Control of Time Delay Force Feedback Teleoperation System With Finite Time Convergence

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In order to make the teleoperation system more practical, it is necessary to effectively control the tracking error convergence time of the teleoperation system. By combining the terminal sliding mode control method with the neural network adaptive control method, a bilateral continuous finite time adaptive terminal sliding mode control method is designed for the combined teleoperation system. The Lyapunov theory is used to analyze the stability of the closed-loop system, and the position tracking error is able to effectively converge in time. Finally, the effectiveness of the proposed control scheme is verified by MATLAB Simulink numerical simulation, and the numerical analysis of the results shows that the method has better system performance. Compared with the traditional two-sided control method (TPDC) of PD time-delay teleoperation system, the control method in this paper has good performance, improves stability, and makes steady-state errors smaller and better tracking.

Keywords: the teleoperation system, the terminal sliding mode control method, the neural network adaptive control method, the Lyapunov theory, tracking error

INTRODUCTION

By improving the mechanical design of the teleoperation robot, as well as the control structure and algorithm of the system, the performance and application range of the teleoperation system have been greatly improved. The general remote operation robot system mainly includes the master module, operator module, master controller, communication channel, slave controller, slave environment, and so on. The general remote operation robot system has been applied in many fields, such as unmanned submersible (Sayers and Paul, 1994), space robots (Bejczy, 1994; Wright et al., 2006), remote surgery robots (Sayers and Paul, 1994; Tang et al., 2020a), teleoperation robots (DiMaio et al., 2011), etc.

From the research status of teleoperation system, for the uncertain control system, the control algorithm based on the sliding mode can achieve well-control, and it is robust to the internal parameter uncertainty and external interference, which has been widely used (Feng et al., 2002; Yu et al., 2005; Li and Huang, 2010; Neila and Tarak, 2011; Nekoukar and Erfanian, 2011). But in the above literature, the sliding mode control method is linear. The state variables of the system with linear sliding mode control strategy converge to the equilibrium point on the sliding surface at an exponential rate. Although the appropriate parameters can be adjusted arbitrarily and quickly, the power system cannot reach stable in a limited time.
In the practical application of teleoperation system, it is more desirable to complete the error convergence in finite time, because it can complete the task better and faster. In order to obtain the characteristic that the tracking error of the system converges to zero in finite time, St (Yu and Man, 2002) proposed a terminal sliding mode control method, using non-linear sliding mode hyperplane for the first time. Then, many studies have carried out in-depth research and improvement on this method (Salcudean et al., 2000; Xu and Yao, 2001; Nuno et al., 2008; Zhang et al., 2009; Nekoukar and Erfanian, 2011; Liu and Zhang, 2013). Compared with the control method based on the linear sliding mode hyperplane, the terminal sliding mode control method has better characteristics, such as faster, finite time convergence and so on. However, in practical engineering, it is not only difficult to realize the existing terminal sliding mode controller, but also, when the design parameters are not suitable, there will be a singular problem (Guo et al., 2021; Ma et al., 2021; Zhang et al., 2021). In order to solve these problems, there are many control methods. However, for the design of the remote operation system controller, these methods are not applicable. In teleoperation system, not only the influence of the operator module and the environment module but also the time delay of the communication channel should be considered. Therefore, the finite time sliding mode control strategy for a robot cannot be directly used in bilateral teleoperation system (Tang et al., 2020a). So, we need to further study the sliding mode control strategy of teleoperation system and propose a new algorithm to obtain the appropriate switching function and controller so as to ensure the asymptotic stability of the sliding mode in the motion process of the system, and then complete the finite time tracking error convergence and improve the overall stability and tracking performance of the system.

Therefore, in this paper, in order to make the teleoperation system with time-delay force feedback more practical, a finite time non-linear terminal sliding mode adaptive bilateral control method is designed for the teleoperation system with constant time delay. Meanwhile, the constant time delay generated by the communication channel in the teleoperation system and the influence of uncertainties on the model are solved, and the tracking error of the teleoperation system can converge in finite time (Li et al., 2015, 2016).

