Design and test of laser-controlled paddy field levelling-beater

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Abstract: The technology for implementing a precise soil beating after precise soil levelling was proposed to improve the flatness of the paddy field and shorten the cycle time between the soil beating and levelling; in addition, a laser-controlled paddy field levelling-beater was designed according to the working principle. And the grade and tilt of the levelling scraper and beating mechanism are automatically controlled according to the levelling-beater vertical height and the tractor roll angle, respectively. The designed levelling-beater is capable of precise levelling and beating paddy fields at the same time with an adjustable beating depth. A paddy field test of the levelling-beater was conducted to compare the performance under both manual and automatic control modes, with the roll angles of the tractor and the levelling-beater measured using two attitude and heading reference systems (AHRSs), and the change in grade of the levelling-beater was measured using a global navigation satellite system (GNSS). The test results demonstrate that the operational quality of the levelling-beater is more stable when operating in automatic control mode than when operating in manual control mode. More specifically, the elevation of the levelling-beater varied ±4 cm around the mean elevation and roll angle varied within the range of ±0.5° when operating in automatic control mode. However, when operating in manual control mode, the elevation and roll angle were greater than ±11 cm and ±2.5°, respectively. The test results also demonstrate that the laser-controlled paddy field levelling-beater significantly improves the paddy field flatness, and enables it to operate at a stable depth to realise an even levelling and beating layer. More specifically, the maximum variation of elevation was reduced from 26.4 cm before the levelling and beating operation to 11.5 cm after the operation. In addition, the standard deviation of the elevation was reduced from 4.13 cm to 2.18 cm after the operation. The total number of flatness sampling points with the absolute difference of the desired elevation less than or equal to 3cm was more than 86%. The effective beating depth was 14.2 cm, compared with the set beating depth of 15cm, and the standard deviation of the beating depth was 2.46 cm.

Keywords: laser control, levelling, beating, paddy field, flatness

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1 Introduction

Paddy field tillage is a major process of rice production. The precise tillage of paddy fields increases the utilization rate of manure and water, reduces the number of weeds, and raises yield[1-6]. Rice production needs to be well levelled and filled with an about 3 cm uniform thin water layer. To cope with this requirement, a laser-controlled paddy field leveller that is compatible with the rice transplanter was developed, based on its research on laser receiver, roll angle sensor, scraper grade and tilt adjustment control. Field applications demonstrate that the laser-controlled paddy field leveller satisfies the rice planting requirements of flatting accuracy and overall effect[7-15]. To further improve the operational efficiency of the laser-controlled paddy field leveller, a version compatible with a wheeled tractor was also developed[3,16,17]. Soil beating needs to be carried out prior to paddy field levelling, usually using manual-controlled implements such as a rotary tiller or beater. Very often, such manual-controlled implements cannot guarantee a consistent operating depth; an overly large operating depth may result in a tractor overloaded and shut down. In addition, such manual-controlled implements may fail to achieve the desired level of quality, damage the original underlying hard layer of the paddy fields (thereby resulting in an uneven hard layer)[18], and compromise the service life of the tractor and implements. For this reason, many researchers have attempted to realise the automatic control of the grade and tilt of soil cultivation implements by adding cylinders on the three-point suspension mechanism of tractors[19-23]. However, it is difficult to realise the compatibility of such additional cylinders with the three-point suspension mechanisms of different tractors. Yu et al.[24] designed an automatic tilt adjustment device for a paddy field compound levelling implement that consists of a cutaway harrow and a tail plate. However, the rotation center of the tilt adjustment mechanism is located at the middle of the suspension, thereby limiting the transmission of the PTO power of the tractor into the rotary tiller or beater. Tractors with an electro-hydraulic-controlled lifting system are an ideal solution for automatic control of tillage implements[25-28]. However, most tractors produced in

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China are not equipped with an electro-hydraulic-controlled lifting system. Moreover, beating and levelling are usually carried out separately in paddy field, with levelling carried out after a certain period of sedimentation of the beaten soil. This results in a complex paddy field beating-levelling process and a long time interval between the beating and levelling operations. The separation of soil beating and levelling operations also contributes to larger investments in machinery and higher labor costs. Furthermore, additional operations of a tractor on a paddy field incur more damage to the underlying hard layer of the field. Adding a tracer-controlled levelling device behind a soil beating mechanism is a good technical solution to paddy field beating and levelling. Li[29] and Xu et al.[30] designed a soil puddling-levelling machine for paddy fields that is capable of puddling and flatting at the same time. However, this puddling-flatting machine is manually controlled and the working quality relies primarily on the operator's experience. To improve the quality and automatic level of beating and levelling operations, Wan et al.[31] designed a levelling mechanism with automatic tilt control that operates on a rotary tiller. However, the grade of the levelling mechanism is not controlled, and the grade of the rotary tiller that determines the depth of soil cultivation is realised through the manual control. Yang[23] designed a laser-controlled paddy-field beating-leveller. However, the additional cylinders must be designed according to different tractor models[32].

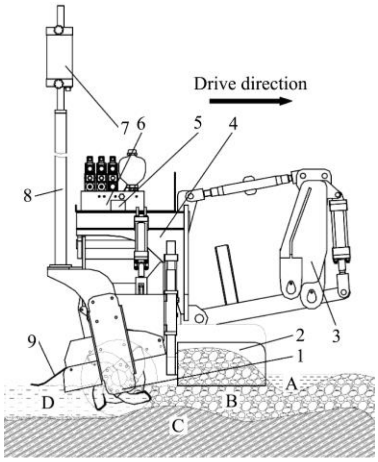
This paper presents the design of a laser-controlled paddy field levelling-beater, with the levelling mechanism mounted in front of the beating mechanism. With a built-in grade and tilt control mechanism, the levelling-beater is capable of precise levelling and beating of paddy fields at the same time. Field experiments were carried out to verify the precision of levelling and the stability of beating depth as well as the superiority of laser control over the manual operation in efficiency and quality.

