

Postprint: Research Status and Development Trends of Key Technologies for Tractor Leveling and Rollover Prevention in Hilly and Mountainous Terrain

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Abstract

[Purpose/Significance] Mechanization and intelligentization of hilly and mountainous areas are hotspots for research and development in the agricultural machinery industry. In China, cultivated land in hilly and mountainous areas accounts for more than 50% of the total, and faces constraints from various environmental factors such as steep slopes, narrow roads, fragmented plots, and complex terrain, resulting in the practical problem of “no suitable machinery available, and no good machinery to use” in various production stages, and lacking theoretical support for the development of agricultural machinery equipment suitable for large slopes in hilly and mountainous areas. [Progress] This paper reviews the research status of leveling and anti-rollover systems for tractors in hilly and mountainous areas at home and abroad. Among them, the parallel four-bar and hydraulic differential height types of tractor body leveling technology have simple structures, the articulated and torsional types are more suitable for continuously undulating rugged roads, and the center-of-gravity adjustable and omnidirectional leveling types have good traction performance and adaptability on slopes; cab and seat leveling technology is based on adaptive control with angle sensors, with the key being to alleviate driving fatigue and improve comfort; cooperative control technology for tractor body and implement attitude mostly uses PID control technology to achieve coordinated control, but lacks a feedback mechanism for operational effectiveness; tractor anti-rollover protection devices and warning technologies are based on rollover protective structures, and predict rollover danger signals in advance through environmental simulation perception and provide timely feedback. [Conclusions/Outlook] Future development directions for tractor leveling, anti-rollover warning, unmanned, and automation technologies in hilly and mountainous areas: 1) Re-

search on hill tractor leveling systems with optimized structure, high sensitivity, and good stability; 2) Research on profiling systems for agricultural implements with good slope adaptability; 3) Research on anti-rollover warning technology with environmental perception and automatic intervention; 4) Research on precision navigation technology for agricultural machinery, intelligent monitoring technology, and remote scheduling and management technology for agricultural operations; 5) Research on longitudinal stability theory for slopes. This aims to provide references for developing high-reliability, high-safety hill tractors suitable for the complex operating environments of China's hilly and mountainous areas.

Full Text

Preamble

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Research Advances and Development Trend of Mountainous Tractor Leveling and Anti-Rollover System

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Abstract:

[Purpose/Significance] The mechanization and intelligentization of hilly and mountainous regions represent a hot spot for future research and development in the agricultural machinery industry. In China, cultivated land in hilly and mountainous areas accounts for a significant proportion of the total, yet faces multiple environmental constraints including steep slopes, narrow roads, fragmented plots, and complex terrain, resulting in a practical problem of “no suitable machinery available, and no good machinery to use” across production stages. Moreover, there is a lack of theoretical support for developing agricultural machinery suitable for large slopes in hilly and mountainous regions.

[Progress] This paper reviews the research status of tractor leveling and anti-rollover systems for hilly and mountainous areas both domestically and internationally. Among these, tractor body leveling technologies—such as parallel four-bar and hydraulic differential height systems—feature simple structures, while folding-waist and twisting-waist designs are better suited for continuously undulating rugged terrain, and both center-of-gravity adjustable and omnidirectional leveling systems demonstrate good slope traction and adaptability. Cab

and seat leveling technologies employ angle sensor-based adaptive control, with the key being to alleviate driver fatigue and improve comfort. Body and implement attitude cooperative control technologies mostly adopt PID control for synchronized management, but lack feedback mechanisms for operational performance. Tractor rollover protection devices and warning technologies build upon rollover protective frames, using environmental simulation and perception to predict rollover danger signals in advance and provide timely feedback. [**Conclusions/Prospects**] Future development directions for hilly and mountainous tractor leveling, anti-rollover warning, and unmanned automation technologies include: (1) research on mountain tractor leveling systems with optimized structures, high sensitivity, and good stability; (2) development of implement profiling systems with good slope adaptability; (3) research on anti-rollover warning technologies with environmental perception and automatic intervention; (4) research on precision navigation technology, intelligent monitoring technology, and remote scheduling and management technology for agricultural machinery; and (5) theoretical research on longitudinal stability on slopes. This review aims to provide references for developing high-reliability, high-safety mountain tractors suitable for China's complex hilly and mountainous operating environments.

Keywords: hilly and mountainous areas; tractor leveling; suspension implement leveling; anti-rollover system; rollover

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The mechanization, automation, and intelligentization of agricultural equipment are critical for improving operational efficiency, liberating labor, and promoting sustainable agricultural development, playing a vital role in ensuring national food security and increasing agricultural productivity and income. China is a vast agricultural country with a high proportion of hilly and mountainous terrain, accounting for approximately 70% of its land area. According to the "Third National Land Survey" [2], China's cultivated land area is 1.3×10^6 km², ranking third in the world. Among this, cultivated land with slopes of 2° and below covers 7.9×10^5 km² (61.93% of total cultivated land); land with slopes between 2° and 6° (including 6°) covers 2.0×10^5 km² (15.32%); land with slopes between 6° and 15° (including 15°) covers 1.7×10^5 km² (13.40%); land with slopes between 15° and 25° (including 25°) covers 7.7×10^4 km² (6.04%); and land with slopes above 25° covers 4.2×10^4 km² (3.31%). Flat land (≤ 2°) and gentle slopes (2°–6°) are easy to cultivate, and ordinary tractors

can operate smoothly and efficiently. Hilly terrain (6° – 15°) requires mountain tractors with leveling functions or low center of gravity to ensure operational safety and quality. When working on slopes of 15° – 25° , tractors are prone to overturning, and using unmanned tractors instead of manual driving can greatly ensure driver safety. Land with slopes above 25° is prohibited for crop cultivation and requires soil conservation measures. Thus, nearly one-quarter of China's large-slope hilly and mountainous land urgently needs specialized and reliable mountain tractors.

