

Research Progress on Electric Agricultural Operation Platforms

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Abstract: This Agricultural equipment electrification is an important pathway to promote the green and low-carbon transformation of agriculture. As the core carrier of electrified agricultural machinery, electric agricultural operation platforms have become a frontier hotspot in academic research and industrial application. This paper systematically reviews key literature in the field of electric agricultural operation platforms from three dimensions: whole-machine structural design, power platform research, and energy management strategy research. The analysis indicates that existing research exhibits a phased characteristic of “structural innovation first, configuration research following, and control strategies catching up,” with obvious shortcomings in the adaptation of core components to agricultural scenarios, the construction of standard testing systems, industrial chain collaboration, and infrastructure support. Future efforts should be coordinated around modular universal platform design, optimization of multi-source hybrid power system configurations, field verification of intelligent energy management strategies, and the construction of standard testing systems.

Keywords: electric agricultural operation platform; hybrid power; energy management strategy; terrain adaptability

1. INTRODUCTION

In recent years, with the transformation of the global energy structure and the advancement of the “dual carbon” strategy, traditional fuel-powered agricultural machinery faces increasingly stringent emission restrictions, and the electrification transformation of agricultural power equipment has become an industry consensus. Wang Xujing et al. pointed out that diesel tractors emit large amounts of exhaust gas during operation, adversely affecting air quality, and electric tractors have attracted high attention from domestic and foreign manufacturers as an alternative^[1]. Zhang Chuanshuai et al. further indicated that electric tractors integrate advanced technologies such as satellite positioning, path planning, unmanned driving, automatic implement control, and energy control, possessing the advantages of low carbon, environmental protection, and suitability for intelligent control, and are important technical supports for the development of intelligent agricultural machinery and smart agriculture^[2].

Electric agricultural operation platforms are the product of the integration of electrification technology and agricultural production scenarios, undertaking the task of replacing traditional fuel-powered agricultural machinery and reducing field carbon emissions, while also facing the requirement of improving the adaptability of agricultural machinery operations under complex terrain. Ouyang An et al. pointed out in a macro review that new energy tractors present a parallel evolution pattern of pure electric, hybrid, and clean fuels; new energy micro-tillers are transforming from “pure electric dominance” to “electric-hybrid parallel development and intelligent self-propulsion”; and operation platforms are developing along the technical path of “electric drive as the mainstay, supplemented by hydrogen/biofuels, and multi-form collaboration of wheeled/tracked/wheel-legged mechanisms”^[3].

This field currently faces problems such as insufficient adaptation of core technologies, imperfect standard testing systems, weak industrial chain collaboration, and lagging infrastructure, which restrict electric agricultural machinery from moving from prototypes to mass production^[2,3]. This paper follows the framework of “whole-machine equipment research—existing problems—research trends—conclusions” for the review. The whole-machine equipment research part sorts out existing achievements from three levels: structural design, power platform, and energy management strategy,

aiming to reveal research gaps and provide references for subsequent research.

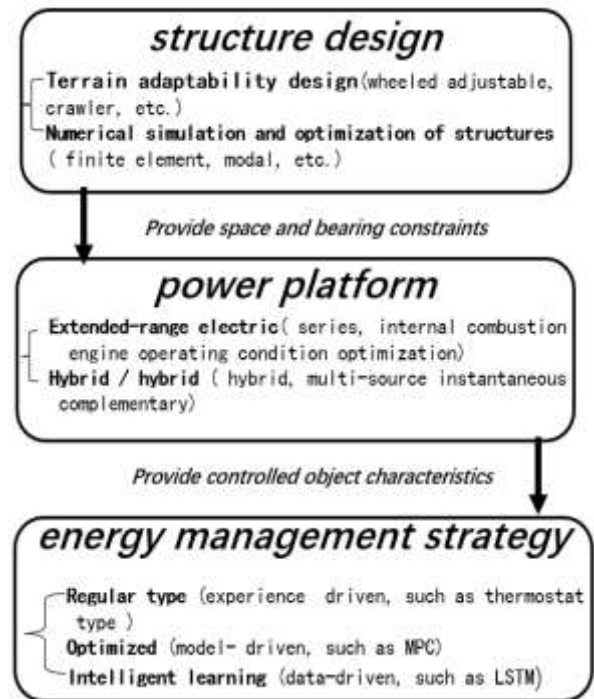


Fig. 1 Technical route and classification overview of electric agricultural operation platform

2. WHOLE-MACHINE EQUIPMENT RESEARCH

2.1.1 Whole-machine structural design

Whole-machine structural design determines the platform’s passability, stability, and operational adaptability. Existing research concentrates on two routes: “terrain-adaptive structural innovation” and “structural numerical simulation and optimization.”

