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Study on Tracking Control Strategy of Sandblasting System for Wind Turbine Blade Based on Recursive Least Squares Algorithm

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Abstract

The path tracking of sandblasting robot for wind turbine blade after path planning is likely to be influenced by environmental factors and path parameters. To reveal the tracking control coupling relationship between the actual and theoretical positions of wind turbine blade during sandblasting in a noise environment, this study proposed a fast filtering and position tracking control strategy based on the adaptive recursive least squares(RLS) algorithm. By adjusting the weighted value of the RLS algorithm, this study developed a mathematical model of sandblasting path tracking control for wind turbine blade based on a variable weight RLS algorithm combined with blade surface morphology and interference noise characteristics. Different interference noises and path conditions were analyzed according to the tracking error between the real-time and theoretical positions of the nozzle. Moreover, experiments were conducted to verify the accuracy of the model. For the tracking theoretical path of the robot during sandblasting, the response time of the fast filtering and position tracking control strategy based on the RLS algorithm was proportional to the rate of curvature change of the theoretical path. Result demonstrate that the response time of the suggested algorithm to the straight and curve paths is less than 2.0 s. Compared with the traditional PID control algorithm, the proposed algorithm has a higher response rate, a control accuracy error under 10 mm, and a maximum response error below 5 mm/s. These qualities meet the field requirements of sand blasting for wind turbine blade. This study also provides reference for evaluating the performance of a wind turbine blade.

Keywords: Wind blade, Path tracing, RLS algorithm, Software simulation, Field investigation

1. Introduction

Wind turbine blades are mostly installed in sand-wind zones and marine applications. Their uniformly distributed coating surface has strong adhesion and can protect blades in harsh environments [1]. The demolded blade has a smooth surface that should be sandblasted to meet the requirements for rough surfaces during the subsequent spraying process. Surface sandblasting preprocessing is a key process influencing the adhesion of blade coating. A robot is an automatic operation device that can imitate some action functions of human beings. It can grasp and carry objects or operate tools [2]. Robots are widely used in paint spraying, grinding, and surface micro flaw detection because they can replace the heavy labor of humans to realize automatic production.

However, the increasingly large size and complex shapes of wind turbine blades, demands a more refined sandblasting process and higher sandblasting efficiency. Therefore, robot sandblasting and grinding has become the optimal scheme [3] for wind turbine blade post-processing. To ensure the real-time optimization of the sandblasting process parameters of the robot during grinding, the error between the actual and theoretical positions should be constantly corrected. However, the traditional PID control algorithm has the disadvantages of low efficiency, weak anti-interference ability, and low control accuracy [4]. Consequently, the study of sandblasting for wind turbine blade in path tracking is confronted with major challenges.

Chinese and foreign scholars have performed numerous studies on the path tracking of robots using the traditional PID control method [5-8]. However, in the field of wind turbine blades, the study of the coupling relationship between the theoretical and actual paths under the influence of a complex surface and strong noise deviates from the actual working state. Therefore, an urgent need exists for accurately predicting the motion path of robots in terms of wind turbine blades and determining the position tracking relationship between the theoretical and actual paths.

Therefore, the weighted value in the Adaptive recursive least squares (RLS) algorithm was adjusted. Combined with a blade surface morphology, the path parameter characteristics, and the RLS algorithm, a mathematical model of the sandblasting System for wind turbine blade in path tracking control based on a variable weight RLS algorithm was constructed, with the expectation of predicting the tracking coupling relationship between the real-time and theoretical positions of the nozzle under strong interference noise. Moreover, a more efficient filtering algorithm model was developed to provide a reference for constructing the sandblasting test-bed for wind turbine blade and evaluating the performance.

2. State of the art

Scholars have performed numerous studies of robot path tracking. Hitesh Jangid [9] proposed an end effector path

