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Sensing Technologies for Grain Crop Yield Monitoring Systems: A Review

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Abstract

Purpose: Yield monitoring systems are an essential component of precision agriculture. They indicate the spatial variability of crop yield in fields, and have become an important factor in modern harvesters. The objective of this paper was to review research trends related to yield monitoring sensors for grain crops. **Methods:** The literature was reviewed for research on the major sensing components of grain yield monitoring systems. These major components included grain flow sensors, moisture content sensors, and cutting width sensors. Sensors were classified by sensing principle and type, and their performance was also reviewed. **Results:** The main targeted harvesting grain crops were rice, wheat, corn, barley, and grain sorghum. Grain flow sensors were classified into mass flow and volume flow methods. Mass flow sensors were mounted primarily at the clean grain elevator head or under the grain tank, and volume flow sensors were mounted at the head or in the middle of the elevator. Mass flow methods used weighing, force impact, and radiometric approaches, some of which resulted in measurement error levels lower than 5% (R^2 = 0.99). Volume flow methods included paddle wheel type and optical type, and in the best cases produced error levels lower than 3%. Grain moisture content sensing was in many cases achieved using capacitive modules. In some cases, errors were lower than 1%. Cutting width was measured by ultrasonic distance sensors mounted at both sides of the header dividers, and the errors were in some cases lower than 5%. **Conclusions:** The design and fabrication of an integrated yield monitoring system for a target crop would be affected by the selection of a sensing approach, as well as the layout and mounting of the sensors. For accurate estimation of yield, signal processing and correction measures should be also implemented.

Keywords: Grain flow, Grain moisture content, Harvester cutting width, Precision agriculture, Yield monitoring system

Introduction

TPrecision agriculture (PA), also known as site-specific crop and field management, is an information-based agricultural strategy for pursuing maximum output and profitability with minimum input and environmental adverse effects. PA has been adopted relatively well not only in North America, Europe, and Australia (where fields and harvesters are large), but has also attracted interest in Asian countries, where fields are relatively small. Srinivasan (1999) suggested that PA would be more effective in Asian countries, as a result of (1) social concerns regarding environmental problems, (2) pressure to strengthen the value of agricultural products, and (3) labor shortages resulting from a diminishing, aging rural population.

The underlying concept of PA is to accept the existence of variability in site parameters such as crop growth and yield, soil properties, environmental factors, and field topography on a point-by-point basis within field locations, and to manage that variability to optimize economic returns and/or minimize environmental impacts. PA can best be thought of as a cycle of procedures consisting of (1) intensive data collection, (2) decision making or management planning, (3) precision field operation, and (4) evaluation (Sudduth,

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1998). The collection and utilization of spatial data on crop, soil, and environmental parameters is a critical step in implementing PA.

Yield measurement and mapping have been key in the development of PA. Yield monitoring is the real-time sensing of crop yields by a harvester traveling on the field, and yield mapping is the representation of spatial yield variability. The creation of yield maps is critical to PA, because yield maps provide important data for the evaluation phase of the precision farming cycle. For example, a yield map can provide local information on nutrient absorption, soil variability, and the effects of special treatment strategies (Reitz and Kutzbach, 1996). Furthermore, crop yield is the basis for many agricultural input recommendations. On-the-go sensor-based acquisition of crop yield and position data (resulting in yield map creation) was accomplished in the late 1980s by Bae et al. (1987) and Searcy et al. (1989). Since that time, yield monitoring systems have improved significantly, with some commercial systems providing average load accuracies of approximately ± 1% (Murphy et al., 1995).

Previous research on yield monitors and mapping algorithms has been well-reported (Colvin and Arslan, 2000; Demmel, 2013; Singh et al., 2012; Reyns et al., 2002). Over the past 30 years, yield monitoring and mapping systems have been developed for various grain, forage, root, and other crops. Yield monitoring and map creation are conceptually easy to understand, but obtaining an accurate and reliable yield map is challenging due to six major factors (Blackmore and Marshall, 1996):(1) the time lag of grain through a threshing mechanism, (2) the unknown crop width entering the header during harvest, (3) 'wandering' errors from the GPS, (4) surging grain through the combine transport system, (5) grain losses from the combine, and (6) sensor accuracy and calibration.

