RESEARCH STATUS AND PROSPECTS OF KEY TECHNOLOGIES IN AGRICULTURAL MACHINERY CHASSIS FOR FIELD FARMING OPERATIONS
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面向大田作业的农机底盘关键技术研究现状与展望

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ABSTRACT
As the locomotion system of agricultural machinery, the chassis significantly influences operational efficiency and maneuverability. This study focuses on two key aspects: field-oriented agricultural machinery chassis components and their intelligent development. The study examines the historical evolution of agricultural machinery chassis. A detailed analysis is provided on the operational mechanisms, technical features, and global application status of chassis drive systems, steering mechanisms, and leveling control technologies. Building upon this analysis, the study further explores future trends in field-oriented agricultural machinery chassis development. Field agricultural machinery chassis will develop towards intelligent technology, modular design, new energy and autonomous driving technology applications. Incorporating advanced sensor networks, machine learning algorithms, and artificial intelligence, the chassis system will implement tightly coupled multi-sensor fusion and control strategies to enable synergistic optimization of powertrain, steering, and leveling mechanisms, with integrated prognostic and health management capabilities.

摘要
农机底盘作为农业机械的行走部件，是其性能直接影响着农业机械的作业效率和灵活性，本文主要从面向大田场景的农业机械底盘部件及其智能化两个方向进行阐述，同时归纳总结了新结构新技术在农业机械底盘上的研究成果和具体应用，分析了农业机械底盘的发展历史，详细阐述了农机底盘传动技术、转向技术以及调控技术的工作原理、技术特点及国内外应用现状。在此基础上对大田场景下的农机底盘的发展趋势进行了展望，并指出农业机械底盘机械化和智能化未来的研究重点：大田农业机械底盘将朝着智能化技术、模块化设计、新能源化和自动驾驶技术的应用方向发展。通过利用先进的传感器、机器学习和人工智能技术，底盘系统将采用多模态传感器融合和控制技术深度耦合，实现动力传动、转向、调平等系统的协同优化，并集成故障预测与健康管理功能。

INTRODUCTION

Functioning as a core mobile platform, the chassis integrates powertrain, locomotion, steering, braking, and electro-hydraulic control systems into a unified mechanical framework. As the structural and functional backbone, the chassis transmits propulsion power throughout agricultural operations including tillage, seeding, crop management, and harvesting. Consequently, advancements in chassis technology serve as critical indicators of agricultural modernization and intelligentization, particularly for field-scale machinery systems. Recent scholarly efforts have pioneered innovative research on wheeled, tracked, and hybrid-track chassis systems, emphasizing operational efficiency, intelligent control, and environmental sustainability. Breakthroughs in powertrain optimization, adaptive steering mechanisms, and intelligent chassis regulation have substantially enhanced operational capabilities *(Bechar et al., 2017)*.

Developed countries in Europe and America have witnessed more than a century of agricultural machinery evolution. Modern agricultural equipment employs multi-sensor systems and intelligent control technologies to enhance chassis intelligence. The manufactured agricultural machinery features large-scale, integrated, and intelligent characteristics. The operational quality and performance of their agricultural machinery chassis have been significantly improved. China's agricultural machinery development commenced in the 1950s.

It has undergone developmental stages including introduction, imitation, technical improvement, and independent R&D. A relatively complete supporting system for agricultural machinery R&D and production has been established. However, the informatization and intelligence level of Chinese agricultural machinery remains relatively low. In recent years, domestic researchers have continuously improved agricultural machinery chassis structures. Deeply integrating intelligent control technologies to vigorously promote the transition from basic mechanization to intelligent, multifunctional, and integrated development. (*Fan et al.*, *2024)*.

This study systematically reviews recent advances in agricultural machinery chassis research, with dual focus on structural components and intelligent control systems, through comparative analysis of global developments. Furthermore, it elucidates critical research directions for next-generation chassis development. The findings provide strategic insights to facilitate the transition from conventional mechanization to intelligent agricultural systems.

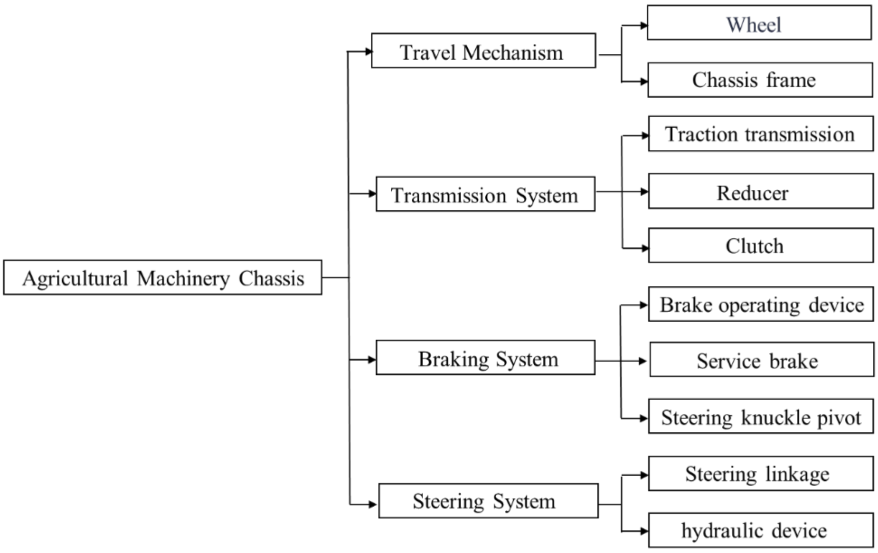


Fig. 1 - Agricultural machinery chassis structure module

Table 1

Development Status of Agricultural Machinery Chassis for Field Farming Operations