**METHODS**

The main goal of this paper is to design a two-sided controller based on the position error control structure, considering the internal friction, external interference, and constant time delay between the master robot and the slave robot in the teleoperation system to make the convergence time of the position tracking error of the system converge to 0 in a finite time. Similarly, the RBF neural network adaptive method is also used to approximate the uncertainty of the system model, but the treatment of the uncertainty is different (Li et al., 2018; Dankwa and Zheng, 2019; Yang et al., 2019; Xu et al., 2020).

**Controller Design and Stability Analysis of Teleoperation System**

In the control of teleoperation system with forward channel delay and reverse channel communication delay, considering the mechanical internal friction and external interference of the master robot and the slave robot in the system, our control goal is to calculate the control torque input of the master robot and the slave robot, respectively, so that the position error between the master robot and the slave robot in the teleoperation system can converge to 0 in finite time and guarantee the stability of the system (Li et al., 2017a,b, 2020; Zheng et al., 2017; Yin et al., 2019; Chen et al., 2020; Tang et al., 2020b).

In this paper, the control block diagram of time-delay force feedback teleoperation system based on position error structure with finite time convergence is shown in Figure 1. Considering the influence of the constant time delay and the non-linear uncertainties of the system model on the teleoperation system, as well as the singularity and chattering problems of the sliding mode control, a finite time non-linear sliding mode adaptive bilateral controller is adopted. Compared with the linear sliding mode controller, the controller can make the teleoperation system work well. The tracking error of the system can converge to 0 quickly and finitely, and ultimately ensure the global stability of the teleoperation system.

**Controller Design**

From the control block diagram of time-delay force feedback teleoperation system based on position error structure shown in Figure 1, it can be defined that the position tracking error of the master robot and the slave robot is as the following Formula (1):

\[ e_m = q_m - q_s(t - T_m), \quad e_s = q_s - q_m(t - T_s) \] (1)

Here, \( T_m \) is the communication delay of the forward channel, and \( T_s \) is the communication delay of the reverse channel. The position and velocity errors of the master robot and the slave robot are defined as the following Formula (2):

\[ \dot{e}_m = q_m - \dot{q}_s(t - T_s), \quad \dot{e}_s = \dot{q}_s - \dot{q}_m(t - T_m) \] (2)

Then, based on the non-singular terminal sliding mode method, the sliding mode function is defined as follows:

\[ s_m = e_m + \alpha_m \text{sign}(e_m)^{\gamma_m} + \beta_m \text{sign}(\dot{e}_m)^{\gamma_m} \] (3)

\[ s_s = e_s + \alpha_s \text{sign}(e_s)^{\gamma_s} + \beta_s \text{sign}(\dot{e}_s)^{\gamma_s} \] (4)

Where, \( \text{sign}(\xi) = \begin{bmatrix} |\xi_1|^{\alpha_1} \text{sign}(\xi_1), |\xi_2|^{\alpha_2} \text{sign}(\xi_2), \ldots, |\xi_n|^{\alpha_n} \text{sign}(\xi_n) \end{bmatrix}^T \), \( \xi = [\xi_1, \xi_2, \ldots, \xi_n]^T \in \mathbb{R}^n, \alpha_i = \text{diag}(\alpha_{i1}, \alpha_{i2}, \ldots, \alpha_{in}) > 0, s_i = [s_{i1}, s_{i2}, \ldots, s_{in}] \in \mathbb{R}^n, \) and \( \beta_i = \text{diag}(\beta_{i1}, \beta_{i2}, \ldots, \beta_{in}) \) are positive diagonal matrices, and \( \gamma_i > 0, 1 < \gamma_1, \gamma_2, \ldots, \gamma_n < 2; i = m, s; j = 1, 2, \ldots, n. \)

\[ S = e + \alpha \text{sign}(e)^{\gamma} + \beta \text{sign}(\dot{e})^{\gamma} \] (5)
Through a Formula (5), the derivation of the Formula (3) and the Equation (4) is obtained

\[ \dot{s}_m = \dot{e}_m + \varepsilon_m \alpha_m \text{diag}([e_m|^{\gamma_m - 1}]^{-1}) e_m \]

\[ \dot{s}_s = \dot{e}_s + \varepsilon_s \alpha_s \text{diag}([e_s|^{\gamma_s - 1}]^{-1}) e_s \]

