Tractor steering teleoperation control with fuzzy PID algorithm based on delay time measurement with timestamp

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2020 Chinese Automation Congress (CAC) | 978-1-7281-7687-1/20/$31.00 ©2020 IEEE | DOI: 10.1109/CAC51589.2020.9326587

***Abstract*—Because of the labor shortage and aging of population in rural areas, and considering of the technological limitations nowadays, the tele-operational driving robot of human-in-loop is developed to help people to drive a tractor without physical attendance. The time delay control is vital for remote control of tractor steering because of the changeable weather condition and communication channel which leads to communication time delay. Firstly, the timestamp method is utilizing to measure the random time delay to transfer the problem of random time delay control to constant time delay control. Then the PID controller suitable for different time delay is study and the fuzzy controller is using to adjust the control parameters dynamically. Finally, design the experiment to evaluate the position tracking performance of the proposed algorithm which shows that the average and maximum position tracking errors are 10cm and 18cm respectively under the random time delay ranged from 0 to 1000 ms. The results indicate that the tractor steering teleoperation control with the fuzzy PID algorithm based on delay time measurement with timestamp has good tracking performance, strong robustness and important application prospects in intelligent agricultural industry.**

Keywords—Teleoperation, time stamp, tractor, human in loop.

I. Introduction

Agricultural mechanization is an inevitable trend in China due to the aging population and accelerated urbanization process[1]. Unmanned intelligent tractor is a good technology which lead to hotspot nowadays[2]. Comparing with the standardized environment of unmanned vehicles on the road[3], it's hard to go breakthrough in short time to develop an autonomous smart tractor which can work in the field safely and reliably because of the complex, variable and even harsh farmland environment[4].

So, as an alternative solution, the teleoperation control of tractor has important practical significance because the human-in-loop mode can add human knowledge and intelligence into the control system[5]. The teleoperation technology has been widely using in harsh operating environments such as aerospace, satellite remote sensing telemetry, in-depth sea exploration and nuclear energy development[6] or other harsh operating environments[7] which indicate its feasibility and effect. However, wireless network communication is susceptible to meteorological conditions such as wind and rain, lightning, etc., especially in the thunderstorm season which is easy to cause time delay in network communication[8]. The time delay will result in positive feedback of control signals Which will also lead to instability and poor robustness[9].

Fund Projects: National Natural Science Foundation of China (32071896,31960487); General Project of Jiangsu Natural Science Foundation (BK20181315); Agricultural Science and Technology Independent Innovation Project of Jiangsu Province (CX(20)3068).

For the delay control problem, Typical and commonly used control methods in domestic and foreign research include predictive control, passive control, fuzzy control, virtual reality technology, etc. According to the effect of different control methods, the intuitive comparison in Table Ⅰ below is obtained[10-11].

TABLE I. COMPARISON OF CONTROL METHODS

Control Method	Advantage	Disadvantage
Passive control	Improved the stability of systems with random delays	Operation and transparency cannot be guaranteed
H_∞ Theoretical control	Robust to uncertain interference	More conservative in handling larger delays
Predictive control	Increased robustness of time delay system	Non-linear, time-varying system is difficult to model
Virtual reality	Improve immersion and control quality	Can not fundamentally improve the delay impact
Delay compensation	Improve system stability and control tracking effect	Difficult to design a controller for time-varying, and nonlinear environmental models

Unfortunately, none of these methods can be used in the field of agricultural teleoperation. In actual agricultural applications, it is not only cost-sensitive, but also requires high-quality and high-reliability farmland operations.

In addition, some scholars have applied the fuzzy theory to the teleoperation field and achieved good results[12-13]. The fuzzy system's approximation performance can effectively overcome the interference of modeling errors and external disturbances on the system. So, our system is robust to model errors, parameter mismatches, time delays, resistance disturbances and other uncertainties by adjusting control parameters online in different soft and hardware environments.

