Development and test of an automatic height-adjusting cotton topper

Chen Zhaoyang[1,2], Shi Lei[2*]

(1. *Graduate School of Chinese Academy of Agricultural Sciences, Beijing 100081, China*;
2. *Nanjing Research Institute for Agricultural Mechanization, Ministry of Agriculture, Nanjing 210014, China*)

Abstract: A fine-tuned height-adjustable cotton topper was developed and evaluated in this study. Cotton is topped at the late flowering stage because spindling reduces cotton production and complicates harvest. The main disadvantage of traditional cotton toppers is that their topping height cannot be adjusted according to the heights of individual cotton plants, resulting in a high percentage of missed tops and overcutting that damages fruit branches. To solve this problem, a mechanical-electronic topping prototype was developed that could be adjusted according to the height of cotton. The prototype includes a shearing machine system that can be tuned vertically and an automatic height control system that can detect cotton heights and actuate the mechanical system. This cotton topper was attached to a tractor by a three-point hitch and tested in the field. In the trial, the prototype was tested at ground speeds of 1.1 km/h, 1.5 km/h and 2.2 km/h and excision lengths (from the peak to the cutting point) of 9 cm and 11 cm. Under all tested conditions, the pass rate (the percentage of buds accurately cut without hurting the fruit branch), which reached 74%, was significantly higher than the ideal pass rates of traditional toppers, which were much lower than 50% or even 40%. The dominate factors affecting topping quality were tested. The pass rate was significantly influenced by the forward speed; the missing rate (rate of missed topping) was significantly influenced by the forward speed and excision length; and the overcut rate was significantly influenced by the excision length. The optimized topping speed and excision length were 1.1 km/h and 11 cm respectively, and the other parameters varied according to different user preferences. A replicate trial was conducted and showed that topping at 1.1 km/h and 9 cm prevented further spindling of 90% of the plants, and topping at 1.5 km/h and 11 cm prevented further spindling of 83% of the plants.

Keywords: cotton topper, height-adjusting, topping quality, field test, automatic control
DOI: 10.3965/j.ijabe.20171002.2492

Citation: Chen Z Y, Shi L. Development and test of an automatic height-adjusting cotton topper. Int J Agric & Biol Eng, 2017; 10(2): 44–55.

1 Introduction

During the late period of flowering and boll bearing, spindling has a remarkably adverse effect on cotton production because excessive vegetative growth results in reduced cotton flower and boll setting[1]. Two dominant methods have been developed to inhibit vegetative overgrowth. One method is the application of farm chemicals, such as mepiquat chloride, and the other method is the mechanical cutting the terminal bud of the plant[2]. Topping the cotton plants is not sufficient alone but can dramatically decrease the required dose of mepiquat chloride[3].

During the nineteenth century, cotton-topping machines were invented to cut apical buds. Then, early machines powered by animals were replaced by multi-row cotton toppers driven by the drive axels of tractors[4,5]. Stroman et al.[6] developed a cotton topper that could be attached to a tractor by a three-point hitch. This cotton topper uses a rotating blade to cut the tops of plant buds and a shell to guide the resulting debris to the soil between the rows. The cotton topper developed by Stroman was an original model of the toppers that were

Received date: 2016-03-28 **Accepted date:** 2016-08-11

Biographies: Chen Zhaoyang, Master of Engineering, Research Assistant, research interest: agricultural machinery, Email: czyjinan@outlook.com.

***Corresponding author: Shi Lei**, Professor, research interest: agricultural machinery. Nanjing Research Institute for Agricultural Mechanization, Ministry of Agriculture, Nanjing 210014, China. Tel: +86-15366092908, Email: 623435554@qq.com.

used until recently. Heard[7] modified the traditional topper by mounting knives in a zigzag pattern on either side of a beam to prevent the knives from striking each other. Both of these machines and their improved versions cut the top buds by using a rotating blade at a determined height.

Although the productivity of mechanical powered cotton toppers has dramatically improved over time, the cutting accuracy of these devices has been hampered by the lack of an automatic control system. Moreover, because of their flexibility, cotton stalks slide backward when topped by a rotating blade[8], which limits the cutting effectiveness of traditional toppers. In fact, topping at one height is not suitable. The heights of cotton plants can vary by more than 20 cm in modern tropical cotton fields. Cutting the terminal buds of cotton plants at one height can miss shorter plants and over-cut taller plants, leading to potential boll loss.

During the late nineteenth century, a variety of mepiquat chloride formulations were invented, which can shorten the intermodal length of cotton plants and control excessive vegetative growth[9]. This farm chemical was first registered in the USA in 1980 to be used as a growth regulator of cotton and was reregistered in 1997 by the Environmental Protection Agency (EPA) for its use in the USA[10]. Now, mepiquat chloride is formulated as an emulsifiable concentrate at concentrations lower than 5% (w/v)[11]. Consequently, cotton farmers began applying large doses of mepiquat chloride to decrease excessive vegetative growth. Expert systems, such as GOSSYM-COMAX[12], were developed to calculate application strategy based on fertilizer application, irrigation application, etc. However, the efficiency of mepiquat chloride is affected by ambient conditions, such as weather and planting pattern[13]. Additionally, the over-use of agrochemicals has resulted in environmental contamination concerns. For example, the maximum dose of PDADMAC used in drinking water treatment processes has been regulated in Canada and the USA, and the residual concentration of PDADMAC in drinking water has must remain below 50 g/L in the USA[14,15]. An eco-friendlier approach for managing excess vegetative growth is to combine precise mechanical cutting with a low chemical application rate. Thus, mechanical topping should be revisited.

