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FINITE-TIME DISTURBANCE OBSERVER BASED NONSINGULAR TERMINAL SLIDING MODE CONTROL OF GREENHOUSE TEMPERATURE

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Abstract. *In this paper, the strong coupling greenhouse temperature system is modeled as a second-order nonlinear system, and the disturbance enters the system with a different channel from the control input. The non-singular terminal sliding mode controller is proposed to address the problem. The nonlinear dynamic sliding mode surface is designed based on a disturbance observer. The observer's error system is proved to be finite-time stable. The simulation shows that the proposed control method can shift any initial state to the equilibrium point in finite time with a smoother control.*

Keywords: Finite-time disturbance observer, Greenhouse temperature, Non-singular terminal sliding mode control, Mismatched disturbance

1. **Introduction.** The greenhouse temperature control is concerning the creation of adequate environment for the crop in order to reach predetermined results for high yield quality. However, the greenhouse temperature system control has always been a challenging task in the system control field because the greenhouse is a multi-variable coupling, time varying and nonlinear complicated system [1].

In recent years, the most popular greenhouse temperature controller is PID [2,3], this method guarantees simple implementation and good performance, but it exhibits high overshoot which is undesirable [3]. The other main greenhouse temperature controller is the MPC controller [4,5], but MPC needs to iteratively solve the optimization problem at each time step, and the response speed is hard to guarantee. The greenhouse temperature controller needs to maintain response speed while ensuring control accuracy. To pursue the stability and the response speed of the nonlinear greenhouse temperature, many achievements have been accomplished. However, the performance has not been fully researched.

In this paper, we establish an equivalent model based on heat transfer and thermoelectric similarity theory, the system is modeled as a network of resistors and capacitors, where temperature corresponds to potential and heat flow corresponds to current. So we can simplify complex greenhouse system into a second-order plant to control. To deal with the disturbances widely existing in the system, we use a finite-time disturbance observer (FTDO) to estimate the matched and mismatched disturbance [6] in this plant. The FTDO retains the nominal performance since it serves like a patch to the baseline control and does not cause any adverse affects on the greenhouse system. Then we select the sliding-mode control to address the coupling greenhouse states. In this paper, we design a novel nonsingular terminal sliding-mode control method; the nonlinear surface is based on the FTDO estimation. It can achieve the fast finite-time convergence without

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causing any singularity problem encountered in the traditional terminal SMC (TSMC) [7]. Via this method, the greenhouse temperature states are driven to the desired setpoint in finite-time.

The remainder of this paper is organized as follows. In Section 2, we describe the problem and preliminaries. In Section 3, the main results are given: The FTDO form and the finite-time convergence proof is introduced in the first part; the greenhouse non-singular terminal sliding-mode controller based on the FTDO has been proposed in the second part. The simulation is given in Section 4. In Section 5, we give the conclusion of the paper.

2. Problem Statement and Preliminaries.

We use the thermoelectric similarity theory to regard the model as a grid of resistances and capacitors. The basic heat flow of the system has following four pathways [8]:

1) Heat is exchanged between the interior air and the walls by means of the heat convection. This way will affect both the interior air and the wall simultaneously;
2) Heat is exchanged between the interior air and the outside air through the window by means of the heat convection;
3) The heat can lose through the heat exchange between the wall and the outside air. The form of that heat transfer is heat convection;
4) The thermal control equipment will transfer heat to the wall by means of the heat conduction. The heat time-varying transfer function is expressed as $u(t)$.