By 2022, China's total agricultural machinery inventory approached 200 million units (sets), with a comprehensive mechanization rate for crop cultivation, planting, and harvesting exceeding 72%. However, the comprehensive mechanization rate in hilly and mountainous areas remains below 50%. China's hilly and mountainous regions are vast, with complex terrain, fragmented plots, and steep, narrow roads. Agricultural development in these areas is relatively backward, and agricultural production faces the practical problem of “no suitable machinery available, and no good machinery to use” [3]. Currently, domestic hilly and mountainous operation machinery mainly consists of micro or small tillers and field management machines, which generally suffer from problems such as easy overturning, difficult operation, and difficulty ensuring personnel safety. These factors seriously affect operation quality and hinder the mechanization and modernization of agriculture in hilly and mountainous areas.

The “14th Five-Year Plan for National Agricultural Mechanization Development” issued by the Ministry of Agriculture and Rural Affairs clearly states that “it is necessary to actively develop efficient and specialized agricultural machinery for hilly and mountainous production, and accelerate the improvement of agricultural mechanization shortcomings in these areas.” Therefore, there is an urgent need to accelerate the research, development, and promotion of agricultural machinery equipment for hilly and mountainous regions.

Countries with many hilly and mountainous areas worldwide include Sweden, Switzerland, Japan, Spain, Finland, Iran, etc. The working environment in hilly and mountainous areas is complex and dangerous, with frequent safety accidents. Globally, tractor rollover accidents account for more than half of all tractor-related fatalities. The driving safety of hilly and mountainous tractors has become a hot research topic for scholars both domestically and internationally.

To address the problems of complex terrain and steep, narrow roads in hilly and mountainous operations, existing solutions mainly involve two approaches: leveling technology and anti-rollover technology. Tractor leveling systems can achieve coordinated control between the vehicle body and suspended implements in uneven operating environments, improving driver comfort, safety, and tractor operation reliability. Tractor anti-rollover systems ensure the safety of both the tractor and the driver. This paper reviews the research status of mountain tractor body and suspended agricultural implement attitude leveling technologies and mountain tractor anti-rollover devices and systems, both domestically and

internationally, along with research progress on their operational performance. Combined with the actual terrain characteristics of China's hilly and mountainous areas, it discusses existing problems in slope operation machinery, slope operation mechanisms, tillage modes, and anti-rollover mechanisms and strategies, aiming to propose solutions such as tractor body and suspended implement leveling slope adaptive strategies and steep slope tractor anti-rollover technologies, providing a technical foundation for further research and development of suitable mountain tractors, matching implements, and tractor anti-rollover systems and strategies.

1.1 Body Leveling Mechanisms

The complex environmental characteristics of farmland operations in hilly and mountainous areas lead to several challenges for current machinery. First, operating conditions are affected by soil types (sandy soil, clay soil, loam, etc.), soil parameters (moisture content, firmness, etc.), ground undulation amplitude (height difference, frequency), fragmented and scattered plots, and narrow, curved farm roads, requiring tractors to have flexible steering, stable structures, easy operation, and good driving stability. Second, in specific environments such as orchards, the growth morphology of fruit tree branches affects machinery mobility—power machinery should not be too tall or large, otherwise it cannot pass smoothly. Third, operation stages include plowing, planting, management, harvesting, transportation, and many other links, and power machinery must match and meet the operational needs of each stage. When a tractor operates in rugged slope environments, the vehicle's attitude not only affects the driver's experience but also increases the risk of lateral sliding and rollover. Tractors equipped with body leveling systems can actively adjust the body attitude according to position and posture when encountering uneven or inclined road conditions, keeping the body attitude horizontal or adjusting the vehicle's center of gravity within a stable range, thereby improving driver operational safety, driving comfort, and the tractor's anti-slip and anti-rollover capabilities on lateral slopes [4, 5].

Currently, mountain tractor body leveling control systems can be divided into five types based on different working principles: hydraulic differential height, parallel four-bar, center-of-gravity adjustable, folding-waist and twisting-waist, and omnidirectional leveling mechanisms.

1.1.1 Hydraulic Differential Height Leveling Mechanism

The hydraulic differential height leveling mechanism directly adjusts the hydraulic cylinder piston rod installed on the walking mechanism to achieve lifting or lowering of a single track. Through this mechanism, the tractor can maintain a horizontal body during contour line driving on slopes, avoiding dangers such as rollover. The principle is shown in Figure 1 [Figure 1: see original paper].

To address the poor slope adaptability of mountain crawler tractors when oper-

ating in complex terrains such as hills and mountains, the Yang Fuzeng team from Northwest A&F University improved the walking system based on existing crawler tractors and developed a micro remote-controlled mountain crawler tractor (Figure 2 [Figure 2: see original paper]). This tractor can achieve vertical adjustment of both tracks in opposite directions according to the operating terrain. Using remote control operation, it realizes human-machine separation, ensuring driver safety during operations. Through lateral attitude adjustment, the tractor can maintain a horizontal body and complete contour line operations on slopes of 0° – 23° , improving the stability and safety of crawler tractor slope operations and significantly reducing the probability of accidents [6-10].

1.1.2 Parallel Four-Bar Leveling Mechanism

The parallel four-bar leveling mechanism consists of a platform frame, secondary link, lower frame, and main link. The lateral leveling cylinder provides power to the main link, pushing it to swing. Through a pull rod, it drives the secondary link to swing, thereby changing the parallelogram shape. This creates a height difference between the walking mechanisms on both sides when the vehicle travels on slopes, achieving body leveling effects, improving the stability of the profiling process, and completing unilateral attitude adjustment of the body. The push rod extension control is provided by feedback signals from angle sensors. Simultaneous operation of lateral leveling cylinders on both sides of the body can adjust the ground clearance of the entire machine, improving passability. The parallel four-bar mechanism features simple structure, smooth motion, strong load-bearing capacity, convenient installation and adjustment, and good profiling effects. The structural diagram of the parallel four-bar leveling mechanism is shown in Figure 3 [Figure 3: see original paper].