In the late twentieth century, mechanical topping machines became larger and had varying power transmission. However, accurate topping machines were not created until Yang added a height feedback control system to cotton toppers[16]. In 2010, Zhou developed a 3WDZ-6 self-propelled cotton topper that is automatically controlled and can adjust to an adequate cutting height based on the heights of each plant. An evaluation article of a 3WDZ-6 self-propelled cotton topper indicated that the machine can detect plant heights using a reflection-type laser sensor, which controls the height of the blade based on a PID algorithm and tops the plants using a rotary cutter[17]. But this article only explained a laboratory test on 12 samples, and no further field studies have been reported. Subsequently, He and Liu developed a vertical lift-type single-profiling cotton-topping machine. These authors analyzed the similarities between the cutting routines and the assumed connecting line between cotton tops. The topper worked well in a well-managed flat cotton field with minimal height differences[18]. However, further studies regarding the use of this cotton topper in ordinary commercial cotton fields have not been conducted.

The height control systems of detasseling machine and topping machines used for other crops can also serve as useful references, such as corn detasseling machines and tobacco toppers. However, none of these machines apply directly to cotton topping because cotton plants have different geometric characteristics and require much higher control accuracy is required.

The primary goal of this research was to develop a practical cotton topper capable of shearing down the tops of cotton plants at appropriate points on the main branch while maintaining a practical forward speed. In other words, the specific objective of this study was to develop a topper capable of terminating the terminal bud while inflicting the least amount of damage to the branches potentially bearing bolls.

The four following aims were addressed in this study:

1) Develop models to demonstrate the common structure of cotton tops and the height distribution of

cotton.

2) Design a mechanical system capable of accurately cutting cotton tops without sliding.

3) Devise an automatic control system that can accomplish the “detecting-computing-actuating” process.

4) Test the prototype to identify its optimized parameters.

2 Materials

2.1 Specifications of the prototype

The prototype is composed of two parts: a mechanical system for mechanical motion and an electronic system for automatic control. The entire system is powered by a vehicle-mounted 220DC electric generator (YL 6500E Diesel Generators, Hansa corp., Shanghai, China). The prototype is attached to a tractor as shown in Figure 1.

Figure 1 Self-developed cotton topper prototype attached to a tractor

2.2 Mechanical system

2.1.1 Main structure

Figure 1 shows a photograph of the topper mounted on a tractor, and Figure 2 shows the final assembly of the topper. The main frame of the cotton topper holds three individual topping systems that function independently of each other and are attached to the main frame by u-shaped bolts. The cotton topper can be attached to modern tractors by a three-point hitch. This design ensures that the length of the main frame, the number of individual topping systems, and the topping sway can be modified as needed. The topping system described in this article is shown as the unit in the middle of Figure 2. The other two systems shown in the picture are other prototypes that were tested in this study but performed poorly.

Figure 2 Schematic and photograph of the topper

2.1.2 Mechanical height-adjustable shear system

In an individual topping system, a cuboid frame holding the mechanical system is mounted on the main frame. Two major parts of the machine are a pair of rotating disc cutters and a pinion-rack system for adjusting its height. The mechanical topping system 1) drives the two-disc cutter to rotate smoothly and oppositely toward the center point and 2) shifts the height of the shear system vertically without altering the geometric structure of the system. The height of the topper is accurately and rapidly controlled by an electronic controller, which is described later in this article. The functions of the two main parts of the topper are described below.

2.1.3 Counter-rotating shear system

The structure of the counter-rotating shear system is shown in Figure 3. A pair of serrated discs is perpendicularly attached to the output shafts of two brush-less motors. The back ends of these electric motors are mounted to the lower ends of two hollow shafts. Electric wires are embedded inside the central holes of the shafts, and the upper end of the shaft is connected perpendicularly to a joint bar. The two shafts and a joint bar form an ‘n’-shaped fixed part. These two shafts are centered by two guide sleeves welded on the frame. Structurally, the two shafts and the discs at the ends of the shafts are each paired parallel. Thus, although the discs partly overlap, the vertical distance of 5 mm between the discs prevents them from colliding.

Figure 3 Counter-rotating shear system

As shown in Figure 4, the two discs rotate inwardly to fix the top of a plant and shear it. When moving forward, the counter-rotating saw teeth draw the top leaves inward and shear the top. The rough saw teeth prevent the leaves from sliding out when the tops are sheared. The rotation speed is approximately 500 r/min, and although the rotation speed is important, it is not strictly controlled. The sheared debris accumulates on the discs between the shafts only if the rotation speed is too low. In contrast, if the rotation speed is too high, severe disc vibration occurs, which is not destructive but results in a harsh noise due to friction between the discs.

2.1.4 Pinion-rack system height-adjusting system

The structure of the pinion-rack height-adjusting system is shown in Figure 5. The midpoint of the joint bar is joined to a perpendicular rack on one side of the system. The back of the rack is placed in a slide mounted on the frame. On the other side, a pinion is attached to the output shaft of a servomotor and the motor is mounted on the frame. The pinion engages with the rack as shown in Figure 5. Therefore, when the output shaft of the servomotor rotates, the rack accurately ascends or descends vertically. The rapid and precise action of the pinion-rack height-adjusting system guarantees accurate and rapid placement of the shear for cutting.

