Development of sensor systems for precision agriculture in cotton

Ruixiu Sui[1*], J. Alex Thomasson[2], Yufeng Ge[2]

(1. *United States Department of Agriculture*, *Agricultural Research Service*, *Crop Production Systems Research Unit*, *Stoneville*, *MS*, *USA*;
2. *Biological & Agricultural Engineering Department*, *Texas A&M University*, *College Station*, *TX*, *USA*)

Abstract: Precision agriculture (PA) is an information-based technology, using detailed information within an agricultural field to optimize production inputs on a spatially variable basis, maximize farm profit, and minimize environmental impact. Information collection and processing plays a very important role in PA. In recent years PA technologies have been gradually adopted in cotton production. Several sensor systems for PA were developed and field-evaluated in cotton, including a plant height measurement system (PHMS), the Mississippi cotton yield monitor (MCYM), and cotton fiber quality mapping. The PHMS used an ultrasonic sensor to scan the plant canopy and determine plant height in real time in situ. A plant height map was generated with the data collected with the PHMS. Cotton plant height showed a close relationship with yield (R^2=0.63) and leaf-nitrogen content (R^2=0.48). The MCYM was developed for cotton yield mapping. A patented mass-flow sensor technology was employed in the MCYM. The sensor measured optical reflectance of cotton particles passing through the sensor and used the measured reflectance to determine cotton-mass flow rates. Field tests indicated that the MCYM could measure cotton yield with an average error less than 5%, and it was easy to install and maintain. The cotton fiber-quality mapping research involved a wireless cotton module-tracking system (WCMTS) and a cotton fiber quality mapping system (CFQMS). The WCMTS was based on the concept that a cotton fiber-quality map could be generated with spatial information collected by the system during harvesting coupled with fiber quality information available in cotton classing offices. The WCMTS was constructed and tested, and it operated according to design, with module-level fiber-quality maps easily made from the collected data. The CFQMS was designed and fabricated to perform real-time measurement of cotton fiber quality as the cotton is harvested in the field. Test results indicated that the sensor was capable of accurately estimating fiber micronaire in lint cotton (R^2=0.99), but estimating fiber quality in seed cotton was more difficult. Cotton fiber quality maps can be used with cotton yield maps for developing field profit maps and optimizing production inputs.

Keywords: sensor, precision agriculture (PA), cotton, yield monitor, fiber quality, plant height
DOI: 10.3965/j.ijabe.20120504.001

Citation: Sui R X, Thomasson J A, Ge Y F. Development of sensor systems for precision agriculture in cotton. Int J Agric & Biol Eng, 2012; 5(4): 1－14.

1 Introduction

Cotton is one of the world's major crops, and its fiber is the most popular natural fiber for clothing and other textile products. World cotton production was about 27 million tonnes in 2011. China is the largest cotton producer and cotton importer in the world, while the USA is the largest cotton exporter in the world[1].

Cotton plants need careful field management to

Received date: 2012-09-25 **Accepted date:** 2012-11-29

Biographies: J. Alex Thomasson, Professor, PhD, P.E. Research interests: Cotton engineering, precision agriculture, remote sensing, sensor development, bioenergy, identity preservation. Tel: (979) 458 3598; Email: thomasson@tamu.edu. **Yufeng Ge**, Assistant Research Professor, PhD, Research interests: Cotton engineering, visible and near infrared spectroscopy, optical sensor development, precision agriculture, and bioenergy. Tel: (979) 845 2440; Email: yg36@tamu.edu.

***Corresponding author: Ruixiu Sui,** Research Agricultural Engineer, PhD, United States Department of Agriculture, Agricultural Research Service, Crop Production Systems Research Unit, Stoneville, MS 38776, USA. Expertise: Sensors and controls, precision agriculture, and cotton engineering, new technologies for water management and irrigation automation, including development of soil-water and plant-water stress sensor networks and sensor-based feedback algorithms for monitoring and control of irrigation and nutrient applications of crops. Dr. Sui is also interested in the research on cotton ginning machinery for improvement of cotton fiber quality and ginning efficiency. Tel: (662) 686 5382; Email: ruixiu.sui@ars.usda.gov.

achieve desirable cotton yield and fiber quality. In recent years, precision agriculture (PA) technologies have been used to improve field practices in cotton production. PA provides a way to optimize agricultural production inputs based on plant needs at individual areas within a field, rather than applying uniform applications across the entire field. The PA is an information-based technology. The three main components involved in PA are information collection, data interpretation, and variable-rate application. For PA practices to be successful, spatial information on field conditions as well as inputs and outputs of the field must be accurately collected. The information required from the field include spatial data from a global positioning system (GPS) receiver, soil properties such as texture and fertility, plant growth status like plant stresses in water, nutrient, and pest, and crop yield and quality. Data interpretation requires understanding the collected data and finding their spatial relations so as to economically and environmentally optimize field-input prescriptions. Variable-rate application uses site-specific prescriptions to apply various inputs, such as fertilizers, water, and herbicides at varying rates appropriate for each location.

1.1 Plant height measurement

Plant height is an important parameter to be considered for management decision making. Plant biomass and the biomass growth rate, which are directly related with plant height, are influenced by various field inputs such as water, fertilizer, chemicals, etc. Plant height can be used as a sensitive measure of plant health status and yield potential in making adjustment of the field inputs[2-4]. A technique for performing real-time, in-situ, non-destructive plant height evaluation is desirable for PA. Production-related treatments such as fertilization, irrigation, and pesticide applications would be greatly aided by the ability to rapidly and conveniently measure their effects upon plant height at different points in a field.

Ultrasonic sensing technology has been applied in agricultural research and production. Sui et al.[5] used ultrasonic sensors to develop a microcomputer-based measurement system to allow in-situ, non-destructive measurement for the morphological characteristics of bush-type plants. They employed seven ultrasonic sensors in the system to scan a plant row for distance-to-plant measurements at three different positions on each side of the row and one position above the row. Their results showed that measured plant canopy volume was strongly correlated with the plant biomass weight. Aziz et al.[6] studied ultrasonic sensing technology as one approach for corn plant canopy characterization. Height of individual leaves in a corn canopy was computed by analysis of the echo signal from the canopy. Ultrasonic measurement of the leaf height was closely correlated to the manually measured height. Jones et al.[7] estimated plant biomass using the product of top-view surface area of the plant and plant height resolved through ultrasonic distance sensing. Tumbo et al.[8] investigated the measurement of citrus tree volume using ultrasonic sensors. They found that ultrasonic sensors could be used for automatic mapping and quantification of the canopy volumes of citrus trees.

In addition to ultrasonic sensors, Searcy and Beck[9] developed and field-tested an optical sensor using a “light curtain” for the cotton plant height measurement. The light curtain was placed across cotton rows, and the number of blocked beams was interpreted to determine the height of the cotton plants in a section of row. This optical plant height sensor might require cleaning because the sensor windows could possibly be contaminated by the plant canopy in field operations; such is not an issue with the ultrasonic sensor. Ehsani and Lang[10] reported a laser-based sensor to estimate plant volume in real time. They indicated that the sensor also could be calibrated to measure the biomass and leaf area index of a plant.