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tracking control scheme on the basis of neural network theory to control the path of the end effector, but the open-loop control logic leads to extensive control deviation. Manuel Mera [10] used a first-order sliding mode control method to examine a robot on various admissible smooth reference trajectories (nonholonomic constraints), but the robustness of the trajectory tracking was not considered. J. Czyzowicz [11] developed a linear time off-line optimization algorithm for the path tracking of a robot on complex surfaces, an approach which was not suitable for scenarios with susceptible external factors, like wind turbine blade grinding. Gholamreza Nazmara [12] utilized a fuzzy estimator and facilitated the adjustment of the parameters of a robot controller under different physical conditions and uncertainties. Moreover, a two-connecting-rod planar robot with adjustable expected trajectory and different values of environmental stiffness was simulated. Nevertheless, the tracking error characteristics were not theoretically studied. From the perspective of behavior control, Panda [13] suggested a path tracking control algorithm based on the genetic algorithm for the dynamic motion planning of a mobile robot in an uncertain dynamic environment, but the problem of low path tracking efficiency was not solved. Viseras [14] put forward a heuristic automatic sampling frequency modification strategy which can improve the performance of a path planning and tracking algorithm. However, the problem of noise interference during path tracking remained. By making decision points, De Carvalho Santos [15] used the genetic algorithm to identify the robot path execution strategy of decision points and improved the efficiency of robot path execution; nonetheless, the problem of external interference remained unresolved. Nagy [16] developed a sequential optimization method to explore the shortest time path tracking, but the efficiency of path tracking was not analyzed. Chen Zhi [17] selected the path according to pseudo-random state transition rules, adaptively adjusted the proportion of deterministic and random selection, and introduced the optimal and worst solutions to improve the global pheromone updating method. However, the problem of a local optimal trap was not settled. Based on the chemical odor source localization algorithm, Chen Xinxing [18] developed a smoke plume path tracking algorithm according to a particle filter, thereby providing a new filtering method for path tracking, but the algorithm was not fully applicable to wind turbine blade grinding. Wang Ting [19] transformed the particle tracking of a robot into the numerical evolution of a curve and identified the optimal time path by solving the Hamilton–Jacobi equation. The numerical calculation accuracy of the improved path tracking ensures the feasibility of path planning, but the strong noise signal interference remained unaddressed. To prove that all signals of the closed-loop tracking error system were bounded uniformly and ultimately, Chen Ziyin [20] performed simulation experiments to verify the effectiveness of cascade control, but failed to create a path tracking strategy after noise interference. On the basis of predictive control theory, Shi Zhenhong [21] put forward a path tracking control algorithm which adaptively adjusted the weight coefficient of a cost function according to the tracking deviation and road curvature; nevertheless, the robustness of the system was poor. Based on nonlinear model predictive control, Bai Guoxing [22] presented a tracking scheme to decrease the number of control steps or the control frequency, but detailed theoretical analysis was not given. Wang Xiaowei [23] employed the Lyapunov theory and the back stepping method to ensure the stability and robustness of the system, but the tracking accuracy of the system is not ideal.

The above study results focus on the design method of robot trajectory planning and robot control characteristics in low noise environments. Nevertheless, research on the path tracking in a strong signal noise environment is scarce, especially the path tracking of a grinding robot in wind turbine blade field. The current work proposed a tracking control strategy of the actual and target positions according to the RLS algorithm. By adjusting the weighted value of the RLS algorithm and incorporating a RLS fast filtering algorithm, a mathematical model of the sandblasting System for wind turbine blade in path tracking control according to a variable weight RLS algorithm was established. The filtering ability and the path tracking characteristics of RLS algorithm under interference noise were analyzed according to the tracking error between the real-time and theoretical positions of the nozzle. Model accuracy was verified by experiments. The study results provide reference for the construction and performance evaluation of a sandblasting test-bed for wind turbine blade.

The remainder of this study is structured as follows. Section 3 describes the control principle of a sandblasting and grinding system for wind turbine blade and constructs the physical and mathematical models of the path tracking of the grinding robot. Based on the RLS control algorithm, Section 4 calculates the tracking error between the real-time and theoretical positions of the nozzle and presents the MATLAB simulation and test to obtain the tracking characteristics of the moving position of the nozzle under different working conditions. Finally, Section 5 summarizes the study and draws its conclusions.

3. Methodology

3.1 Physical model

A sandblasting and grinding system for wind turbine blade mainly consist of a ground track, multi-degree of freedom robot, sand blasting system, dust cleaning and noise removal system, and field control system. An image of sand blasting and grinding system for wind turbine blade is shown in Fig. 1.