2 Design of laser-controlled paddy field levelling-beater

2.1 Technical principle

The paddy-field levelling and beating technique is suitable for paddy fields that have been ploughed, raked, and soaked in water. Figure 1 illustrates the principle of this technique. The levelling mechanism is mounted in front of the beating mechanism, and the scarper flats a paddy field by transferring the soil in areas of higher elevations to areas of lower elevations, and the beating mechanism beats the flatted soil, appropriately rendering the paddy field for rice planting. The levelling and beating mechanisms are controlled using a leveller control system so that a consistent operating depth and tilt can be maintained. The beating depth can thus be adjusted by changing the elevation of the scarper relative to the beating mechanism.

To operate the laser-controlled paddy field levelling-beater, set the operating depth of the beating mechanism (beating depth) and then the operating elevation (relative to the beating mechanism) and tilt angle (usually set at zero) of the levelling mechanism. The underlying hard layer of a paddy field is frequently uneven. Thus, the sinking depths of the four wheels of a wheeled tractor operating on the paddy field are inconsistent, and the working depth and attitude of the levelling-beater continuously change. The laser receiver detects the reference plane signal from the laser transmitter. Thus, when the effective operating depth of the levelling-beater is lower than the pre-set value, the controller increases the travel of the hydraulic cylinder to lift the levelling-beater to the pre-set plane; when the levelling-beater is higher than the pre-set plane, the controller lowers it to the appropriate plane. The roll angle sensor detects the roll angle of the tractor body in real time. The controller adjusts the travel of the tilt adjustment cylinder according to the detected roll angle. Thus, the angle of the levelling-beater relative to the tractor is maintained at the pre-set value[33]. With the automatic control of the grade and tilt, the levelling-beater is capable of precise levelling and beating. With the levelling mechanism placed in front of the beating mechanism, the soil to be beaten by the beating mechanism is already levelled. Thus, the beating mechanism maintains a consistent beating depth, and its beating blades are evenly loaded. This not only results in a better beating effect it also prevents a degradation of the aggregate structure of the paddy field soil as otherwise may be caused by repeated disturbances of the soil.



1. Beating mechanism 2. Levelling mechanism 3. Elevation adjustment mechanism 4. Tilt adjustment mechanism 5. Roll angle sensor 6. Hydraulic valve module 7. Laser receiver 8. Laser receiver lifting rod 9. Tail plate A. Water B. Soil to be levelled and beaten C. Uncultivated soil D. Levelled and beaten soil

Figure 1 Illustration of the working principle of the levelling-beater

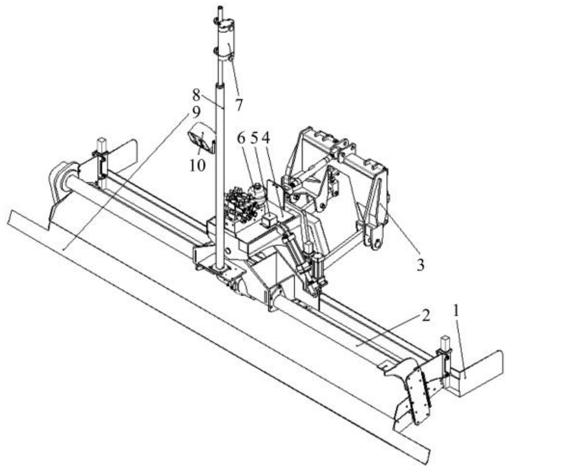
2.2 The levelling-beater design

The laser-controlled paddy field levelling-beater consists of the following major components: a levelling mechanism, a beating mechanism, an automatic tilt adjustment mechanism, a grade adjustment mechanism, a hydraulic system, and a control system. As shown in Figure 2, the levelling mechanism is located in front of the beating mechanism, and both the levelling and beating mechanisms are coupled with the automatic grade and tilt adjustment mechanisms. The angle of the levelling and beating mechanisms is adjusted through the cylinder of the automatic tilt adjustment mechanism. The grade adjustment mechanism is coupled with the three-point suspension mechanism of the wheeled tractor and controls the grade of the automatic tilt adjustment mechanism, the levelling mechanism, and the beating mechanism through the grade adjustment cylinder.

2.3 Design of major components

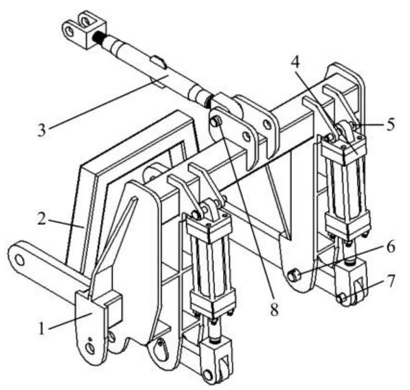
2.3.1 Grade adjustment mechanism

The grade adjustment mechanism mainly consists of a grade adjustment bracket, an upper link, a lifting bracket, and grade adjustment cylinders. As shown in Figure 3a, the front end of the grade adjustment mechanism is coupled with the three-point suspension mechanism of the tractor, and the rear end is coupled with the tilt adjustment mechanism. The tilt adjustment support, upper link, grade adjustment bracket, and lifting bracket constitute a parallelogram mechanism. Thus, the grade adjustment cylinder adjusts the grade of the tilt adjustment mechanism through the parallelogram mechanism, as shown in Figure 3b. In the space (with a trapezoid-shaped cross-section) between the grade adjustment bracket and the lifting bracket, a universal-joint coupling is mounted to transmit the PTO power of the tractor to rotate the blade assembly of the beating mechanism. The front end of the grade adjustment mechanism is compatible with different types of tractors. The parallelogram mechanism ensures that the levelling and beating mechanisms only travel in the vertical direction and the travel does not affect the transmission of the PTO power of the tractor to the beating mechanism.