1.2 Cotton yield monitoring

Crop yield is the most important piece of information required in determining farm profit and making field management decisions. Knowledge of a crop’s yield at specific sites within a field is critical for the successful implementation of PA. A yield monitor is able to measure crop yield at individual locations in a field. A yield map can be generated with yield data collected simultaneously with spatial data from a GPS receiver. A yield map can visually show the yield variability across a field and can be used to determine the feasibility of PA in the field. Meanwhile, yield data combined with spatial information can be used as an essential factor in developing field input prescriptions. In recent years, development and commercialization of yield monitors has been more rapid for grain crops such as corn, wheat, and soybeans than for cotton. However, the use of cotton yield monitors is increasing in the USA[11].

Several cotton yield monitors have been commercially available. AgriPlan Corp. (Stow, MA) released its first cotton yield monitor in 1997 and upgraded the system in 1998 and 2000. The FarmScan (Perth, Western Australia) cotton yield monitor with the Can-link 3000 console was released by Computronics in 1999. Micro-Track Systems (Eagle Lake, MN.) marketed its first cotton yield monitor in 1997. The first Ag Leader cotton yield monitor system was released in 2000. It consisted of a PF3000 data-acquisition unit and optical mass flow sensors, which were developed by Wilkerson et al.[12,14] and Moody et al.[13] at the University of Tennessee. In 2007, Ag Leader Technology (Ames, IA) upgraded the system by replacing the PF3000 with an InSight display that includes a 10.4-inch color touch screen and maps cotton yield on-the-go. John Deere introduced their cotton yield monitor system with microwave-based mass-flow sensor in 2004. Ag Leader and John Deere's cotton yield monitor systems remain the principal ones on the market.

A cotton mass flow sensor is the core technology in a cotton yield monitor system. All cotton yield monitors mentioned above used attenuation-based optical cotton-flow sensors except the John Deere system. These optical sensors are based on the same principle and are similar in configuration and operation. Each sensor unit has two parts, a light emitter and a light detector mounted opposite each other on a pneumatic duct. The sensor measures light attenuation caused by cotton particles passing through the duct. Sensor installation requires two ports to be cut in the duct and proper alignment of the light-emitter and a light-detector. The John Deere (Moline, Illinois) system use microwave-sensing technology to measure cotton flow at each duct of a cotton picker. Evaluations of these cotton yield monitors were performed and the results varied significantly[15-17]. In general, they were able to provide a realistic estimate of the yield variability within a field when they were frequently calibrated and well maintained[18]. However, they have not been widely accepted in the marketplace, having had problems with installation, cost, accuracy and maintenance.

1.3 Cotton fiber quality mapping

Cotton fiber quality is one of the most important issues in cotton production because of its large effect on the price producers receiving for their cotton. For optimum profitability, cotton producers must have success not only in crop yield, but also in the quality of the crop. It is well established that spatial variability in cotton quality exists in farm fields[19-22]. As yield maps have been essential to understand spatial relationships between field-management practices and crop yield, quality maps are required to understand relationships between field-management and fiber quality. Additionally, with both cotton yield maps and fiber-quality maps, revenue maps can be generated and help the producer to determine which parts of fields require higher or lower levels of agricultural inputs. Studies in PA have pointed to the potential of site-specific field-management and harvesting to optimize cotton quality and maximize a producer's profit. One way to achieve this potential is to vary farming inputs according to the historical relationship between inputs and fiber quality at each specific location within the field. Another strategy is to make use of existing fiber-quality variability by segregating the crop into categories as it is harvested. Often there is a portion of the crop that is of higher quality than the rest, and its value is usually averaged with that of the rest of the crop. If the high-quality portion could be segregated, it could be sold at a higher price, while the rest of the crop could potentially be sold at its current value. To implement either the variable-rate application or segregation harvesting strategy, the main lacking ingredient has been an efficient method of measuring fiber quality in the field.

1.4 Objectives

As mentioned previously, several studies have focused on plant height measurement in various crops, but a robust solution for cotton production has been lacking. Cotton yield monitors have been available, but their adoption has been slow. Instruments for cotton fiber quality mapping are not commercially available. However, research in each of these sensing areas has been conducted with specific focus on PA application in cotton, and significant strides have been made.

This article reports research in development of sensor systems for measuring the cotton plant height and for mapping cotton yield and quality. Real-time in-situ measurements by such sensor systems could be used in PA for cotton production.

2 Sensor development for precision agriculture in cotton

2.1 Plant height measurement system

A plant height measurement system (PHMS) was developed to make non-contact measurements of plant height in real time in situ. The system consisted of an ultrasonic sensor, a GPS receiver, and a data-acquisition and processing unit (DAQ). The system could be installed on a field vehicle such as a sprayer. In operation, the ultrasonic sensor determined plant height. The DAQ simultaneously logged plant height data from the sensor and spatial information from the GPS receiver at each individual location of a field while the vehicle travelled across a field. Plant height data were used to generate a plant height map. Both the data and the map could be employed for optimizing field management practices.

2.1.1 Sensor implementation

The ultrasonic sensor (model 607281, Senix Corp., Bristol, VT, USA) used in the system was driven by an ultrasonic ranging module (model R135-SONAR4, Senix Corp., Bristol, VT, USA). As the ranging module was triggered by an initiation signal from an interface module (model ULTRA-SR-20, Senix Corp., Bristol, VT, USA), the ranging module generated a set of pulses and sent them to the ultrasonic sensor. Through the ultrasonic sensor the ultrasonic pulses were transmitted toward a plant canopy at a speed of about 350 m/s. When the first ultrasonic pulse was echoed back from the plant canopy to the sensor, the ranging module detected the returning echo and sent an echo signal to the interface module. The difference in time between initial and echo signal was a measure of the air distance from the ultrasonic sensor to the plant canopy. Plant height could be calculated by subtracting the distance measured by the ultrasonic sensor from the known distance between the ground and the sensor. The ultrasonic sensor included an electrostatic transducer operated at 50 kHz, with a beam angle of 12º, and operating temperature range of -30℃ to 70℃. The interface module included a serial data connection (RS-232), which was used to connect the ultrasonic system to a DAQ to collect and display the ultrasonic sensor measurements. The measurement range of the ultrasonic system was from 5 cm to 11 m.

2.1.2 Data acquisition

A single-board-computer-based DAQ with a touch screen was designed and fabricated for collecting and processing the data from the ultrasonic sensor and the GPS receiver. The system had two serial ports, a PCMCIA controller, audio output, and an 8-channel 12-bit analog-to-digital converter. The digital signal from the interface module was read by the DAQ through one of its two serial ports. The other serial port was employed to record spatial information from a GPS receiver in real time so that a plant height map could be made. Plant height and spatial information were displayed on a color screen and stored in a PCMCIA memory card. The entire DAQ was powered by a 12-volt battery. Embedded Visual Basic was used as the programming language for the system operation code.