In order to solve the influence of system model uncertainty, \( P_i(q_i, \dot{q}_i, \ddot{q}_i) \) on system stability, this paper uses radial basis function neural network to approximate it. As a result:

\[ P_i(q_i, \dot{q}_i, \ddot{q}_i) = \Theta_i^T \psi(Z_i) + \delta_i(Z_i) \]

According to the expression of the uncertainty, \( P_i(q_i, \dot{q}_i, \ddot{q}_i) \) of the system model, we can choose the input signal \( Z_i = [q_i^T, \dot{q}_i^T, \ddot{q}_i^T] \) of the network, \( \delta_i(Z_i) \) as the bounded estimation error, which satisfies \( \| \delta_i(Z_i) \| \leq \varepsilon_i, \varepsilon_i \) is a constant. \( \Theta_i \) is the weight that needs to be adjusted.

The terminal sliding mode control method and the radial basis function estimation method are used to design appropriate controllers for the master robot and the slave robot in the teleoperation system with constant time delay.

\[ \tau_m = -M_{om}(q_m)(I + F_m)\beta_m^{-1} T_m^{-1} \varepsilon_m + M_{om}(q_m)(q_m \hat{q}_m(t - T_m) + C_{om}(q_m, q_m) \dot{q}_m(t) + G_{om}(q_m) - M_{om}(q_m) K_{sm} + B_{sm} \dot{g}_m)^{\gamma_m} \]

\[ \tau_s = -M_{as}(q_s)(I + F_s)\beta_s^{-1} T_s^{-1} \varepsilon_s + M_{as}(q_s) \dot{q}_s(t - T_m) + C_{as}(q_s, \dot{q}_s) + g_s(q_s) - M_{as} \dot{q}_s + B_{as} \dot{g}_s)^{\gamma_s} \]

Here, for all the \( K_i, B_i \) are positive diagonal matrices, where \( i = m, s, 0 < \rho_i < 1, \dot{\Theta}_i = \Theta_i - \tilde{\Theta}_i, h_i = s_i^T \gamma_i \beta_i \text{diag}([e_i|^{\gamma_i - 1}]^{-1}) M_{ai}^{-1}(q_i), F_i = \alpha_i \varepsilon_i \text{diag}([e_i|^{\gamma_i - 1}]^{-1}), \hat{\Theta}_i \) is the estimated value of \( \Theta_i \), and the estimation law adopted is as the following Formula (11):

\[ \dot{\hat{\Theta}}_i = \Lambda_{11} \psi(Z_i) \dot{q}_i^T - \Lambda_{12} (\hat{\Theta}_i - \Theta_i^* \psi(Z_i)) \]

Analysis of System Stability and Tracking Performance

The time-delay force feedback teleoperation system includes a bilateral position control loop, and its control structure is shown in Figure 1. The stability of the closed-loop teleoperation system and the position tracking performance analysis of bilateral position control are discussed below.

Theorem 5: In the case of constant forward and reverse channel delays, uncertain model parameters, and external interference, the non-linear sliding surface of Formulas (3) and (4) is selected, and the bilateral continuous terminal sliding model control with effective time convergence of Formulas (9) and (10) is adopted. The controller and the control of neural network adaptive law described in the Formula (11) are as follows:

1. The whole closed-loop system is globally stable, and all closed-loop signals are globally bounded.
2. In the whole closed-loop teleoperation system, the tracking error of the master robot and the slave robot can converge to 0 in finite time.

Prove (1): now, the Lyapunov candidate functions can be constructed as the following Formula (12):

\[ V = V_1 + V_2 \]

Among them, \( V_1 = \sum_{i=m,s} \frac{1}{2} s_i^T S_i, V_2 = \frac{1}{2} \sum_{i=m,s} Tr(\dot{\hat{\Theta}}_i^T \Lambda_{11}^{-1} \dot{\hat{\Theta}}_i) \). The derivative of \( V_1 \) is obtained as Formula (13):

\[ \dot{V}_1 = \sum_{j=m,s} s_j^T \dot{S}_j \]
By substituting Formula (6) and Formula (7) into Formula (13), the results are as Formula (14):

\[
V_1 = \sum_{i=m,s} \{-s_j^T K_i \hat{q}_j - s_j^T B_i \text{sig}(s_j) \rho_i + s_j^T \gamma_i \beta_i \text{diag} ((|\epsilon_i|)^{\gamma_i-1}) M_{ij}^{-1}(q_j) \times \left( P_i + \frac{h_j}{\alpha_i} \hat{q}_j \varphi(Z_j) \right) - s_j^T \gamma_i \beta_i \text{diag} (|\epsilon_i|)^{\gamma_i-1} \} \text{diag} (\hat{q}_i)^{\sim T} \tilde{\Theta}_i \varphi(Z_i)
\]

