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Research Article

Parameter Matching and Tillage Depth Control Method for Electric Crawler Tractor Platforms

Hangxu Yang[1,2,3], Jun Zhou[1,*], Xu Wang[1] and Yongshuang Wu[1]

[1]College of Engineering, Nanjing Agricultural University, Nanjing 210031, China
[2]College of Mechanical and electrical Engineering, Jinhua Polytechnic, Jinhua 321017, China
[3]Key Laboratory of Crop Harvesting Equipment Technology of Zhejiang Province, Jinhua 321017, China

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Abstract

Conventional electric crawler tractor platforms are ineffective in parameter matching. The fluctuation of tractor implements during rotary tillage operation results in unstable tillage depth, which compromises operational quality. In order to improve tillage depth control by electric crawler tractors, this study proposed a parameter matching and tillage depth control method based on a prediction model for the rotary tillage operation of the tractor. Utilizing the electric tractor platform in the laboratory, regression models for the energy consumptions per unit area of rotary tillage and whole machine operations were created against the forward velocity, the blade roller speed, and the tillage depth. Tillage depth was predicted by establishing a tillage depth prediction model based on the matching of operational parameters. Finally, the feasibility of the control program and the accuracy of the model were validated through experiments. Results demonstrate that when the proposed method is not used, the tillage depth fluctuates greatly during the rotary tillage operation, with a maximum tillage depth reaching 4 cm. The tillage depth is greatly affected by the fluctuation of tractor implements, and the operational quality is drastically reduced. By using the proposed method, the maximum extremum of tillage depth data is only 2.6 cm, which immensely improves the stability of tillage depth. This study can serve as a reference for the research of tillage depth control for electric crawler tractors.

Keywords: Electro motion, Crawler tractor, Parameter matching, Tillage depth control

1. Introduction

Conventional agricultural machineries cause serious exhaust pollution because they use gasoline and diesel as power fuels [1]. In small vegetable greenhouses, exhaust gas not only pollutes crops but also seriously affects human health. Wheeled tractors are also prone to slippage when running on wet and soft soil, which affects driving safety and traction. By contrast, electric crawler tractors have good slope stability against overturning and sliding because of their low center of gravity and high adhesion coefficient [2]. They are also characterized by maneuverability with small turning radius and off-road performance with strong climbing ability. Compared with wheeled tractors, electric crawler tractors are better adaptable to farmland and terrace operations in greenhouses and in mountainous and hilly areas, especially when equipped with rubber crawlers, which are all-terrain machineries [3].

However, scholars in China and other countries have focused on proposing design methods for crawler tractors, preliminarily investigating their power and driving force during turning and conducting tests of transmission efficiency and driving force. Electric crawler tractors have rarely been studied, such as their platform parameter matching and tillage depth stability. Electric crawler tractors generally have the disadvantages of fluctuating implements and unstable tillage depth during rotary tillage operation, which are affected by numerous factors. Hence, their study is technically difficult.

In view of this, scholars have studied the parameter matching and stability control of tillage depth for crawler electric tractors under major modes, such as rotary tillage and ploughing [4-5]. However, an excellent solution to the parameter matching and unstable tillage control problems of such tractors remains lacking. Hence, accurate correlation models between energy consumption per unit area and parameters such as tillage depth in the rotary tillage operation must be established to minimize energy consumption while ensuring operational quality.

Utilizing the electric crawler tractor platform in the laboratory, this study proposed a parameter matching and tillage depth control method based on a prediction model for the rotary tillage operation of the tractor. Multivariate nonlinear regression models and a tillage depth prediction model were established and used to analyze the correlations of forward velocity, blade roller speed, and tillage depth with unit energy consumption. The matching study and experimental validation of related parameters were also accomplished. This study aimed to address accurately the stability control problem of tillage depth in rotary tillage operation to provide a reference for the development and optimization of electric crawler tractors.

