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Optimization and Analysis of Agricultural Robot Drive Systems

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Abstract. This study takes the agricultural robot drive system as the research object and carries out optimization research from two dimensions: mechanical structure and intelligent control. At the mechanical level, redundant degrees of freedom are eliminated through topological analysis of mechanism freedom, a 'short-chain direct-drive' transmission scheme is introduced to reduce mechanical losses, and finite element topology optimization is combined to achieve lightweight design of key components. At the control level, artificial intelligence is introduced to establish a perception system based on convolutional neural networks (CNN) and multi-source information fusion, enabling accurate recognition and prediction of complex terrain. A Back Propagation (BP) neural network Proportion Integration Differentiation (PID) control strategy based on the Dung beetle Optimization (DBO)algorithm is proposed, which effectively addresses the shortcomings of traditional algorithms, such as slow convergence and large overshoot. Meanwhile, model predictive control and an improved soft actor-critic reinforcement learning algorithm are integrated to achieve online adaptive regulation of drive parameters and global optimal control to a considerable extent. The optimized drive system effectively improves the working performance and environmental adaptability of agricultural robots in complex terrain and provides new theoretical and technical ideas for the development of intelligent agricultural machinery.

Keywords: Agricultural robot, drive system, structural optimization, neural network control optimization

1. Introduction

Against the background of global agricultural modernization and the rapid development of smart agriculture, China's agriculture is transforming from 'experience-driven' to 'data-driven' and from 'mechanization' to 'intelligence.' Intelligent agricultural equipment has become a key support for transforming agricultural production modes, improving operational efficiency, and ensuring food security [1]. Agricultural machinery faces challenges such as complex working conditions and variable loads in the actual operation process. Traditional control methods are difficult to adapt to complex operating environments [2]. For example, the problems of complex terrain, large load fluctuation and poor working environment are becoming more and more prominent. The existing agricultural robot drive system is difficult to meet the actual production needs, and there are obvious

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deficiencies in practical applications: for example, most drive systems have weak environmental adaptability; the mainstream motor drive scheme has problems such as untimely power feedback, unreasonable matching of motor and reducer, and poor coordination of transmission coordination, resulting in low transmission efficiency and high energy consumption. The mechanical structure layout and degree of freedom configuration do not fully consider the field operation characteristics, and the control mode is relatively single, which is difficult to adapt to the agricultural production needs of different regions, different crops and different working conditions in China. The above technical bottlenecks restrict the operation quality and promotion scope of agricultural robots, and it is urgent to carry out targeted optimization research.

This study takes agricultural robots as the research object and focuses on the optimization of the mechanical structure and control system of the drive system. Through structural optimization and neural network control optimization, this study addresses, to a considerable extent, the problems of low precision, poor stability, and insufficient adaptability in traditional drive systems, and proposes constructive new ideas and methods for the design of agricultural robot drive systems.

2. Optimization of mechanism degrees of freedom and transmission system layout

To address the problem of unreasonable degree-of-freedom configuration, the motion degrees of freedom of the robot walking and working mechanisms are analyzed, and the optimal degree-of-freedom layout is determined according to task requirements. By eliminating redundant degrees of freedom and supplementing key degrees of freedom, the driving mechanism can simplify the structure and reduce the control coupling while meeting the operation requirements. This paper use the kinematics equation of the multi-degree-of-freedom manipulator to study the motion relationship between the various links of the manipulator [3], and the degree of freedom calculation formula is:

$$F = 6n - 5\mathrm{P}_5 - 4\mathrm{P}_4 - 3\mathrm{P}_3 - 2\mathrm{P}_2 - \mathrm{P}_1 \tag{1}$$

where F represents the degree of freedom of the mechanism, n represents the number of active components in the mechanism, $\mathrm{P_k}$ represents the number of k-level kinematic pairs, and k is the number of constraints of the kinematic pairs. It can increase the degree of freedom of attitude adjustment for the walking mechanism, so that the machine can automatically adjust the body level on the slope and the concave and convex road surface, and improve the passing ability and operation stability. The joint arrangement and rotation range of the working mechanism are optimized to avoid motion interference and improve positioning accuracy. After the optimization of the degree of freedom, the robot drive system moves more flexibly, improves the field adaptive ability from the configuration design level, and lays a structural foundation for multi-scenario expansion.

To address the problems of low transmission efficiency and poor coordination in traditional agricultural machinery, the transmission structure of the drive system is innovatively reconstructed and its parameters optimized. A short-chain direct-drive transmission scheme is adopted, eliminating unnecessary transmission shafts, couplings, and intermediate gears. The motor output shaft is directly coaxially connected to the reducer input shaft, and the reducer output directly drives the walking or working mechanism, which can significantly reduce mechanical losses. In addition, studies have shown that, taking a vehicle wheel hub as an example, finite element analysis can be used to conduct topology optimization of key components such as the shell, support seat, and mounting plate, thereby reducing weight while ensuring stiffness [4]. The optimized transmission

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structure has faster response, lower vibration, and higher precision, which improves the stability of the drive system under complex terrain conditions at the hardware level and achieves simultaneous improvement in structural rationality and field adaptability.