As shown in Figure 1, the differential equations describing the dynamic behavior of the greenhouse temperature system can be derived from the above principles and are given by

$$\begin{aligned} C_i \frac{dT_i}{dt} &= \frac{1}{R_{iw}} (T_w - T_i) + \frac{1}{R_o} (T_o - T_i) \\ C_w \frac{dT_w}{dt} &= \frac{1}{R_{iw}} (T_i - T_w) + \frac{1}{R_{ow}} (T_o - T_w) + u(t) \end{aligned} \tag{1}$$

where i, w, o respectively represent the interior air, the wall and the outside air; C, T are the specific heat capacity and the temperature of the object; R is the thermal resistance between the two media. The atmosphere temperature T_o is a complex function related to the real time, referred to [9], it can generally be expressed as $T_o = \alpha \sin \omega_i + \beta$, where

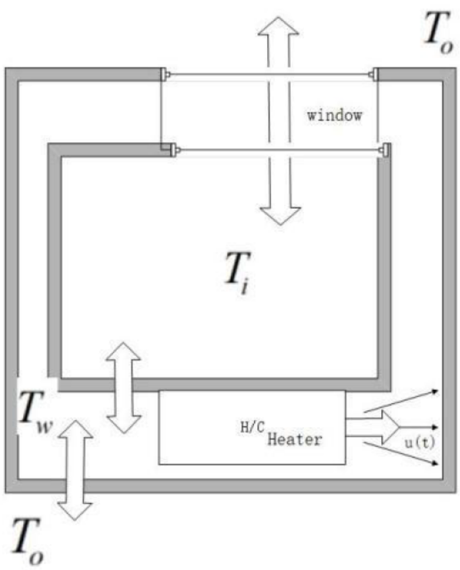

Figure 1. Model of the greenhouse heat flow

α denotes the maximum of the atmosphere temperature difference and β denotes the average value of the atmosphere, ω_i is the current time angle. We can see that T_o is a variable with a high frequency of change, so we treat T_o as an external disturbance.

Define the control system state as $x_1 = T_i$, $x_2 = \frac{1}{R_{iw}C_i}T_w$. Then, the following dynamic state-space equation for the integral chain of the temperature can be obtained from (1) as

$$\begin{aligned} \dot{x}_1 &= x_2 - \frac{1}{C_i}\left(\frac{1}{R_o} + \frac{1}{R_{iw}}\right)x_1 + \frac{1}{R_oC_i}T_o \\ \dot{x}_2 &= \frac{1}{R_{iw}C_iR_{iw}C_w}x_1 - \frac{1}{C_w}\left(\frac{1}{R_{ow}} + \frac{1}{R_{iw}}\right)x_2 + \frac{1}{R_{ow}C_w}\frac{1}{R_{iw}C_i}T_o + \frac{1}{R_{iw}C_i}\frac{1}{C_o}u(t) \end{aligned} \tag{2}$$

Next, consider the disturbance and some system variables of x_1 channel as d_1, the disturbance of x_2 channel as d_2. We can see that $d_1 = -\frac{1}{C_i}\left(\frac{1}{R_o} + \frac{1}{R_{iw}}\right)x_1 + \frac{1}{R_oC_i}T_o$ and $d_2 = \frac{1}{R_{ow}C_w}\frac{1}{R_{iw}C_i}T_o$ denote the mismatched and matched disturbances, respectively.

The greenhouse temperature model can be simplified to a second-order system with coupled states and various disturbances, which will be stabilized via a novel non-singular terminal sliding mode control in Section 3.

3. Main Results.

3.1. The finite time disturbance observer design.

It is assumed that the disturbance d_i in (2) is $(n-i+1)$ the order differentiable and d_i has a Lipschitz constant L_i $(i = 1, 2)$, $L_i > 0$. All the states of system (1) are measurable, and the controller output is variable in real time. Then the second order FTDO [10] for the mismatched disturbance in system (1) is given by

$$\begin{aligned} &\dot{z}_0 = v_0 + x_2,\ v_0 = -\lambda_0 L^{\frac{1}{3}}\mathrm{sgn}^{\frac{2}{3}}(z_0 - x_1) + z_1 \\ &\dot{z}_1 = v_1,\ v_1 = -\lambda_1 L^{\frac{1}{2}}\mathrm{sgn}^{\frac{1}{2}}(z_1 - v_0) + z_2 \\ &\dot{z}_2 = v_2,\ v_2 = -\lambda_2 L\mathrm{sgn}(z_2 - v_1) \\ &\hat{x}_1 = z_0,\ \hat{d}_1 = z_1,\ \hat{\dot{d}}_1 = z_2 \end{aligned} \tag{3}$$

