A REVIEW OF INTELLIGENT HEADER TECHNOLOGY FOR GRAIN COMBINE HARVESTER
/
谷物联合收获机智能化割台技术研究综述

Jin WANG[1,2], Fuqiang GOU [1,2], Zhenjie QIAN [1], Youliang NI [1], Chengqian JIN *,[1,3]
[1] Nanjing Institute of Agricultural Mechanization, Ministry of Agriculture and Rural Affairs, Nanjing, Jiangsu / China
[2] Graduate School of Chinese Academy of Agricultural Sciences, Beijing / China
[3] School of Agricultural Engineering and Food Science, Shandong University of Technology, Zibo, Shandong / China
Tel: +8615366092900; E-mail: jinchengqian@caas.cn
DOI: https://doi.org/10.35633/inmateh-73-62

Keywords: *Grain combine harvesters, intelligent header, agricultural machinery, height control systems*

ABSTRACT
With the rapid advancement of agricultural mechanization, intelligent header technology has emerged as a pivotal element in optimizing the efficiency and quality of grain combine harvesters. This paper offers a comprehensive analysis of the current state of intelligent header technology, with a particular emphasis on the structure, working principles, contour-following mechanisms, and height control technologies. By integrating cutting-edge sensor technologies, advanced control algorithms, and optimized mechanical designs, intelligent headers can achieve precise control over height and posture, thereby significantly reducing crop losses and enhancing both harvesting efficiency and quality. Despite substantial progress, challenges remain in areas such as response speed, real-time performance, height measurement accuracy, and control algorithm effectiveness. Future research will likely concentrate on improving control system performance, refining component and system designs, and incorporating emerging technologies to better accommodate diverse crops and complex terrains. This paper also provides a critical evaluation of current limitations in intelligent header research and projects future trends, offering valuable theoretical and practical insights for optimizing header structures, minimizing losses, and enhancing intelligent functionalities. The ultimate aim is to drive continuous innovation and advancement in header technology for grain combine harvesters.

摘要
随着农业机械化技术的不断进步，智能割台技术已成为提升谷物联合收获机效率和质量的关键部件。本文全面分析了智能割台技术的发展现状，重点探讨了割台的结构与工作原理，以及仿形与高度智能化控制技术。通过整合先进的传感器技术、控制算法和机械结构优化，智能割台实现了对高度和姿态的精确控制，显著减少了作物损失，提升了收割效率和作业质量。尽管取得了显著进展，智能割台在响应速度、实时性、高度测量和控制算法方面还存在局限。展望未来，研究将集中在提升控制系统性能、优化部件与系统设计，并引入新技术以适应多样化的作物和复杂地形。本文还详细评述了当前智能割台研究的不足，并展望了未来的研究发展趋势，提供了割台结构优化、损失减少及智能化水平提升的理论与实践参考，旨在推动联合收获机割台技术的持续进步与创新。

INTRODUCTION
With the continuous advancement of modern agricultural mechanization, the deployment of grain combine harvesters has become increasingly prevalent. Among the critical components of these machines, the header plays an indispensable role in the harvesting process. Traditional headers, however, are often characterized by limited intelligence and imprecise control, resulting in substantial crop losses that significantly hinder harvesting efficiency and economic returns (*Geng et al., 2020; Goltyapin et al., 2021*). In recent years, the development of intelligent headers has emerged as a focal point within both academia and industry. By integrating advanced sensor technologies, sophisticated control algorithms, and optimized mechanical designs, intelligent headers have achieved precise control over height and posture, leading to a marked reduction in crop losses and improvements in harvesting efficiency and quality. These technological advancements are particularly advantageous in complex terrains and under diverse crop conditions. The implementation of these innovations not only enhances the functionality of headers but also improves their adaptability across various operational environments (*Goossens et al., 2023; Wang et al., 2024; Ji et al., 2023*).

Jin Wang, Stud. Eng.; Fuqiang Gou, Stud. Eng.; Zhenjie Qian, Associate Prof. Ph.D. Eng.; Youliang Ni, Eng.; Chengqian Jin, Prof. Ph.D. Eng.

The development of intelligent headers provides critical technical support for precision agriculture, fostering the optimization of operational processes and enhancing the economic and environmental sustainability of harvesting systems.

This review systematically examines the current state of intelligent header technology in grain combine harvesters. It delves into the structure and working principles of headers, explores contour and height control technologies and their applications, and investigates the intelligent control methods of key components. Additionally, it identifies existing challenges and limitations in the research on intelligent headers and anticipates future developmental trends, offering both theoretical insights and practical guidance for further research and technological implementation.

Header Structure and Working Principles

The combine harvester integrates the header, threshing unit, and intermediate conveyor system, enabling the simultaneous execution of cutting, threshing, separating, cleaning, and grain collection (*Xu et al., 2013*). The header, located at the front end of the harvester, is one of its essential components (*Tai et al., 2020*). As shown in Fig. 1, it comprises a reel, cutter, divider, and conveyor system. The primary function of the header is to sever crops and continuously convey them to the threshing unit, facilitating efficient harvesting (*Zhou et al., 2023; Liu, 2022*). Currently, by replacing certain parts (such as the cutter, reel, and auger), the header can adapt to harvesting both rice and wheat as well as soybeans.

During operation, the header, functioning as the harvester's primary cutting mechanism (*Nalobina et al., 2019*), initiates the process by directing crops into the cutting area via the divider. The reel then guides the grains towards the cutter, where the cutting occurs. Following this, the reel advances the cut crops onto the platform, where the auger accumulates them to the right side. Retractable fingers then feed the grains into the inclined conveyor. The conveyor chain transports the crops to the drum for threshing, completing the transition from harvesting to threshing in an efficient, continuous sequence (*Wang et al., 2022; Li et al., 2014; Huang et al., 2020*).

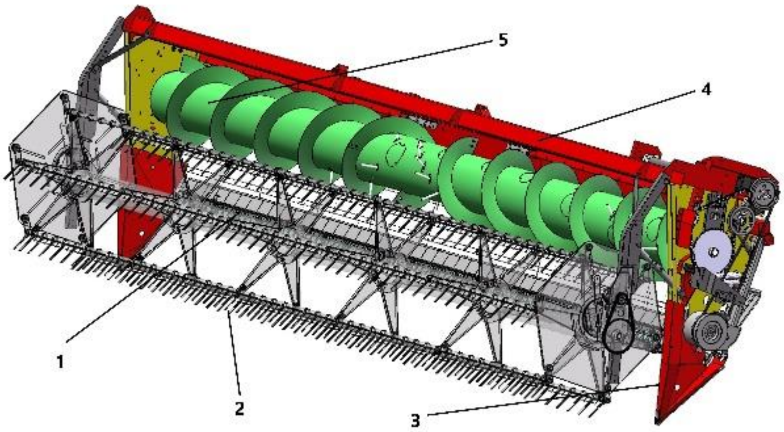

Fig. 1 - Schematic Diagram of the Header Structure
1.Cutter; 2. Reel; 3. Divider; 4. Header Frame; 5. Feeding Auger

Development of Contour Following and Height Control Systems for Cutting Headers

The header is a critical component of the combine harvester, with intelligent control being pivotal for optimizing harvesting efficiency and quality. Internationally, leading agricultural machinery companies are at the forefront of header development, particularly in areas such as power consumption, feed rate, reliability, and intelligent features. These advancements continually enhance the functionality and intelligence of headers (*Wang et al., 2021; Huawei et al., 2022*). In contrast, domestic researchers have concentrated on the adaptability of headers, achieving significant progress in contour following and height control. Innovations in height control systems and contour-following devices have effectively managed the operational posture of the header, minimized errors, and increased adaptability across various crops and environments (*Tan et al., 2023; Ji et al., 2022*). Currently, research is focused on optimizing the structure, working principles, and intelligent control systems of headers, with a particular emphasis on improving response speed and real-time performance. By integrating advanced control technologies and utilizing sensors such as image processing and ultrasonic distance measurement, researchers have significantly enhanced control precision and effectiveness. These innovations have not only optimized the header's structure but also reduced crop losses, thereby improving the overall performance of combine harvesters (*Xie & Alleyne, 2011; Liu et al., 2019; Lin et al., 2021*).