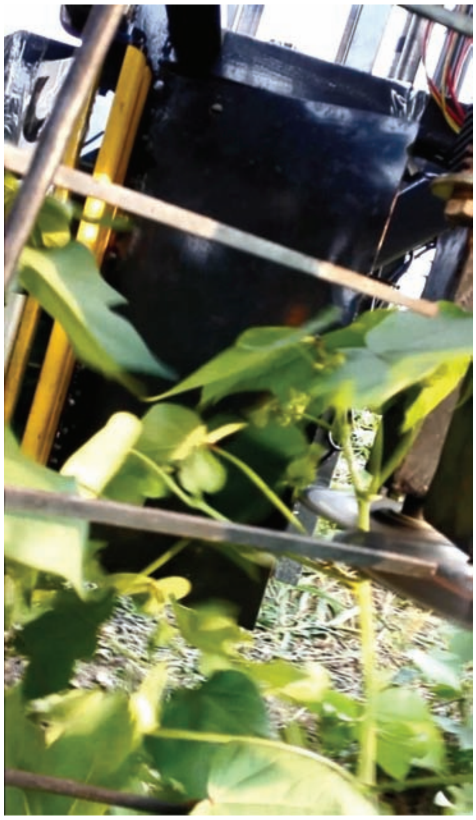

Figure 4 An example of the topper shearing a cotton top

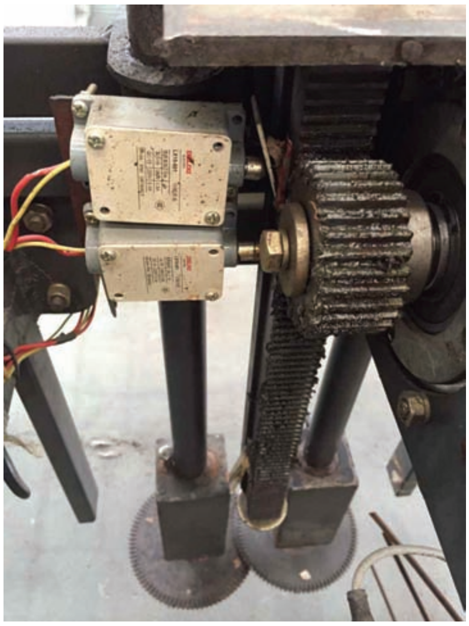

Figure 5 Pinion-rack height-adjusting system

In practical trials of this mechanical system, the shears rotated flexibly and precisely. In addition, no movement interferences occurred during horizontal rotation and vertical sliding.

2.2 Electronic control system

The electronic control system includes three parts: a height-sensor system, a control center and a servo system, which are responsible for detecting, computing and actuating, respectively.

2.2.1 Height-sensor system

The height-sensor system measures the height of each cotton plant and sends a signal to the control center. Considering cost and accuracy, an optical grating detector was used (Optical Height Detector, Zebra corp., Shenzhen, China). The working mechanism of the sensor is described as follows: The 64 small transmission tubes on one side of the optical gratings transmit 64 infrared ray lines, and 64 receivers on the other side of the optical gratings receive the ray lines. If an object appears in the middle of the optical gratings, some of the signal is obstructed and does not reach the receiver. By measuring the signals of the obstructed infrared rays, the size of the obstructing object can be calculated. The on/off signal is sent out by an 8-bit RS232 port to the controller for further computing. The accuracy of this type of sensor depends on the intensity of the infrared transmitter and the receiver along the optical grating. The optical curtain height sensor used by this prototype has an accuracy of 5 mm.

2.2.2 Center controller

The controller is a 32-bit board card that includes a STM32F103ZE CPU (EMB 8612A Embedded industrial control block, Zhongqianlingyun corp., Xian, China). The controller receives height signals, calculates the signal and creates an order to drive the servomotor (the control flow will be explained later in this article). STM32 was chosen because of its stable operation, high speed and its development environment, which supports C language.

2.2.3 Servo

An AC servo driver (EPS-B1, Donglin Corp., Jiaxing, China) and a servo (130DNMA1-0001, Donglin Corp., Jiaxing, China) were installed on the prototype. Servo systems permit high rotation precision, convenient operation and high torque at high speeds. The servo works in ‘position control mode’ to accurately adjust the cutting height according to the height of each cotton plant. Several parameters, including the PID parameters of the servo, must be optimized to ensure that the servo can act quickly without too many alarms.

2.2.4 Other materials

As shown in Figure 6, a comparison trial of the ultrasonic sensor and optical curtain sensor was conducted. In field trials, we found that although the ultrasonic sensor is cheaper, the optical curtain sensor had two advantages over the ultrasonic sensor (UB2000-F42-E6-V15, PEPPERL+FUCHS corp., Shanghai, China). Firstly, the detection cycle of the ultrasonic sensor (150 ms) is longer than that of the optical curtain sensor, which is 9600 bauds (equal to a detection cycle of 6 ms). Secondly, the detection region of the ultrasonic sensor is sector shaped. If the plants entering the detection zone deviate from the centerline, inaccurate measurement will occur, such as no signal reflection. These measurement errors result in malfunctions. Thus, because the ultrasonic sensor was less sensitive and robust in the field test, the optical curtain sensor was chosen as part of the prototype.

Figure 6 Infrared and ultrasonic sensors

In another trial, a speed sensor was installed on the tractor attached to the topper to detect the forward speed. This sensor could be used to adjust the time delay of the topping action based on the forward speed, which is similar to the control flow described by Jeon and Zhu[19] and Jeon et al.[20] However, this sensor was finally eliminated because of different planting patterns and field environmental problems. Firstly, in contrast with commercial groves where the tree-to-tree distance can exceed three meters, the distance between cotton plants in commercial cotton fields is 23 cm and the forward speed is approximately 0.6 m/s. The topper must detect the heights of cotton plants and adjust the cutting height within approximately 300 ms. The additional speed sensor and algorithm prolonged the calculation time and resulted in an unacceptable time delay. Secondly, during a rainy summer, the speed sensors, which are mounted on the wheels of the tractor, are very easily choked by mud and result in malfunctions such as extremely long delay times. Consequently, forward speed detection was eliminated, and the prototype was controlled at the highest speed to obtain the highest productivity.

