Review of electro-hydraulic hitch system control method of automated tractors

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Abstract: The automatic and intelligent degree of tractor hitch system determines the operations quality, efficiency, tractor power output and energy consumption, and automatic control of electro-hydraulic hitch is one of the key technical problems in the realization of automated tractor. In this study, the adjustment methods and characteristics of electro-hydraulic hitch system were summarized. The development of electro-hydraulic hitch control technologies was elaborated and analyzed from both the electro-hydraulic control strategy and slip control strategy perspectives. The implementation methods and control characteristics were discussed. A new idea for the development of automated tractor was put forward that integrating cutting-edge technologies such as big data, fusion control and artificial intelligence. In addition, based on the precise and efficient control of electro-hydraulic hitch system, a high reliability of the control system of the tractor with intelligent application of the control algorithm was obtained. The results can provide a reference for the precise operation of automated tractors under the big data in agriculture.

Keywords: automated tractors, electro-hydraulic hitch, control algorithm, draft-position control, slip rate control

DOI: 10.25165/j.ijabe.20211403.6175

Citation: Wang L, Wang Y, Dai D, Wang X, Wang S M. Review of electro-hydraulic hitch system control method of automated tractors. Int J Agric & Biol Eng, 2021; 14(3): 1–11.

1 Introduction

A combination of factors, including increased international competition in the agricultural sector, advances in computer technology, and the rapidly decreasing costs of new technology, has brought us to a time when widespread application of intelligent machines in agriculture is imminent[1,2].

Tractors are machines used to perform agricultural operations or to drive agricultural implements. The automated tractor, integrated with electronic and control technology, can monitor and adjust the tractor operation parameters in real-time, which improves the operation productivity. As important machines in agricultural production, the significance of the development of automated tractors is self-evident.

Automated tractors can improve the quality and efficiency of agricultural operations. Essentially, automated tractors are perceptive machines that can be programmed to power various types of agricultural implement[3] and can provide increased operating speeds while reducing downtime and eliminating human-related problems[4]. However, most previous research has indicated that incorporation of intelligent technology into agriculture has proved difficult because of the significant variations encountered in the different tasks to be performed, the structures of the implements used, and the operating environment (including ground surface conditions, temperature, humidity, dust, and mud)[1,5].

Automated tractors can save energy. Tillage is a very important practice in agriculture and is thus a major cause of energy consumption in agricultural production[6,7]. According to Maradun et al.[8], a power intensity of 0.4 kW/hm^2 is currently required to provide acceptable levels of agricultural production, regardless of location. Developed countries such as the USA have already reached a level of 0.783 kW/hm^2. An automated tractor can control its operating state to optimize efficiency: energy savings are achieved by regulating wheel slippage to within the 10%-15% range, where the power consumption is low[9,10]. Additionally, Shafaei et al.[11] indicated that tractors that use intelligent control algorithms can improve the overall energy efficiency by 73%.

Automated tractors can provide increased economic benefits. With the decline in the labor force and the increases in real (i.e., inflation-adjusted) wages (as shown in Figure 1)[12], the use of intelligent machines has affected the economics of agriculture[13]. Automated tractors can reduce the dependence on the labor force, maintain good operating conditions, and reduce overall maintenance costs in the long term[8,14].

At present, a variety of operational optimization methods for automated tractors have been proposed that include traction control[4,15-18], slip rate control[19-21] and fuel consumption optimization[22-25]. However, these studies were based on theoretical studies of the dynamics with the main purpose of exploring the impact of environmental parameters on the system and thus were not fully developed for use in practical control applications. Because of its intermediate role in transmitting the tractor's power to agricultural tools[26], control of the tractor electro-hydraulic hitch system provides one of the most direct and effective methods to improve the efficiency, quality, energy savings and economic benefits of these tractors[3]. However, control of this system is challenging because of the variations in the

Received date: 2020-09-23 **Accepted date:** 2021-02-08

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operating environment parameters and the multi-parameter control and comprehensive optimization requirements of automated tractors.

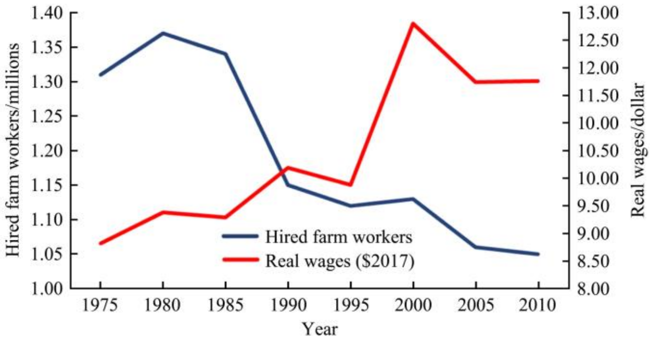


Figure 1 Hired US farm worker employment and real farm worker wages (1975-2010)[12]

2 Adjustment methods for tractor electro-hydraulic hitch system

Early mechanical hydraulic hitch systems were largely reliant on manual adjustment and the quality and efficiency of operation of these systems could not be guaranteed[27]. With the ongoing development of electronic technology, tractor electro-hydraulic hitch systems, which are highly integrated with hydraulic, electronic, sensing and control technologies, are currently gradually replacing mechanical hydraulic systems, and the system control mode has also changed from manual to electric[28,29].

Height control is the most commonly used adjustment method for traditional mechanical hydraulic hitch systems. With the application of electro-hydraulic hitch systems and the development of the associated control technology, draft control, position control, mixed draft-position control, and slip control methods have also appeared[29]; the characteristics of these methods are listed in Table 1[30]. Different adjustment methods have different effects on both the working environment and the tractor's performance parameters. Therefore, in implementation of the electro-hydraulic hitch control algorithm, it is necessary not only to switch the adjustment method but also to adjust the hitch state according to the operating parameters[31]. Multi-parameter adjustment can generally be combined with a variety of influencing factors and the weight distribution method can reduce the adverse effects of single-parameter adjustment; this has a positive effect in improving both the operating efficiency and the farming quality of the tractor. However, multi-parameter adjustment requires the support of a hardware system and the control of this system is complex.