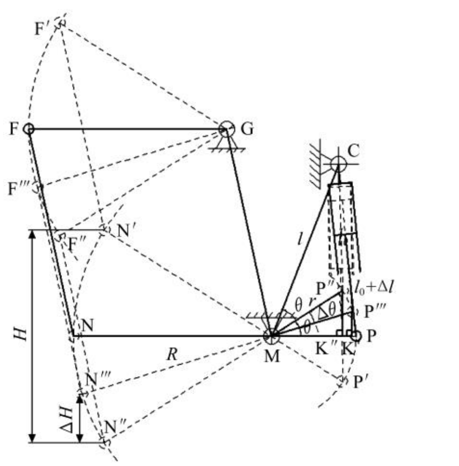


1. Levelling mechanism 2. Beating mechanism 3. Tilt adjustment mechanism 4. Grade adjustment mechanism 5. Hydraulic valve module 6. Laser receiver lifting rod 7. Laser receiver 8. Roll angle sensor 9. Tail plate 10. Controller

Figure 2 Diagram of the levelling-beater structure



a. Three-dimensional schematic of grade adjustment mechanism



b. Illustration of the principle of grade adjustment mechanism

1. Grade adjustment bracket 2. Lifting bracket 3. Upper link 4. Grade adjustment cylinder 5-8. Pins

Figure 3 Grade adjustment mechanism

Figure 3b illustrates the working principle of the grade adjustment mechanism. In the figure, C is the connection point of the upper end of the grade cylinder, F is the connection point of the far end of the upper link (with F', F'', and F''' designating different positions of F), G is the connection point of the near end of the upper link, M is the coupling point of the lifting bracket and the grade adjustment bracket, N is the connection point of the lower end of the tilt adjustment mechanism (with N', N'', and N''' designating different positions of N), and P is the connection point of the lower end of the grade adjustment cylinder (with P', P'', and P''' designating different positions of P). In addition, H is the maximum range of the grade adjustment; F', N', and P' represent the position of the parallelogram mechanism when the grade adjustment cylinder travels to its maximum stroke length; F'', N'', and P'' represent the position of the parallelogram mechanism when the grade cylinder travels to its minimum stroke length; and F''', N''', and P''' represent the position of the parallelogram mechanism when the grade cylinder travels to a stroke length of Δl. The parallelogram mechanism (FGMN) ensures that the beating mechanism always travels in the vertical direction. The grade variation ΔH and cylinder stroke variation Δl can be obtained using Equations (1) through (4):

$$\Delta H = \frac{R}{r}\Delta h \tag{1}$$

$$\Delta h = r\sin\theta_1 - r\sin(\theta_1 - \Delta\theta) \tag{2}$$

$$\cos(\theta + \Delta\theta) = \frac{l^2 + r^2 - (l_0 + \Delta l)^2}{2lr} \tag{3}$$

$$\sin^2\Delta\theta + \cos^2\Delta\theta = 1 \tag{4}$$

where, θ_1 is the angle $\angle$CMP'', (°); $\Delta\theta$ is the angle $\angle$P'''MP'' or the angular change resulting from a change in cylinder travel Δl, (°); θ is the angle $\angle$CMP'', (°); l is the length of line CM, cm; l_0 is the length of line CP'' or the length of line CP at the minimum stroke length of the grade cylinder, cm; Δl is a change in the travel of the grade cylinder, cm; and r is the length of line MP, cm; MP', MP'', and MP''' represent line MP at different stroke lengths of the grade cylinder.

2.3.2 Tilt adjustment mechanism

The tilt adjustment mechanism mainly consists of a bracket, a connection module, a cylinder, and a pin. As shown in Figure 4a, the lower end of the connection module is fixed to the beating mechanism; the part of the connection module that can swing in the left-right direction is coupled with the bracket in a rotary manner. The travel of the tilt adjustment cylinder results in the connection module, the levelling mechanism, and the beating mechanism moving in the left-right direction.

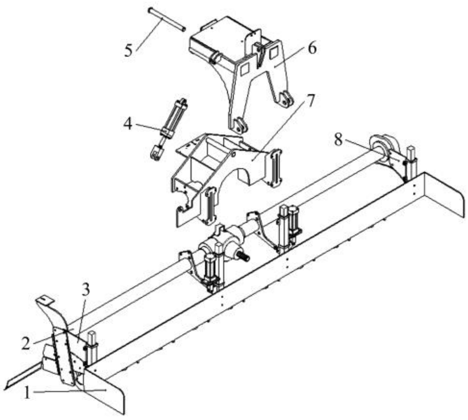
Figure 4b illustrates the working principle of the tilt adjustment mechanism. The stroke length of the tilt adjustment cylinder l and the angle of the beater relative to the tractor θ satisfy the following equation[33]:

$$\theta = 180 - \alpha - \beta - \frac{180}{\pi}\arccos\frac{l_a^2 + l_b^2 - (l_0 + l)^2}{2l_a l_b} \tag{5}$$

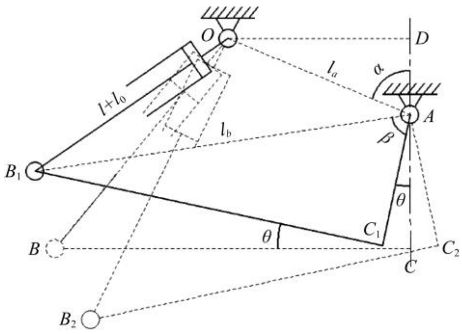
where, α is the angle $\angle OAD$, (°); β is the angle $\angle B_1AC_1$, (°); l_a is the length of line OA, cm; l_b is the length of the line AB_1, cm; l_0 is the minimum stroke length of the tilt adjustment cylinder, cm.

2.3.3 Levelling mechanism

The levelling mechanism is mounted in front of the beating mechanism and mainly consists of tracks, columns, cylinders, and a scraper. As shown in Figure 5. The tracks at the two sides are coupled with the beating mechanism through the support plates at the two sides, and the two tracks in the middle are fixed to the connection module of the tilt adjustment mechanism. The lower ends of the columns are fixed to the scraper, and the middle and upper parts of the columns can slide in the tracks. The grade of the scraper relative to the beating mechanism can be adjusted by adjusting the travel of the cylinders, thereby adjusting the soil beating depth.