2.3 Control flow and program

2.3.1 'Separate by section' algorithm

Before explaining the control flow, a key algorithm for identifying the plant tops amidst bunches of leaves is described. Previously, studies in which height-adjustable toppers were designed relied on height sensors to detect the heights of cotton plant crowns and cut them along a profile line. However, the plant-to-plant distances are very small in commercial cotton fields. This tracking method does not find the top, which results in a lot of redundant action and the incorrect cutting of cotton branches. Searching the entire plant before locating its top is also impractical because if the detection system was required to measure the height of the entire plant (from the front and first contact point to the last point) and locate the point below the bud before making a cut, it would be too late to move the shear shaft. The cutter will pass the cutting point of the target plant because of the time delay, and it would be difficult to prevent cutting the next plant by mistake.

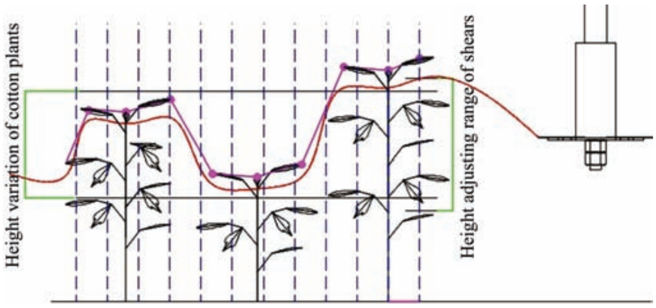

Figure 7 'Separate by section' algorithm

To solve this problem, an algorithm described as follows was used for the topper. This process is shown in Figure 7. The optical grating measures the entire zone in front of the shear and sends height signals back to the controller. Inside the program, the reflected signals are stored in an array with determined lengths that result in the separation of signals into periods called peak searching-sections (shown by blue strips). Then, the controller searches for the highest point of each section (in Figure 7, the highest point is identifiable by a pink dot) and sends the highest point as the next "top" to cut, which determines the next position. Although this highest point may not be the real top, it prevents the height control program from being disturbed by voids between cotton leaves and maintains a smooth path that can pass the actual cutting point. Actually, this routine fitting from point to point is smoothed by the servo LSPB trajectory program. In Figure 8, more vivid pictures of the process of detecting a plant and cutting it are shown. a) A cotton plant enters the detecting zone and sensors measure its height. b) When the plant approaches the shears, the shears lift and adjust for proper placement (Figure 8b). c) The shears clamp the plant (Figure 8c) and d) the top of the plant is sheared and carried behind the plant before the next plant enters its range (Figure 8d). As shown in Figure 8, the prototype only shears a small top, just as humans would.

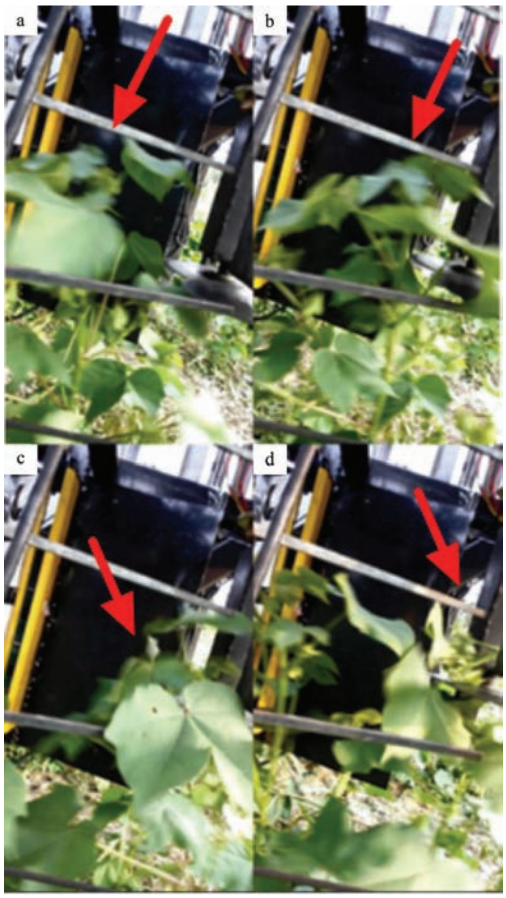

Figure 8 One example of the cutting process

In field studies, this algorithm resulted in stable and accurate operation. In addition, the following agronomic characteristic supports this algorithm: the top bud and the two leaves on both sides of the bud are nearly flat and almost at the same height above the other leaves. Thus, the cutting point is very detectable. As shown in Figure 7, the shears stop at each plant and cut the bud before moving to the next plant.

2.3.2 Flow control

The control cabinet is mounted on the main frame behind the topper. Inside the control cabinet, the entire control program is downloaded to a board card. The control flow is shown in Figure 9, once the topper is started, a few minutes are required to initialize the system and check the working conditions of every component. After preparation, the controller reads the signals from the infrared sensor, measures the height of the object between the gratings and determines the peak point of the plant as specified above. Then, the controller determines whether the deviation between the position of the shears and the next cutting point is sufficiently large to require rotating the servomotor to a certain angle. After the height is set, the shears reach the position and cut the top. Then, new height signals arrive, and the cycle repeats itself.