$\lambda_0, \lambda_1, \lambda_2 > 0$ are the observer coefficients to be designed respectively, we define $\sigma_0 = z_0 - x_1$, $\sigma_1 = z_1 - d_1$, $\sigma_2 = z_2 - d_2$; combining (2) with (3), the observer estimation error is governed by

$$\begin{aligned} &\dot{\sigma}_0 = -\lambda_0 L^{\frac{1}{3}}\mathrm{sgn}^{\frac{2}{3}}(\sigma_0) + \sigma_1 \\ &\dot{\sigma}_1 = -\lambda_1 L^{\frac{1}{2}}\mathrm{sgn}^{\frac{1}{2}}(\sigma_1 - \dot{\sigma}_0) + \sigma_2 \\ &\dot{\sigma}_2 \in -\lambda_2 L\mathrm{sgn}(\sigma_2 - \dot{\sigma}_1) + [-L, L] \end{aligned} \tag{4}$$

Remark 3.1. *The form of the disturbance observer in (3) is used to estimate d_1 and $\dot{d}_1$. After changing the latter form of the first equation, we can observe d_2 in a similar way.*

Lemma 3.1. *Suppose that the states x_1, x_2 and $u(t)$ are measured with no noise. The parameters λ_0, λ_1, λ_2 being chosen sufficiently large in the reverse order [10], the observer error system (4) is finite-time stable, that is there is a finite time such that the error converges to zero, while the state of FTDO can estimate the disturbance accurately.*

Proof: The differential equation of the error system (4) is invariant with respect to the combined time-coordinate transformation [11]. G_K: $(t, \sigma_i)| \to (kt, d_k\sigma_i)$, the $d_k\sigma_i$ is the dilation of σ_i, that is $(k^3\sigma_0, k^2\sigma_1, k\sigma_2)$. So system (4) is homogeneous of the degree -1.

Consider the first item of the $\dot{\sigma}_0$ equation, a $-\lambda_0 L^{\frac{1}{3}}\mathrm{sgn}^{\frac{2}{3}}(\sigma_0)$ always has the effect of making $\dot{\sigma}_0$ converge to 0. We can consider the σ_1 as a disturbance, for a given $|\sigma_1|$, there is always some $|\sigma_0|$ for $\dot{\sigma}_0$ to zero, and the value of $|\sigma_0|$ is called the k_ith amplitude. We can easily prove that the amplitude decreases as the number of oscillations increases by contradiction. Similar results can be obtained for other equations in this way: oscillation attenuation in each state of the system, the trajectory of $|\sigma_i| \leq |S_i'|$ will converge to a circle with a smaller radius. We can obtain the observer error system (4) is finite-time stable [9].

3.2. **Design of non-singular terminal sliding mode controller based on FTDO.** The novel nonlinear dynamic sliding mode surface [6] is selected for the second-order system (2):

$$S = x_1 + \frac{1}{\beta}\left(x_2 + \hat{d}_1\right)^{\frac{p}{q}} \tag{5}$$

where β, p, q are well defined, $\beta > 0$ is a designed constant, and p, q are positive odd integers which satisfy the condition that $1 < p/q < 2$ [10], $\hat{d}_1$ is the observer (3) estimation.

Lemma 3.2. *For the greenhouse temperature system with the proposed nonlinear sliding mode surface, if the non-singular terminal sliding mode controller is designed as (6):*

$$u = -\frac{1}{b}a(x) + \beta\frac{q}{p}\left(x_2 + \hat{d}_1\right)^{2-p/q} + \hat{d}_2 + \dot{\hat{d}}_1 + k_1 s + k_2 \operatorname{sgn}(s)|s|^{\alpha} \tag{6}$$

where $k_2 \geq k_1 > 0$, $0 < \alpha < 1$ is the parameters to be designed, and the $\dot{\hat{d}}_1$, $\hat{d}_2$ have been given in the FTDO mentioned above, then the system output $y = x_1$ will converge to zero in finite time, that is the system can converge to equilibrium point under the control law.