2.1.1.1 Terrain-adaptive structural design

In terms of terrain adaptability, the wheeled adjustable platform shown in Figure 2-a and the tracked platform shown in Figure 2-b are representative directions. Li Junda took the planting row spacing and agronomic ground clearance of soybeans, corn, and sugarcane as constraints, designed an electric mobile platform with adjustable wheel track and ground clearance functions. Theoretical calculations showed that the maximum longitudinal climbing angle under four-wheel drive is 38.7° and the lateral climbing angle is 30.9° , and a “one-sided compensation height” strategy was proposed to break through the lateral climbing angle limitation within the adjustment range. This study used ADAMS and ANSYS to conduct dynamic simulation and finite element analysis on the two adjustment mechanisms, verifying the platform’s adjustment capability^[4]. Tian Yuhang et al. selected hub motors and steering motors as drive mechanisms, completed the design of height and wheel track adjustment mechanisms, and verified the kinematic rationality through longitudinal and lateral slope kinematics analysis^[5].

Lu Ming designed an electric tracked orchard management machine power platform for orchard operation conditions, using dual-motor independent drive, equipped with a 512V/50Ah lithium iron phosphate battery pack, a lifting part with an electric servo cylinder rated at 20 kN output force, and a truss-type welded frame structure. Virtual assembly, interference check, and anti-rollover analysis were completed in SOLIDWORKS, with a maximum constant angle of 50.4° , and the overall stability met the requirements^[6].

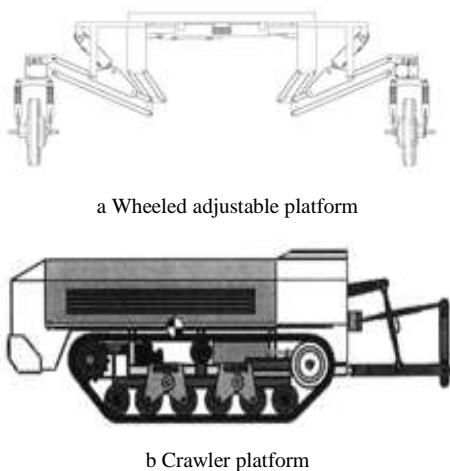


Fig.2 Comparison diagram of two typical terrain adaptive structures

2.1.1.2 Structural numerical simulation and optimization

In terms of frame finite element analysis, Liu Yongcheng conducted static and dynamic analysis on the frame of a micro electric tractor prototype. Based on three-point hitch force testing under plowing conditions, a static analysis was completed, confirming that strength and stiffness met requirements. The first six natural frequencies and mode shapes were obtained through free modal analysis, providing a basis for vibration avoidance design. Random fatigue strength analysis was carried out based on the fatigue cumulative damage hypothesis, and vibration reduction measures were proposed in combination with steering performance and vibration response tests^[7]. Chen Haolin took a certain tractor

frame as an example for modal analysis, extracting the first six natural frequencies and mode shape characteristics, providing parameter references for structural improvement^[8].

In terms of chassis system optimization, Yuan Xin designed an anti-overturn suspension for the front frame mount to address field rollover problems, established a planar dynamic model of the hydraulic front suspension. Numerical simulation and field tests showed that the model could accurately simulate system behavior under high and medium load configurations^[9]. Duan Deqiang addressed the problems of high vibration and noise and complex pipeline layout in the hydraulic system of high-horsepower tractors, integrating dispersed valve blocks into a single valve group, and field verification showed improvements in vibration and noise^[10]. Zhao Menglong et al. took the Dongfeng 1004 tractor as an example to analyze the inspection and adjustment methods for the clutch, brake, bearing clearance, and toe-in, providing operational guidance for chassis maintenance^[11].

2.1.2 Power platform research

The configuration of the power platform directly affects the power output characteristics, energy efficiency, and operational economy of the whole machine. Existing research mainly develops along two routes: extended-range and compound/hybrid power.

