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Research on Adaptive Design and Lightweighting Technology for Agricultural Machinery in Hilly and Mountainous Regions

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Abstract: Hilly and mountainous regions constitute a vital part of China's agricultural production landscape. However, their complex natural environments pose unique challenges for the deployment of agricultural machinery. Existing machinery often suffers from poor mobility, low operational efficiency, and inadequate adaptability in these areas, thereby hindering agricultural modernization. This paper addresses the specific characteristics of agricultural production environments in hilly and mountainous regions, thoroughly analyzing how factors such as terrain, soil conditions, and crop types influence machinery design. It explores the theoretical foundations and a collaborative framework integrating adaptive design with lightweighting strategies. By focusing on adaptive design of the working system, running gear, and control system—and combining this with material selection for lightweighting, structural optimization, and integrated design approaches—the study establishes a co-optimization model that jointly considers adaptability and lightweighting. The coupling relationship between these two objectives is analyzed, and appropriate algorithms are selected to achieve optimal solutions. The findings provide theoretical support and practical guidance for the development of specialized agricultural machinery tailored to hilly and mountainous regions, offering significant implications for enhancing agricultural productivity and promoting sustainable agricultural development in these areas.

Keywords: Agricultural machinery for hilly and mountainous areas; Adaptive design; Lightweight design; Collaborative optimization; Agricultural production efficiency

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1. Introduction

Hilly and mountainous areas in China cover vast territories across multiple provinces and play a crucial role in meeting the food demands of a large population and supporting the development of specialty agriculture. Unlike the plains, agricultural production in these regions has long been constrained by challenging natural conditions, with traditional manual and animal-powered operations still accounting for a significant proportion. Consequently, the level of mechanization remains far below the national average.

With the advancement of China's rural revitalization strategy, agricultural mechanization has emerged as a key driver for enhancing productivity in hilly and mountainous areas. However, most existing agricultural machinery is designed primarily for flat terrain and exhibits significant inadequacies when deployed in the complex environments of hilly and mountainous regions. Fragmented land plots and steep slopes impede stable machine operation, while variations in soil adhesion and diverse cropping patterns frequently lead to malfunctions of working components. Moreover, excessive machine weight not only increases energy consumption but may also cause soil compaction, further degrading arable land quality[1].

Therefore, research into adaptive and lightweight design of agricultural machinery tailored for hilly and mountainous areas addresses urgent practical challenges in current production systems and aligns with the inevitable trend toward precision, efficiency, and sustainability in agricultural equipment development. This work holds substantial practical significance for ensuring national food security and promoting high-quality agricultural development.

2. Analysis of Agricultural Production Environment Characteristics in Hilly and Mountainous Areas

2.1. Topographic and Geomorphic Features of Hilly and Mountainous Areas

Hilly and mountainous areas feature significant terrain undulations, with slopes commonly between 15° and 35°, and exceeding 40° in places. Farmland is fragmented into small plots, typically under 0.07 hectares, often separated by ridges and ditches. Rural roads are narrow, winding, unpaved, and turn muddy and slippery in rain. These conditions demand high maneuverability, steering agility, and climbing ability from machinery. Large equipment often cannot access fields, while smaller machines struggle with limited turning radius and unstable travel. Additionally, elevation variations create diverse microclimates that indirectly affect machinery performance and durability[2].

2.2. Soil and Crop Characteristics in Hilly and Mountainous Areas

Hilly and mountainous areas have diverse soils—primarily red, yellow, and purple—with varying textures. Some regions have clay-rich soils that compact when wet and harden when dry, while others are sandy with poor water and nutrient retention. Soil moisture is topography-dependent: slopes drain quickly and stay dry, whereas low-lying areas retain water and become saturated.

Crop cultivation is highly diversified and vertically layered. Besides staples like rice, maize, and wheat, a wide range of economic crops such as tea, fruits, and medicinal herbs are grown. These crops differ in planting density, spacing, and structure, leading to varied mechanization needs for tillage, seeding, and harvesting. Contour farming, commonly practiced, further complicates field operations.