During the last three decades, yield monitoring systems have been developed for different crops using different sensing principles. Various hardware systems are commercially available. In this paper, research trends over the past three decades have been reviewed. First, the basic components and principles of yield monitoring system are explained. Then, the development of hardware components by crop and measurement variables is reviewed.

Components and principles of yield monitoring system

Figure 1 shows a diagram of the basic components of yield monitoring systems, as well as those components' individual roles. Yield monitoring systems measure point-by-point crop yield continuously and in real time

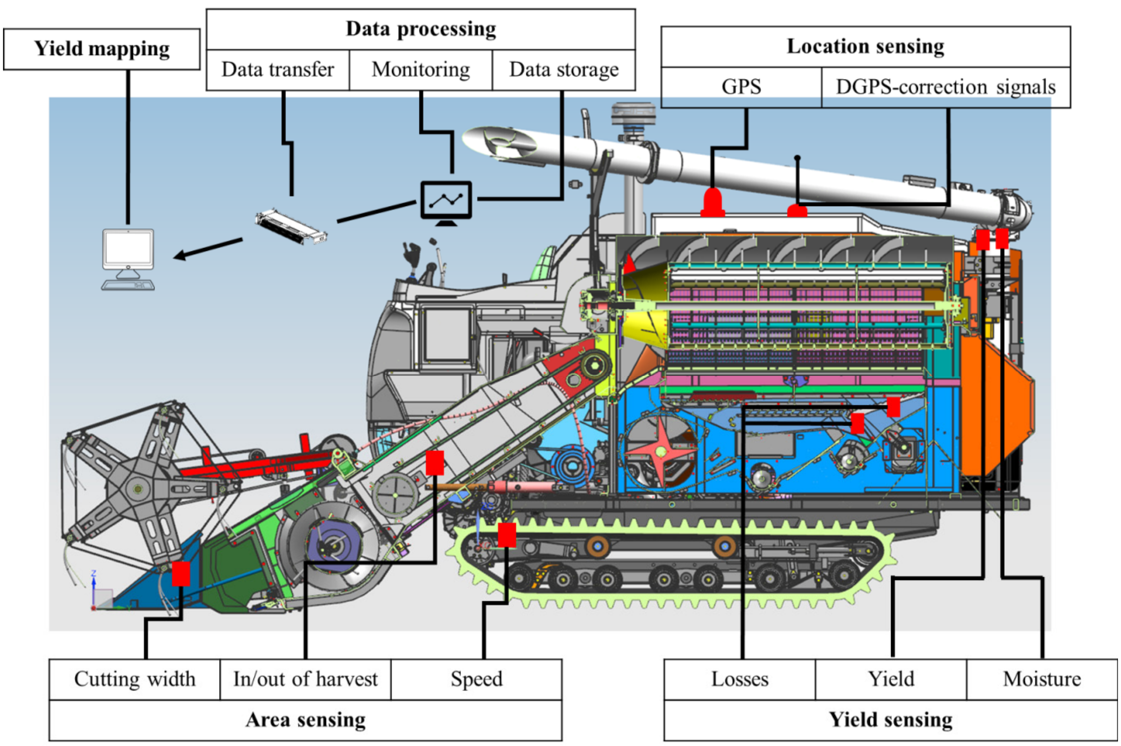

Figure 1. Diagram showing basic yield monitoring components and their roles in yield monitoring systems.