Table 1 Parameter adjustment methods comparison[30]

Item	Draft control	Position control	Draft-position mixed control	Slip control
Purpose	To maintain tractor engine load steady	To maintain tillage depth consistent	To optimise engine load and tillage depth	To maintain high traction efficiency
Input	Traction draft	Tillage depth	Traction draft, tillage depth and coefficient	Traction draft, tillage depth and slip rate
Control mode	Single-Parameter	Single-Parameter	Multi-Parameters	Multi-Parameters
Application	General tillage	Shallow tillage, off-ground operations	All operation	All operation
Uniformity of tillage depth on different soil	Bad	Best	Good	Best
Uniformity of tillage depth on rough surface	Good	Bad	Best	Best
Engine load stability	Best	Bad	Good	Best
Traction efficiency	Good	Bad	Good	Best
Economy	Good	Bad	Good	Best

To realize automatic and intelligent control of the tractor electro-hydraulic hitch system, this paper summarizes the adjustment and measurement methods of tractor electro-hydraulic hitch systems. By combining these methods with the characteristics of the electro-hydraulic hitch system, the control strategies are divided into two categories. The first category is for control strategies based on the tractor's electro-hydraulic system, which refers to control of the hydraulic power components of the tractor's electro-hydraulic hitch system to enable adjustment of the operating parameters. The second category is for control strategies based on the tractor slip rate, which is used to ensure high traction efficiency and realizes hitch regulation by monitoring the tractor slip rate on the basis of electro-hydraulic system control. The implementation methods and control characteristics of the control algorithm required are discussed based on these two strategy types, and this provides a reference for automatic and intelligent control of the tractor electro-hydraulic hitch system. Finally, the research and development directions for electro-hydraulic hitch technology for intelligent agricultural machinery are presented.

3 Studies of tractor electro-hydraulic control strategy

Electro-hydraulic-based control systems have been widely applied by researchers because of their flexibility in receiving and sending control signals, their lack of both friction and hysteresis, their simple displacement and force measurement capabilities, and their self-diagnostic troubleshooting assistance ability[11], which provides a basic and direct way to maintain optimal tractor performance in different operating environments[18]. Based on an analysis of the tractor hitch parameter measurement methods, which provide the required foundation to achieve precision control, the electro-hydraulic control strategy is summarized in this section.

3.1 Measurement methods of tractor hitch parameters

3.1.1 Draft measurement

The draft is the resistance force acting between the soil and the implement during tractor operation. Three methods are used to measure the draft: upper links measurement method, lower links measurement method and dynamometer-based measurement method. These measurement methods are illustrated in Figure 2.

In upper links measurement method, a force sensor, which is generally a strain gauge-type transducer, is used to attach the upper links to the implement. Wang et al.[32,33] and Chen[34] used this method to achieve draft measurements. This approach uses a simple structure, but the weight of the implement and the vertical force between the soil and the implement have a major impact on its accuracy[35].

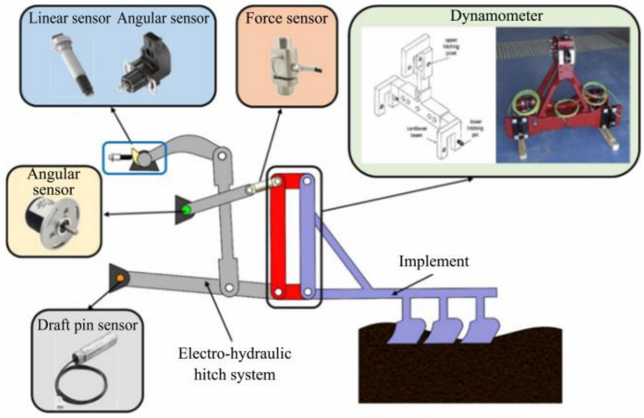


Figure 2 Schematic illustration of the installation of sensors for measurement of tractor hitch parameters

In lower links measurement method, a draft sensing pin is used to attach the lower links to the implement. The output is an electrical signal that is proportional to the shear stress experienced by the surface of the pin. The shear stress is measured using the internal pin electronics, which senses a subtle change in the magnetic permeability of the surface material. The draft pin that was developed by Bosch is widely used because of its high accuracy and sensitivity[27,36-41]. In addition, Gao et al.[42] developed mathematical models of the upper and lower links measurement method. Their simulation results showed that both of these methods cannot eliminate the error caused by gravity acting on the implement, but the absolute error of lower link measurement was smaller than that of upper link measurement. Therefore, lower link measurements should be used to improve the accuracy.

A dynamometer can measure the vertical force, the horizontal force, and the resultant force for a tractor hitch system using multiple force sensing elements to build a space force matrix. Green et al.[43] measured the draft using a proving ring load cell mounted on the front end of an existing drawbar. This load cell consisted of a full Wheatstone bridge assembly with a 35 Ω gage located with the proving ring to maximize the effects of the axial forces and minimize the effects of the bending moments. Similarly, Al-Suhaibani et al.[44], Al-Jalil et al.[45], and Roca et al.[46] developed an easily adaptable dynamometer based on a two-frame configuration where the two frames were linked using six independent connecting rods with ball joints at their ends. The pin force sensors were located at one end of each connecting rod to ensure that the force at one rod was not affected by the forces at the other rods. A mathematical model was established to evaluate the accuracy and the disruptive effects of the dynamometer and a prototype were constructed to carry out field tests.

3.1.2 Tillage depth measurement

Tillage depth refers to the depth of implements into the soil, which is important for the control of electro-hydraulic hitch system. Tillage depth can be measured by indirect measurement approaches. Chen[34], Xie[35], and Shen[38] mounted angular sensors on the rock shaft to sense the rotation angles of the upper links and then calculated the depth based on the kinematic relationship between the upper link and the implement (Figure 2). This method offers simple sensor installation and high accuracy. However, it is necessary to obtain the structural parameters of the agricultural implement in advance to construct the kinematic relationship required. In addition, there is another way to measure the tillage depth: a rocker rotation mechanism was designed to convert the angle of rotation into the linear displacement (Figure 2). This structure, which provides good linearity and can eliminate the adverse effects of vibration, was used by Bhondave et al.[26], Macqueene et al.[36], Orbach[37], Guo[40], Lu et al.[41], and Xu[47]. In addition, Lee et al.[48,49] noted that the tillage depth can be calculated based on the lift arm angle, the pitch angle of the tractor, and the heights of the sensors from the ground surface. They, therefore, proposed a foresight control system in which ultrasonic sensors were used to detect the tractor height and angle sensors were used to detect the lifting and pitching angles. Their experiments were conducted in an actual field to evaluate the adaptability of the control system; the results demonstrated that the control system produced a better performance than that of the non-foresight control or no control cases, and indicated that the engine speed parameter should be considered to construct a more accurate control system in a follow-up study.