One detail should be highlighted. First, the pair of optical gratings that measures the height of the cotton has a measurement range of 55-85 cm. If nothing is located between the gratings, the height should be 55 cm. However, this reading more often occurs when a narrow void exists between plants not really because the target plant is very short. All previous topper machines regarded such a reading as resulting from a very short plant, which would result in a malfunction. In these cases, the toppers push down the cutters mistakenly and cut the next cotton plant because the void is too narrow to pull up the shears and prevent cutting the next plant. In the prototype presented in this study, the knives will wait at the middle height when a narrow void is encountered and until the next plant arrives, as shown in Figure 7. This algorithm dramatically improved the stability of the control system.

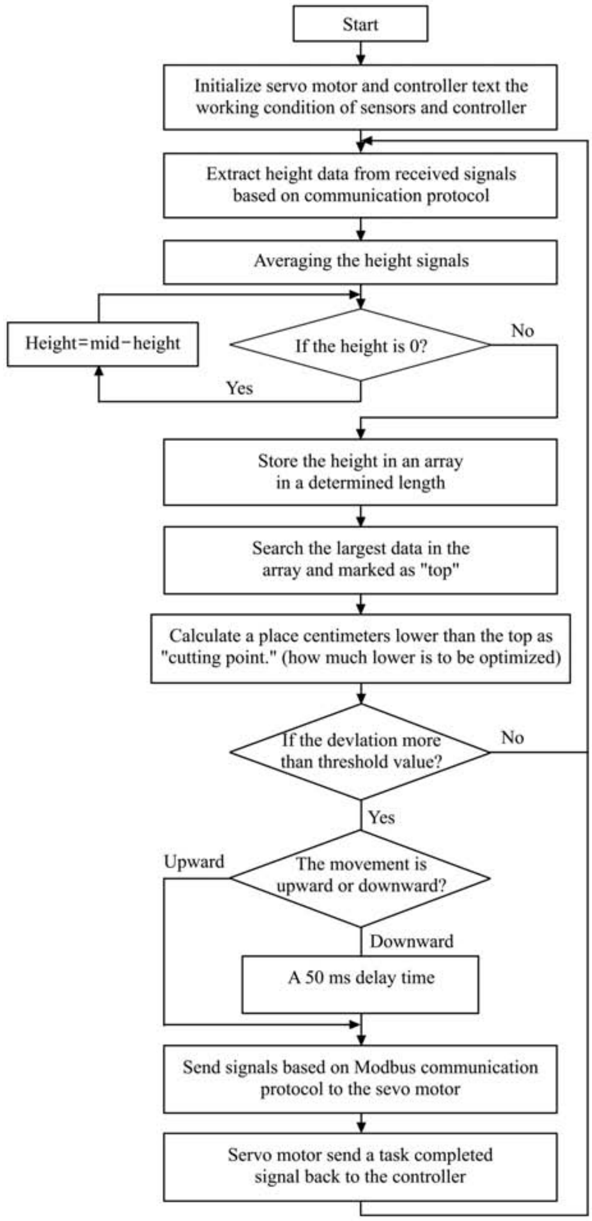

Figure 9 Control flow

3 Test procedure

3.1 Cropping pattern

The cotton topper was tested in a commercial cotton field. Measurements and tests were conducted in Shandong Province, China, 117.6E, 37.73N. The cotton variety China Cotton 619 was sown on May 31 and topped from August 15 to 30. The cropping pattern presented in Figure 10 shows the relative directions and locations of the cotton plants in a commercial cotton field. The distance between rows was 76 cm, with a plant-to-plant distance of 23 cm.

The goals of the experiment were to 1) build a model of the common structure and parameters of cotton tops; 2) compare the new prototype with traditional toppers;

and 3) analyze the significant factors that influence the performance of the prototype and optimize its parameters.

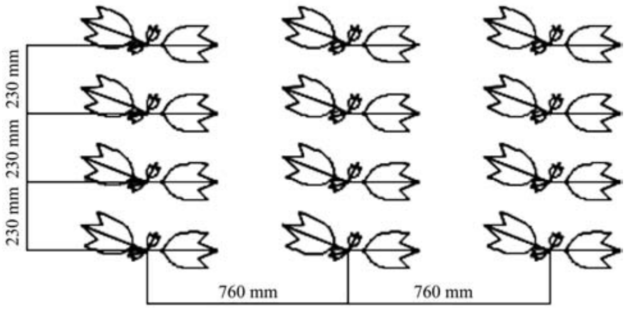

Figure 10 Cropping pattern

3.2 Test methods and instruments

1) When developing the cotton topping model used in the first two trials, researchers used a Vernier caliper to measure stem length (accurate at the millimeter scale). The length was measured from the peak point to the bifurcation of the stem or the end of the bud. 2) When developing the model of the cotton height distribution, researchers used a meter stick to measure cotton heights.

To test the topper, it was attached via a three-point hitch to an H-1000 Foton Europard tractor with 100 horsepower and high clearance. The tractor acted as a high-clearance mobile platform for the topper, but no power transmission passed between the tractor and topper. Instead, the topper was powered by an independent and transportable electronic generator that was carried by the tractor. Researchers measured the heights of the cotton before and after topping and compared them to calculate the lengths of the stems excised by the topper.