2.3. Problems with Current Agricultural Machinery Applications

Existing agricultural machinery faces several challenges in hilly and mountainous areas. The running gear often mismatches the terrain: wheeled machines slip on slopes, while tracked versions compact soil and lack maneuverability.

Most working systems have limited width and depth adjustability, performing poorly across varied plots and crops, leading to uneven seeding or fertilizing. Additionally, machinery tends to be bulky and heavy, increasing energy consumption, while insufficient power on steep slopes reduces efficiency[3].

Furthermore, inadequate protective design leaves components vulnerable to corrosion and wear in humid, dusty conditions, raising failure rates, complicating maintenance, and ultimately increasing farmers' operating costs.

2.4. Design Requirements for Agricultural Machinery in Hilly and Mountainous Areas

Agricultural equipment for hilly and mountainous areas must meet key design requirements:

Mobility: small turning radius, strong climbing ability, and stable travel for challenging terrain.

Operational Flexibility: adjustable working width/depth and multifunctionality to suit diverse crops and soils.

Structural Design: lightweight yet strong to reduce soil compaction and energy use while bearing operational loads.

Usability & Reliability: simplified, intelligent controls and environmental resilience to humidity, dust, and temperature changes for reliable field use.

3. Theoretical Foundations of Adaptive and Lightweight Design for Agricultural Machinery

3.1. Theory and Methods of Lightweight Design

Lightweight design reduces machinery weight while maintaining performance and reliability, mainly through material, structural, and process optimization.

Material-based lightweighting replaces conventional steel with high-strength, low-density alternatives like aluminum/magnesium alloys and engineering plastics. Structural lightweighting uses topology, size, and shape optimization to remove excess material and refine components under strength and stiffness constraints. Process-oriented methods, such as precision casting and improved welding, enhance accuracy and reduce waste. Crucially, lightweighting must balance weight reduction with operational requirements to avoid compromising functionality or durability.

3.2. Theoretical Framework for Collaborative Adaptive and Lightweight Design

The collaborative design framework for adaptability and lightweighting is grounded in systems engineering principles, treating the two objectives as an integrated, interdependent whole rather than isolated goals[4].

This framework begins by clearly defining the operational requirements and environmental constraints specific to agricultural machinery in hilly and mountainous areas. It then establishes a comprehensive set of design indicators for both adaptability and lightweighting, assigning appropriate weights and priorities based on practical needs.

During the design process, a multidisciplinary collaborative optimization approach integrates knowledge from mechanical engineering, materials science, control engineering, and other relevant fields to holistically analyze and optimize the machine's structure, performance, and material selection.

A coupling relationship model between adaptability and lightweighting is developed to quantitatively assess their mutual influences. This ensures that enhancements in adaptability do not undermine lightweighting effectiveness—and vice versa—thereby preventing trade-offs that could degrade overall system performance.

Through this synergistic design strategy, an optimal balance among performance, weight, and environmental adaptability is achieved, ultimately improving the machinery's cost-effectiveness, operational efficiency, and market competitiveness[5].

4. Adaptive Design of Agricultural Machinery for Hilly and Mountainous Areas

4.1. Adaptive Design of the Operating System

The operating system's adaptive design should address varied crop and soil needs. A modular approach allows quick replacement of tillage, seeding, and harvesting modules, enhancing versatility. To suit fragmented plots, the working width should be steplessly adjustable. Tillage components need adjustable penetration angle and depth, controlled hydraulically or electrically for precise soil adaptation. For seeding, a multi-row mechanism with adjustable spacing meets different crop densities, while a precision seeding system improves uniformity[6].

4.2. Adaptive Design of the Traveling System

The traveling system is key to stable operation in hilly terrain. A combined wheel-track structure merges wheel mobility with tracked adhesion, switching modes based on road conditions. The chassis is optimized to lower the center of gravity, improving slope stability and reducing rollover risk. Off-road tires with large diameter, wide tread, and deep patterns enhance ground contact and grip while reducing soil compaction[7]. An independent suspension system absorbs terrain shocks, protects components, and increases comfort. A differential lock and anti-slip control further improve safety on wet or muddy surfaces.

