to the environment and space planning ability, and it can effectively replace humans to engage in high-risk work. For example, in the fields of complex environment exploration, disaster rescue, military target attack, it can take the place of human to carry out related operations, thus avoiding human casualties. In the design of humanoid biped robot, the space path planning and design of robot is the key. Through path planning, the trajectory tracking control ability of robot is improved to ensure that the robot can reach the predetermined position accurately. It has great significance to study the path planning and control method of robot walking so as to improve the ability of environment adaptation and autonomous control of robot^[1].

The basis of path planning for biped robot is taken based on correction of the trajectory shift. The disturbance between the two feet and the ground makes the robot produce trajectory deviation, so it is necessary to control the trajectory correction of the robot. Trajectory correction control is a process that the robot adjusts its terminal position and posture in real time and reduces the trajectory tracking error when it performs the trajectory tracking task. The common robot trajectory correction control



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methods mainly include inverse kinematics control method, end position and attitude correction control method, Cartesian space position correction method, fuzzy PID control method^[2-4], by adding a fretting control device to the end of the original robot, combining the above control methods, the terminal position and pose are adjusted, the inertial dynamic parameter adjustment of the robot is realized in Descartes space. The micro-adjustment of the robot terminal position and the correction of the dynamic trajectory shift are realized, and the trajectory tracking control ability of the biped robot is improved. For example, the MotomanUP6 robot of Igawa Company of Japan adopts the trajectory correction method based on fuzzy PID control to control the position correction of the robot's end actuator along the direction of Descartes space, so as to realize the path fuzzy correction. However, the tracking accuracy of this method is poor in the presence of small perturbations. In reference ^[5], an integral rectifying controller is proposed to improve the path tracking stability of the robot by correcting the heating error of the workpiece during the welding process of the robot. This method requires the robot to track the position and direction of the radio signal accurately with time. When the signal intensity is insufficient, the error correction control performance is not good.

Aiming to solve the above problems, a biped robot driving walking stability correction control method is proposed based on centroid state compensation. Firstly, the motion equation of the center of mass of the robot is constructed, and the horizontal velocity of the center of mass is controlled by controlling the displacement of the center of mass in a single step period. Then the robot trajectory correction system model is constructed to obtain the position and pose of the robot end and the feedback controller is constructed to control the robot path offset compensation to realize the biped robot walking path planning control. Finally, the simulation is taken, experiment results show that the proposed method can improve the ability of path planning and offset correction control of biped robot.

2. Model of trajectory correction system for robot

2.1. Robot Model

Because the sensor measurement noise and nonlinear disturbance exist in the walking process of the robot, the disturbance control model of the robot is established under the constraint of the centroid acceleration, the rectifying controller is designed^[6]. Combined with the dynamic characteristics of humanoid biped robot, the trajectory correction system model is established. In order to describe the robot, the robot model is composed of two identical legs and thighs. The motion space planning model of humanoid biped robot is shown in figure 1.

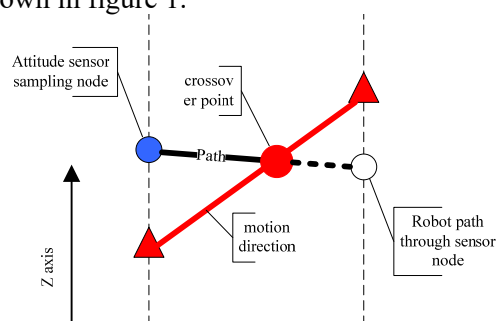


Fig 1. Motion space programming model for humanoid biped robot

According to the space planning model of Figure 1, the trajectory tracking control model of the robot is designed. The kinematic chain model of the robot at t time is described as $\{A^0, A^1\}$. The inertia parameter A^0 of the robot running to any position in space is regarded as the root of the motion chain. The single axis trajectory control method is used to adjust the robot motion parameters adaptively^[7]. When the inertial rotation angle of the robot is 0, the inertia moment of lateral displacement is α_0 , the steering angle is γ_0 . Therefore, the dynamic parameter distribution model of

the robot is $\mathbf{q}_0 = [\alpha_0, \beta_0, \gamma_0]^T \equiv [\theta_1, \theta_2, \theta_3]^T$. The kinematic inertial coordinate system of the four-bar robot is established, and the position and attitude measurement matrix of the three-dimensional motion given space is obtained as $\mathbf{q}_1 = [q_1, \dots, q_7]^T \equiv [\theta_4, \dots, \theta_{10}]^T$.