3.3 Test one: cotton crown model

A model of the cotton plant crowns was developed that shows the geometric structure of the branches and leaves around the tops of the cotton plants. This model can determine the cutting point. As shown in Figure 11, a typical cotton crown consists of four parts: the bud, main branch, last lateral branch, and penultimate lateral branch. Covered on both sides by leaves, the terminal bud is at the top of the plant on the main branch and above the last lateral branch and penultimate lateral branch. The parameters for the distributions of cotton crown branches are presented in Table 1.

Successful topping by this prototype is achieved when buds are eliminated without cutting the penultimate branches. Not taking last branches into consideration because it is extremely difficult to top without injuring them. As show in Figure 12, the last lateral branch (Length 2) locates near the bud (Length 1). As shown in Table 1, the stem between the bud and last branch is too short to prevent injury of the last lateral branch when shearing the bud, which follows a normal distribution, N (2.83 cm, 1.40 cm^2). Thus, a topper that shears down the bud without cutting the penultimate branch is defined as successful.

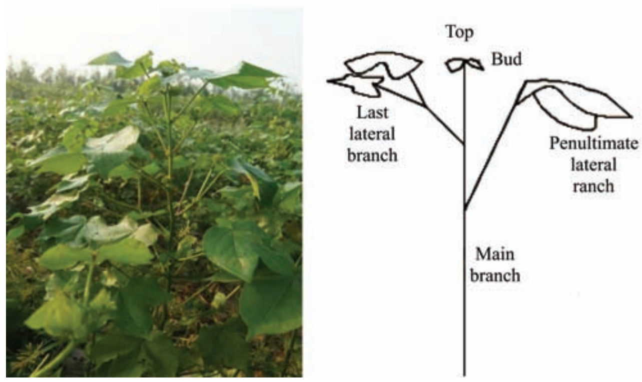

Figure 11 Model of the cotton crown

Table 1 Parameters for the distribution of branches (cm)

Targets	Average	Standard deviation	Cumulative percentage	Cumulative percentage
length 1	2.74	0.825	1.5 (10%)	3 (80%)
length 2	5.57	0.846	4 (10%)	6.5 (90%)
length 3	13.17	2.247	11 (10%)	16.5 (90%)

Note: 1. The length between the terminal bud and peak point 2. The length between the end of the stalk of the last lateral branch and the peak point 3. The length between the penultimate lateral branch and the peak point

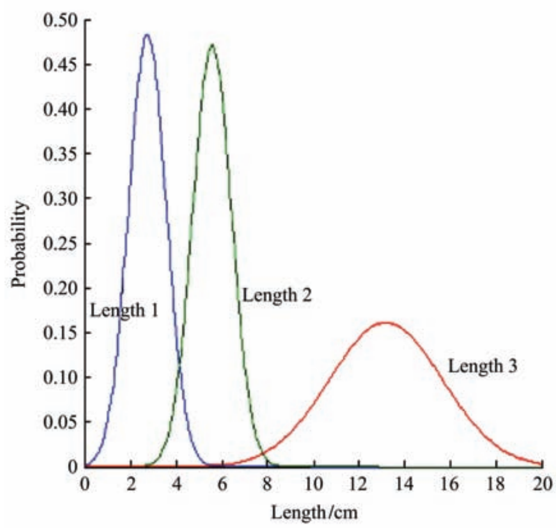

Figure 12 Length distributions of the branches of cotton crowns

Based on statistical analysis, the suitable range that can be cut is 3-11 cm. Within this cutting area, the top of the bud can be cut without hurting the penultimate branch, so it results in a successful cut. The pass rate refers to the percentages of successful cuts, the missing rate refers to percentages of missed cuts (<3 cm), and the overcut rate refers to the percentage of overcuts (>11 cm).

3.4 Test two: the cotton height model

The cotton height model shows the height distribution of cotton in a typical cotton field. The heights of cotton plants in a field vary greatly. This model is built to indicate where cotton crowns are most likely to appear and how the cutting height should be adjusted accordingly. The height that the topper shears can shift should cover nearly all of the cutting points of the tops. Besides, for cost efficiency, this adjustment range is not expected to reach extremely tall or short tops.

Height modeling assumes that the cotton heights are normally distributed because the number of samples is very large (920 samples). The height distribution is presented in Table 2. Based on this model, it is reasonable to design a topper with an adjustment range of 55-85 cm to cover 91.06% of the cotton heights.

Table 2 Cotton plant heights

Targets	Average /cm	Standard Deviation/cm	Cumulative percentage 10%	Cumulative percentage 90%
Height	68.84	8.13	58	80

3.5 Comparison of this prototype with traditional cotton toppers

Traditional toppers, as is shown in Figure 13, normally cut tops with a cylinder cutter at one uniform height in a field. The uniform height is usually judged by experience or some sample measurements. However, the height of cotton varies largely within commercial fields. Cutting plants with different heights at one pre-determined height will result in a high percentage of damaged fruit branches or missed plants. Moreover, missed plants must be topped manually, which increases human labor cost[2].

Although the percentage of unsuccessful topping by traditional toppers is high, their topping pass rate has rarely been studied because no detailed height distribution model existed previously. The three rates stated above can be calculated based on the height distribution of model cotton stated in this article. Figure 14 shows how the pass, miss and overcut rates change according to the different heights that the users choose.