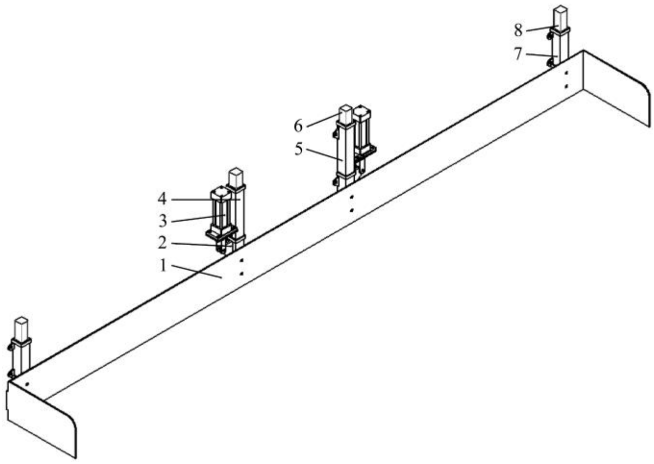
a. Three-dimensional schematic of tilt adjustment mechanism



b. Working principle of tilt adjustment mechanism

1. Levelling mechanism 2. Beating mechanism 3. Right support plate of levelling mechanism 4. Cylinder 5. Pin 6. Bracket 7. Connection module 8. Left support plate of levelling mechanism

Figure 4 Tilt adjustment mechanism



1. Scraper 2. Left-middle column 3. Cylinder 4. Right-middle track 5. Left-middle track 6. Left-middle column 7. Side track 8. Side column

Figure 5 Diagram of the levelling mechanism

2.3.4 Automatic control system

Figure 6 presents a block diagram of the automatic control system. The laser receiver detects the signals of the reference plane from the laser transmitter. The controller computes the difference between the actual and pre-set elevation according to the signals detected by the laser receiver and adjusts the travel of the grade adjustment cylinder through the electromagnetic valve module. With this automatic grade control, the levelling-beater operates at the pre-set elevation. The roll angle of the tractor measured using the roll angle sensor. The linear displacement sensor of the tilt adjustment cylinder measures the angle of the levelling-beater relative to the tractor body. With these input data, the controller adjusts the travel of the tilt adjustment cylinder through the solenoid directional valve. Thus, an automatic adjustment of the roll angle of the levelling-beating mechanisms is realised, and the levelling-beater operates at the pre-set angle.

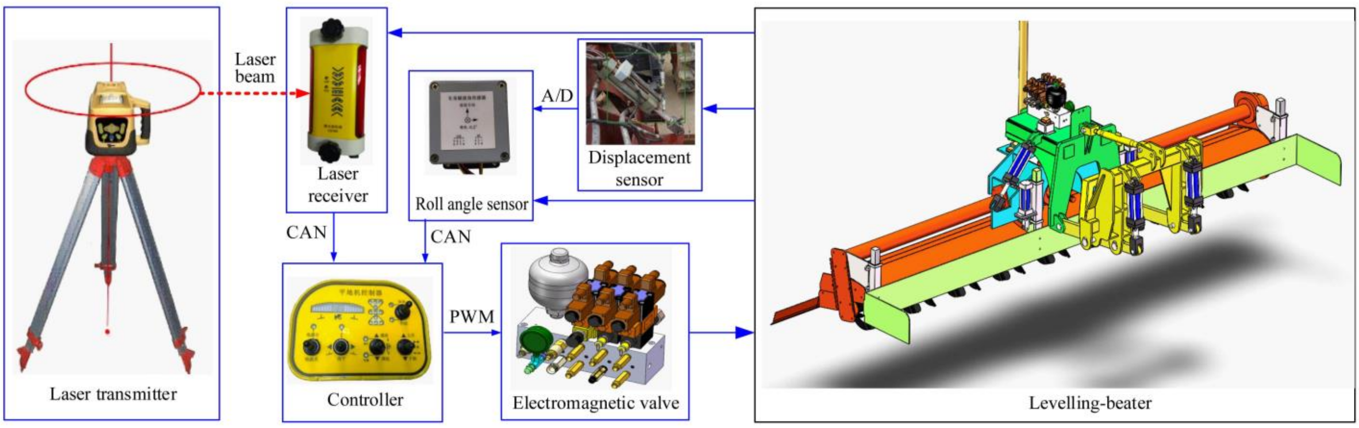


Figure 6 Block diagram of the automatic control system

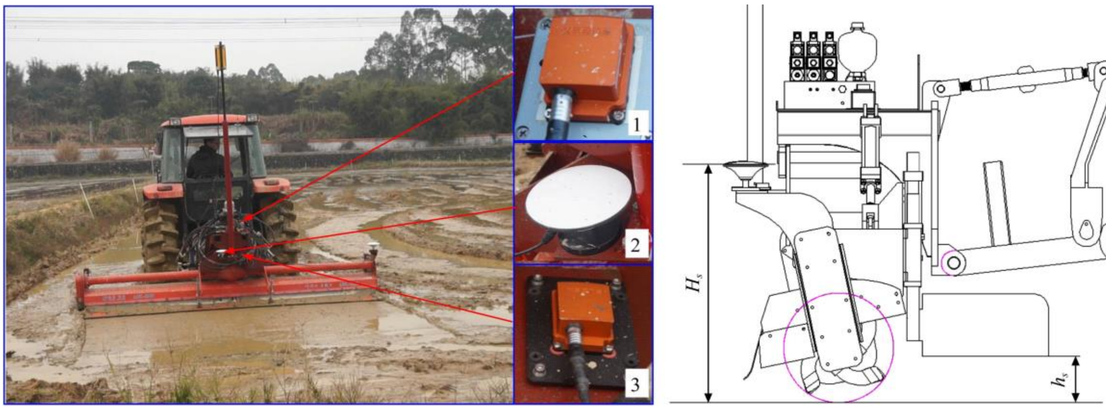
3 Testing and analysis

3.1 Testing materials

A 1JSL-320 paddy field beater (Baoma Juntian) is adopted as the beating mechanism of the paddy field levelling-beater. The beater has a mass of 380 kg and a beating width of 320 cm. The integrated levelling-beater has a total mass of 550 kg and a levelling width of 340 cm, with its grade adjustable within the range of 40 cm, tilt adjustable within the range of –12°-12°, and beating depth adjustable within the range of 14-24 cm. The levelling-beater was mounted on a M704KQ tractor (Kubota). The PTO revolving speed of the tractor was set at 720 r/min, and the revolving speed of the beater was set at 370 r/min. The tractor was set to travel at an average speed of 0.56 m/s.