3.2 Electro-hydraulic control method

Several control strategies have been suggested by previous researchers to control the draft or the depth of the mounted implement during tillage operations. These strategies can be classified into three main groups based on use of closed feedback controllers, proportional-integral-derivative (PID) controllers and intelligent controllers. The control strategies, implementation of the algorithm and analysis methods are described in detail below.

3.2.1 Closed feedback controllers

The closed-feedback controller serves as the foundation for tractor electro-hydraulic control. At this stage, the basic principle of the electro-hydraulic control algorithm was formed: the hydraulic system of the tractor raises or lowers the implement within the soil based on the feedback signals acquired from the draft and tillage depth sensors, as shown in the schematic illustration in Figure 3.

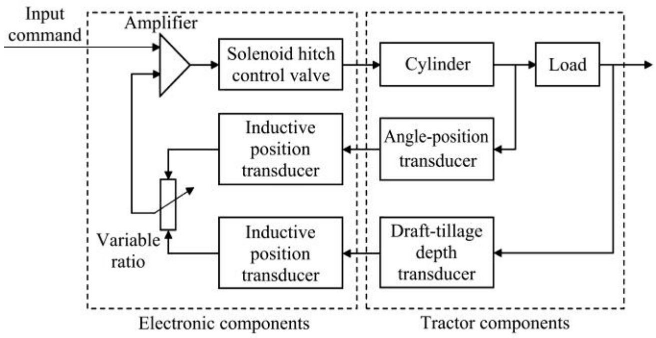


Figure 3 Schematic illustration of the closed-feedback control system[50]

Hobbs et al.[50] developed a hitch control system in which the required parameters were input through the control panel; the parameters included the draft or tillage depth control ratio and the sensitivity coefficient. To realize the desired reaction from the system, the measured values can be mixed in a variable ratio ranging from 100% draft control to 100% depth control and the response time can also be adjusted by multiplying the sensitivity coefficient by the feedback signal.

Dobrinska et al.[51] noted that radio frequency interference was a problem with application of the control system and this interference must be eliminated via meticulous circuit design. In addition, appropriate shielding of all connecting cables was also required. Orbach[37] improved the control system that had been developed by Dobrinska et al.[51] and extended the hitch control functions to include the position state, the draft state, the switch-up state, and the momentary state. Field test results showed that their control system could follow the terrain in a variety of environments, which is very helpful in improving the quality of operations. However, the test data indicated that the stability and accuracy of their system needed to be improved.

Macqueene et al.[36] first proposed an engine load sensing technique for automotive draft control for the Ford New Holland agricultural tractor. In this technique, the engine load was calculated based on the engine's governor characteristics by comparing the no-load engine speed to the actual engine speed.

Application of the electro-hydraulic control system represented an important step toward improved tractor automation, but the system still required manual operation. When compared with mechanical control, the closed feedback controller obviously provided a better performance. However, the controller's processing speed was limited by the development status of the required electronic technology, which resulted in poor real-time performance. In addition, the control characteristics of the algorithm could not be analyzed quantitatively, which meant that the adaptability and the stability of the algorithm could not be verified or optimized.

3.2.2 PID controllers

Tractor electro-hydraulic hitch control was realized by controlling the electro-hydraulic servo valves, so the essence of this method is control of the hydraulic components[30]. Therefore, the controller's characteristics can be analyzed and optimized by establishing the transfer function of the hydraulic system, which is also a required process for PID controller optimization. According to the studies of Pang et al.[28], Xie et al.[31], Xie[35], Li[52], and Zhu et al.[53], the general transfer function of the tractor's electro-hydraulic system is shown by Equations (1) and (2). Equation (1) represents the transfer function between the displacement of the end of the hydraulic cylinder and the spool position; Equation (2) represents the transfer function between the displacement of the end of the hydraulic cylinder and the external loading force. From these transfer functions, it can be seen that the factors that affect the displacement and the external loading force of the cylinder are the hydraulic pressure, the properties of the oil, the system leakage, the specifications of both the hydraulic valves and the cylinders, and the load force characteristics[30,54]. Figure 4 shows a schematic of the position control approach that combines a PID controller and a transfer function and this approach can be used to analyze the stability, the response characteristics, the dynamic and static errors, the anti-interference ability and the nonlinearity of the electro-hydraulic hitch system. The notations used in Equations (1) and (2) are described in the nomenclature given in Table 2.

$$\frac{Y(S)}{X_v(s)}=\frac{K_q/A}{\frac{MV_t}{4\beta_e A^2}s^3+\left(\frac{MK_{ce}}{A^2}+\frac{B_m V_t}{4\beta_e A^2}\right)s^2+\left(1+\frac{B_m K_{ce}}{A^2}+\frac{KV_t}{4\beta_e A^2}\right)s+\frac{KK_{ce}}{A^2}} \tag{1}$$

$$\frac{Y(S)}{F_L(s)}=\frac{-K_{ce}\left(1+\frac{V_t}{4\beta_e K_{ce}}S\right)}{\frac{MV_t}{4\beta_e A^2}s^3+\left(\frac{MK_{ce}}{A^2}+\frac{B_m V_t}{4\beta_e A^2}\right)s^2+\left(1+\frac{B_m K_{ce}}{A^2}+\frac{KV_t}{4\beta_e A^2}\right)s+\frac{KK_{ce}}{A^2}} \tag{2}$$