Additionally, to address the poor terrain adaptability and safety of tractors on rugged roads and slope conditions, SUN et al. [11] added a “dual-frame mechanism” based on previous research (hydraulic differential height device). The tractor’s maximum lateral leveling angle is 15° , and the maximum longitudinal leveling angle is 10° , enabling both lateral and longitudinal attitude adjustment of the body. The longitudinal leveling principle of the mountain tractor is shown in Figure 4 [Figure 4: see original paper], where the longitudinal leveling cylinder lifts the upper frame to complete longitudinal leveling, improving the slope adaptability and operational safety of mountain crawler tractors.

Gao Moyao [12] derived the relationship between chassis tilt angle and adjustment drive cylinder stroke through structural calculation of the differential height mechanism, conducted a comprehensive and systematic analysis of the entire hydraulic leveling system and its working principle, and thus proposed a body leveling design scheme. The tilt sensor determines the body’s tilt status, and then controls the stroke of hydraulic cylinders on the front and rear sides to change the shape of the parallel four-bar mechanism, thereby achieving body leveling.

1.1.3 Center-of-Gravity Adjustable Leveling Mechanism

Tractors are prone to problems such as reduced plowing stability, decreased traction efficiency, and reduced uphill stability due to improper center-of-gravity position during plowing operations and uphill driving. The center-of-gravity adjustable leveling mechanism changes the vehicle's center-of-gravity position by moving or swinging counterweights or certain parts of the vehicle body to better adapt to slope operations. Taking the adjustment of certain vehicle body parts to change the overall center-of-gravity position as an example, the schematic diagram of the center-of-gravity adjustable leveling mechanism is shown in Figure 5 [Figure 5: see original paper]. The position of the cargo platform relative to the vehicle body is changed through lateral and longitudinal sliding rails to alter the machine's center-of-gravity position.

To address the poor adaptability of mountain orchard transport vehicles on rugged roads, Han Zhenhao et al. [13] designed an adaptive mountain orchard transport vehicle that can automatically adjust the machine's center-of-gravity position in real-time according to terrain conditions to reach a balanced state. This design prevents cargo from falling due to road undulations, improves transport efficiency and speed, and provides excellent slope driving performance and terrain adaptability. Ning Pucui [14] designed a longitudinal center-of-gravity adjustment mechanism for electric tractors, which improves traction efficiency and stability when going uphill or downhill by moving the front battery pack's longitudinal position. The essence of vehicle leveling is actually the adjustment of the center-of-gravity position. The effect of changing the center-of-gravity position is the change in track ground pressure (the critical state of vehicle rollover is when one side's track pressure equals zero), ultimately affecting the traction force changes on both sides of the vehicle tracks. It is necessary to establish a mathematical model for the center-of-gravity of tracked vehicles on slopes, explore the corresponding relationship between vehicle leveling angle, center-of-gravity position, and slope gradient, and derive the ground pressure improvement coefficient and traction force improvement coefficient after leveling, which provides guiding significance for the design of center-of-gravity adjustable tractors.

1.1.4 Folding-Waist and Twisting-Waist Adjustment Mechanism

To simplify the body leveling mechanism, a folding-waist and twisting-waist tractor was developed based on the single-point ball hinge principle. Compared with traditional tractors, the biggest advantage of folding-waist and twisting-waist tractors is good passability and compact structure. The structural diagram of the folding-waist and twisting-waist adjustment mechanism is shown in Figure 6 [Figure 6: see original paper]. The folding-waist mechanism is controlled by folding steering hydraulic cylinders on both sides, allowing the front of the tractor to rotate directly by a certain angle, which can significantly reduce the turning radius. The twisting-waist mechanism adopts a front-rear segmented connection, with a twisting swing attitude adjustment device (composed of a

power transmission universal joint and a twisting profiling shaft) designed in the middle of the transmission system to connect the rear body gearbox. This allows the front and rear bodies to twist at a certain angle, enabling reliable adhesion of driving wheels and walking wheels on surfaces of different heights, facilitating flexible operation in narrow spaces and on rugged roads, with good traction capacity and climbing stability, making it particularly suitable for China's hilly and mountainous regions. However, the later maintenance and repair of folding-waist and twisting-waist tractors are difficult.

The Italian Antonio Carraro company's MACH 4R mountain tractor (Figure 7 [Figure 7: see original paper]) can achieve four-wheel drive and wheel-track interchange [15], featuring folding-waist and twisting-waist functions, with strong power and adaptability to various uneven roads, showing good adaptability to gentle slopes. However, this tractor is slightly large and relatively expensive. Since the whole vehicle cannot be leveled, its safety and mountain adaptability are poor when working on large slopes, making it difficult to adapt to China's hilly and mountainous operating environment with steep slopes, narrow roads, and fragmented plots. The Italian BCS company's Sky-Jump-V950 mountain tractor [15] (Figure 8 [Figure 8: see original paper]) features folding-waist and twisting-waist functions. The front-wheel and rear-track mode offers advantages of good traction performance and small compaction damage, and is widely used in complex operating scenarios such as orchards, tea factories, and nurseries. It is equipped with a DUALSTEER dual-direction steering system that enables a turning angle of up to 70° , further reducing the turning radius and providing good traction and stability during steep slope operations.

To improve the leveling precision and dynamic real-time attitude adjustment of hilly and mountainous tractors, Shandong Agricultural University, in collaboration with Shandong Wuzheng Group [16], designed a twisting-waist wheeled tractor (Figure 9 [Figure 9: see original paper]) by drawing on foreign folding-waist and twisting-waist technology. The front and rear bodies of this tractor can rotate at a certain angle around the middle twisting shaft. The twisting-waist attitude adjustment device can improve the terrain adaptability and operational efficiency of hilly and mountainous tractors. To adapt to the domestic hilly and mountainous terrain with fragmented plots, narrow roads, and poor economic conditions, Yituo Group has developed and produced three horsepower segments of hilly and mountainous tractors (70, 80, and 90 horsepower) (Figure 10 [Figure 10: see original paper]), focusing on meeting market demands in northwest loess hills, Shandong hills, and other slope-cultivated lands after suitable mechanization transformation. These tractors adopt new technologies including front engine layout, folding-waist steering, four equal-sized wheels, dual-direction driving, and four-wheel braking, offering good stability, high passability, and flexible steering for hilly and mountainous operations, making them particularly suitable for special operating environments such as hilly and mountainous areas, slope-cultivated lands, and orchards.