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2. State of the art

Existing studies have focused on the parameter matching and control strategy of electric tractors, whereas technical studies related to electric crawler tractors have been scarce. Comparatively, more studies concentrated on the matching of powertrain parameters and control strategies for electric or hybrid electric vehicles than on the tillage depth control of electric crawler tractors. Cui et al. [6] developed a small multi-purpose electric crawler platform for greenhouses and experimentally explored its basic performance. The dual mode control system they developed could achieve remote control and button operation. It has a high degree of intelligence, thereby facilitating the further development of greenhouse machineries. However, given its simple functionality, their platform could only complete picking and transportation functions as a carrying platform and cannot complete farmland operations, thereby restricting its popularization. Mocera F [7] investigated the performance of a parallel hybrid tractor in actual operating scenarios of an orchard and proposed a load observation-based energy management strategy to allocate the power demands of two power sources. Simulations revealed that their solution could not only provide the same power as conventional tractors under different operating conditions but also could achieve the same effect with a smaller engine. However, their energy management strategy is ineffective for operations such as ploughing. To address the low efficiency of small household electric tractors, Vogt Hans Heinrich [8] improved the farmland efficiency by innovatively planning the batteries in various operating energy transition configurations. However, this battery scheme performs poorly in controlling power consumption balance. To investigate the electric energy consumption of crawler tractors under the load change drive condition of the powertrain system, Plizga Krzysztof [9] built a tractor model under moving condition and replaced an internal combustion engine with a DC motor. Experimental results showed that the intensities of current and voltage collected by battery power supply are correlated with ambient temperature and motion resistance. However, the rule of energy consumption during farming was not revealed. To determine the reduction ratio of a 78 kW all-wheel drive tractor, Kim et al. [10] constructed a load measurement system for the tractor and conducted field load tests under such agricultural operations as rotary tillage and ploughing. Results proved that the selected reduction ratio and motor satisfy the load demands for the above operations. However, they failed to probe deep into the tillage depth adjustment in the rotary tillage mode. Aiming at the parameter matching problem for a four-wheel independent drive electric tractor, Zhou et al. [11] explored the torque distribution strategy under ploughing and transportation conditions and matched the system parameters for the tractor. Although the feasibility of the strategy was verified through experimentation, the rotary tillage condition and the adjustment and control of tillage depth were not considered. Liu et al. [12] proposed a coordinated management strategy for battery packs and supercapacitors in response to the battery life problem in electric crawler tractors and verified the strategy by hardware-in-the-loop test. However, they failed to explore the parameter matching in rotary tillage operation. Seung-Yun Baek [13] created a simulation model of a 120-kW electric all-wheel drive tractor. Tests demonstrated that the operable time is 6 h for a driving operation and 2.4 h for a ploughing operation, thus proving the reliability of the model. The shortcomings are that the operable time in rotary tillage mode is shorter than that in ploughing mode, and the stability control of tillage depth is insufficient. In response to the motor performance problems in vineyard and orchard operations, Diego Troncon et al. [14] measured the thermal equivalent torque and overload capacity of the motor of an electric crawler tractor for orchards. They verified their results through a thermal model at actual duty ratio but failed to investigate the tillage depth control in specific tractor operations. Focusing on the energy management problem of electric crawler tractors under different operating conditions, Shang et al. [15] developed a tractor control strategy by designing a fuzzy PID control algorithm in normal mode and a limping algorithm in failure mode to enhance tractor efficiency. However, studies on the control strategy in rotary tillage mode are lacking. Du et al. [16] proposed a nonlinear system for tillage depth monitoring based on the suspension attitude and constructed a mathematical model between the suspension attitude and the tillage depth of the rotary tiller, thereby achieving the prediction of tillage depth (by detecting rotary tillage attitude) and the subsequent adjustment of tillage depth. However, they failed to reveal the parameter matching mechanism in rotary tillage operation. Guan et al. [17] developed an electric tractor for facility cultivation and proposed a corresponding drive system scheme where a traction motor is used to drive the tractor movement and PTO operation and a lifting motor is used to drive the hitch implement. The shortcomings are that the use of a single traction motor easily causes interference to the movement and operation, thereby decreasing operational quality. In addition, the battery life time is short and the labor intensity is high because of the need for manual driving. Mocera Francesco [18] developed a model-based energy management strategy by exploiting the hardware-in-the-loop technique to improve the performance of parallel hybrid tractors for orchards. The strategy is stable in terms of load splitting and speed control between two power sources but yields poor adjustment of tillage depth in the rotary tillage scenario. Rol [19] developed a loss model for a 150-kW agricultural machinery and calculated the loss of a series hybrid powertrain. Despite a superior effect to tractors of the same power, the loss of the powertrain shows no advantage in rotary tillage and ploughing operations. Wang et al. [20] investigated the control strategy for extended-range electric tractors. They created a forward predictive model of motor power and proposed an exponential smoothing model approach based on the historical data of motor power, which improve the starting smoothness and reduce the starting energy. However, their study failed to consider specific scenarios of tractor operations, such as rotary tillage and ploughing.

The foregoing literature focused primarily on the parameter matching, structural design, and control strategy of various electric and electric crawler tractors but scarcely explored the platform design and control strategy of electric crawler tractors, especially their parameter matching and tillage depth control. Unlike the conventional electric crawler tractor platforms, this study separately built the optimal models between the energy consumptions per unit area of rotary tillage and whole machine operations and the related parameters in the case of rotary tillage operation and predicted tillage depth by creating a model based on the matching of operational parameters. Finally, the feasibility of the control program and the accuracy of the model were validated experimentally. The findings of this study provide a basis for the optimization and application of electric crawler tractors.