Therefore, we can get:

\[
V_1 \leq -s_j^T \Psi_1 S - s_j^T \Psi_2 \text{sig}(S)^{\rho}
\]

Among which, \(\text{sig}(S)^{\rho} = [(\text{sig}(s_m)^{\rho})^T, (\text{sig}(s_s)^{\rho})^T]^T\).

Then, we can deduce that the convergence time satisfies:

\[
T \leq \frac{1}{\Psi_1 (1-\rho)} \ln \frac{2 \Psi_1 V_1^{(1-\rho)/2}(s(0)) + 2^{(1-\rho)/2} \Psi_2}{2^{(1-\rho)/2} \Psi_2}
\]

To sum up, we can prove that the joint position tracking error of the master robot and the slave robot in the closed-loop teleoperation system with time-delay force feedback based on the continuous adaptive terminal sliding mode bilateral controller in this chapter can converge to 0 in finite time, and all the signals of the closed-loop system are bounded, which can not only ensure the stability of the system but also improve the tracking performance of the system.

**EXPERIMENTS**

Simulink is used for simulation verification (Wang et al., 2021), and the S-function is used to establish the system model (Li et al., 2021, and then the closed-loop control system of time-delay force feedback teleoperation system with finite time convergence is built as shown in Figure 1. Compared with the traditional PD (proportional and derivative) control method, the simulation results are analyzed.

Therefore, we can conclude that all the signals in the closed-loop system are bounded, such as the sliding mode variable \(s_i\), the joint position tracking error \(\epsilon_i\) and the estimation error \(\hat{\Theta}_i\) of the adaptive law. And then we used barbara’s theorem to know that \(V(t)\) asymptotically tends to 0, and then, when \(t \to \infty, s_i \to 0\) and then \(\dot{\epsilon}_i \to 0\).

Prove (2): from (1), we know the Lyapunov candidate function

\[
V_1 = \sum_{j=m,s} \frac{1}{2} S_j^T S_j
\]

In the same way, it is deduced that:

\[
V_1 \leq \sum_{j=m,s} -s_j^T K_j s_j - s_j^T B_j \text{sig}(s_j)^{\rho}
\]

In this paper, the master robot and the slave robot in the teleoperation system adopt the 2-DOF, 2-link, rotary joint robot. For the sake of simplicity and generality, the moment of inertia of the rod is ignored. The mathematical models of joint space dynamics are as follows:

In addition, the external interference of the master robot and the slave robot in the system is also set as \(f_i(q_i, \dot{q}_i) = [0.1q_{i1}\dot{q}_{i1}\sin(t) \quad 0.1q_{i2}\dot{q}_{i2}\sin(t)]^T\), and the internal friction of the master robot and the slave robot is \(f_{im}(\dot{q}_m) = [f_{i1}\dot{q}_{i1} + k_1 \text{sign}(\dot{q}_{i1}) f_{i2}\dot{q}_{i2} + k_2 \text{sign}(\dot{q}_{i2})]^T\), respectively, and \(f_{is}(\dot{q}_s) = [f_{i1s}\dot{q}_{i1} + k_1s \text{sign}(\dot{q}_{i1}) f_{i2s}\dot{q}_{i2} + k_2 \text{sign}(\dot{q}_{i2})]^T\), where \(f_{i1}, f_{i2}, k_1, k_2\) are constants, and \(i = m, s\).

