A Backstepping Control of Plant Protection Boom System Considering Input Constraints

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Abstract. Aiming at the plant protection machine boom system with input constraints, uncertain disturbances and various nonlinear factors, a backstepping controller considering input saturation uncertain interference is proposed. The method introduces an auxiliary system, realizes the compensation of control saturation by designing new error variables, and solves the amplitude constraint problem of the control input. By constructing the appropriate Lyapunov function, the stability of the planter boom system is guaranteed. The simulation results show that the designed controller has good tracking performance and robustness.

1. Introduction
With the rapid development of agriculture, plant protection machines are increasingly demanding for precise spraying. And it is of great significance to achieve precise application and improve pesticide utilization for development of accurate pole position control for plant protection machines. Large-scale domestic boom sprayers have low automation, relatively poor monitoring and control [1]. In this regard, many literature have studied control strategies such as robust control and intelligent control of the plant protection sprayer system, and have achieved satisfactory results [2,3]. Literature[4] analysis of the three movement modes of the sprayer of the plant protection machine and explained the movement method that has the greatest influence on the plant protection machine, but there is no research on the control of the sprayer. Literature [5] although the dynamic analysis of the response of large and wide booms is performed, the booms are not controlled and adjusted. However, the input saturation problem of the actuator is not considered in this article. None of the above literature consider the input saturation of the boom system.

In this paper, aiming at the problem of amplitude constraint in the control input of the boom system, considering the non-linearity and uncertain interference of the system, by introducing an auxiliary system, the Backstepping method is used to stabilize the augmented error system. Simulation results show that the control method the boom has good tracking performance and robustness under the condition of satisfying the input constraints.

2. Modeling Research
Figure 1 is a schematic diagram of the sprayer of the plant protection machine. It can be seen from the figure that the sprayer is mainly composed of two ultrasonic ranging sensors located at the end, a fixed bracket that plays a role of damping and supporting, and a hydraulic cylinder that adjusts the position of the sprayer.
The main principle of the boom position control system is that when the boom sprayer is operating in the field, the height of the boom is monitored in real time by ultrasonic sensors at both ends of the boom, and the monitored height is compared with the desired boom position to obtain the height. The difference is sent to the controller as an input signal for algorithm calculation, and the control signal is output to make the hydraulic cylinder of the actuator of the sprayer move, so that the spray rod reaches the specified target position.

The equal percentage valve is selected as the control valve of the boom system. And its installation flow characteristics are as follows:

\[ \frac{Q_l}{Q_{\text{max}}} = K \frac{l}{L} \]  

Considering that the response frequency of the actual boom system is much lower than the response frequency of the control valve, the voltage of the control valve and the spool displacement can be approximated as a linear link.

\[ l = K_v \mu \]  

In equation (2), \( K_v \) indicates the spool voltage-displacement gain flow gain; \( \mu \) is the spool voltage.

Then the continuous flow equation of the hydraulic cylinder can be expressed as:

\[ Q_l = A_p \frac{dx_p}{dt} + C_p P_l + \frac{V_p}{4\beta_v} \frac{dp}{dt} \]  

Taking into account the various frictions of the hydraulic cylinder, the system force balance equation is as follow

\[ m \frac{d^2 x_p}{dt^2} = A_p P_l - B_p \frac{dx_p}{dt} + F_s + F_c \left( x_p \right) + mg \]  

In equation (4), \( F_c \) indicates stribeck friction for hydraulic cylinders.

\[ F_c \left( x_p \right) = \begin{cases} f_{s1} x_p + f_{s2} e^{\left[ \frac{x_p}{\delta_{s1}} \right]} & x_p > 0 \\ f_{s2} x_p + f_{s1} e^{\left[ \frac{x_p}{\delta_{s2}} \right]} & x_p < 0 \end{cases} \]  

among them, \( f_{s1}, f_{s2} \) indicate the coefficient of static friction, \( f_{v1}, f_{v2} \) indicate the coefficient of viscous friction, \( f_{s1}, f_{s2} \) indicate stribeck friction coefficient, \( \delta_{s1}, \delta_{s2} \) as the coefficient of experience. Equation (5) can be abbreviated as

\[ F_c = b_0 + b_1 x_p + b_2 sgm \left( x_p \right) \]  

In equation (3), \( b_0, b_1, b_2 \) indicate the coefficient of friction, \( sgm(h) = \frac{1 - e^{-\delta h}}{1 + e^{-\delta h}} \).