The hydraulic system of the levelling-beater consists of three components, a grade adjustment, a tilt adjustment, and a beating depth configuration. The grade and the roll angle of the levelling and beating mechanisms were adjusted by adjusting the travel of the cylinders of the hydraulic circuit for grade and tilt adjustments, respectively. The grade of the scraper was set prior to the start of the levelling-beating operation by adjusting the travel of the two cylinders of the hydraulic circuit for the beating depth configuration.

Two MTi-100 attitude and heading reference systems (AHRSs) (Xsens, Holland) with a dynamic angle measurement accuracy of 0.3° were employed to measure the roll angles of the tractor and levelling-beater. A K728 global navigation satellite system (GNSS) (ComNav, China) with a static elevation accuracy of $\pm(5 + 1 \times 10^{-6} \times D)$ mm and a dynamic elevation accuracy of $\pm(20 + 1 \times 10^{-6} \times D)$ mm (where D is the measurement range in kilometers) was employed to measure the operating trajectory of the levelling-beater. As shown in Figure 7, one AHRS was mounted behind the tilt adjustment bracket, and the other was mounted behind the connection module of the tilt adjustment mechanism—on the right side of the rod for mounting the laser receiver—for a synchronous measurement of the roll angles of the tractor and levelling-beater, respectively, with the baud rate set at 115200 bps and the sampling frequency set at 40 Hz. The antenna of the GNSS was mounted on the rear side of the connection module of the tilt adjustment mechanism and the left side of the rod for mounting the laser receiver, with the distance to the lowest working point of the beating blades (H_s) set at 77.2 cm, the baud rate set at 115 200 bps, and the sampling frequency set at 10 Hz. Other instruments and tools used in the test include a MOXA Uport 1450 multi-serial-port data acquisition card, AT-B4 level (Topcon), stopwatch, and tape (50 m, 0.01 m).



1. AHRS for tractor body 2. GNSS antenna 3. AHRS for levelling-beater

Note: H_s: distance from the GNSS antenna to the lowest working point of the beating blades; h_s: distance from the bottom surface of the scraper to the lowest working point of the beating blades.

Figure 7 Locations of mounted sensors

3.2 Test method

The test was conducted in a paddy field in the Zengcheng Experimental Base of South China Agricultural University. The field measured approximately 0.31 hm^2 (approximately 4.68 mu) in area. It was left dry after the harvest of the previous season of rice, tilled using a rotary tiller, and soaked in water for 48 h. Firstly, the soil was levelled and beaten for one round on the red line trajectory in Figure 8 by manually adjusting the levelling-beater through the three-point suspension mechanism of the tractor. Then, the soil was levelled and beaten for an additional round by driving the tractor along the same trajectory and operating the levelling-beater through the laser control. The above process was then repeated an additional time. The AHRS and GNSS data during the above operations were collected. A fixed reference point (O) was set on the ridge of the paddy field. The lengths of the sides of the field and the distances from the sides to point O are measured using a measuring tape. The paddy field was divided into a grid, as shown in Figure 8. The intersection points (flatness sampling points) of the grid lines were marked. The position of each sampling points relative to point O was measured using a measuring tape. The elevations of point O and the sampling points were measured using a level. A reference station for the GNSS was set up. The antenna of the GNSS was placed at point O. The WGS84 coordinates of point O were recorded. Finally, the field in the grid area in Figure 8 was levelled and beaten using the laser-controlled levelling-beater. The measurement data of the AHRS and GNSS were collected. After the operation, the elevations of point O and the flatness sampling points were measured.

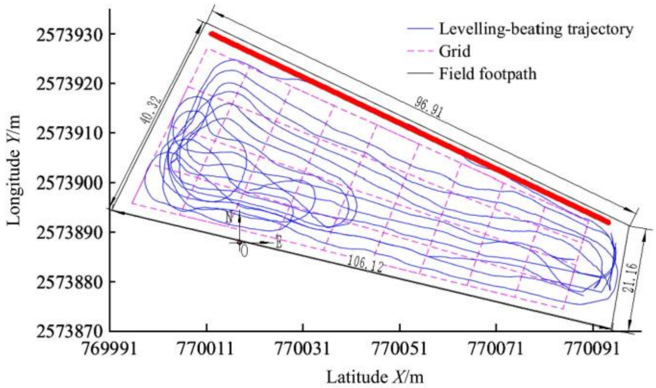


Figure 8 Grids and tractor trajectory of the test paddy field

3.3 Data treatment method

3.3.1 Transformation of data coordinates and levelling-beating trajectory of the levelling-beater

The testing data mainly include the GNSS data for positioning the operation of the levelling-beater and elevation measurements for a field flatness evaluation (obtained using a level). The above data were transformed into the same coordinate system as follows. According to the distances of the sampling points to point O and the elevation data (the elevation of point O, h_o, and the elevations of the flatness sampling points, h_i), if the three-dimensional coordinate of point O is designated as (0, 0, 0), and the flatness sampling points are (Δx_i, Δy_i, Δh_i). The coordinate of point O (at which the GNSS antenna was mounted) was designated after the Gauss–Krüger projection as (x_o, y_o, z_o), and the coordinates of the flatness sampling points (X_i, Y_i, Z_i) prior to the test can be expressed as follows:

$$\begin{cases} X_i = x_O + \Delta x_i \\ Y_i = y_O + \Delta y_i \\ Z_i = z_O + \Delta z_i \end{cases} \tag{6}$$

where, i = 1, 2, $\cdots$; 50 and $\Delta h_i = h_o - h_i$.