Technosphere	Characteristic	Current Situation	Key Technology
Transmission Technology	Electronic control architecture	Industrialization of electro-hydraulic hydrostatic stepless speed change system	Hybrid power technology, machine learning algorithms, big data systems
	Intelligent power integrated control	Hybrid power systems are developing rapidly	Topological and soil resistance analysis technology.
Steering Technology	The steering mechanism works in coordination with GNSS	The intelligent steering system becomes the core	Navigation technology, machine learning optimization
	Unmanned diversified field operations	Integrate advanced data analysis technologies	Data analysis algorithms, remote monitoring
Leveling Technology	Actively level to maintain consistent operation depth	Foreign technologies are mature and highly intelligent	Sensor technology, machine learning algorithms
	Precise variable operation (fertilization/sowing)	The domestic production volume has a low degree of industrialization	Coordinate control strategies and integrate vehicle control architectures

RESEARCH ON AGRICULTURAL MACHINERY CHASSIS TRANSMISSION TECHNOLOGY

Based on power delivery mechanisms, agricultural drivetrains are fundamentally classified into discrete-ratio transmissions and continuously variable transmissions. The core subsystems comprise clutch assemblies, transmission units, and final drive mechanisms. Predominant discrete-ratio configurations in modern agricultural applications include synchronized manual transmissions (SMTs) and power-shift transmissions (PSTs). Continuous power transfer solutions are primarily represented by hydrostatic transmissions (HSTs) with closed-loop hydraulic circuits, hydromechanical continuously variable transmissions (HMCVTs) and emerging electrified CVT systems (eCVTs) with dual-motor power-split architectures.

The clutch assembly, positioned at the engine-transmission interface, serves as a power interruption device for torque transfer engagement/disengagement. Western agricultural machinery predominantly employs dry-type dual-stage clutch (DSC) configurations with independent actuation mechanisms. Japanese-designed systems typically adopt single-stage diaphragm spring clutches with integrated preload adjustment. Operational challenges include thermal-induced slippage and partial disengagement *(Park et al., 2015; Zhu, 2017)*. Current research mainly focuses on the stability of clutch engagement/disengagement. *Hu et al. (2016)* developed a grey relational analysis (GRA)-based reliability assessment framework for agricultural clutches. The study constructed failure-mode-oriented grey relational models (GRM-I to GRM-IV) to derive reliability ranking matrices. Used Matlab to plot line charts for optimal prototype selection. Wen's team investigated the prevalent mean time between failures in compact utility tractors. The research integrated parametric optimization, 3D CAD modeling, finite element analysis (FEA), and digital mock-up (DMU) kinematic simulation. A novel Belleville spring clutch was engineered to supersede conventional helical compression spring designs *(Li W. et al., 2012)*. *Li et al.* conducted comparative analysis of engagement dynamics between friction clutches and positive engagement claw clutches. The team developed a multi-mode hybrid clutch system with detailed operational phase analysis *(Caifeng et al., 2014)*.

Table 2

Clutch classification and key characteristics

Classification Methods	Types	Structural	Characteristics
Friction Plate Count	Single-Plate Clutch	1 friction pair	The connection is smooth, with little impact and vibration, and the transmitted torque is small.
	Multi-Plate Clutch	Multiple friction plates	The torque transmission is strong and the structure is complex.
Pressure Plate Assembly	Spring Compression	The clamping force between the driving and driven friction components is generated by a pressure spring	A spring-pressure clutch featuring high and stable torque transmission capacity, simple and compact structure, with reduced disengagement efficiency
	Lever-Type Pressure Plate	Uses lever mechanism's elastic force to create interfacial pressure between friction pairs	A normally-disengaged clutch with low operation effort, though exhibiting challenges in precise power transmission control.
Friction surface operating conditions	Dry clutch	Operates without oil lubrication; friction discs are exposed to ambient air	High torque transfer efficiency; Better fuel economy; Fast engagement & high clamping force; Poor drivability; Slow cooling; Shorter service life
	Wet clutch	Operates in an oil bath, using lubricant for cooling and reduced wear.	Superior drivability; Efficient cooling; Extended service life; Lower torque transfer efficiency; Delayed engagement response

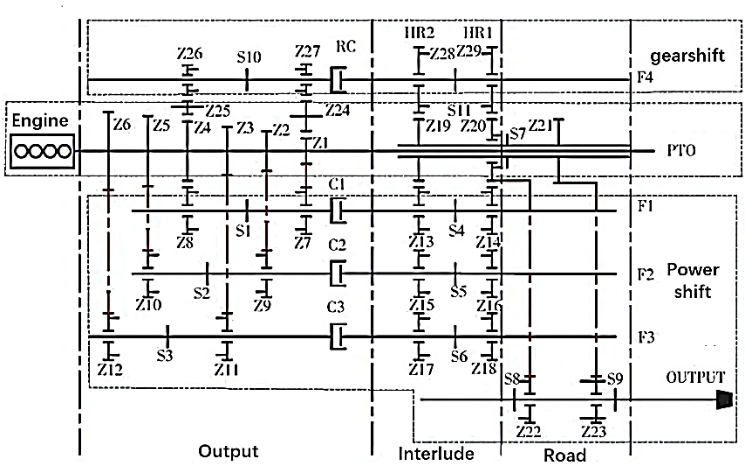


Fig. 2 - Structural sketch of full power shift transmission
(Wang et al., 2024)

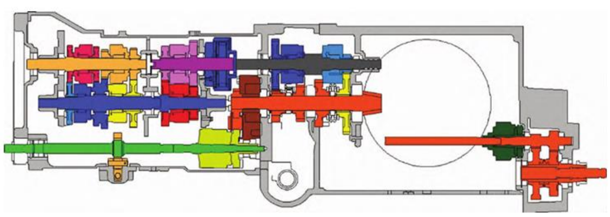


Fig. 3 - Power shift drive train
(Jiang，Bin, 2023)