2.1.3 Test procedures

The ultrasonic PHMS was tested in the laboratory prior to field testing. The ultrasonic sensor was hanged from a ceiling facing down towards a floor of 3.72 m below. At each setting of distance between the ultrasonic sensor and the floor, two distance measurements were made, one by the sensor and the other with a tape measure. Thirteen distance- settings were used within a range from 0.36 m to 3.72 m. Performance of the ultrasonic system for distance measurement was evaluated by comparing the distance measured by the sensor with that by the tape measure[23].

Field tests of this system were conducted on cotton plants at Mississippi State University's North Farm during the 2004 growing season when plants were at the pinhead square growth stage. Twenty-five experimental plots were set up in a non-irrigated cotton field with sandy loam soil. Each plot was 23 m × 15 m in size, and there were 25 rows in each plot. Row spacing was 97 cm, and a 3 m wide buffer was used between plots. In order to generate variation in N content of cotton plants, five N application rates (0, 39, 78, 112 and 168 kg/ha) had been used, and each N application rate was replicated five times. One N-application rate was randomly assigned to each plot. Fifteen days after the cotton was planted, all plots except those with zero N received an N application at a rate of 39 kg/ha. The remaining N for plots with 78, 112 and 168 kg/ha application rate was applied 40 days after planting.

The ultrasonic system was field tested by scanning five rows (the 6th, 10th, 14th, 18th, and 22nd) of each plot. The ultrasonic sensor was mounted on a frame facing down toward the cotton canopy. The frame was attached in front of a high clearance tractor (Figure 1). A Trimble AgGPS 132 DGPS receiver and the DAQ were installed inside the tractor's cab. The ultrasonic sensor was situated 1.57 m above the ground. The sensor continuously scanned the cotton canopy, and the DAQ collected data from the sensor and GPS receiver, storing it at 1.0-s intervals as the vehicle moved along the row at approximately 4.0 km/h.

Figure 1 Ultrasonic PHMS installed in a tractor was conducting plant height measurement in a cotton field

In order to analyze the N content in leaf tissues and determine relationships between the N content and the measured plant height, plant leaf samples were collected from rows that were scanned with the ultrasonic system. Ten uppermost fully expanded main-stem leaves were collected to make one leaf sample. Three leaf samples were collected in each scanned row of each plot. There were 375 leaf samples in total. All leaf samples were analyzed for N content at the Soil Testing Laboratory of the Mississippi Cooperative Extension Service. Cotton was harvested with a cotton picker. Seed cotton yield in each scanned row was collected and weighed to evaluate the relationship between measured plant height and yield. In total, 125 yield samples were taken from all the plots.

2.1.4 Test results

Lab-test results indicated that the distance measured by the system was extremely close to the tape-measured distance. The maximum error was 0.4% with an average absolute error of 0.24%. Plant height determined by the system in the field test had a reasonably strong linear relationship (R^2=0.48, Figure 2) with leaf N content. Plant height had a closer relationship with yield (R^2=0.63, Figure 3). Results of the field test made it apparent that the plant height as measured with the ultrasonic sensor could be used as an indicator of plant growth conditions, including plant N status and yield potential.

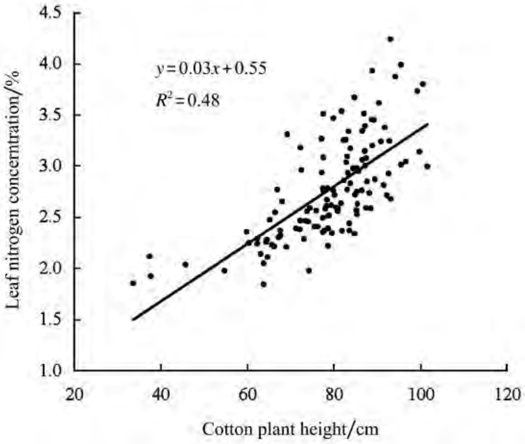

Figure 2 Relationship between leaf nitrogen content and cotton plant height determined by the ultrasonic plant height measurement system

N fertilization in cotton must be carefully managed to optimize yield with respect to cost of application. In conventional N management systems, N fertilizer is uniformly applied across a cotton field. However, due to spatial variability of soil properties in the field, plants in some parts of the field may need more N while plants in other parts may require less. It is desirable to diagnose N status of plants in individual locations within the field and site-specifically apply the amount of N that the plants need. Since plant height is a reasonably good indicator of plant N status, there is potential to use the cotton plant height measured by the ultrasonic system as an input to trigger a control device for variable-rate N application in cotton.

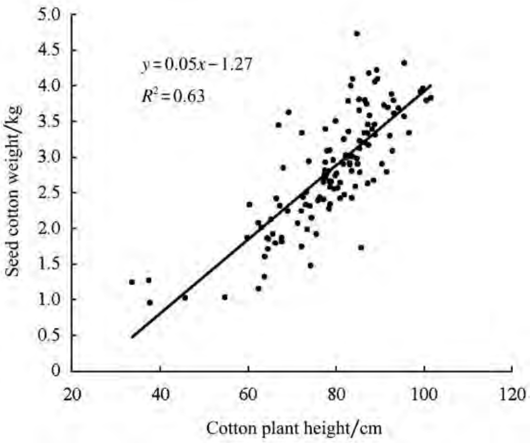

Figure 3 Relationship between yield and the cotton plant height

During field testing, the ultrasonic sensor and DAQ performed well. All collected data were useful for statistical analysis. Combined with the location information obtained from the GPS receiver, a plant height map of the experimental plots was created. The variation of plant height could be easily identified on the map, and it compared favorably to visible field conditions (Figure 4).

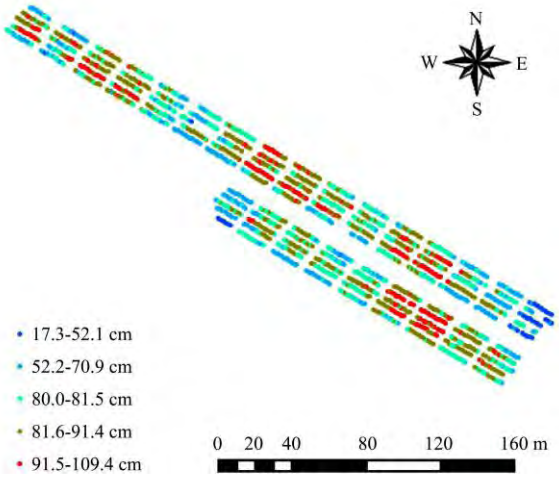

Figure 4 Cotton plant height map

2.2 Mississippi cotton yield monitor

2.2.1 Mass-flow sensor

A reflectance-based optical mass-flow sensor was designed and fabricated by Thomasson and Sui (US Patent No. 6809821)[24]. The reflectance-based sensor included a light source and detectors in one housing unit (Figure 5). In operation, the sensor could be mounted on one wall of a pneumatic duct of a cotton picker or stripper, requiring only one port to be cut in the duct, and so there is no requirement for alignment. As the light emitted from the light source is reflected by cotton particles that pass through the duct in view of the sensor, the detectors measure the amount of light reflected from the particles. The amount of reflected light measured is used to determine the flow rate of the cotton. This cotton-flow sensor is different from all attenuation-based optical cotton-flow sensors of commercially available cotton yield monitors. The attenuation-based optical sensors include one housing for detectors on one side of the duct and one housing for light sources on the opposite side of the duct. Thus, their installation requires two ports to be cut in a duct instead of one, and proper alignment of light sources and detectors. This creates difficulties in installation and possible misalignment over time due to vibration of the sensor; such is not the case with this reflectance-based cotton-flow sensor.

