DIFFERENTIAL AND INTEGRAL SLIDING MODE ADAPTIVE CONTROL ALGORITHM FOR DRAFT AND POSITION INTEGRATED CONTROL OF ELECTRO-HYDRAULIC HITCH IN AGRICULTURAL TRACTOR
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基于微分与积分自适应滑模的拖拉机电液悬挂力位综合控制

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ABSTRACT
The accuracy of tractor plowing is an important link to ensure the quality of agricultural crops. The integrated control of draft-position in plowing is an effective plowing precision control technology which can be used to improve the tractor's plowing efficiency. The hydraulic system of the tractor hitch has the characteristics of large load and complex working environment. A differential and integral sliding mode adaptive controller (DI-SMAC) is designed for the tractor hitch hydraulic system with strong nonlinearity, uncertainty and time-varying parameters. Compared with the traditional PID controller, integral sliding mode adaptive controller(I-SMAC) and differential and integral sliding mode adaptive controller (DI-SMAC) in the electro-hydraulic hitch control system, the numerical simulation verifies the advantages of the differential and integral sliding mode adaptive controller. The real test platform of the agricultural tractor is built. The test results show that the DI-SMAC can realize the integrated control function of draft-position. In the position control mode, there is no static error, and the anti-interference ability is strong; Under the draft control mode, compared with the traditional PID controller, the range of traction error of differential and integral sliding mode controller is reduced by 32.9%, and the standard deviation is reduced by 38.6%; When the weight coefficient is changed, the traction force and tillage depth fluctuation are different with different weight coefficients. It is shown that the DI-SMAC is stable and effective, and the developed method is expected to provide technical support for the fine plowing operation of tractors.

摘要
拖拉机犁耕作业精度是保证农业作物种植质量的重要环节。犁耕作业中的力位综合控制是一种有效的犁耕作业精度控制技术，可用于提高拖拉机的犁耕作业效率。本研究以拖拉机电液悬挂为研究对象，综合考虑拖拉机位姿状态和地面起伏和土壤沉陷对电液悬挂控制的影响，建立拖拉机机组电液悬挂动力学数学模型。拖拉机悬挂装置液压系统的负载质量大，作业环境复杂。针对拖拉机悬挂装置液压系统的强非线性、不确定性和参数时变性等特点，设计了微分与积分自适应滑模控制器。通过仿真对比传统 PID 控制器、积分滑模自适应控制器和微分与积分滑模自适应控制器，验证了微分与积分滑模自适应控制器的优越性。搭建实车试验平台，结果表明：采用微分与积分滑模自适应控制器，在位置控制模式下，基本无静差，抗干扰能力强；力控制模式下，相比传统 PID 控制器，微分与积分滑模控制器牵引力误差的极差降低了 32.9%，标准方差降低了 38.6%；力位综合控制模式下，不同权重系数牵引力和耕深波动也不同。说明微分与积分滑模自适应控制器是稳定有效的，所开发的方法有望为拖拉机精细犁耕作业提供技术支持。

INTRODUCTION
The hydraulic hitch control system is an essential device for large agricultural tractors. Hydraulic pressure is used as the power to lift and control agricultural tools. The hydraulic hitch is the core component to realize the power transmission and intelligent control of high-power tractors in the field.

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The tractor electro-hydraulic hitch control system is helpful to improve the quality of plowing operation (*Bentaher et al*., *2008*; *Janulevičius et al., 2019; LeeKim et al., 2016*). The performance of hydraulic hitch control directly affects the operation of the tractor and the energy consumption of the unit in the field *(Bacenetti, et al., 2018; Balsari et al., 2021; Pranav et al 2012)*. The hydraulic hitch control modes of agricultural tractors mainly include position control (*Saeys et al., 2004*), draft control (*Treichel et al., 1984*) draft-position integrated control *(Wang et al., 2021*), pressure control *(Liu et al., 2020*), slip rate control (*Gupta et al., 2019*) and vibration reduction control *(Cheng et al., 2017)*.