The evolution of agricultural discrete-ratio transmissions has progressed through four technological generations: manual transmission (MT), synchronized manual transmission (SMT), power-shift transmission (PST), and automated power-shift transmission (APST). Early agricultural machinery commonly used mechanical shifting, i.e., manual transmission (MT). To improve shifting ease and speed, synchronizer technology was adopted, with inertial synchronizers being most prevalent today. Power-shift systems are categorized into partial power-shift (PPS) and full power-shift (FPS) configurations *(Bi, 2018)*, distinguished by torque interruption levels. PPS systems utilize a series-coupled architecture integrating power-shift modules with mechanical range groups (typically 4+4 or 6+2 arrangements). FPS systems predominantly employ planetary gearsets with multi-plate wet clutches in epicyclic configurations. The power-shift system comprises three core subsystems: (1) multi-range transmission assembly, (2) electro-hydraulic proportional control unit (EHCU), and (3) closed-center hydraulic circuit. Internationally, power-shift technology reached commercialization stage in the 1980s (e.g., John Deere PowerShift™ 1972). As the pioneer of power-shift technology in China, YTO Group (First Tractor Works) initiated domestic R&D in this field since 2012. The company's Hi-Lo power-shift series commenced with LF804 (80 hp) and LF1104 (110 hp) models, Subsequent launches of LF1504 (150 hp), F2204 (220 hp) and Dongfanghong LZ2604 (260 hp) established a complete power-shift portfolio covering 80-260 hp. In 2024, China YTO Group accomplished self-sufficient R&D in 260-320 hp transmission systems for heavy-duty automatic power-shift technology. In 2015, Weichai Lovol introduced the Apolos series—P5000, P6000, and P7000—three distinct platforms of power-shift tractors. In 2024, Zhejiang Haitian Machinery developed a spatially parallel dual-clutch power-shift assembly for tractors, enhancing power transmission efficiency while markedly decreasing shift duration and minimizing power loss. The FSP26, developed by Fast Gear, represents the industry’s first 6-forward/3-reverse parallel-shaft fully automatic power-shift transaxle, utilizing a cascaded multi-stage transmission system integrating primary and secondary gearboxes *(Jiang Bin, 2023)*.

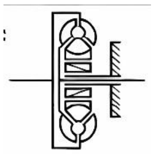
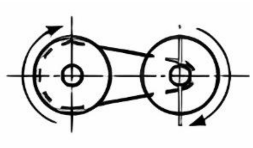
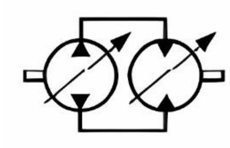
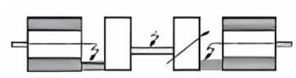
The integration of microelectronics-based electronically controlled power-shift transmissions (ECPST) has emerged as a pivotal advancement in power-shift technology, significantly enhancing operational efficiency while accommodating complex field conditions and dynamic load variations. The integration of microelectronics-based electronically controlled power-shift transmissions (ECPST) has emerged as a pivotal advancement in power-shift technology, significantly enhancing operational efficiency while accommodating complex field conditions and dynamic load variations. A power-oriented control mode is activated during field operations to maintain optimal traction torque, whereas an economy mode prioritizes fuel efficiency during road transit. The ZF Eccom series, as an industry pioneer, incorporated electronic control units (ECUs) to achieve millisecond-level shift precision through real-time monitoring of engine speed, vehicle velocity, and load conditions via integrated sensors. CAN bus-based communication facilitates seamless integration between the transmission, engine, and vehicle control systems, establishing an intelligent cooperative control network. Electro-hydraulic control systems, representing the state-of-the-art in power-shift technology, employ proportional solenoid valves for precise hydraulic pressure modulation during clutch engagement, coupled with overload protection mechanisms to mitigate shift shocks and dynamic loads, thereby substantially improving shift quality. A representative example is John Deere's PowerShift transmission, which incorporates 4 closely spaced power-shift speeds, 6 forward gears, and a power reverser, utilizing closed-loop shift technology to dynamically optimize shift quality through multi-parameter adaptive control. CNH Industrial introduced an innovative 19-forward/4-reverse full power-shift system in 2012 for its premium Case IH and New Holland tractor lines (see Figure 5.41). Case Corporation's tractors implement pulse-width modulated (PWM) electromagnetic valve, which are precisely regulated by the central controller to algorithmically optimize the shift process rationality.

Recent years have witnessed sustained intensification in power-shift technology research, Shi Xinxin and Xia Guang developed a constant-torque shift strategy for high-horsepower tractors during traction operations, derived from systematic analysis of power-shift control mechanisms. Investigating modular power-shift transmissions for medium-large tractors *(Xinxin Shi et al., 2019)*, Cao Wenda and Sun Baoqun established an innovative shift control algorithm parameterized by throttle position and output shaft rotational speed, implemented through a quad-range power-shift module *(Cao et al., 2019)*. Xu Liyou et al. identified limitations in traditional shift quality assessment criteria when evaluating dual-clutch transmission (DCT) performance during high-load agricultural operations, systematically characterizing the temporal effects of odd/even-gear clutch actuation sequences on shift quality, while formulating comprehensive DCT shift dynamics models and quality simulation frameworks specifically for agricultural tractors *(Xu et al., 2015)*.

Continuously Variable Transmission (CVT) has been widely recognized as one of the most efficient vehicular speed regulation technologies, particularly as the advancement of driver-assistance systems has driven growing CVT adoption rates in agricultural equipment. Continuously Variable Transmission (CVT) has been widely recognized as one of the most efficient vehicular speed regulation technologies, Table 1 summarizes the operational principles of mainstream CVT configurations currently available on the market. Hydraulic torque converters offer cost advantages yet demonstrate constrained speed ratio ranges, chain-driven mechanical systems achieve high transmission efficiency, typically combined with hydraulic or electric drives. Hydrostatic transmissions, despite lower efficiency, show good adaptability and are mainly used in small agricultural machinery. Electronically controlled CVT (e-CVT) systems have emerged as a prominent research focus in recent years, though their commercial implementation remains limited.