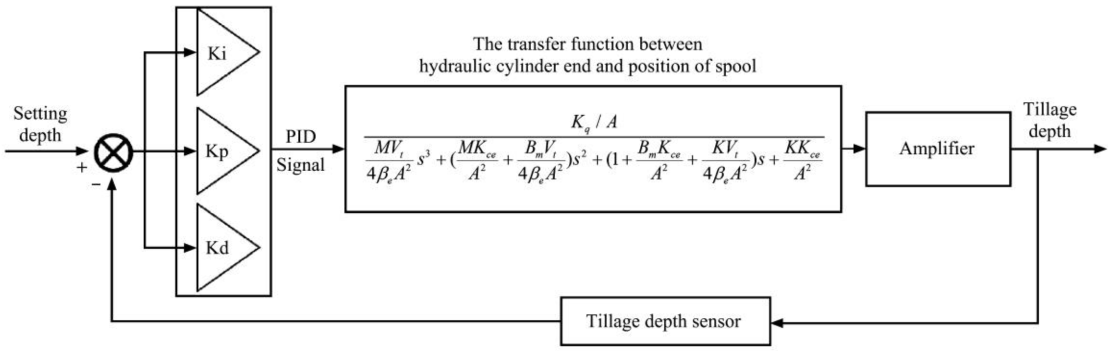


Figure 4 Schematic of PID controller based on the transfer function

Table 2 Nomenclature for equations

Symbol	Description	Unit
P_L	Pressure of the hydraulic cylinder	Pa
A	Area of hydraulic cylinder	m^2
y	Hydraulic cylinder position	m
M	Inertia mass	kg
B_m	Viscous co-efficient of fluid	N s/m
K	Spring constant	N/m
F_L	External load	N
β_e	Bulk modulus of oil	Pa
V_t	Fluid volume	m^3
C_t	Leakage co-efficient of the hydraulic cylinder	m^3/(s·Pa)
q_L	Inlet flow to the hydraulic cylinder	m^3/s
x_v	Spool position	m
ρ	Density of oil	kg/m^3
c_d	Valve discharge flow co-efficient	
K_q	Valve flow co-efficient	
K_c	Valve pressure co-efficient	
K_{ce}	Total leakage co-efficient	$K_{ce}=K_c+C_t$

In the study of Xie[35], the Fiat 780 tractor was reformed to realize PID control of its electro-hydraulic system. Based on Equation (2), the tractor's draft control characteristics were analyzed using Matlab. The scale factor Ka of the amplifier was obtained via system continuity analysis and was in the range from 0.1 to 43; the stability margin of the system was 8.5932 dB with Ka being equal to 5; and in the time domain analysis, the system's response time was 1.085 s and the steady-state error was 1.5%, which indicated the good performance of the controller. An electro-hydraulic PID control system was then developed based on a single-chip microcomputer and was tested in the laboratory. The results obtained were similar to the simulation results, thus demonstrating that the transfer function is accurate. This study presented the complete process of analysis, development and testing of electro-hydraulic PID control of the tractor, but field tests were required to verify the reliability of the proposed system.

Zhu et al.[53] used Matlab to analyze an electro-hydraulic hitch system based on a PID position control strategy. The transfer function was established based on the DF-354 tractor (DFAM, China) and the system characteristics when using no controller, a proportional controller (P), a proportional-integral controller (PI), a proportional-differential controller (PD), and a PID controller were simulated and compared. Finally, the system characteristics were determined as follows: rise time: 0.0298 s; adjustment time: 0.179 s; and static error: 0. This study acted as a reference work for optimization of the tractor's electro-hydraulic control system. However, the study only analyzed the system based on the premise of its hydraulic transfer function, without considering the interference in real situations.

Anthonis and co-workers performed a study of an automatic position control system for online measurement of the spatial variation in the soil compaction of tractors. Mouazen et al.[55] presented the development of a model to calculate the soil compaction, which was indicated as dry bulk based on the measured draught of a subsoiler, the soil moisture content and the soil depth using the signal output from a depth sensor. The behavior of the tractor-subsoiler combination was modeled using a mixed 'grey-box' physical model described in Saeys et al[56]. Using a semi-analytical model multiplied by a conversion factor, a proportional (P) controller, a lead compensator, a PID controller and a PID controller with a filtered derivative (D), the required actions were designed in Anthonis et al[57]. All controllers provided satisfactory results and depth changes were controlled to within 10 mm, but the controller was weak in terms of its anti-interference ability and was easily affected by environmental parameters. This study provided a method to analyze the control system's characteristics by combining the kinematics equations with a transfer function. The tractor body angle was used to control the depth, but the field experiments showed that the PID controller is less robust.

3.2.3 Intelligent controllers

The controller of a tractor is typically a nonlinear system with random factors and a variable working state during tractor operation, and it is thus difficult to develop a mathematical model of such a controller[29,58]. PID controllers provide poor performance for nonlinear systems, thus leading to poor adaptability in field tests. The fuzzy controller and the fuzzy-PID controller are intelligent algorithms based on logical reasoning and thus demonstrate better performance in the control of nonlinear systems.

Wang[33] and Chen[34] developed a tractor electro-hydraulic fuzzy control system for draft control based on the C51 single-chip controller. A hydraulic computer-aided test platform was used to analyze the dynamic and static draft control performances. The step response time of the control system was 1.6 s and the interference signal can be self-adjusted to within 0.6 s, which indicated that the control system was both stable and fast. Based on their studies, a draft-position mixed control strategy based on a fuzzy controller was proposed by Guo[40] and by Han et al.[59] that included the draft, the depth, and the draft-position mixed ratio. The draft was converted into a depth based on the soil resistance theory, and then the mixed depth was calculated using the draft-position mixed ratio. A schematic of this strategy is shown in Figure 5. The laboratory tests conducted by Guo[40] showed that the response time required for the control system to adjust the depth from 0 to 20 cm was 1.7 s and the static error was ±1 cm. Using a Jinma 1204 tractor, an electro-hydraulic hitch prototype was constructed by Han et al.[59] and draft-position control experiments were performed in the field. The results showed that the static error for the depth was less than ±2 cm and the response time was 4.8 s. The large difference between the laboratory and field test results in terms of their response times was caused by the complex environment. However, it is obvious that the stability of the control system was improved by use of the draft-position mixed control strategy based on the fuzzy controller. However, because this control system used an 8-bit single-chip controller, the processing speed for fuzzy control needed to be improved. Additionally, the use of a controller area network (CAN) bus should be promoted so that the status signals of the whole machine can be monitored and controlled comprehensively.

