RESEARCH ON TERRAIN-FOLLOWING CONTROL STRATEGY FOR THE HEADER OF 4SZ-1.5 BUCKWHEAT WINDROWER
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4SZ-1.5 型荞麦割晒机割台仿形控制策略研究

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ABSTRACT
Aiming at the problem of uneven stubble height caused by large topographic relief and scattered plots of buckwheat fields in Hilly and mountainous areas, taking 4SZ-1.5 buckwheat windrower as the research object, an omni-directional header profiling strategy based on fuzzy control was proposed. By constructing the cooperative control system of the rotary lateral profiling mechanism (rotary hydraulic cylinder) and the lifting longitudinal profiling mechanism (lifting hydraulic cylinder), combined with the sliding plate angular displacement sensor, the real-time road elevation information is obtained. The random road excitation is generated by the filtered white noise time-domain model, and the Mamdani type fuzzy controller is established. The hydraulic cylinder expansion and contraction command is output with the left and right angle deviation as the input. Simulink simulation shows that the fuzzy controller can effectively perceive the real-time fluctuations of the terrain on both sides, realize the adaptive adjustment of the header to uneven ground, and has good stability and anti-interference. Field test verification: compared with the manual mode, the coefficient of variation (CV%) of stubble height in the automatic mode is 40%~60% lower than that in the manual mode, and the CV% remains ≤ 11.76 when the vehicle speed rises to 2m/s, significantly improving the adaptability to complex terrain.

摘要
针对丘陵山区荞麦地地形起伏大、地块分散导致的割茬高度不均问题，以 4SZ-1.5 型荞麦割晒机为研究对象，提出一种基于模糊控制的全方位割台仿形策略。通过构建旋转式横向仿形机构（旋转液压缸）与升降式纵向仿形机构（提升液压缸）的协同控制系统，结合滑板式角位移传感器实时获取路面高程信息；采用滤波白噪声时域模型生成随机路面激励，建立 Mamdani 型模糊控制器，以左右侧角度偏差为输入，输出液压缸伸缩量指令。Simulink 仿真表明：模糊控制器能够有效感知两侧地形的实时起伏，实现割台对不平地面的自适应调节，且具有良好的稳定性和抗干扰性。田间试验验证：相比手动模式，自动模式下割茬高度变异系数（CV%）较手动模式降低 40%~60%，且车速升至 2m/s 时仍保持 CV%≤11.76，显著提升复杂地形适应性。

INTRODUCTION

At present, buckwheat is mainly planted in hills and mountainous areas, with uneven ground, large fluctuations, scattered planting areas and small plots, the mechanical harvesting of buckwheat generally adopts the methods of segmented cutting and drying harvester (*Lu et al., 2020*), and the stubble height is generally controlled by manually operating the overall height of the header relative to the ground through the manual hydraulic valve, which does not have the function of real-time profiling, especially when working on hills and slopes (*Huang et al., 2018*). Due to the limited height of buckwheat, the vertical and horizontal height changes of the plot are easy to cause the stubble height to be too low or too high, resulting in increased harvest losses. The cutting device is inserted into the soil to damage the machine body and affect the harvesting quality. Therefore, the header of buckwheat windrower or combine harvester should have all-round profiling function, which requires not only vertical lifting profiling, but also horizontal profiling.

Early pioneering work was conducted with a floating wheel installed behind the cutter bar for direct ground height detection *(Clayton et al., 1977)*. In the 21st century, a significant advancement was achieved through the introduction of sensor technology, where a header height control system based on an ultrasonic sensor was designed, utilizing a single-chip microcomputer as the core and employing a PID algorithm for real-time adjustment *(Yang et al., 2008)*.