Table 3

Classification and characteristics of continuous transmission

Types	Torque Converter	Mechanical Drive	Hydrostatic Transmission	Electric drive
Schematic diagram				
Principle of energy transfer	Fluid mass forces in pumps and turbines	Traction force on frictional contact surfaces	Hydrostatic pressure in pumps and motors	Electromagnetic forces on generators and motors
Ratio control system	Load	Traction radius	Unit flow rate	Frequency of current
Typical Applications	Passenger cars, Construction machinery	Passenger cars, agricultural machinery	Mobile machine	Passenger cars, construction machinery
Efficiency	Low	Excellent	Moderate	Better

The 1970s marked the widespread adoption of hydraulic drive systems in self-propelled combine harvesters across European and North American markets, offering distinct advantages over conventional mechanical transmission systems by mitigating inherent limitations. Hydraulic power transmission utilizes fluid media to transfer energy via controlled variations in either kinetic energy (flow velocity) or potential energy (pressure) within closed-loop circulating systems. Practical implementations typically integrate hydraulic transmission with mechanical drivetrains or hybrid configurations to optimize performance *(Pullen et al., 2014)*.

The Hydrostatic Transmission (HST) system constitutes an integrated hydrostatic drive assembly comprising a hydraulic pump, motor, and embedded control valving, where a mechanical gearbox interposed between the hydraulic motor output and final drive axle extends the efficient speed modulation range, enabling segmented continuous variable transmission (CVT) operation. Sun Shumin's team advanced HST architecture by consolidating both wheel-drive and header gear trains within a unified housing, establishing a space-efficient closed hydraulic circuit with enhanced power density. Leading international manufacturers have implemented hydrostatic CVT walking mechanisms in semi-feeding combine harvesters, achieving substantial gains in overall machine performance metrics.

Current Chinese-built harvesters predominantly utilize either HST systems or traditional mechanical transmissions for chassis propulsion *(Sun et al., 2014)*. Recent years have witnessed expanding adoption of full hydrostatic four-wheel-drive (4WD) systems in agricultural machinery, where supplementary rear-wheel drive augments the primary front-wheel drive, delivering exceptional traction performance in waterlogged fields with demonstrated improvements in terrain adaptability and field passability rates, while simultaneously enhancing integrated control between harvesting implements and chassis propulsion systems through unified hydraulic signaling *(Zou et al., 2007)*.

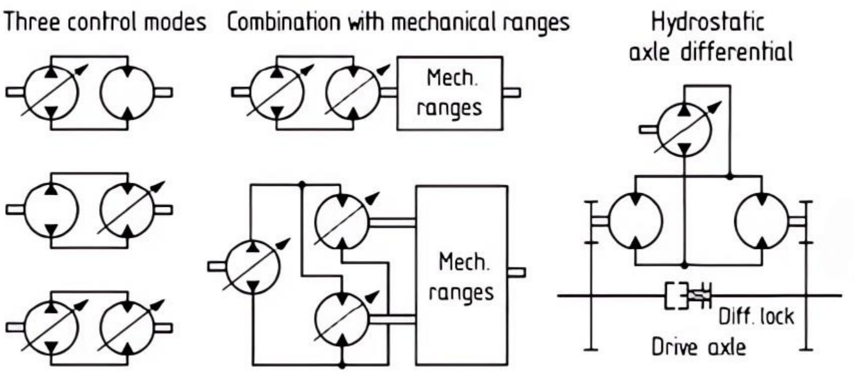


Fig. 4 - Main forms of hydrostatic devices
(Eck; Theissen et al., 2014)

The advancement of electromechanical-hydraulic integration has significantly promoted the adoption of Continuously Variable Transmission (CVT) systems in agricultural machinery, delivering enhanced operational efficiency and superior driving ergonomics. Given the demanding operational requirements of tractors working under low-speed/high-torque conditions, modern tractor CVT systems necessitate the coordinated operation of planetary gear mechanisms and hydraulic motors to ensure optimal power transmission. CVT technology eliminates power interruption during gear shifts characteristic of conventional transmissions, enabling persistent operation of the engine within its optimal fuel-efficiency zone, with documented 15-20% improvements in comprehensive energy efficiency. Current commercial CVT configurations primarily fall into three categories (as illustrated in Figure 4): 1) Input-coupled power-split transmission, 2) Output-coupled power-split transmission, and 3) Compound-coupled power-split transmission.

With a development history exceeding two decades, CVT technology currently dominates the high-power tractor market, capturing >60% market penetration for 200+ horsepower tractors in European and North American markets. As a representative case, the Massey Ferguson 8700DYNA-VT series incorporates the DYNA-VT continuously variable transmission system coupled with an advanced electronic control management system (*Fendt, 2018*). This configuration represents an input-coupled design, wherein the drive shaft bifurcates power transmission: mechanically through a primary gear train and hydraulically via auxiliary oil circuits. Speed modulation is achieved through an epicyclic gear mechanism capable of bidirectional speed regulation John Deere pioneered the AutoPower continuously variable transmission system in its 8030 series tractors.

The powertrain architecture features engine-driven left sun gear activation, with subsequent power bifurcation occurring at dual planetary gear stages. The ring gear energizes a hydrostatic drive unit that selectively actuates either the planetary carrier or central sun gear, establishing a characteristic output-coupled transmission topology. China's CVT tractor development initiated comparatively later. The LW4004 CVT tractor developed by YTO Group premiered at China's 12th Five-Year Plan Scientific Innovation Achievements Exhibition (2016), addressing critical technological voids in domestic heavy-duty tractor manufacturing. The 2021 market introduction of Lovol P7000CVT intelligent tractor represented a watershed moment as China's first commercially viable smart CVT tractor.