Draft-position integrated control is a common mode of tractor plowing operation. Scholars have carried out extensive research on draft-position integrated control mode of tractor electro-hydraulic hitch during plowing operation. *Lee et al. (1998)* proposed a control system for the depth of tillage of agricultural tractors to improve the precision of the depth of tillage during operation. They tested the dynamic characteristics of the control system. With the maturity of mechatronics, the electrical control system is gradually applied in tractors, and the hydraulic hitch of tractors is further developed. *Luo et al. (2015)* used an electric push rods for hydraulic hitch system control and passed the test to meet the automatic operation requirements of the tractor hydraulic hitch system. *Lu et al. (2013)* studied the automatic control method for the tillage depth of tractor electro-hydraulic hitch system, and put forward an automatic control method for tillage depth of the electro-hydraulic hitch system based on fuzzy control and the concept of integrated coefficient. *Li et al. (2013)* introduced the fuzzy PID control algorithm into the integrated draft-position control mode and carried out the position control and draft control experimental research, respectively, which improved the draft-position integrated control performance and control precision. *Li et al. (2018)* obtained better potential control performance by introducing soil-specific resistance parameters to change the draft-position integrated control weight of potential. In the above research, most of the draft-position integrated control focuses on the change of weight coefficient. Still, less attention is paid to the non-linear factors of the hydraulic hitch system. At present, the non-linear controller is gradually applied in agricultural equipment. *Song et al. (2022)* carried out research on tractor roll-over prevention by introducing a variable structure sliding mode control algorithm. *Li et al. (2014)* put forward an adaptive sliding mode control method based on a non-linear integral sliding surface for steering control of agricultural vehicles and achieved satisfactory steering control performance. *Zhou et al. (2021)* converted the original motion task into a common tracking control problem and introduced LQR optimal control and integral sliding mode control to design a robust tracking controller for TTWMS.

At present, fuzzy PID controller has been widely used in draft-position integrated control (*Li et al., 2013; Wang et al., 2018*). The parameter adjustment process is complicated and the control effect is totally dependent on the experience of the designer. In this paper, a controller is designed based on the mathematical model of hydraulic system with stronger robustness and adjustable control law parameters, which provides new ideas and methods for the design of nonlinear controller of hydraulic hitch tillage system. In this paper, it would be shown that there is a suitable nonlinear controller, and affect the dynamic response. The problem with analyzing the hitch system is that the effect of these is not easily generalized. The focus of this paper is to analyze and describe the various types of draft-position integrated control, and to provide control effect for different draft-position weight. A differential and integral adaptive sliding mode controller is designed and the control performance of tractor hydraulic hitch force level integrated control is verified by simulation. An agricultural tractor real-vehicle test platform is built to verify the effectiveness of the controller designed.

MATERIALS AND METHODS

DESIGN OF ELECTRO-HYDRAULIC HITCH SYSTEM CONTROLLER

Mathematical model of hydraulic system

The principle of the electro-hydraulic hitch hydraulic system is shown in Figure 1, which is composed of the proportional lifting valve, proportional lowering valve, safety valve, and single-acting cylinder.

In the figure, x_v is the spool displacement (m); p_s is inlet pressure (Pa); p_0 is return port pressure (Pa); A_p is the piston area without rod cavity of hydraulic cylinder (m^2); m_L is equivalent load; k_L is equivalent stiffness of hydraulic system (N/m); B_L is equivalent damping for hydraulic system; h_P is ploughing depth (m).

In the process of establishing the mathematical model of the hydraulic system, assuming that there is no elastic load in the design, ignoring the viscous damping coefficient on the piston, ignoring the influence of oil density and compressibility, the return oil pressure is 0.

(1) Pressure flow characteristic equation of electro-hydraulic proportional hitch control valve

To simplify the analysis and explanation, the influence of nonlinear factors, such as the insensitive area of the electro-hydraulic proportional control valve, is temporarily ignored, and it is approximately regarded as a linear system (i.e., approximate linearization).

$$q_L = K_{sv} i - K_c p_L \tag{1}$$

where: i is the control current of the proportional control valve of the electro-hydraulic hitch (A), K_{sv} is the flow coefficient of the electro-hydraulic proportional control valve (m^3 s^{-1} A^{-1}), K_c is the flow-pressure coefficient of the electro-hydraulic proportional control valve (m^3 s^{-1} Pa^{-1}), and p_L is the load pressure (Pa).