Therefore, This paper aims to develop a homogeneous structural virtual reality driver and its control system according to our existing tractor driving robot. Then the tractor steering teleoperation control in the case of random time delay is study and the random delay time detection with time stamp method combined with fuzzy PID control strategy are proposed.

II. HOMOGENEOUS STRUCTURAL TRACTOR DRIVING ROBOT VIRTUAL REALITY TELEOPERATION CONTROL SYSTEM

In this system, the master is composed of a tele-operator, virtual reality equipment and control computer. The slaver is made up by the tractor driving robot and its control system. The master side and the slaver side are communicational connected by a cloud server[14]. As previously mentioned, the farmland operation environment is ununiform, uncertain and complex. So, the time delay during communication between the master side and the slaver side is inevitably exist.

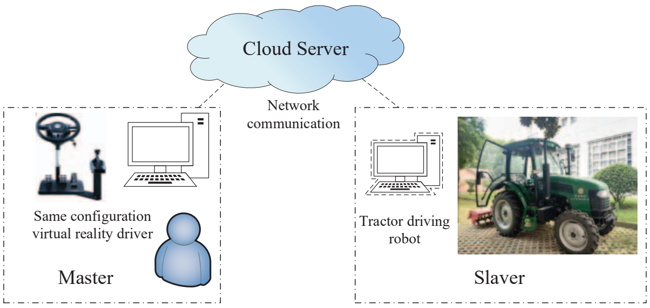


Fig. 1. Homogeneous structural virtual reality teleoperation system framework.

In the remote operation of the tractor, the steering control system is particularly important which determine working quality. Considering the steering control is conditioned by the ground resistance, the traditional steering control method is difficult to achieve steady and rapid control. So, a new tractor steering control method which is based on the timestamp and fuzzy PI teleoperation control technique are proposed.

III. MODELING OF THE TRACTOR DRIVING ROBOT STEERING MANIPULATOR

The steering manipulator of the tractor driving robot is driven by Maxon RE35 DC motor. The rated voltage of the motor is 24V , the rated power is 90W, the armature resistance is R_a=1.2Ω, and the inductance is L_a=$3.4\cdot10^{-4}H$, the reduction ratio I is 39 , the motor working efficiency η is 0.84, the moment of inertia of the rotor is $J = 6.81\cdot10^{-6} kg\cdot m^2$. The physical model of the steering DC motor is shown in Fig. 2 below.

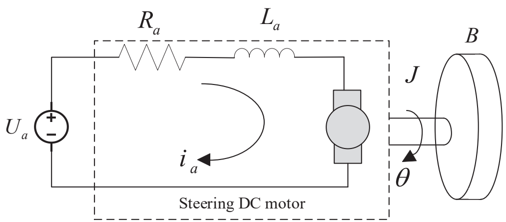


Fig. 2. Physical model of the steering DC motor.

The differential equations for each part of the system are calculated as:

$$L_a\frac{di_a(t)}{dt}+R_a i_a(t)+K_e w(t)=u_a(t) \quad (1)$$

$$J\frac{dw(t)}{dt}+Bw(t)=K_m i_a(t)-M_c(t) \quad (2)$$

Among them, u_a is the armature input voltage (V), θ is the motor output angle (rad) , $i_a(t)$ is the armature current generated in the armature circuit, $w(t)$ is the motor speed, and $M_c(t)$ is the total load torque equivalent to the motor shaft. Besides, the motor torque coefficient $K_m = 4.3\times10^{-2} N\cdot m\cdot A^{-1}$, the back electromotive force coefficient $K_e = 2.7\times10^{-2} V\cdot r^{-1}\cdot s$ .According to the formula, and the viscous damping coefficient of the motor is $B = 9.55K_e^2\cdot R^{-1} = 5.8\times10^{-3} N\cdot m\cdot s$.