4.3. Adaptive Design of the Control System

The adaptive design of the control system focuses on operational convenience and stability. Electro-hydraulic proportional control technology is adopted to achieve precise control of various mechanical actions, simplify the operation process, and reduce labor intensity. An adjustable driver's seat and control handle are designed to adapt to farmers of different heights and operating habits, improving operational comfort. An intelligent navigation and positioning system is equipped, which combines topographic data of hilly and mountainous areas to realize automatic path planning and precise operation of the machinery, reduce manual operation errors, and improve operational efficiency. During slope operations, the system can automatically detect changes in slope angle, and maintain the horizontal state and operational stability of the machinery by adjusting parameters of the traveling system and operating system. In addition, emergency braking and safety protection devices are installed[8]. When the machinery is in dangerous situations such as excessive tilt angle and excessive speed, braking is automatically triggered to ensure the safety of operators.

5. Lightweight Design of Agricultural Machinery for Hilly and Mountainous Areas

5.1. Selection and Application of Lightweight Materials

The selection of lightweight materials shall comprehensively consider factors such as material mechanical properties, cost, and processing technology. For the mechanical body and frame, high-strength aluminum alloy materials are adopted, which possess advantages of low density, high strength, and corrosion resistance. Compared with ordinary steel, they can reduce weight by 30%-40% while meeting structural strength requirements. For operating components such as seeders and fertilizer applicators, engineering plastics or carbon fiber composite materials are selected. These materials are not only lightweight but also have good wear resistance and corrosion resistance, which can effectively reduce the weight of components. For key parts in the transmission system such as gears and shafts, high-strength steel is used for precision forging. On the premise of ensuring strength, the material consumption is reduced by optimizing cross-sectional dimensions. During the material application process, strict performance testing and reliability analysis must be conducted to ensure the applicability and durability of materials in actual operating environments[9].

5.2. Structural Lightweight Optimization of Key Components

Topology optimization methods are used to optimize the structure of key mechanical components such as frames and chassis crossbeams. Under the constraints of meeting strength and stiffness requirements, software simulation is used to analyze the stress distribution of components, and materials in areas with low stress are removed to form hollow or special-shaped structures, realizing efficient material utilization. Hollow structure design is adopted for shaft components, which can significantly reduce weight compared with solid shafts under the same bending and torsional resistance performance. The tooth profile and structural parameters of gears are optimized, and modified gear design is adopted to reduce the volume and weight of gears while improving their transmission efficiency and load-bearing capacity. For box-type components, thin-walled structure design is adopted, and the optimized arrangement of reinforcing ribs is used to enhance structural stiffness and reduce material consumption. After structural optimization, prototype trial production and performance testing shall be carried out to verify the effectiveness and reliability of the optimization scheme.

5.3. Lightweight Achievement through Integrated Design

Integrated design reduces the number of components and achieves overall weight reduction by integrating multiple functional components of the machinery. Power transmission components such as engines, gearboxes, and hydraulic systems are arranged in an integrated manner, and the design of pipelines and circuits is optimized to reduce connecting components and space occupation, thereby lowering the overall volume and weight of the machinery. Multifunctional integrated components are adopted, such as integrating seeding and fertilization functions into one operating module[10]. By sharing the power transmission system and control system, the number of independent components is reduced. The control system is integrated, and a centralized control panel is adopted to integrate multiple operating functions into one controller, reducing the number of control handles and buttons and simplifying the structure of the control system. Integrated design must ensure the coordinated operation of various components, avoid functional interference, and facilitate maintenance and upkeep.