The remainder of this study is organized as follows: In Section 3, the multivariate nonlinear regression model is constructed, and the regression model is developed based on orthogonal design. Furthermore, a prediction model-based strategy of tillage depth control is formulated, and an experimental protocol is designed. In Section 4, experiments and data analysis are carried out to verify the control effect. The final section summarizes the article and draws relevant conclusions.

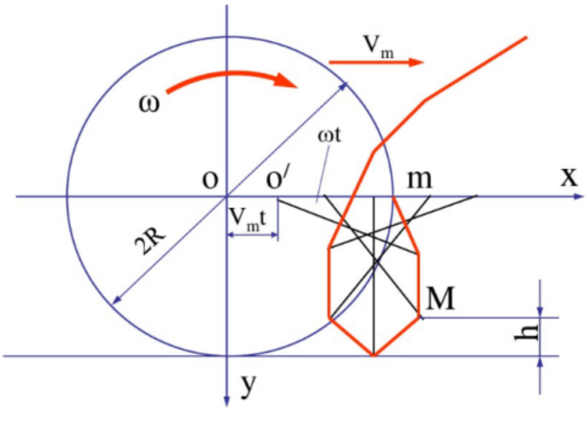
3. Methodology

3.1 Construction of multivariate nonlinear regression models

(1) Orthogonal test design

Through the orthogonal design, the number of tests can be greatly reduced without affecting the influence of multivariate on performance indicators. An orthogonal test with the above operating parameters was designed to investigate the effects of various platform parameters (forward velocity Vm, rotary tillage depth H, and blade roller speed of rotary tiller N) in the operational processes (Fig. 1 displays the laboratory tractor platform) on the energy consumption per unit area during rotary tillage operation. A reasonable selection of various operating parameters was required to ensure the operational quality of the rotary tiller. On the basis of the motion trajectory analysis of blade operation, the rotary tiller could only operate normally when formula 1 was established.

Fig. 1. Electric crawler tractor platform



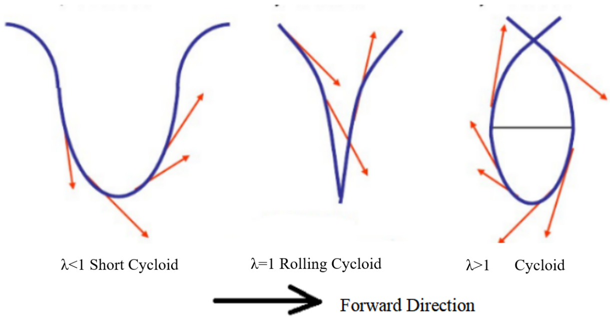


Fig. 2. Absolute trajectory of rotary tiller blade

$$\begin{cases} V_m < (R-h)\omega \\ \lambda = \dfrac{V_d}{V_m} = \dfrac{R\omega}{V_m} > 1 \end{cases} \tag{1}$$

Where V_m - Tractor forward velocity (m/s);

R — Maximum turning radius of rotary tiller blade end (m);

h — Tillage depth (m);

ω — Angular velocity of blade rotation (rad/s).

Calculation yielded a tractor forward velocity range of 0.1–0.3 m/s, a blade roller speed range of 150–300 rpm, and a tillage depth range of 5–15 cm. An L25 (54) orthogonal array with three factors and five levels was designed, and Tab. 1 details the levels and factors.

Table 1. Levels of factors

Level	Factor			
	Forward velocity (m/s)	**Blade roller speed N/(rpm)**	**Tillage depth H/(cm)**	**Error column E**
1	0.10	150	5	1
2	0.13	170	7	2
3	0.16	190	9	3
4	0.19	210	11	4
5	0.22	230	13	5

(2) Construction of regression models

After the foregoing orthogonal tests, regression models were constructed through field experiments and correlation and significance tests as shown in Formula (2), where the energy consumption per unit area of rotary tillage operation SI and the energy consumption per unit area of tractor operation SII were used as the evaluation indicators.

$$\begin{aligned} S_I &= 43686.2943V_m + 0.2694N^2 - 72.6777N + 740.6533H + 15037.0652 \\ S_{II} &= 45997.5980V_m + 0.1907N^2 - 44.1855N + 899.8646H + 15272.7340 \end{aligned} \tag{2}$$

3.2 Regression model-based research of operating parameter matching strategy

For the rotary tillage operation of an electric crawler tractor, the parameter matching strategy comprised determining the forward velocity matching strategy, the blade roller speed matching strategy, and the tillage depth matching strategy. The tractor forward velocity Vm, blade roller speed N, and tillage depth H constituted the major operating parameters. When one of these values was ascertain, the optimal combination of the two other operating parameters with the lowest energy consumption could be obtained via the prediction model, thereby attaining improved battery life of the tractor.