At the same time, the external force from the operator is selected as \(f_h = [25(1 - \cos(\pi t))]^T\), and the external force
### TABLE 1 | Master-slave robot parameters and operator and environment parameters.

| $m_{m1}$ | $l_{m1}$ | $m_{m2}$ | $l_{m2}$ | $m_{s1}$ | $l_{s1}$ | $m_{s2}$ | $l_{s2}$ |
|----------|----------|----------|----------|----------|----------|----------|----------|
| 0.5 kg   | 0.6 m    | 0.5 kg   | 0.4 m    | 0.5 kg   | 0.6 m    | 0.5 kg   | 0.4 m    |
| 9.81 m/s^2 | 1       | 2       | 3       | 3       | 3       | 2       | 4       |
| $k_i$    | $M_i$    | $B_i$    | $K_i$    | $M_i$    | $B_i$    | $K_i$    | $M_i$    |
| 6        | 0.2 kg   | 50 Ns/m  | 1,000 N/m | 0.1 kg   | 20 Ns/m  | 1,000 N/m | 0.1 kg   |

$\text{sign}(\xi) = \begin{bmatrix} |\xi_1| \alpha_1 \text{sign}(\xi_1) & |\xi_2| \alpha_2 \text{sign}(\xi_2) & \cdots & |\xi_n| \alpha_n \text{sign}(\xi_n) \end{bmatrix}^T \in \mathbb{R}^n, \alpha_1, \alpha_2, \ldots, \alpha_n > 0.$

#### FIGURE 2 | Tracking performance between master and slave robots. 
(A) Tracking of master and slave robots' joints; (B) position tracking error of master and slave robots' joints.

#### FIGURE 3 | Input torque $\tau_m$ and $\tau_s$ of robot joints. 
(A) The master robot joint input torque $\tau_m$; (B) the slave robot joint input torque $\tau_s$. 
from the interaction between the robot and the environment is selected as $F^e = [0 0]^T$.

In the process of building a closed-loop teleoperation system, the mechanical constant parameters related to the dynamics of the master robot, the slave robot, the operator, and the environment are shown in Table 1.

In the simulation, it is assumed that the uncertain part of the master robot’s dynamic model is $\Delta M_m = 0.3 \sin(2t) M_{om}$, $\Delta C_m = 0.2 \sin(3t) C_{om}$, $\Delta G_m = 0.1 \sin(4t) G_{om}$ and that of the slave robot’s dynamic model is $q_m (0) = [0.4 \pi & 0.2 \pi]^T$, $q_s (0) = [0.1 \pi & 0.05 \pi]^T$. Set the initial position of the master robot and the slave robot. The time delay of forward and reverse communication channels of teleoperation system is $T_m = T_s = 0.6s$.

In the simulation teleoperation system, the master robot and the slave robot controller adopt Formula (9) and Formula (10). After repeated debugging, the controller parameters in the remote operation system are $K_m = K_s = diag (3, 3)$, $B_m = B_s = diag (3, 3)$, $\alpha_m = \alpha_s = diag(1, 1)$, $\beta_m = \beta_s = diag(1, 1)$, $\epsilon_m = \epsilon_s = diag(3, 3)$, $\gamma_m = \gamma_s = diag(1.5, 1.5)$, $\rho_m = \rho_s = diag(1/3, 1/3)$. The adaptive law is equation. After repeated
debugging, its parameters are $\Lambda_{m1} = \Lambda_{s1} = \text{diag}(2, 2)$, $\Lambda_{m1} = \Lambda_{s1} = \text{diag}(0.5, 0.5)$. In order to further observe whether the teleoperation system can keep stable if the external force changes due to the interaction between the robot and the environment, in the simulation, we reset $f^*_e = [0.80]^T$ as $f^*_e = [20\&20]$ at runtime $= 4s$. Meanwhile, we reset $K_e = 1,000$ as $K_e = 1, 100$.

In order to explain the advantages of the continuous adaptive terminal sliding mode bilateral controller objectively, comparative experiment is carried out. In the simulation, after repeated debugging, the parameters $L_m$, $L_s$, $N_m$, $N_s$ in the controller are $L_m = L_s = \text{diag}(100, 100), N_m = N_s = \text{diag}(100, 100)$, respectively.