After the above formulas are simplified by the Laplace transform, the transfer function of the motor rotation angle output $\varphi(s)$ is:

$$\varphi(s)=\frac{1.943\cdot10^7}{s^3+4336s^2+3.762\cdot10^6 s}\cdot U_a(\mathrm{s}) \quad (3)$$

Considering the structure of the wheel manipulator, the motor rotates synchronously with the wheel, and there is a dynamically varying damping torque on various road surfaces, the disturbance function is added to the model. So, the final transfer function of the motor $\theta(s)$ is as follow:

$$\theta(s)=\frac{1.94\cdot10^8 U_a(s)-(3.89\cdot10^3+1.23\cdot10^3)M_c(s)}{s(s^2+43400s+3.76\cdot10^7)} \quad (4)$$

IV. TIMESTAMP-BASED TIME DELAY MEASUREMENT METHOD

A. *Timestamp based delay measurement*

The remote operation control of the tractor is easily affected by weather, which leads to a random network communication delay. The long delay brings a phase lag to the system loop, which reduces the stability margin and causes the instability of the system. All these factors will reduce the system performance. It is still challenging to design a suitable compensator for such a random delay system[14].But the existed research shows that the fixed time delay can be easy compensated by using time-lag control, PID control, etc.[8]. Hence, the delay time measurement method is using to transfer the random time delay control to fixed time delay control for engineering application.

To obtain the delay time, the timestamp method has been utilized which basic idea is that:

- Step 1: The master and slave initialize to perform synchronous time calibration. The master sends the local time (T_1) as a timestamp to the slave with control message;
- Step 2: The slave receives the control message and parses the timestamp in the control message (T_1), and records the slave time at this time as (T_2);
- Step 3: Calculate the specific random delay time $\Delta T = T_2 - T_1$;

The specific flowchart and working process are shown in Fig. 3 and Fig. 4 below.

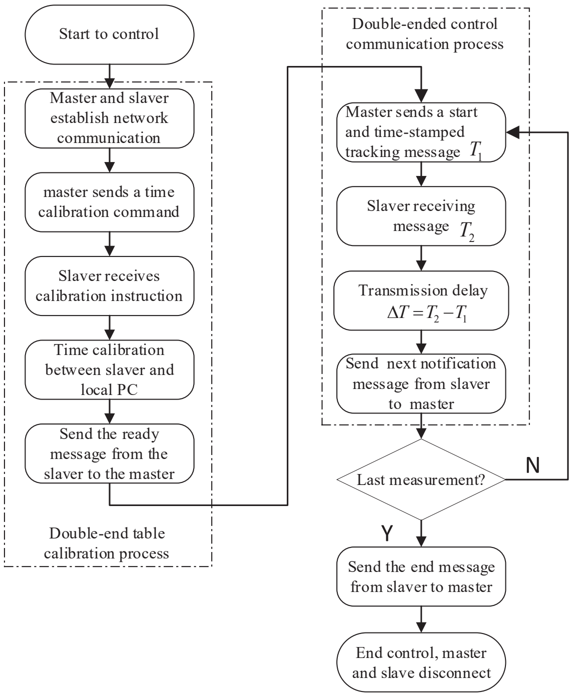


Fig. 3. Timestamp-based delay measurement flowchart.

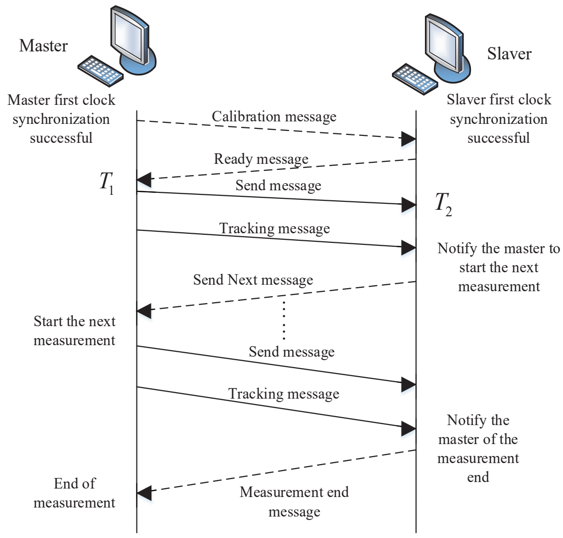


Fig. 4. Timestamp-based delay measurement process.