(1) Determination of tillage depth matching strategy

According to the prediction model (2) of energy consumption per unit area for the rotary tillage operation of the tractor, the subsequent research proceeded by setting the tillage depth at H=10 cm. Substituting H=10 cm into (2) yields:

$$S_{II} = -45997.5980V_m + 0.1907N^2 - 44.1855N + 24271.3800 \quad (3)$$

Where $0 < V_m < 0.22m/s, 150 < N < 300rpm$.

$$\begin{cases} \frac{\partial S_{II}}{\partial V_m} = -45997.5890 < 0 \\ \frac{\partial S_{II}}{\partial N} = 0.3814N - 44.1855 \end{cases} \quad (4)$$

$\frac{\partial S_{II}}{\partial N} = 0, N \approx 116rpm$, which was not within the range of (150-300 rpm). Since the function monotonously increased within the $\frac{\partial S_{II}}{\partial N} > 0$ range, the tillage depth matching strategy was selected. When the minimum S_{II} value was taken, $V_m = 0.22m/s$ and $N = 150rpm$.

During the rotary tillage operation, the soil fragmentation rate and the tillage bottom flatness were directly affected by the soil cutting pitch, which can be calculated by the following formula:

$$s = \frac{6000V_m}{NZ}, \quad (5)$$

Where h - Soil cutting pitch (cm);

V_m - Platform forward velocity (m/s);

N - Blade roller speed (rpm);

Z - Number of blades on the same rotary surface.

Substituting $V_m = 0.22m/s$ and $N = 150rpm$ into Formula (5) yields $s = 4.4cm$. The soil cutting pitch of rotary tiller should be within 6-14 cm to meet the requirement on soil fragmentation rate. In the present study, it was calculated to be 4.4 cm, thus satisfying the above rate requirement. Hence, arguably, not only the low energy usage was ensured during the parameter matching; the effectiveness of parameter matching strategy and the operational quality were also considered. Selection of forward velocity and blade roller speed according to Fig. 3(a) ensured that the unit energy consumption of rotary tillage operation for the tractor was within low range and that a reasonable combination of these two parameters was selected.

(2) Determination of forward velocity matching strategy

To proceed with subsequent research, the forward velocity was set at $V_m = 0.15m/s$ herein. Substituting $V_m = 0.15m/s$ into the formula (2) yields:

$$S_{II} = 899.8646H + 0.1907N^2 - 44.1855N + 8373.0943 \quad (6)$$

Where $0 < V_m < 0.22m/s, 150 < N < 300rpm$.

$$\begin{cases} \frac{\partial S_{II}}{\partial H} = 899.8646 > 0 \\ \frac{\partial S_{II}}{\partial N} = 0.3814N - 44.1855 \end{cases} \quad (7)$$

Formula (6) increased with increasing H and N. During selection of the forward velocity matching strategy, H= 5 cm and N= 150 rpm when the minimum SII value was taken, which conformed to the operation requirements. After determining the forward velocity value, parameters such as tillage depth and blade roller speed should be selected according to Fig. 3(b).

(3) Determination of blade roller speed matching strategy

To proceed with subsequent research, the blade roller speed was set at N= 180 rpm herein. Substituting N= 180 rpm into Formula (2) yields:

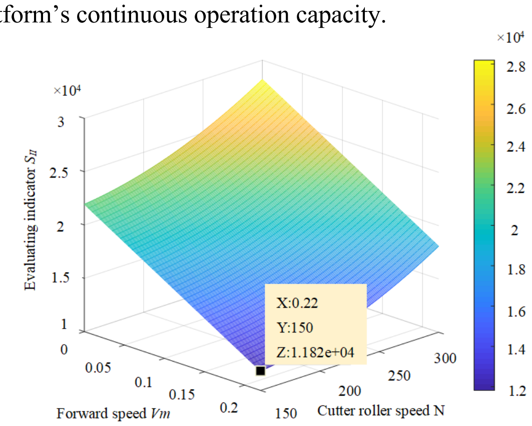
$$S_{II} = -45997.5980V_m + 899.8646H + 13498.024 \quad (8)$$

Where $5 < H < 15cm, 150rpm < N < 300rpm$

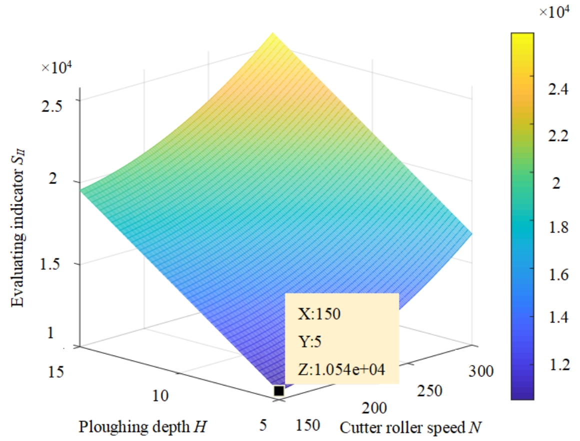
$$\begin{cases} \frac{\partial S_{II}}{\partial V_m} = -45997.5890 < 0 \\ \frac{\partial S_{II}}{\partial H} = 899.8646 > 0 \end{cases} \quad (9)$$

Formula (8) decreased with increasing Vm and increased with increasing H. Accordingly, during selection of the blade roller speed matching strategy, Vm= 0.22 m/s and H= 5 cm when the minimum SII value was taken. The calculated soil cutting pitch satisfied the operation requirements. After determining the blade roller speed, parameters such as forward velocity and tillage depth were selected according to Fig. 3(c).