Research on Contour Following and Height Control Methods for Cutting Headers

The primary methods for controlling the height of headers in soybean harvesting equipment encompass manual, mechanical/electromechanical, hydraulic or pneumatic, and electro-hydraulic systems. Manual control, which relies on the operator's expertise, offers flexibility but is highly dependent on operator skill and is prone to inconsistency. Mechanical control employs linkages or cams to adjust the height automatically, offering reliability in simpler environments but limited adaptability in variable field conditions. Hydraulic or pneumatic control facilitates rapid and precise adjustments through hydraulic systems, making it well-suited for environments requiring swift responses to changes in terrain. However, its effectiveness can be limited by the complexity of the terrain and crop variability. Electro-hydraulic control, integrating sensors and electronic systems with hydraulic mechanisms, allows for intelligent, real-time adjustments that enhance precision and operational efficiency. This method, which often incorporates ground contour-following skids, represents a significant advancement in mechanized harvesting technology, aligning with future trends toward automation and precision agriculture (*Pan et al., 2019; Li et al., 2016*). The selection of an appropriate control method should be guided by specific operational requirements, with electro-hydraulic systems increasingly favored for their ability to optimize harvesting efficiency and accuracy in diverse conditions.

(1) Mechanical/Electromechanical Control

Li Zerui et al. (2024) designed a mechanical-hydraulic combined contour-following device for soybean headers, as illustrated in Fig. 2. The height contour-following function of the mechanical harvesting header primarily relies on a floating cutter. The floating cutter consists of a cutting blade, an elastic header base plate, and a four-bar linkage. During soybean harvesting, the lower base plate assembly maintains contact with the ground, allowing the floating cutter to move up and down with the terrain's undulations, ensuring close ground adherence for low-stubble harvesting. This design enables mechanical contour-following of the header height within a range of 0–70 mm (*Li et al., 2024*).

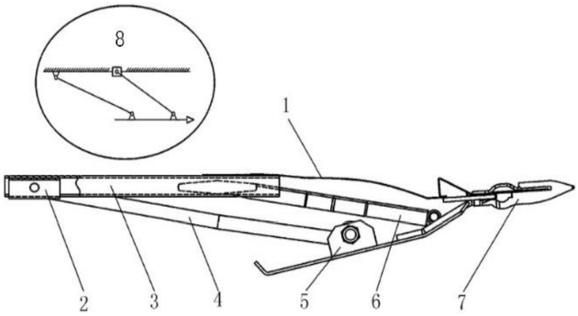

Fig. 2 - Schematic Diagram of the Floating Cutter Structure (*Li et al., 2024*)
1.Elastic Header Base Plate; 2. Mounting Plate; 3. Base Trough Plate; 4. Rotary Arm Assembly; 5. Lower Base Plate Assembly; 6. Limiting Plate Assembly; 7. Cutter; 8. Principle of Four-Bar Linkage Mechanism

(2) Hydraulic or Pneumatic Control

Wang Xibo et al. (1998) designed a suspended header with a hydraulic contour-following mechanism, as illustrated in Fig. 3. This mechanism primarily comprises mechanical and hydraulic components, without involving electronic controllers. An oil pump driven by a diesel engine sends oil through a pressure-reducing valve into a cylinder, where it pushes a piston rod acting on a buffer spring to adjust the header's height from the ground. It can achieve automatic contour-following on both flat and uneven surfaces but requires manual adjustment of bolts to adapt to different fields and stubble heights. Although the design enables automatic contour-following, the adjustment process is cumbersome, and the response speed of the hydraulic system significantly affects the contour-following performance (*Wang & Yin, 1998*).

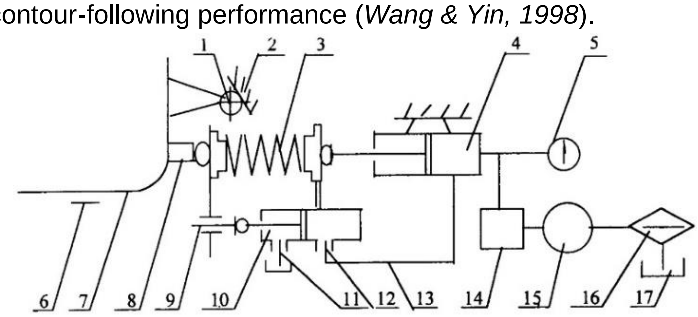

Fig. 3 - Schematic Diagram of the Hydraulic Profiling Mechanism for a Suspended Header (*Wang & Yin, 1998*)
1. Hinge; 2. Frame; 3. Buffer Spring; 4. Cylinder; 5. Pressure Gauge; 6. Profiling Plate; 7. Header; 8. Press Block; 9. Adjusting Bolt; 10. Quick Release Valve; 11. Oil Outlet; 12. Oil Inlet; 13. Pipeline; 14. Pressure Reducing Valve; 15. Oil Pump; 16. Oil Filter; 17. Oil Reservoir

(3) Electro-Hydraulic Control

Yi Fengyan et al. (2020) designed a header height control system based on an inclination sensor, which automatically adjusts the platform's angle by detecting changes in terrain angle. This system employs a hydraulic power model integrated with fuzzy control and PID control to achieve precise height control of the platform. The effectiveness of the algorithm was validated through simulations and experiments (*Yi et al., 2020*). *Ni Youliang et al. (2021)* developed a height adjustment system for soybean harvester headers that combines a contour mechanism with hydraulic drive. This system utilizes angle sensors to make real-time, precise height adjustments to the header, as shown in Fig. 4. Field tests demonstrated that the adjustment error of the header can be controlled within 2 millimeters (*Ni et al., 2021*). *Liu Gangwei et al. (2023)* designed an automatic height control system for soybean harvester headers, which integrates a contour mechanism, an ECU control unit, and a hydraulic system, enabling human-machine interaction via an industrial touch screen. Field trials indicated that the adjustment error of the header height in automatic mode was only 4 millimeters, with a coefficient of variation of 0.1, achieving a control accuracy of 93%, significantly surpassing manual operation and effectively enhancing the stability and operational quality of the harvester (*Liu et al., 2023*). *Yang Ranbing et al. (2022)* developed an automatic header height adjustment system based on terrain monitoring. The system uses sensors to detect real-time changes in ground height and employs an improved PID algorithm (EVPIVS-PID) to dynamically adjust the hydraulic system, ensuring precise height control of the header (*Yang et al., 2022*). *Xie Yangmin et al. (2010)* created an automatic header height control system for combine harvesters based on terrain following. By precisely setting state and cost functions, the system uses an optimal state feedback LQR controller to achieve height control (*Xie et al., 2010*). *Lopes G.T. et al. (2002)* developed a header height control system that employs a Linear Quadratic Gaussian with Loop Transfer Recovery (LQG/LTR) method. This system aims to optimize combine harvester performance by precisely controlling header height, significantly improving the harvester's disturbance rejection capability on irregular terrain without increasing energy consumption (*Lopes et al., 2002*). *Wang Zhichao et al. (2024)* designed a contour-following height control system for cutting platforms, which uses angle sensors to monitor ground undulations and employs an electro-hydraulic control strategy to automatically adjust the header height to various terrains. The system also incorporates integrated electro-magnetic proportional valves instead of traditional electro-hydraulic directional valves, achieving precise height adjustments through PWM signal control (*Wang et al., 2024*).