Figure 5 Reflectance-based optical mass-flow sensor

2.2.2 Data acquisition

The reflectance-based optical mass-flow sensor was included in a cotton yield monitor, known as Mississippi Cotton Yield Monitor (MCYM), which was developed at Mississippi State University. The MCYM consists of two cotton-flow sensors, a DAQ, and a GPS receiver (Figure 6). Each sensor is mounted on a pneumatic duct of a cotton harvester. During operation, the sensors detect the cotton flowing in the duct, and each provides an analog output signal to the DAQ, which simultaneously processes and records sensor outputs and spatial information from the GPS receiver in real time. A standard external GPS receiver producing NMEA output strings is employed to provide spatial data that is read directly by the DAQ. The GSA and RMC sentences from the GPS receiver are recorded to provide location, PDOP (position dilution of precision), and speed data. Yield and spatial information are displayed on the monitor's screen and stored on a PCMCIA card. These data can be downloaded to a computer later and processed with GIS (geographical information system) software[25].

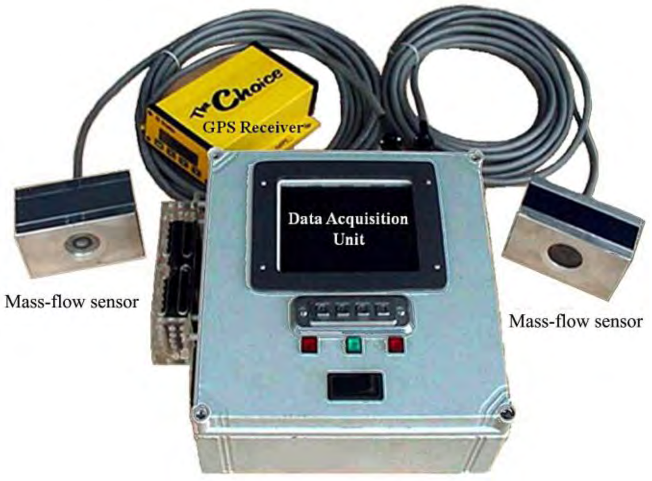

Figure 6 Mississippi cotton yield monitor including mass-flow sensors, a data acquisition unit, and a GPS receiver

2.2.3 Installation and calibration

Cotton yield monitors must be adapted for two types of mechanical cotton harvesters available on the market, the cotton picker and the cotton stripper. A cotton picker uses threaded spindles to pull the cotton fiber from the plant, and the cotton is then pneumatically conveyed through ducts into a storage basket. A cotton stripper uses brushes to remove entire cotton bolls, fiber and hull together, and the cotton is again conveyed pneumatically through a duct into a basket. In the stripper, there is often a cleaning device between the brushes and the basket that removes some of the hull material and sticks. With both harvester types, cotton yield monitor sensors are typically mounted on the duct where the flowing cotton is suspended in air and flowing toward the basket.

In evaluation of the MCYM on a cotton picker, the sensors were mounted with a bracket on the bottom side of the top section of two ducts (Figure 7). On a cotton stripper, they were mounted at two strategic locations on the collective duct between the cleaning device and the basket (Figure 8). Only one 76 mm diameter hole was cut in the duct for each sensor installation. Sensors were cleaned once per day during routine maintenance, usually in early morning before harvesting. The DGPS receiver was mounted in the harvester's cab along with the DAQ, which was affixed on a wall. Each sensor was connected to the DAQ through a 7.6 m long cable. The DGPS antenna was mounted on the top of the cab, and the receiver's output was connected to the DAQ so that location information could be collected[26].

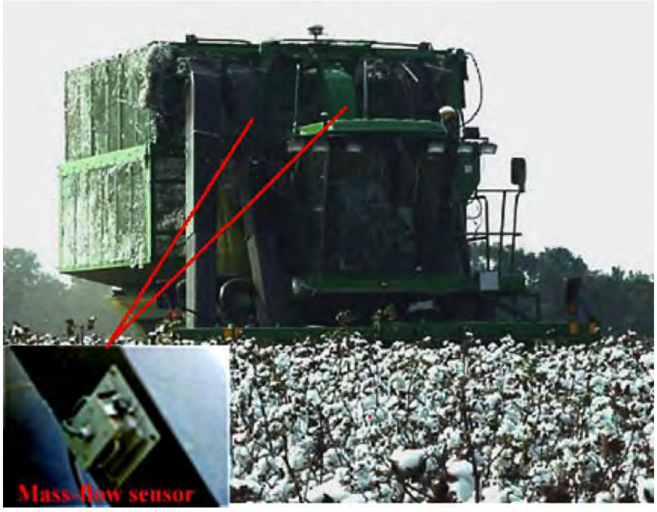

Figure 7 Mass-flow sensor mounted at the bottom side of top section of the duct with a bracket (one sensor was used in one duct, and two sensors for a four-row cotton picker)

Figure 8 Two mass-flow sensors installed in a cotton stripper harvester

A cotton yield monitor's accuracy is directly dependent on the calibration method. Based on the authors' experience, it is believed that cotton yield monitors should be calibrated in each field to maintain their high accuracy. In an actual production situation, however, producers are usually unwilling to devote much time to calibration, which is done in general by weighing the first three to five loads in a field. This is especially true when small fields are involved. Most producers will calibrate the system once at the beginning of the harvesting season. For the load-by-load accuracy evaluation, the method used to calibrate the cotton yield monitor was based on post-correction with known field weights[25,26]. This method uses the total field weights as measured at the gin, and the integrated sensor output for the field, to calculate a ratio of cotton weight to sensor output, which is known as the calibration coefficient. Then yield at each field location is calculated with the calibration coefficient prior to generating final yield maps for the field. This calibration method is the most accurate one for developing whole-field yield maps, and it is also practical for management decisions based on yield data. On the other hand, some producers like to see a measure of yield in real time. This requirement can be satisfied by using an estimated calibration coefficient derived from a few basket-load weights at the beginning of the season. This allows the producer to have a display of estimated yield in real time, although a real-time estimate would likely be significantly less accurate than the value after post-correction.