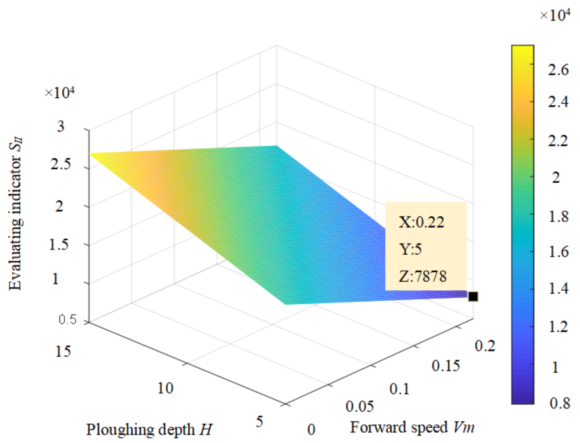
In sum, by the action of prediction model SII, an optimal combination of parameters could be obtained for the electric crawler tractor platform as per the parameter matching strategy regardless of what arbitrary operating parameter was given. Thus, the operational quality could be ensured while reducing the energy usage and enhancing the platform's continuous operation capacity.



(a) S_{II} variations with V_m and N at a tillage depth of 10 cm



(b) S_{II} variations with H and N at a forward velocity of 0.15 m/s



(c) S_{II} variations with H and V_m at a blade roller speed of 180 rpm

Fig. 3. Parameter-dependent variation trends of energy consumption per unit area of the whole tractor

3.3 Prediction model-based research of tillage depth control strategy

(1) Strategy proposal

During operation, the electric crawler tractor platform was lowered to the working position only through the hitch, and the rotary tillage implement rotated to complete the operation. However, in the forward process, the platform fluctuated because of uneven ground or other reasons, which drove the fluctuation of operation implements. However, the hitch was not adjusted with the implement fluctuation, resulting in poor tillage depth stability and compromised operational quality.

This study proposes a tillage depth control strategy based on a prediction model of rotary tillage operation. Initially, the functional relationship between each operating parameter and PTO motor power was sought via the prediction model. During parameter determination, the power of the PTO motor under the corresponding operating parameter was predicted based on the model, and the current and voltage signals were monitored in real time, thereby measuring the real-time power of the PTO motor. The implement fluctuation at this time was assessed by comparing the magnitude relationship between the predicted and real-time power values.

The energy consumption per unit area of rotary tillage operation can be calculated by the following formula:

$$S_1 = \frac{\sum P\Delta t}{B\sum V_m \Delta t} = \frac{\sum UI\Delta t}{B\sum V_m \Delta t} \tag{10}$$

Where P - Real-time power of PTO motor;
B -Working width of rotary tiller;
V_m - Forward velocity;
U - PTO motor voltage;
I - PTO motor current.

Simplification yields:

$$S_I = \frac{UI}{BV_m} = -43686.2943V_m + 0.2694N^2 - 72.6777N + 740.6533H + 15037.0652 \tag{11}$$

Calculation yields:

$$I = \frac{BV_m(-43686.2943V_m + 0.2694N^2 - 72.6777N + 740.6533H + 15037.0652)}{U} \tag{12}$$

The relationship between PTO motor current and each operating parameter was deduced as shown in Formula (12). During the actual operation, the voltage of PTO motor was basically equal to the battery voltage, whose value was rather stable. In the event of changes in the motor power, the motor current would primarily undergo changes. Therefore, we simplified the monitoring of real-time power of PTO motor into the monitoring of its real-time current. The status of operation implements could be determined by monitoring the magnitude relationship between the predicted and real-time current values. If the predicted current was greater than the real-time value, it indicated that the working power of the implements was less than the predicted value. At this time, the tillage depth was considered less than the set value. Thus, the hitch should be lowered to increase the tillage depth. By contrast, if the predicted current was less than the real-time value, then the working power of the implements exceeded the predicted value. At this time, the tillage depth was considered greater than the set value. Thus, the hitch should be lifted to reduce the tillage depth.