Table 4

Market mainstream CVT tractor

Model number	**Massey Ferguson 8700 DYNA-VT Tractor**	**John Deere 8030 Series Tractor**	**Dongfanghong LW4004 CVT Tractor**	**Lovol P7000 CVT Smart Tractor**
Picture				
Dynamical system	MTU 520kW Hydrogen Hybrid Engine	455kW PowerTech Pro	285kW YTO-6DA	320kW YTO-6DIESEL

Model number	Massey Ferguson 8700 DYNA-VT Tractor	John Deere 8030 Series Tractor	Dongfanghong LW4004 CVT Tractor	Lovol P7000 CVT Smart Tractor
Fuel efficiency	2.1L/kWh	2.4L/kWh	2.8L/kWh	2.5L/kWh
Transmission System	12+4i-CVT	8+4P-CVT	6+2M-CVT	10+3e-CVT
Transmission efficiency	94.7%	89.2%	86.5%	91.8%
Maximum torque	3200Nm	2700Nm	1800Nm	2200Nm
Maximum lifting force	68kN	55kN	42kN	58kN

Researchers worldwide have systematically investigated continuously variable transmission (CVT) technologies for agricultural tractors, with significant contributions from both domestic and international research teams. Zhang et al. conducted pioneering research on economic optimization of CVT operation patterns, the study formulated an optimization model with efficiency maximization as the objective function under operational constraints, numerically solving for total drivetrain efficiency. Results quantified the optimal hydraulic-mechanical CVT (HMCVT) ratio, engine speed, and torque configurations for peak efficiency conditions. The team innovatively developed a Power-Circulating HMCVT (PCHMCVT) prototype specifically designed for heavy-duty agricultural applications *(Zhang M. et al., 2020)*. Kozhushko et al. pioneered a novel circuit configuration strategy that synchronizes dual-power flow transmission with output planetary gear sets. The method enables dynamic reconfiguration of hydraulic circuits to optimize dual-flow HMCVT performance across operating conditions (85-92% efficiency range) *(Kozhushko et al., 2024)*. Xi's team developed an integrated control strategy combining engine speed regulation with hydraulic speed modulation for precise HMCVT output speed-torque ratio management. Co-simulation results demonstrated the strategy's efficacy, showing 23% faster response to acceleration demands and 35% better stability under step load disturbances *(Xi et al., 2024)*.

An electric drive system transmits motor-generated power either to drivetrains/axles or through direct multi-hub motor drive, representing an integrated hydraulic-electric transmission solution. The system architecture comprises: (1) variable-flow hydraulic power units with frequency-converted/DC-controlled motors coupled with high-efficiency, low-ripple fixed-displacement pumps; (2) electro-hydraulic actuators integrating motor-pump assemblies, hydraulic cylinders, or low-speed high-torque hydraulic motors; and (3) hybrid powertrain configurations for agricultural vehicles. As a critical performance metric for hybrid vehicles, energy management strategies (EMS).

Mocera et al. developed a hybrid tractor architecture featuring electric CVT (eCVT) functionality, under the hybrid eCVT architecture, combining the best features of simpler parallel and series hybrid layouts, different numerical model control strategies were adopted to achieve peak power performance with relatively small motors *(Mocera et al., 2020)*. Zhang et al. formulated a tillage-specific EMS using Bellman's optimal dynamic programming approach, which leverages cost-effective electric power to achieve superior speed-torque decoupling (with 92% decoupling efficiency), thereby extending the eCVT hybrid system's seamless speed regulation range by 35% compared to conventional designs *(Zhang K. et al., 2024)*.

Table 5

The layout of mainstream manufacturers in the field of new energy agricultural machinery

Manufacturer	Technical route	Principle	Advantages	Market Layout
John Deere	Hybrid and pure electric dual-track parallel strategy	Launch the hybrid tractor equipped with an Intelligent Energy Management System	Implement AI-driven powertrain optimization to reduce fuel consumption by over 20%	Implement Autonomous Operation System (AOS) and Remote Telemetry & Monitoring (RTM) across
CNH Industrial	Implement Parallel-Series Hybrid Power Architecture	High-Efficiency Energy Recovery System Integrated with CVT	Heavy-Duty Operation Optimization: 30% fuel consumption reduction & 50% noise reduction	2025 Electric Tractor for Hilly Terrain: Technical Implementation Plan

Manufacturer	Technical route	Principle	Advantages	Market Layout
AGCO	Electric Drive and Hydrogen Fuel Cell Technology	Pure Electric Tractors with Modularized Battery Architecture	8-Hour Continuous Operation per Hydrogen Refueling	Integrated Autonomous Navigation System and IoT Platform for Precision Agricultural Operations
Kubota	50–100 PS Pure Electric Tractor Series	Permanent Magnet Synchronous Motor (PMSM) with Lightweight Architecture for 50–100 PS Electric Tractors	6-Hour Endurance with 80% Fast-Charge in 1 Hour: Enhanced Energy Solution for Electric Tractors	Collaborative Development with Battery Suppliers for Ultra-High Energy Density Cells
CLAAS	Hydrogen Fuel Cell Prototype Development for Agricultural Tractors	Integration of Fuel Cell Systems with Energy Storage Modules for Agricultural Tractors	Single Hydrogen Refueling Endurance of 8 Hours for Agricultural Tractors: Technical Implementation	Hydrogen Tractor Pilot Program Implementation in Germany & France

RESEARCH ON STEERING TECHNOLOGY OF AGRICULTURAL MACHINERY CHASSIS

Steering performance is an important aspect of agricultural vehicle evaluation, not only directly reflects maneuverability and accuracy during steering, but also affects tracked vehicles' dynamics, stability, and operational efficiency. Agricultural machinery mainly has wheeled and tracked drive types, with their most obvious difference being steering methods *(Fashutdinov et al., 2020)*. Wheeled harvesters' steering systems generally consist of three parts: control mechanism, steering gear, and linkage. Operating on Ackermann geometry, the system achieves trajectory tracking through precisely controlled wheel angles. Independent steering axles/wheels enable precise positioning for accurate turning radius control. Figure shows four wheeled vehicle steering kinematic models.