2.2.4 Field evaluation

The first prototype of the optical-reflectance-based mass-flow sensor was developed and field tested in 1999, and results indicated excellent agreement between actual mass flow and that measured by the sensor[27] (Figure 9). Three similar prototypes were developed and field tested extensively in Texas, Georgia, and Mississippi (USA) in 2000 with good results, but concerns about ambient temperature fluctuation and stray light remained. Therefore, a modified prototype was modified to include anti-stray-light and temperature-stabilization features in the sensor[28]. Five prototypes of the modified version were fabricated and field tested in 2001 on three cotton pickers and two cotton strippers at five locations in Georgia, Texas, and Mississippi again. A total of 1230 ha of cotton with different varieties and large yield variations was harvested with the yield monitors from September to December of 2001. Results indicated reliable performance with an average error less than 5%. Cotton yield monitors with the upgraded sensors appeared to be improved over previous versions. A private company soon thereafter signed a commercialization agreement with Mississippi State University regarding the cotton yield monitor. The system was then enhanced with a more commercially viable DAQ and beta tested. Ten prototypes were built and extensively tested on ten harvesters over four states in 2002. Results were once again uniformly excellent, with average error under 5%[26] (Figure 10). Cotton yield maps were generated with data from the MCYM. Those maps realistically exhibited yield variations within

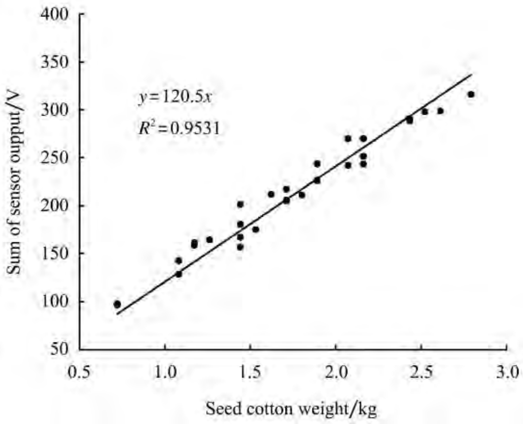

Figure 9 Signal output of mass-flow sensor versus seed cotton weight measured

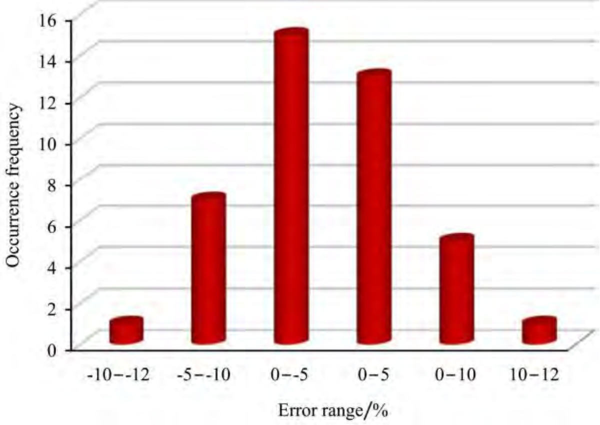

Figure 10 Distribution of measurement error in field tests of MCYM (There were 48 loads in total. Average absolute error for all loads was 3.8%)

fields, based on the expectations of experienced producers and consultants (Figure 11). The tests also indicated that the system was reliable and easy to install, operate, and maintain. Currently MSTX Agricultural Sensor Technologies, LLC (Hearne, TX) licensed this technology from Mississippi State University and made the optical reflectance-based mass flow sensor for cotton yield monitor commercially available.

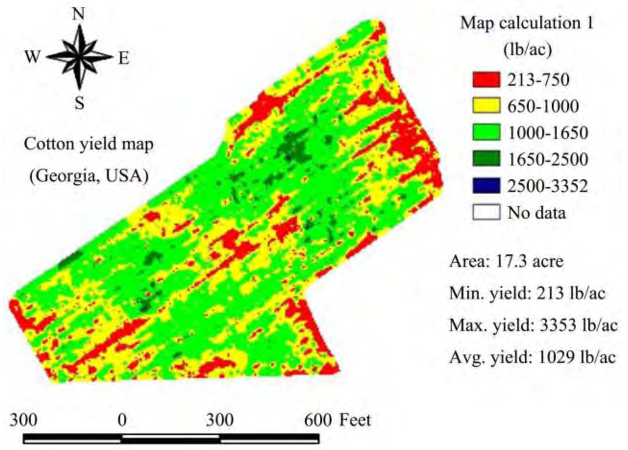

Figure 11 Example of cotton yield maps created using the data collected by MCYM

2.3 Cotton fiber quality mapping

2.3.1 Wireless cotton module-tracking system

The main purposes of the wireless cotton module-tracking system (WCMTS) are to (1) track harvested cotton modules from their original field locations, and (2) enable automated cotton fiber quality mapping with fiber-quality data from the USDA cotton classing offices.

The WCMTS consisted of three subsystems: a harvester subsystem (referred to as HS), a boll buggy subsystem (BBS) and a module builder subsystem (MBS), each to be mounted on its respective field vehicle[29]. The HS can be connected to a GPS receiver and record position information of harvested baskets while the harvester is traveling across a field. Each subsystem is equipped with a wireless transceiver that enables the communication of information among field vehicles. When a harvester basket is full of seed cotton and a dump of its basket occurs, the HS will generate a unique basket number and transmit that number to the subsystem whose field vehicle (can be either a boll buggy or a module builder) is receiving the cotton basket. If a module builder receives cotton, the MBS will send the current module number (which is input into the MBS in advance by an MBS operator) to the HS which assigns it to the basket number (and thus all of the GPS positions associated with that basket). If a boll buggy receives cotton, the basket number will be transmitted to and stored in the BBS, and then further sent to the MBS when the boll buggy dumps its basket into the module builder. The MBS then sends the current module number to the HS. A microcontroller was used in each subsystem to control all hardware components. Figure 12 shows the HS and MBS of WCMTS and their installation on field vehicles.

Figure 12 Wireless cotton module tracking system: (A) harvester subsystem (HS), (B) module builder subsystem (MBS), (C) wireless antenna of HS on top of the picker's light bar to enhance wireless transmission, (D) installation of HS in the cab of a cotton picker, (E) installation of MBS on a module builder

It is important to point out that cotton farms usually vary greatly in size, equipment and management practices, so different numbers and types of field vehicles may be used during harvest. In a harvest that involves only a harvester and a module builder, there is only one type of basket dump. However, the complexity grows rapidly when more field vehicles are involved. Figure 13 shows twelve types of dump possible in a harvest scenario with two harvesters, two boll buggies, and two module builders. Therefore, system expandability is an important design criterion. From a hardware standpoint, expandability means that functional subsystems can be easily added or removed to accommodate different harvest scenarios. From a software standpoint, it means that the program can reliably implement basket tracking regardless of the number of field vehicles involved in the harvest.