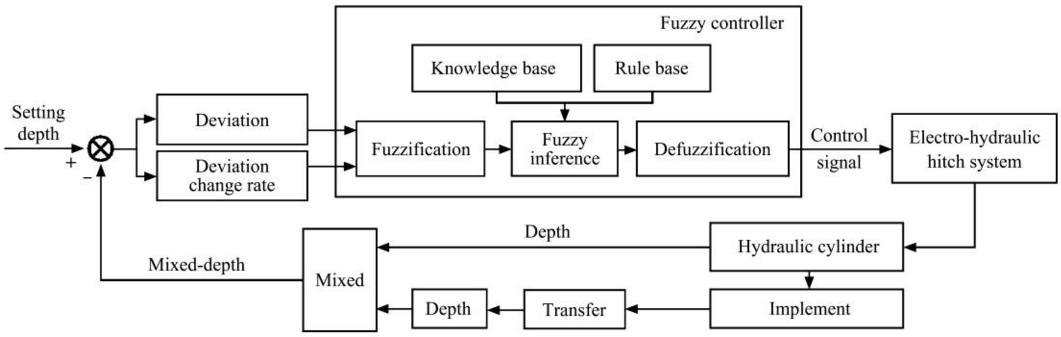


Figure 5 Schematic of draft-position mixed control strategy based on fuzzy controller[59]

Performance comparisons between the PID controller and the fuzzy controller were conducted by Tan[30] and by Gao et al[60]. When compared with PID controllers, fuzzy controllers have an obvious advantage in that they do not need to build mathematical models of the control systems. Based on Xie's study[35], Tan developed a PID controller and a fuzzy controller for the tractor electro-hydraulic system. Simulations and indoor experiments showed that the PID controller provided high accuracy, but that it was unstable; the fuzzy controller kept the hydraulic pump in the unloaded state when the deviation was small, which can save energy, but it had a static error. The energy consumption control mentioned in this study was only in terms of a theoretical analysis and was not realized in practice. In addition, field test validation was required. Gao et al.[60] compared the two controllers through field experiments. Their results showed that the error of the fuzzy controller was 2 cm while the PID controller had a large overshoot, which demonstrated that the fuzzy controller is more stable than the PID controller. However, the effects of surface irregularities and changes in the soil density were not analyzed during their experiments.

Shafaei et al.[11] developed a fuzzy depth and draft control system for tractor-implement. In their study, the forward speed was considered as an influencing factor. The fuzzy controller consisted of an electrical sensing device, a controller, and an electro-hydraulic actuator unit, and a command set that included four fuzzy rules was programmed for the controller unit. Field experiments were performed at three plowing depth levels (10 cm, 20 cm and 30 cm), three forward speeds (2 km/h, 4 km/h and

6 km/h), and with three implementation types (moldboard, disk, and chisel plow) while using the system mounted on a tractor (MF-399, ITM, Iran) to determine the merits of the system. The results showed that the system increased both the tractive efficiency and the overall energy efficiency up to 20% and 73%, respectively, while the plowing depth error, the driving wheel slip, and the fuel consumption decreased by up to 53%, 34% and 34%, as shown in Figure 6. This study showed that the performance of the fuzzy control system was not sensitive to either the implement type or the plowing depth, although it was influenced by the forward speed.

Li et al.[61] designed a fuzzy-PID controller to achieve both draft and position control of the tractor electro-hydraulic system. The draft deviation signal and the change rate of the deviation signal were input into the controller and the new PID parameters were then calculated using the fuzzy controller. The control signal was then output via the new PID controller. The schematic of draft control base on Fuzzy-PID controller is shown in Figure 7. The performance of the proposed fuzzy-PID controller was verified in both simulations and field tests. In the position control mode, the response time of the controller in the simulation was 4.5 s without overshoot, while in field tests, the response time was 4.0 s without overshoot; in the draft control mode, the response time of the controller in the simulation was 5.2 s with a small overshoot, while in field tests, the response time was 5.0 s with a 25% overshoot. The reason for this large overshoot is the hysteresis of the soil parameters and the forward speed, which will both affect the draft. Therefore, in the design process for the electro-hydraulic control system, the effects of both the soil and the tractor operating parameters must be considered.

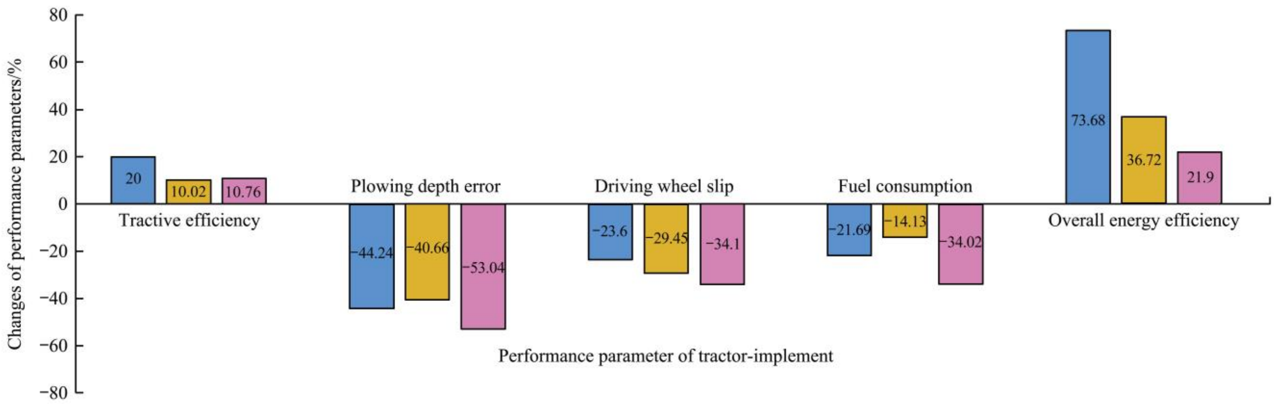


Figure 6 Changes in performance parameters of tractor implement during tillage operations when affected by application of the fuzzy control system rather than the draft control system of the tractor[11]

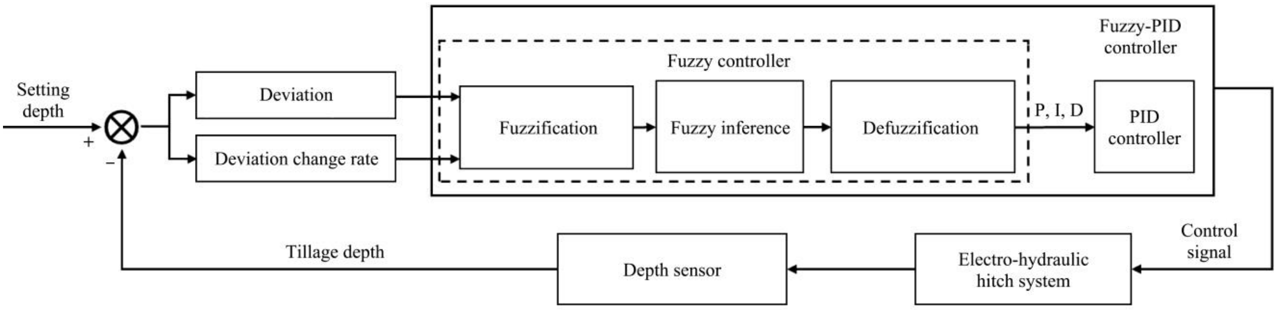


Figure 7 Schematic of draft control strategy base on Fuzzy-PID controller[61]