Folding-waist and twisting-waist tractors have small turning radii and flexible

maneuverability, making them very suitable for China's complex operating environment with steep slopes, narrow roads, and fragmented plots. Subsequent research can combine folding-waist and twisting-waist mechanisms with leveling structures to achieve both compact flexibility and safety reliability, solving existing problems of difficult transfer between plots, fragmented land, and steep, uneven terrain. However, the front and rear of folding-waist and twisting-waist tractors are two independent parts, and the research difficulty lies in how to coordinate the relationship between the folding-waist/twisting-waist and leveling systems to optimize the ground pressure of each wheel.

1.1.5 Omnidirectional Leveling Mechanism

Since parallel four-bar, hydraulic differential height, and folding-waist/twisting-waist leveling mainly achieve lateral leveling of the whole machine, they lack longitudinal leveling. The omnidirectional leveling mechanism enables the body to maintain a horizontal state at all times when driving on rugged slopes through four-wheel independent hydraulic leveling mechanisms or multi-layer frame hydraulic leveling mechanisms, achieving both lateral and longitudinal leveling simultaneously. However, it requires synchronous cooperation of multiple sensors and has high requirements for precision and response time.

Denis et al. [17] from Blaise Pascal University in France proposed an online adaptive observer that combines changes in vehicle center-of-gravity height and total vehicle mass to assess and avoid rollover risks of moving grape harvesters in off-road terrain, and achieved whole machine leveling through a four-wheel independent hydraulic leveling mechanism (Figure 11 [Figure 11: see original paper]). The vehicle's rollover assessment system, combined with the four-wheel independent hydraulic leveling mechanism, can achieve reliable adhesion of all four wheels on different planes, ensuring consistent ground pressure and horizontal body position, thus providing better adaptability and safety. However, the whole vehicle is too tall and requires structural integration and optimization.

When crawler combine harvesters operate on uneven surfaces, the tractor body tilts and bumps, resulting in poor operating environments and seriously affecting operational efficiency and driving comfort. Wang Zhihan [18] used a neural network Proportional-Integral-Derivative (PID) control algorithm to solve the problems of large overshoot and high leveling delay in PID control, verifying that neural network control is superior to traditional PID control and confirming the reliability of simulation experiments. Shu Xin [19] proposed a leveling control strategy combining "position error control method + angle error control method." This automatic leveling system can complete ground clearance adjustment and chassis leveling, significantly improving adaptability on rugged slopes. Yang Huabing [20] designed a fuzzy PID control algorithm for tractor automatic leveling control systems and established mathematical models for X-axis and Y-axis speed leveling control of the tractor body platform. Shanghai Jiao Tong University, in collaboration with Shandong Wuzheng Group, developed a dual-closed-loop PID control algorithm that can actively adjust the tractor

body attitude according to terrain characteristics, showing good slope adaptability [21]. Zhao Enpeng [22] designed and developed a body leveling system for wheeled hilly and mountainous tractors, achieving body leveling by separately changing the stroke of leveling hydraulic cylinders in the front and rear drive axles, and verified it from kinematic and dynamic aspects. However, the research lacks verification of the overall structural strength, making it difficult to guarantee structural safety under high-speed bumps or high impact loads. Li Honglong [23] designed a tractor leveling hydraulic system and established a mathematical model that enables tractors to drive smoothly on 15° slopes without rollover risk. Liu Pingyi et al. [24] designed a profiling dynamic leveling chassis that can achieve leveling by adjusting the suspension arm angle, with full-time multi-wheel drive ensuring high traction efficiency and high response speed. Traditional tractors basically will not roll over when operating on 15° slopes. Subsequent research should focus on emergency response strategies when encountering sudden situations (such as encountering raised soil ridges or deep pits) while driving on slopes of 15° and above, establishing corresponding mathematical and dynamic models.

Jilin University, in collaboration with Sichuan Chuanlong Tractor Manufacturing Co., Ltd., developed an attitude-adjustable four-wheel independent hydraulic leveling mountain tractor, as shown in Figure 12 [Figure 12: see original paper]. This prototype can achieve four-wheel independent drive and independent lifting, with omnidirectional leveling functions. Based on a multi-sensor fusion detection method for body attitude, it can individually control the height, travel speed, and direction of each wheel according to terrain characteristics, greatly improving the tractor's adaptability to complex terrain and providing good driving comfort and safety [25, 26].

To address the problems of low operational safety and poor performance caused by the inability of tractor bodies to adaptively balance with terrain undulations during operations in hilly and mountainous areas, Zou Daqing et al. [27] proposed a point-line composite support "three-layer frame" hydraulic omnidirectional leveling system (Figure 13 [Figure 13: see original paper]) based on the operational requirements of agricultural machinery in hilly and mountainous areas. This system's omnidirectional leveling angle can reach up to 20° , laying a foundation for the construction of a complete machine dynamics model and leveling controller design for crawler working machines, and improving the operational efficiency and safety of agricultural machinery in complex terrain environments of hilly and mountainous areas. However, the multi-layer frame increases the overall design height of the machine, requiring structural integration and optimization. To address the problems of large body inclination angle changes, poor work quality, and operational safety during agricultural machinery operations in hilly and mountainous areas, Sun Zeyu et al. [28] also designed a hydraulic omnidirectional leveling system based on a "three-layer frame" for crawler working machines, and proposed a composite Q-learning-Back Propagation (BP) neural network-PID omnidirectional leveling control strategy. They conducted whole machine tests on transverse and longitudinal slope roads, meet-

ing the leveling performance requirements of agricultural machinery in hilly and mountainous areas.