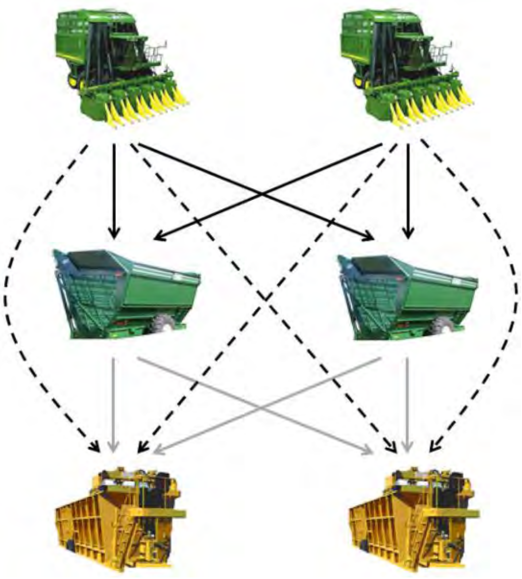

Figure 13 Schematic diagrams showing 12 types of dump that could occur among the field vehicles in a harvest scenario with two harvesters, two boll buggies, and two module builders

On November 7, 2006, the WCMTS was field tested on a producer's farm near Plains, TX, USA. The harvesting equipment included a six-row cotton stripper (John Deere model 7460, Deere and Company, Moline, IL, USA) and a module builder (Husky model, Bush Hog, Selma, AL, USA). The HS (including wireless-communication antenna) was mounted inside the stripper cab and the MBS atop the module-builder cab. No BBS was used in this field test. Five completed modules covering about 12 ha were harvested during the test. These modules were transported to the New-Tex Gin (Plains, TX, USA) and ginned into 48 bales.

The second field test was conducted on a cotton field (referred to as the Riverside field) at the Texas AgriLife Research farm in Burleson County. Cotton was machine harvested from October 9 to 14, 2007. The harvest equipment included a John Deere six-row picker, a Big12 module builder (Scott Manufacturing, Inc., Lubbock, TX, USA) and a KBH Mule Boy boll buggy (Delta Gin Company, Clarksdale, MS, USA). Since the Big12 module builder did not have an operator cab, the MBS had to be mounted on the tractor used to move the module builder. The tractor was changed during the harvest such that the MBS had to be uninstalled and reinstalled on another tractor. Similarly, the BBS was mounted on the tractor used to move the boll buggy. The wireless system antennas were mounted atop the cabs of the tractors. Eleven cotton modules were harvested in this field test, covering an area of 25 ha. The modules were transported to Scarmardo Gin (Caldwell, TX, USA) and ginned there into 131 bales.

The third test of the system took place from September 22 to 25, 2008 again in a cotton field at the Texas AgriLife Research farm. The field is approximately 32 ha. No boll buggy was used during the testing period, only the cotton picker and a single module builder (CBSK Module Builder, Crustbuster Speed King, Dodge City, KS). Installation of the system was similar to the second test.

In all field tests, the module ID was determined in a pre-defined manner. These IDs were subsequently used by the gins and classing offices to identify individual modules. Overall, three types of data were collected: (1) GPS-based field positions to identify the harvest area for a given module, (2) basket and module IDs for tracking, and (3) the HVI bulk fiber-quality data that the USDA cotton classing offices measure. After each field test, log files of GPS data stored in the HS were downloaded into a PC and processed with ArcGIS version 9.2 (ESRI, Redlands, California, USA) to produce module-boundary maps. The fiber-quality data included color in reflectance (Rd) and yellowness (+b), length, length uniformity, strength, and micronaire (a measure of fiber maturity and fineness). When these bale-level fiber-quality data became available to the gin, the data for bales within a particular module were averaged and combined with the module-boundary maps to produce module-level fiber-quality maps[30].

New features were added to an improved WCMTS system to make it capable of automatic wireless message triggering when the harvester or boll buggy is dumping a basket, and compatible with multiple instances of similar machinery (i.e., more than one harvester, boll buggy, and/or module builder) in a given field[31,32]. Automatic wireless message triggering was effected through (1) using an inclinometer to sense the tilt angle of the harvester or boll-buggy basket to determine when a dump was taking place, (2) using load cells to sense the remaining load in the basket to verify the completeness of a basket dump, and (3) using RFID to identify machines involved in a load transfer so that wireless messages could be sent to specific machines when multiple machines were present. The improved WCMTS was successfully field tested, and results indicated that the automated WCMTS worked as designed.

2.3.2 Cotton fiber quality sensor

Though WCMTS effectively maps cotton fiber quality, it is accurate only to the cotton-module level. To make a fiber quality map with higher resolution, a sensor is required to measure cotton fiber quality in real time as cotton is harvested in field. Toward this goal, a prototype cotton fiber quality sensor was developed based on the characteristics of the cotton fiber reflectance spectrum. The sensor consists of a VisGaAs camera, optical bandpass filters, a halogen light source, and an image collection and processing system. Images of lint samples in three near-infrared (NIR) wavebands (1 450, 1 550 and 1 600 nm) were acquired and analyzed to determine the relationship between histogram-based image pixel values and cotton fiber micronaire[33].

The sensor prototype was evaluated in the laboratory. Six types of International Cotton Calibration Standards (ICCS) (Cotton Program, USDA, Memphis, TN) were used for the evaluation. They were Am-8, Bm-2, Cm-19, Dm, Gm-10, and Im-37, with micronaire values of 5.58, 4.58, 3.41, 4.03, 2.67, and 5.03, respectively. The sensor was used to collect cotton fiber images of ICCS samples at the central wavelengths of 1 450 nm, 1 550 nm, and 1 600 nm, respectively. The images were processed with IRVista software (Indigo Systems Corp, Goleta, CA, USA). A histogram was collected for each sample at each waveband, giving 18 histograms in total. Histograms were analyzed and pixel values of interest were identified. It was observed that the pixel values of interest in each histogram were consistently within roughly a 496-pixel-value range around the maximum-frequency pixel value. Therefore, after the maximum-frequency pixel value in each histogram was identified, pixels values within a 496-pixel-value range around that value were extracted, and their average pixel value was computed. The histogram data were analyzed with multiple linear regression (the PROC REG procedure, SAS®, Triangle Research Park, NC, USA) to determine relationships between image pixel values of cotton fiber and the fiber's micronaire values.

A ruggedized prototype of the multispectral fiber quality sensor was developed for installation on a cotton harvester[34]. A filter wheel was added to the sensor system, and software was used to control the selection of optical filters so that images at selected wavebands could be acquired automatically. The ruggedized sensor acquires images of seed cotton, which contains a considerable amount of foreign matter, at three NIR wavebands and one visible band, used to exclude pixels that represent foreign matter before determining fiber quality with the NIR images.

Tests of the ruggedized sensor were conducted to determine its ability to measure fiber quality of seed cotton. Thirty seed cotton samples were collected from the cotton harvested by a cotton picker. For each sample, three NIR images at wavebands of 1 450 nm, 1 550 nm, and 1 600 nm, and one image in the visible range were taken by the sensor. Pixels of trash particles in the seed cotton were removed based on contrast in the visible image. Then, the NIR images were analyzed for fiber quality prediction.

2.3.3 Field and lab tests

Wireless cotton module-tracking. Results of the field tests indicated that all subsystems of the WCMTS were easily installed on field vehicles and generally operated reliably. The system was run over 100 hours altogether in three field tests, and few hardware and no software problems occurred. When tractors had to be changed during field test 2, both the BBS and MBS were detached and reinstalled in a few minutes, without significantly delaying the harvest. In field test 1, the GPS unit experienced occasional signal loss, leading to some missing points along the stripper's harvesting path. No such problems occurred in field tests 2 and 3, where a John Deere Starfire1 GPS unit was used.

