Design and experiments of electronic steer-by-wire system in electric tractor

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Abstract. Aiming at the problems of large free travel, heavy steering and slow response of the existing mechanical steering system of electric tractor, a steer-by-wire system directly driven by linear actuator was proposed and studied in this paper. The steering process of steer-by-wire system was analysed theoretically, and the simulation model was established based on MATLAB/Simulink. The following response and step response of steering system were simulated and tested. In order to verify the steering performance of the steer-by-wire system in electric tractor, the in-situ steering test and road-drive test were carried out on the modified prototype. The results showed that the designed steer-by-wire system could meet the requirements of low-speed driving of electric tractors, with fast response, stable steering and good overall tracking performance.

1. Introduction

In recent years, energy and environmental problems caused by agricultural mechanization had become increasingly prominent.

Agricultural machinery in China has low efficiency and high energy consumption. The dramatic increase in tractors output had brought about a large amount of energy consumption [1]. Agricultural tractors are off road equipment used in the worst terrains available on earth. They are exposed to high friction surfaces-farm fields. The front axle steering forces vary in a very large scale with respect to loads and coefficient of friction of the farmland [2,3]. Popular technologies available in tractors are manual steering system using mechanical linkages and power steering system using hydraulic power pack. The former one is a fixed ratio system with high steering effort. The later one is a highly effortless system but the sensitivity is not adjustable, consumed a good amount of engines energy thereby affecting the mileage [4].

Steer-by-wire system, as a new intelligent vehicle development technology, has the characteristics of variable angular transmission ratio and force transmission ratio, which can greatly improve the steering sensitivity and accuracy [5,6], and consumes only very less amount of energy to work. There are two kinds of steer by wire system, that are, the hydraulic steer-by-wire system and the electronic steer-by-wire system. The advantages of the hydraulic steer-by-wire system are that, it combined hydraulic steering technology with the steer-by-wire technology, which can freely set the angular transmission ratio, reduce the complexity of the oil circuit arrangement, and improve the steering performance of the vehicle [7]. The advantages of the electronic steer-by-wire system are that, on the one hand, incorporating an electronic system would eliminate many mechanical parts inherent to a
typical hydraulic steering system, thereby reducing the overall weight of the tractor and reducing manufacturing costs. Electronic steer-by-wire systems, on the other hand, are completely self-contained and do not require external pumps or hoses, with environmental protection, no oil leakage, low energy consumption and other characteristics [8].

Jiangxue Chang et al. contrasted and analyzed the PID control algorithm and the fuzzy control algorithm in the tractor hydraulic steering system, and studied the steering control strategy to some extent [9]. Zhixiong Lu et al. studied the road sensation characteristics of the hydraulic steer-by-wire system of wheeled tractors, and designed different citrus characteristics for farmland operation and transportation modes [10]; Susu Fang et al. put forward a tractor hydraulic steer-by-wire system and carried out a prototype performance test. The results showed that compared with the hydraulic steering system, each performance had been effectively improved [11]. Guangqing Zhang of Nanjing Agricultural University carried out steering-by-wire technology research on articulated swing-rod heavy tractor. Fuzzy self-tuning PID control strategy was adopted, which has advantages in system steady-state error, followability and rapidity [12].

In the above research, the steer-by-wire system in tractors mostly combined with the hydraulic steering system. Since the designed electric tractor was no longer equipped with hydraulic system, an electronic steer-by-wire system directly driven by linear actuator was presented in this paper, which had obvious advantages over the hydraulic steering-by-wire system: it is directly powered by electric tractor batteries, efficient and easy to control, and the steering accuracy could be improved by higher control precision of the motor.

2. Structural scheme of steer by wire system

2.1. Scheme of overall design

Steer-by-wire system eliminated the mechanical connections between the steering wheel and front wheels, controls the movement of linear actuator through SBW Controller, and designs the angular transmission ratio according to working characteristics of electric tractor [13]. As shown in Fig.1, the schematic diagram of the steer by wire system driven directly by linear actuator.

![Figure 1. Steer By Wire Layout.](image)

This system adopted linear actuator as the main actuator, which could realize automatic steering and manual steering. When the automatic steering switch was closed, the signal of the steering wheel angle sensor was sent to SBW Controller, which could calculate the target displacement of the linear actuator, and the potentiometer fed back the actual displacement signal of the linear actuator to the SBW
Controller. To control the movement of the linear actuator, SBW Controller sent a control command to motor driver, and then the steering ladder arm was driven to realize tractor steering.