Subsequently, a fusion of contact and non-contact methods was explored. A method combining a trailed soil wheel with averaged measurements from multiple ultrasonic sensors was adopted to capture ground profile, achieving a high-precision sowing depth control error of ±10 mm *(Pasi and Timo, 2015)*. A contact-type mechanical profiling structure was utilized to develop a header ground profiling control system, where an angle sensor and a displacement sensor were integrated to acquire ground fluctuations and hydraulic cylinder status, respectively, with field tests verifying that the header height error was controlled within 12 mm *(Wei et al., 2017)*. Furthermore, a linkage mechanism was combined with an angle sensor, and a mathematical model was established to convert electrical signal variations into precise terrain measurements *(Ni, 2021)*. In terms of mechanical design, a vertical floating wheel inspired by aircraft landing gear and connected via an oil-pressure pillar suspension was designed to achieve effective buffering and vertical vibration suppression *(Hijazi et al., 2016)*. Concurrently, control strategies were greatly sophisticated. A robust integrated control design method (IROD) was proposed for header height control, which was demonstrated to achieve superior performance, lower power consumption, and enhanced robustness *(Tulpule et al., 2014)*. A header dynamic model was established, and an LQR control strategy was applied to enable the header to track ground undulations through pitch and roll adjustments, with the validity of the control scheme verified via simulation *(Hu et al., 2018)*. Additionally, a position sensor and a pressure sensing system were introduced into the chassis height detection for real-time feedback on the cutter bar's ground contact state *(Daenio et al., 2017)*. More recently, a header height control system for a blueberry harvester with five individual headers was developed, and the effectiveness of electric and hydraulic actuators was evaluated, revealing that the hydraulic actuator required only 2.30 s under load, significantly faster than the 13.96 s needed by the electric actuator *(Travis et al., 2020)*. In summary, the research is mainly used to realize the overall longitudinal profiling, and the research on the transverse profiling of the header remain limited.

In view of the above problems, the 4SZ-1.5 buckwheat mower header independently developed by Shanxi Agricultural University is selected as the research object. The machine is equipped with an integral lifting longitudinal profiling mechanism and a rotary transverse profiling mechanism, which are driven and controlled by hydraulic cylinders respectively. Firstly, the profiling principle is analyzed, and then the profiling effect under fuzzy control is simulated by using the Simulink tool.

MATERIALS AND METHODS

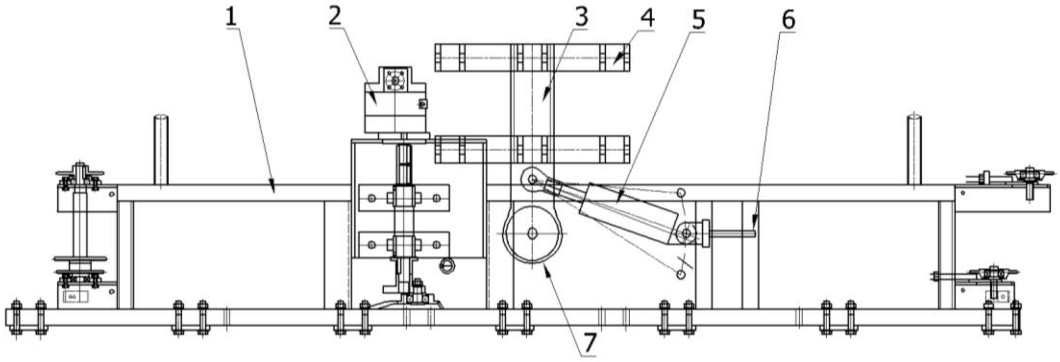
Analysis of profiling principle

The 4SZ-1.5 buckwheat windrower has a cutting width of 1.5 meters and adopts a combined hydraulic and chain transmission system *(Zhao, 2019)*. It is equipped with an electro-hydraulic automatic copying mechanism and a longitudinal-transversal height sensing device based on angle sensors, enabling integrated header copying and stable control of the minimum stubble height at or above 50 mm. Its planetary gear-type lateral swath delivery device ensures efficient and orderly crop laying. To address power adaptation issues in tractors without hydraulic output, the machine innovatively integrates the hydraulic power unit onto the three-point hitch. Field tests confirm an actual cutting width of 1.507 m, a header loss rate of only 1.2%, compact overall dimensions (1390 × 1500 × 828 mm), a machine weight of 110 kg, and a compatible power range of 18.4–36.7 kW, demonstrating excellent operational adaptability and reliability.