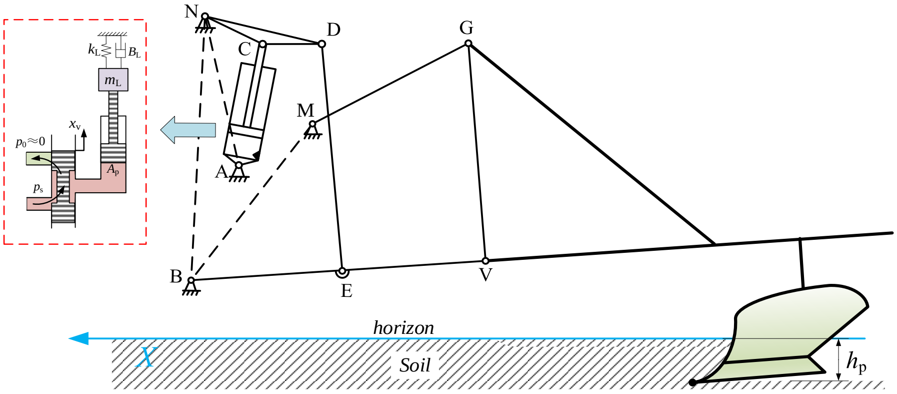


Fig. 1 –Schematic diagram of electro-hydraulic hitch

(2) Electro-hydraulic hitch system is a single-acting cylinder, lifting the flow continuity equation of the cylinder.

$$q_L = A_L \frac{dx_L}{dt} + C_t p_L + \frac{V_L}{\beta_e}\frac{dp_L}{dt} \tag{2}$$

where A_L is the effective area of the hitch system hydraulic cylinder (m^2), x_L is the motion displacement of the hitch system hydraulic cylinder (m), C_t is the total leakage coefficient of the hitch system hydraulic cylinder, V_L is the total volume of two cavities of the hitch system hydraulic cylinder (m^3) and β_e is the effective volume elastic modulus of hitch system hydraulic oil (Pa).

(3) The force balance equation of the cylinder load is:

$$A_L p_L = m_L \frac{d^2 x_L}{dt^2} + B_L \frac{dx_L}{dt} + k_L x_L + F_L \tag{3}$$

where, F_L is the accidental load force of the hydraulic cylinder of the hitch system (N).

Control Principle

Draft-position integrated control is a control method to integratedly deal with the variation of farm implements position and draft. The principle of draft-position integrated control is shown in Figure 2.

The controlled object of this system is the weighted comprehensive value of the traction force and the plowing depth of the implement. Feedback signals from angle displacement sensor of lifting arm and draft sensor are weighted and fed back to the controller for comparison. The controller outputs reasonable control quantities according to the deviation of the feedback signal to realize the lifting and lowering of agricultural implements. It can be seen from the control schematic that when the weight coefficient a=1, the system is in position control mode. When the weight coefficient a=0, the system is in draft control mode. Therefore, the performance of position control and draft control can be analyzed dynamically by draft-position integrated control simulation.

