Rocket Tank Surface Glue Layer Thickness Measurement Robot Trajectory Tracking Control Based on Adaptive Iterative Learning

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Abstract. Thickness measurement of surface glue layer of rocket tank is a critical part to ensure the quality of rocket tank. When measuring, the industrial robot equipped with a non-contact thickness measurement end actuator performs measurement tasks along the planned trajectory. Because traditional position tracking algorithm inevitably has hysteresis, the actual trajectory of the control point has a large error with the ideal trajectory, which directly affects the thickness measurement accuracy. Iterative learning controller is used in this paper for trajectory tracking control of rocket tank surface glue thickness measurement robot. Considering the non-repetitive disturbance and time-varying factors in the measurement process, an adaptive iterative learning controller is proposed to improve the trajectory tracking control process of the thickness measurement robot. The effectiveness of the control method is verified by Matlab/Simulink simulation.

1. Introduction
In manufacture of rocket tanks, it is necessary to apply a uniform thickness layer of glue on the surface of the tank, for subsequently bonding the polyurethane foam heat insulation layer. If the thickness of the glue is not uniform or the thickness does not satisfy the technical specifications, the bonding strength of partial glue will be reduced, the insulation layer will be detached, the effect of heat insulation will be reduced, and the reliability of the tank will be directly affected, which determines the success or failure of rocket launch. Therefore, accurate measurement of the thickness of the glue layer is an important method to ensure the quality of rocket tank. In measurement process, it is necessary to strictly require the industrial robot to carry the thickness measurement end actuator to measure along the planned path as shown in Fig 1 and Fig 2. Traditional PID trajectory tracking control belongs to progressive tracking algorithm, and there is inevitably an error between ideal and actual trajectory. This error directly affects the accuracy of thickness measurement of rocket tank. Iterative learning control theoretically enables position-controlled object to completely track ideal trajectory [1]. In addition, the thickness measurement robot will repeat the operation along the planned trajectory, and the initial position of each run will be fixed, which compliances with iterative learning control application conditions [2]. Based on the research of iterative learning control algorithm, iterative learning control strategy is used in this paper to control thickness measurement robot. Considering the non-repetitive disturbance and time-varying factors neglected in the dynamic model, adaptive iterative learning controller is used to improve the thickness measurement robot trajectory tracking control [3]. And Then the two algorithms are simulated and compared.
2. The dynamic model of rocket tank surface glue thickness measurement robot and the design of trajectory tracking controller

2.1. Establishment of dynamic model of rocket tank surface glue thickness measurement robot

According to the Lagrange function method, the dynamic equations of n links manipulator system are obtained [6]:

\[
T_i = \sum_{j=1}^{n} \sum_{k=1}^{n} \text{Tr}(\frac{\partial T_j}{\partial \dot{q}_k} I_j \frac{\partial T_j^T}{\partial \dot{q}_i} \ddot{q}_k) + I_{a_i} \ddot{q}_i + \sum_{j=1}^{n} \sum_{k=1}^{n} \sum_{n=1}^{n} \text{Tr}(\frac{\partial^2 T_j}{\partial q_k \partial \dot{q}_m} I_j \frac{\partial T_j^T}{\partial \dot{q}_i} \ddot{q}_k \ddot{q}_m - \sum_{j=1}^{n} m_i g r_i \frac{\partial T_j^T}{\partial q_i} r_i) \tag{1}
\]
Take \( n = 6 \), the equations above can be simplified as a matrix form:

\[
T = M(q)\ddot{q} + C(q, \dot{q}) + G(q)
\]

(2)

Among them:

\[
M(q) = M_a = \sum_{j=\max(k,6)}^{6} \text{Trace}(U_{jk}J U^T_{jk}),
C(q, \dot{q}) = \sum_{k=1}^{6} \text{Trace}(U_{jk}J U^T_{jk})
\]

\[
h_{\text{new}} = \sum_{j=\max(k,6)}^{6} \text{Trace}(U_{jk}J U^T_{jk}),
U_{jk} = \frac{\partial^0 T_i}{\partial q_j}, U_{jm} = \frac{\partial^2 T_j}{\partial q_i \partial q_m}
\]

In these equations, \( q \in R^n \) is joint angular displacement, \( M(q) \in R^{n \times n} \) is robot inertia matrix, \( C(q, \dot{q}) \in R^n \) represents the centrifugal force and Coriolis force of the robot, \( G(q) \in R^n \) is gravity, \( T \in R^n \) is robot driving torque.