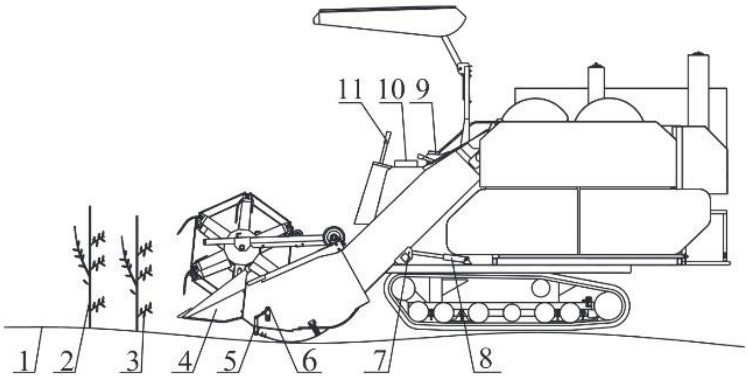

Fig. 4 - Schematic Diagram of the Header-Height Adjustment System for a Soybean Harvester (*Ni et al., 2021*)
1. Ground; 2. Soybean plant; 3. Bottom pod of soybean; 4. Header; 5. Profiling mechanism; 6. Angular transducer; 7. Articulated mechanism; 8. Double-acting hydraulic cylinder; 9. Controller; 10. Solenoid directional valve; 11. IPC.

Research on Contour Following and Height Measurement Methods for Headers

Current methods for measuring the height of headers in soybean harvesting include ultrasonic distance measurement, image processing-based techniques, and multi-sensor integrated height measurement with contour-following technology. Ultrasonic distance measurement is advantageous in harsh harvesting environments due to its insensitivity to smoke and other particulate matter. However, when deployed as a standalone method, it is prone to significant errors, often failing to meet the stringent precision requirements necessary for optimal harvesting efficiency (*Jia et al., 2019*). Image processing-based measurement utilizes computer vision to capture and analyze images of stubble, providing data to adjust the header height. Despite its potential for high precision, this method is vulnerable to system and environmental interferences and requires high-performance computational hardware, which can be a limiting factor (*Jeught & Dirckx, 2019*).
Recent advancements in sensor technology have led to the development of multi-sensor integration, combining sensors that measure angles, displacement, and pressure with ultrasonic sensors.

This integrated approach facilitates more accurate distance measurement and enhances contour-following capabilities, offering robust real-time performance and wide applicability across diverse harvesting conditions. As a result, multi-sensor integrated height detection is emerging as a promising technology for the future, potentially setting new standards in precision and efficiency in agricultural mechanization (*Nguyen et al., 2020*).

Through the combined efforts of domestic and international scholars and research institutions, these three methods have achieved significant advancements in contour following and height measurement for headers, laying a solid foundation for innovative research.

(1) Height Measurement Method Based on Ultrasonic Distance Measurement

Ultrasonic waves are non-contact mechanical waves that are not affected by light, dust, or electromagnetic interference, making them suitable for harsh harvesting environments. Compared to other detection methods, ultrasonic waves offer superior controllability and directionality. However, their sensors have a wide beam angle, and measurement accuracy can be influenced by field crops and changes in air density, potentially leading to errors (*Gamarra-Diezma et al., 2015*). *Zhang Cong (2020)* developed a contour-following system for headers based on ultrasonic array sensors and mechanical contour-following structures. This system utilizes an STM32 microcontroller for data processing, CAN bus communication, and closed-loop control. The least squares method was applied to enhance sensor measurement accuracy, and a fuzzy adaptive PID control strategy was designed to effectively adjust the header and achieve efficient ground contour-following (*Zhang, 2020*). *Yang Shuming et al. (2008)* designed a header height control system for combine harvesters based on ultrasonic sensors, as illustrated in Fig. 5. This system employs ultrasonic sensors for non-contact height detection of the cutting platform and uses an AT89C52 microcontroller to control the transceiver circuit and electro-hydraulic proportional directional valve. The system processes signals using the PID algorithm, thereby enabling automatic ground contour-following for the header (*Yang et al., 2008*).

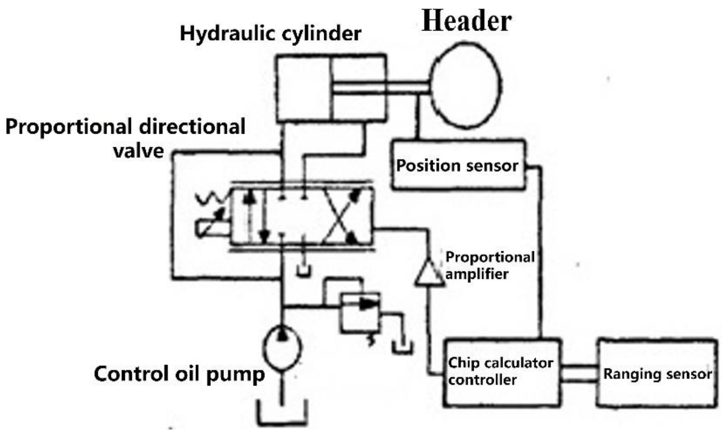

Fig. 5 - Schematic Diagram of the Header Height Measurement and Control System Based on Ultrasonic Sensors (*Yang et al., 2008*)

(2) Measurement Method Based on Image Processing

The image processing method adjusts the header height by rapidly acquiring parameters, enabling accurate, robust, and quick determination of stubble height during detection, thus meeting the real-time requirements of harvesters. However, this method has several limitations: it needs to process a large volume of images, which can affect real-time performance; additionally, errors in acquiring and calibrating stubble height image signals and uncertainties from human factors in visual measurements can significantly impact the accuracy of stubble height measurement (*Lida et al., 2010*). *Wu Yuanyuan et al. (2017)* designed an intelligent parameter acquisition system for leafy vegetable harvesters based on visual recognition and image processing. As shown in Fig. 6, the system first uses image preprocessing and robust regression methods to automatically acquire navigation parameters, enabling automatic adjustment of the harvester's operational direction. It then acquires stubble height through image processing, which serves as the parameter for adjusting the header height. The system achieved a navigation line recognition accuracy of 97% under natural light, with an average stubble height measurement error of 8 mm, providing technical support for the precise operation of autonomous leafy vegetable harvesters (*Wu et al., 2017*).

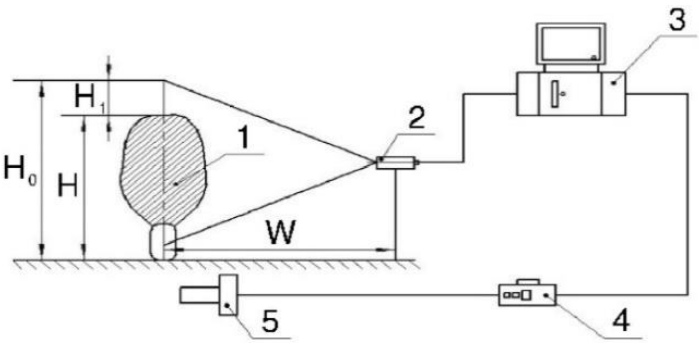

Fig. 6 – Schematic Diagram of the Header-Height Adjustment System for a Soybean Harvester (*Wu et al., 2017*)
1.Crop to be measured; 2. CCD Camera; 3. Computer; 4. Potentiometer; 5. Harvester Cutting Device

(3) Measurement Method Based on Multi-Sensor Integration

With the advancement of sensor technology, using sensors for header height monitoring and control has become a major trend in modern agricultural machinery development. This technology aims to enhance the operational efficiency and harvesting quality of agricultural machinery through more precise height monitoring. Research indicates that sensor applications in header height control include ground contour monitoring mechanisms and height feedback mechanisms based on angle sensors. For example, *Yang Ranbing et al. (2022)* designed an adaptive header height control system based on ground contour monitoring. This system uses angle sensors to monitor ground contours and employs electromagnetic proportional valves and PWM control technology for precise hydraulic cylinder adjustment. Experimental results demonstrated that the improved EVPIVS-PID algorithm dynamically adjusts PID parameters based on operational speed, ensuring stability in height control of the header. The stubble height error did not exceed 2 cm, meeting the speed requirements of 5–11 km/h for harvesting (*Yang et al., 2022*). *Ruan Mingjian et al. (2022)* developed an automatic header height control system for combine harvesters, with the schematic diagram shown in Fig. 7. The core components include a multi-sensor data fusion contour detection mechanism with angle and displacement sensors, a controller, and a proportional solenoid valve. The system uses a BP neural network to process sensor data and employs a fuzzy PID control algorithm to adjust the hydraulic cylinder height. Field tests showed that the average error for preset heights of 10 cm, 20 cm, and 30 cm was within 15 mm, effectively meeting the requirements for automatic height control (*Ruan et al., 2022*).