Yang's team developed an omni-directional steering module featuring:

(i) retractable wheel mechanism,

(ii) closed-loop hydraulic drive, and

(iii) PID-controlled servo system. Field validation demonstrated 50% time reduction, 80% path length optimization, and 50% headland space savings *(Yang Y. et al., 2022)*.

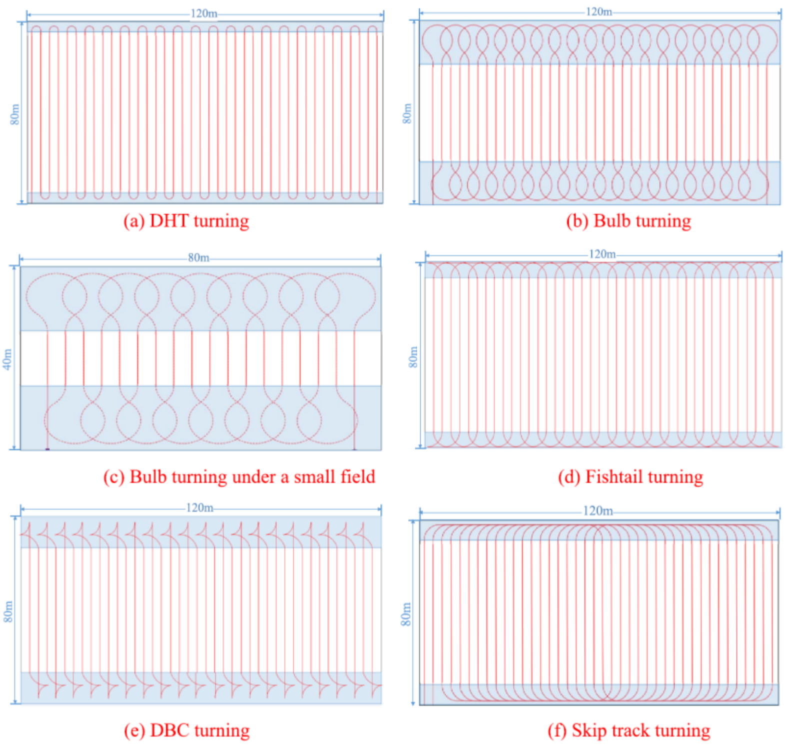
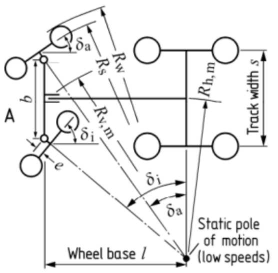


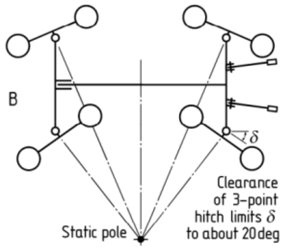
Fig. 5 - Comparison of different methods of ground steering under global path planning
(Yang Y. et al., 2022)

Lv et al. proposed a front-axle swing steering mechanism, using chassis pins to swing the front axle around stationary drive wheels for steering. Provides better maneuverability than conventional tractors. Tests confirmed stable straight-line travel and omnidirectional steering *(Lv et al., 2015)*.

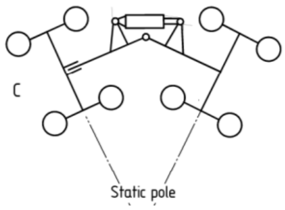
Wang et al. addressed poor adaptability of paddy field chassis, designing a high-clearance articulated multi-purpose chassis. Finite element analysis identified frame weak points. Theoretical and field tests confirmed compliance with operational requirements for speed, turning radius, gradeability, and ridge clearance *(Wang J. et al., 2017)*.



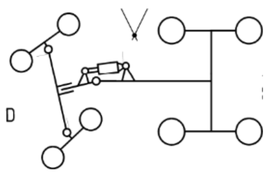
(A) Two-Wheel Steering



(B) All-Wheel Steering



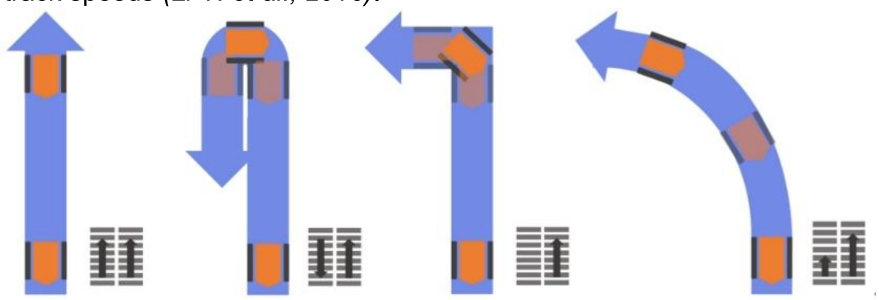
(C) Articulated Steering



(D) Combined Steering

Fig. 6 - Wheeled Steering Kinematics *(Brenninger, 2003)*

Tracked propulsion systems eliminate conventional steering wheels, utilizing differential speed control between bilateral crawlers for directional changes. They exhibit superior maneuverability with smaller turning radii, benefiting small-field operations *(Guan et al., 2020)*. Modern tracked harvesters implement three principal steering mechanisms: (i) Clutch-based steering: Single-side power interruption through multi-plate wet clutches, creating 100% torque differential for pivot turns. (ii) Using planetary gear systems to brake/decelerate one side while accelerating the other. 3. (iii) Compound planetary steering: Adding a countershaft to drive planetary carriers, superimposing/subtracting speeds to axles for steering *(Chen et al., 2010)*. Yanmar series harvesters use dual-HST (straight-steering) mechanical transmissions, achieving differential/brake/counter-rotation steering via 6-position steering wheel control *(Wang J. et al., 2017)*. Li Yaoming developed a counter-rotation steering mechanism, braking power output gear enables single-side brake steering, utilizing ground resistance on non-braked gear for skid steering, using central transmission's counter-rotation principle for equal-but-opposite track speeds *(Li Y. et al., 2016)*.