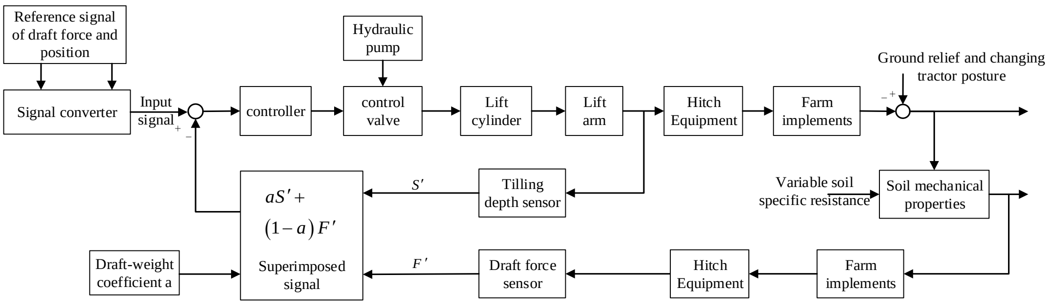


Fig. 2 –Schematic diagram of the draft- position integrated control

The draft-position integrated control converts the input signal into the lift arm displacement angle signal. The draft signal is converted into a lifting arm angular displacement signal reflecting the value of tillage depth. The actual feedback angular displacement is obtained by mixing the angular displacement of the lifting arm converted from the traction signal, and then the force position can be controlled comprehensively by only controlling the angular displacement of the lifting arm. The displacement control of the hydraulic cylinder can be carried out by using the proportional relationship between the angle of the lifting arm and the displacement of the hydraulic cylinder. The displacement control of hydraulic cylinder can be developed as a non-linear controller based on the mathematical model of the hydraulic system, and the draft- position integrated control algorithm is designed by control strategy. The hydraulic system of tractor hitch has a large load, complex operation environment, strong nonlinearity, uncertainty, and parameter variability. Traditional PID is widely used because of its simple principle and stable operation (*Khodayari Balochian, 2015*). Still, its adaptability is poor when it is applied to a nonlinear electro-hydraulic hitch systems, and its parameter tuning is cumbersome.

In addition, the faster response speed is often accompanied by a larger overshoot and a larger number of shocks, which easily causes the vibration of tractor machinery, resulting in a larger pitch movement of the entire unit, and it is difficult to achieve the preset control performance. Sliding mode variable structure control, as a control method which is suitable for both linear and non-linear systems (*HungGao Hung, 1998*), has the advantages of fast response, insensitivity to parameters and disturbances, simple realization and is very suitable for the control of non-linear tractor hitch system. In this study, adaptive control is added to the nonlinear differential and integral sliding mode controller (DI-SMAC), and the uncertain parameters of the hydraulic hitch system are identified by using the adaptive law (*RenLin Yin, 2005*). Thus, the controller can automatically adapt to the control requirements of different operating conditions. The tractor hydraulic hitch system has better robustness in different operating environments.

To verify the control performance of the tractor hydraulic hitch nonlinear differential and integral sliding mode variable structure adaptive control algorithm, PID controller for tractor hydraulic hitch system is also designed (*Chiriță et al, 2023*). The control performance of PID, I-SMAC and DI-SMAC are compared and analyzed by numerical simulation.

Control algorithm

The expression of a traditional PID controller is:

$$u = k_p e_{\alpha_{ANC}} + k_i \int e_{\alpha_{ANC}} dt + k_d \dot{e}_{\alpha_{ANC}} \tag{4}$$

where, u is the output voltage of the controller (V), $e_{\alpha ANC}$ is the lifting arm angular displacement deviation (deg), k_p, k_i, and k_d are proportional, integral and differential coefficients, respectively.

Different from the traditional sliding mode control, the integral sliding mode variable structure control introduces the integral term of the tracking error into the switching function (*Cheng Zhu, 2005)*, and uses the state variable to replace the error term, so that the derivative terms of the tracking signal of the displacement output of the hydraulic cylinder can be eliminated. The switching function is defined as:

$$s_1 = c_1 x_1 + c_2 x_2 + x_3 + c_0 \int_0^t \left(x_1 - x_d \right) d\tau \tag{5}$$

where x_d is the reference signal for cylinder displacement in electro-hydraulic control system (m).

The expression of the differential integral sliding mode adaptive control law is:

$$u = -\frac{1}{K_{sv}\hat{\beta}_1}\left(c_1 x_2 + c_2 x_3 + \hat{a}_1 x_3 + \hat{a}_2 x_2 + \hat{d} + c_0 \left(x_1 - x_d \right) + k s_1 + u_0 \right) \tag{6}$$

where u_0 is the differential controller quantity, and it can be obtained:

$$\begin{aligned} \dot{s}_1 &= c_1 x_2 + c_2 x_3 + (\hat{\beta}_1 + \tilde{\beta}_1) K_{sv} u + (\hat{a}_1 + \tilde{a}_1) x_3 + (\hat{a}_2 + \tilde{a}_2) x_2 + \hat{d} + \tilde{d} + c_0 \left(x_1 - x_d \right) \\ &= \tilde{\beta}_1 K_{sv} u + \tilde{a}_1 x_3 + \tilde{a}_2 x_2 + \tilde{d} - k s_1 - u_0 \\ &= \tilde{\beta}_1 K_{sv} u + \tilde{a}_1 x_3 + \tilde{a}_2 x_2 + \tilde{d} - k s_1 - \varphi(e) \dot{s}_1 \end{aligned} \tag{7}$$

Then:

$$\dot{s}_1 = \frac{\tilde{\beta}_1 K_{sv} u + \tilde{a}_1 x_3 + \tilde{a}_2 x_2 + \tilde{d} - k s_1}{1 + \varphi(e)} \tag{8}$$