Wireless transmission range (maximum distance between subsystems at which data are accurately transmitted) is a critical parameter that is important for the applicability of WCMTS. In field test 1, in which the wireless antennas were placed inside the vehicle cabs, the system had a limited transmission range of about 100 m. The transmission range was greatly enhanced (over 800 m) when the wireless antennas were placed outside the vehicle cabs in the subsequent field tests. An examination of the downloaded log files showed that all module IDs had been reliably transmitted to the HS. Such a wireless transmission range would be adequate for a medium-sized field of about 50 ha.

As an example, the Cotton module boundary map and the module-level cotton fiber-quality map developed in the field test 2 are shown in Figures 14 and 15, respectively. As expected, the fiber-quality maps are of coarse spatial resolution, with each module corresponding to multiple hectares of area. However, substantial in-field variation can still be detected. More importantly, these variations can be linked to the USDA cotton loan schedule and related to different monetary returns. Secondly, these variations can be linked to soil maps for agronomic interpretations.

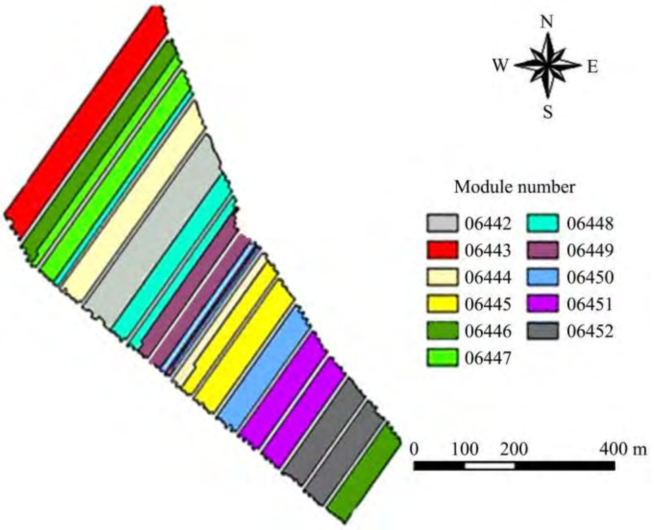

Figure 14 Cotton module boundary map in field test 2

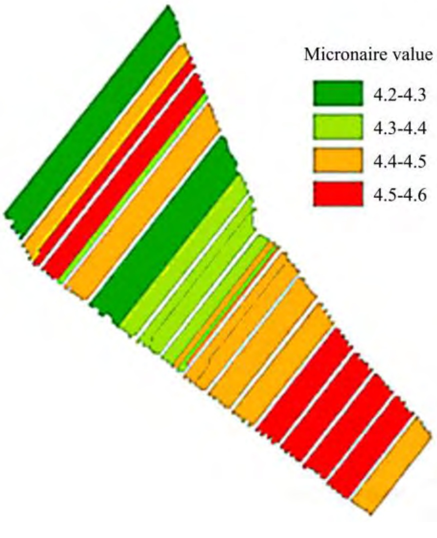

Figure 15 Module-level cotton fiber-quality map in field test 2

Cotton fiber quality sensor. Results of the cotton fiber quality sensor test with ICCS samples showed that the sensor measured pixel values of the samples at 1 450 nm, 1 550 nm, and 1 600 nm had a very strong linear relationship with their micronaire values (R^2= 0.99)[33]. The sensor was capable of accurately estimating the micronaire of the lint cotton (Figure 16). The sensor test with seed cotton samples indicated that after excluding the trash pixels from the images by using a visible image, the NIR reflectivity of seed cotton measured by the sensor illustrated a reasonably strong correlation with the fiber micronaire values (R^2=0.56)[34]. After improving the measurement accuracy in seed cotton, this sensor could be adapted for measuring cotton fiber quality along with spatial data from a GPS receiver as the cotton is harvested in the field, making it possible to generate cotton fiber quality maps in real time. The sensor also has the potential to be used for segregating cotton at harvest based on fiber quality.

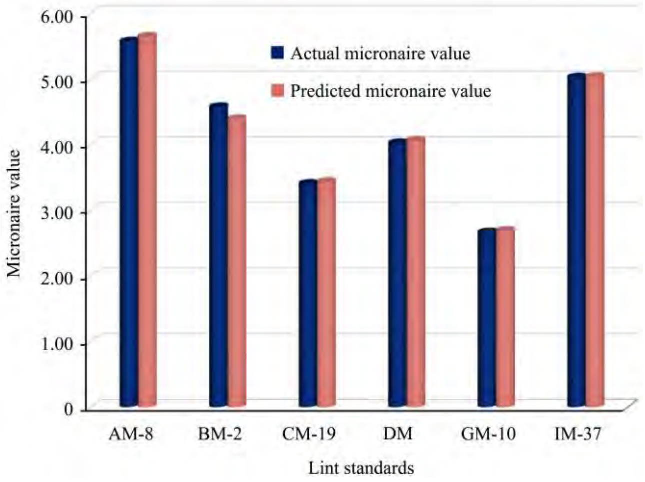

Figure 16 Actual micronaire value very strongly correlated with that predicted using the regression model involving two wavebands (1 550 nm and 1 600 nm)

3 Conclusions

A PHMS was developed with an ultrasonic sensor for the purposes of plant-height measurement and mapping. In distance measurement, laboratory tests showed that the maximum measurement error of the system was 0.4% with an average absolute error of 0.24%. The system was evaluated in a cotton field and performed well in field tests. The plant heights measured by the system had a close relationship with the plant leaf nitrogen content and yield. Plant height maps illustrated plant height variation well and reflected realistic plant growth conditions of the field. Cotton plant height measurements could potentially be used as an indicator of plant nitrogen status and yield potential.

An optical-reflectance-based mass-flow sensor was invented and used in the development of the MCYM. In field tests in multiple locations across cotton production regions in the USA, the MCYM achieved reliable performance with an average error less than 5%. Compared with other cotton yield monitors, the MCYM was accurate, and its unique design made it easy to install and maintain.

A wireless cotton module-tracking system (WCMTS) was developed and tested. With the WCMTS, module averages of fiber-quality data can be mapped to their original locations on the producer's field. To make a fiber quality map with higher resolution, a multispectral sensor was developed to measure cotton fiber quality in real time as cotton is harvested in field. Results showed that the sensor was capable of accurately estimating the fiber micronaire of lint cotton. With fiber quality maps generated from WCMTS data or fiber quality sensor data, along with maps of yield and cost, an accurate profit map can be created for cotton producers. The PHMS, MCYM, WCMTS, and the fiber quality sensor are useful tools for PA in cotton.

Disclaimer

Mention of a commercial product is solely for the purpose of providing specific information and should not be construed as a product endorsement by the authors or the institutions with which the authors are affiliated.

[References]

[1] NCC. http://www.cotton.org/econ/cropinfo/cropdata/rankings.cfm/, 2011; Accessed on [2011-09-15].

[2] Sarwar G, Chowdhry M A, Tujammal M A. Correlation of plant height with yield and other characters in gossypium hirsutum. Pakistan Journal Agricutural Research, 1984; 5(3): 144-148.