Although different body leveling mechanisms have varying structures and principles, their ultimate goal is to achieve stable driving on complex roads. A comparison of the advantages and disadvantages of the five types of leveling mechanisms is shown in Table 1. Parallel four-bar and hydraulic differential height systems have simple structures but relatively average leveling effects on complex terrain. Folding-waist and twisting-waist types are more suitable for small-scale continuously undulating rugged roads but have almost no leveling effect on large-slope contour line operations. Center-of-gravity adjustable and omnidirectional leveling types represent the future development trend for mountain leveling tractors, offering good slope traction and adaptability, but manufacturing and maintenance costs need to be reduced.

1.2 Cab and Seat Leveling Technology

The operating environment of mountain agricultural machinery is complex. Cab and seat leveling technology uses angle sensors to provide real-time feedback and calibrate the cab or seat attitude, keeping it horizontal at all times. When applied to hilly and mountainous tractors, this technology can alleviate the driver's posture inclination or left-right bumps during rough or slope operations, reduce driver fatigue and damage to the lumbar and cervical spine, improve driving comfort, maintain a stable driving posture, and enhance driving safety and operational efficiency. Considering driver comfort, when encountering frequently swinging road conditions, if the leveling system has high sensitivity, fast response, and good real-time performance, the cab or seat will also swing frequently. Although this achieves real-time leveling, frequent swinging is more likely to cause driver discomfort. Therefore, the research difficulty lies in eliminating frequent swinging while satisfying cab or seat leveling, balancing driver comfort.

Cab leveling technology was first applied to automobiles. Through sensors and on-board computers controlling solenoid valves to supply oil to cylinders, automatic cab leveling was achieved. The Swiss company St. Regis produces the SKH-60 mountain tractor (Figure 14 [Figure 14: see original paper]), and the Swiss company Aebi produces the Terratrac series mountain tractors (Figure 15 [Figure 15: see original paper]), both featuring adjustable cab attitudes (cab leveling means only the cab adjusts its angle with terrain changes, which is different from body leveling where the entire vehicle's posture is adjusted). This allows drivers to maintain a horizontal driving posture during slope operations. The machines have low centers of gravity, good traction adhesion, and off-road capability, with large tires and wheel tracks that facilitate stable slope operations. However, they lack active leveling functions, posing certain safety hazards when operating on highly undulating fields, and their wide wheel tracks are not ideal for China's complex operating environment with steep slopes, narrow roads, and fragmented plots.

The Zhu Ruixiang team [29-31] designed an automatic seat attitude adjustment system that hinges one side of the seat to a fixed base and installs a sliding guide rail on the other side. When the vehicle tilts laterally, based on the collected seat inclination information, a drive motor moves a screw rod to drive a push rod, changing the height of that side of the seat to restore it to a horizontal state. When the vehicle tilts severely enough to affect normal operation, the system automatically alarms the driver. The Chen Liqing team [32] designed an ergonomics-based automatic leveling system for agricultural machinery seats (Figure 16 [Figure 16: see original paper]). Their research found that when the seat tilts at different angles, the driver's upper torso presents different postures, and they proposed an ergonomic seat comfort leveling control strategy. Angle sensors transmit seat position and attitude in real-time and feed back to the controller to achieve automatic seat leveling. Shi Mingqi [33] adopted a spatial circular form to allow the seat to rotate within a spatial circle, achieving seat leveling through a two-degree-of-freedom series mechanism. Yao Zongbo [34] designed an automatic leveling system for forestry equipment driving platforms (Figure 17 [Figure 17: see original paper]), which can maintain the driving platform level during large undulations and obstacle crossing, reducing bumps and vibrations during operation. Wang Xiao [35] designed a three-point support positioning automatic leveling system based on a full hydraulic crawler chassis tractor for hilly and mountainous areas, which can adaptively adjust the body angle in real-time with slope changes, with a maximum leveling time not exceeding 3 seconds, meeting the operational requirements of tractors.

Mountain agricultural machinery cab and seat leveling technologies mostly borrow from automotive seat technologies. Cab leveling provides higher driving comfort, while seat leveling alone is simpler in structure and control but offers general comfort. Current research is limited to lateral leveling of cabs or seats. During tractor uphill driving or slope turning, longitudinal driving leveling is lacking, and the front lifting during uphill driving can easily create a blind spot in the forward view, preventing timely detection of sudden situations ahead (such as soil ridges or pits). Multi-source environmental perception systems (such as radar and multi-eye cameras) should be added to provide timely warnings when obstacles or pits are detected ahead. Environmental perception human-machine interaction systems are also needed, while balancing driver comfort during cab or seat leveling. This can be achieved by adding a certain leveling margin based on PID control to eliminate frequent shaking. Overall, manned hilly and mountainous tractors operating on rugged or sloping terrain should be equipped with cab leveling or seat leveling devices. The application of cab and seat leveling technology can not only greatly alleviate driver fatigue but also improve driving comfort, safety, and operational efficiency.

1.3 Body and Implement Attitude Cooperative Control Technology

The large slopes and uneven ground in hilly and mountainous areas create complex operating environments. Under these conditions, tractor bodies frequently tilt, deteriorating driving stability and significantly impacting operational effectiveness and efficiency. Particularly when tractors perform operations such as rotary tillage, seeding, plant protection, and field management in hilly and mountainous areas, implements are usually connected to the rear of the body through three-point suspension. After body leveling, the suspended implement changes its attitude with the body's movement and cannot continue ground-following operations. To ensure implement profiling operations, a synchronized control system for the body and implement is required, enabling the suspended implement to achieve slope adaptive adjustment and ground-following profiling simultaneously with body leveling. The cooperative control of tractor body and implement on slopes is shown in Figure 18 [Figure 18: see original paper], where attitude adjustment cylinders are installed on both left and right sides of the suspension. Under feedback regulation from tilt sensors, the body leveling cylinder and left/right suspension cylinders are controlled to extend and retract, achieving both body leveling and implement ground-following profiling. To ensure operational effectiveness in hilly and mountainous areas (such as tillage depth consistency, seeding depth consistency, and spray uniformity), it is essential to equip implements with slope adaptive leveling devices to maintain horizontal contact with the ground at all times, achieving ideal operational results. On the other hand, given the widespread distribution of hilly and mountainous areas, diversified crop planting, varying soil types, different agronomic requirements, and differences in climate, temperature, and precipitation, developing specialized agricultural implements suitable for regional hilly and mountainous operations will significantly improve agricultural production in these regions, increasing farmers' income and productivity while liberating labor. Therefore, developing tractor implement slope adaptive leveling technology is crucial for achieving slope profiling operations.