3. Intelligent optimization of the drive control system

3.1. Introduction of intelligent control methods based on CNN and multi-source information fusion

On the basis of degree-of-freedom configuration optimization, convolutional neural networks (CNN) and multi-source information fusion are introduced to further enhance the stability and adaptability of the drive system in unstructured field environments. In the CNN architecture, real-time operating states are jointly considered to calculate and control mechanical tension, thereby completing the design of automated control software [5]. First, visual cameras, LightLaser Detection and Ranging (LiDAR), and other devices are deployed on the robot body to collect field terrain images, slope information, soil characteristics, and driving wheel motion state data. CNNs are used for feature segmentation and feature extraction from terrain images, automatically identifying typical operating conditions such as slopes, ridges, uneven roads, and muddy areas. The system outputs key parameters such as terrain type, slope grade, and road surface flatness, thereby providing an environmental perception basis for the drive system.

Second, an adaptive drive-parameter adjustment model based on CNN-based working condition recognition is constructed. The terrain feature vectors extracted by the CNN are input into a pre-trained reinforcement learning controller. According to terrain complexity and load variation trends under different working conditions, the controller adjusts online the degree-of-freedom constraint range, joint damping coefficient, and posture adjustment threshold of the drive mechanism. For example, when a slope greater than 20° is detected, the CNN model rapidly outputs the body inclination angle and the direction of center-of-gravity deviation. The drive system immediately activates the posture adjustment degrees of freedom, adjusts body leveling through coordinated joint motion, and simultaneously optimizes the power distribution ratio between the left and right driving wheels to avoid rollover risk. When muddy or soft road surfaces are detected, the CNN model combines the slip-rate data from wheel encoders to estimate the soil adhesion coefficient, automatically reduces the driving wheel speed, increases output torque, and adjusts the degree-of-freedom motion trajectory of the walking mechanism to reduce wheel slippage.

The fusion algorithm of model predictive control (MPC) and CNN condition prediction is introduced [6] to improve the dynamic stability of the system. The CNN predicts the change trend of the road surface in front of it through the continuous frame of the topographic image sequence, and outputs the switching signal of the working condition 1-2 seconds in advance. The MPC controller adjusts the control parameters of the driving system in advance based on the prediction results, and realizes the active control of 'pre-judgment-pre-adjustment' to avoid the jitter and impact caused by terrain mutation in traditional passive control. At the same time, through the off-line training of historical operation data by CNN, the stability evaluation model of the drive system under different working conditions is constructed. The vibration, joint force and power output state of the fuselage can be evaluated in real time during on-line operation. When the stability index is detected to exceed the safety threshold, the protection control strategy is automatically triggered to limit the movement speed and load of the drive mechanism and ensure the safety of the operation.

The introduction of intelligent control methods breaks through the limitations of the idea of improving adaptability only from the configuration level, and deeply integrates structural

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optimization and artificial intelligence algorithms. On the one hand, taking advantage of CNN's strong ability to extract obvious features, it can realize accurate perception and prediction of complex field environment, and avoid the problems of low recognition accuracy and weak anti-interference ability of traditional sensors in complex scenes. On the other hand, the adaptive control strategy based on CNN enables the drive system to dynamically adjust the motion mode and power output according to the real-time working conditions of the robot, so that the drive mechanism has high flexibility and high stability while maintaining the simple structure, thus enabling the robot to realize the upgrade from 'passive adaptation to terrain' to 'active adaptation to working conditions'.

3.2. Optimization of traditional neural network controllers

To address parameter perturbations, sudden load changes, terrain disturbances, and strong control coupling in agricultural robot drive systems under unstructured field environments, this study improves the structure, weight optimization, and algorithmic fusion of traditional neural network controllers, thereby constructing an intelligent control core with high precision and strong robustness [7].

3.2.1. Controller structure innovation

A Back Propagation (BP) neural network Proportion Integration Differentiation (PID) controller optimized by the dung beetle optimization algorithm is proposed to overcome the shortcomings of traditional BP-PID control, such as susceptibility to local optima, slow convergence, and large overshoot. A three-layer network structure is constructed with speed error, error change rate, load torque, and posture inclination as multidimensional inputs, and the three PID parameters: Kp, Ki and Kd as real-time outputs. The adaptive learning rate and inertia factor are introduced, and the gradient descent combined with back propagation is used to correct the weights and thresholds online, which significantly improves the convergence speed and steady-state accuracy. Aiming at the strong disturbance conditions in the field, a nonlinear disturbance observer is embedded in the control loop to estimate the lumped disturbances such as unmodeled dynamics, soil resistance mutation, and transmission clearance in real time, and feedforward compensation is performed to effectively suppress jitter and impact, and improve the anti-interference ability and running stability of the system [7].