Following the above data-treatment method, the coordinates of the flatness sampling points after the test can be expressed as (X_i, Y_i, Z_{1i}). Projecting the GNSS data collected during the levelling-beating operation into the Gauss–Krüger coordinate system, the resulting coordinates of the GNSS antenna (X_{2j}, Y_{2j}, Z_{2j}) (where j = 1, 2, $\cdots$; 41,077 based on a total of 41,077 effective data points) were used to express the levelling-beating trajectory of the levelling-beater. Figure 8 shows the operating trajectory and flatness sampling points (X_i, Y_i, Z_i).

3.3.2 Flatness before and after levelling-beating operation

As shown in Figure 8, the elevations at 50 of the flatness sampling points were measured using a level during the test. The standard deviations (S_d) of the measurements were used as a quantitative indicator of the flatness of the paddy field[34]. The percentage of the number of sampling points based on an absolute value of the difference between the measured and desired elevation of no larger than 3 cm to the total number of sampling points was used as an indicator to characterise the distribution of the elevation surface variations in the paddy field. The standard deviation and percentage indicators were obtained using Equations (7) and (8), respectively:

$$S_d = \sqrt{\sum_{i=1}^{n} (Z_i - \overline{Z})^2 / (n-1)} \tag{7}$$

$$P(\left|Z_i - \overline{Z}\right| \leq 0.03) = \frac{m}{n} \times 100\% \tag{8}$$

where, Z_i is the elevation of the flatness sampling point, m; $\overline{Z}$ is the desired elevation of the flatness sampling points, m; n is the number of flatness sampling points; and m is the number of sampling points with the absolute value of the difference between the measured and desired elevation of smaller than 3 cm.

3.3.3 Beating depth

The three-dimensional topography of the paddy field can be expressed through (the coordinates of) the flatness sampling points (X_i, Y_i, Z_{1i}), which were combined using the computed coordinates of the lowest working point of the beating blade to obtain the beating depth. Designating the distance from the GNSS antenna to the lowest working point of the beating blades as H_s, the coordinates of the lowest working point of the beating blades can then be expressed as (X_{2j}, Y_{2j}, $Z_{2j}-H_s$). As shown in Figure 8, the levelling-beating trajectory of the levelling-beater (as obtained using the measurements of the position of the GNSS antenna) is not always aligned with the flatness sampling points. To correlate the flatness sampling points with the levelling-beating trajectory, the elevations of all lowest working points (X_{2j}, Y_{2j}, Z_j-H_s) within 170 cm (half of the operating width (340 cm) of the levelling-beater) of a flatness sampling point were averaged to indicate the elevation of the lowest beating point at the sampling point Z_{2i} (as expressed in Equation (9)). Thus, the beating depth of the sampling point (h_i) is the elevation of the soil surface after the flatting-beating operation minus the elevation of the lowest working point of the beating blades during the flatting-beating operation, as expressed in Equation (10).

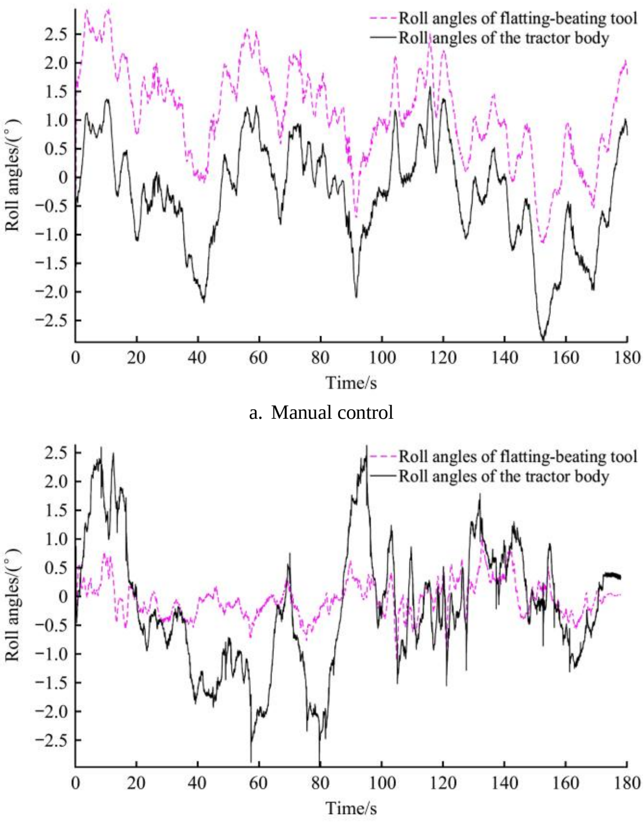
$$\sqrt{(X_{2j} - X_i)^2 + (Y_{2j} - Y_i)^2} \leq 170 \tag{9}$$

$$h_i = Z_{1i} - Z_{2i} \tag{10}$$

3.4 Experimental Results and Analysis

3.4.1 Test results of the automatic levelling adjustment of the levelling-beater

Figure 9 shows the roll angles of the tractor body and the levelling-beater obtained using the two AHRSs, whereas Figure 9a presents the measured roll angles during the levelling-beating operates using manual control. The measurements show that the roll angles of the tractor body and the levelling-beater varied in completely the same pattern. Figure 9b shows the measured roll angles during the levelling-beating operates using automatic tilt control. The measurements show that the roll angles of the tractor body and the levelling-beater varied with the ranges of ±2.5° and ±0.5°, respectively. The unevenness of the underlying hard layer of the paddy field affects the operational quality of the levelling-beater in the transverse direction if the levelling-beater is manually controlled. The maximum roll angle of the levelling-beater using manual control is 2.5°, which is translated to a field surface unevenness of 7.42 cm within the operating width of the levelling-beater (340 cm); the maximum roll angle of the tool using automatic levelling control is reduced to ±0.5°, which is translated to a reduced field surface unevenness of 1.48 cm within the operating width of the levelling-beater. That is, the automatic tilt control contributed to a better flatness of the field soil tilled by the levelling-beater.



a. Manual control

b. Automatic tilt control

Figure 9 Real-time roll angle measurements during the test

3.4.2 Test results of the automatic grade adjustment of the levelling-beater

Figure 10 shows the real-time grade of the levelling-beater using manual control (by adjusting the three-point suspension mechanism of the tractor) and laser control as measured with a GNSS. The figure shows that the grade of the levelling-beater operating in automatic control mode keeps stable. The test data show that, when operating in automatic control mode, the elevation of the levelling-beater varies within the range of ±4 cm of the average elevation, where the root-mean-square error is 2.05 cm; in addition, when operating in manual control mode, the average elevation varies within the range of ±11 cm of the average elevation, where the root-mean-square error is 4.56 cm.