Proof: For the proposed sliding surface, its derivatives along the system dynamics is

$$\begin{aligned}\dot{s} &= \dot{x}_1 + \frac{1}{\beta}\frac{p}{q}\left(x_2 + \hat{d}_1\right)^{p/q-1}\left(\dot{x}_2 + \dot{\hat{d}}_1\right) \\ &= -\frac{1}{\beta}\frac{p}{q}\left(x_2 + \hat{d}_1\right)^{p/q-1}\left[k_1 s + k_2\operatorname{sgn}(s)|s|^{\alpha} + \left(\hat{d}_2 - d_2\right)\right] - \left(\hat{d}_1 - d_1\right)\end{aligned} \tag{7}$$

Define $\tilde{x}_2 = x_2 + \hat{d}_1$, $e_1 = \hat{d}_1 - d_1$, $e_2 = \hat{d}_2 - d_2$, and then we can obtain

$$\dot{S} = \frac{1}{\beta}\frac{p}{q}\tilde{x}_2^{p/q-1}[k_1 s + k_2\operatorname{sgn}(s)|s|^{\alpha} + e_2] - e_1 \tag{8}$$

$$\dot{\tilde{x}}_2 = -\beta\frac{q}{p}\tilde{x}_2^{2-p/q} - k_1 s - k_2\operatorname{sgn}(s)|s|^{\alpha} - e_2 \tag{9}$$

We assume that the convergence time of finite-time disturbance observer is t_f ($t_f > 0$).

When $t < t_f$, define a finite-time bounded function [11] $v = \frac{1}{2}\left(s^2 + x_1^2 + x_2^2\right)$ for the sliding mode (8) and the state dynamics (9). Note that $|s|^{\alpha} < 1 + s$. Taking the derivative of V, we can obtain that

$$\begin{aligned}\dot{V} &= -\frac{1}{\beta}\frac{p}{q}\tilde{x}_2^{p/q-1}\left(k_1 s^2 + k_2|s|^{\alpha+1} + e_2 s\right) - e_1 s + x_1\left(\tilde{x}_2 - e_1\right) \\ &\quad + \tilde{x}_2\left(-\beta\frac{q}{p}\tilde{x}_2^{2-p/q} - k_1 s - k_2\operatorname{sgn}(s)|s|^{\alpha} - e_2\right) \\ &\leq \frac{1}{\beta}\frac{p}{q}\left(1 + |\tilde{x}_2|\right)|e_2 s| + |e_1 s| + |x_1\tilde{x}_2| + |x_1 e_1| + |\tilde{x}_2|\left[k_1|s| + k_2(1 + |s|)\right] + |\tilde{x}_2|\,|e_2| \\ &\leq \frac{1}{\beta}\frac{p}{q}\left(\frac{e_2^2 + s^2}{2} + |e_2|\frac{\tilde{x}_2 + e_2^2}{2}\right) + \frac{s^2 + e_1^2}{2} + \frac{x_1^2 + \tilde{x}_2^2}{2} + \frac{x_1^2 + e_1^2}{2} \\ &\quad + (k_1 + k_2)\frac{s^2 + \tilde{x}_2^2}{2} + k_2\frac{1 + \tilde{x}_2^2}{2} + \frac{e_2^2 + \tilde{x}_2^2}{2} \\ &\leq Max_1 V + Max_2\end{aligned} \tag{10}$$

where $Max_1 = \max\left\{1 + k_1 + k_2 + \frac{p}{\beta q}, 2 + k_1 + 2k_2 + \frac{p}{\beta q}|e_2|\right\}$, $Max_2 = \max\left\{e_1^2 + \frac{k_2}{2} + \frac{1}{2}\left(1 + \frac{p}{\beta q}\right) + \frac{p}{2\beta q}e_2^3\right\}$, because of the boundness of the e_1, e_2, we can easily obtain that Max_1, Max_2 are bounded constants. Then the s, x_1, x_2 satisfied the uniform forward completeness. We can conclude the sliding mode surface and the system state x_1, $\hat{x}_2$ will not escape in finite time, that is sufficient to guarantee the finite-time convergence [14].