Fig. 1. Image of a sand blasting and grinding system for wind turbine blade

In Fig. 1, the system track is parallel to the blade girder, and the multi-degree of freedom robot is installed on the track. The sandblasting system is attached to the robot. The nozzle is at the end of the robot actuator. The dust cleaning and noise removal system have the main function of abrasive recovery and noise shielding. The field control system is the control core of the sandblasting and grinding system for wind turbine blade and ensures the accurate path tracking of the nozzle via the control algorithm. The control topology of the sandblasting for wind turbine blade and grinding system is shown in Fig. 2.

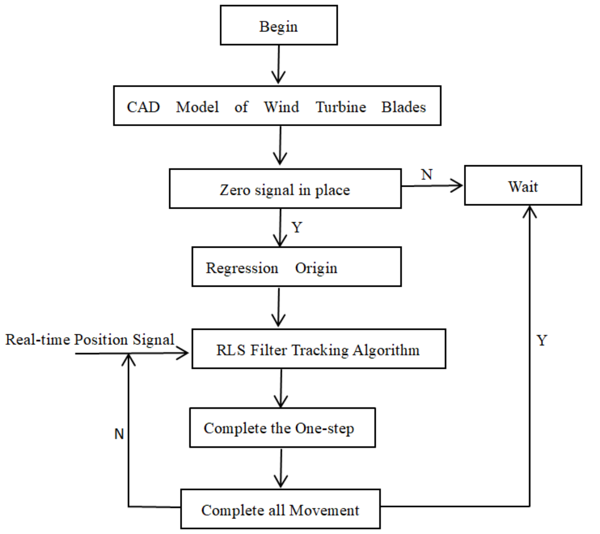

Fig. 2. Control topology of the sandblasting and grinding system for wind turbine blade

In Fig. 2, the Trio controller, which realizes the control strategy output, is the core of the controller. The robot can track the position of the nozzle and its track position in real time via an Omron absolute value encoder.

3.2 Construction of the calculation model

The input signal of the sandblasting and grinding system for wind turbine blade varies with time and is affected by the interference signal in a strong noise environment. Therefore, the said signal belongs to a hard-to-distinguish system. As discussed in Section 1, the traditional closed-loop PID control cannot establish accurate control parameters for hard-to-distinguish systems (such as the proportion and calculus), and realizing accurate tracking control of the sandblasting path is difficult.

To avoid the adverse impact of noise on control accuracy and realize the complete tracking of the actual path and the target path in the sandblasting process, a path tracking control strategy with the RLS algorithm as the core is established for the sandblasting and grinding system for wind turbine blade.

The block diagram of the RLS control strategy is given in Fig. 3 [24].

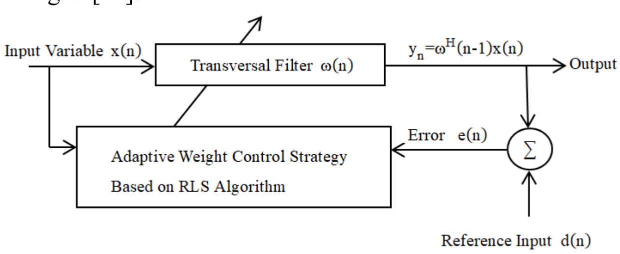

Fig. 3. Block diagram of the RLS tracking strategy

In Fig. 3, $x(n)$ is the actual position signal of the nozzle, which includes two parts: the effective signal x and interference noise signal v; $d(n)$ is the reference theoretical position signal; y_n is the output signal of the motion controller and approximates the reference input $d(n)$ through the adaptive controller and traces the theoretical and actual positions of the nozzle; and *e(n)* is the error signal.

The transverse filter sieves the input signal. The adaptive weight control strategy on the basis of the RLS algorithm determines the controller's weight vector processing to the actual position signal $x(n)$, thereby rendering the actual position signal of the nozzle approximate to the reference theoretical signal $d(n)$. The path tracking control strategy of the sandblasting and grinding system for wind turbine blade according to the RLS algorithm is described in Formula (1):

$$\begin{cases} y_n = \omega^H(n-1)x(n) \\ e(n) = d(n) - y_n \\ \omega(n) = \omega(n-1) + g(n)e^*(n) \end{cases} \tag{1}$$

where, $\omega(n)$ is $\omega_0 \bullet \omega_1 \bullet\bullet\bullet$ at time n; ω_{N-1} is the weight vector; $g(n)$ is the gain vector at time n, and its value is mainly related to the influence factor λ. According to the inertia parameters of the sandblasting and grinding system for wind turbine blade, the value of λ ranges from 0 to 1.