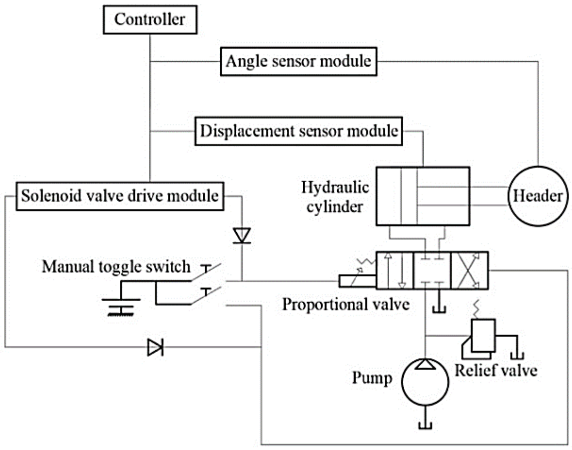

Fig. 7 – Working principle diagram of header height control
(*Ruan et al., 2022*)

Research on Control Methods and Algorithms for Contour Following and Height Control Systems of Headers

In the control of combine harvester headers, mechanical structures serve as the foundation, while control methods and algorithms determine overall performance. PID control is known for its stability and reliability. Fuzzy control effectively handles imprecise information, addressing system uncertainties and nonlinearities, thereby enhancing disturbance rejection capabilities and adapting to variations in crop height and terrain. Robust feedback linearization control excels in managing system uncertainties and external disturbances, offering higher disturbance resistance and adaptability, which is essential for maintaining header stability in complex agricultural environments and improving harvesting efficiency and accuracy.

Neural network algorithms leverage self-learning and adaptation to automatically adjust control parameters using data, enhancing response speed and accuracy. Genetic algorithms optimize control parameters through simulated natural selection and mutation, achieving efficient control (*Tulpule & Kelkar, 2014; Shojaei, 2021; Hanping et al., 2020*). Thus, the selection and optimization of robust feedback linearization control and other advanced algorithms are critical in contour following and height control of headers, significantly boosting system performance when applied appropriately.

(1) Application Research of Traditional Control Methods and Algorithms

Traditional methods for header control primarily include PID control and fuzzy control, which have improved system accuracy, reduced height adjustment errors, and accelerated response times. De Keyser et al. addressed the challenge of inconvenient height adjustment during combine harvester operation by proposing an adaptive adjustment system with minimal error and rapid response, using PID and Model Predictive Control (MPC) algorithms. The system comprises a crop height detection device, header height detection device, hydraulic actuator, and control unit. Test results indicated that the system's height adjustment error was within 2 cm in the 0–2 cm range, significantly improving harvesting efficiency and reducing field crop loss (*De Keyser et al., 2022*). Zhou Dongdong et al. (2019) proposed a header height control system based on fuzzy logic algorithms, as illustrated in Fig. 8. This system consists of an angle displacement sensor for the header, a hydraulic actuator, and a control unit. Real-time detection and fuzzy control allow for automatic height adjustment of the header. Field tests demonstrated that the system exhibited good real-time performance, accuracy, and stability, maintaining the header height within the set range, thereby improving harvesting efficiency and reducing crop loss (*Zhou et al., 2019*). Zhang Meng (2020) designed an intelligent control system for corn harvester headers based on PID and fuzzy PID control algorithms, using the STM32F4ZGT6 microcontroller. The system includes a floating compression contour mechanism, a row-following mechanism, a speed monitoring module, and an electromagnetic valve drive module. The PID control algorithm achieved precise height control with an average error of only 3.25 mm, while the fuzzy PID control algorithm ensured accurate row following within the 0–4.2 km/h speed range. This study significantly enhanced the intelligence level of corn harvesters (*Zhang, 2020*).

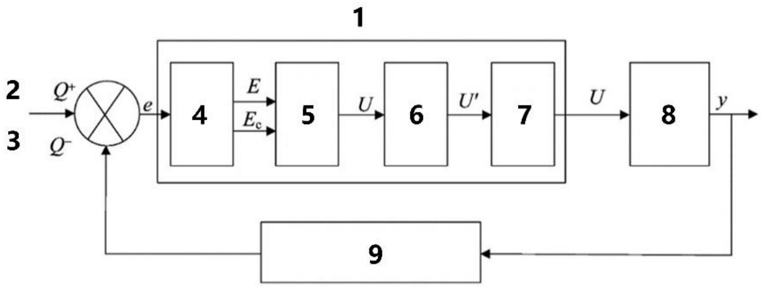

Fig. 8 – Schematic Diagram of the Header Height Fuzzy Control Principle (*Zhou et al., 2019*)

1. Fuzzy controller; 2. Cutting platform height; 3. Cutting platform height; 4. Fuzzification; 5. Fuzzy control algorithm; 6. Fuzzy decision; 7. Defuzzification; 8. Electromagnetic valve left and right relay energizing time; 9. Cutting platform height sensor

(2) Research on Innovative Control Methods and Algorithm Applications

In the study of the header height control system, scholars have proposed new methods with superior performance, in addition to further in-depth research on traditional algorithms such as PID. For instance, robust feedback linearization control has demonstrated excellence in handling uncertainties and external disturbances; neural networks have improved response speed through self-learning to adjust control parameters; and genetic algorithms have achieved more efficient control by simulating the natural evolution process through selection, crossover, and mutation operations. *Kassen Daniel and Kelkar Atul (2017)* proposed a header height control strategy based on robust feedback linearization control by constructing sensitivity equations and utilizing the current parameters of the hydraulic system control output. The research results indicate that the robust feedback linearization controller significantly outperforms the traditional PID controller in terms of header height tracking performance under various conditions, including different driving speeds, terrain sine amplitudes, and terrain periods (*Kassen & Kelkar, 2017*). *Ji Kuizhou et al. (2022)* designed an automatic header height adjustment system based on BP neural network multi-sensor data fusion, as illustrated in Fig. 9. They conducted simulation analysis of the hydraulic adjustment mechanism using AMESim software and employed fuzzy PID control to regulate the header height. Simulation and field test results demonstrate that the system achieves a header height error of less than 1.5 cm when harvesting rapeseed, millet, and rice (*Ji et al., 2022).*

Zhang Cong (2020) designed a fuzzy PID control system for header height optimized by a genetic algorithm, dynamically adjusting PID controller parameters through fuzzy rules to enhance the system's dynamic response capability and robustness against external disturbances. Simulation analysis using MATLAB and field tests show that the fuzzy adaptive PID control system can achieve fast and stable control under different terrain conditions, with a stubble height error of less than 1.5 cm (*Zhang, 2020*).