When the automatic steering switch is turned on, SBW Controller received the automatic steering signal and controls the movement of linear actuator. When the switch outputs high level, the built-in DC motor of linear actuator rotated clockwise, the front wheels turned right, and vice versa. At the same time, a feedback signal was transmitted to SBW Controller by the potentiometer, and SBW Controller controls the position of linear actuator in real time. The automatic steering function in this paper was set to pave the way for further research on the automatic driving technology of the electric tractors.

2.2. Components of steer-by-wire

The steer-by-wire system of electric tractor designed in this paper consists of steering wheel module, the execution module and controller module. The steering wheel module removed the steering gear from the original mechanical steering system and redesigned, including the steering wheel fixation, sensor fixation and installation, as shown in Fig.2.

![Figure 2. Physical map of Steering wheel module.](image)

The execution module, as shown in Fig.3, was mainly composed of linear actuator, steering knuckle arm, trapezoidal arm and steering tie rod, etc.

![Figure 3. Execution module of steer by wire system.](image)
The main function of SBW controller is to collect the sensor signals and get the control commands of DC motor through control strategy to control the movement of linear actuator to realize manual or automatic steering of the tractor. In this paper, Arduino Uno R3 was used as the processing chip to design the peripheral circuit, so as to complete the signal input and output functions.

3. Theories analysis
The key of electric tractor steer-by-wire control system is to accurately control the displacement of linear actuator according to the steering wheel angle, so it is of great significance to find the relation between steering wheel angle and linear actuator displacement through theoretical analysis.

Steer-by-wire system in electric tractor adopts trapezoidal steering mechanism. The steering diagram is shown in Fig. 4. The tractor then turns to the right, the linear actuator extends forward displacement S, the front end extends from point A to point B, and the knuckle arm J rotates around point O.

![Figure 4. Schematic diagram of electric tractor steering.](image)

In triangle OAB, according to cosine theorem:

$$\cos \theta = \frac{J^2 + J^2 - S^2}{2J \times J}$$

(1)

J is the length of steering knuckle arm; S is the displacement of linear actuator; \( \theta \) is turning angle of front wheel, °. According to the measured parameters \( J=0.12m \), the relationship between \( \theta \) and S is obtained:

$$\cos \theta = 1 - \frac{S^2}{0.0288}$$

(2)

In addition, the angle of steering wheel has the following relationship with the angle of front wheel:

$$i = \frac{\theta_s}{\theta}$$

(3)

\( i \) is ideal transmission ratio, \( \theta_s \) is the angle of steering wheel. Therefore, the relationship between steering wheel angle \( \theta_s \) and linear actuator displacement S can be written as:

$$\cos \frac{\theta_s}{i} = 1 - \frac{S^2}{0.0288}$$

(4)
The transmission ratio \( i \) of the steer-by-wire system varies with the angle of steering wheel. Combining with the working characteristics of the electric tractor, the curve of angular gear ratio designed in this paper are plotted in Fig.5. With the angle of 0°~60°, the steer-by-wire system has a large steering gear ratio to meet the requirements of straight-line driving. Continue to increase the steering wheel angle, the angular gear ratio decreases rapidly, and finally stabilized.

![Figure 5. Curve of ideal steering ratio.](image)

In summary, the relationship between the steering wheel angle and the displacement of linear actuator can be obtained, which was approximately linear, as shown in Fig.6.

![Figure 6. Relationship between steering wheel angle and displacement of linear actuator.](image)

Based on the relationship between steering wheel angle and linear actuator displacement, the steer-by-wire control system of electric tractor was designed. The schematic is shown in Fig.7, and the whole structure is closed loop control system. Firstly, SBW controller collects the position signal of the
automatic steering switch and selects the steering mode (manual steering or automatic steering). In manual steering mode, the controller detects the steering wheel angle signal and displacement signal of linear actuator, obtains the output value according to PID control algorithm, and gets a control voltage after D/A conversion, and then controls the movement of linear actuator. If the steering is automatic, the automatic steering signal is collected, and the linear actuator is controlled by the high and low levels.

\[ D_i \text{ is target displacement of linear actuator, } \tau \text{ is actuator torque, } D_a \text{ is actual displacement of linear actuator.} \]

4. **Prototype test and results analysis**

Performance of steering system is directly related to the safety, comfort and reliability of the tractor. In order to verify the performance of the designed steer-by-wire system, tests were carried out on an electric tractor prototype equipped with the steer-by-wire system, including in-situ steering test and road driving test, as shown in Fig.8 is the steer-by-wire test electric tractor.

\[ \text{Figure 8. Steer-by-wire test electric tractor.} \]

4.1. **In-situ steering test**

In the in-situ steering test, the front wheels are raised off the ground so as to isolate the influence of static friction at the tire-ground interface. Mainly including response speed test, small angle tracking test and large angle tracking test.