The sandblasting and grinding system for wind turbine blade based on the RLS algorithm adopts direct aiming control and aims forward along the tangential direction of the path with the position of the nozzle as the aiming point. Moreover, the position deviation between the aiming point and the theoretical target point is taken as the control model.

The schematic diagram of the current position and the aiming point position is shown in Fig. 4. Point (x, y) is the position of the nozzle, (x_y, y_y) is the aiming point of the nozzle, and vector($x_y - x$, $y_y - y$)is the aiming distance. XOY is the global coordinate, and xoy is the local coordinate system of the nozzle.

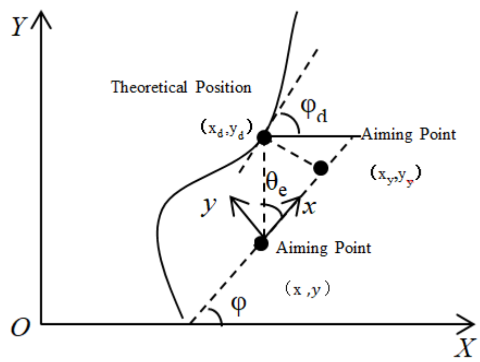

Fig. 4. Schematic diagram of the current position and the aiming point position

In Fig. 4, the difference between x_d and x_y is the lateral deviation of the nozzle position in the global coordinate system. Moreover, the difference between y_d and y_y is the longitudinal deviation. The course deviation is the difference between the tangent of the target point and the X-axis coordinate and nozzle course angle. The above pose deviation is converted to the robot nozzle coordinate system, and the conversion is shown in Formula (2).

$$\begin{cases} y_e = -\sin(\phi)(x_d - x_y) + \cos(\phi)(y_d - y_y) \\ x_e = \cos(\phi)(x_d - x_y) + \sin(\phi)(y_d - y_y) \\ \phi_e = \phi_d - \phi \end{cases} \tag{2}$$

The calculation of the aiming deviation is shown in Formula (3).

$$\theta_e = ar\cos\left[\frac{(x_d - x)(y_d - y) + (x_y - x)(y_y - y)}{\sqrt{(x_d - x)^2 + (y_d - y)^2}\sqrt{(x_y - x)^2 + (y_y - y)^2}}\right] \quad (3)$$

3.3 Adaptive filtering strategy based on the RLS algorithm

As the order of the RLS algorithm increases, the calculation amount increases significantly and the response speed of the system decreases. To enhance the response speed and reduce the effect of the interference noise on the system, the robot sandblasting and grinding system adopts a new RLS-based adaptive filtering algorithm, which solves the forward predictor, the backward linear predictor, the joint process estimator, and the auxiliary filter.

The posteriori forward prediction error is shown in Formula (4).

$$\varepsilon_f(k,N) = x(k) - \omega_f^T(k,N)x(k-1,N) = x^T(k,N+1)\begin{pmatrix}1\\ -\omega_f^T(k,N)\end{pmatrix} \quad (4)$$

Where $\varepsilon_f(k,N)$ is the n-order forward prediction error at time k, and is the tap coefficient vector of the n-order forward prediction at time k.

The time update formula is shown in Formula (5).

$$\xi_{\text{fmin}}^d(k,N) = \lambda\xi_{f\min}(k-1,N) + e_f(k,N)\varepsilon_f(k,N) \quad (5)$$

Where $\xi_{\text{fmin}}^d(k,N)$ is the minimum time update coefficient in the n-order forward direction at time k.

The conversion factor is updated in Formula (6).

$$\gamma(k,N+1) = \frac{\lambda\xi_{f\min}(k-1,N)}{\xi_{f\min}(k,N)}\gamma(k-1,N) \quad (6)$$

The renewal equation of the tap coefficient vector of the forward prediction is shown in Formula (7).

$$\omega_f(k,N) = \omega_f(k-1,N) + \varphi(k-1,N)\varepsilon_f(k,N) \quad (7)$$

Where

$$\varphi(k,N+1) = \begin{pmatrix}0\\ \varphi(k-1,N)\end{pmatrix} + \frac{e_f(k,N)}{\lambda\xi_{f\min}^d(k-1,N)}\begin{pmatrix}1\\ -\omega_f(k-1,N)\end{pmatrix} \quad (8)$$