A novel control method proposed by Lyu[62] was able to adjust the mixed coefficient automatically according to the draft to prevent the tractor from exceeding the rated load during operation, which is similar to the approach of Guo[40]. When the tractor started to operate, the initial value of the mixed coefficient was 1, and the system would then check whether the draft was within the optimal working range. If the draft exceeded this range, the controller would then automatically reduce the mixed coefficient to reduce the draft until the draft was within the required range; otherwise, the mixed coefficient would remain unchanged. Software called the Advanced Modeling Environment for performing Simulation of Engineering Systems (AMESim, Siemens) was used to build hydraulic component models and hydraulic circuits. A co-simulation of the controller using AMESim and Matlab was conducted to compare the performances of the PID controller and the fuzzy-PID controller. This study provided a new method to analyze the electro-hydraulic system, but some of the parameters of the hydraulic components were difficult to obtain, which led to errors in the simulation. Second, the simulation model and the controller were not tested, meaning that the system's reliability and accuracy must still be verified.

Another novel electro-hydraulic hitch control system based on a CAN bus and a back propagation (BP) neural network was developed by Xi et al[63,64]. Based on a previous study by Guo[40] and Han et al.[59], a draft-position mixed control method with variable weight was proposed. The BP neural network adjusted the mixed ratio based on the draft and the tillage depth. The BP neural network included one input layer, one output layer and one hidden layer, and the numbers of nodes for each of these layers were two, one, and fifteen, respectively. The sigmoid function was used as the activation function. After training and verification, the results showed that the average error for output of the mixed ratio was 0.08%. The control system was then developed based on the CAN bus, and preliminary functional verification of this system was performed using a hydraulic test platform. There were two concerns about this study. First, many factors can affect the control characteristics of the system, including the soil, the forward speed, and the slip rate, but this study only considered the effects of the draft and the tillage depth, which will affect the accuracy of the mixed ratio. The neural network input layer should thus be extended to include the relevant factors. Second, this control system was not integrated into the tractor electro-hydraulic system. However, it should be noted that this study was an exploration for future tractor electro-hydraulic hitch control systems.

3.3 Summary of tractor electro-hydraulic control

To date, numerous studies on tractor electro-hydraulic hitch control have been conducted and many control methods have been proposed, not only illustrating the difficulty involved in implementation of different control algorithms and differing requirements for the hardware but also providing references and for the development of the automated tractor.

Although the closed-feedback controller has a simple structure, its control characteristics cannot be analyzed quantitatively in real applications and its adaptability must also be verified. The PID controller is widely used in tractor electro-hydraulic control because of its simple and accurate characteristics, while the transfer function of the tractor electro-hydraulic system was also established to optimize the system characteristics. Although the PID controller has demonstrated better performance in both simulations and laboratory experiments, field tests showed that the PID controller is weak in terms of its anti-interference performance and that it is easily affected by the environment. There are two reasons that lead to that conclusion: the fixed parameters of the PID controller are not suitable for nonlinear systems[65]; in addition, environmental interference is not considered during the simulations. In view of the complex conditions required for tractor operation and the inaccurate mathematical model, better performance in hitch control, an improved anti-interference ability, and elimination of the mathematical modeling steps can be achieved using the intelligent controller, and particularly the fuzzy-PID controller and the neural network. Field experiments indicated that the intelligent controller can adapt to complex operating conditions and improve both the efficiency and the quality of tractor operation. However, the research for the application of the intelligent controller to tractor electro-hydraulic control is still at the preliminary exploration stage and it will be necessary to enable promotion of this technology.

4 Study of tractor slip control strategy

The slip rate is used to evaluate the traction wheel slippage that occurs during the vehicle driving process and represents one of the most significant parameters to influence the tractor's traction efficiency and power consumption[15,16]. For tractor traction control, Sunusi et al.[4] summarized the process of and method for online traction control from a dynamics perspective. To ensure the quality of the operation, traction efficiency maximization and power minimization, slip rate control must be realized on the basis of the electro-hydraulic control.

4.1 Measurement methods for tractor slip rate

One common method that is used to calculate the tractor slip rate is based on the theoretical and actual speeds of the tractor. The theoretical speed is easy to obtain and many of the methods used were mentioned in previous studies, including use of photoelectric sensors, Hall sensors, laser sensors, infrared sensors, and magnetoelectric sensors. However, it is difficult to measure the actual speeds of a tractor accurately because of slippage or jumping that can occur during operation[21,66]. A comparison of the common forward speed measurement methods used in previous studies is listed in Table 3.

Table 3 Comparison of speed measurement methods

Methods	Principle	Advantages	Disadvantages	Reference
Fifth wheel	Actual speed is calculated by using output signal of the encoder mounted on the fifth wheel dragged by tractor	1. Simple structure 2. Easy to operate 3. Low cost	1. Easily affected by environmental factors 2. Larger error	Shafaei et al.[11,67]; Al-Suhaibani et al.[68]
Non-driving wheel speed	Use non-driven wheel linear speed approximation the actual speed.	1. Simple structure 2. Low cost	1. Errors occur when tractor non-driven wheels slip 2. Limited accuracy	Raheman et al[69]; Al-Suhaibani et al.[44]; Pranav et al.[70,71]; Kumar et al.[72]; Kumar et al.[73]
Doppler effect velocimetry	Actual speed is obtained by calculating the frequency difference between the transmitted signal and the reflected signal wave based on doppler effect (Ultrasonic sensors, radar sensors, GPS).	1. High accuracy 2. Easy installation	1. The accuracy is influenced by environmental conditions (stubble coverage, dust, crop motion, and wind) 2. High cost	Wan Ismail et al.[22]; Imou et al.[74,75]; Keskin et al.[76]; Chosa et al.[77]; Pexa et al.[78]; Zhang et al.[79]

4.2 Slip control methods based on electro-hydraulic control

As a multi-parameter control method, slip control is divided into slip-draft control and slip-position control. The essence of the slip control strategy is to control the electro-hydraulic hitch system according to the slip rate. When the slip rate is within a set threshold range, the control system will remain in its original state; if the slip rate is below the threshold, the hitch system will then be moved down (to increase the tillage depth) until the slip rate moves back to the threshold; in contrast, the reverse action (to reduce the tillage depth) will be taken by the system when the slip rate exceeds the threshold. In this way, the operational efficiency and quality can be improved[79,80]. A flow chart of the slip-draft control procedure is shown in Figure 8.