Figure 13 A traditional cotton topper

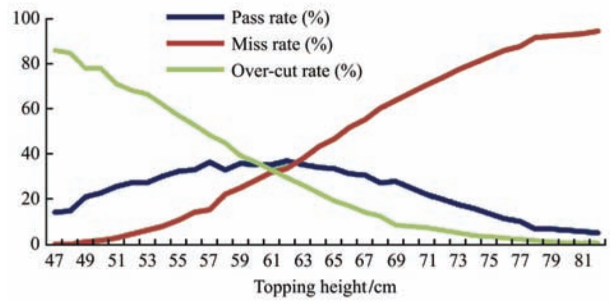

Figure 14 Changes in the pass rate, missing rate and overcut rate with topping height

This calculation is not based on a particular type of cotton topper but calculates the inevitable unsuccessful topping rate of traditional toppers theoretically. For example, when considering a traditional topper height of 61 cm, approximately 37% percent of the cotton is 3-11 cm taller than the cutting point and will be topped at a proper height. Also, some of the plants are not at the proper height (taller or shorter), resulting in misses and overcutting. As long as users choose a position within the range between the shortest and tallest plants, some plants will be cut successfully, some plants will be overcut and some plants will not be cut. As shown in Figure 14 the pass rate (blue line) of a traditional topper cannot exceed 50%, even under theoretically ideal conditions

3.6 Factorial experiment using this prototype

3.6.1 Experimental methods and factors

The prototype was tested in the same commercial field in Shandong Province, China. A factorial experiment with unequal subclasses was conducted to determine the performance of the prototype at three different speeds (A_1: 1.1 km/h, A_2: 1.5 km/h and A_3: 2.2 km/h) and two different excision lengths (B_1: 9 cm and B_2: 11 cm). The total numbers of samples and replications conducted under different factors and different parameters (levels) are presented in Table 3. For example, under the experimental condition of a ground speed of 1.1 km/h and an excision length of 9 cm, the experiment was repeated 9 times. In each repeat of an experiment, 20 samples were topped and measured. Accordingly, the total sample number in this case was 180. Notably, this preset excision length is not the exact actual excision length, but rather the ideal preset excision length. Actual excision lengths deviate by several centimeters from these values because of the unstructured environment of the field.

Table 3 Factors and corresponding parameters used in the experimental study

	B_1 (9 cm)		B_2 (11 cm)		Sum	
	Samples	Replicates	Samples	Replicates	Samples	Replicates
A_1 (1.1 km·h^{-1})	180	9	180	9	360	9
A_2 (1.5 km·h^{-1})	180	9	180	9	360	9
A_3 (2.2 km·h^{-1})	100	5	100	5	200	5
Sum	460		460		920	

In the trial, the cotton heights before and after topping were compared. Researchers measured the heights of each cotton plant before topping and placed a marker after every 10 samples. After topping, the heights of the cotton plants were measured again. The difference between the plant heights before and after topping was recorded as the actual excision length. Based on the cotton crown model described above, the excision length can be used to determine whether topping is accurate. The definitions of the miss pass and overcut rates were the same as those described above.

3.6.2 Comparison of the pass rates with traditional toppers

Within the conditions stated above, a field trial was conducted and the resulting pass rate was presented in Table 4, including the pass rates of every replicated experiment and the overall average pass rates.

As stated above, the pass rates of traditional toppers cannot be greater than 50% because their topping heights cannot be adjusted and because the heights in commercial cotton fields vary. If the pass rate of the prototype is significantly higher than 50%, it will have a significantly higher pass rate than traditional toppers. Table 5 shows statistics of the comparison.

Table 4 Pass rates of the prototype at 3 different ground speeds and 2 excision lengths

	B_1 (9 cm)			B_2 (11 cm)			Average
A_1 (1.1 km·h^{-1})	0.75	0.8	0.75	0.75	0.6	0.7	0.715
	0.85	0.7	0.75	0.7	0.65	0.75	
	0.65	0.7	0.7	0.6	0.8	0.65	
A_2 (1.5 km·h^{-1})	0.65	0.6	0.65	0.65	0.75	0.55	0.66
	0.6	0.75	0.7	0.75	0.7	0.5	
	0.6	0.65	0.75	0.6	0.75	0.7	
A_3 (2.2 km·h^{-1})	0.55	0.65	0.7	0.6	0.7	0.6	0.605
	0.55	0.55		0.55	0.6		
Average		0.67			0.65		0.67

Table 5 Comparison between traditional toppers and the prototype

Condition	Average	Standard deviation	Comparison with 50%	Confidence interval
1.1 km·h^{-1} 9 cm	73.89%	6.01%	significantly higher	(70.17%, 77.61%)
1.1 km·h^{-1} 11 cm	68.89%	6.97%	significantly higher	(64.57%, 73.21%)
1.5 km·h^{-1} 9 cm	66.11%	6.01%	significantly higher	(62.38%, 69.84%)
1.5 km·h^{-1} 11 cm	66.11%	9.28%	significantly higher	(60.36%, 71.86%)
2.2 km·h^{-1} 9 cm	60.00%	7.07%	significantly higher	(53.33%, 66.67%)
2.2 km·h^{-1} 11 cm	61.00%	5.48%	significantly higher	(55.78%, 66.22%)

The topping pass rate of the prototype was significantly higher than that of the traditional toppers for all three ground speeds (1.1 km/h, 1.5 km/h and 2.2 km/h) and the preset excision lengths (9 cm and 11 cm) at a confidence level of 95%. Thus, the prototype had significantly better performance than the traditional toppers. Compared with manual topping, which can be conducted at a rate of 0.2-0.33 hectare per person per day, a triple unit cotton topper is 20-30 times more productive, with a rate of 3.3-6.6 acres per driver per day.

3.6.3 Analysis of factors that influence pass rate

To farther exam the factors that have a significant influence on pass rate, variances are analyzed as Table 6.