B. Controller design for variable time delay

The traditional PID controller has several advantages, such as easy adjustment and realization, which make it widely using in industrial process control. However, since there are nonlinear and time-varying uncertainties in the farmland operating environment system, the traditional PID control algorithm is difficult to guarantee the control effect. The fuzzy PID control algorithm is often employed to take the place of traditional PID control method to control the steering motor. The fuzzy rules are used to adaptively adjust the parameters of the PID controller so that the controlled object remains in a good static and dynamic state[14].

The fuzzy control system is composed of five parts: fuzzy controller, input and output interface, actuator, measuring device and controlled object. The specific control schematic diagram is shown in Fig. 5.

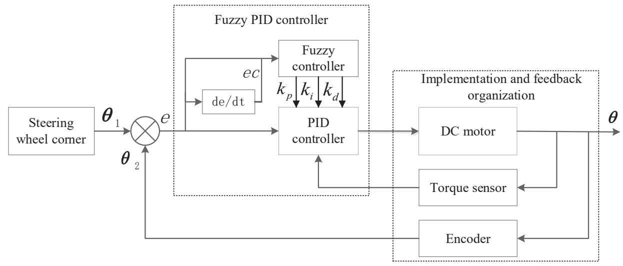


Fig. 5. Fuzzy PID control schematic diagram of steering system of the tractor driving robot.

In this control system, the actual steering angle (θ) information is collected by the encoder and the torque sensor to form a closed-loop position feedback. θ_1 is the desired steering angle of the steering wheel, θ_2 is the feedback rotation angle adjusted by the controller Steering angle error e, current deviation and last deviation change ec are calculated respectively. The fuzzy controller can give the parameters such as P, I, D to the PID controller.

- **Fuzzy rule**

The actual variation range of errors e and ec are the basic domain on the fuzzy set, respectively [-1, 1] and [-6, 6]; the fuzzy domains of the output control parameters P, I, D are [-0.02 ,0], [-0.0001,0.0001], [-10,10]. In the controller, the fuzzy linguistic variables are divided into 7 sub-items: " negative big" (NB), "negative middle" (NM), "negative small" (NS), "zero" (ZO), "positive small" (PS), " positive middle " (PM), " positive big " (PB). The error e, the current deviation and the last deviation change ec and the fuzzy subset of the output control parameters P, I, D are {NB, NM, NS, ZO, PS, PM, PB}. After repeated trials, the fuzzy inference rules are given in the following Tables Ⅱ.

TABLE II. FUZZY PARAMETER CONTROL RULE

ΔK_p	ec						
e	PB	PB	PM	PM	PS	ZO	ZO
	PB	PB	PM	PS	PS	ZO	NS
	PM	PM	PM	PS	ZO	NS	NS
	PM	PM	PS	ZO	NS	NM	NM
	PS	PS	ZO	NS	NS	NM	NM
	PS	ZO	NS	NM	NM	NM	NB
	ZO	ZO	NM	NM	NM	NB	NB

(a) Fuzzy parameter P control rule

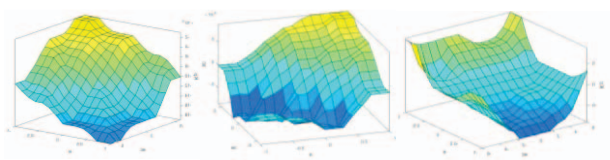
ΔK_I	ec						
e	NB	NB	NM	NM	NS	ZO	ZO
	NB	NB	NM	NS	NS	ZO	ZO
	NB	NM	NS	NS	ZO	PS	PS
	NM	NM	NS	NS	PS	PM	PM
	NM	NS	ZO	ZO	PS	PM	PB
	ZO	ZO	PS	PS	PM	PB	PB
	ZO	ZO	PS	PS	PM	PB	PB