When $t > t_f$, referred to Lemma 3.1, the disturbance estimation error e_1 and e_2 will converge to zero; the sliding mode dynamics (9) is then reduced to

$$\dot{s} = -\frac{1}{\beta}\frac{p}{q}\tilde{x}_2^{p/q-1}\left[k_1 s + k_2 \mathrm{sgn}(s)|s|^{\alpha}\right] \tag{11}$$

We define a Lyapunov function $V_2 = \frac{1}{2}s^2$, combined with Equation (11) yields

$$\begin{aligned}\dot{V}_2 &= s\dot{s} = -\frac{1}{\beta}\frac{p}{q}\left[k_1 s^2 + k_2|s|^{\alpha+1}\right] \\ &\leq -\frac{1}{\beta}\frac{p}{q}\tilde{x}_2^{p/q-1}\left[k_1|s| + k_2|s|^{\alpha}\right]|s| \leq -\frac{1}{\beta}\frac{p}{q}\tilde{x}_2^{p/q-1}\left[k_1|s| + k_2|s|^{\alpha}\right]\sqrt{2}V^{\frac{1}{2}}\end{aligned} \tag{12}$$

For the case of $\tilde{x}_2 \neq 0$ we can get $\frac{1}{\beta}\frac{p}{q}\tilde{x}_2^{p/q-1} > 0$, the system state can reach the sliding mode $s = 0$ within finite time [15]. For $\tilde{x}_2 = 0$, Equation (9) is reduced to

$$\dot{\tilde{x}}_2 = -k_1 s - k_2 \mathrm{sgn}(s)|s|^{\alpha} \tag{13}$$

For $s > 0$, it is obtained $\dot{\tilde{x}}_2 < -k_1 s - k_2|s|^{\alpha}$, and for $s < 0$, $\dot{\tilde{x}}_2 > (k_2 - k_1)s + k_2$, showing that $\tilde{x}_2 = 0$ is not an attractor [13]. The phase plot of the system is shown in Figure 2. We can see that there exists a vicinity of $x_2 = 0$ such that for a small $\delta > 0$ such that $|x_2| < \delta$, the crossing of the trajectory from the boundary of the vicinity $x_2 = \delta$ to $x_2 = -\delta$ for $s > 0$, and from $x_2 = -\delta$ to $x_2 = \delta$ for $s < 0$. Therefore, it can be concluded that the sliding mode $s = 0$ can be reached from anywhere in the phase plane in finite time.

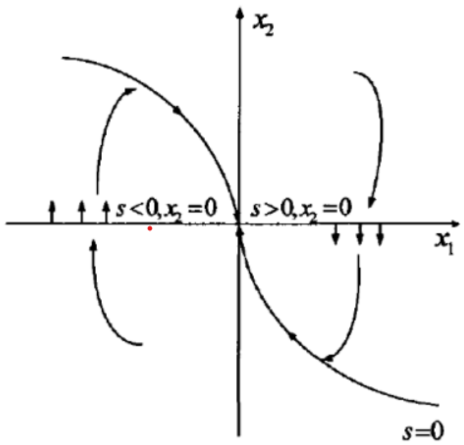

Figure 2. The phase plot of the system

After the system state reaches the sliding surface, there is $s = 0$, and we can obtain from the sliding surface (5) and the system dynamics (2) that

$$s = x_1 + \frac{1}{\beta}\left(x_2 + \hat{d}_1\right)^{p/q} = x_1 + \frac{1}{\beta}\dot{x}_1^{p/q} = 0 \tag{14}$$

With the chosen parameters, system (3) is finite-time stable, which completes the proof.

4. **Simulation.** The intrinsic parameters of the greenhouse temperature system are $C_i = 49.618$ kwh/°C, $C_w = 323.732$ kwh/°C, $R_o = 5.057$°C/kw, $R_{ow} = 4.811$°C/kw, $R_{iw} = 0.409$°C/kw, which are estimated by the maximum likelihood method for experimental data collected [16].