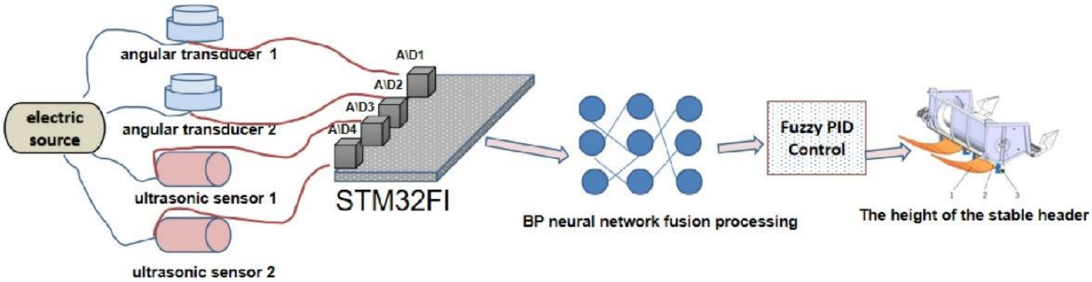

Fig. 9 – Schematic diagram of the header height measurement system (*Ji et al., 2022*)

Research on the Control System of Key Components of the Header

During combine harvester operations, header loss is a critical issue affecting overall harvest efficiency and economic benefits, accounting for the majority of total losses. Studies have shown that the motion patterns and working postures of core components such as the reel, cutter, and auger significantly impact the harvesting effect. Fine-tuning the control and structural optimization of these key components can significantly reduce header losses. Therefore, it is essential to study control systems that adjust the speed, angle, and synchronization of these components, optimizing their motion parameters and operating modes to ensure efficient harvesting. Additionally, the adoption of advanced sensor technologies and intelligent control algorithms is necessary to achieve real-time monitoring and dynamic adjustment of key components. This approach enhances operational performance and stability, thereby reducing header loss and improving harvesting efficiency and quality (*Wang & Su, 2021; Wang et al., 2019; Yuan et al., 2023*).

Current Research on Cutter (Sickle) Control Systems

The cutter is one of the key components of the header, functioning to cut the stalks through the reciprocating motion of the sickle driven by the cutting mechanism. Reciprocating cutters are widely used in combine harvesters due to their simple structure, high reliability, support for cutting, and high cutting quality. The frequency of the reciprocating motion of the sickle directly affects the harvest quality. Adjusting the sickle frequency to match the forward speed of the harvester effectively reduces re-cutting and missed cutting, thereby lowering power consumption from re-cutting and minimizing losses from missed cuts (*Sheheda et al., 2021; Abdelmotaleb et al., 2009*). To achieve precise adjustment of the sickle frequency, various control methods and algorithms have been studied and applied. *Li Ying et al. (2021)* designed a segmented control system for the cutter frequency of combine harvester headers. By constructing the sickle trajectory equation, the influence of forward speed and cutting frequency on the cutting area was analyzed, and the optimal cutting frequency range was determined using a segmented control method with regulation algorithms. Test results showed that the device adjusted the cutting frequency with a deviation within ±0.8Hz and a maximum relative error of -8.6%, significantly reducing missed and repeated cutting, thus improving harvest quality and efficiency (*Li et al., 2021*). *Yin Yanxin et al. (2021)* studied a feedforward compensation control method for the cutting frequency of combine harvester sickles. By establishing a relationship model between sickle cutting frequency and cutting energy, the effects of wheat stem moisture content and cutting cross-sectional area on sickle cutting frequency were analyzed, making the actual field cutting frequency closer to the optimal value. Experimental results showed that this method reduced the maximum deviation by 28.33%, significantly improving harvesting performance (*Yin et al., 2021*). *Guan Zhuohuai et al. (2020)* proposed a cutting speed follow-up adjustment system based on a Proportional-Integral-Derivative (PID) control algorithm. Numerical simulation analysis of the sickle motion trajectory determined the optimal cutting speed ratio to be 1.1. Field tests indicated that the system controlled the sickle cutting speed error within 1.5%, with a response delay of 1.5 seconds, significantly reducing header and sickle losses (*Guan et al., 2020*).

Current Research on Reel Control Systems

The reel is an essential part of the header, used to direct grain towards the cutter, support stalk cutting, and clear the sickle to prevent clogging. The reel's rotational speed impacts operational quality; too low a speed results in untimely feeding, while too high a speed causes grain loss. Research on reel control systems helps stabilize reel speed, reducing crop impact and header loss, thereby improving header efficiency and harvest quality (*Zendehdel & Shamoradi, 2019*). *Yang Zhengtao et al. (2022)* investigated the impact of reel speed on harvesting operations and proposed a reel control system based on a finite state machine algorithm. This system adjusts the reel speed in real time according to vehicle speed, grain density, and lodging conditions, ensuring the relative horizontal speed of the reel teeth is zero when contacting the crop, reducing crop impact, improving harvesting efficiency, and preventing clogging issues (*Yang et al., 2022*). *Omid Mahmoud et al. (2010)* designed an automatic reel speed control system using a fuzzy logic control algorithm. Sensors detect grain losses at the straw separator and upper sieve positions, and a programmable logic controller (PLC) processes the data and sends control commands to achieve precise reel speed adjustment (*Omid et al., 2010*). *Cui Yong et al. (2018)* developed an automatic reel speed control system using the 87C196KC microcontroller. The system controls the thyristor trigger using the cosine cross-intercept method, and combines motion and speed mathematical models to determine reel operating parameters and motor power. By adopting three-phase AC power and AC frequency conversion technology, along with voltage stabilization, synchronization, and amplification circuits, precise reel speed control was achieved (*Cui et al., 2018*). *Du Juan et al. (2020)* designed an automatic reel speed control device based on the PID control algorithm. The control principle diagram is shown in Fig. 10. The device measures the difference between actual and target speeds using sensors and sends control signals to achieve precise reel speed control, exhibiting high stability (*Du et al., 2020*).

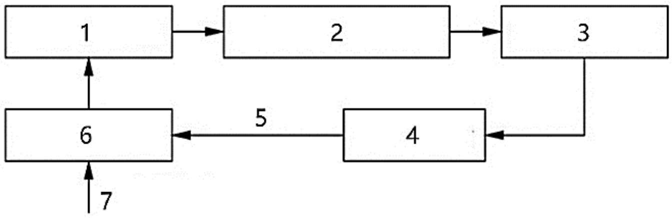

Fig. 10 – Block Diagram of the Automatic Reel Speed Control Principle (*Du et al., 2020*)
1. Motor driver; 2. Motor and transmission mechanism; 3. Reel main shaft; 4. Speed measurement; 5. Actual speed; 6. Speed controller; 7. Target speed

Issues and Challenges in the Intelligent Development of Headers

Despite significant advancements in the intelligent development of grain combine harvester headers, driven by continuous efforts from scholars and enterprises, there are still several issues and challenges in terms of structure and overall control. These challenges are primarily reflected in the following aspects:

Inadequate Intelligent Control and Response Speed

Current domestic research on intelligent control of headers mainly focuses on longitudinal height control, with relatively little attention to lateral height profiling and intelligent control. Although longitudinal control has made significant progress, headers still face issues with slow response speeds and insufficient real-time performance during actual operations. This is particularly problematic in complex terrains, where rapid adjustments in height and angle are necessary to prevent crop losses. Furthermore, there is limited research on the intelligent control of parameters such as reel speed and position adjustment, auger speed, and cutter frequency. This limits the system's application scope, thereby restricting harvest efficiency and quality. Therefore, it is essential to enhance the development of intelligent control systems for headers, improving response speed and real-time performance to minimize losses due to posture adjustments.

Limitations of Header Technology and Structure

A significant issue in the intelligent development of headers is the limitation of height measurement technology and control algorithms. Current measurement methods primarily rely on mechanical or laser sensors, which often lack precision and reliability in complex terrains and varying crop conditions. Mechanical sensors are prone to interference in uneven farmland environments, while laser sensors may fail due to changes in reflectivity, leading to inaccurate data. Moreover, existing control algorithms have limited capabilities in processing real-time data and dynamic adjustments, failing to fully consider the complexity of farmland environments and crop diversity. Introducing vision sensors based on image recognition and multi-sensor fusion technology, along with the development of more intelligent and adaptive control algorithms, is necessary. Additionally, the current header structure suffers from insufficient rigidity and adaptability, necessitating the use of lighter, more flexible materials and designs to enhance adaptability and operational efficiency.