The Lyapunov function is defined as:

$$V = \frac{1}{2} s_1^2 - \frac{1}{2\gamma_1}(\beta_1 - \hat{\beta}_1)^2 - \frac{1}{2\gamma_2}(a_1 - \hat{a}_1)^2 - \frac{1}{2\gamma_3}(a_2 - \hat{a}_2)^2 - \frac{1}{2\gamma_4}(d - \hat{d})^2 \tag{9}$$

The law of adaptive control system is:

$$\begin{cases} \dot{\hat{\beta}}_1 = \dfrac{s_1\gamma_1 K_{sv} u}{1+\varphi(e)} \\ \dot{\hat{a}}_1 = \dfrac{s_1\gamma_2 x_3}{1+\varphi(e)} \\ \dot{\hat{a}}_2 = \dfrac{s_1\gamma_3 x_2}{1+\varphi(e)} \\ \dot{\hat{d}} = \dfrac{s_1\gamma_4}{1+\varphi(e)} \end{cases} \tag{10}$$

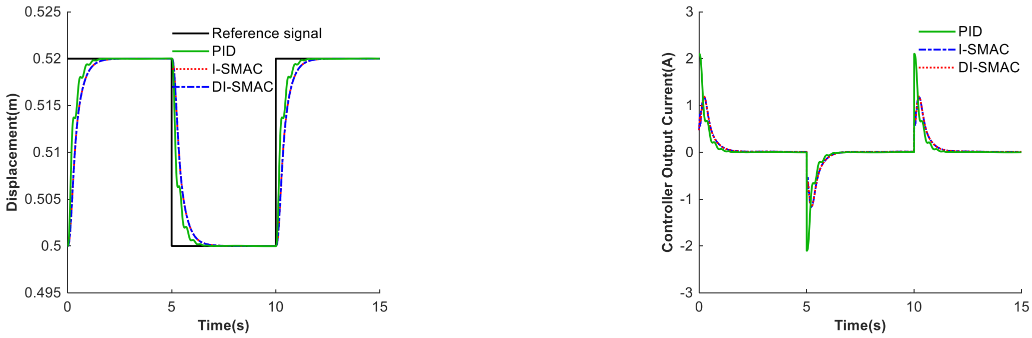
Substituting the adaptive law formula (10) into the formula (9), it can be obtained:

$$\dot{V} = -\frac{k s_1^2}{1+\varphi(e)} \le 0 \tag{11}$$

It can be seen from the above formula that the system is still asymptotically stable when differential control variables are introduced.

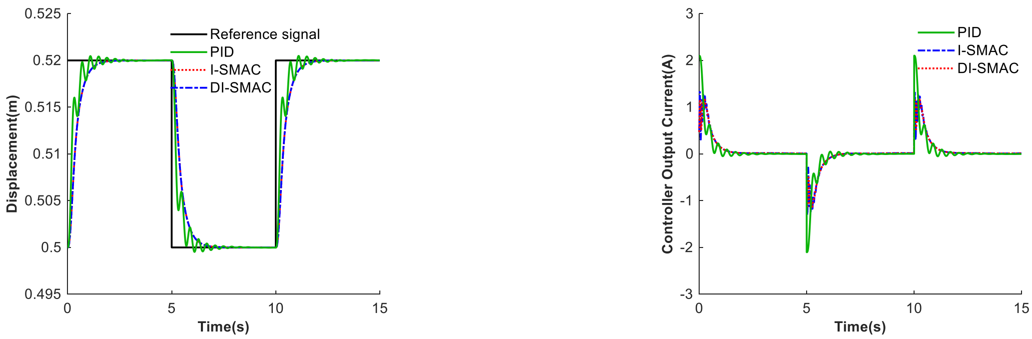
COMPARATIVE ANALYSIS OF CONTROL ALGORITHM SIMULATION

When the tractor is working in the field, it will sometimes change different plows and adjust the length and position of each link, especially the adjustment at the lifting rod and the pull-down rod. The transmission ratio and load quality of the linkage will change, and long-term operation will also lead to leakage of the hydraulic system. To verify the superior performance of the differential integral sliding mode adaptive controller (DI-SMAC) proposed for the tractor electro-hydraulic hitch system in this study, MATLAB is used to establish simulation models to compare different equivalent masses under different control algorithms and the dynamic response characteristics of the system.