[3] Yin X, McClure M A, Jaja N, Tyler D D, Hayes R M. In-season prediction of corn yield using plant height under major production systems. Agronomy Journal, 2011; 103(3): 923-929.

[4] Yin X, Hayes R M, McClure M A, Savoy H J. Assessment of plant biomass and nitrogen nutrition with plant height in early- to mid-season corn. Journal of the Science of Food and Agriculture, 2012; 92(13): 2611-2617.

[5] Sui R, Wilkerson J B, Wilhelm L R, Tompkins F D. A microcomputer-based morphometer for bush-type plants. Computer and Electronics in Agriculture, 1989; 4(1989): 43-58.

[6] Aziz S A, Steward B L, Birrell S J, Shrestha D S, Kaspar T C. Ultrasonic sensing for corn plant canopy characterization. ASAE Paper No. 041120. St. Joseph, Mich.: ASAE. 2004.

[7] Jones C L, Maness N O, Stone M L, Jayasekara R. Sonar and digital imagery for estimating crop biomass. ASAE Paper No. 043061. St. Joseph, Mich.: ASAE. 2004.

[8] Tumbo S D, Salyani M, Whitney J D, Wheaton T A, Miller W M. Investigation of laser and ultrasonic ranging sensors for measurements of citrus canopy volume. Applied Engineering in Agriculture, 2002; 18(3): 367-372.

[9] Searcy S W, Beck A D. Real time assessment of cotton plant height. In proceedings of the 5th International Conference on Precision Agriculture, Bloomington, MN. 2000;

[10] Ehsani M R, Lang L. A sensor for rapid estimation of plant biomass. In Proc. the 6th Intl. Conf. on Precision Agri., Bloomington, MN, July, 2002; 14-17.

[11] Mooney D F, English B C, Velandia M, Larson J A, Roberts R K, Lambert D M, et al. Trends in cotton precision farming: 2000-2008. In Proc. Beltwide Cotton Conf. Memphis, TN: Nat. Cotton Counc. Am. 2010; 476-481.

[12] Wilkerson J B, Kirby J S, Hart W E, Womac A R. Real-time cotton flow sensor. ASAE Paper No. 941054. St. Joseph, Mich.: ASAE. 1994.

[13] Moody F H, Wilkerson J B, Hart W E, Goodwin J E, Funk P A. Non-intrusive flow rate sensor for harvester and gin application. In Proc. Beltwide Cotton Conf. Memphis, TN: Nat. Cotton Counc. Am. 2000; 410-415.

[14] Wilkerson J B, Moody F H, Hart W E. Implementation and field evaluation of a cotton yield monitor. Applied Enginerring in Agricuture, 2002; 18(2): 153-159.

[15] Durrence J S, Perry C D, Vellidis G, Thomas D L, Kvien C K. Evaluation of commercially available cotton yield monitors in Georgia field conditions. ASAE Paper No. 983106. St. Joseph, Mich.: ASAE. 1998.

[16] Sassenrath-Cole G F, Thomson S J, Williford J R, Hood K B,

Thomasson J A, Williams J, et al. Field testing of cotton yield monitors. In: Proc. Beltwide Cotton Conf. Memphis, Tenn.: Nat. Cotton Council Am. 1999; 364-366.

[17] Wolak F J, Khalilian A, Dodd R B, Han Y J, Keshlkin M, Lippert R M, et al. Cotton yield monitor evaluation, South Carolina–year 2. In: Proc. Beltwide Cotton Conf. Memphis, Tenn.: Nat. Cotton Council Am. 1999; 361-364.

[18] Vellidis G, Perry C D, Rains G C, Thomas D L, Wells N, Kvien C K. Simultaneous assessment of cotton yield monitors. Applied Engineering in Agricuture, 2003; 19(3): 259-272.

[19] Ping J L, Green C J, Bronson K F. Identification of relationships between cotton yield, quality, and soil properties. Agronomy Journal, 2004; 96(6): 1588-1597.

[20] Ge Y, Thomasson J A, Sui R. Variability of soil moisture content and cotton fiber quality in irrigated and dry-land cotton fields. In Proc. Beltwide Cotton Conf. Memphis, TN: Nat. Cotton Counc. Am. 2006a; 2134-2142.

[21] Ge Y, Sui R, Thomasson J A. Influence of soil moisture content upon cotton fiber quality for both irrigated and rainfed cotton. In Proc. Beltwide Cotton Conf. Memphis, TN: Nat. Cotton Counc. Am. 2006b; 469-474.

[22] Ge Y, Thomasson J A, Sui R. Spatial variability of fiber quality in a dryland cotton field. In Proc. Beltwide Cotton Conf. Memphis, TN: Nat. Cotton Council. Am. 2007, 929-937.

[23] Sui R, Thomasson J A. Ground-based sensing system for cotton nitrogen status determination. Transactions of the ASABE, 2006; 49(6): 1983-1991.

[24] Thomasson J A, Sui R. Optical-reflectance-based mass-flow sensor. US Patent No.: 6809821, 2004.

[25] Thomasson J A, Sui R. Mississippi cotton yield monitor: three years of field test results. Applied Engineering in Agriculture, 2003; 19(6): 631-636.

[26] Sui R, Thomasson J A, Mehrle R, Dale M, Perry C D, Rains G. Mississippi cotton yield monitor: beta test for commercialization. Computers and Electronics in Agriculture, 2004; 42(3): 149-160.

[27] Thomasson J A, Sui R. Advanced optical cotton yield monitor. In: Proc.2000 Beltwide Cotton Conf., Richter D A ed., Memphis, TN: National Cotton Council of America. 2000, 408-410.

[28] Sui R, Thomasson J A. Test of temperature and stray-light effect on mass-flow sensor for cotton yield monitor. Applied Engineering in Agriculture, 2002; 18(4): 127-132.

[29] Ge Y, Thomasson J A, Sui R. Wireless-and-GPS system for cotton fiber-quality mapping. Precision Agriculture, 2012; 13: 90-103.

[30] Ge Y, Thomasson J A, Sui R, Morgan C L S. A module-specific post-processing calibration to improve cotton yield mapping. Computers and Electronics in Agriculture, 2009; 68: 161-167.

[31] Sjolander A J, Thomasson J A, Sui R, Ge Y. Wireless tracking of cotton modules. Part 1: Automatic message triggering. Computers and Electronics in Agriculture, 2011a; 75: 23-33.

[32] Sjolander A J, Thomasson J A, Sui R, Ge Y. Wireless tracking of cotton modules. Part 2: Automatic machine identification. Computers and Electronics in Agriculture, 2011b; 75: 34-43.

[33] Sui R, Thomasson J A, Ge Y, Morgan C. Multispectral sensor for in-situ cotton fiber quality measurement. Transactions of the ASABE, 2008; 51(6): 2201-2208.

[34] Schielack V P, Sui R, Thomasson J A, Hequet E, Morgan C. Harvester-based cotton fiber quality sensor. ASABE Paper No. 096264. St. Joseph, Mich.: ASABE, 2009.