Complexity and Reliability Issues of Header Systems

Although existing hydraulic and electro-hydraulic control systems are powerful, their complexity impacts the efficiency and reliability of header systems. Hydraulic control systems are prone to response delays and insufficient control precision during transmission, especially under high-intensity operating conditions, increasing the risk of equipment wear and failure. While electro-hydraulic control systems offer improvements in control precision and response speed, their complex hardware and software structures increase the failure rate and maintenance costs of header systems. To enhance overall performance, it is crucial to simplify the structure of hydraulic and electro-hydraulic control systems, adopting more reliable control components and techniques to improve system stability and usability, thereby advancing the intelligent level of combine harvester headers.

Future Trends in the Intelligent Development of Headers

The future trends in the intelligent development of headers include the following aspects: improving header control system performance and response speed through high-precision sensors and optimized control algorithms; continuously optimizing key components and control systems for energy efficiency; introducing new technologies and multifunctional designs to meet the harvesting needs of various crops and terrains; and enhancing vibration control and intelligent monitoring to improve harvest efficiency and reduce losses. These trends collectively drive headers toward greater efficiency, precision, and intelligence, achieving significant advancements in intelligent research.

High-Precision Sensors and Optimization of Control Algorithms

One important trend in the future development of intelligent headers is the installation of various high-precision sensors on header components to obtain more accurate and convenient parameters. Combining data from these sensors with optimized control methods and algorithms can significantly enhance the overall performance of header control systems, increasing control precision and response speed. Effective control systems verified through theoretical analysis, field experiments, and simulation software (such as MATLAB and ANSYS) show significant advantages in practical applications. Such high-precision, fast-response intelligent control systems ensure optimal performance of the header under various working conditions.

Optimization of Key Components for Energy Efficiency

Another critical trend is the continuous optimization of key header components (such as the reel) and the development of their control systems. Optimized headers can adjust parameter combinations promptly under different crops and working conditions, reducing loss rates during harvesting, lowering power consumption, and enhancing the adaptability and operational efficiency of grain combine harvesters. Future harvesters are expected to evolve toward high power, multifunctionality, and energy efficiency to meet the urgent needs of large-scale farmland and high-throughput harvesting.

New Technologies and Multifunctionality

The development trend of headers also includes the introduction of new technologies and the realization of multifunctionality. Internationally, headers have been designed to accommodate different cutting widths to meet regional and yield demands while improving header profiling structures to maintain consistent cutting heights on both flat and undulating terrains. Future developments will focus on how to universalize header chassis to install specialized headers, meeting the harvesting needs of various crops (such as soybeans and rapeseed). Additionally, addressing the issue of accumulation during harvesting is essential to improve efficiency and reduce losses.

Vibration Control and Intelligent Monitoring

Reducing vibrations generated during header operations is key to improving harvest efficiency and minimizing losses. The primary source of header vibrations is the cutter transmission system; thus, focused research on vibration reduction is necessary. Moreover, the development of headers should incorporate the application of global positioning systems (GPS) to gather information on crop yields and growing environments, optimizing the control of header height, reel height, harvester forward speed, and reel speed. Intelligent monitoring and control systems based on GPRS and GPS technology can detect the physical and mechanical properties of grains, intelligently adjusting the reeling device to enhance harvest efficiency and reduce loss rates. The development of new reeling device structures and materials using bionic technology will further improve the efficiency and lifespan of reeling devices.

CONCLUSIONS

This paper reviews the current state of intelligent header technology in combine harvesters, both domestically and internationally, detailing the types, characteristics, mechanical structures, operating principles, contour following, and height control advancements. The research indicates that China lags behind developed countries in the application of intelligent header technology. This lag is primarily due to the concentration of technological research and development within leading enterprises in developed countries and China's shortcomings in response speed and real-time capabilities of intelligent control systems. Additionally, regional disparities in agricultural mechanization and uneven research levels pose challenges for the adoption of intelligent header technology in China. To address these issues, this paper proposes strategies tailored to China's agricultural conditions, aiming to accelerate the development of intelligent header technology and enhance the operational efficiency and quality of grain combine harvesters in the country.

ACKNOWLEDGEMENT

We greatly appreciate the careful and precise reviews by the anonymous reviewers and editors. This research was funded by the National Key Research and Development Plan project (2021YFD2000503) and the National Natural Science Foundation of China (No. 32171911), and CAAS Center for Science in Smart Agriculture and Equipment (CAAS-SAE-202301).

REFERENCES

[1] Abdelmotaleb, I. A., El-Gendy, H. A., Hassan, M. A. (2009). Combine header control. *Misr Journal of Agricultural Engineering*. Vol. 26, no. 3, pp. 1478-1500. Egypt. https://doi.org/10.21608/mjae.2009.108719

[2] Cui, Y., Zhai, X., Tao, D. (2018). Design of Automatic Speed Control System of Combine Reel (联合收割机拨禾轮转速自动控制系统设计). *Journal of Agricultural Mechanization Research*. Vol.40, no.3, pp.128-132. Jiangsu / China. https://doi.org/10.13427/j.cnki.njyi.2018.03.026

[3] De Keyser, R., Birs, I. R., Copot, D., Ghita, M., Muresan, C. I., Ionescu, C. M. (2022). Versatile solutions for the combine harvester header height control problem. *Proceedings of the 13th Asian Control Conference (ASCC 2022)*. pp. 221-226. South Korea. https://doi.org/10.23919/ASCC56756.2022.9828248

[4] Du, J., Jiang, B., Yin, H., Zhang, L., Jin, C., Yin, X. (2020). Development of an automatic control system for the rotation speed of combine harvester reel (稻麦联合收获机拨禾轮转速自动控制装置研制). *Journal of Chinese Agricultural Mechanization*. Vol.41, no.12, pp.1-10. Shandong / China. https://doi.org/10.13733/j.jcam.issn.2095-5553.2020.12.001

[5] Gamarra-Diezma, J. L., Miranda-Fuentes, A., Llorens, J., Cuenca, A., Blanco-Roldán, G. L., Rodríguez-Lizana, A. (2015). Testing accuracy of long-range ultrasonic sensors for olive tree canopy measurements. *Sensors*. Vol.15, no.2, pp.2902-2919. Spain. https://doi.org/10.3390/s150202902

[6] Geng, A., Zhang, M., Zhang, J., Zhang, Z., Gao, A., Zheng, J. (2020). Design and Experiment of Automatic Control System for Corn Header Height (玉米收获机割台高度自动调控系统设计与试验). *Transactions of the Chinese Society for Agricultural Machinery*. Vol.51, no. S2, pp.118-125. Shandong / China. https://doi.org/10.6041/j.issn.1000-1298.2020.S2.014

[7] Goltyapin, V.Ya., Golubev, I.G., Buklagin, D.S. (2021). Global trends in the improvement of combine harvesters. *E3S Web of Conferences*. Vol.282, pp.07008. Russian. https://doi.org/10.1051/e3sconf/202128207008

[8] Goossens, J., Lenaerts, B., Devos, S., Gryllias, K., De Ketelaere, B., Saeys, W. (2023). Anomaly detection on the cutter bar of a combine harvester using cyclostationary analysis. *Biosystems Engineering*. Vol.226, pp.169–181. Belgium. https://doi.org/10.1016/j.biosystemseng.2023.01.013

[9] Guan, Z., Wu, C., Li, Y., Mu, S., Jiang, L. (2020). Cutting speed follow-up adjusting system of bidirectional electric drive side cutter for rape combine harvester. *Science Progress*. Vol.103, no.3, pp.1-19. Jiangsu / China. https://doi.org/10.1177/0036850420935728

[10] Hanping, M., Jiahui, W., Gaoyong, X., Zhiyu, Z., Qinglin, L. (2020). Design and simulation of the operating speed regulation algorithm of plot cabbage seed combine harvester. *Journal of Advances in Agriculture*. Vol.11, pp.160–169. Jiangsu / China. https://doi.org/10.24297/jaa.v11i.8862

[11] Huang, M., Li, Y., Chen, A., Xu, L. (2020). Design and Test of Double-Cutterbar Structure on Wide Header for Main Crop Rice Harvesting. *Applied Sciences*. Vol.10, no.13, pp.4432. Jiangsu / China. https://doi.org/10.3390/app10134432