The atmosphere temperature disturbance imposed on the greenhouse is represented as (2) with $T_o = \sin(20\pi t)$. The parameters of the sliding mode controller (6) are designed as $\beta = 50$, $k_1 = 5$, $k_2 = 50$, $\alpha = 0.5$, $p = 5$, $q = 3$; the FTDO parameter used to estimate d_1 is $\lambda_1 = 2$, $\lambda_2 = 1.5$, $\lambda_3 = 0.01$, $L = 100$; the one estimates d_2 is $\lambda_1 = 3$, $\lambda_2 = 2$, $\lambda_3 = 1.5$, $L = 1$.

The disturbance d_1, d_2, the disturbance observation $\hat{d}_1$, $\hat{d}_2$ and the disturbance observation error $\tilde{d}_1$, $\tilde{d}_2$ of the finite-time disturbance observer (5) are shown in Figure 3

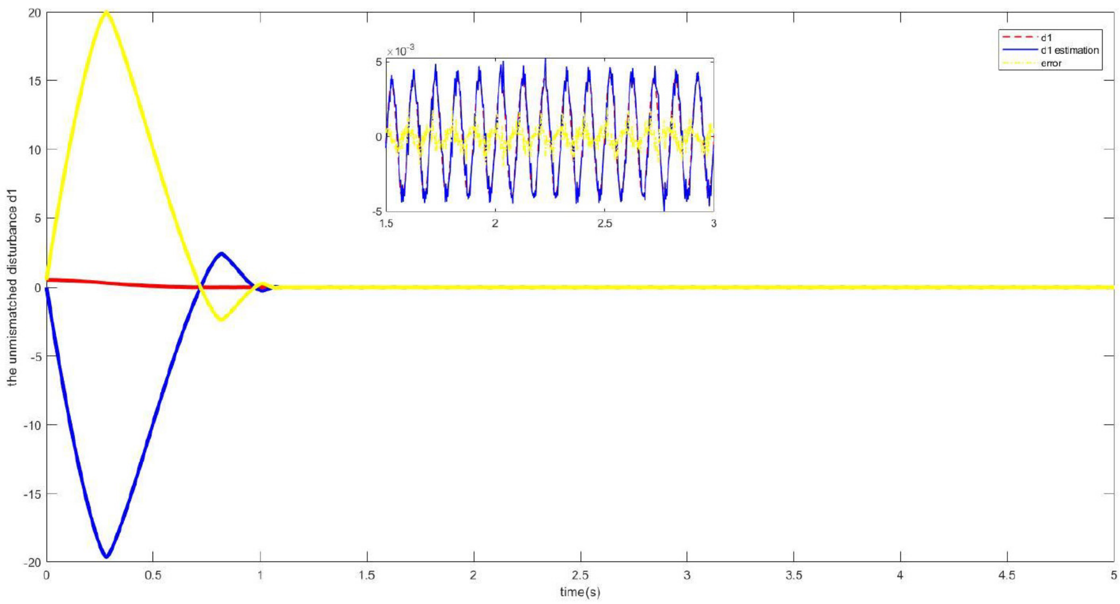

FIGURE 3. The disturbance d_1, the disturbance observation $\hat{d}_1$ and the disturbance observation error $\tilde{d}_1$