The connecting rod number of fixed robot is $n = 10$. In the spatial coordinate system, the angle between the virtual bar and the vertical plane is obtained by considering the requirements of the Lawson protocol in the walking process of the robot, and the angle between the virtual rod and the vertical plane is obtained as $\boldsymbol{\theta} = [\mathbf{q}_0^T, \mathbf{q}_1^T]^T \equiv [\theta_1, \dots, \theta_{10}]^T$, the normal vector of the active joint moment of the machine in inertial coordinate system is $\mathbf{g}_c = \{g_0, \dots, g_{N_r}\}$, the forward kinematics equation is $\mathbf{p}_e = \mathbf{f}(\boldsymbol{\theta})$. According to the above-mentioned robot model, path planning and correction control are carried out.

Motion State Model of Robot centroid

In the phase of walking with one foot, the system composed of robot and ground has four degrees of freedom, while the robot has only three active driving moments. The attitude parameters within a given robot's single motion cycle satisfy $\boldsymbol{\theta}_{start} \in \mathbf{C}_{free}$ (free C-space), the robot motion trajectory \mathbf{p}_{obj} and the target tracking trajectory set \mathbf{g}_c are obtained, and the set of state parameters of the robot's centroid is obtained as $M = \{m_i | i = 1, 2, \dots, m\}$, and the robot motion is obtained. The discrete form of observation equation of state equation and attitude determination parameter is obtained as follows:

$$\begin{aligned} x(k+1) &= \Phi_i(k)x(k) + w_i(k) \quad i = 1, 2, \dots, m \\ z(k) &= H_i(k)x(k) + v_i(k) \quad i = 1, 2, \dots, m \end{aligned} \quad (1)$$

Where, $w_i(k)$ and $v_i(k)$ are the attitude vectors and disturbance noise of the robot in inertial coordinate system. The dynamic walking process of the robot is tracked dynamically by inverse kinematics. The measurement information of the robot's walking speed and the state of the center of mass are $Q_i(k)$ and $R_i(k)$ respectively.

Thus, the motion equation of the center of mass of the robot walking is constructed:

$$Z_c \begin{bmatrix} U \\ V \\ 0 \end{bmatrix} = \begin{bmatrix} \frac{f}{d_x} & 0 & U_0 & 0 \\ 0 & \frac{f}{d_y} & V_0 & 0 \\ 0 & 0 & 1 & 0 \end{bmatrix} \begin{bmatrix} R & T \\ O^T & 1 \end{bmatrix} \begin{bmatrix} X_w \\ Y_w \\ Z_w \\ 1 \end{bmatrix} \quad (2)$$

In the formula, Z_c denotes the reference trajectory of the robot's end, (x_w, y_w, z_w) is the position of the centroid of mass, (U_0, V_0) is the displacement of the center of mass relative to the contact point, and (U, V) is the point coordinate of the joint's independent motion.

3. Control algorithm optimization

3.1. Identification of Terminal position and pose parameters of Robot

According to the cycle characteristics of the robot walking system, the horizontal velocity of the robot's centroid motion is taken as the controlled object, and the 6-DOF parameter of the robot's rotational joint is taken as the control constraint parameter^[8]. During the complete walking period, the

biped machine is controlled. Inverse Jacobian matrix of terminal position and attitude of biped robot is:

$${}^{i-1}T_i = \begin{bmatrix} c\theta_i & -s\theta_i & 0 & a_{i-1} \\ s\theta_i c\alpha_{i-1} & c\theta_i c\alpha_{i-1} & -s\alpha_{i-1} & -d_i s\alpha_{i-1} \\ s\theta_i s\alpha_{i-1} & c\theta_i s\alpha_{i-1} & c\alpha_{i-1} & d_i c\alpha_{i-1} \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (3)$$