(A) Linear Motion; (B) Differential Reversal Steering; (C) Unilateral Braking Steering; (D) Differential Steering

Fig. 7 - Primary Steering Methods for Track-Type Agricultural Machinery
(Wang Y.et al., 2023)

In recent years, navigation and assisted driving technologies have been widely applied in agricultural production. Requires controllable system modifications to powertrain and transmission systems based on perception and path planning. Control systems process sensor/path data via algorithms to command powertrain responses to achieve path tracking and assisted driving along predefined trajectories.

Electric steering wheels are widely used due to easy retrofitting and flexible installation. Electro-hydraulic valves are mainstream for high-precision wheel control. Nevertheless, difficult retrofitting is a major limitation. Current path tracking algorithms include linear models, PID, optimal control, fuzzy logic, neural networks, and pure pursuit. The specific advantages and disadvantages are shown in the table as follows.

Table 6

Common path tracking algorithms and their characteristics

Control methodology	Key characteristics	Advantages	Disadvantages
Linear Model Algorithm	Requires predefined proportional relationships	Simple implementation	Limited accuracy, unable to eliminate steady-state error
PID Control	Translation: PID Control | Requires mathematical model & transfer function	Good adaptability, strong robustness, effective algorithm optimization	Prone to overshoot, oscillation, and long response time
Optimal Control	Requires solving optimal control parameters	Good performance metrics	Poor robustness, limited adaptability
Fuzzy Algorithm	Uses linguistic methods, no mathematical model required	Strong robustness, good fault tolerance, excellent human-machine interaction	Lacks systematic design, poor precision
Pure Pursuit Model	Derives control equations through geometric modeling	High control accuracy, strong stability	Difficult to adjust lookahead distance
Sliding Mode Variable Structure Control	Control Discontinuity	anti-interference ability	Chattering phenomenon

Addressing complex control challenges in specialized agricultural environments, Xu Yang developed an integrated path-tracking stability control framework combining model predictive control (MPC) with an enhanced fuzzy logic algorithm. The methodology incorporates a four-wheel steering (4WS) kinematic model coupled with lateral stability dynamics, enabling simultaneous optimization of path-tracking precision and rollover prevention. Simulations and experiments showed this strategy outperforms traditional methods in tracking performance and stability *(Yang X. et al., 2024)*. Gülşah Demirhan Aydın designed trajectory tracking and slip ratio controllers for rear-wheel independent drive electric unmanned tractors, with mathematical model simulations. Experimental results confirmed 15% slip ratio maintenance (±2% variation) with simultaneous 2.5 cm tracking precision, achieving 22% energy savings during headland turns *(Aydın et al., 2024)*.

Guangshun An proposed a fuzzy-based electric automatic steering system (EASS) with PID for wheeled agricultural machinery steering and parameter self-tuning. Control rules were developed by analyzing the relationship between resistance torque and steering angle, applied to rice transplanters, tractors, and high-clearance sprayers *(An et al., 2024)*. Yafei Zhang's EDO-SMC framework incorporates an enhanced kinematic model with slip compensation and a 50Hz-bandwidth disturbance observer for unstructured terrain navigation. By improving kinematic models, designing extended disturbance observers, and optimizing sliding surfaces, it effectively compensates wheel slip, with validated accuracy and robustness *(Zhang Y. et al., 2025)*.

Path planning for harvesters requires comprehensive consideration of field boundaries, harvested/unharvested areas, and internal obstacles. Develop rational navigation routes according to crop-specific harvesting requirements and harvester mechanical characteristics. Current approaches mainly include global and local path planning. Mu Yuanjie et al. generated operational paths by calculating turning points, entry/exit points using field corner coordinates, crawler equipment properties, and working spacing *(Mu et al., 2023)*. Liu Tingmin et al. planned paths using fixed-step continuous point search based on field dimensions and effective working width. Local path planning generates real-time trajectories under global guidance using sensor-perceived environmental data. Planning must optimize global path following while addressing dynamic environmental constraints *(Liu Tingmin et al., 2020)*. Zeng Hongwei et al. segmented unharvested areas using region growing algorithm. Growth thresholds were adaptively calculated via Gaussian multi-peak fitting of image histograms. Morphological processing of binary images extracted boundaries between harvested/unharvested zones. Least squares method then fitted the harvester navigation line *(Hongwei et al., 2020)*.

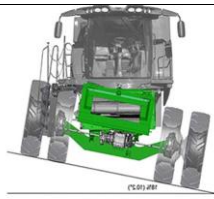
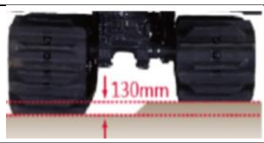
RESEARCH STATUS OF AGRICULTURAL MACHINERY CHASSIS LEVELING TECHNOLOGY

Western countries have high land intensification, with auto-leveling technology widely used in large agricultural machinery, especially combine harvesters. The designed combine harvester auto-leveling systems feature advanced technology and high intelligence. They significantly improve harvesting efficiency and operational safety. Leveling systems are highly integrated with harvesters, with deep coupling between control systems. Table 3 lists agricultural machinery with chassis adjustment technologies currently available. Currently, China's market has limited crawler combine harvesters with lateral leveling capability e.g. Jiangsu Donghe's C805GT/GCT semi-feeding combines. YTO Group's 525EX semi-feeding rice harvesters. Anhui Jingtian's 865EX-T semi-feeding combines. These machines share similar auto-leveling operating principles. All use lift mechanisms between crawler frames and chassis to adjust ground clearance. Achieving chassis height and lateral tilt angle adjustment *(Li D., 2014)*.