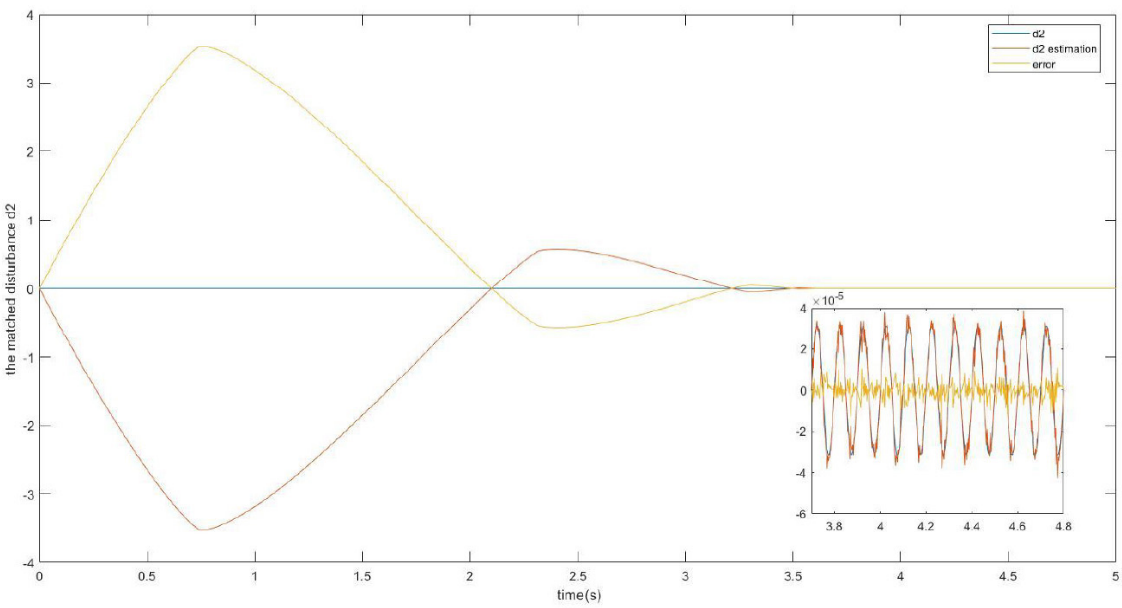

FIGURE 4. The disturbance d_2, the disturbance observation $\hat{d}_2$ and the disturbance observation error $\tilde{d}_2$

and Figure 4, respectively. It can be seen that the observation error of the disturbance observer is small and converges to zero gradually over a period of time for both $\tilde{d}_1$, $\tilde{d}_2$. It is proposed that whatever the matched and mismatched disturbance, the proposed finite-time disturbance observer has a high accuracy performance.

Then the response curves of the system state variables under the FTDO-NTSMC and the traditional NTSMC are shown in Figure 5. The NTSMC method can only attenuate the disturbance to a specified small region while the proposed method has nearly removed such disturbance. Meanwhile, the FTDO-NTSMC takes less time to reach the desired setpoint from the initial states. The corresponding control signals of two methods are shown in Figure 6; we can stabilize the system with a smaller amount of control. In other words, we can achieve the aim with a smaller amount of control.