The front suspension automatic profiling mechanism of 4SZ-1.5 buckwheat windrower is shown in Fig.1, which is mainly composed of frame *1*, hydraulic motor *2*, lifting hydraulic cylinder *3*, connecting frame *4*, rotary hydraulic cylinder *5*, cylinder connecting plate *6* and frame rotating shaft *7*. An angle sensor is installed at the hinge between the profiling mechanism and the divider. When the windrower works on the ground, if the left ground in front of the machine is higher than the right ground, and the change value of the angular displacement sensor installed on the left side of the frame *1* is greater than that on the right side, the rotary hydraulic cylinder *5* is controlled to extend, and the steel pipe shaft on the frame and the rotary shaft sleeve rotate clockwise, so as to achieve the effect of being parallel to the ground. When the right ground in front of the machine is higher than the left ground, control the rotary hydraulic cylinder 5 to shorten and force the frame to rotate counterclockwise to achieve the purpose of being parallel to the ground.

When the cutter is too low from the ground, the angular displacement signals on both sides increase at the same time. The control system acts on the lifting hydraulic cylinder *3* to extend the hydraulic cylinder, lift the frame *1* and increase the distance between the cutter and the ground. On the contrary, lower the frame *1* to reduce the distance between the cutter and the ground. In order to avoid the phenomenon that the system is unstable and easy to overshoot due to tracking the ground trajectory, the leveling operation will not be carried out if the angle value changes slightly.

The time-domain model of random roughness of pavement is built to form the random elevation excitation signal of pavement, and the fuzzy control strategy is used to control the expansion and contraction of hydraulic cylinder.



1-frame; 2-hydraulic motor; 3-lifting hydraulic cylinder; 4-connecting frame; 5-rotary hydraulic cylinder; 6-cylinder connecting plate; 7-frame shaft

Fig. 1 -Schematic diagram of front suspension automatic profiling mechanism

Time domain model of pavement random unevenness

The system excitation is derived from the unevenness of the road elevation and is the most important excitation when the vehicle is driving. A large number of tests and analysis show that the road roughness has the characteristics of randomness, stationarity and ergodicity, which can be analyzed and described by the theory of stationary random process. Typical models include harmonic superposition model, linear filtered white noise model, filtered Poisson model, discrete time series model based on rational function PSD, etc. (*Liang et al., 2025*). Here, the filtered white noise time-domain pavement input model is used to simulate the change of ground height (*Huang et al., 2021*):

$$\dot{q}(t) = -2\pi n_{00} u q(t) + 2\pi n_0 \sqrt{G_q(n_0)u} W(t) \tag{1}$$

In the formula, n_{00} is the lower cut-off spatial frequency, taken as 0.011m^{-1}; u is the vehicle speed; $q(t)$ is random elevation displacement of pavement; n_0 is the reference spatial frequency, taken as 0.1 m^{-1}; $G_q(n_0)$ is the roughness coefficient of pavement, which can be taken as different values according to different pavement grades, such as 1024×10^{-6} for grade D pavement and 4096×10^{-6} for Grade E pavement; $W(t)$ is a Gaussian white noise with a mean value of 0.

Profiling control strategy and controller design

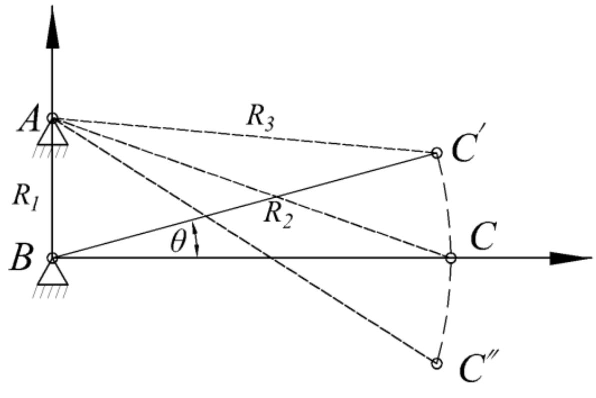


Fig. 2 - Action diagram of rotary hydraulic cylinder

The movement of the rotary hydraulic cylinder can be simplified as Fig 2. Point A and point B are fixed on the header. The length of point AB is R_1, equal to 100 mm, and the length of point BC is R_2, equal to 285 mm. Point C rotates around point B, and the upper and lower limit positions are C' and C'' respectively. AC represents the rotary hydraulic cylinder, its action range is R_3, which is 276~326 mm ($AC' \sim AC''$), and the header tilt angle θ is:

$$\theta = 90^0 - arccos(\frac{R_1^2 + R_2^2 - R_3^2}{2R_1R_2}) \tag{2}$$

Header left elevation:

$$z_0 = \sin(\theta) * \frac{L}{2} + L_0 \tag{3}$$

Header right elevation:

$$z_1 = -\sin(\theta) * \frac{L}{2} + L_0 \tag{4}$$

where L is the frame width and L_0 is the status value of the lifting hydraulic cylinder.

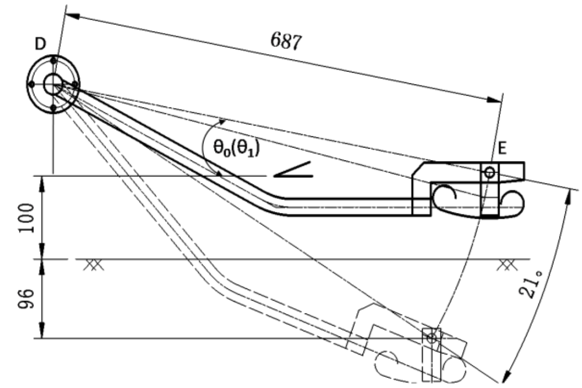


Fig. 3 - Schematic diagram of sliding plate type angular displacement sensor

The sliding plates installed on the left and right sides of the header are in contact with the ground and move with the fluctuation of the ground. An angle sensor is installed at point D of the sliding plate rotation center to convert the height change of the ground into the angle change.

Left angle:

$$\theta_0(t) = arcsin((z_0 - q_0(t))/l_{DE}) \tag{5}$$

Right angle:

$$\theta_1(t) = arcsin((z_1 - q_1(t))/l_{DE}) \tag{6}$$

In the formula, l_{DE} is the length of sensor point D and E, $q_0(t)$ is the random elevation displacement of left pavement, and $q_1(t)$ is the random elevation displacement of right pavement.

Mamdani fuzzy inference method is used to design the fuzzy controller, and the simulation model is established in Simulink (*Cheng et al., 2018*). The left angle and the right angle are selected as the controller inputs, and the corresponding fuzzy language values are divided into five levels, namely NB (large negative angle, small angle), NS (small negative angle, small angle), ZO (zero, middle angle), PS (small positive angle, large angle), PB (large positive angle, large angle) control quantity is the system input ***U***, which is also divided into five levels, namely NB (header up), NS (header counterclockwise), ZO (header does not act), PS (header clockwise), PB (header down). The area bisection method is used to convert the output fuzzy set into a single value. The fuzzy control rules established according to the relationship between input and control quantity are shown in Table 1 below.

Table 1

Reasoning rule table of fuzzy controller

U		$\theta_1(t)$				
		NB	NS	ZO	PS	PB
$\theta_0(t)$	NB	NB	NB	PS	PS	PS
	NS	NB	NB	ZO	PS	PS
	ZO	NS	ZO	ZO	ZO	PS
	PS	NS	NS	ZO	PB	PB
	PB	NS	NS	NS	PB	PB