The relationship between the priori and posteriori forward prediction errors is shown in Formula (9).

$$e_f(k,N) = \frac{\varepsilon_f(k,N)}{\gamma(k-1,N)} \quad (9)$$

Similarly, the relationship between the priori and posteriori forward prediction errors is expressed in Formula (10).

$$e_b(k,N) = \frac{\varepsilon_b(k,N)}{\gamma(k,N)} \quad (10)$$

Formula (11) is the time update formula.

$$\xi_{\text{bmin}}^d(k,N) = \lambda\xi_{b\min}^d(k-1,N) + e_b(k,N)\varepsilon_b(k,N) \quad (11)$$

The updated equation of the tap coefficient vector ω_b of the backward prediction is shown in Formula (12).

$$\omega_b(k,N) = \omega_b(k-1,N) + \varphi(k-1,N)\varepsilon_b(k,N) \quad (12)$$

Where

$$\begin{pmatrix}\varphi(k,N)\\ 0\end{pmatrix} = \varphi(k,N+1) - \frac{e_b(k,N)}{\lambda\xi_{b\min}^d(k-1,N)}\begin{pmatrix}-\omega_b(k-1,N)\\ 1\end{pmatrix} \quad (13)$$

$$\varphi_{N+1}(k,N+1) = \frac{e_b(k,N)}{\lambda\xi_{b\min}^d(k-1,,N)} \quad (14)$$

$$\gamma^{-1}(k,N) = \gamma^{-1}(k,N+1) - \varphi_{N+1}(k,N+1)e_b(k,N) \quad (15)$$

Finally, the joint process estimation approximates the input and expected signals, and the prior error is shown in Formula (16).

$$e(k,N) = d(k) - \omega^T(k-1,N)x(k,N) \quad (16)$$

The relationship between the prior and posterior errors is shown in Formula (17).

$$\varepsilon(k,N) = e(k,N)\gamma(k,N) \quad (17)$$

Formula (18) is the time update formula of the tap coefficient.

$$\omega(k,N) = \omega(k-1,N) + \varphi(k,N)\varepsilon(k,N) \quad (18)$$

3.4 Path tracking strategy based on the RLS algorithm

In the sandblasting and grinding process, the nozzle has two paths, namely, the straight and the curve paths. As the change rate of the slope of the straight path in the tracking process is 0, the ordinary algorithm is applicable. As for the path tracking strategy based on the RLS algorithm, the curve path is approximated by the sinusoidal curve.

The ideal path of the sandblasting and grinding for wind turbine blade is assumed to exhibit a sinusoidal change, and its input and weight are shown in Formulas (19) and (20), respectively.

$$x(n) = [x(n), x(n-t)]^T = [C\sin(\omega n), C\cos(\omega n)]^T \quad (19)$$

$$\omega(n) = [\omega_1, \omega_2] \quad (20)$$

To obtain the output of the system, Formulas (19) and (20) are substituted into Formula (1)

$$y(n) = \omega_1 C\sin(\omega n) + \omega_2 C\cos(\omega n) = C\sqrt{\omega_1^2+\omega_2^2}\left[\frac{\omega_1\sin(\omega n)}{\sqrt{\omega_1^2+\omega_2^2}} + \frac{\omega_2\cos(\omega n)}{\sqrt{\omega_1^2+\omega_2^2}}\right] \quad (21)$$

$\cos\theta = \frac{\omega_1}{\sqrt{\omega_1^2+\omega_1^2}}, \sin\theta = \frac{\omega_2}{\sqrt{\omega_1^2+\omega_1^2}}, A_y = C\sqrt{\omega_1^2+\omega_1^2}$ are substituted into Formula (21), and the simplified system input is shown in Formula (22).

$$y(n) = A_y \sin(\omega n + \theta) \tag{22}$$

where A_y is the amplitude of the system input path fluctuation, and θ is the initial angle of fluctuation. ω_1 and ω_2 have a functional correlation. Therefore, the sandblasting and grinding system for wind turbine blade changes the values of ω_1 and ω_2 via the path tracking control strategy based on the RLS algorithm, thereby influencing the values of A_y and θ. In this way, the full tracking of sandblasting path can be realized.