The selected state variables are: \( x = [x_1, x_2, x_3]^T = [x_p, x_1, P_l]^T \) Simultaneously (1) (2) (3) (4) (6) get the equation of state of the boom system:
\[
\begin{align*}
\dot{x}_1 &= x_2 \\
\dot{x}_2 &= Ix_3 - Jx_2 - D \\
\dot{x}_3 &= -Px_2 - Qx_3 + R\mu
\end{align*}
\] (7)

\[
I = A_p/m, \quad J = B_p/m, \quad P = 4\beta_c A_p/V_t, \quad Q = 4\beta_c C_p/V_t, \quad R = 4\beta_c K, Q_{\max}/LV_t, \quad D = F_c + F_d \left(\dot{x}_p\right)/m + g
\]

In the actual system, the actuator hydraulic cylinder can only provide limited control force. Take the maximum input as \( \mu_{\max} > 0, \mu = \text{sat}(\nu) \), define \( \delta = \mu - \nu \). The saturation function of the control input can be expressed as

\[
\mu = \text{sat}(\nu) = \begin{cases} 
\text{sgn}(\nu)\mu_{\max}, & |\nu| \geq \mu_{\max} \\
\nu, & |\nu| < \mu_{\max}
\end{cases}
\] (8)

3. Controller Design

This paper considers that there is a input saturation problem in the sprayer system.

\[
\begin{align*}
\dot{\lambda}_1 &= -a_1 \lambda_1 + \lambda_2 \\
\dot{\lambda}_2 &= -a_2 \lambda_2 + b \delta
\end{align*}
\] (9)

First define a new error variable:

\[
z_1 = x_1 - y_d - \lambda_1
\] (10)

Step1 We differentiate the equation(10).

\[
\dot{z}_1 = x_2 - y_d - (\dot{\lambda}_2 - a_1 \lambda_1)
\] (11)

The first Lyapunov function is considered as:

\[
V_1 = \frac{1}{2} z_1^2
\] (12)

\[
\dot{V}_1 = z_1 \left[ x_2 - y_d - (\dot{\lambda}_2 - a_1 \lambda_1) \right]
\] (13)

Define the second error variable

\[
z_2 = x_2 - \alpha_1
\] (14)

Take \( \alpha_1 = y_d + (\lambda_2 - a_1 \lambda_1) - c_1 z_1 \), among them \( c_1 > 0 \) as constant, then

\[
\dot{V}_1 = -c_1 z_1 z_2 + z_1 \dot{z}_2
\] (15)

Step2 We differentiate the equation(14).

\[
\dot{z}_2 = Ix_3 - Jx_2 - D - y_d^{(2)} - \left[ -a_2 \lambda_2 + b \delta - a_1 (\lambda_2 - a_1 \lambda_1) \right] + c_1 \dot{z}_1
\] (16)

The second Lyapunov function is defined

\[
V_2 = V_1 + \frac{1}{2} z_2^2
\] (17)

Derivation of the above formula can be obtained
\[
\dot{V}_2 = \dot{V}_1 + z_1 \dot{z}_1 = -c_1 z_1^2 + z_1 z_2 + z_1 \left[ Jx_3 - Jx_2 - D - y_3^{(2)} + \left( -a_1 \dot{x}_2 + \delta - a_3 (\dot{x}_2 - \lambda_1 + \lambda_2) \right) + c_1 \dot{z}_1 \right]
\] (18)

Define the third error variable.

\[
z_3 = x_3 - \alpha_2
\] (19)

The control component is designated

\[
\alpha_2 = \frac{1}{I} \left[ Jx_2 + D + y_3^{(1)} + \left( -a_2 \dot{x}_2 + \delta - a_3 \left( -a_3 \dot{x}_2 + a_3 \dot{\lambda}_1 \right) \right) - c_1 \dot{z}_1 - z_1 - c_2 z_2 \right]
\] (20)

among them \( c_2 > 0 \), simultaneous equation (18) and equation (20)

\[
\dot{V}_2 = -c_1 z_1^2 - c_2 z_2^2 + Pz_1 z_3
\]

Step3 We differentiate the equation (19)

\[
\dot{z}_3 = -P x_2 - Q x_3 + R \mu - S_1
\] (21)

Among them

\[
S_1 = \dot{\alpha}_2 = \frac{1}{I} \left\{ J (Jx_3 - Jx_2 - D) + y_3^{(1)} + \left[ -a_2 \dot{x}_2 - a_3 \left( -a_3 \dot{x}_2 + a_3 \dot{\lambda}_1 \right) \right] - c_1 \dot{z}_1 - z_1 - c_2 z_2 \right\}
\] (22)