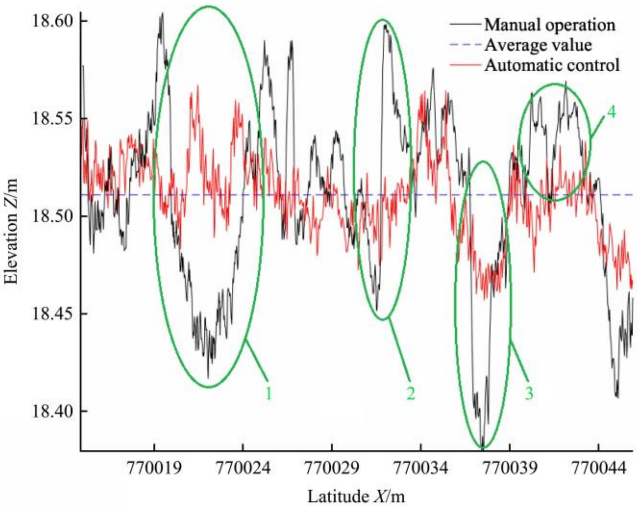
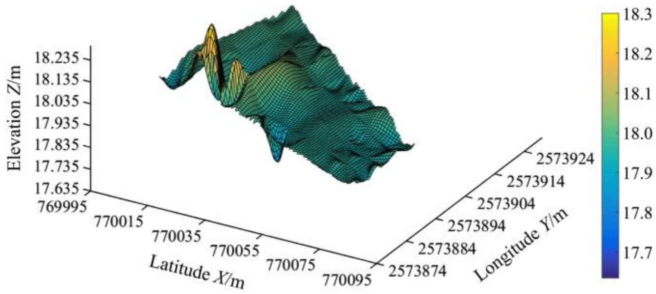


Figure 10 Real-time elevation measurements taken during the test

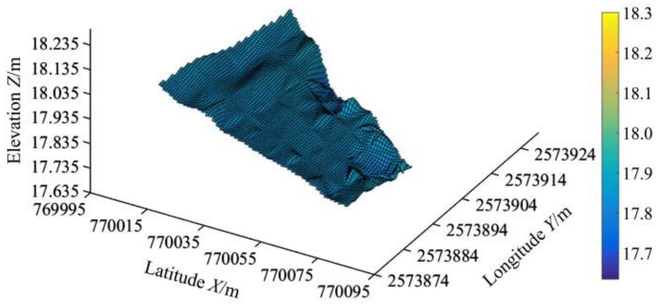
The elevation measurements marked by circle 1 in Figure 10 were obtained when the levelling-beater was operated in a concave area of the underlying hard layer. When the levelling-beater was operated in a concave area in manual control mode, the elevation first increased and then decreased. Although the driver attempted to adjust the elevation by manually adjusting the three-point suspension mechanism of the tractor, some of the adjustments were excessive (for example, the elevations marked by circle 2 in the figure), owing to a delay or inaccuracy of the manual adjustment. This resulted in an operating depth excessively smaller or larger than the pre-set value, with maximum operating depths deviating from the pre-set value by 8.7 cm shallower and 9.4 cm deeper, respectively. When operating in automatic control mode, the levelling-beater maintained the elevation near the average elevation; in addition, although the maximum operating depth deviated from the pre-set value by 5 cm shallower, the levelling-beater quickly resumed a stable operating depth. The elevation measurements marked by circle 4 in the figure further demonstrate that automatic control is superior to the manual control in terms of accuracy and stability. More specifically, the elevation of the levelling-beater operating in manual control mode varies in an M-shaped pattern, owing to repeated manual adjustments, whereas the elevation of the levelling-beater operating in automatic control mode keeps stable. The beating depths of the levelling-beater operating in automatic control mode, as marked by circle 3, were sustained at levels greater than the pre-set value because the levelling-beater was operated in a deep concave area. Although the elevation was automatically adjusted to the upper limit, it was still smaller than the pre-set value, and this situation did not change until after the tractor travelled out of the deep concave area. In summary, the automatic grade adjustment contributed to a markedly better operating quality and stability of the levelling-beater.

3.4.3 Flatness and beating depth of levelling-beating operation

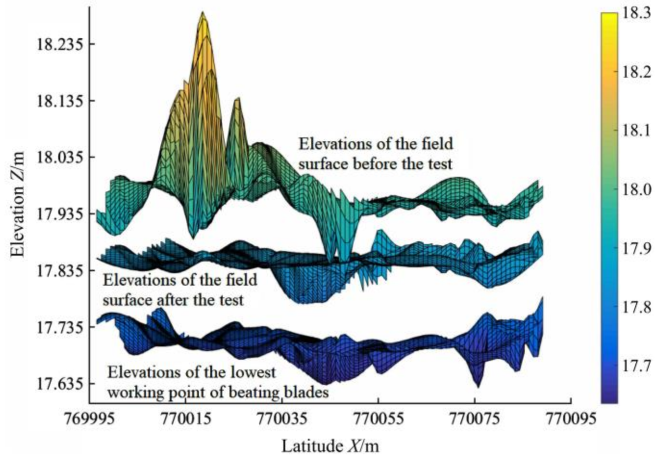
Figures 11a and 11b show the three-dimensional rendering of the field flatness before and after the levelling-beating operation, respectively. The figures indicate that the field flatness after the operation is markedly better than before. Figure 11c shows the elevations of the soil (added) before and after the levelling-beating operation and the lowest working point of the beating blades. Figure 11c shows that the elevations of the lowest working point of the beating blades and the soil after the levelling-beating operation vary in a similar pattern or in a parallel manner. The average difference between the elevation of the lowest working point of the beating blades and soil after the levelling-beating operation, or the average beating depth, is 14.2 cm, whereas the pre-set beating depth is 15 cm. That is, the deviation of the effective beating depth from the pre-set value is insignificant.



