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A Framework for Advancing Intelligent Electrical Agricultural Machinery Technologies in Mountainous Regions

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Abstract: The complex terrain of the hilly and mountainous regions in southwestern China presents significant challenges to agricultural mechanization, resulting in a level that is markedly lower than the national average. Focusing on the key development needs for intelligent agricultural machinery in these areas. This paper systematically delineates four core technological domains: lightweight machine design, detachment and drag reduction in heavy clay soils, slope adaptability, and remote operation and maintenance. The study aims to provide technical insights for overcoming the bottlenecks in mechanizing hilly and mountainous agriculture, thereby contributing to rural revitalization and national agricultural development strategies.

Keywords: Electrical agricultural machinery; Mountainous regions; Design

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1. Introduction

Southwestern China, characterized by its predominantly hilly and mountainous terrain and abundant agricultural resources, serves as a strategic national hinterland and a vital production base for grains, oils, fruits, vegetables, tea, and sugar. This region is thus crucial for ensuring the security of agricultural product supply. Data indicates that cultivated land and crop-sown areas in the southwestern hills and mountains account for one-third of the national total, involving nearly 300 million agricultural workers. Against a backdrop of complex international dynamics, stabilizing agricultural production is of strategic importance for safeguarding national food security and advancing rural revitalization [1].

However, the region's complex terrain, steep slopes, and heavy clay soils pose formidable challenges. Large and medium-sized machinery common in plains struggle with field access, operation, and maneuverability. The limited availability of small machinery often necessitates manual labor, leading to high labor intensity and low efficiency, which in turn constrains agricultural mechanization and intelligence development [2]. While the national comprehensive mechanization rate for crop cultivation, planting, and harvesting has reached 73%, it remains at only 55% in hilly and mountainous areas. Taking potato cultivation as an example, with a national planting area of approximately 4.67 million hectares, the southwestern mountainous regions, as the main production area, account for 40.6% of this total. Yet, their comprehensive mechanization rate is below 30%, with mechanized planting and harvesting rates under 10%. Furthermore, domestically produced tractors specialized for small plots and steep slopes are lacking. Large-scale rice transplanters and combine harvesters are prone to bogging down in wet fields, and there is a scarcity of lightweight machinery for transplanting and harvesting root crops (e.g., sweet potatoes) in heavy clay soil [3,4].

Consequently, there is an urgent need for targeted technological breakthroughs to address the critical bottleneck of having "no suitable machinery available, nor high-quality machinery accessible" for grain, oil, fruit, and vegetable production in these regions. Such advancements would promote modern agricultural development, foster rural economic prosperity and increased farmer income, and support national strategies for rural revitalization and building an agricultural powerhouse. This paper systematically elaborates on four key technology areas for intelligent agricultural machinery suited to the southwestern mountainous regions: lightweight design, detachment and drag reduction in clay soil, slope adaptability, and remote operation and maintenance. The goal is to guide future research, development, and application improvements.

2. Lightweighting technologies for mountainous intelligent agricultural machinery

Reducing the overall weight of machinery enhances its adaptability to small plots and steep slopes. This can be achieved through structural, material, and process lightweighting strategies [5].

2.1. Structural lightweighting technology

Structural lightweighting involves establishing optimization constraints through finite element-based continuum topology and discrete structural topology optimization algorithms. This process enables the identification of optimal lightweight structural solutions that meet performance requirements for body strength, modal characteristics, noise, vibration, and harshness (NVH), and crashworthiness, thereby achieving overall weight reduction [6].

2.2. Material lightweighting technology

Material lightweighting strategies include replacing ordinary steel with high-strength steel to reduce plate thickness while maintaining performance. For specific structural components, substituting with aluminum-magnesium alloys enables lightweight design that meets modal, stiffness, and reliability targets [7]. Research on optimizing dimensional parameters for plastics and composites can also expand the use of lightweight non-metallic materials, further reducing component weight.

2.3. Process lightweighting technology

Process lightweighting explores techniques like multi-material laser welding to reduce overall weight. Developing component manufacturing technologies based on hot stamping and part redesign effectively addresses issues with high-strength steel, such as limited deformation range, cracking susceptibility, and high spring back at room temperature [8]. Designing lightweight components (e.g., frames, control arms, steering rods) suitable for hydroforming technology is also highly effective for reducing individual part mass.