The last Lyapunov function is defined

\[
V_3 = V_2 + \frac{1}{2} \dot{z}_3
\] (23)

We differentiate the equation (23)

\[
\dot{V}_3 = -c_1 z_1^2 - c_2 z_2^2 + I z_2 z_3 + z_3 (\dot{P} x_2 - Q x_3 + R \mu - S_1)
\] (24)

The control law is designated

\[
\mu = \frac{1}{R} \left( P x_2 + Q x_3 + S_1 - I z_2 - c_3 z_3 \right)
\] (25)

Among them \( c_3 > 0 \), then

\[
\dot{V}_3 = -c_1 z_1^2 - c_2 z_2^2 - c_3 z_3^2 \leq 0
\] (26)

According to the above analysis, the control deviation of the system \( z_1, z_2, z_3 \) Continuous and bounded; if and only if \( z_1 = z_2 = z_3 = 0 \) Time, \( \dot{V}_3 = 0 \); According to Lyapunov stability principle, the system is progressively stable.

4. System Simulation Verification

The relevant parameter references and actual working conditions of the system are taken as:
Table 1. Parameters Table

| Parameter   | Numerical value | Parameter   | Numerical value |
|-------------|-----------------|-------------|-----------------|
| $A_p$ / $m^2$ | $1.88 \times 10^{-3}$ | $C_{ip}$ / $m^3 / s \cdot Pa$ | $9.2 \times 10^{-13}$ |
| $B_p$ / (N $\cdot$ m / m) | 7500 | $K_r$ / (m / V) | $2.33 \times 10^{-4}$ |
| $\beta_r$ / (MPa) | 1000 | $K$ | $6.8 \times 10^{-4}$ |
| $V_i$ / (m$^3$) | $3.8 \times 10^{-2}$ | $Q_{max}$ / (L / min) | 5.89 |
| $m$ / kg | 250 | $L$ / m | 0.04 |

As simulation shown in the figure, for all step responses, the static error of the boom is 0.2 mm. For the entire boom system, the static error is so small that it can be ignored. In summary, the control performance of the boom position controller performs well. Through the comparison of the descending curve and the step curve, it can be seen that the rise and fall of the sprayer of the plant protection machine is asymmetric, and it can be clearly seen that the time for the descending curve to reach stability is faster than the rising curve.

![Figure 2. 0.1m step curve](image1)

![Figure 3. 0.3m step curve](image2)

![Figure 4. 0.4m step curve](image3)

![Figure 5. 0.6m step curve](image4)

![Figure 6. 0.1m drop curve](image5)

![Figure 7. 0.3m drop curve](image6)
The tracking curve can be seen that the boom quickly reached the specified target position, and the maximum tracking error was 1.5mm after reaching the specified target position. It can be seen that the designed controller has good tracking performance.

The simulation is shown in the figure(12)(13): We add upward and downward interference signal with an amplitude of 2000N on 1s and 2s. The sprayer was quickly adjusted to the specified position, which shows that the designed controller is very robust.

5. Conclusion
The control strategy combining the auxiliary system proposed in this paper and the Backstepping control method is applied to the position control system of the boom of the plant protection machine, which solves the nonlinear problem of the system and improves the tracking performance of the system. Simulation results show that the controller has good tracking and robustness.

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References
[1] Wang Jin, Yang Hua, Hu Linshuang, Min Fanxiang. Research status and development trend of sprayer sprayer [J / OL]. Agricultural Machinery Use and Repair, 2019 (10): 7-9 [2019-10-11]. https://doi.org/10.14031/j.cnki.njwx.2019.10.003.
[2] J. Anthonis, H. Ramon. Design of an active suspension to suppress the horizontal vibrations of a spray boom [J]. Journal of Sound and Vibration, 2003, 266(3).

[3] Wang Qiang, Zhang Wen'ai, Wang Xiu, et al. Design of a Highly Intelligently Adjustable Agricultural Boom Control System [J]. Research of Agricultural Mechanization, 2016 (9).

[4] Li Shujiang, Xia Bin, Su Xihui, Wang Xiangdong. Design of the Sprayer Position Controller for Plant Protection Machinery [J]. Journal of Agricultural Mechanization Research, 2019, 41 (06): 83-87.

[5] Patrik Kennes, Herman Ramon, Josse De Baerdemaeker. Modelling the Effect of Passive Vertical Suspensions on the Dynamic Behaviour of Sprayer Booms [J]. Journal of Agricultural Engineering Research, 1999, 72(3).