Table 1. Comparison of grain flow sensors for yield monitoring systems

Sensing type	Location	Crop	Accuracy	Reference
Mass flow (Weighing, load cell)	Below the pivoted auger	Wheat, corn	Error ≤ 5% in laboratory	Wagner and Schrock, 1987
	Under the grain tank	Rice	Error: 9.5~23.1%	Iida et al., 1999
Mass flow (Force impact, load cell)	Clean grain elevator head	Corn, wheat, barley	Error: 4.06%	Kormann et al., 1998
	Elevator curve part	Corn	R^2: 0.89	Perez-Munoz and Colvin, 1996
(Diaphragm impact sensor) (Piezo-electric film)	End of threshing rotor	Corn	R^2: 0.90~0.97	Schrock et al., 1997
		Rice	Error: 12% in field	Zhao et al., 2011
Mass flow (Radiometric, gamma ray) (X-ray)	Clean grain elevator head	Corn, wheat, barley	Error: 4.07%	Kormann et al., 1998
		Corn	R^2: 0.99 in laboratory	Arslan et al., 2000
Volume flow (Paddle wheel)	Clean grain elevator head	Corn, wheat, barley	Error: 4%	Kormann et al., 1998
Volume flow (Optical type, light beam)	Clean grain elevator middle part	Corn, wheat, barley	Error: 3.43%	Kormann et al., 1998
		Corn	Error: 3%	Pfeiffer et al., 1993
		Corn, wheat	Error: 9%	Strubbe et al., 1996

while a harvester operates on a field. Yield monitoring systems consist primarily of four parts:a crop flow sensing part, an area sensing part, a location sensing part, and a data processing part. Generally, crop yield (Y) is expressed as weight (Q, crop flow rate) per area (A) (e.g., ton/ha), as in Eq. (1), therefore weight and area should be measured. Grain flow, expressed as weight per time, can be measured by sensing the values of crop flow rate and moisture content, in order to correct the measured wet flow rate according to the reference moisture content. For the calculated area, cutting width and travel speed must be measured. Finally, the calculated crop yield (Y) is stored with locational information (e.g., GPS coordinates) (Morgan and Ess, 2010). Data processing is conducted either in real-time in the harvester or as post-processing in the office.

Location sensing is relatively straightforward. Positioning is conducted either by relative systems (e.g., inertial method) or absolute triangulation systems. Absolute systems can be divided into land-based systems that use radio transmitters and a receiver, and satellite-based systems that use satellites as transmitters. Recently, most yield monitoring systems have used satellite-based positioning systems. Harvester travel speed can be measured either by a contact-type shaft speed sensor that detects the rotational speed of a driveshaft (or wheel) using a magnetic sensor, or by a non-contact type radar or ultrasonic sensor that emits high-frequency sound wave signals toward the ground and receives the returned signals. Travel speed can be also obtained from the GPS receivers. In/out of harvesting work is detected by using a magnetic sensor to monitor header height. Sensing approaches for measuring crop flow rate, moisture content, and cutting width (or area) are explained in the later sections of the paper.

$$Y = \frac{Q}{A} \qquad (1)$$

Where

Y: instantaneous crop yield (weight/area),

Q: crop flow rate corrected to the reference moisture content (weight/time),

A: area

Grain Flow Sensing

Grain crop combine harvesters cut crop plants at the header and transport them to a threshing mechanism. Threshed crop grains fall through a separation screen to a horizontal transportation auger. Then, a clean grain elevator (or vertical auger) moves the grains and discharge to a grain bin (or tank). When the grain tank is full, the grains are discharged through a pivoted auger to a separate trailer or cargo vehicle. Grain flow sensors are mounted along the route of crop and grain transportation.