3.2.2. Multi-network fusion innovation

In order to solve the shortcomings of the current drive system with poor adaptability to unstructured fields, it is necessary to achieve end-to-end optimization from environment perception to drive control. Based on this consideration, it is necessary to integrate multiple networks to give full play to the respective advantages of different networks and cooperate to achieve the above purposes. This leads to the idea of constructing a CNN +RBF(Radial Basis Function Neural Network)+LSTM (Long Short-Term Memory) three-network fusion architecture. Specifically, CNN is used to complete terrain feature extraction and accurate identification of working conditions, and output key parameters such as slope, flatness, and soil adhesion coefficient [8]. RBF neural network is used to nonlinearly map high-dimensional state variables to improve parameter approximation speed and control accuracy. LSTM network is introduced to model the time series of terrain time series signal and driving state, so as to realize the prediction of the front working condition 1 - 2s in advance, from passive adaptation to active pre-control, which can significantly reduce the impact and

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trajectory offset caused by terrain mutation. In this way, through multi-network collaboration, it can better solve the problem of insufficient feature extraction and poor dynamic adaptability of a single neural network in complex field scenarios.

3.2.3. Global optimization innovation

An improved soft strategy critic reinforcement learning algorithm is proposed to globally optimize the initial weights, thresholds and control gains of the neural network. The ITAE time-weighted error integral, energy consumption and tracking accuracy are used as multi-objective optimization functions to achieve comprehensive optimal control performance [9]. A dynamic weight distribution mechanism is designed to automatically adjust the weights of LSTM and fully connected network according to real-time working conditions, and improve the weight of time series features in harsh scenes such as slope land and soft soil, so as to give priority to ensuring stability and trafficability. Improve efficiency weight on flat roads and emphasize reducing energy consumption. The mechanism of experience playback and target network separation is introduced to solve the problem of sparse reward signal and training instability in the field. The learning efficiency is increased by more than 40 %, the reasoning speed is increased by 1.8 times, and the amount of strategy network parameters is reduced by about 28 %. The improved scheme has been effectively verified in the power adaptive control of electric tractor.

3.3. Implementation of closed-loop feedback and adaptive regulation of the drive system

Based on the technical route of multi-sensor fusion perception-layered closed-loop control-dynamic parameter adaptation, the full closed-loop feedback and adaptive adjustment system of agricultural robot drive system is established to realize the coordinated and accurate control of speed, torque, position and attitude.

Specifically, the perception layer can use wheel encoders, inertial measurement units, current sensors, attitude sensors, vision sensors, and LiDAR to obtain in real time state information such as rotational speed, displacement, acceleration, inclination angle, slip rate, load torque, and terrain features, forming multidimensional state feedback. Kalman filtering and data fusion algorithms are then adopted to suppress noise and outliers and improve the reliability of feedback signals.

In the control layer, the double closed-loop cascade structure is considered, that is, the speed loop is used as the outer loop, and the deviation between the target speed and the actual speed is used as the input, and the torque given value is generated by the neural network PID controller. The current /torque loop is used as the inner loop to achieve fast response and current limiting protection, ensuring dynamic response speed and control stability [10]. For the four-wheel independent drive model, this paper can calculate the ideal speed and torque of each wheel in real time by constructing the cooperative distribution and slip suppression mechanism of the drive wheel. When slip is detected, it can automatically reduce the speed, increase the torque and adjust the power ratio of the left and right wheels. In this way, the robot's passing ability and straight-line walking accuracy can be greatly improved.

Based on the working condition identification and model reference adaptive strategy, the adaptive adjustment layer introduces nonlinear disturbance observation and compensation. The load fluctuation, ground resistance and transmission clearance are regarded as lumped disturbances, and the control variables are estimated and compensated in real time, so that the system can still maintain the ideal dynamic characteristics under strong disturbances [11]. Through the Controller Area Network (CAN bus) and the real-time operating system, the signal high-speed interaction and

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control cycle synchronization are realized to ensure the closed-loop bandwidth and real-time control. Finally, the control objectives of fast response, high precision, strong anti-interference and wide adaptation of the drive system are realized to meet the needs of complex field continuous operation.

4. Conclusion

In summary, through the dual technical breakthroughs of a mechanical configuration integrating stiffness and lightweight design and an intelligent control core based on multi-network fusion, this study establishes a drive system that can adapt to complex terrain environments and achieve full-condition closed-loop adaptive regulation. Experimental results show that the system demonstrates clear advantages in adaptability, operational accuracy, stability, and anti-interference capability. This not only provides a feasible technical path for exploring solutions to agricultural mechanization problems in complex scenarios such as hilly and mountainous regions in China, but also offers meaningful reflections and explorations for promoting the evolution of intelligent agricultural machinery toward embodied intelligence integrating perception, decision-making, and execution.

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