3. Detachment and drag reduction technology for heavy clay soils

Research on key technologies, including adhesion reduction and detachment for soil-engaging components, drag and energy consumption reduction, reliability enhancement, and structural adaptability design, is essential to improve machinery performance in the heavy clay soils prevalent in mountainous regions .

3.1. Adhesion reduction and detachment technology for soil-engaging components

Drawing on bionic principles, soil-engaging components can be designed with special structures and textures inspired by the unique surfaces of dung beetles, earthworms, and burrowing animals to minimize soil adhesion [11,12]. Surface modification techniques like carburizing and coating can further reduce adhesion. Additionally, incorporating detachment mechanisms such as mechanical scrapers or vibration assistance enables active adhesion reduction.

3.2. Drag and energy consumption reduction technology

Inspired by natural drag-reduction mechanisms (e.g., the skin structures of earthworms and pangolins), machinery surfaces can be designed with bionic characteristics to decrease contact area and friction coefficients with soil [13]. Designing appropriate vibration generation mechanisms to induce specific frequencies and amplitudes during operation can also reduce soil adhesion and friction forces on the equipment.

3.3. Reliability enhancement technology for soil-engaging components

Enhancing reliability involves developing impact- and wear-resistant materials and processing technologies based on a tribological analysis of the “environment-component-material” system [14]. Utilizing high-strength, wear-resistant materials ensures stable operation under complex loads. To meet the high toughness demands of mountainous environments, new materials can be developed using tough alloys and fracture toughness optimization, with heat treatment processes employed to refine microstructure and improve toughness and impact resistance [15].

4. Slope adaptability technology

Addressing the slope adaptability needs of both the machinery chassis and its implements through self-leveling technologies is crucial for improving operational safety and quality on inclines [16].

4.1. Implement slope adaptability technology

To mitigate issues like implement sinkage and poor ground contact, ground profiling mechanisms can be optimized through design. Simulation software aids in analyzing and optimizing key components to obtain optimal profiling parameters [16]. Research into depth detection methods for working components can reduce adjustment errors, enabling optimal parameter matching across different tillage conditions and thereby improving efficiency and quality.

4.2. Chassis self-leveling technology

To counter the poor stability and overturning risks of lightweight machinery in complex terrain, a three-point active leveling method based on position error can be employed. This approach addresses issues like leveling interruption due to limited actuator (hydraulic/pneumatic cylinder) stroke and helps manage the machine’s center of gravity, enhancing anti-overturning capability and operational safety [17].

5. Remote operation and maintenance technology

The complex working conditions in southwestern mountains lead to diverse and frequent machinery faults. Studying fault diagnosis and prediction methods and developing remote O&M tools are vital for ensuring efficient operation.

5.1. Fault diagnosis and prediction technology

Sensor data combined with AI algorithms enable real-time monitoring and fault diagnosis, facilitating early detection of potential issues. Building on this, fault prediction models can forecast fault timing and severity, allowing for preventive measures to avoid major failures and downtime [18]. Fault simulation using digital twins and physical models can replicate scenarios to refine diagnostic and predictive algorithms, improving their accuracy and reliability.

5.2. Remote operation and management technology

IoT platforms can connect machinery to remote O&M centers for remote diagnosis, online updates, and maintenance guidance [19,20]. AR/VR technologies can provide remote assistance and virtual training, enhancing maintenance efficiency and safety. Mobile apps and cloud platforms enable real-time location tracking, status monitoring, and remote control, streamlining remote management.

5.3. Decision-making and optimization technology

AI and operations research algorithms can establish O&M decision models to automatically generate maintenance suggestions and repair schedules. Big data analytics and machine learning can optimize resource allocation and maintenance workflows, improve efficiency and reduce costs [21]. Multi-objective optimization techniques can balance factors like cost, reliability, availability, and safety to generate optimal O&M strategies.

6. Conclusion

This paper details key technologies for developing intelligent agricultural machinery in mountainous areas, encompassing lightweight design, detachment and drag reduction in clay soil, slope adaptability, and remote O&M. Lightweighting, achieved through integrated structural, material, and process optimization, enhances adaptability to small, sloped plots. For clay soils, combining bionic design, surface modification, and vibration techniques boosts operational efficiency. For slopes, chassis self-leveling and implement profiling optimization improve safety and quality stability. For O&M, a remote intelligent system based on IoT, digital twins, and AI enables fault prediction and optimized decision-making. These advancements provide a foundational framework for overcoming mechanization barriers and promoting sustainable agricultural development in challenging terrains.

Disclosure statement

The author declares no conflict of interest.

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