The bilateral PD controller proposed in Reference 16 is chosen for comparative simulation. The expression of the controller is as follows:

$$\tau_m = -L_m(q_m(t) - q_s(t - T_s)) - N_m\dot{q}_m + G_m \quad (24)$$

$$\tau_s = -L_s(q_s(t) - q_m(t - T_m)) - N_s\dot{q}_s + G_s \quad (25)$$

**RESULTS**

In order to illustrate the effectiveness of using the continuous adaptive terminal sliding mode control bilateral controller in the closed-loop teleoperation system with time-delay force feedback, the simulation results are shown in Figures 2, 3. Figure 2 shows the tracking performance between the master and slave robots of the teleoperation system. Figure 3 shows the input torque signals of Joint 1 and Joint 2 of the master robot and the slave robot under the system.

In order to further observe whether the teleoperation system can continue to maintain stability when the external force changes due to the interaction between the robot and the environment, the simulation results of position tracking error and the environmental force change are shown in (a) and (b) in Figure 4.

In order to explain the advantages of the continuous adaptive terminal sliding mode bilateral controller objectively, comparative experiments were carried out, and the experiment results are shown in Figures 5, 6. Figures 5, 6 show the comparison of angular position tracking errors of the Joint 1 and Joint 2 of the master robot and the slave robot under the control method in this paper and the traditional PD control method, respectively. “ATSMCGFT” refers to “adaptive terminal sliding mode bilateral controller with guaranteed continuous finite time”; “TPDC” refers to “traditional proportional and derivative bilateral controller.”

In addition, Figure 6 shows the comparison diagram of the contact force tracking error between the master robot and the slave robot.

**DISCUSSION**

The controller of the master robot and the slave robot is designed based on the non-singular terminal sliding mode control method, and the neural network adaptive method is also incorporated into the controller to approximate the uncertainty of the teleoperation system model so as to eliminate the influence of the system model uncertainty on the system stability. Based on Lyapunov stability theory and terminal sliding mode control theory, the stability of the teleoperation system with time-delay force feedback and the tracking error of the master robot and the slave robot can converge to 0 in limited time. Based on the theory of the terminal sliding mode control, the non-linear sliding mode variable is defined, and the appropriate controller algorithm is designed to solve the chattering and singularity problems. The ASMC-GFT method proposed in the manuscript has a smaller convergence time. The experimental data results show that using the time-delay force feedback teleoperating system of this method, although the joint position tracking error of the master and slave robots can converge to 0 in a limited time, that is, the convergence time of the tracking error has been improved, the average tracking error index is slightly lower. There exists a decrease in error accuracy.

**CONCLUSION**

Through experiments, we can see that the robot can track the movement of the upper master robot in 2s, and from the simulation experiment results that the position tracking error of the master robot and the slave robot of the teleoperation system in this paper can quickly converge to zero, and the system is globally stable and has good instantaneous characteristics. Besides, we also can observe that the input torque of each joint of the master and slave robot under the control method designed in this paper is bounded. At the same time, we can also see that the slave robot can track the upper master robot in 2s.
The experimental results show the control method designed in this paper has good performance.

It can be seen from the results that, when $t = 4$ s, after the environmental force becomes larger, the tracking error of the teleoperation system can also be adjusted to the area near 0 in a limited time, while maintaining the stability of the system.

It also can be seen from the results that the convergence time of the position tracking error $e_m$ of the master robot under the control method in this paper is about $[2 \ 2]T$, and that of the position tracking error $e_i$ of the slave robot is about $[2 \ 2.5]T$. While the convergence time of the master robot position tracking error $e_m$ under the traditional PD control method is about $[6 \ 5]T$, and the convergence time of the slave robot position tracking error $e_i$ is about $[4.5 \ 5.2]T$.

To sum up, from the comparison of experimental results, we can observe that the control method in this paper has better performance; the tracking error of its position and contact force can converge to near 0 in a short time; at the same time, it has good performance of force feedback-tracking control.