The slip-draft control method is based on draft control while simultaneously monitoring the slip rate to achieve dual adjustment of the draft and the slip rate. This method can keep the load characteristics of the engine in a stable state with the aim of ensuring the tractor's efficiency. Similarly, the slip-position control method is based on position control while simultaneously monitoring the slip rate to achieve dual adjustment of the tillage depth and the slip rate. This approach can improve the tillage depth uniformity based on the high traction efficiency of the tractor.

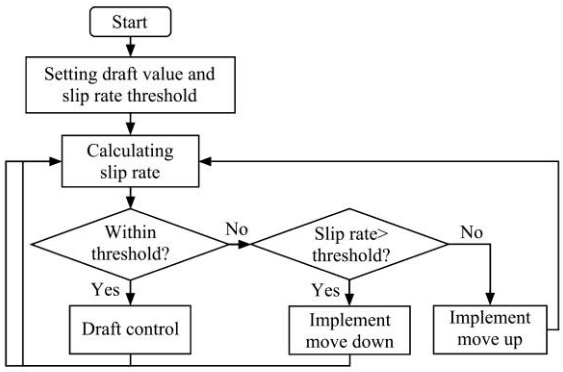
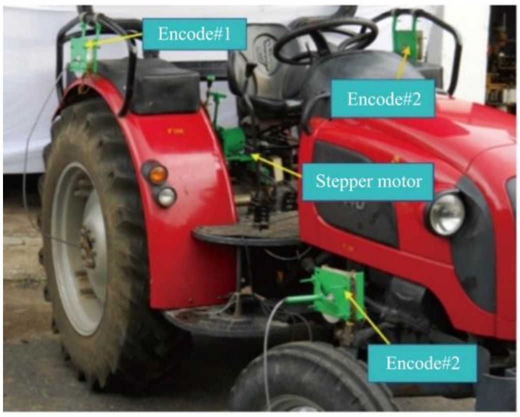


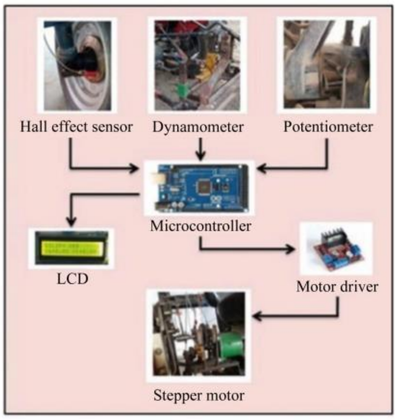
Figure 8 Flow chart of slip-draft control procedure

Kovačev et al.[81] tested the EHC (Electro-hydraulic Hitch Control) system developed by Bosch Rexroth on a tractor. When compared with the existing mechanical hydraulic control system, the slip rate achieved using the EHC system is reduced by 7%-30%, the energy consumption is reduced by 2%-3%, and the work efficiency is improved by 3.4%-3.8%. Although this study is simply a validation of the EHC system, it serves as a reference for slip control studies.

Pranav et al.[70,71] designed and developed a microcontroller-based automatic wheel slip control system for a two-wheel drive (2WD) tractor (Figure 9a). This system measures the slip rate continuously under field conditions and generates commands for depth adjustment if the wheel slip falls outside the desired range. The slip rate was calculated by measuring the rotational speeds of the front and rear wheels and a stepper was then used to operate the hydraulic control lever to adjust the depth. Field tests showed a significant reduction in fuel consumption per hectare (by 20%-30%), an increase in field capacity (by 7%-38%), and a gain in tractive efficiency (from 4% to 10%) when using the slip control system versus the existing draft control system. Similar to the work of Pranav et al.[70], Gupta et al.[80] also developed an automatic slip-draft control system that could measure and control the slip rate and draft synchronously. Hall sensors were used to obtain the actual and theoretical speeds (Figure 9b). This novel intelligent slip-draft control system can ensure that the slip and the draft remain within a set range, which led to improvements in the tractive performance of 9.17% and 6.05% during ploughing and harrowing, respectively. Although the use of the stepper motor to control the hydraulic control lever provides a simple way to achieve hitch control, the accuracy and speed of this approach are poor. In future research, it will be necessary to combine slip control with electro-hydraulic control.



a.



b.

Figure 9 Overview of the installed encoders and the stepper motor on an agricultural tractor (a)[70] and flow chart of the developed embedded system (b)[80]

Zhang et al.[79] developed a slip-draft control system based on a PID controller that used radar and an encoder to calculate the slip rate. A mixed control strategy was developed using the Freescale MC9S12XS128 controller, and the schematic diagram is shown in Figure 10. Field experiment results showed that the mixed control algorithm could reduce the tillage depth and draft errors by 31.96% and 36.54%, respectively. The slip rate fluctuation range was also reduced by 41.71%. However, the experiments showed that the stability of the control system was poor, indicating that the PID controller was disturbed by the operating environment.