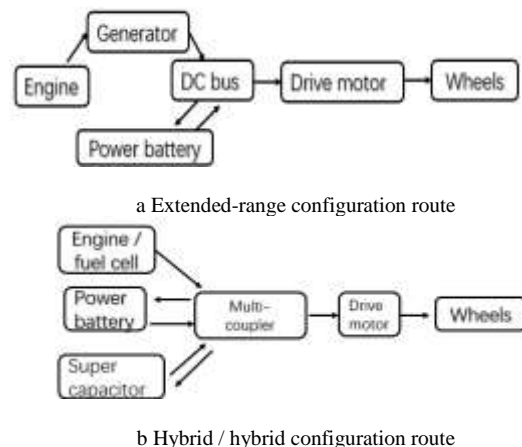


Fig. 3 Topology diagram of extended-range and hybrid / hybrid platform configuration

2.1.2.1 Extended-range electric platform

Liu Mengnan et al. took the Dongfanghong 500 tractor as the object, designed an extended-range electric scheme and conducted modeling and simulation based on CRUISE, analyzing traction performance, ground characteristics under low-speed cycle conditions, and energy consumption. They also established an equivalent model of the rotary tillage unit for coupling simulation. The results showed that the operating speed was about 3.65 km/h, the rotary tiller spindle speed was about 200 r/min, the vehicle speed increased by 14%, and fuel consumption decreased by 34.4%^[12]. Chen Siyuan et al. used GT-SUITE to establish a diesel engine model and calibrate parameters, built an extended-range power system simulation model, and compared multiple power generation operating points under the non-road transient cycle condition. The thermostat-type control made the diesel engine operate stably in the high-efficiency zone. Under the working condition of 2100 r/min and 104.60 N·m, the fuel saving rate reached 10.95%, and the optimal power generation point was located in

the medium torque region of the diesel engine fuel consumption rate curve^[13].

2.1.2.2 Compound/hybrid power platform

Zheng Hao et al. reviewed the energy management technologies for compound power systems of electric tractors, analyzed the power fluctuation characteristics of typical working conditions such as plowing, rotary tillage, and transportation, summarized working condition construction methods based on standard cycles, stage division, stochastic modeling, and field measurement, and summarized the output characteristics of fuel cells, power batteries, and supercapacitors and the applicable scenarios of multi-source coupling topologies^[1]. Ni Nana et al. sorted out the classification and working principles of hybrid power system architectures, and compared the applicable scenarios and performance differences of different strategies^[5]. Ouyang An et al. pointed out that the series type is simple in structure and suitable for scenarios with relatively stable working conditions; the parallel type can achieve power coupling and is suitable for field operations with large load fluctuations; the series-parallel hybrid type combines the advantages of both but has higher system complexity and cost^[6].

The extended-range route realizes internal combustion engine operating condition optimization through the “engine-generator-battery-motor” series structure, reducing fuel consumption while maintaining fuel supply compatibility. The compound power route emphasizes the instantaneous power complementation of multiple power sources to cope with field load fluctuations. The former has advantages in system simplicity and reliability, while the latter has greater potential in transient response and energy efficiency optimization.

2.1.3 Energy management strategy research

Energy management strategies determine the energy consumption level and operational sustainability. Existing research can be classified into three schools: rule-based, optimization-based, and intelligent learning-based.

2.1.3.1 Rule-based strategies

Rule-based strategies formulate control rules based on expert experience, featuring simple implementation and good robustness. The thermostat-type control by Chen Siyuan et al. is a typical rule-based approach—the engine starts when SOC is below the threshold and stops when above the threshold^[13]. Ni Nana et al. pointed out that rule-based strategies have strong real-time performance and low engineering barriers but are difficult to achieve global optimality^[14]. Fan Zhenguo et al. proposed a wavelet transform-fuzzy control strategy for the compound power supply system: wavelet transform decomposes the required power, assigning the impact high-frequency components to the supercapacitor to reduce the battery burden. Joint simulation using ADVISOR and MATLAB showed that under plowing conditions, the peak current was reduced by 31.9% and 16.5% compared to single power supply and compound power supply fuzzy control, power loss was reduced by 22.55% and 1.79% respectively, and power fluctuation was reduced by 42.1% and 24.1% respectively^[15]. Hu Youyao et al. developed a portable calibration system based on CODESYS, which can assist in the assembly calibration of angle sensors and flexible adjustment of field vehicle speed, fertilization amount, and seeding amount^[16].

2.1.3.2 Optimization-based strategies

Optimization-based strategies use algorithms such as dynamic programming and model predictive control to pursue optimal energy distribution under known or predicted operating conditions. Sheng Zhipeng et al. designed a dual power source system with lithium battery and supercapacitor, using model predictive control as the energy management method, establishing a plowing condition power prediction model based on LSTM, and using dynamic programming to solve the optimal lithium battery output current. Simulation showed that, compared with fuzzy control, the peak current was reduced by 40%, the supercapacitor SOC maintained a high level, and energy consumption per unit distance was reduced by 2.17%^[17]. Zheng Hao et al. commented on the advantages and disadvantages of optimization-based, rule-based, and intelligent learning-based strategies in real-time performance, economy, and adaptability to operating conditions^[1].