Simulation model establishment and result analysis

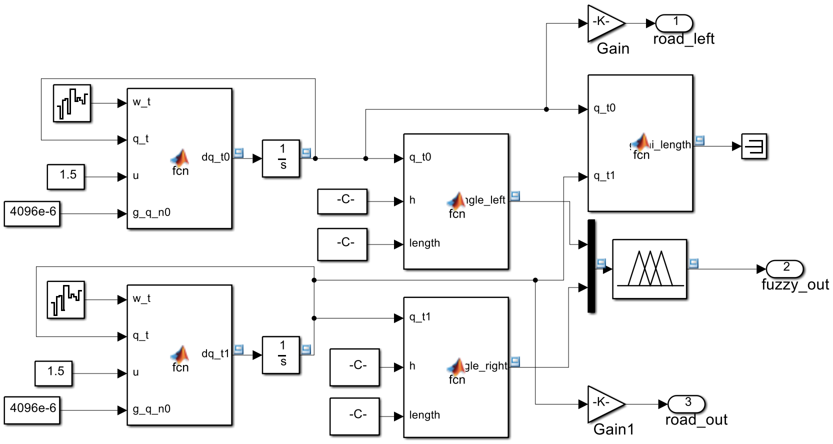


Fig. 4 - Stochastic pavement generation model

According to equation (1), the random road generation model on the left and right sides of the header can be established in MATLAB/Simulink, as shown in Fig 4. To ensure that the random elevation values on both sides differ, distinct random seeds are used to initialize the Gaussian white noise. The fuzzy rule set shown in Table 1 is incorporated using the Fuzzy Control Toolbox. The system input u acts on the electromagnetic directional valve to control the extension and retraction of the hydraulic cylinder.

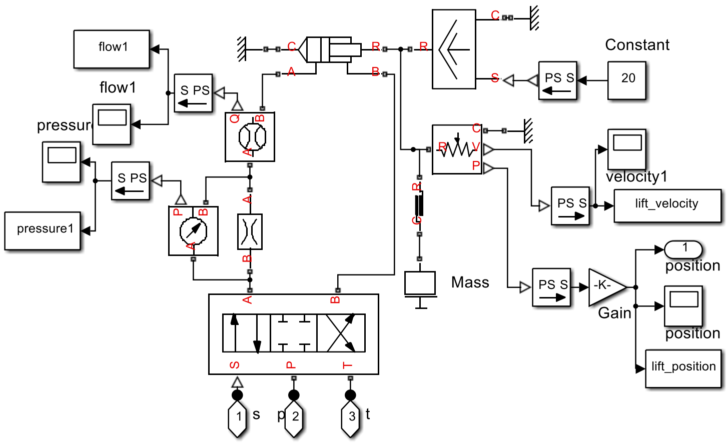


Fig. 5 - Simscape physical model of hydraulic system

The physical model of the hydraulic system is built by using the Simscape module in Simulink, as shown in Fig 5. The main parameters of the hydraulic system are set as follows: the displacement of the pump is 6 ml/r, and the speed is 1000 r/min; the opening pressure of overflow valve is 12 MPa; the total stroke of the rotary hydraulic cylinder is 50 mm, the piston diameter is 40 mm, and the piston rod diameter is 16 mm; the total stroke of the lifting hydraulic cylinder is 300 mm, the piston diameter is 50 mm, and the piston rod diameter is 20 mm.