(b) Fuzzy parameter I control rule

ΔK_D	ec						
e	PS	NS	NB	NB	NB	NM	PS
	PS	NS	NB	NM	NM	NS	ZO
	ZO	NS	NM	NM	NS	NS	ZO
	ZO	NS	NS	NS	NS	NS	ZO
	ZO	ZO	ZO	ZO	ZO	ZO	ZO
	PB	NS	PS	PS	PS	PS	PB
	PB	PM	PM	PM	PS	PS	PB

(c) Fuzzy parameter D control rule

The three-dimensional output of fuzzy rules for the control parameters P, I and D are as follows.



(a) control parameters P (b) control parameters I (c) control parameters

Fig. 6. The three-dimensional output of fuzzy rules.

- **Simulation and Analysis of Fuzzy PID Controller**

According to the steering manipulator modelling and transfer function, the Simulink simulation diagram is set up, shown in Fig. 7, including the fuzzy PID controller and motor model.

The system is easy to be unstable or even makes the machine out of control if time delay exists in the teleoperation control system. Therefore, when the time exceeds 1s and the delay appears multiple times in this system, it is diagnosed as a network communication failure or network disconnected. When these happened, the control system stops the tractor, sends alarm information and waits for the commands from the master.

- **Simulation and analysis of fuzzy PI controller for stochastic delay system**

To simulate and study the controllability and stability of the tractor steering system, a random number generator is adopted in the environment of Simulink to generate a random time delay within 0-1s. In the experiment, PID parameters are determined by fuzzy controller based on the measured time delay.

According to the change of the actual input signal during the steering operation of the tractor, three types of signals (the sinusoidal signal, the triangular signal and the square wave signal) are selected as the steering wheel angle signals.

Since the ground damping moment of tractor varies while working in different type of field conditions. The average torque values in the sediment, grassland and cement filed are measured as $0.45N \cdot m$, $0.80N \cdot m$ and $2.51N \cdot m$. Therefore, the random value of $0 \sim 3N \cdot m$ is selected as the damping torque disturbance input. Tracking performance between the master side and slave side is an important indicator to evaluate the teleoperation system. So, the tracking precision is selected as indicating parameter.

To compare the effects of the control algorithms, the motor system without the algorithm is simulated simultaneously under the same conditions. The simulation curve is shown in Fig. 8. In the simulation, set the simulation step size to Auto and the signal source frequency to $5 rad \cdot \sec^{-1}$, and ensure that at least 50 sampling points are taken during the entire simulation process, which effectively prevents the system from distorting the simulation results because the sampling points are too sparse. In order to achieve the best control effect, the time delay of each signal is set as 0.524s, 0.256s, and 0.828s respectively.

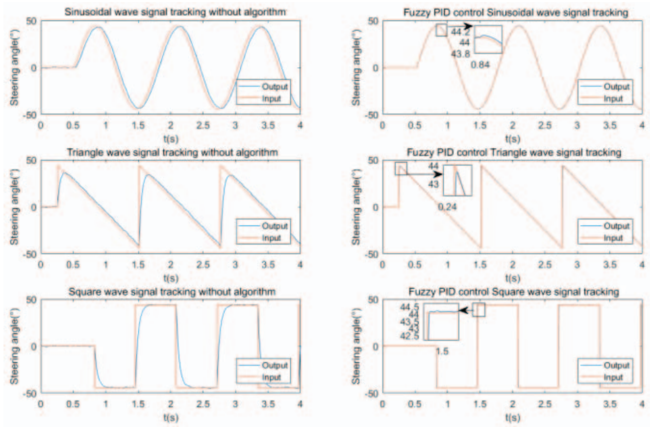


Fig. 8. Fuzzy PID Simulink simulation result.