a. Three-dimensional rendering of the field flatness before the test



b. Three-dimensional rendering of the field flatness after the test



c. Elevations of the soil before and after the test, and the lowest working point of the beating blades

Figure 11 Three-dimensional rendering of testing results

Table 1 shows the statistical analysis results of the levelling and beating depth. The maximum variation in the elevation reduced from 26.4 cm before the levelling-beating operation to 11.5 cm after the operation, the standard deviation (of elevation) reduced from 4.13 cm to 2.18 cm, the number of the sampling points with a deviation from the desired elevation value of no bigger than 3 cm is higher than 86%, and the standard deviation of the beating depth is 2.46 cm. This demonstrates that the laser control significantly improved the field flatness of the levelling-beater, enabling it to operate at a stable depth.

Table 1 Statistical results of the field levelling-beating test

Field status	Average /cm	Max elevation /cm	S_d /cm	$P(\lvert Z_i - \bar{Z} \rvert \leq 0.03)$ /%
Before levelling-beating	17.971	26.4	4.13	78
After levelling-beating	17.852	11.5	2.18	86
Lowest working point of beating blades	17.710	16.3	2.58	80
Beating depth	0.142	12.8	2.46	88

Figure 12 shows the measurements when the tractor travelled from west to east along the third line from the top, as shown in Figure 8. The figure shows that the field flatness after the levelling-beating operation and the operating depth vary insignificantly. The three time-series of the elevation measurements in the figure were fitted using the least squares method (using the fitting lines plotted as dashed lines). The fitting reveals that the elevation of the western side of the field was higher than that of the eastern side before the levelling-beating operation. The fitting line for the elevation measurements after the operation is basically horizontal. This indicates that the levelling-beating operation improved the flatness of the field by transferring soil in areas of higher elevations to areas of lower elevations, and that the levelling-beater operates through the working principle described in Section 1.1. Moreover, the fitting line for the beating depth measurements is also basically horizontal and parallel to the fitting line for the field flatness measurements after the operation, with the distance between the two fitting lines being 14.8 cm. This indicates that the design of the soil beating after soil flatting contributes to a more consistent beating depth and is consistent with the working principle of soil beating described in Section 1.1.

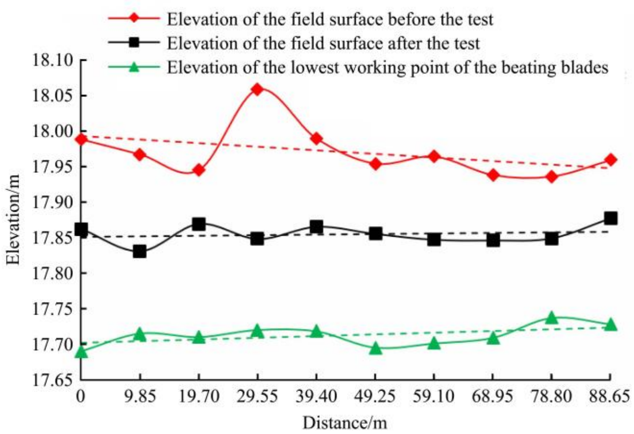


Figure 12 Elevation measurements before and after the test

Figures 11c and 12 indicate that the field elevation after the flatting-beating operation is 11.8 cm lower on average than that before the operation. Although the measurements obtained from the test were transformed into a different coordinate system, the transformation was made consistently using point O as the reference point, and the data were confirmed to be reliable through multiple rounds of checks. The reduction in the field elevation mainly results from the following mechanism: The scraper of the laser-controlled levelling-beater cuts the soil from areas of higher elevations to fill in areas of lower elevations, with a cut and fill ratio of greater than 1[1]; in addition, the irregular soil blocks were crushed by the levelling-beater, and the resulting soil particles were adequately mixed with water to form mud, allowing the trail plate of the beating mechanism to press the beaten soil.

4 Conclusions

A new levelling-beating technology for the preparation of paddy field was proposed. To apply precise soil beating after levelling, the levelling mechanism is installed in front of the beating mechanism. Moreover, it is capable of levelling and beating paddy fields at the same time with an adjustable beating depth.

A laser-controlled paddy field levelling-beater was designed, and the grade and tilt of it are automatically controlled according to the levelling-beater vertical height and the tractor roll angle, respectively. The automatic control significantly improves the operational quality and stability of the levelling-beater. The elevation of the levelling-beater varied ±4 cm around the mean elevation and roll angle varied within the range of ±0.5° using automatic control. However, the elevation and roll angle were greater than ±11 cm and ±2.5°, respectively, without automatic control.

The paddy field test shows that the maximum variation of the elevation was reduced from 26.4 cm before the levelling-beating operation to 11.5 cm after the operation, and the standard deviation was reduced from 4.13 cm to 2.18 cm. The total number of flatness sampling points with the absolute difference of the desired elevation less than or equal to 3 cm was more than 86%. The effective beating depth was 14.2 cm, compared with the set beating depth of 15 cm, the standard deviation was 2.46 cm. The results show that the laser-controlled paddy field levelling-beater significantly improves the paddy field flatness, and enables it to operate at a stable depth to realise an even levelling and beating layer.

The data of paddy field elevation before and after the levelling-beating operation and beating depth were transformed into the same coordinate system, which provides a method for the quality analysis and evaluation of levelling and beating for future studies.

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