6. Collaborative Optimization Design of Adaptability and Lightweight

6.1. Establishment of the Collaborative Optimization Design Model

The collaborative optimization design model constructs a multi-objective optimization model with mechanical operating efficiency, driving stability, structural strength, weight, etc., as objective functions, and terrain conditions, soil characteristics, crop requirements, etc., as constraint conditions. Quantitative expressions for each objective function are determined: for example, operating efficiency is represented by the operating area per unit time, driving stability by the maximum rollover angle, structural strength by the maximum stress of components, and weight by the total mass of the machinery[11]. Adaptive design indicators and lightweight design indicators are converted into design variables of the model, such as the adjustment range of operating width, ground contact pressure of the traveling system, material density, and component dimensions. By establishing the mathematical relationship between objective functions and design variables, a complete collaborative optimization design model is formed, providing a foundation for subsequent optimization calculations.

6.2. Analysis of the Coupling Relationship between Adaptability and Lightweight Design

There is a complex coupling relationship between adaptability and lightweight design. On the one hand, lightweight design may affect mechanical adaptability: for instance, excessive weight reduction may lead to a decrease in structural strength, impairing the machinery's operational stability and durability in complex terrain. On the other hand, certain measures in adaptive design, such as adding adjustment mechanisms and adopting modular structures, may increase the machinery's weight, conflicting with the lightweight goal. Through simulation analysis and experimental research, the degree of coupling between the two is quantified, and a coupling relationship matrix is established to clarify the influence coefficients of different design variables on adaptability and lightweight indicators[12]. For example, the use of high-strength materials can both reduce weight and improve structural strength, which is conducive to enhancing mechanical adaptability; while improving the shock absorption performance of the suspension system may increase a certain weight, it can improve driving stability and strengthen adaptability. The analysis of the coupling relationship provides a basis for collaborative optimization and realizes the coordinated development of the two[13].

6.3. Selection and Implementation of the Collaborative Optimization Algorithm

According to the characteristics of the collaborative optimization design model, the Non-dominated Sorting Genetic Algorithm II (NSGA-II) is selected as the optimization algorithm. This algorithm has excellent multi-objective optimization capabilities and can find multiple Pareto optimal solutions in a complex solution space, providing designers with diversified optimization schemes. During the algorithm implementation process: first, design variables are encoded, and their value ranges and precision are determined. Algorithm parameters such as population size, number of iterations, crossover probability, and mutation probability are set, and the optimal parameter combination is determined through experimental debugging[14]. The constructed collaborative optimization design model is imported into the algorithm for iterative calculation. In each iteration, individuals undergo evaluation, selection, crossover, and mutation operations to gradually approach the optimal solutions. After the iteration, the scheme with the best comprehensive performance is selected from the Pareto optimal solution set, which is the optimal design scheme for the collaborative optimization of adaptability and lightweight. Finally, verification and analysis of the optimization scheme are conducted to ensure it meets the design requirements[15].

7. Conclusion

Through an in-depth analysis of the agricultural production environment in hilly and mountainous areas, this study has clearly identified the limitations of existing agricultural machinery and the specific design requirements for such regions. A theoretical framework for the collaborative design of adaptability and lightweighting has been established, and systematic research has been conducted on both adaptive and lightweight design methodologies tailored to agricultural machinery in these challenging terrains. Furthermore, a synergistic optimization approach integrating both objectives has been successfully implemented.

The research demonstrates that modular and intelligent adaptive design strategies can significantly enhance machinery's capability to cope with the complex terrain, diverse soil conditions, and varied cropping systems typical of hilly and mountainous areas. Meanwhile, through the strategic selection of lightweight materials, structural optimization, and integrated design, substantial weight reduction can be achieved without compromising mechanical performance—thereby lowering energy consumption and minimizing soil compaction.

The co-optimization of adaptability and lightweighting enables their organic integration, achieving an optimal balance among machine performance, weight, and environmental suitability. These findings provide a practical and technically viable pathway for the development of specialized agricultural machinery for hilly and mountainous regions, contributing to the advancement of mechanization, and supporting more efficient, precise, and sustainable agricultural production in these areas.

Future work should further integrate intelligent technologies—such as digital twins, AI-driven design, and real-time sensing—into the collaborative optimization process to enhance design efficiency and accuracy. Additionally, extensive field trials are needed to validate the real-world performance of proposed designs, thereby offering stronger empirical support for the industrial-scale adoption and promotion of next-generation agricultural machinery.

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