2.1.3.3 Intelligent learning-based strategies

Intelligent learning-based strategies introduce neural networks and deep learning methods. The LSTM power prediction by Sheng Zhipeng^[17] and the wavelet transform-fuzzy control by Fan Zhenguo^[15] both belong to this category. Ni Nana et al. pointed out that in the future, it is necessary to combine intelligent algorithms with multi-energy coupling technologies and promote the construction of standardized testing platforms^[14]. Zheng Hao et al. believed that intelligent learning-based strategies have potential in adapting to operating conditions, but computational burden and training data dependency are still the main obstacles to engineering application^[18].

The three types of strategies have different emphases. Rule-based strategies have strong real-time performance and low implementation barriers but insufficient optimality. Optimization-based strategies pursue optimal solutions but are sensitive to the accuracy of operating condition prediction. Intelligent learning-based strategies have strong adaptive ability, but computational burden and interpretability still need to be addressed. The evolution of the three types reflects the deepening process of energy management from “experience-driven” to “model-driven” and then to “data-driven.”

Table 1 Comparison of three types of energy management strategies

comparative dimension	Rule-based strategy	Optimized strategy	Intelligent Learning Strategy
true time	High	Medium	Low
optimality	Low	High	Medium
condition adaptability	Low	Medium	High
computational burden	Low	Medium	High
Realization threshold	Low	Medium	High
typical method	Thermostat control, fuzzy control	Dynamic programming, model predictive control	Neural network, wavelet transform
Representative literature	[8][10]	[15]	[15][10]

2.1.3.4 Other control technologies

Cooperative control and anti-slip control technologies ensure the implementation of energy management commands at the actuator level. Zhu Xiaoyong et al., addressing the synchronization control challenge of dual wheel-side motors, proposed a nonlinear predictive cooperative control strategy with load feedforward torque difference compensation. Tests showed that under straight-line driving with variable load, the synchronization error fluctuation was reduced by 68%, and the adjustment time was reduced by 53.4%; under curve driving, they were reduced by 64.3% and 42.1%, respectively^[19]. Du Yongbao et al., aiming at the slipping problem in the “electric platform + implement” operation mode in facility agriculture, designed a fully power-decoupled platform and proposed a model predictive anti-slip control strategy. In field tests, under different soil compaction and tillage depth conditions, the peak slip rate was reduced by 7.14% to 73.86%, and traction efficiency was improved by 4.47% to 35.56%^[20].

In terms of battery monitoring, Shen Fengmei et al. designed a battery data monitoring system using CAN bus and 4G communication, built an embedded platform on VMware, and field tests showed that the system can accurately monitor capacity, voltage, and current and upload them to a remote server in real time^[21]. Zhang Xiaorui et al. designed a fuzzy PID strategy for the vehicle speed control requirement of a chassis dynamometer. Matlab-Cruise simulation and dynamometer tests showed that fuzzy PID has higher speed tracking accuracy and faster response than traditional PID^[22]. Yao Yanchun et al. designed a piezoelectric-electromagnetic coupled vibration energy harvesting device with a dual-crystal piezoelectric cantilever beam structure, with an adjustable resonance frequency of 14.8–31.0 Hz. In field tests on an EH2604 tractor, the maximum output power reached 25.97 μ W^[23].

3. EXISTING PROBLEMS

Based on the above literature analysis, the current research has the following prominent problems.

First, the adaptation of core technologies to agricultural scenarios is insufficient. Ouyang An et al. pointed out that existing electric agricultural machinery mostly directly adopts automotive-grade or industrial-grade “three-electric” systems, lacking special design and system integration for the high humidity, high vibration, and high dust environment of agriculture, making it difficult for the reliability, durability, and safety of the whole machine to meet agricultural production requirements^[3]. Zhang Chuanshui et al. also confirmed this judgment from the perspective of promotion and application^[2]. Although the battery monitoring system by Shen Fengmei et al. has complete functions, the core hardware is still based on a general-purpose platform^[21].

Second, the standard testing system is absent. As an emerging equipment, electric agricultural operation platforms have not yet formed systematic standards for performance testing, safety assessment, and field operation quality inspection^[3]. Zheng Hao et al.^[18] and Ni Nana et al.^[14] both emphasized the urgency of building standardized testing platforms.

Third, industrial chain collaboration is weak. The electric agricultural machinery industry is small in scale, and a dedicated supply chain has not been formed. Power batteries, dedicated motors, and electronic control chips mostly rely on

the automotive or industrial fields, resulting in high cost, low customization, and unstable supply^[2,3].