[12] Huawei, L., Ping, Z., Xiaohui, Y., Yujie, D., Keying, L., Guohai, Z. (2022). Research on the status and development of grain combine harvester cutting table intelligence in China (国内谷物联合收获机割台智能化现状与发展研究). *Journal of Chinese Agricultural Mechanization*. Vol.43, no.4, pp.189-197. Zibo, Shandong / China. https://doi.org/10.13733/j.jcam.issn.2095-5553.2022.04.027

[13] Iida, M., Ikemura, Y., Suguri, M., Masuda, R. (2010). Cut-edge and stubble detection for auto-steering system of combine harvester using machine vision. *IFAC Proceedings Volumes*. Vol.43, pp.145–150. Japan. https://doi.org/10.3182/20101206-3-JP-3009.00025

[14] Jeught, S. V. D., Dirckx, J. J. J. (2019). Deep neural networks for single shot structured light profilometry. *Optics Express*. Vol.27, no.17, pp.17091-17101. Belgium. https://doi.org/10.1364/OE.27.017091

[15] Ji, K., Li, Y., Li, G., Wang, X., Wang, H. (2023). Design and test of height auto-control device of combine header (联合收获机割台高度自动调节装置设计与试验). *Journal of Agricultural Mechanization Research*. 2023(9), pp.85-94. Jiangsu / China. https://doi.org/10.13427/j.cnki.njyi.2023.09.021

[16] Ji, K., Li, Y., Zhang, T., Xia, S. (2022). Technology of adjusting the header height of the harvester by multi-sensor data fusion based on BP neural network. *INMATEH Agricultural Engineering*. Vol.68, no.3, pp.91-98. Bucharest / Romania. https://doi.org/10.35633/inmateh-68-09

[17] Jia, L., Xue, B., Chen, S., Wu, H., Yang, X., Zhai, J., Zeng, Z. (2019). A high-resolution ultrasonic ranging system using laser sensing and a cross-correlation method. *Applied Sciences*. Vol.9, no.7, pp.1483. Tianjin / China. https://doi.org/10.3390/app9071483

[18] Kassen, D., Kelkar, A. (2017). Combine harvester header height control via robust feedback linearization. *2017 Indian Control Conference (ICC)*, pp.1-6. India. https://doi.org/10.1109/INDIANCC.2017.7846442

[19] Iida, M., Ikemura, Y., Suguri, M., Masuda, R. (2010). Cut-edge and stubble detection for auto-steering system of combine harvester using machine vision. *IFAC Proceedings Volumes*. Vol.43, pp.145–150. Japan. https://doi.org/10.3182/20101206-3-JP-3009.00025

[20] Li, Q., Chen, G., Sun, Y., Sun, Y., Peng, Q. (2016). Study on corn harvester harvesting table height copying control. *J. Chin. Agric. Mech*. Vol.37, pp.43–47. Beijing / China.

[21] Li, Y., Guan, Z., Chen, Y. (2021). Development and test of frequency subsection regulation system for combine harvester header cutter. *INMATEH Agricultural Engineering*. Vol.65, no.3, pp.283-292. Bucharest / Romania. https://doi.org/10.35633/inmateh-65-30

[22] Li, Y., Li, Y., Xu, L., Hu, B., Wang, R. (2014). Structural parameter optimization of combine harvester cutting bench (联合收获机割台机架结构参数优化). *Transactions of the Chinese Society of Agricultural Engineering*. Vol.30, no.18, pp.30–37. Jiangsu / China. https://doi.org/10.3969/j.issn.1002-6819.2014.18.004

[23] Li, Z., Xu, L., Xu, X., Xu, L., Chai, X. (2024). Design and simulation of a mechanical-hydraulic combined soybean header profiling device (机械-液压组合式大豆割台仿形装置设计与仿真). *Transactions of the Chinese Society for Agricultural Machinery*. Vol.55, no.5, pp.150-160. Jiangsu / China. https://doi.org/10.13427/j.cnki.njyi.2024.05.030

[24] Lin, X., Cai, J., Tong, L., Long, Z. (2021). Topology optimization design and modal analysis based on header frame of combine harvester. *In Proceedings of the 2021 2nd International Conference on Artificial Intelligence and Education (ICAIE)*, pp.204–208. China.

[25] Liu, G. (2022). Research on profiling technology of soybean combine harvester header (大豆联合收获机割台仿形技术研究) (*Master's thesis*). *Chinese Academy of Agricultural Sciences, Nanjing Institute of Agricultural Mechanization*. Nanjing / China. https://doi.org/10.27630/d.cnki.gznky.2022.000712

[26] Liu, G., Ni, Y., Yang, T., Qi, Y., Jin, C. (2023). Design and experiment of an automatic height control system for soybean harvester header (大豆收获机割台高度自动控制系统设计与试验). *Journal of Chinese Agricultural Mechanization*. Vol.44, no.6, pp.220-230. Zibo, Shandong / China. https://doi.org/10.13733/j.jcam.issn.2095-5553.2023.06.022

[27] Liu, H., Reibman, A. R., Ault, A. C., Krogmeier, J. V. (2019). Video-based prediction for header-height control of a combine harvester. *In Proceedings of the 2019 IEEE Conference on Multimedia Information Processing and Retrieval (MIPR)*, pp.310–315. USA.

[28] Lopes, G. T., Magalhães, P. S. G., Nobrega, E.G.O. (2002). Optimal header height control system for combine harvesters. *Biosystems Engineering*. Vol.81, no.3, pp. 261-272. Brazil. https://doi.org/10.1006/bioe.2001.0016

[29] Nalobina, O. O., Vasylchuk, N. V., Bundza, O. Z., Holotiuk, M. V., Veselovska, N. V., Zoshchuk, N. V. (2019). A new technical solution of a header for sunflower harvesting. *INMATEH - Agricultural Engineering*. Vol.58, no.2, pp.129. Bucharest / Romania. https://doi.org/10.35633/INMATEH-58-14

[30] Nguyen, T. H., Nguyen, T. M., Xie, L. (2020). Tightly-coupled ultra-wideband-aided monocular visual SLAM with degenerate anchor configurations. *Autonomous Robots*. Vol.44, no.11, pp.1519–1534. Singapore. https://doi.org/10.1007/s10514-020-09944-7

[31] Ni, Y., Jin, C., Chen, M., Yuan, W., Qian, Z., Yang, T., Cai, Z. (2021). Computational model and adjustment system of header height of soybean harvesters based on soil-machine system. *Computers and Electronics in Agriculture*. Vol.183, pp.105907. Nanjing / China. https://doi.org/10.1016/j.compag.2020.105907

[32] Omid, M., Lashgari, M., Mobli, H., Alimardani, R., Mohtasebi, S., Hesamifard, R. (2010). Design of fuzzy logic control system incorporating human expert knowledge for combine harvester. *Expert Systems with Applications*. Vol.37, no.8, pp.7080–7085. Iran. https://doi.org/10.1016/j.eswa.2010.03.010

[33] Pan, Y., Zhao, Z., Liu, W., Meng, W. (2019). Research on header height automatic regulatory system. *In Proceedings of the 2019 Chinese Automation Congress (CAC)*, pp.203–206. IEEE: Hangzhou / China.

[34] Ruan, M., Jiang, H., Zhou, H., Ye, J., Hu, J. (2022). Design and test of automatic control system for header height of combine harvester. *INMATEH Agricultural Engineering*. Vol.68, no.3, pp.569-578. Bucharest / Romania. https://doi.org/10.35633/inmateh-68-56

[35] Sheheda, K., Shokarev, O., Kiurchev, S., Danchenko, M., Mykhailova, L. (2021). Results of research of combine harvester cutterbar. PhD Thesis. Ukraine.