(a) Displacement response curve of hydraulic cylinder (b) Controller input curve

Fig. 3 – Dynamic response diagram with the equivalent mass of 55000 kg



(a) Displacement response curve of hydraulic cylinder (b) Controller input curve

Fig. 4 – Dynamic response diagram with the equivalent mass of 85000 kg

It can be seen from the curve comparison in the above figures that when the PID controller, integral sliding mode adaptive controller (I-SMAC) and differential and integral sliding mode controller (DI-SMAC) are designed according to the equivalent mass of 55000 kg, the three controllers have good control performance. However, when the equivalent mass is changed to 85000 kg (this exists in the actual operation condition, flip plow and non-flip plow), the step response curve of the PID controller begins to shake, and the system oscillates upward, slightly overshooting.

Although the dynamic response curve of the integral sliding mode adaptive controller (I-SMAC) is consistent with that of the differential and integral sliding mode adaptive control (DI-SMAC), the controller input jitters, while the DI-SMAC have good dynamic performance, and the controller output does not jitter.

Thus, compared with the traditional PID controller, the DI-SMAC designed for the tractor electro-hydraulic hitch system can overcome the influence of changing parameters on the system performance when the equivalent mass changes, and has stronger adaptability.

RESULTS AND DISCUSSIONS

TRACTOR FIELD TEST AND RESULT DISCUSSION

Construction of tractor real vehicle test platform

To verify the control performance of the differential integral adaptive sliding mode controller (DI-SMAC) proposed in this study for tractor electro-hydraulic suspension systems, comparative tests were conducted on the traction and position control systems using PID controllers and DI-SMAC controllers. At the same time, the real vehicle test research of the draft-position integrated control was carried out, and a tractor test platform was built based on a certain type of tractor, as shown in Figure 5.

Fig. 5 – Field test platform of tractor electro-hydraulic hitch control system

1. Upper computer; 2. Power supply; 3. Controller; 4. Proportional amplifier; 5. CAN series module; 6. Lift arm angle sensor; 7. Displacement sensor; 8. Pressure sensor; 9. Force measuring pin; 10. Electro-hydraulic proportional valve; 11. Front wheel speed measurement encoder; 12. Rear wheel speed measurement encoder

The main hardware parameters of field test platform for tractor hydraulic hitch control system are shown in Table 1.

Table 1

Hardware parameter table of electro-hydraulic hitch test platform

Type	Model	Operating parameters
Force measuring pin	YZC-9	Working voltage: 24V, output: -10V~10V analog signal, customized measuring range -50000N~50000N, comprehensive error <0.05
Displacement sensor	LWH-0250	Working voltage: 12V, output: 0~10V analog signal, measuring range 0-250mm, resolution > 0.01mm
Pressure sensor	MIK-P300	Working voltage: 24V, output: 0-5V analog signal, accuracy 12 bits, customized range 0-20MPa
Controller	TMS320F28335	Working voltage: 3.3V, with strong signal processing and communication capability, two ways to enhance eCAN, support floating point operation, support external serial communication
Proportional amplifier	AEG-12A-02	Working voltage: 24V, CAN bus input interface, maximum output current adjustable, 0.2~3A

Field test of tractor electro-hydraulic hitch position control system

The test plot is a typical northern China field in Shangzhuang Test Station of China Agricultural University (116.1 ° E, 40.07 ° N). The soil firmness of 20 cm below the surface is about 130.5 kPa on average, and the soil hardness of the plot changes greatly. The plot is uncultivated land after corn harvest, and the ground undulates greatly.

The fitting formula between tillage depth and displacement of hydraulic cylinder is:

$$h_{\mathrm{p}}=8.81x_{\mathrm{L}}-0.866 \tag{12}$$

The tractor is set in B1 gear and the engine is maintained at 2000 r/min. After plowing into the soil, carry out relevant control according to control instructions. During the field test of the tractor, keep the speed stable. To prevent excessive skidding of the tractor during plowing, the four-wheel drive mode is adopted. After the plow body is stabilized in the soil, set the plow depth to a step change of 30 cm to 24 cm, and use the upper computer to conduct real-time monitoring and data recording on the message information transmitted on the CAN network during the plowing period. Intercept the test data within 35 s, and obtain the plow depth change curve, as shown in Figure 6.