In the 6-DOF space model, by multiplying the transformation of each connecting rod, the pose transformation matrix of the bionic robot is obtained as:

$${}^0_6 T = {}^0_1 T {}^1_2 T {}^2_3 T {}^3_4 T {}^4_5 T {}^5_6 T \quad (4)$$

The upper expression is the pose matrix of the robot's end actuator. The dynamic variable of attitude angle is $x = [\varphi, \dot{\varphi}, \theta]^T$, the pose of robot end is obtained, and the feedback controller is constructed to control the robot path offset compensation^[9]. The horizontal component of the robot's center of mass and supporting foot is taken as the input variable, the state under the standard position and pose structure is x_0 ($x_0 = [\varphi_0, \dot{\varphi}_0, \theta_0]^T$), and the equilibrium condition of motion is: $f(x_0, u_0) = 0$. The identification parameter of the displacement control of the center of mass relative to the contact point is m_j ($j = 1, 2, \dots, m$) $\forall m_j \in M$. The robot is subjected to horizontal and vertical ground action, and the velocity attenuation process is described as follows:

$$\bar{c}_j = \sum_i^m P_{ij} u_i(k-1) \quad (5)$$

Thus, the identification model of the terminal position and pose parameters of the robot is obtained as follows:

$$u_{i/j}(k-1/k-1) = P(m_i(k-1)/m_j(k), z^{k-1}) = \frac{1}{\bar{c}_j} P_{ij} u_i(k-1) \quad (6)$$

By introducing the error gain coefficient to eliminate the equivalent swing of the center of mass of the rod, the optimal identification output of the position and pose parameters is obtained as follows:

$$\hat{x}^{0j}(k-1/k-1) = \sum_i^m \hat{x}^i(k-1/k-1) u_{i/j}(k-1/k-1) \quad (7)$$

$$P^{0j}(k-1/k-1) = \sum_i^m u_{i/j}(k-1/k-1) \{ P^i(k-1/k-1) + [\hat{x}^i(k-1/k-1) - \hat{x}^{0j}(k-1/k-1)] [\hat{x}^i(k-1/k-1) - \hat{x}^{0j}(k-1/k-1)]^T \} \quad (8)$$

Where, $\hat{x}^{0j}(k-1/k-1)$ and $P^{0j}(k-1/k-1)$ are used as the control input of trajectory deviation, the trajectory correction system model of robot is constructed, and the offset correction control is carried out[10].

3.2. Centroid trajectory generation and offset correction

The horizontal velocity of the robot centroid motion is taken as the controlled object. The optimal guidance law of the robot end tool in the reference trajectory is obtained as follows:

$$\hat{x}(k/k) = \sum_j^m \hat{x}^j(k/k) u_j(k) \quad (9)$$

$$P(k/k) = \sum_j^m u_j(k/k) \{P^j(k/k) + [\hat{x}^j(k/k) - \hat{x}(k/k)][\hat{x}^j(k/k) - \hat{x}(k/k)]^T\} \quad (10)$$

Ignoring the influence of dynamics and dynamic characteristics of robot motion control system, under the convergence control of trajectory correction error[11], the configuration space function of error correction is obtained as follows:

$$KL' = \sum_{i=1}^{m+a} \frac{1}{N} \ln \frac{1}{Nw_d^i(H)} + \sum_{i=1}^{N-m-a} \frac{1}{N} \ln \frac{1-Kd_i^{\max}}{N} \ln \frac{1-Kd_i^{\max}}{Nw_d^i(H)} + \sum_{i=1}^{N-m-a} \frac{1}{N} \ln \frac{Kd_i^{\max}}{N} \ln \frac{Kd_i^{\max}}{Nw_d^i(L)} \quad (11)$$