Currently, implement slope adaptive leveling technology mostly uses PID control, including classical PID control, fuzzy PID control, dual-closed-loop fuzzy PID algorithm, incremental PID control, and BP neural network PID control. PID control is low-cost, environmentally adaptable, simple, and reliable. For applications where control precision requirements are not extremely high but system reliability is prioritized, PID control for implement slope adaptive leveling offers high cost-effectiveness.

Zhang Jinhui et al. [36] designed a body and implement attitude synchronous control system based on a neural network PID algorithm, improving the response speed and control accuracy of the attitude control system to meet stable and efficient tractor operations in complex hilly and mountainous scenarios. Zhou Hao et al. [37] designed an automatic leveling system for rotary tillers, whose control system controls solenoid valves based on feedback from angle sen-

sors to drive leveling cylinders. Through linear displacement sensors measuring the extension of leveling cylinders and using the geometric relationship between the rotary tiller and leveling support frame, automatic leveling closed-loop control of the rotary tiller mechanism is achieved, improving the ground-following capability of the rotary tiller. Jiang Jun et al. [38] designed an electro-hydraulic suspension system suitable for hilly and mountainous tractors to meet the adaptability of matching implements to slope terrain. They built a system simulation model using AMESim software and conducted simulation analysis under constant and variable load conditions. Results showed that speed and displacement errors were controlled within 5%, basically meeting design requirements. Yang Fuzeng et al. [39] proposed a crawler lifting automatic tensioning device for contour line operations on slopes that require maintaining both body level and implement adaptive ground-following operations to meet hilly and mountainous operation requirements. Based on a dual-closed-loop fuzzy PID algorithm, they designed a body and implement attitude cooperative control system (Figure 19 [Figure 19: see original paper]) that can perform various operations such as plowing, planting, and management on slopes. Wu Fan [40] designed a remote control driving and automatic leveling system for rotary tillers. The tractor's rear suspension and implement leveling system mechanical structure consists of a three-point suspension device, with hydraulic cylinders replacing lifting rods. A controller regulates the oil inflow and outflow to adjust hydraulic cylinder extension, thereby achieving ground-following operations of the rotary tiller. Xie Bin et al. [41] designed an adaptive method for measuring implement tillage depth, installing tilt sensors on lifting arms. The controller can derive the functional relationship between voltage values and tillage depth values based on feedback angle information characteristics. However, this method only indirectly derives tillage depth values from angle sensor information, with too many uncertain factors (such as sensor cumulative errors, information transmission delays) and external environmental interferences (such as high-frequency sensor shaking, signal filtering processing). A multi-sensor fusion strategy should be used to increase measurement accuracy and real-time performance. Irsel et al. [42] designed a more precise, economical, reliable, and ergonomic laser control leveling system to improve the operational efficiency of laser-controlled slope leveling machines, redesigning existing laser control leveling blades to achieve higher automation. This machine can level hard ground with fewer repetitions and lower fuel consumption, with a leveling accuracy of 0.05° .

The main difficulties in implement leveling slope adaptive technology are: First, meeting the synchronized control of body and implement attitudes. This requires high consistency, control precision, and response time, and any failure to meet these standards will directly affect operation quality. Second, sensor selection. Currently, the most widely used method is using angle sensors to measure tilt angles and controlling corresponding cylinder extension through feedback signals. After adding PID control, rapid, stable, and accurate control of implements to reach specified tilt angles can be achieved. Laser technology can also be applied to implement leveling and rotary tillage ground leveling,

offering faster response and higher precision. Third, operation information feedback. After implement profiling operations, there is a lack of timely feedback and adjustment of actual operation effects. Corresponding sensors should be added for operation feedback and adjustment, such as real-time monitoring of each seed's sowing depth information during seeding operations.

2 Anti-Rollover Protection Devices and Warning Systems

The rugged terrain, steep slopes, and narrow roads in hilly and mountainous areas pose significant rollover risks for tractors, which is one of the main causes of driver casualties. In 2018, Japan experienced 274 fatal farm accidents, including 56 tractor rollover accidents [43]. In 2021, South Korea had 44,302 agricultural machinery-related accidents, including 11,683 rollover and overturning accidents [44]. In the United States, more than 400 people die annually from tractor rollover accidents [45]. China also frequently experiences tractor rollover accidents causing casualties [46]. Tractor rollover protection devices can prevent personal injury to drivers when tractors roll over. Tractor rollover warning systems can inform drivers in advance of the dangerous state of the tractor, issue timely alarms, or have the computer take over the tractor directly, improving driving safety. Therefore, developing anti-rollover protection devices and warning systems for hilly and mountainous tractors is crucial for ensuring driver safety.

2.1 Anti-Rollover Protection Devices

Since the 1950s, tractor rollover problems have attracted widespread attention. The currently widely accepted vehicle anti-rollover solution is the Roll-Over Protective Structure (ROPS) invented in 1956. The function of ROPS is to reduce collisions between drivers and the vehicle body under seat belt protection when the vehicle rolls over, protecting driver personal safety [47, 48]. The tractor rollover protection structure is shown in Figure 20 [Figure 20: see original paper].

Despite progress in tractor safety design, lateral rollover remains one of the most dangerous situations when operating tractors, requiring the design of more robust rollover protection structures. Due to the large loads that safety frames must withstand during rollover from vehicle weight and inertia, Jang et al. [47] from the University of Bologna, Italy, developed a model for calculating the energy absorption of actual tractor protective structures based on ROPS to better protect driver safety during tractor rollover. ROPS is currently applied to most tractors as the only device to protect operators, but it cannot prevent casualties and machine damage caused by rollover accidents. Considering the impact of safety devices on tractor operational passability, Ayers et al. [48] from the University of Tennessee developed and tested a foldable ROPS lifting assist lever that can be operated from the tractor seat. The universal lift-assist design (lever and torsion spring-integrated stop bracket) can meet ergonomic standards. Latorre-Biel et al. [49] from the Public University of Navarre, Spain, developed an inexpensive rollover energy dissipation device that can absorb

rollover energy without collapsing or severely deforming and intruding into the safety zone, improving the safety provided by ROPS structures.