REFERENCES

Bejczy, A. K. (1994). Toward advanced teleoperation in space. Progr. Astronaut. Aeronaut. 161, 107–107. doi: 10.2514/5.9781600866333.0107.0138

Chen, X., Yin, L., Fan, Y., Song, L., and Zheng, W. (2020). Temporal evolution characteristics of PM2.5 concentration based on continuous wavelet transform. Sci. Total Environ. 699, 134244. doi: 10.1016/j.scitotenv.2019.134244

Dankwa, S., and Zheng, W. (2019). Special issue on using machine learning predictions in the prediction of kyphosis disease: a comparative study. Appl. Sci. 9, 3322. doi: 10.3390/app9163322

DiMaio, S., Hanuschik, M., and Kreaden, U. (2011). The da Vinci Surgical System. Sunnyvale, CA: Springer, 199–217. doi: 10.1007/978-1-4419-1126-1_9

Feng, Y., Yu, X., and Man, Z. (2002). Non-singular terminal sliding mode control of rigid manipulators. Automatica 38, 2159–2167. doi: 10.1016/S0005-1098(02)00147-4

Guo, F., Yang, B., Zheng, W., and Liu, S. (2021). Power frequency estimation using sine filtering of optimal initial phase. Measurement 186, 110165. doi: 10.1016/j.measurement.2021.110165

Li, T.-H. S., and Huang, Y.-C. (2010). MIMO adaptive fuzzy terminal sliding-mode controller for robotic manipulators. Inform. Sci. 180, 4641–4660. doi: 10.1016/j.ins.2010.08.009

Li, X., Lam, N., Qiang, Y., Li, K., and Zheng, W. (2016). Measuring county resilience after the 2008 Wenchuan earthquake. Int. J. Disaster Risk Sci. 7, 393–412. doi: 10.1007/s13753-016-0109-2

Li, X., Yin, L., Yao, L., Yu, W., She, X., and Wei, W. (2020). Seismic spatiotemporal characteristics in the Alpide Himalayan Seismic Belt. Earth Sci. Informatics 13, 883–892. doi: 10.1007/s12245-020-00468-3

Li, X., Zheng, W., Lam, N., Wang, D., Yin, L., and Yin, Z. (2017b). Impact of land use on urban waterlogging disaster: a case study of Beijing and New York cities. Environ. Eng. Manag. J. 16, 1211–1216. doi: 10.30683/emj.2017.127

Li, X., Zheng, W., Wang, D., Yin, L., and Wang, Y. (2015). Predicting seismicity trend in southwest China based on wavelet analysis. Int. J. Waveslets Multiresol. Inform. 13, 1550011. doi: 10.1142/S0219691315500113

Li, X., Zheng, W., Yin, L., Yin, Z., and Xia, T. (2017a). Influence of social-economic activities on air pollutants in Beijing, China. Open Geosci. 9, 314–321. doi: 10.1515/geo-2017-0026

Li, Y., Zheng, W., Liu, X., Mou, Y., Yin, L., and Yang, B. (2021). Research and improvement of feature detection algorithm based on FAST. Rendiconti Lincei. Scienze Fisiche e Naturali 32, 775–789. doi: 10.1007/s12210-021-01020-1

Liu, H., and Zhang, T. (2013). Neural network-based robust finite-time control for robotic manipulators considering actuator dynamics. Robot. Comput. Integr. Manuf. 29, 301–308. doi: 10.1016/j.rcim.2012.09.002

Liu, S., Wang, L., Liu, H., Su, H., Li, W., and Zheng, W. (2018). Deriving bathymetry from optical images with a localized neural network algorithm. IEEE Trans. Geosci. Remote Sens. 56, 5334–5342. doi: 10.1109/TGRS.2018.2814012

Ma, Z., Zheng, W., Chen, X., and Yin, L. (2021). Joint embedding VQA model based on dynamic word vector. PeerJ. Comput. Sci. 7, e353. doi: 10.7717/peerj-cs.353

Nella, M. B. R., and Tarak, D. (2011). Adaptive terminal sliding mode control for rigid robotic manipulators. Int. J. Automat. Comput. 8, 215–220. doi: 10.1007/s11633-011-0576-2

Nekoukar, V., and Erfanian, A. (2011). Adaptive fuzzy terminal sliding mode control for a class of MIMO uncertain nonlinear systems. Fuzzy Sets Syst. 179, 34–49. doi: 10.1016/j.fss.2011.05.009

Nuno, E., Ortega, R., Barabanov, N., and Basanez, L. (2008). A globally stable PD controller for bilateral teleoperators. IEEE Trans. Robot. 24, 753–758. doi: 10.1109/TRO.2008.921565