2.2. Design of trajectory tracking controller

The goal of this paper is to design a trajectory tracking controller for thickness measurement robot to achieve the effect of high-precision tracking of the ideal trajectory. The controller of this system can be expressed as below:

\[
\begin{cases}
\{x(t+1) = f(x(t), u(t), t)
\{y(t) = h(x(t), t)
\end{cases}
\]

(3)

This discrete system run repeatedly during \([0, 1, 2, \cdots, T]\), and the function, \( f \) and \( g \), doesn’t change each time. This system is repeatable. The certain mathematical model of this system is unknown. The thickness measuring robot returns to the same initial state after each measurement \( x_k(0) \), which satisfies \( x_k(0) = x^0 (k = 0, 1, \cdots) \). The goal of control is to find the right control law which can make

\[
\lim_{k \to \infty} \lim_{t \to \infty} e_x(t) = 0,
\]

when \( k \to \infty \). Because the PD-type closed-loop learning law which can make convergence rate than the open-loop learning law, this paper adopts closed-loop PD-type learning law. Closed-loop PD-type learning law is [2]:

\[
u_{k+1}(t) = u_k(t) + K_p(q_d(t) - q_{k+1}(t)) + K_d(\dot{q}_d(t) - \dot{q}_{k+1}(t))
\]

(4)

The control algorithm flow is shown in Fig 3.

![Figure 3. Control algorithm flow of PD-type closed-loop ILC](image-url)

3. Simulation of closed-loop PD type iterative learning control

To verify the validity of the algorithm, simulate in Matlab/Simulink. Establish a two-degree-of-freedom robot dynamics model. The robot system parameters are:
\[
M = \begin{bmatrix} 28.625 + 1.5 \cos q_2 & 3.25 + 6.75 \cos q_2 \\ 3.25 + 6.75 \cos q_2 & 2.45 \end{bmatrix}, \quad C = \begin{bmatrix} -6.75 \dot{q}_2 \sin q_2 & -6.75 \dot{q}_1 \sin q_2 - 6.75 \dot{q}_2 \sin q_3 \\ 6.75 \dot{q}_1 \sin q_2 & 0 \end{bmatrix}
\]
\[
G = \begin{bmatrix} 206.01 \cos q_1 + 44.145 \cos(q_1 + q_2) \\ 44.145 \cos(q_1 + q_2) \end{bmatrix}, \quad g = 9.81
\]

Ideal position command are \( t^3 - 4.5t^2 + 4.5t, \cos(20t) \), initial state is \( x(0) = [0, 4.5, 1, 0] \), and disturbance is \( r_d = [\sin t \quad 1 - e^{-t}] \). The simulation results of closed-loop PD-type ILC are shown in Fig 4 and Fig 5.

![Figure 4. Position tracking process during 20 iteration times](image1)

![Figure 5. Change of maximum error during 20 iteration times](image2)

From the simulation results, the closed-loop PD-type iterative learning control has good convergence, and the iterative speed is fast, but it still has residual error after 20 iterations.
4. Simulation of adaptive closed-loop PD type iterative learning control

Although PD type iterative learning controller can get the result of convergence in the precision interval, it must ensure that the dynamic model of the thickness measurement robot is unchanged. In each repeated thickness measurement task, this controller requires that disturbance is also repeated.\[7\] Obviously, the requirement of ILC cannot be satisfied in actual work process. Considering the model uncertainty factors and the non-repetitive disturbance $T_r$, the robot dynamics model is rewritten as \[4\]|5|:

$$
T = M(q)\ddot{q} + C(q, \dot{q}) + G(q) + \Delta M(q)\ddot{q} + \Delta C(q, \dot{q}) + \Delta G(q) + T_r 
$$

(5)

The adaptive iterative learning control law is:

$$
u_{k+1}(t) = u_k(t) + K_p(t)(q_k(t) - q_{k+1}(t)) + K_d(t)(\dot{q}_k(t) - \dot{q}_{k+1}(t)) + \epsilon \text{sgn}(\delta y_k(t)) 
$$

(6)

Using the established robot model in Section 2, the adaptive iterative learning control law is simulated. The results are as follows:

![Figure 6. Position tracking process during 20 iteration times](image1)

![Figure 7. Change of maximum error during 20 iteration times](image2)

Figure 6. Position tracking process during 20 iteration times

Figure 7. Change of maximum error during 20 iteration times

It can be seen from the simulation results in Fig.6 and Fig.7 that the convergence speed of adaptive ILC is faster and the error is more smaller, because adaptive ILC consider the uncertainty of robot
dynamic model and the non-repetitive disturbance. Besides, the adaptive iterative learning control has a very stable accuracy after convergence, and no longer fluctuates due to external non-repetitive interference [8].

5. Conclusion
Iterative learning control algorithm can achieve high precision, or even completely tracking of ideal trajectory, which reduces trajectory tracking error and improves the accuracy of thickness measurement of surface glue layer of rocket tank. Therefore, ILC strategy is suitable for trajectory tracking control of thickness measurement robot. Due to the non-repetitive disturbance during the operation of the thickness measuring robot, and the thickness measurement robot system is a highly coupled nonlinear time-varying system, the adaptive iterative learning control will greatly improve the tracking accuracy of the thickness measuring robot and ensure the bonding reliability of glue layer.

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