In recent years, researchers have conducted a series of studies on the automatic leveling system. Shi Xin et al. (2017) developed a self-propelled corn combine leveling system. Using electromechanical control for automatic lateral (±17.5°) and longitudinal (-11°~17.5°) tilt adjustment. Static/dynamic tests verified >62.5% leveling success rate *(Xin Shi, 2017)*. Jin Chengqian's team developed an omnidirectional-leveling crawler harvester chassis with auto/manual dual-mode adjustment longitudinal range: -5°~7°, lateral: ±6.5°. Effectively adapts to complex terrain operations *(Jin C. et al., 2020)*. Jing Bo's team (2019) developed a multi-point lifting crawler combine chassis. Structure includes front/rear swing arms, leveling cylinders, undercarriage and frame. ADAMS simulation validated structural design. Load-sensing circuit reduces pressure fluctuation (26.5%) and throttling loss (18.3%) *(Jin B., 2019)*.

Table 7

Market agricultural machinery with leveling device

Model number	Types	Characteristics	Picture
LAVERDA AL QUATTRO TECHNO	Universal Terrain Harvester	Tilt Compensation with Maximum Lateral Tilt of 21.8°, Longitudinal Uphill Slope of 16.7°, and Longitudinal Downhill Slope of 5.7°	
DEERE 2975	Mountain Terrain Combine Harvester	A maximum tilt compensation of 15 ° can be achieved	
Massey Ferguson 7370	Grain Combine Harvester with ParaLevel System	The maximum adjustment angle is 8.5 ° for the two-drive harvester and 11.3 ° for the 4-drive harvester	
New Holland CR9000 Series	Combine Harvester with SLS (Self-Leveling Shoe) Cleaning System	The cleaning system can be kept level on an 8.5 ° slope	
Kubota WHR1200	Combine Harvester Frame Lateral Leveling System	The cutting table is fixed with the car body, and the ground clearance can reach 305 m - 415 mm by adjusting the tilt angle of the car body laterally	
Yanmar YH6118R	Harvester Machine Body Leveling Automation (UFO)	Supporting 130mm vertical lifting displacement, the vibrating screen is kept in the horizontal state for cleaning	
Fendt 1000 Vario Series Tractor	Fendt Stability Control System (FSC); Fendt VarioGrip Tire Pressure Regulation System	Ideal tire pressure can be maintained according to different field conditions	

CONCLUSIONS AND RECOMMENDATIONS

To date, both domestic and international agricultural machinery manufacturers have demonstrated notable advancements in field machinery chassis innovation, with researchers yielding substantial scientific outcomes. This section outlines the key research directions for future field machinery chassis development, focusing on three critical areas: drivetrain technology, steering systems, and intelligent leveling control strategies.

(1) Powertrain technology for agricultural chassis: Contemporary drivetrain systems are transitioning from electronically controlled architectures to intelligent powertrain solutions, with the primary objective of enhancing integrated energy efficiency. Notably, electro-hydrostatic CVT systems have gained extensive industrial adoption in modern agricultural equipment. Parallel efforts are devoted to hybrid powertrain development, achieving simultaneous improvements in emission reduction and dynamic torque response characteristics. The integration of machine learning algorithms enables autonomous analysis of field conditions (e.g., terrain topography, soil resistance) through big data systems, facilitating predictive optimization of power allocation and delivery. Future agricultural chassis powertrains will evolve along electrification and intelligentization trajectories, demanding superior dynamic responsiveness. Their convergence with autonomous navigation and precision farming technologies promises significant improvements in operational efficiency and accuracy.

(2) Steering systems for agricultural chassis: The ongoing advancements in GNSS positioning and sensor precision are driving autonomous field operations toward becoming the predominant paradigm in agricultural machinery, with intelligent steering systems emerging as a critical technological component. The future development trajectory emphasizes autonomous steering technologies, particularly in enabling fully automated agricultural machinery to execute diverse field operations without human oversight. Advanced steering systems will serve as the cornerstone for this technological transformation. Modern steering systems are increasingly being integrated with sophisticated data analytics and machine learning algorithms to dynamically optimize operational parameters. Remote monitoring and control capabilities, empowered by cutting-edge connectivity solutions, are granting farmers unprecedented ability to supervise and adjust machinery operations remotely, thereby enhancing both operational efficiency and user convenience. In summary, intelligent steering systems are revolutionizing agricultural practices by facilitating more accessible and efficient precision farming. These advanced systems deliver multifaceted benefits encompassing enhanced operational efficiency, significant cost reductions, improved crop productivity, operator workload alleviation, and notable environmental advantages.

(3) Chassis leveling technology: in precision variable-rate operations (fertilization/seeding), active chassis leveling systems maintain consistent implement depth, significantly enhancing operational precision and field efficiency. Foreign-designed auto-leveling systems feature advanced technology and high intelligence, with deep integration and coupling between control systems, making direct application to domestically produced combine harvesters difficult. Future advancements will leverage three key technological pillars: high-accuracy sensor arrays, reinforcement learning (RL)-based leveling optimization algorithms, and energy-efficient actuation strategies. Agricultural chassis leveling systems will evolve into intelligent "sense-decide-act" cyber-physical systems, achieving deep integration with vehicle control architectures to form the technological backbone of precision agriculture.

The future development of field agricultural machinery chassis will progress toward intelligent technologies, modular design, new energy applications, and autonomous driving technologies. Leveraging cutting-edge sensors, machine learning algorithms, and artificial intelligence, the chassis system will implement tightly integrated multi-sensor fusion and control strategies to enable synergistic optimization of power transmission, steering, and leveling mechanisms, with embedded prognostic and health management capabilities. Such advancements will significantly improve adaptability to diverse field environments and enhance machine operational versatility. To accommodate these developmental trends, the industry faces challenges including regulatory gaps and lack of data security standards amid technological innovations, necessitating accelerated establishment of autonomous agricultural machinery safety regulations to advance smart agriculture.

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