The robot joints are always in Θ when the trajectory is rectified, and the control function of the robot's rectifying configuration is obtained as follows:

$$f_1(x) = \frac{1}{N} \sum_{i=1}^{m+a} x_H^i + \frac{1}{N} \sum_{i=1}^{N-m-a} x_S^i (1-Kd_i^{\max}) + \frac{1}{N} \sum_{i=1}^{N-m-a} Kd_i^{\max} x_L^i \quad (12)$$

$$f_2(x) = \sum_{i=1}^N x_D^i w_D^i \quad (13)$$

The path planning of biped robot is carried out by replacing the trajectory correction controller with the proportional integral controller. The correlation between the error correction and the time derivative of the trajectory deviation is:

$$KL = \sum_{i=1}^{m+a} \frac{1}{N} \ln \frac{1}{Nw_d^i(H)} + \sum_{i=1}^{N-m-a} \frac{1}{N} \ln \frac{1}{N} \ln \frac{1}{Nw_d^i(H)} + 0 \quad (14)$$

$$\sum_{i=1}^m n_i = \sum_{i=1}^N = N \quad (15)$$

Where the integral control term is $\{W_{final}\}$, and the error correction of the robot is rewritten as:

$$\{W_{final}\} = \{x_F^i\}_{i=1}^N = \left\{ \frac{1}{N} \sum_{i=1}^{m+a}; x_H^i, \frac{1}{N} \sum_{i=1}^{N-m-a} (1-Kd_i^{\max}); x_S^i, \frac{1}{N} \sum_{i=1}^{N-m-a} Kd_i^{\max}; x_L^i \right\} \quad (16)$$

In order to realize the periodic stable walking, the space path planning objective function of the robot system under the constraint of the modified centroid control is:

$$\text{s.t.} \quad \begin{cases} \sum_{j \in N} x_{i,j} = 1, \forall j \in N \\ \sum_{i \in N} x_{i,j} = 1, \forall i \in N \\ \sum_{i \in M} \sum_{j \in N-M} x_{i,j} \geq 1, M \subset N \end{cases} \quad (17)$$

The displacement of the mass center is adjusted online to generate the behavior trajectory of the robot M_{ω_1} and M_{ω_2} , finally, the pose parameters of the robot are obtained as $T_6^1, T_6^2, \dots, T_6^{m-1}$, the correction control in the path planning of biped robot is realized.

4. Simulation experiment and result analysis

In order to test the performance of this method in the implementation of biped robot walking path planning and deviation correction control, the simulation experiment is carried out. The experiment adopts Matlab design, and the biped robot prototype is a ER10L-C10 robot, as shown in Figure 2.

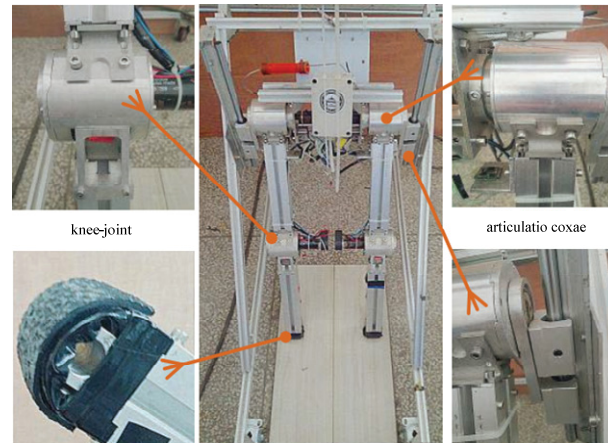


Fig 2. ER10L-C10 robot

In figure 2, the total mass of robot body is 12 kg, the frequency of deviation detection is 24Hz, the frequency of joint position servo is 250Hz, the standard deviation of correction error is 0.01, the complexity of obstacle area of robot path movement is 0.76. The planning area is 4000,000mm, and the interference coefficient matrix is:

$$\Gamma_{k+1,k} = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 \\ 0.64 & 0.64 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1.28 & -0.32 & 0 & 0 \\ 0 & 0 & 0 & 0 & 2.56 & 0.64 \end{bmatrix} \quad (18)$$