3.5 Simulation verification model

The effectiveness and superiority of the fast filtering and position tracking control strategy based on the RLS algorithm in terms of interference noise elimination and path tracking are verified by conducting a simulation experiment on the Desktop Real-Time platform of MATLAB/Simulink software. The processor is an Intel®Core™i5-8500, and the memory is 4GB. The PID control algorithm and the fast filtering and position tracking control strategy based on the RLS algorithm are used. To verify the filtering effect, two kinds of interference signals are selected to carry out filtering using the above two strategies. Moreover, the filtering effects and processing time of the two algorithms are compared. Two typical paths of straight path tracking and curve path tracking are selected for simulation to ascertain the effectiveness of the position tracking control strategy, and the position control errors of the two algorithms are compared. The parameters of the simulation verification model are listed in Table 1.

Table 1. Parameters of simulation verification model

Parameter	RIS path tracing algorithm	Traditional PID control algorithm
Control period / S	0.2	0.2
Sampling period / S	0.2	0.2
Control parameters	Initial parameters P=2 I=0.2 D=0.04	Fixed parameter P=2 I=0.2 D=0.04

3.6 Test validation model

The test platform is the SIASUN robot in Fig. 5, and the SNRC-4C-H10 local controller is taken as the field operation controller for the robot. The useful load is 10 Kg, the working range is 1393 mm, the number of effective axes is 6, the repetitive positioning accuracy is ± 0.05 mm, and the protection grade is IP65.

4 Result Analysis and Discussion

To verify the filtering effect of the fast filtering and position tracking control strategy based on the RLS algorithm under interference noise, the signal generator in MATLAB software in line with the mathematical model established in Section 3 generates the oscillation signal with sawtooth harmonics randomly. The traditional PID control algorithm and the fast filtering and position tracking strategy based on the RLS algorithm are employed for simulation. The interference noise of the signal is not completely eliminated by the filter of the traditional PID control algorithm. Given the robustness of PID control parameters, the harmonic signal is enhanced and the influence range of the noise is further extended. The vibration noise is ± 0.5 mm, and the processed signal exhibits signal loss. The filtering effect diagram of the ordinary PID control algorithm is presented in Fig. 6.

Fig. 5. SIASUN robot test platform

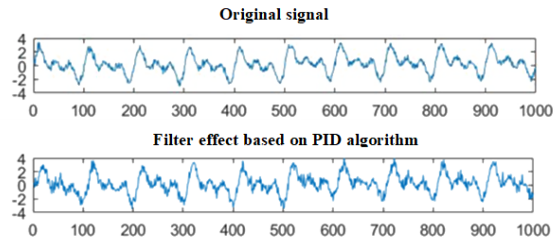

Fig.6. Filtering effect diagram of the ordinary PID control algorithm

Fig. 7 shows the filtering effect of the fast filtering and position tracking control strategy based on the RLS algorithm. After the input signal is processed by fast filtering using the RLS algorithm and position tracking control strategy, the interference noise signal is removed, and the original signal is not lost. Thus, the fast filtering and position tracking control strategy based on the RLS algorithm has a filtering effect.

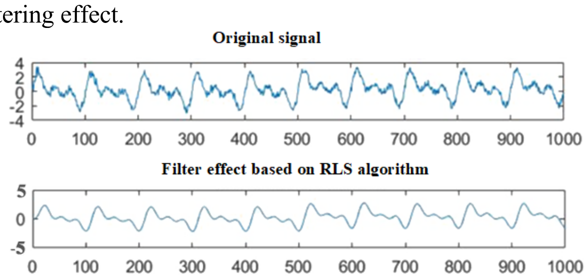

Fig.7. Filtering effect of the tracking control strategy based on the RLS algorithm

Fig. 8 shows the simulation results of the straight path tracking effect of the traditional PID control algorithm and the tracking control strategy based on the RLS algorithm. In the initial stage, both algorithms have good performance, and the displacement control errors are ≤10 mm. However, in the corner position of the curve, the traditional PID control algorithm presents a position control overshoot phenomenon because of its control inertia, and the displacement control error is still ≥ 50 mm. Meanwhile, the tracking control strategy based on the RLS algorithm has good control effect and the displacement control accuracy is ≤10 mm, thereby meeting the path tracking requirements of sand blasting for wind turbine blade.