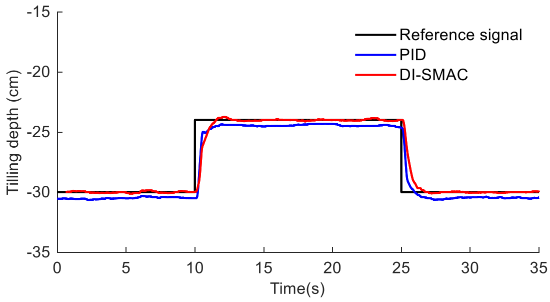
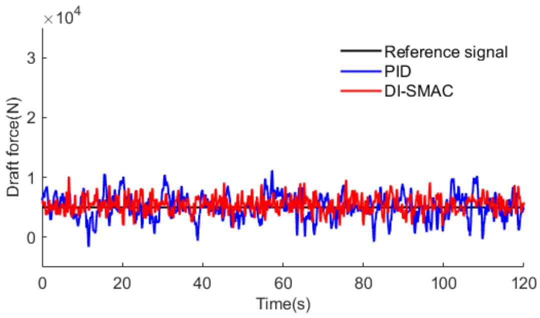


Fig. 6 – Response curve of position controlled tillage depth

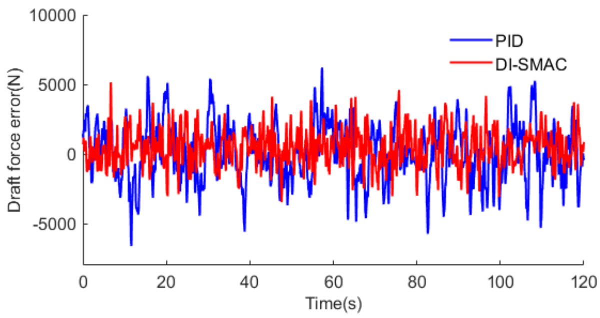
From Figure 6 it can be seen that the lifting process using the PID controller and DI-SMAC has no overshoot, and the response time is about 1.7 s. However, the static error of the depth control using the PID controller is about 0.5 cm, while the DI-SMAC has no static error basically. In the descent process, the response time of the PID is about 1 s, while that of DI-SMAC is about 1.6 s. The DI-SMAC can overcome the influence of nonlinear factors of control valve lifting and lower on the hitch system, and the control performance is better.

Field test of tractor electro-hydraulic hitch control system

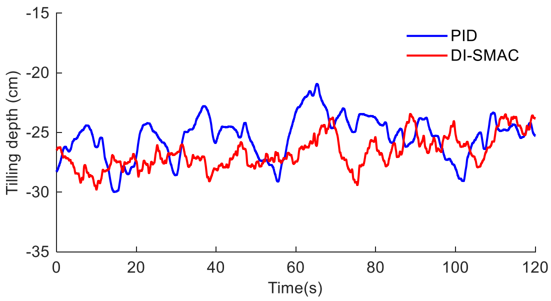
During the field draft control test, keep the tractor speed stable. When the plow body is stable in the soil, the draft setting value is 5000 N. The upper computer monitors and records the message information transmitted on the CAN network in the real time during the plowing period, intercepts the test data within 120 s, and obtains the test results as shown in Figure 7.