It can be known from the simulation tracking curve: after the fuzzy PID controller dynamically adjusts the parameters, the system improves the average control accuracy by 2.04° under the sinusoidal signal input response; increases the average control accuracy by 3.26° under the triangular wave signal input response; and inputs the rectangular wave signal in response, the average control accuracy is improved by 4.32°.

The simulation tracking curves indicate that the designed fuzzy PI controller has a fast response and excellent tracking performance under the condition of different time delay of the input signals. The overall tracking effect is still good and has excellent controllability even under the influence of random damping torque input.

V. EXPERIMENTAL

A. *Experimental system*

The tractor driving robot (Fig. 9) was used to upgrade the tractor (Manufacturer is Changfa Co., Tractor model is CFD504A) nondestructively. The driving robot consists of various actuators such as steering arm/legs [10], sensing system, industrial personal computer, motor and hydraulic control unit, and multiple power output units. The combination of motor drive and hydraulic drive is used to complete the precise control of the driving robot.

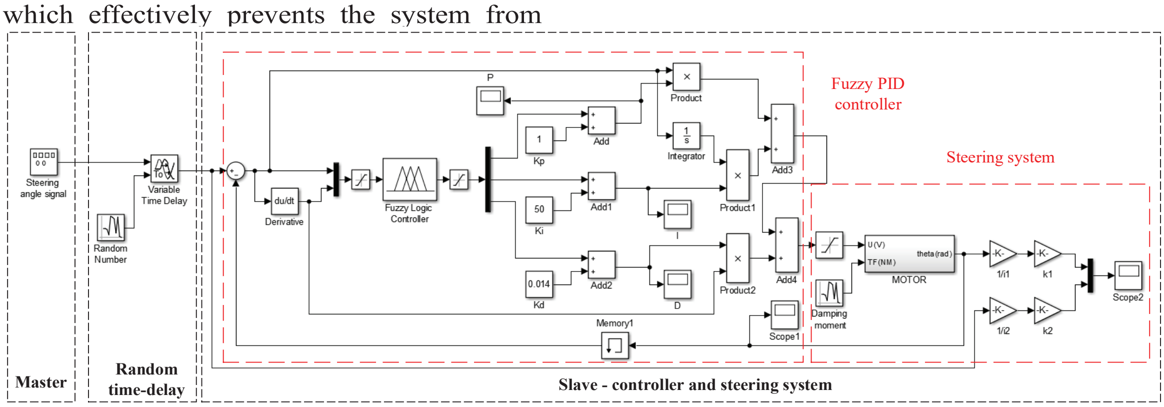


Fig. 7. Fuzzy PID Simulink simulation diagram.

Fig. 9. Overall layout of the driving robot.

1. Steering arm 2. Hydraulic drive 3. Pedal mechanical leg 4. Shifting manipulator 5. Rotary tiller lifting manipulator

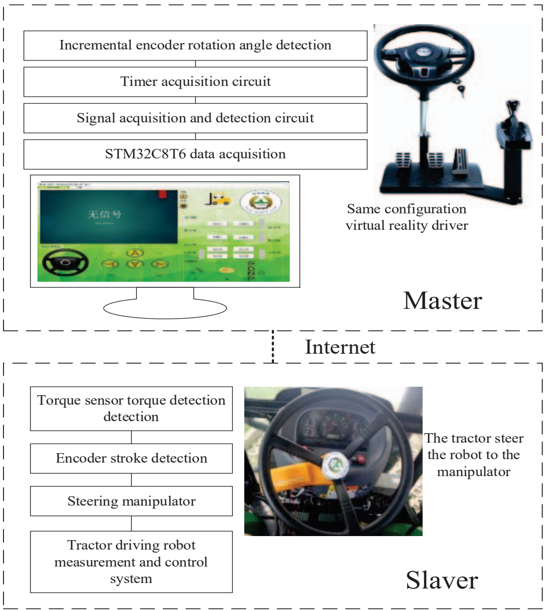


Fig. 10. Virtual reality remote control system.