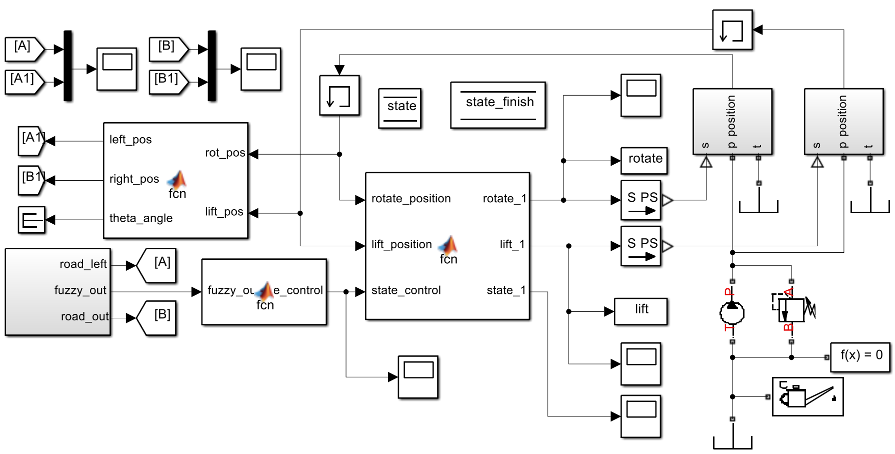
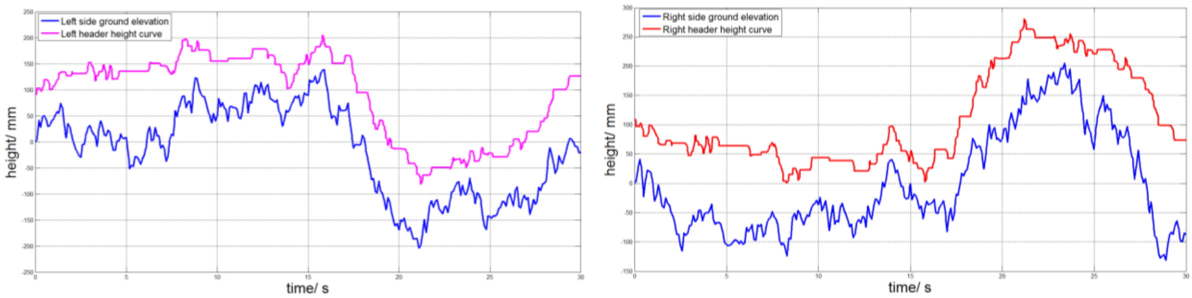
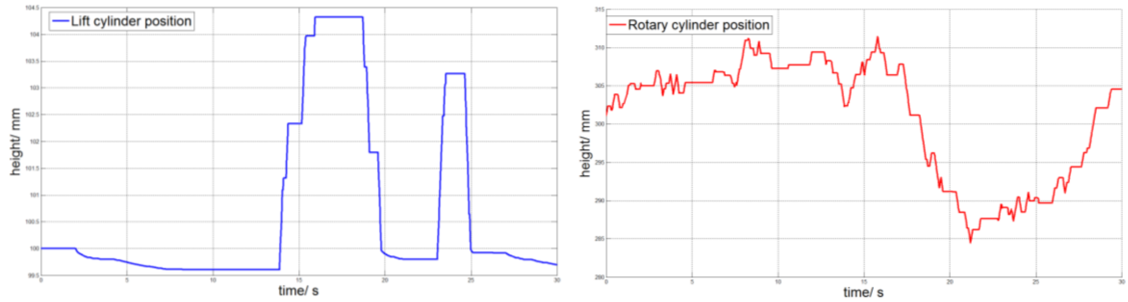


Fig. 6 - Overall simulation model of header control system



(a) Left side ground elevation and header height curve *(b) Right side ground elevation and header height curve*

Fig. 7 - Ground elevation and header height curve on both sides



(a) Height curve of lifting hydraulic cylinder *(b) Height curve of rotary hydraulic cylinder*

Fig. 8 - Ground elevation and header height curve on both sides

When the vehicle speed is 1.5 m/s and the road grade is e, the comparison of the ground elevation and header control height on the left and right sides is shown in Fig 7, and the changes of the rotary hydraulic cylinder and lifting hydraulic cylinder are shown in Fig 8. It can be seen that between 0 and 14 s, the lifting hydraulic cylinder shows a downward trend, the rotary hydraulic cylinder shows an upward trend, the header rotates slowly clockwise while slowly falling, the height of the right header shows a downward trend, the height of the left header shows an upward trend, and the header curves on both sides can closely follow the change trend of the ground elevation curve on the corresponding side.

Between 14 and 20 seconds, the ground on the right side suddenly rises, and the ground on the left side suddenly decreases. At this time, the rotary hydraulic cylinder drops, the header rotates counterclockwise, and the ground heights on the left and right sides fall and rise respectively to adapt to the change of ground elevation.

Between 20~30 s, the right ground becomes lower and the left ground becomes higher. At this time, the rotary hydraulic cylinder rises, the header rotates clockwise, and the ground heights on the left and right sides rise and fall respectively to adapt to the change of ground elevation. This shows that the designed fuzzy controller can effectively perceive the real-time fluctuations of the terrain on both sides, realize the adaptive adjustment of the header to the uneven ground, and has good stability and anti-interference: when the terrain changes slightly, the controller output does not change significantly; when the left and right sides of the ground vary greatly, the header moves and can remain stable for a long time.