2.2 Anti-Rollover Prediction and Warning Systems

Anti-rollover prediction and warning systems can perceive rollover danger before vehicle rollover, playing a crucial role in driving safety of hilly and mountainous tractors. Tractor rollover essentially occurs when the tractor's center-of-gravity position falls outside the safety zone, and the ground pressure of wheels or tracks on one side approaches zero. The key is to establish a rollover prediction model based on tractor driving speed and whole vehicle center-of-gravity position. Before the tractor reaches the critical rollover angle, the system automatically triggers the active anti-rollover system through angle sensors and control modules to adjust the tractor to a stable state.

Tractor driving simulators are powerful tools for predicting and preventing rollover accidents. Watanabe and Sakai [43] from the University of Tokyo developed a tractor driving simulator with a motion system that reproduced tractor rollover accidents on steep Japanese slope passages in virtual test drives. This simulator can be applied to tractor safety research and product development. Vehicle steady-state models can effectively predict vehicle stability conditions. Malviya and Mishra [45] from the University of Huddersfield, UK, developed an analytical multi-variable steady-state vehicle stability model to study vehicle stability under various maneuvers, crosswinds, and inclined ground conditions, feeding key information back to the system in real-time to predict vehicle status. Baker and Guzzomi [50] found that the front-to-rear mass distribution of tractors affects slope driving stability, with data showing that stability decreases as front mass increases. Guzzomi [51] from the University of Western Australia proposed installing four-wheel brakes on tractors, which would increase the consumption of whole vehicle kinetic energy when rollover risk occurs, thereby hindering further rollover development. Jang et al. [44] from Kangwon National University, South Korea, analyzed the effects of ground slope angle, obstacle shape, and height on tractor roll and pitch during hard surface driving through dynamic simulation. To examine the impact of different tractor geometries and mass specifications on vehicle lateral stability when operating on irregular inclined ground, Ahmadi [52] developed a dynamic model to study tractor instability during rollover and slip, and formulated a tractor stability index. Li et al. [53] from Kyushu University, Japan, established a rollover prediction model through mechanical calculations, concluding that tractor speed and slope angle significantly affect rollover stability. When tires are about to lose contact with the ground, operators can actively correct tractor movement according to system prompts to prevent rollover. Ojados et al. [54] from the Polytechnic University of Cartagena, Spain, designed a deployable rollover protective structure that automatically deploys when a tractor is about to roll over. After rollover, the system automatically sends a phone message with Global Positioning System (GPS) location to contact emergency responders. Liu and Koc [55] from

Columbia University developed a tractor rollover detection and emergency reporting software application that can detect tractor GPS position, speed, and stability status in real-time, and send accident reports to emergency contacts when a rollover occurs, greatly ensuring driver safety. The tractor rollover detection system is shown in Figure 21 [Figure 21: see original paper].

Currently, domestic research on tractor active anti-rollover is limited. Professor Li Zhen's team [56-58] proposed an active anti-rollover control method based on a momentum flywheel system, using active steering control as an auxiliary anti-rollover method to effectively reduce vehicle lateral acceleration during sideslip, oversteer, and sharp turns. When the controller predicts potential rollover, the momentum flywheel accelerates to rotate in the same direction as the vehicle roll to provide reverse torque and prevent vehicle rollover, but this system is currently only at the model testing stage and has not been applied to tractors. The scale-model tractor rollover test is shown in Figure 22 [Figure 22: see original paper].

Guo Tengfei [59] designed a wheeled tractor rollover warning system to reduce the risk of tractor rollover during slope operations. The system provides real-time body angle information to the controller, judges the tractor's posture and whether it is at the rollover critical value based on the limit rollover angle and delayed operation reaction angle, and feeds back rollover warning information in real-time to improve driver driving safety. Kang Jie et al. [60] designed an active anti-rollover system based on tire pressure changes. Tire pressure sensors constantly monitor each tire's pressure changes to determine rollover risk. When the system detects rollover risk, the tractor automatically takes active deceleration or shutdown actions to avoid the lag of driver response after receiving rollover warnings, reducing rollover risk. Zhuang Jiapeng [61] designed an attitude-adjustable hilly and mountainous tractor. The rear axle final drive mechanism has an independent rotation and swing function, rigidly connected to the tire, and can rotate around the rear axle half-shaft sleeve. The front axle adopts a parallel four-bar mechanism with ground floating and profiling capabilities, improving tractor anti-rollover stability. Rollover tests based on dynamic simulation software showed that rollover stability improved by 10% compared to the limit state before attitude adjustment, ensuring driver and tractor safety. Li Yankai [62] designed an anti-rollover control strategy for high-clearance plant protection machines that are prone to rollover due to high center-of-gravity. When the dynamic lateral vertical load transfer rate exceeds the rollover threshold during operation, the anti-rollover control activates to prevent rollover through active steering and speed control strategies. Yuan Guan hao [63] designed a lateral speed estimator based on kinematic and dynamic models, then designed an anti-rollover warning control system based on adaptive sliding mode control theory, automatic steering system model, and internal model PID control theory according to a three-degree-of-freedom rollover dynamic model and tire vertical load transfer coefficient model, with the goal of controlling the rollover index (Figure 23 [Figure 23: see original paper]).

2.3 Challenges Facing Active Warning and Anti-Rollover Systems for Hilly and Mountainous Tractors

Anti-rollover protection devices and warning systems for hilly and mountainous tractors concern driver personal safety and will become a hot spot and difficulty in future research. ROPS protective structures have matured over half a century in terms of energy-absorbing materials, structures, and deployment methods. Foreign research has evolved from focusing on optimization and improvement of ROPS protective structures to current rollover environment simulation and prediction models and rollover warning research, but has not fundamentally prevented vehicle rollover through control strategies or environmental perception systems. Domestic research focuses on improving vehicle and frame structures and installing active anti-rollover and warning devices.