Salcuțeanu, S. E., Zhu, M., and Zhu, W.-H. (2000). Transparent bilateral teleoperation under position and rate control. Int. J. Robot. Res. 19, 1185–1202. doi: 10.1177/02783640022068020

Sayers, C., and Paul, R. (1994). Coping with delays-controlling robot manipulators underwater. Indus. Robot Int. J. 21, 24–26. doi: 10.1108/106507294020004162

Tang, Y., Liu, S., Deng, Y., Zhang, Y., and Zheng, W. (2020a). Construction of force haptic reappearance system based on Geomatic Truth haptic device. Comput. Methods Programs Biomed. 190, 105344. doi: 10.1016/j.cmpb.2020.105344

Tang, Y., Liu, S., Li, X., Fan, Y., Deng, Y., Liu, Y., et al. (2020b). Earthquakes spatio-temporal distribution and fractal analysis in the Eurasian seismic belt. Rendiconti Lincei. Scienze Fisiche e Naturali 31, 203–209. doi: 10.1007/s12210-020-06871-4

Wang, Y., Tian, J., Liu, Y., Yang, B., Liu, S., Yin, L., et al. (2021). Adaptive neural network control of time delay teleoperation system based on model approximation. Sensors 21, 7443. doi: 10.3390/s21127443

Wright, J., Hartman, F., Cooper, B., Maxwell, S., and Morrison, J. (2006). Driving on Mars with RSVP. IEEE Robot. Automat. Magazine 13, 37–45. doi: 10.1109/MRA.2006.1638014

Xu, C., Yang, B., Guo, F., Zheng, W., and Poignet, P. (2020). Sparse-view CBCT reconstruction via weighted Schatten p-norm minimization. Optics Express 28, 35469–35482. doi: 10.1364/OE.404471

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

AUTHOR CONTRIBUTIONS

SL, BY, WZ, and LY contributed to the design of this work. JW, JT, and XZ contributed to the writing of the manuscript. JW and JT designed the model and implemented it in the framework, together with WZ and LY revised the manuscript. All authors contributed to the article and approved the submitted version.

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Xu, L., and Yao, B. (2001). Adaptive robust precision motion control of linear motors with negligible electrical dynamics: theory and experiments. *IEEE ASME Trans. Mechatr.* 6, 444–452. doi: 10.1109/3516.974858

Yang, B., Liu, C., Zheng, W., Liu, S., and Huang, K. (2019). Reconstructing a 3D heart surface with stereo-endoscope by learning eigen-shapes. *Biomed. Optics Express* 9, 6222–6236. doi: 10.1364/BOE.9.006222

Yin, L., Li, X., Zheng, W., Yin, Z., Song, L., Ge, L., et al. (2019). Fractal dimension analysis for seismicity spatial and temporal distribution in the circum-Pacific seismic belt. *J. Earth Syst. Sci.* 128, 22. doi: 10.1007/s12040-018-1040-2

Yu, S., Yu, X., Shirinzadeh, B., and Man, Z. (2005). Continuous finite-time control for robotic manipulators with terminal sliding mode. *Automatica* 41, 1957–1964. doi: 10.1016/j.automatica.2005.07.001

Yu, X., and Man, Z. (2002). Fast terminal sliding-mode control design for nonlinear dynamical systems. *IEEE Trans. Circuits Syst. I Fundam. Theory Appl.* 49, 261–264. doi: 10.1109/81.983876

Zhang, T.-P., Zhou, C.-Y., and Zhu, Q. (2009). Adaptive variable structure control of MIMO nonlinear systems with time-varying delays and unknown dead-zones. *Int. J. Autom. Comput.* 6, 124–136. doi: 10.1007/s11633-009-0124-5

Zhang, Z., Liu, Y., Tian, J., Liu, S., Yang, B., Xiang, L., et al. (2021). Study on reconstruction and feature tracking of silicone heart 3D surface. *Sensors* 21,7570. doi: 10.3390/s21227570

Zheng, W., Li, X., Yin, L., Yin, Z., Yang, B., Liu, S., et al. (2017). Wavelet analysis of the temporal-spatial distribution in the Eurasia seismic belt. *Int. J. Wavelets Multiresol. Inform. Process.* 15, 1750018. doi: 10.1142/S0219691317500187

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