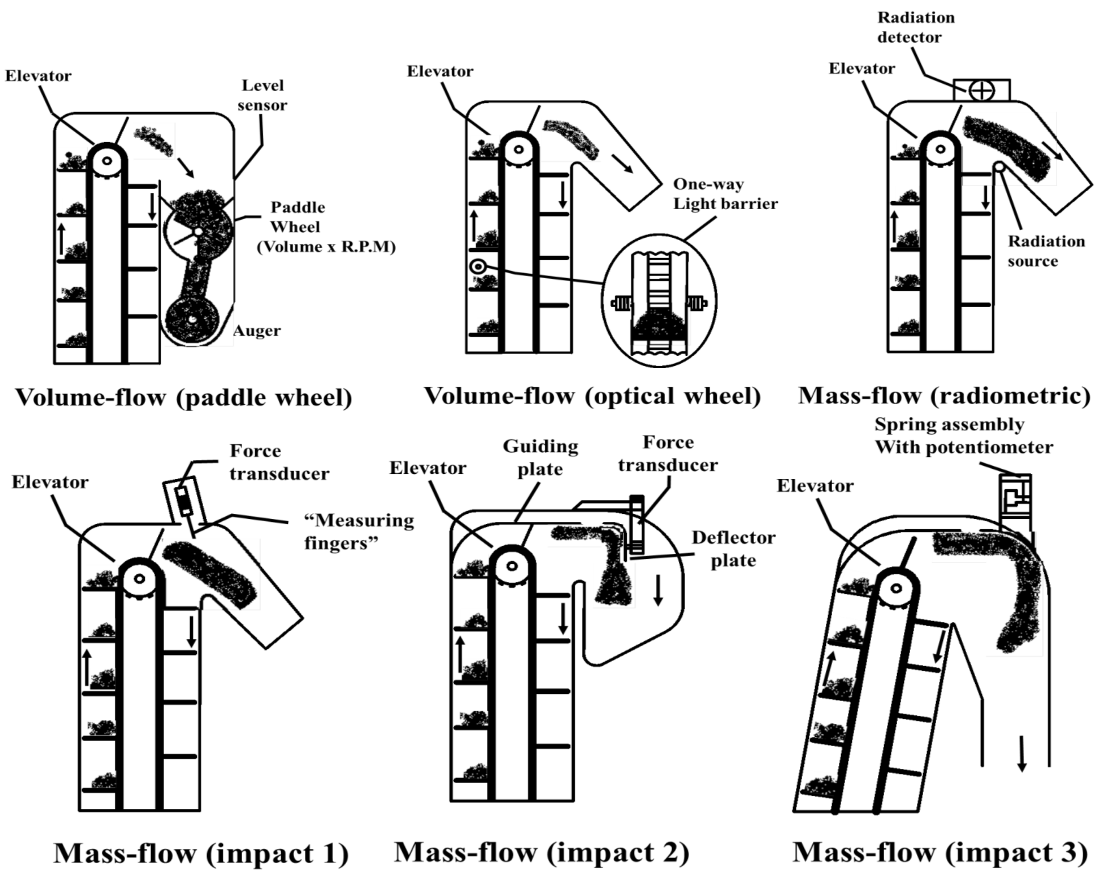

Figure 2. Volume-flow and mass-flow continuous and real-time sensing approaches for grain crops.

Grain flow sensing approaches are generally classified into two categories, which are mass flow and volume flow methods (Figure 2). Kormann et al. (1998) and Morgan and Ess (2010) provided a good classification and description of grain flow sensing methods. A summary of selected volume flow and mass flow sensing approaches is shown in Table 1.

Mass flow methods

Mass flow methods (mainly contact-type) employ weighing-type, impact-type, and radiometric-type units. Weighing-type units utilize load cells and are mounted in the middle of grain transportation routes (e.g., augers or grain tanks). Wagner and Schrock (1987) instrumented a pivoted auger that discharges clean grains to a grain tank using a load cell, and tested performance for wheat and corn. They found that grain flow errors were lower than 5% if the grain moisture content was in the range of 10~15.5% (w.b.) for wheat and 14~19.2% (w.b.) for corn. The random variability of the grain flow sensor was 40% lower for wheat than for corn.

Iida et al. (1999) installed load cells under a grain tank to measure and accumulate the weight of falling rice grains in a Japanese rice field. The moisture content of the rice ranged from 9.5~23.1%, and the indoor test and field test showed correlation coefficients of 0.99 and 0.74, respectively. Zandonadi et al. (2010) used a load cell to measure the torque required to drive a clean grain elevator shaft, and, using edible beans, evaluated its potential for use as a mass flow sensor. Tests were conducted using a test bench with a flow rate range of 0~3.4 kg/s. The average accumulated mass errors of the sensor were less than 3.1%, and the maximum accumulation error was 4.9%.