RESULTS

To validate the field applicability of the header control strategy, a comparative experiment of buckwheat harvesting was conducted at the Taigu Shenfeng experimental base, as shown in Fig. 9. The experiment compared a manual mode against an automatic control mode. The dynamic change of the header height was inferred from the stubble height. The operating speeds were set at 1, 1.5, and 2 m/s, respectively, with a preset stubble height of 100 mm over an operation interval of 10 m. In the manual mode, the stubble height maintained the preset value without real-time adjustment during operation. In contrast, in the automatic mode, the header height was adaptively adjusted according to terrain variations.

Fig. 9 - Field experiment on profile control of buckwheat windrower header

Within the stable operation section of the harvester, 30 groups of stubble height samples were continuously collected. The average stubble height on the left and right sides and the Coefficient of Variation (CV) of the stubble height were selected as the evaluation metrics. The CV is calculated as follows (*Liu 2022 and Liao et al., 2018*):

$$CV = \frac{\sqrt{\frac{\sum_{i=1}^{n_1}(L_i - \bar{L})^2}{n_1 - 1}}}{\bar{L}} \tag{7}$$

This metric effectively normalizes the measure of dispersion, allowing for comparison across datasets with different means. A lower CV indicates better stability and consistency of the stubble height.

A subset of the raw measurement data (the first 10 groups) for the left stubble height is presented in Table 2, providing a preliminary view of the data fluctuations under different working conditions.

Table 2

Left stubble height measurement (top 10 groups)

Speed/ (m/s)	Working mode	Measurement point cutting height /mm									
		1	2	3	4	5	6	7	8	9	10
1	Manual	95	100	100	105	75	80	115	110	100	90
	Automatic	95	82	93	112	102	92	100	105	87	105
1.5	Manual	86	71	91	114	56	71	96	81	87	96
	Automatic	101	85	100	100	80	102	95	75	105	98
2	Manual	82	85	97	122	82	73	81	112	97	77
	Automatic	105	103	100	98	92	90	110	110	120	110

The comprehensive analysis of the experimental data is summarized in Table 3. The data clearly demonstrate the significant advantages of the automatic mode over the manual mode, primarily reflected in a substantial improvement in height stability. This advantage becomes more pronounced with increasing vehicle speed.

The experimental results demonstrate that the automatic control mode offers significant advantages over manual operation in both accuracy and stability of stubble height maintenance. In terms of accuracy, the automatic mode reduced the error between average stubble height and the preset value (100 mm) to below 5 mm across all tested speeds, compared to errors of less than 7 mm in manual mode. More notably, the automatic mode's superiority was most evident in stability performance, as reflected by the substantially lower coefficient of variation (CV). While the manual mode exhibited CV values reaching nearly 20%, the automatic mode maintained CV values below 12% throughout all operating conditions.

This stability advantage of the automatic mode was consistently observed across different operating speeds. At low speed (1 m/s), the automatic mode's CV values were only approximately 49% (left side) and 53% (right side) of those in manual mode, indicating nearly 50% suppression of height fluctuations. Even at high speed (2 m/s), where both modes showed degraded stability due to increased operating velocity, the automatic mode maintained CV values that were only about 60-62% of the manual mode's values. This demonstrates that while speed increase negatively impacts both control strategies, the automatic system exhibits significantly better robustness, maintaining its stability advantage even under demanding high-speed operating conditions. To visualize the stability advantage of the automatic control more intuitively, the trend of the stubble height CV versus operating speed is plotted in Fig. 10, based on the data from Table 3.