[36] Shojaei, K. (2021). Intelligent coordinated control of an autonomous tractor-trailer and a combine harvester. *European Journal of Control*. Vol. 59, pp. 82 - 98. Iran. https://doi.org/10.1016/j.ejcon.2021.02.005

[37] Tai, J., Sun, H., Zhao, M., Yang, Z. (2020). Rapid design of maize ear harvester header based on knowledge engineering. *INMATEH Agricultural Engineering*. Vol.61, no.2, pp.296-303. Bucharest / Romania. https://doi.org/10.35633/inmateh-61-29

[38] Tan, H., Wang, G., Zhou, S., Jia, H., Qu, M., Xiang, M., Gao, X., Zhou, Z., Li, H., Zou, Z. (2023). Design and experiment of header height adaptive adjustment system for maize (Zea mays L.) harvester. *Sustainability*. Vol.15, no.19, pp.14137. Changchun / China. https://doi.org/10.3390/su151914137

[39] Tulpule, P., Kelkar, A. (2014). Integrated robust optimal design (IROD) of header height control system for combine harvester. *Proceedings of the American Control Conference (ACC)*, pp.2699-2704. Iran. https://doi.org/10.1016/j.ejcon.2021.02.005

[40] Wang, G., Su, R. (2021). Research on ground profiling control of combine harvester based on the symmetric algorithm. *Journal of Physics: Conference Series*. Vol.1827, no.1, pp.012211. Jiangsu / China. https://doi.org/10.1088/1742-6596/1827/1/012211

[41] Wang, H., Shen, H., Cao, S., Xu, X., Han, T., Guo, H. (2019). Hydraulic system design of combined harvester header and simulation of header lifting system. *IOP Conference Series: Earth and Environmental Science*. Vol.233, no.3, pp.032012. Jinan / China. https://doi.org/10.1088/1755-1315/233/3/032012

[42] Wang, L., Li, S., Lv, D., Ekhlo, G. (2021). Multi-sensor signal acquisition and data processing analysis of combine harvester. *INMATEH Agricultural Engineering*. Vol.63, no.1, pp.335-344. Bucharest / Romania. https://doi.org/10.35633/inmateh-63-34

[43] Wang, R., Chang, Y., Li, B., Lü, W., Liu, J. (2022). Design and experiment on the key components of millet combine harvester header (谷子联合收获机割台关键部件设计与试验). *Journal of Agricultural Mechanization Research*. 2022(10), pp.30-37. Luoyang / China. https://doi.org/10.13427/j.cnki.njyj.2022.10.006

[44] Wang, X. B., Yin, K. H. (1998). Design of suspended header contour-following mechanism. *Rural Area Mechanization*. (4), Total Issue 44. Beijing / China.

[45] Wang, Z., Yang, R., Chen, D., Wang, J., Li, X. (2024). Design of a Header Profile Height Control System Based on PID Regulation (基于PID调控的割台仿形高度控制系统的设计). *Research on Agricultural Mechanization*. Vol. 46, no. 2, pp.53-57. Qingdao / China. https://doi.org/10.13427/j.cnki.njyi.2024.02.008

[46] Wu, Y., Shang, X., Zhang, C., Xie, X. (2017). Acquisition of operation parameters of intelligent leaf vegetable harvester under natural lighting (自然光照下智能叶菜收获机作业参数的获取). *Acta Agriculturae Zhejiangensis*. Vol.29, no.11, pp.1930-1937. Ningxia / China. https://doi.org/10.3969/j.issn.1004-1524.2017.11.21

[47] Xie, Y., Alleyne, A. (2011). Integrated Plant and Controller Design of a Combine Harvester System. *In Proceedings of the ASME 2011 Dynamic Systems and Control Conference and Bath/ASME Symposium on Fluid Power and Motion Control*, pp.819-825. USA. https://doi.org/10.1115/DSCC2011-5959

[48] Xie, Y., Alleyne, A., Greer, A., Deneault, D. (2010). Header Height Control of a Combine Harvester System. *In Proceedings of the ASME 2010 Dynamic Systems and Control Conference*, Vol.7, pp.345-353. USA. https://doi.org/10.1115/DSCC2010-4088

[49] Xu, L., Li, Y., Tang, Z., Wang, L., Jiao, Z. (2013). 4LQZ-6 type tangential-flow combine harvester (4LQZ-6 型切向流联合收割机). *Transactions of the Chinese Society for Agricultural Machinery*. Vol.44, no.8, pp.94–98, 111. Beijing / China.

[50] Yang, R., Wang, Z., Shang, S., Zhang, J., Qing, Y., Zha, X. (2022). The Design and Experimentation of EVPIVS-PID Harvesters' Header Height Control System Based on Sensor Ground Profiling Monitoring. *Agriculture*. Vol.12, no.2, pp.282. Haikou / China. https://doi.org/10.3390/agriculture12020282

[51] Yang, S., Yang, Q., Yang, Y., Yang, S. (2008). Design of a combine harvester header height control system based on ultrasonic sensors (基于超声波传感器的割台高度控制系统设计). *Journal of Agricultural Mechanization Research*. Vol.3, pp.134-136. Beijing / China. https://doi.org/10.13427/j.cnki.njyi.2008.03.035

[52] Yang, Z., Wang, H., Sun, H., Wang, P., Cao, Q. (2022). Experimental Study on Electric Harvesting of Combine Harvester. *Journal of Physics: Conference Series*. Vol.2218, pp.012064. Shanghai / China. https://doi.org/10.1088/1742-6596/2218/1/012064

[53] Yi, F., Liu, J., Jiao, Z., Zhou, J. (2020). Study on height Control of Corn harvester in Hilly and mountainous area. *In 2020 Chinese Automation Congress (CAC)*, pp.3272-3276. IEEE: Hangzhou / China. https://doi.org/10.1109/CAC51589.2020.9327115

[54] Yin, Y., Qin, W., Zhang, Y., Chen, L., Wen, J., Zhao, C., Meng, Z., Sun, S. (2021). Compensation control strategy for the cutting frequency of the cutterbar of a combine harvester. *Biosystems Engineering*. Vol.204, pp.235-246. Beijing / China. https://doi.org/10.1016/j.biosystemseng.2021.01.023

[55] Yuan, L., Lan, M., He, X., Wei, W., Wang, W., Qu, Z. (2023). Design and Experiments of a Double-Cutterbar Combine Header Used in Wheat Combine Harvesters. *Agriculture*. Vol.13, no.4, pp.817. Henan / China. https://doi.org/10.3390/agriculture13040817

[56] Zendehdel, N., Shamoradi, Y. (2019). Online control of combine reel height in presence of farm roughness using an on-off controller. *Tehnički glasnik*. Vol.13, no.2, pp.104-109. Iran. https://doi.org/10.31803/tg-20180926113107

[57] Zhang, C. (2020). Research on header profiling and crop height measurement methods for combine harvesters (收割机割台仿形与作物测高方法研究). *Southeast University Master's Thesis*. Nanjing / China. https://doi.org/10.27014/d.cnki.gdnau.2019.002851

[58] Zhang, M. (2020). Research on the intelligent control system of corn harvester header (玉米收获机割台智能调控系统研究). *Shandong Agricultural University Master's Thesis*. Taian / China. https://doi.org/10.27277/d.cnki.gsdnu.2020.001219

[59] Zhou, D., Jin, C., Ni, Y., Zhang, G. (2019). Design and experiment of a fuzzy control system for the header height of a combine harvester (联合收获机割台高度模糊控制系统的设计与试验). *Jiangsu Agricultural Sciences*. Vol.47, no.13, pp.264-267. Jiangsu / China. https://doi.org/10.15889/j.issn.1002-1302.2019.13.063

[60] Zhou, Y., Luo, B., Liu, D., Liu, D., Qiu, Y., Zhou, Y. (2023). Design and experiment of a rapeseed header for the 4LZ-4.0 grain combine harvester (4LZ-4.0 谷物联合收获机油菜割台设计与试验). *Journal of Chinese Agricultural Mechanization*. Vol.44, no.9, pp.45-51. Zibo, Jiangxi/China. https://doi.org/10.13733/j.jcam.issn.2095-5553.2023.09.004