Perez-Munoz and Colvin (1996) tested a commercial impact-type sensor for corn in both laboratory and field conditions. In the laboratory, the tested grain moisture content, combine speed, and grain mass had ranges of 18~22%, 4.02~4.83 km/h, and 0.34~1.36 kg, respectively. The measured values and sensor outputs showed a high correlation coefficient (r = 0.99). When the sensor was tested on 20-m long field strips, the correlation coefficient was 0.94 (R^2 = 0.89). An impact-type grain yield sensor was fabricated using a load cell, and was mounted at the end of grain elevator. The average and maximum errors were 2% and 3.5%, respectively (Koichi et al., 2011). This error could be reduced by filtering the vibration noise of the combine (Zhou et al., 2014). Fulton et al. (2009) installed a load cell in a covered harvest elevator model to conduct tests according to varying field slopes. Grain flow measurements taken for a left/right slope showed errors ranging from -3.45~3.46%. Grain flow measurements taken for front/back slopes showed errors ranging from -6.41~5.50%.

Arslan and Colvin (1998) compared a load-cell based commercial impact-type flow sensor mounted at the head of a grain elevator with an electronic scale mounted on a grain weigh-tank. A strong correlation was found between the yield monitor and electronic scale (R^2 = 0.99); the average percent difference was 2.11%. Simonovic et al. (2016) tested a force impact-type sensor in field conditions, in which the GPS-based combine speed was related to the grain mass flow. When the crop yield was classified into three groups (i.e., low-, medium-, and high-yielding zones), the impact of the sensor reading on combine speed was significant in the medium-yielding zones for wheat, and all the three yielding zones for barley.

Schrock et al. (1997) introduced a diaphragm impact sensor that used flexible fabric-reinforced rubber to separate grain from a load cell that measured the impact force. The diaphragm impact force showed a good correlation with the grain elevator force, as measured by a conventional load-cell impact sensor (R^2:0.90~0.97). Zhao et al. (2011) fabricated a sensor for grain loss measurement. Piezo-electric PVDF (PolyVinyliDene Fluoride) film was installed at the end of threshing rotor to measure the force of the falling grains. Errors were within 4.5% for the laboratory tests and 12% for the field tests.

Radiometric type (gamma ray) devices use a weak radioactive source and a radiation sensor. Grains that are discharged from elevator paddles pass through a specially designed region between the radioactive source and radiation sensor. The degree of radiation absorption is correlated with the mass per unit area of the grain (Kormann et al., 1998). Low energy X-rays were used in indoor tests to measure grain flow rates of 2~6 kg/s; these showed a fairly good correlation coefficient of 0.99. For higher flow rates, increased X-ray energy was required, and grain moisture content (15~20%) had almost no influence on the measurements (Arslan et al., 2000).

Volume flow methods

Volume flow methods (mainly non-contact type) include paddle wheel type and optical type modules. The paddle wheel type module is a “Shelbourne Reynolds Engineering’s Claydon Yield-o-meter”. Grains coming out of the clean grain elevating auger accumulate on a stationary paddle wheel. When the grain level reaches the capacitive proximity sensor, the sensor activates a relay to turn the paddle wheel in order to discharge the accumulated grains. Searcy et al. (1989) instrumented a commercial grain combine harvester with a six-bladed paddle wheel. Using a microwave land-based positioning system and a 3rd order moving average algorithm for data smoothing, grain sorghum yield data were mapped at 0.73 s intervals.

Pfeiffer et al. (1993) designed an optical type flow rate sensor using photodiodes and a visible light beam, assuming that the light blocked by the grain (i.e., grain height) would be correlated to the amount of grain (i.e., flow rate) on the elevator paddles. Although the performance of the sensor was influenced by the weight and moisture content of the grain, the errors were lower than 3% under most field operating conditions. Strubbe et al. (1996) used multiple optical sensors and evaluated their performance in a laboratory for wheat and corn. When using two horizontally mounted sensors, the errors were about 13%, but they decreased to about 9% when two vertically mounted sensors were added. The spacing between the elevator paddle and the housing was 2 mm.

Choi (2016) compared non-contact sensors for detecting grain flows falling from a threshing cylinder into a horizontal transportation auger. The target grains were rice, soybeans, and barley, and the tested sensors were an optical array, and microwave, laser, and ultrasonic array modules. Results showed that optical array performed with the best accuracy (R^2:0.95~0.97). Microwave and laser modules also showed promising performance, with R^2 ranges of 0.93~0.95 and 0.81~0.88, respectively. Although a single ultrasonic module initially showed low performance (R^2:0.03~0.11), its performance was improved by increasing the number of modules and layout. With 20 modules and three-layer mounting, the prototype ultrasonic array flow sensor produced significantly improved performance; the R^2 values were 0.86 for rice, 0.90 for soybean, and 0.88 for barley, respectively.