(a) Draft response curve



(b) Draft tracking error of different control algorithms



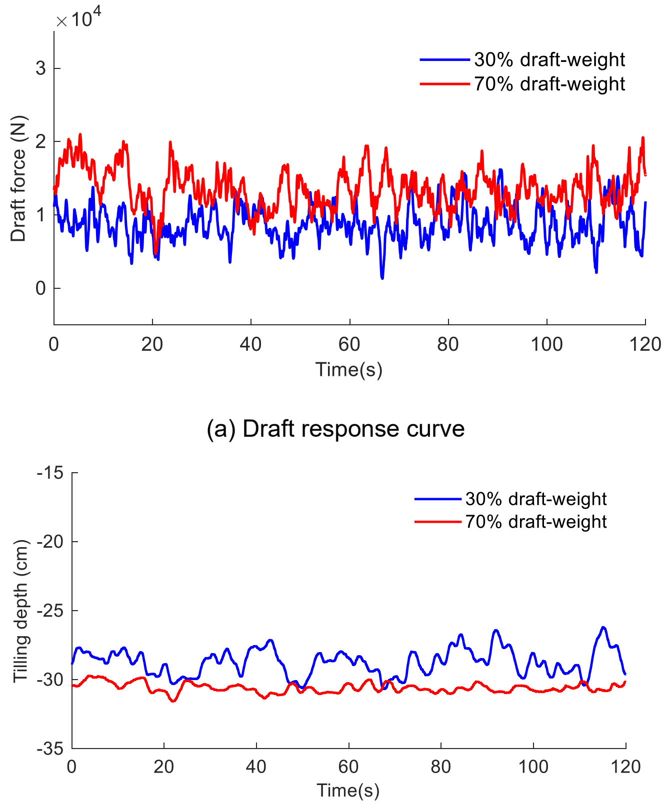
(c) Response curve of tillage depth

Fig. 7 – Response curve of tillage depth under draft control

From Figure 7 (a) it can be seen that when the draft control mode is adopted, the draft fluctuates up and down at the set value. Under different set of the draft values, the fluctuation range of the draft controlled by the PID is 12820 N, and the standard deviation of the draft is 2076 N; the fluctuation range of the draft using differential and integral sliding mode adaptive control (DI-SMAC) is 8590 N, and the standard deviation of draft is 1275 N. When the DI-SMAC is used, the range of draft is reduced by 32.9%, and the standard deviation of the draft is reduced by 38.6%. The DI-SMAC can improve the control performance of the tractor electro-hydraulic hitch draft control system. By comparing the effects of the PID controller and derivative and integral sliding mode adaptive controller (DI-SMAC) of position control and draft control system, it can be seen that the derivative and integral sliding mode adaptive controller (DI-SMAC) designed for tractor electro-hydraulic hitch has better tracking characteristics and higher control accuracy than the traditional PID controller.

Field test of draft and position integrated control

The reference signal of draft is set as 5000 N, the plowing depth is 30 cm, and the draft-weight are set as 30% and 70%, respectively. The DI-SMAC is used for experimental research. During the field test, the upper computer monitors and records the message information transmitted on the CAN network in real time during plowing, intercepts the test data within 120 s, and obtains the test results, as shown in Figure 8.



(b) Response curve of tillage depth

Fig. 8 – Response curve of draft and position integrated control

From Figure 8 it can be seen that when the draft and position integrated control mode is adopted, the variation range of draft fluctuation and tillage depth is different under different draft-weight. When the draft-weight is 30%, the fluctuation range of draft is 14890 N, the standard deviation of draft is 2350 N, and the average value of draft is 8717 N; the fluctuation range of tillage depth is 4.47 cm, the standard deviation of tillage depth is 0.947 cm, and the mean value is -26.1 cm. When the draft-weight is 0.7, the fluctuation range of draft is 16350 N, the standard deviation of draft is 2640 N, and the average value of draft is 13550 N; the fluctuation range of tillage depth is 1.84 cm, the standard deviation of tillage depth is 0.339 cm, and the mean value is -29.7 cm.

When the draft-weight is 0, it is in draft control mode. It can be seen from Figure 7 that when the draft-weight is more minor, the draft fluctuation is smaller, and the tillage depth fluctuation is more significant, which is more consistent with the simulation results.

CONCLUSIONS

The control effect of the tractor electro-hydraulic hitch directly determines the quality of the plowing operation. Based on analyzing the dynamics of the plowing operation of the tractor unit, this study designed a DI-SMAC for the electro-hydraulic hitch system, and different controllers are compared and verified through simulation and field test of the tractor. A more comprehensive mathematical model of the plow unit considering the factors such as tractor pitching motion and ground undulation is established. The feasibility and effectiveness of the designed controller are verified by numerical simulation and tractor field tests. The field tests of the tractor show that the DI-SMAC can realize the draft and position integrated control. In the position control mode, the DI-SMAC has basically no static error and strong anti-interference ability; under the draft control mode, compared with the traditional PID controller, the range of traction error of DI-SMAC is reduced by 32.9%, and the standard deviation is reduced by 38.6%; Under the draft and position integrated control, the fluctuation of traction force and tillage depth is different with different draft-weight. The controller designed for the electro-hydraulic hitch system in this study can provide a method to improve the quality of field work, and provide guidance for further research.

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