(2) Control program design

The program design comprised parameter input, predicted value calculation, measured mean calculation, data comparison, and hitch control. Parameter input was responsible for establishing the channels between addresses corresponding to PLC via the configuration software. After inputting the operating parameters through the touch screen, the program stored the data at the corresponding addresses. Predicted value calculation was responsible for programming the prediction model. The program calculated the predicted value after reading the corresponding input parameters. During measured mean calculation, the actual current values were read via the counter at 0.05 s intervals and then accumulated. Mean value was calculated once every 5 times and output. After outputting the data, the data at corresponding address bits were zeroed; the next accumulation began, and the mean value was calculated. This cycle was repeated. With data comparison, the magnitude of predicted current value I was compared with that of the mean current of PTO motor in 0.25 s, and the mode of hitch control was determined. As for hitch control, it performed the lifting and lowering control of hitch based on the data comparison results. Through the proposed program, the active control of tillage depth could be achieved in the tractor rotary tillage operation, which enhanced the tillage depth stability and improved the operational quality.

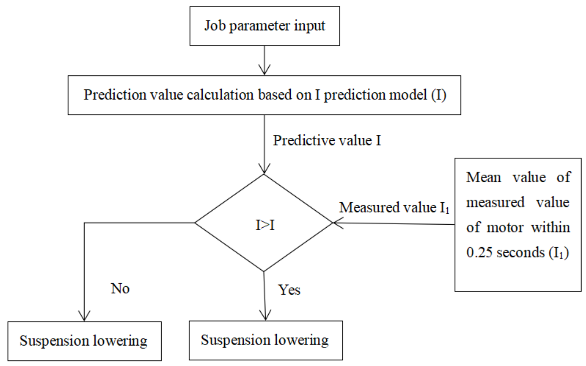
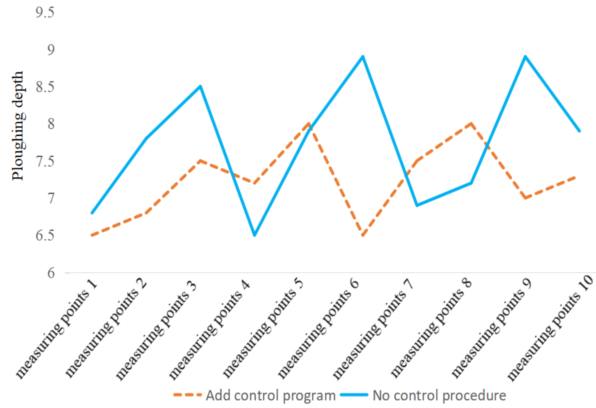


Fig. 4. Principle of tillage depth control

3.4 Rotary tillage experiment

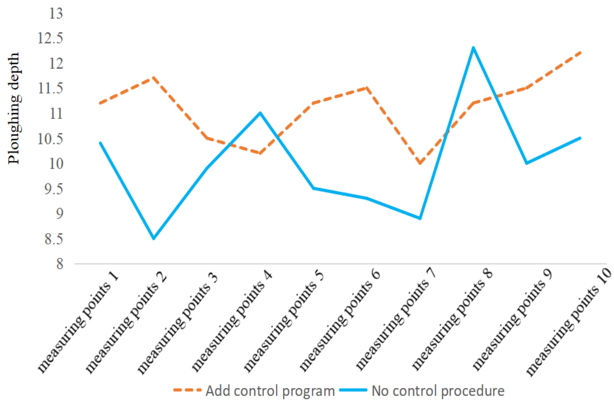
After the completion of the program, the verification experiment was conducted again in the greenhouse that was used for the orthogonal design, as shown in Fig. 5, to verify the feasibility of tillage depth control based on the prediction of rotary tillage operation. Parameter settings were Vm= 0.13 m/s, N= 230 rpm, and H = 7, 9, 11 cm, respectively. The experiment was divided into two scenarios: with and without control program.

Fig. 5. Experimental scene



(a) 7cm tillage depth test

(b) 9cm tillage depth test



(c) 11cm tillage depth test

Fig. 6. Tillage depth comparison results

4. Result Analysis and Discussion

Through the aforementioned rotary tillage experiment without or with tillage depth control program, 10 observation points are selected, of which those at depths of 5, 10, and 15 cm are measured for soil compactness with a TJSD-750 tester. Tab. 2 details the specific data, whereas Tab. 3 lists the experimental data of tillage depth control. The effectiveness of the control program is evaluated through data comparison. Fig. 6 (a)-(c) display the comparison results of tillage depth.