Fourth, field charging and swapping infrastructure is lagging. Rural power grid capacity is limited, fast charging facility coverage is low, and the seasonal concentrated electricity demand of field operations makes the “range anxiety” of electric agricultural machinery more prominent than that of electric vehicles^[1,3].

Fifth, after-sales service is inadequate. The maintenance of electric agricultural machinery requires electrical and electronic professional skills, and such technicians are generally lacking in rural areas^[2].

In addition, there is a methodological deviation of “emphasizing scheme design and neglecting experimental verification.” The designs of Li Junda^[4], Tian Yuhang^[5], and Lu Ming^[6] are mainly based on CAD modeling and simulation. Although Liu Yongcheng completed prototype tests, they were for a micro scientific research prototype^[7]. In terms of control strategies, Zhu Xiaoyong et al.^[19], Du Yongbao et al.^[20], and Yao Yanchun et al.^[23] carried out experimental verification, but overall, the complete verification chain from simulation to bench test to field real vehicle is still insufficient.

4. RESEARCH TRENDS

First, modular universal platforms and multi-form locomotion mechanisms will continue to deepen. The “wheeled/tracked/wheel-legged multi-form collaboration” proposed by Ouyang An et al. indicates that locomotion mechanism design will develop towards multi-mechanism collaborative optimization^[3]. The modular design concept will accelerate, achieving quick switching among sowing, planting, management, harvesting and other stages through standardized interfaces to improve platform utilization. Lu Ming’s tracked platform^[6] has already embodied the scenario-customization approach and will develop towards reconfigurable and expandable directions in the future.

Second, the configuration optimization of multi-source hybrid power systems will become a focus. The multi-source coupling topologies reviewed by Zheng Hao et al.^[18] and the parallel judgment of series/parallel/series-parallel by Ouyang An et al.^[3] require more detailed research to answer which configuration is suitable for different scenarios. The optimization of power generation operating points by Chen Siyuan^[13] is expected to deepen towards adaptive switching among multiple operating points, and the unit coupling simulation method by Liu Mengnan^[12] provides an extensible framework for the joint optimization of power systems and working implements.

Third, intelligent energy management strategies will move towards field verification. The LSTM + model predictive control path by Sheng Zhipeng^[17] represents the integration trend of “data-driven + optimization control,” and the wavelet transform-fuzzy control by Fan Zhenguang^[15] demonstrates the possibility of combining signal processing and control strategies. In the future, it is necessary to jointly optimize energy management with operation path planning and farming season scheduling, and develop robust energy management methods adapted to strong stochastic field conditions.

Fourth, the integration of cooperative control and electronic/electrical architecture will accelerate. The studies by Zhu Xiaoyong et al.^[19] and Du Yongbao et al.^[20] reveal the

evolution direction from energy distribution towards an integrated architecture of “energy management—drive coordination—ground force control.” Zhang Xiaorui’s vehicle speed control system^[22] and Hu Youyao’s calibration system^[16] indicate that the standardization and calibrability of vehicle control software are becoming key infrastructure for industrialization.

Fifth, the standard system and testing technology will accelerate to fill gaps. With the industrialization of electric agricultural machinery, the research and formulation of safety standards, EMC standards, protection level standards, and power battery recycling standards for special agricultural working conditions will speed up, and the construction of third-party testing and pilot-scale verification platforms will be put on the agenda^[3,14,18].

5. CONCLUSIONS

This paper reviews the research progress of electric agricultural operation platforms from three dimensions: whole-machine structural design, power platform research, and energy management strategy research.

In terms of whole-machine structural design, terrain-adaptive design and frame finite element analysis constitute two main lines, with the former having a higher proportion. Most existing achievements remain at the CAD modeling and simulation stage, and field testing of physical prototypes is insufficient.

In terms of power platforms, the extended-range route and the compound/hybrid power route each form their own systems, focusing on fuel economy improvement and multi-energy transient power complementation, respectively. The research on agricultural-specific “three-electric” system scenario adaptation lags behind the automotive field.

In terms of energy management strategies, rule-based, optimization-based, and intelligent learning-based strategies coexist, presenting a pattern of “layer-by-layer progression, coexistence and complementarity,” and have not yet reached a maturity level where one type of strategy dominates.

The current field faces problems such as insufficient adaptation of core components to agricultural scenarios, absence of standard testing systems, weak industrial chain collaboration, lagging infrastructure, and lack of service systems, along with a methodological deviation of “emphasizing scheme design and neglecting experimental verification.” Future efforts should focus on coordinated research in modular universal platform design, scenario-based configuration optimization of multi-source hybrid power systems, field verification of intelligent energy management strategies, and the construction of standard testing systems.

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