Other methods

Although most grain flow sensing has been achieved by mass-flow or volume-flow methods, other approaches have also been tried. Corn population sensors were developed assuming that the corn population at both harvesting time and yield would be closely related. Birrell and Sudduth (1995) designed and fabricated a corn population sensor consisting of a spring-loaded rod and a rotary potentiometer. The population sensor was mounted in front of the gathering chains on the row dividers of the combine head. When tested in the field, the sensed population produced a good estimate of the hand-counted population, with a coefficient of determination of 0.93 (Sudduth et al., 2000). Hummel et al. (2002) introduced a photoelectric corn population sensor instead of a mechanical sensor. An air-jet was used to remove the dust attached to the optical units. Compared to hand counts, an error of 4.4% was observed. Additionally, an error of 3.6% was observed after removing weak plants.

Shrestha and Steward (2003) reported a vision-based machine corn population sensing system for early-growth-stage corn. The system acquired video clips using a digital video camera under daylight conditions. After a series of image processing operations, a plant count was obtained from the total number of plant pixels and their median positions. The system showed an R^2 of 0.90 when correlated to a manual stand count. Domsch et al. (2008) used RGB aerial imagery taken at a growing stage to estimate crop yield at harvesting time. When the researchers used VARI (introduced by Stark et al. (2000)) and the data for a selected few tracks, VARI versus measured yield showed linear patterns for rye fields (R^2:0.40 and 0.75) and power patterns for winter barley fields (R^2:0.76 and 0.86). The performance, however, degraded to R^2 values of 0.34~0.36 for the rye fields and 0.55~0.80 for the winter barley fields, respectively, when data from the whole fields were used in the regression. Long and McCallum (2015) applied commercial yield monitoring sensors to assess post-harvest environmental stress in wheat. Sensors included an impact-type mass flow sensor, an NIR spectrometer, and a LiDAR (light detection and ranging) unit.

Comparing the mass flow and volume flow methods

Birrell et al. (1996) compared volume-based paddle wheel type and mass-based impact type yield monitors. The impact type sensor and paddle wheel type sensor both showed a high correlation with the batch weights (r^2 > 0.99). However, the volumetric monitor showed significant errors in the calculation of instantaneous yield data, due to its discrete operation. Chaplin et al. (2004) compared an impact plate sensor (mounted at the grain elevator head) with a torque sensor, measuring the torque required to drive the grain elevator shaft for corn grains, using a laboratory test bench. They reported that the torque sensor was ten times more sensitive than the impact plate sensor, although the standard error increased at low flow rates (below 3 kg/s).

Kormann et al. (1998) and Demmel (2013) compared four commercial volume-flow and mass-flow grain flow measurement systems in the field during 1991~1995. The tested volume-flow sensors were a paddle wheel type (i.e., CLASS YIELD-O-METER) and an optical type (i.e., RDS CERES); the mass-flow sensors were a radiometric type (i.e., MASSEY FERGOUSON FLOWCONTROL) and a force impact-type (i.e., Ag-Leader YIELD MONITOR). The error ranges of the tested systems were between ± 3.5~± 4%. System performance was also compared on a testing stand. When the mass flow varied from 10 to 30 ton/h, the mean calibration errors were less than 3%. When the mass flow was set at 20 ton/h and the slopes were simulated up to 13°, the relative calibration errors were between -3.38 and -0.02%, and the standard deviations of the relative errors were between 2.17 and 11.73%.