Table 2. Soil compactness data (unit: kpa)

Measuring depth	Measuring point 1	Measuring point 2	Measuring point 3	Measuring point 4	Measuring point 5	Mean soil compactness
5cm	522	629	310	371	439	454.2
10cm	1296	1402	242	1144	1038	1024.4
15cm	1447	947	1356	1098	1083	1186.2

Table 3. Experimental data of tillage depth control

Type	Set tillage depth	Measuring point 1	Measuring point 2	Measuring point 3	Measuring point 4	Measuring point 5	Measuring point 6	Measuring point 7	Measuring point 8	Measuring point 9	Measuring point 10	Mean	Range	Variance
Without control program	7.0	6.8	7.7	8.3	6.8	8.1	9.0	7.0	7.6	9.1	7.8	7.8	2.3	0.7
	9.0	8.5	9.0	8.5	10.0	7.0	10.5	9.5	8.5	7.0	8.6	8.7	3.5	1.3
	11.0	10.3	8.5	10.0	11.0	9.6	9.5	9.0	12.5	10.0	10.5	10.1	4.0	1.2
With control program	7.0	6.2	6.8	7.5	7.4	8.1	6.3	7.7	8.3	7.1	7.3	7.3	2.1	0.5
	9.0	8.9	9.4	10.5	8.9	9.1	9.6	10.3	9.2	8.8	7.9	9.3	2.6	0.6
	11.0	11.3	11.8	10.7	10.5	11.3	11.6	9.8	11.3	11.6	12.4	11.2	2.6	0.5

The foregoing comparison graphs indicate the following:

(1) In the absence of the control program, the tillage depth fluctuates greatly during the rotary tillage operation, with a maximum tillage depth range reaching 4 cm. The overall data variance is large, and the tillage depth fluctuates greatly. The mean tillage depth also differs largely from the set tillage depth. The operational quality is drastically reduced because the tillage depth is greatly affected by the implement fluctuation.

(2) After incorporating the control program, the maximum extremum of tillage depth data is only 2.6 cm. The overall data variance is small, and the tillage depth slightly fluctuates. The mean value also slightly differs from the set value, suggesting that the tillage depth always fluctuates around the set value during the operation process. The variation in tillage depth caused by the implement fluctuation is offset by the hitch adjustment via the control program. Thus, arguably, the control program slightly affects the control of tillage depth variation caused by the implement fluctuation. This phenomenon increases the stability of tillage depth during platform operation, thereby improving the operational quality of the platform.

(4) During the experiment at 7 cm tillage depth, the tillage depth variation is markedly smaller after than before the application of the control program, showing an overall consistent trend, albeit somewhat lagging. During the experiment at 9 cm tillage depth, the tillage depth variation is somewhat correlated with the selection of measuring points after the application of the control program, showing an overall stable variation. When the experimental tillage depth is 11 cm, the tillage depth variation after the application of the control program shows a basically consistent trend with that before the application overall, which is slightly affected by the measuring points.

(5) During the orthogonal experiment, factors such as forward velocity, blade roller speed, and tillage depth are selected to investigate their effects on the fitted multivariate nonlinear models. Therefore, the models fitted in this study have a good control effect on the present platform under identical experimental conditions.

(6) When no control is imposed on different measuring points, the tillage depth variations somewhat differ for the electric crawler tractor platform. For instance, during the experiment at 7 cm tillage depth, the tillage depth reaches peaks at measuring points 3, 6, and 9, indicating low soil hardness and high humidity at these points, which lead to poor adjustment of tilled land. After imposing the control, the tillage depth is evidently reduced. In addition, the adjustment effect is better at measuring points 1, 6, and 9.

(7) During the experiment at 9 cm tillage depth, the tillage depth reaches peaks at measuring points 4 and 6, indicating that the tillage depth is poorly adjusted within this depth range because of the influences of soil hardness and humidity. After imposing the control, the tillage depth is evidently reduced. Moreover, the adjustment effect is better at measuring points 1, 4, and 10.

(8) During the experiment at 11 cm tillage depth, the tillage depth reaches peaks at measuring points 4 and 8, indicating that the tilled land is poorly adjusted within this depth range because of the influences of soil conditions. After imposing the control, the tillage depth is evidently reduced. In addition, the adjustment effect is better at measuring points 1 and 7.

(9) During the experiment at 11 cm tillage depth, the tillage depth reaches peaks at measuring points 4 and 8, indicating that the tilled land is poorly adjusted within this depth range because of the influences of soil conditions. After imposing the control, the tillage depth is evidently reduced. Furthermore, the adjustment effect is better at measuring points 1 and 7.

(10) With the increase in experimental depth, the soil compactness increases continuously. Thus, control becomes difficult when the tillage depth exceeds 11 cm, and the adjustment and control of tillage depth are ineffective.

5. Conclusions

To improve the performance of electric crawler tractors, this study explored the parameter matching and tillage depth control of an electric crawler platform. The energy consumption prediction model and the tillage depth control model were constructed. Furthermore, experimental verification and analysis were carried out in the case of rotary tillage operation. Finally, the following conclusions were drawn:

(1) The improvement of regression model and the operating parameter matching and control method are suitable for the electric crawler tractor platform.

(2) The tillage depth control strategy based on the prediction model of rotary tillage operation proposed in this study allows a tillage depth data extremum of only 2.6 cm, which greatly enhances the stability of tillage depth, ameliorates the fluctuation problem of implement operation, and improves the quality of rotary tillage operation, thereby providing a reference for the research of tillage depth control for electric crawler tractors.