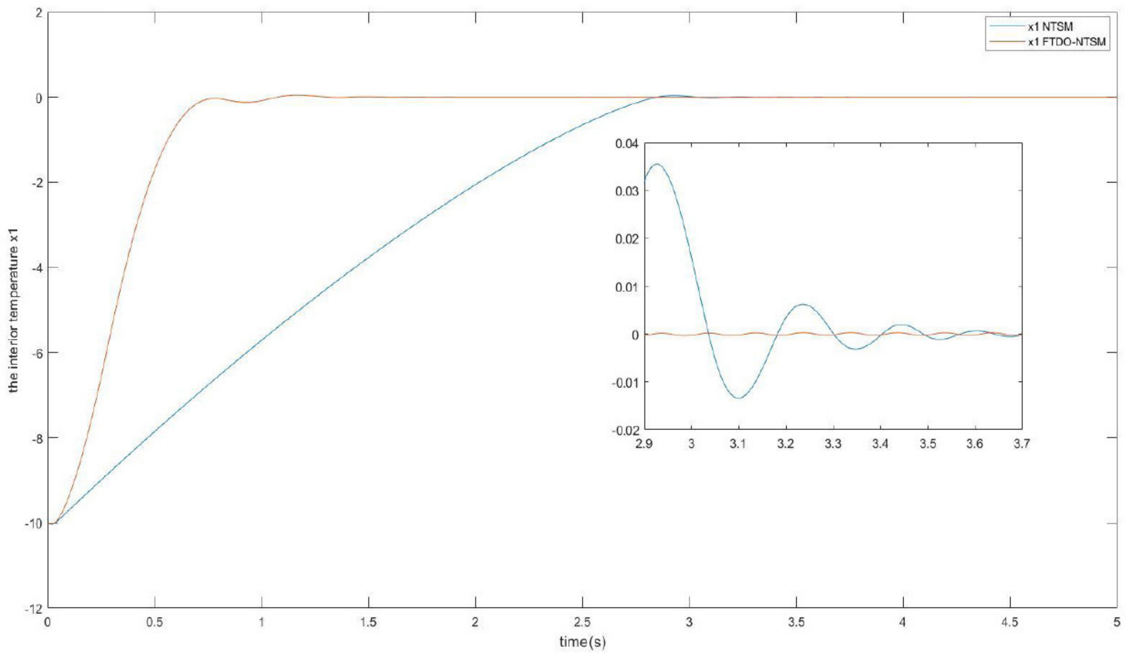

FIGURE 5. x_1 response curve of the greenhouse under two methods

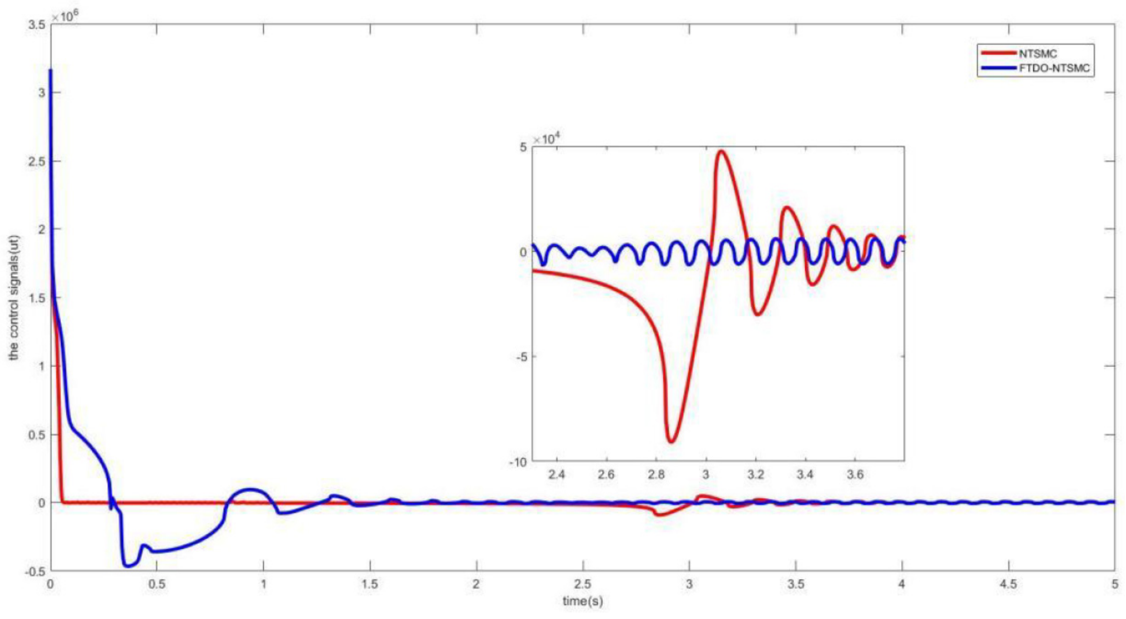

FIGURE 6. The control signal of the greenhouse under two methods

5. **Conclusions.** In this paper, the greenhouse temperature system is modeled as a second-order system with coupled states, matched disturbance and mismatched disturbance. The disturbance source considered in this paper is the atmosphere temperature. Two finite-time disturbance observers are used to estimate the matched and mismatched disturbance respectively. The finite time stability of the observer error system has been proved rigorously in the article. Then the non-singular terminal sliding mode control law including the estimations of the FTDO has been proposed to address the problem. Compared with the traditional NTSMC without the disturbance observer, the proposed method largely alleviates the chattering problem, and the control quantity is more smooth. Lastly, the simulation results on the obtained model have illustrated the efficiency of the proposed method.

However, the influence of model parameter perturbation is not considered in this paper, so the model can be further improved and the problem will become more tricky and interesting.

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