The parameter identification models of robot trajectory tracking control are

$$\Phi_{k+1,k} = \begin{bmatrix} 0.05842 & 0.05 & 0.05 & 0.05 \\ 0 & 1.05 & 0 & 0 \\ 0 & 0 & 1.05 & 0 \\ 0 & 0 & 0 & 1.05 \end{bmatrix} \quad (19)$$

$$\Gamma_{k+1,k} = \begin{bmatrix} 0.7537e-004 & 1.2943e-003 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \end{bmatrix} \quad (20)$$

According to the above simulation environment and parameter setting, the path planning and offset correction simulation analysis of the robot are carried out, and the simulation results of the initial path planning of the robot are shown in figure 3.

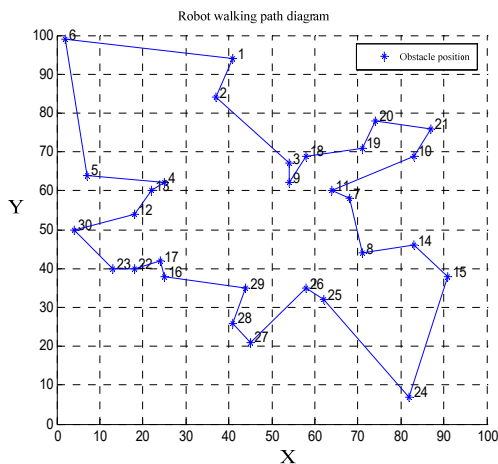


Fig 3. Path planning of the robot

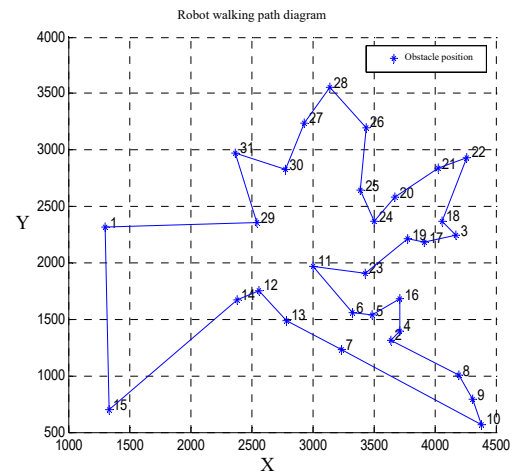


Fig 4. Path planning diagram after robot trajectory shift correction

The path of the robot in figure 3 is affected by disturbance factors, which results in the migration of the robot. The proposed method is used to correct the migration, and the correction results are shown in figure 4.

Figure 4 shows that the proposed method can effectively reduce the path deviation of the robot, and the error of trajectory correction is small. The test results show that different methods are used to control the trajectory of the robot. The maximum error of straight-line trajectory correction is 0.27 mm, and the tracking speed is 3 mm/s, which indicates that the proposed trajectory correction control method has good trajectory tracking control ability.

Table 1. Error performance test(Unit: mm)

Iterations	This method	Reference [2]	Reference [6]
5	0.122	0.752	0.532
10	0.083	0.623	0.463
12	0.051	0.414	0.314
14	0	0.251	0.285

5. Conclusions

In this paper, a method for controlling foot stability of biped robot is proposed based on centroid operation state compensation. The motion equation of the center of mass is constructed and the horizontal velocity of the center of mass is controlled by controlling the displacement of the center of mass in a single step period. The robot walking system and the horizontal velocity of the robot centroid motion are taken as the controlled object, the trajectory correction system model of the robot is constructed, and the position and pose of the robot end are obtained. The feedback controller is constructed to control the path offset compensation of the robot, and the biped robot path planning control is realized. The simulation results show that the trajectory correction control of biped robot with this method has strong ability of path planning and accurate track tracking, and this method can accurately describe the dynamic characteristics of the robot's path, the tracking error is controlled in a lower range, the improved control method shows good application value.

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