Table 3

Analysis of experimental data under different working conditions

Speed/(m/s)	Working mode	Average stubble height on the left side/mm	Variation coefficient of left stubble height/%	Average stubble height on the right side/mm	Variation coefficient of right stubble height/%
1	Manual	93.93	16.69	95.23	15.15
	Automatic	97.96	8.16	95.56	7.96
1.5	Manual	93.73	17.06	93.3	16.37
	Automatic	96.77	9.02	97.43	9.08
2	Manual	94.46	19.13	93.23	18.14
	Automatic	96.43	11.76	98.6	10.95

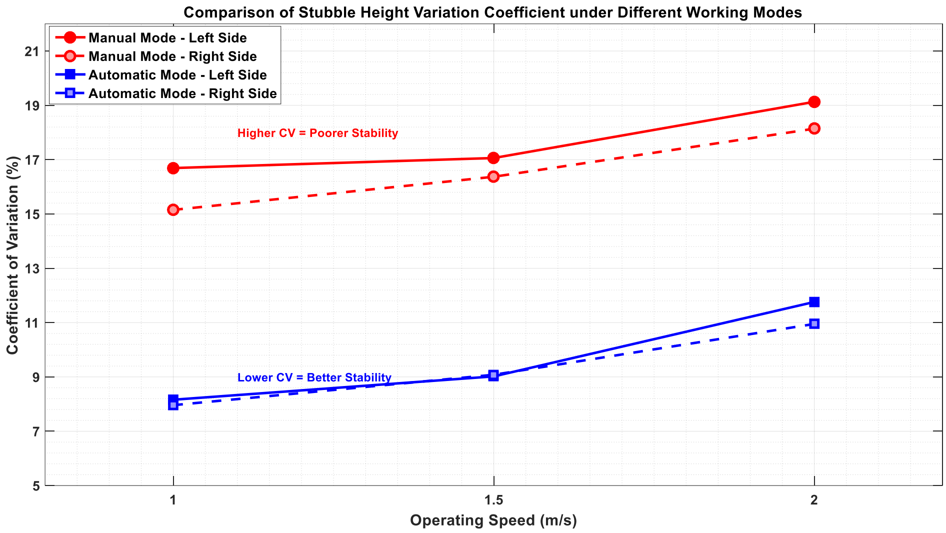


Fig. 10- Comparison of the coefficient of variation for stubble height under different working modes

Figure 10 is a line chart showing the Coefficient of Variation (%) against operating speed (1, 1.5, and 2 m/s). It includes four lines: Manual-Left, Manual-Right, Automatic-Left, and Automatic-Right. The chart would clearly show: (1) at all speed points, the lines for the automatic mode are well below those for the manual mode. (2) As speed increases, all lines trend upward, but the slopes of the automatic mode lines are more gradual.

In conclusion, the experimental results unequivocally demonstrate that the automatic control mode, based on adaptive terrain adjustment, significantly enhances the uniformity of the stubble height. It not only maintains higher absolute stability (lower CV) across the entire speed range but, more importantly, exhibits lower sensitivity to increasing speed, indicating stronger robustness. This holds considerable practical value for combine harvesters operating under demands for high efficiency.

CONCLUSIONS

This study investigated the terrain-following control strategy for the header of a buckwheat windrower to address stubble height variations in hilly areas. The main findings are summarized as follows:

(1) **Effectiveness of the control strategy**: the omni-directional profiling control system of the header based on fuzzy reasoning realizes the synchronous tracking of the longitudinal and transverse terrain fluctuations through the coordinated action of two hydraulic cylinders (the rotary cylinder adjusts the transverse inclination and the lifting cylinder controls the overall height), and solves the problem of large fluctuation of stubble height when the traditional mower operates on the slope.

(2) **Lateral profiling Innovation:** the rotary hydraulic cylinder mechanism (stroke 50 mm) combined with angle sensor feedback realizes the dynamic adjustment of the lateral inclination of the header, filling the technical gap that the existing research focuses on longitudinal profiling.

(3) **Speed adaptability:** field experiments show that the coefficient of variation (CV%) of stubble height in automatic mode is 40%~60% lower than that in manual mode, and the CV% is still controlled within 12% at 2 m/s operation speed, which verifies the robustness of the system under high efficiency harvesting conditions.

(4) **Engineering application value:** the proposed control strategy reduces the average stubble height error from 7 mm to 5 mm, significantly reducing the risk of soil contact by the cutter, and provides a reliable technical scheme for mechanized harvesting of buckwheat in hilly and mountainous areas

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