The virtual reality teleoperation control system was developed based on the Microsoft Visual Studio 2010 platform. The user interface is divided into several functional areas, shown in Fig. 10.

These areas include user information perception area, operation area and video area. The functions provided by the system includes transmission connection situation, display of isomorphic virtual reality driving simulator working status, video transmission sensing interface, internal tractor sensor working condition feedback and other components.

B. *Experiment process*

To verify the reliable teleoperation control of the tractor with a random delay, the control command with random time delay is artificially set at the master side. The slave side receive the command and resolve the timestamp to calculate the time delay. Then the tracking position and time delay input to the fuzzy PID controller and the controller drive the DC motor. The wireless communication was realized by point to point model.

In the test, the desired trajectory is defined as random arc through cement, sand and grass road to generate different damping moment. The expected track was draw by white powder and the track was recorded by water leakage from a bottle fixed in the tractor. The tracking results are as follows.

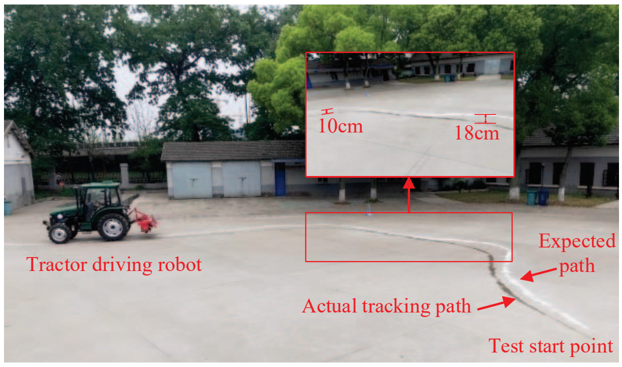


Fig. 11. Tractor teleoperation tracking on the cement road

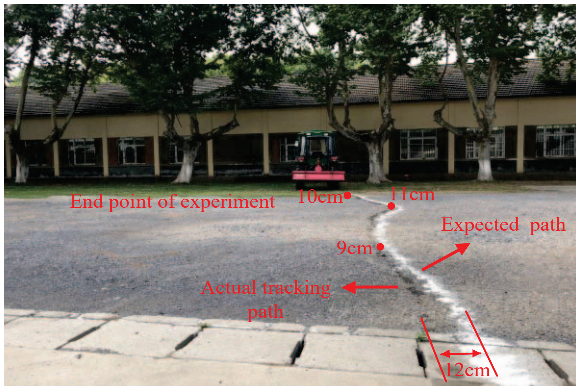


Fig. 12. Tractor teleoperation tracking on the sand and grassland road

These areas include user information perception area, operation area and video area. The functions provided by the system includes transmission connection situation, display of isomorphic virtual reality driving simulator working status, video transmission sensing interface, internal tractor sensor working condition feedback and other components.

During the test, the P、I and D parameter values in the fuzzy PID controller of the steering robot controller were obtained in real time, as shown in Fig. 13.

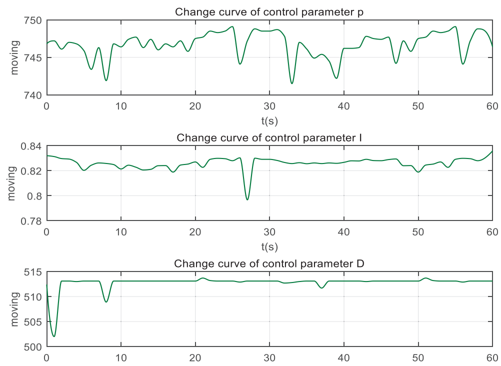


Fig. 13. The actual fuzzy PID parameter curves of the steering manipulator.