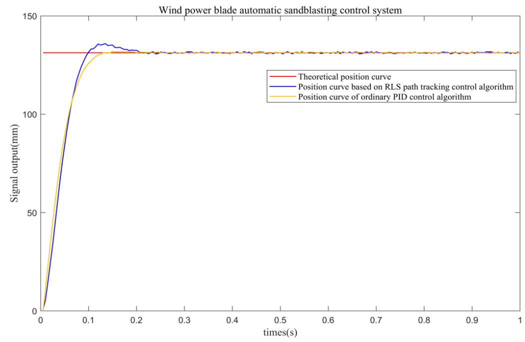

Fig. 8. Straight path tracking control effects of two algorithms

Fig. 9 depicts the simulation results of the curve path tracking of the traditional PID control algorithm and the tracking control strategy based on the RLS algorithm. According to the comparison curve of the path tracking effects in Fig. 3, the path tracking control strategy based on the RLS algorithm has better control performance compared with the traditional PID control algorithm. Moreover, the position control error is ≤1 mm, and the tracking effect at the maximum curvature is satisfactory.

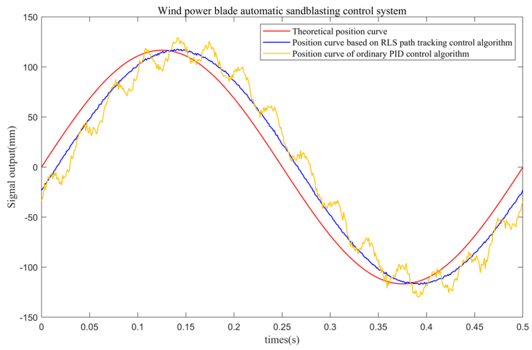

Fig. 9. Control effect of the curve path tracking of two algorithms

Fig. 10 presents the field test diagram of the traditional PID control algorithm and the tracking control strategy based on the RLS algorithm in the actual path tracking. The field test indicates that the input signal contains an interference noise signal which should be shielded in practice. In Fig. 10, the tracking control strategy based on the RLS algorithm filters out the interference noise signal. As for the straight path, both the traditional PID control algorithm and the tracking control strategy based on the RLS algorithm have good tracking effects. However, for the curve path, the tracking control strategy based on the RLS algorithm is superior to the traditional PID control algorithm. Furthermore, the position control accuracy error is ≤1 mm. The results are consistent with the above simulation results.

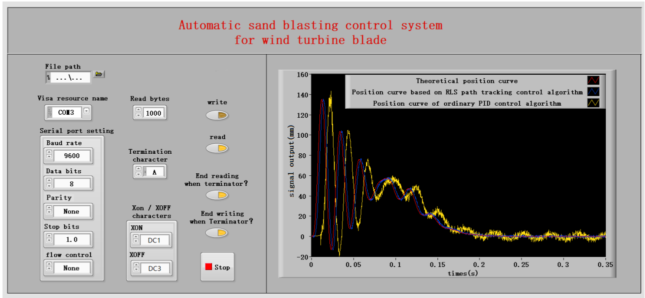

Fig. 10. Actual operation interface of the path tracking of the two algorithms

4 Conclusion

To reveal the tracking control coupling relationship between the actual and target positions in the path tracking process of the sandblasting and grinding for wind turbine blade, this study proposed a fast filtering and position tracking control strategy based on the RLS algorithm. Based on the physical model of wind turbine blade sandblasting, t numerical analysis, simulation technology, and experimental study were conducted to investigate the signal filtering characteristics and path tracking strategy in the sandblasting and grinding process for wind turbine blade. The following conclusions could be drawn:

(1) Given the inadaptability of parameters, the traditional PID control algorithm has low control accuracy in the complex path tracking process.

(2) The path tracking control strategy based on the RLS algorithm can effectively filter the input signal and has good tracking performance for the straight and curve paths.

(3) The path tracking control strategy of the sandblasting grinding scheme for wind turbine blade based on the RLS algorithm can replace manual operation and meet the requirements of surface treatment for wind turbine blade while improving the system efficiency.

By combining an indoor experiment and theoretical study, this work proposes a new understanding of the path tracking of sandblasting and grinding for wind turbine blade. The established blade-grinding model is more simplified and closer to the field practice, thereby providing a reference for the construction and performance evaluation of the sandblasting test-bed for wind turbine blade. As the wind turbine blade structure is not analyzed, future study should modify the model combined with the surface material properties of wind turbine blades, so that the sandblasting and grinding law of the complex curved surface and composite blade can be understood more accurately.

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