The greatest danger in hilly and mountainous farmland operations is tractor rollover. The complex and harsh operating environment poses the following challenges for the development and industrial application of mountain tractors with active warning and anti-rollover systems: First, large ground slopes and varying obstacle heights, depths, and shapes are the main external factors causing tractor rollover. Rollover and rear rollover are more likely to occur when slope increases or tractor center-of-gravity rises. Second, the variation patterns of tractor driving speed and angular momentum when encountering obstacles and the rollover critical state are difficult to determine. Dynamic models need to be established for tractors passing different slopes and types of obstacles at different speeds to predict the rollover critical state. Third, anti-rollover structure and system design is difficult. Anti-rollover structures must meet whole machine strength and stiffness requirements while achieving center-of-gravity adjustment, and anti-rollover warning systems must actively and urgently correct the tractor's critical rollover attitude. However, integrating these structures and systems into tractors and ensuring reliable and effective operation in harsh operating environments with large slopes and high complexity remains challenging.

Future research should focus on equipping anti-rollover protective structures while simultaneously 配备具有人机交互的预警系统 (equipping human-machine interactive warning systems). At the moment when rollover risk is imminent, the tractor should actively take over and trigger anti-rollover control strategies to restore the unstable tractor to a safe state to the greatest extent possible.

3.1 Challenges

Automatic leveling technology with high reliability, good real-time performance, high sensitivity, and precision; real-time monitoring of tractor body status, tractor rollover warning and automatic adjustment technology; and miniaturization, unmanned, and automation technology will become the focus of future hilly and mountainous tractor research. In-depth research needs to be conducted in the following areas:

1. **Tractor Body, Cab, and Seat Leveling Technology:** Explore leveling mechanisms more suitable for mountain operations and responsive leveling algorithms, construct more reliable leveling feedback models, eliminate cumulative angle errors during repeated leveling processes, study the principles of hilly and mountainous tractor attitude leveling, and analyze and verify the stability and reliability of new structures and algorithms. Particularly, ensure that tractors still have good traction adhesion performance after attitude leveling, avoiding line contact or suspension of tires and tracks with/from the ground.
2. **Tractor Implement Slope Adaptive Leveling Technology:** The profiling effect and response speed of implements on slopes directly affect operation efficiency and quality. The most advanced laser control leveling systems can be used for reference. These systems offer faster response and higher precision. Further research is needed on the influence laws of soil moisture content, firmness, and other parameters on tractor suspension implement ground clearance and tillage depth, to construct adaptive tillage mathematical models.
3. **Tractor Anti-Rollover Protection Devices and Warning Systems:** Theoretically, it is necessary to construct mathematical models for vehicle center-of-gravity adjustment posture and slope track traction performance, dynamic models for vehicle slope driving and steering under ground force action, and rollover prediction mathematical models for vehicle limit rollover states. Technically, environmental perception technology can be added to generate advance warnings of the surrounding environment, alerting before the tractor reaches dangerous points rather than only taking measures when at dangerous points, which can greatly reduce rollover risks and ensure human-machine safety.
4. **Miniaturization, Unmanned, and Automation Technology for Hilly and Mountainous Tractors:** Efforts should be devoted to promoting the integration of agricultural mechanization and informatization, researching precision navigation driving technology for agricultural machinery (such as irregular slope path planning and obstacle avoidance), whole-process operation quality monitoring technology for agricultural machinery (such as various soil parameters, tillage depth, seeding depth, missed seeding rate, etc.), and remote scheduling and management technology for agricultural machinery operations (such as multi-machine coordination technology). The key lies in positioning, control, planning, and perception. These technologies can greatly improve operation precision, efficiency, and operator safety, effectively solving the problems of steep slopes, narrow roads, fragmented plots, difficult operations, and high risk factors in hilly and mountainous areas.
5. **Theoretical Reconstruction of Longitudinal Stability Calculation for Hilly and Mountainous Tractors:** When conducting steep slope operations, previous theoretical calculations become inapplicable due to

not considering large slopes (slopes $>25^\circ$), resulting in insufficient tractor climbing ability and forcing tractor drivers to choose reverse uphill driving, affecting operation efficiency. It is necessary to construct soil-pressure prediction models suitable for slope conditions to obtain the variation patterns of vehicle traction force on slopes, which is crucial for parameter selection in the preliminary design of mountain tractors. Longitudinal stability refers to the performance of tractors not rolling over or sliding when driving on slopes, mainly represented by the limit rollover angle and slip angle when going uphill, which is significant for evaluating tractor slope operation adaptability. Therefore, urgent reconstruction of longitudinal stability calculation theory for hilly and mountainous tractors is needed.

3.2 Prospects

This paper summarizes the research status of hilly and mountainous tractor leveling and anti-rollover systems both domestically and internationally, providing a detailed review of tractor body, cab, and seat leveling technology, tractor implement leveling slope adaptive technology, and tractor anti-rollover protection devices and warning technology.

In tractor body leveling technology, parallel four-bar and hydraulic differential height systems have simple structures; folding-waist and twisting-waist types are more suitable for continuously undulating rugged roads; center-of-gravity adjustable and omnidirectional leveling types offer good slope traction and adaptability. Cab and seat leveling technology is based on angle sensor adaptive control, with the key being to alleviate driving fatigue and improve comfort. Body and implement attitude cooperative control technology mostly uses PID control for synchronized management but lacks operation effect feedback mechanisms. Tractor anti-rollover protection devices and warning technology build upon rollover protective frames, using environmental simulation and perception to predict rollover danger signals in advance and provide timely feedback. Affected by complex environments and slopes, the research and development of hilly and mountainous tractors has always been a hot spot and difficulty. Future focus should be on safety and intelligentization.

Affected by complex environments and slopes, the research and development of hilly and mountainous tractors has always been a hot spot and difficulty. Future focus should be on safety and intelligentization.

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