The maximal and average errors between the actual track and the expected path are not more than 18cm and 10cm respectively. The tractor steering tracking control error is obtained as shown in Fig. 14. And the tracking errors has nothing to do with the path and the operation of the tractor.

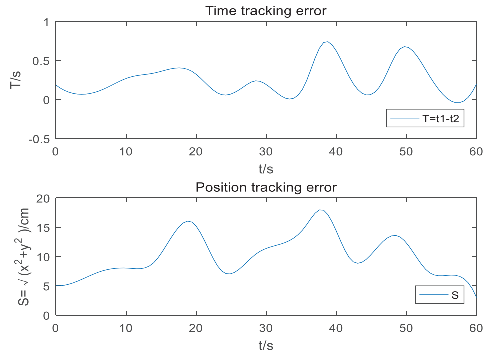


Fig. 14. Tracking error of tractor steering control.

In the experiment, a time-delay curve based on cloud platform was obtained by using time-stamp time-delay measurement method, and 5000 experimental time-delay data are selected to draw the time-delay curve under the cloud platform as shown in Fig. 15. After measured the average random delay is 0.02s, and the maximum delay is 0.523s.

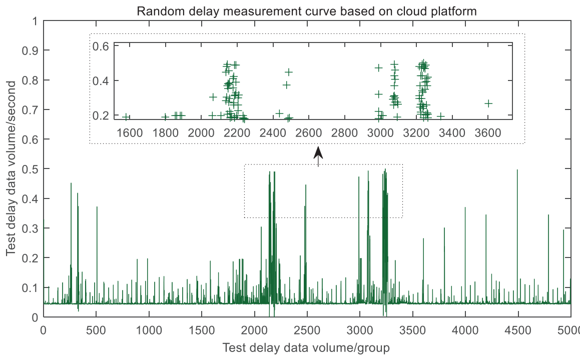


Fig. 15. Random time delay measurement curve based on cloud platform.

In order to compare the teleoperation communication performance based on the cloud platform, the local area network connection communication equipment is replaced in turn for a comparative communication test. Set the local network connection distance is set to 15km, that is, the tractor performs farmland operations within a range of 15Km from the signal transmission source.

In the experiment, the 4G network, the campus WIFI network, and the Rocket M industrial antenna were selected for testing. The results show that the network time-delay can be measured based on the time-stamp delay measurement under different network conditions. The communication delay changes are shown in the Fig. 16 (1000 test data are selected), and their average delay is 0.204s, 0.216s and 0.223s respectively. The maximum delay was 0.288s, 0.291s and 0.296s respectively.

VI. Conclusion

In this paper, the tractor steering teleoperation control with fuzzy PID algorithm based on delay time measurement with timestamp is proposed. The experiment results manifest that the proposed algorithm has good tracking performance in different damping moment roads such as cement, sand and grass pavement. The average and maximum tracking errors are not more than 10cm and 18cm respectively while the delay time ranged from 0 to 1000ms. The proposed algorithm has a good application prospect in complicated, harsh agricultural operating environment for agricultural machinery.

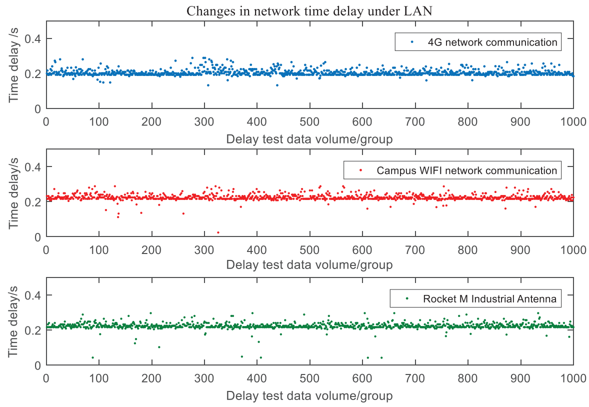


Fig. 16. Time-delay changes under local area network.

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