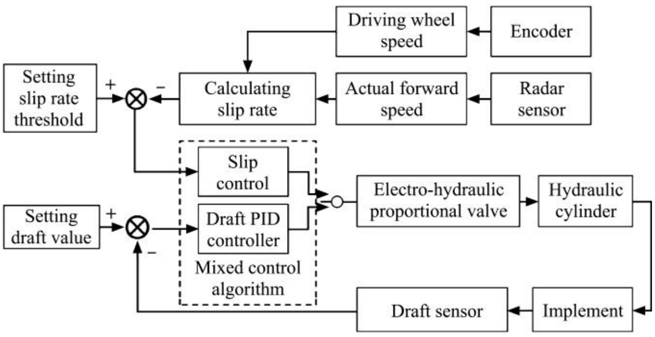


Figure 10 Schematic diagram of the slip-draft control method[79]

A fuzzy controller to control the tilling depth of a tractor based on the slip rate was developed by Bai et al.[82,83]. The performances of PID, fuzzy and fuzzy-PID controllers were simulated using Matlab/Simulink. The results showed that the fuzzy and fuzzy-PID controllers were more suitable solutions than the PID controller, but the fuzzy-PID controller required more variables and seemed to be more complex; a fuzzy control system was developed based on the Freescale MC9S12XS128 controller, which can achieve slip-position control. The laboratory experiments were conducted on a hydraulic loading platform and the step response, the anti-interference ability, and the adaptability of the system were tested; the results demonstrated the good performance of the system. However, the method needed to be tested in a real outdoor environment and improvement of the model was also required to enable it to handle complex terrain.

4.3 Summary of tractor slip control

In a multi-parameter control strategy, it is necessary to measure and control a variety of tractor parameters synchronously during tractor operation to optimize traction efficiency. At present, the proposed slip control strategy is essentially an auxiliary monitoring method; in contrast, the electro-hydraulic system control strategy represents the main control method, which performs lifting and lowering of the hitch system to control the slip rate. Additionally, most studies of the control of the slip rate were implemented using stepper motors to operate the hydraulic control lever and the tractor electro-hydraulic system was not integrated into the control algorithm. In terms of control system implementation, there is no data fusion, while integration control of the traction efficiency and the slip rate is still in its infancy. Therefore, data fusion should be regarded as the research objective in the next stage of development.

5 Future research directions

Although some progress has been made in the automatic and intelligent control of tractors along with the development of electro-hydraulic hitch control technology, the adaptability of the control strategy and the fusion of the control parameters still require further study; this is particularly true from the perspective of the popularization of the control technology, which is still in its initial stages. Therefore, this paper proposes the following research directions for tractor electro-hydraulic hitch control technology development.

5.1 Fusion control strategy

An automated tractor is required to realize automatic adjustment and optimization of its operational efficiency, operational quality and energy consumption. At present, the focus for electro-hydraulic control is on improvement of the operational quality and efficiency, while the focus for slip rate control is to ensure the traction efficiency. However, in general, regardless of which strategy is adopted, operational performance parameters such as the engine load, the fuel consumption rate and the real-time traction efficiency have not been introduced during the control algorithm development process, which has resulted in a weak comprehensive optimization performance during operation. Xie et al.[84] proposed that the function of future automated tractors should be to monitor and optimize the parameters of the entire machine, so the fusion control strategy represents a key development goal for future suspension control and even entire machine control based on a CAN bus[85].

5.2 Application of intelligent algorithms

With the widespread penetration and application of the new generation of artificial intelligence technology, a new exploration of the automatic and intelligent control of agricultural machinery has also begun. Intelligent algorithms such as fuzzy PID, artificial neural networks, and genetic algorithms can adapt well to the control of nonlinear systems and can achieve system control through comprehensive decision-making. The research of Xi[63] indicated the possibility of application of neural networks to the electro-hydraulic control of tractors, which would also benefit from the neural network realization mechanism; the neural network can make decisions based on multiple input parameters to achieve optimal control and is also one of the methods that could realize the fusion control strategy. The intelligent control algorithm puts forward higher requirements not only on the control system, but also on the reliability design of mechanical, hydraulic, and electronic. These issues should be considered in the integration, promotion and application[86,87].

5.3 Test verification

To realize automatic and intelligent control of a tractor, the robustness, speed, adaptability and comprehensive performance of the control system must all be considered. Many simulation and optimization methods are available that can be used to adjust the control parameters during design of the control algorithm and the optimal control effect can also be obtained. However, it is really important to test and verify the control performance during actual operation of the vehicle because of the major differences between the actual field conditions, the simulation parameters and the laboratory environment, and this is the aspect that requires further consideration in most of the current research in this area. Furthermore, Sunusi et al.[4] pointed out that a standard method should also be developed to serve as a benchmark for the performance of the various control algorithms.

6 Conclusions

This paper provided a review of electro-hydraulic hitch control technology in automated tractors. Based on the adjustment methods used for the electro-hydraulic hitch, the control strategies are divided into the electro-hydraulic control strategy and the slip control strategy.

6.1 Tractor electro-hydraulic control strategy

1) Closed feedback serves as the foundation for all the control algorithms. However, its applicability is restricted, meaning that it cannot be applied under varying conditions and in different tractors.

2) The method used to establish the electro-hydraulic mathematical model, which can then be used to analyze and optimize the characteristics of the PID controller, is summarized. The PID controller can achieve draft and position control quickly, but it is weak in terms of its anti-interference ability.

3) The intelligent controller is demonstrated to be the appropriate future research direction because it provides better performance in the control of nonlinear systems, particularly when using the fuzzy-PID controller and neural networks. However, because this technology is still in its infancy, more testing in field-based experiments will be required.

4) In general, the existing research on electro-hydraulic control has not been applied to actual products to date, and the applicability of the control strategy still requires considerable research and verification.

6.2 Tractor slip control strategy

1) The slip rate measurement methods and the control strategy are summarized, and the most common method used to calculate the slip rate is based on use of an encoder, while the most effective and accurate method involves use of the Global Positioning System (GPS).

2) Because this is a multi-parameter control strategy, it is necessary to measure and control the slip rate and hitch parameters synchronously. However, at present, the slip control method is still a switch control method and is discrete. Stepper motors are used to control the lever, but the resulting control method is both basic and unreliable. In addition, the electro-hydraulic control has not been integrated with the slip control to date.

3) For slip control, the primary focus of the research is on limitation of the slip rate within an optimal range via control of the electro-hydraulic hitch system. The strategy required for fusion of the other system information, such as the traction, fuel consumption and engine load data, has not been developed to date but will be highly significant for the automated tractor.

4) The future research directions of automated tractors based on the use of electro-hydraulic hitch control technology have also been proposed. These suggestions have the potential to direct even more research and development toward the development of automated tractors.

Acknowledgements

This work was financially supported by the Thirteen Fifth National Key Research and Development Program of China (Grant No. 2016YFD0700102); National Natural Science Foundation of China (Grant No. 31801783), and China Scholarship Council.

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