This analysis demonstrates that forward speed has a significant influence on pass rate, while preset excision length (at least from 9 cm to 11 cm) and the interaction between the former and the later influence the pass rate but not significantly. This result shows that the optimal parameter is 1.1 km/h and that any preset excision length between 9 cm and 11 cm is acceptable. In addition, because all these preset lengths are usable, 11 cm is an optimal parameter because it minimizes the missing rate and is usually more valuable for users. Notably, an excision length that is too short or too long will significantly influence the pass rate. This factor shows no significant influence is caused by the counterbalance of the miss and overcut rate.

Table 6 Variance analysis of the factors of pass rate

Factor	Sum of squares	Degrees of freedom	Mean sum of square	Influence degree F
Factor A	0.0805	2	0.04025	8.14 (8.14>$F_{0.005}$ (2.40))
Factor B	0.0092	1	0.0092	1.86 ($F_{0.2}$ (1.40)<1.86<$F_{0.15}$ (1.40))
Factor A×B	0.0127	2	0.00635	1.28 ($F_{0.3}$ (2.40)<1.28<$F_{0.15}$ (2.40))
Residual error	0.1976	40	0.00494	
Sum	0.2874	45		

3.6.4 Analysis of factors that influence the missing and overcut rates

In addition to the pass rate, the missing rate and overcut rate significantly influence the performance of the prototype because the missing rate determines whether the user needs to re-top some of the plants manually and the overcut rate determines whether topping cuts down fruit branches that may bear bolls. Table 7 shows the statistics of missing rates.

Table 7 Variance analysis of the factors affecting missing rates

Factor	Sum of squares	Degrees of freedom	Mean sum of square	Influence degree F
Factor A	0.1210	2	0.0605	7.67 (7.67>$F_{0.005}$ (2.40))
Factor B	0.0569	1	0.0569	7.22 (7.22>$F_{0.025}$ (1.40))
Factor A×B	0.0402	2	0.0201	2.55 ($F_{0.1}$ (2,40)<2.55 < $F_{0.05}$ (2.40))
Residual error	0.3152	40	0.00788	
Sum	0.5333	45		

This analysis of the missing rate demonstrates that both the forward speed and preset excision length significantly influence the missing rate. The interaction of these two factors influences the missing rate, but the influence is not significant. To minimize the missing rate, users should top at a speed of 1.1 km/h and use an excision length of 11 cm.

This analysis of the overcut rate demonstrates that only excision length has a significant influence on the overcut rate. To minimize the overcut rate, users should use an excision length as short as 9 cm. Table 8 shows the statistics of overcut rates. However, as noted above, this excision length will result in a higher missing rate. Thus, using a short preset excision length is not recommended.

Table 8 Variance analysis of the factors of overcut rates

Factor	Sum of squares	Degrees of freedom	Mean sum of square	Influence degree F
Factor A	0.00925	2	0.004625	0.60
Factor B	0.0736	1	0.0736	9.57
Factor A×B	0.00585	2	0.002925	0.38
Residual error	0.3075	40	0.007688	
Sum	0.3834	45		

The mechanics of the interactions between forward speeds and excision lengths can be explained by practical observations. When disturbances occur, such as when the cotton plants are directed by the grain lifter or when plants are pushed together, their top leaves are tilted up. This deformation can result in a higher measured height than the actual height. Faster forward speeds correspond with stronger disturbances and deformations. Thus, the forward speed interacts with the excision length. Because of this interaction caused by deformation, the excision length should increase as the forward speed increases.

3.6.5 Optimized parameters for the prototype

In summary, the optimized parameters of the prototype include a forward speed of 1.1 km/h and an excision length of 11 cm. Practically, the preferences of users are more important. For example, if a user would like to achieve higher productivity, the then pass rate will compensate.

Another replicate was conducted to evaluate the actual bud termination rate and confirm the results. The criterion used was if the main branch stopped spindling after topping. After topping at 1.1 km/h with an excision length of 9 cm, 72 of the 80 cotton plants in the topped field stopped spindling (90%). After topping at 1.5 km/h with an excision length of 11 cm, 100 of 120 cotton plants in the topped field stopped spindling (83%).

4 Conclusions

An automatic height-adjusting cotton topper was developed and tested in this article. The cotton topper was equipped with a height-adjustable shear system and an automatic control system capable of detecting cotton height and manipulating a servo system to adjust the topping height.

A cotton height model was established that shows cotton heights are normally distributed N(68.84, 8.13). A cotton crown model was established that shows the structure and geometric parameters of the cotton tops. All of these statistics and models are used to support the design of the prototype.

The prototype was tested in a commercial cotton field to determine its performance and optimize its operating parameters. At ground speeds of 1.1 km/h, 1.5 km/h, and 2.2 km/h and excision lengths of 9 cm to 11 cm, the prototype reached a significantly higher pass rate than traditional toppers. In factors analysis, forward speed has a significant influence on pass rate of this prototype. A lower forward speed of 1.1 km/h and an excision length of 11 cm were optimal for achieving the best pass rate. Forward speed and excision length both significantly influenced the missing rate. A lower speed of 1.1 km/h and a longer excision length are optimal for the missing rate. Only the excision length had a significant influence on the overcut rate. The mechanics of the interactions between speed and excision length are also explained in this article. The final optimized parameters for the best performance of the prototype are 1.1 km/h and 11 cm.

Acknowledgments

We acknowledge that the research was financially supported by the Innovation Project of Chinese Academy of Agricultural Sciences. We are grateful to Jingguo Farm, Inc., the Changfa Company and the local officials in Binzhou, China, for providing us with access to the field site and allowing us to use their equipment for the field tests.

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