4.1.1. **Response speed test.** The purpose of this test is to test the reaction speed of front wheels under the action of steering wheel. Fig. 9 is the result of response speed test. It can be seen that the steering angular velocity increases from zero to maximum, the curve rises vertically and changes rapidly, which proved the steering system was sensitive to the reaction, fast to respond. The average angular velocity was 0.25 rad/s, the fluctuation is small and the steering is stable.
Figure 9. Curve of response speed test.

a Following curve of front steering angle

b D-value between target angle and actual angle

Figure 10. Curves of small angle tracking test.
4.1.2. Small angle tracking test. When tractors work in the field, it mainly travels in a straight line. The range of the steering angle of front wheels is relatively small, generally not exceeding ±6°. Therefore, it is necessary to carry out small angle tracking test, which can test the steering performance of tractor in small angle steering. Fig.10 is the results of small angle tracking test.

It can be seen from Fig.10 (a) that the steering process was smooth, the tracking curve of actual angle was close to the target angle input signal, and the hysteresis was not obvious; Combined with Fig.10 (b), it was further concluded that the maximum tracking error between the target angle and the actual angle was 1.38°, the mean error was 1.02 °. To sum up, the steer-by-wire system designed in this paper has the advantages of small overall error and stable steering at small turning angles, which makes the electric tractor have higher steering follow-up and sensitivity.

4.1.3. Large angle tracking test. The front wheels’ angle of the tractor varied greatly when it transferred or turned around. The test was of great significance for inspecting the performance of the steer-by-wire system during large angle steering, and the steering angle was -30°~30° in this experiment. Fig.11 showed the results of the large angle tracking test. It can be seen that the steering process fluctuated greatly and the hysteresis was obvious. The maximum tracking error was 4.36° and the mean error was 3.14°.

![Figure 11. Curves of large angle tracking test.](image)
4.2. Road-drive test
Road-drive test was mainly carried out in s-shaped form. Due to the low operation speed, the test will focus on the steering stability of the steer-by-wire system. According to test method of the GBT 3871.19-2006 steering capability of wheeled tractors, the tractor tested at a speed of 5Km/h according to the specified trajectory.

In this test, the stability of the steering system was verified by studying the change of yaw angular velocity and lateral acceleration during the s-shaped test. Fig.12 was the results of s-shaped test. It can be seen from Fig. 12(a) and 12(b) that the yaw angular velocity and lateral acceleration changed steadily during the snake-like steering, increased first and then decreased at the turn, the maximum yaw angular velocity is about 0.17 rad/s, the maximum lateral acceleration is about 0.1 mm/s²; Figure 12(c) was a comparison of the yaw angular velocity of front wheels in s-shaped test and in-situ steering test. It can be seen that after front wheels being loaded, the yaw angular velocity is significantly slower, the steering time increased, and the hysteresis is obvious. Due to the required driving torque increased after the front wheels loaded, the speed of built-in DC motor became slow, resulting in an increase in steering time and a slower response speed.

![Graphs showing yaw angular velocity and lateral acceleration](image-url)

a Yaw angular velocity
b Lateral acceleration
5. Conclusion
Aiming at the problems existing in the steering system of electric tractor, a design scheme of steer by wire system directly driven by linear actuator was proposed. Linear actuator could be powered by electric tractor battery pack. This steer-by-wire system had two functions of manual steering and automatic steering, which paved the way for automatic driving and unmanned driving of tractors.

After theoretical analysis, the prototype tests of steer-by-wire system in electric tractor were carried out, including in-situ steering test and road running test. In the in-situ steering test, the steering system had fast response speed, small fluctuation and stable steering, and the performance of small angle steering is better than that of large angle steering. The results of road running test showed that the yaw angular velocity and lateral acceleration of the electric tractor were stable at low-speed continuous turning, which increased first and then decreased. Compared with the mechanical steering system, the steer-by-wire system has higher steering accuracy and handling stability, and faster response speed, which can reduce the driver's working intensity.

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