By employing orthogonal experiment and regression analysis, this study offers a new insight into the parameter matching and tillage depth control of electric crawler tractors. The built models are close to reality, which could serve as a reference for the subsequent research on electric crawler tractors for greenhouses. In subsequent research, intelligent control methods can be applied to the adjustment and control of tillage depth to reduce the extremum of tillage depth.

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References

1. Jian, C. L., "Application strategy of agricultural machinery in facility agriculture". *Farm Machinery Using & Maintenance*, 0(01), 2020, pp.96.
2. Chen, Y. S., Gao, Q.S., Guan, C.S., Yang, Y.T., Cui, Z.C., "Application prospect of small agricultural machinery in protected vegetable production". *Journal of Changjiang Vegetables*, 0(18), 2018, pp.20-22.
3. Teresa D., "Preliminary design of a hybrid electric powertrain for an earthmoving machine". *Science Direct Energy Procedia*, 14(8), 2018, pp.495–502.
4. Liu, F. P., Wu, Z.L., Yang, Y., Liu, Y.F., Nie, Y.Z., Wu, M.L., "Analysis and Simulation of rotary tillage power consumption of rape direct seeding machine based on classical mechanics". *Journal of Hunan Agricultural University (Natural Sciences)*, 46(03), 2020, pp.370–375.
5. Jia, C., Qiao, W., "Modeling and control of hybrid electric vehicles: a case study for agricultural tractors". In:*2018 IEEE Vehicle Power and Propulsion Conference (VPPC)*, Chicago, IL, USA: IEEE; 2018, pp.1-6.
6. Cui, Z.C., Guan, C.S., Chen, Y.S., Gao, Q.S., Yang, Y.T., "Design of small multifunctional electric crawler operation platform for greenhouse". *Transactions of the Chinese Society of Agricultural Engineering*, 35(09), 2019, pp.48–57.
7. Mocera F., Somà A., "Analysis of a Parallel Hybrid Electric Tractor for Agricultural Applications". *Energies*, 13(12), 2020, pp.305-315.
8. Vogt, H.H., "Electric tractor system for family farming: Increased autonomy and economic feasibility for an energy transition". *Journal of Energy Storage*, 40(2), 2021, pp.125-130.
9. Plizga, K., "Analysis of energy consumption by electric agricultural tractor model under operating conditions". *Agricultural Engineering*, 25(1), 2021, pp.1-12.
10. WS, K., SY, B., TJ, K., YS, K., YJ, K., "Word load analysis for determination of the reduction gear ratio for a 78 kW all-wheel drive electric tractor design". *Korean Journal of Agricultural Science*, 25(1), 2019, pp.1-12.
11. Zhou, H.D., Lu, Z.X., Deng, X.T., Zhang, C., Luo, G.J., Zhou, R.D., "Study on torque distribution of traction operation of four-wheel independent drive electric tractor". *Journal of Nanjing Agricultural University*, 41(05), 2018, pp.962–970.
12. Liu, M.N., Zhou, Z.L., Xu, L.Y., Zhao, J.H., Meng, T., "Research on compound energy system of electric tractor based on random load power spectrum". *Transactions of The Chinese Society of Agricultural Machinery*, 49(02), 2018, pp.358–366.
13. Seung-Yun, B., "Development and verification of a simulation model for 120 kW class electric AWD tractor during driving operation". *Energies*, 13(10), 2020, pp.1-12.
14. Diego, T., Luigi, A., "Case of study of the electrification of a tractor: electric motor performance requirements and design". *Energies*, 13(9), 2020, pp.1-15.
15. Shang, G.G., Zhang, J.Z., Zhang, J.J., "Research on control strategy of driving system of tracked electric tractor". *Journal of Chongqing University of Technology (Natural Science)*, 31(11), 2017, pp.38–44.
16. Du, X.W., Yang, X.R., Pan, J., Ji, J.T., Jin, X., Chen, L., "Design and test of depth monitoring system for suspended rotary cultivator". *Transactions of The Chinese Society of Agricultural Machinery*, 50(08), 2019, pp.43–51.
17. Guan, C.S., Hu, K., Chen, Y.S., "Research on small electric tractor for greenhouse". *Journal of Chinese Agricultural Mechanization*, 36(02), 2015, pp.67–76.
18. Mocera, F., "A model-based design approach for a parallel hybrid electric tractor energy management strategy using hardware in the loop technique". *Vehicles*, 3(1), 2020, pp.1-19.
19. Rol, S., "Calculation of the losses of series-hybrid powertrains". *Journal of Agricultural Science and Technology A*, 8(02), 2018, pp.112-119.
20. Wang, L.M., Wang, S.M., Song, Z.H., "Research on control strategy and starting method of incremental electric tractor". *Transactions of The Chinese Society of Agricultural Machinery*, 49(S1), 2018, pp.493–498.