Moisture Content Sensing

Grain moisture content sensing has in many cases been conducted using capacitive, microwave, acoustic, and NIR (near-infrared reflectometry) sensors. The sensors may have a blade or flat surface, and are mainly mounted on the grain auger surface (Figure 3). Reitz and Kutzbach (1996) measured the moisture content of grain entering a cutter bar using a capacitance-type sensor. The average rate of error was 3%, but the maximum error was 10%. This error was eliminated using a data processing technique. Berbert and Stenning (1996) conducted an experiment using a capacitance-type sensor within a temperature range of 19~24°C and a humidity range of 50~60%. The average rate of error was 3.3% and the largest error was in the range of 11.5~16.3%. Lawrence et al. (1998) produced a parallel-plate moisture content sensor in a range of 10~26% for various corn samples grown in various regions of the US. The standard error of the corrected equation was 0.24%, and the R^2 value was

0.99. The prototype sensor produced better results than the commercial moisture meter. Choi (2016) mounted a capacitance module under the horizontal transportation auger to detect the grain moisture content of grains moving through the auger (Figure 3). The test results for rice, soybean, and barley showed that the sensor produced a high coefficient of determination (R^2:0.99). When the flow rates were varied as 50, 150, and 300 g/s, the results also showed clear linear patterns with different regression slopes.

Kocsis et al. (2008) applied the microwave resonator technique to measure the on-line moisture content of wheat for grain dryers. Laboratory tests in a range of 7~29% (w.b.), showed very promising results, with a standard deviation of 0.51% between the microwave-measured and reference moisture content values. At lower moisture ranges (7~18 %), there was a density-independent relationship with the microwave-measured moisture value (R^2:0.99). At higher moisture ranges (18~29%), there was a density-dependent relationship with frequency shift (R^2:0.97). Nelson et al. (2016) also applied the microwave technique, using two patch antennas connected to a network analyzer to measure moisture content and bulk density in flowing corn, soybean, and wheat. Laboratory tests were conducted for two different moisture levels, low (10.94~11.69% (w.b.)), and high (17.15~18.21% (w.b.)), and three flow rates per moisture level. The error levels were lower than 1% for moisture content and 0.01 g cm^{-3} for bulk density.

Lotfi and Darvishi (2015) used an acoustic technique (mainly used in facilities like dryers and storage bins), assuming that the impact sound of grains on a surface (e.g., glass) would be highly affected by grain moisture content. For laboratory tests using wheat grains with moisture contents of 12~32% (w.b.), the microphone-received sound wave property showed a clear linear relationships with the moisture content ($R^2 \geq 0.95$). Ferrari and Pessina (2012) used an acoustic device to relate grain moisture content to the sound spectrum produced by falling kernels on a rigid surface (i.e., a glass plate). Wheat, rice, and corn grains were tested, and the overall sound level and octave band frequency parameters were calculated. In a moisture content range of 11~23%, the overall sound level decreased linearly by about 0.4 dB per 1% moisture content for rice, while the slope was 0.3 dB for wheat and corn. The most sensitive sound frequency bands were found from 2 to 16 kHz.

Maertens et al. (2004) tested the capability of a commercial NIR spectrometer to measure the moisture and protein content of wheat grains in the middle of a clean grain elevator. Laboratory tests showed that by using appropriate low-pass filtering and optimal time shift techniques, the cross-validations errors were 0.57% and 0.31% for on-line protein and moisture content sensing, respectively.

Cutting width sensing

Mass or volume is obtained by measuring flow rate and moisture content, and harvested area is calculated by measuring harvesting width and distance (time x speed). If it is not constant, harvesting or cutting width needs to be measured accurately. Mechanical, image, and ultrasonic sensors have been used for the real-time measurement of cutting width. Stafford et al. (1997) compared the accuracy of an ultrasonic sensor and ultrasonic vibrator, measuring the distance to the paddy rice from the devices. They found that the maximum error for the ultrasonic sensor was 4.2% at a true distance of 720 mm, and the maximum error for the ultrasonic vibrator was 8.9% at a the true distance of 360 mm. Missotten (1998) and Reyns et al. (2002) used a

Figure 3. Capacitive-type grain moisture content sensor: center blade unit (left) and flat surface unit (right).

90-degree rotated ultrasonic sensor and reflecting plates to measure the distance from the crops, in order to measure blind spots. The errors were lower than 5%, but the new design required additional parts and space compared to previous designs. Choi (2016) also used ultrasonic sensors positioned at both sides of the combine head dividers. When the cutting width sensor was tested for rice, soybean, and barley fields, the RMSE values were 4.33, 4.81, and 6.44 cm, respectively. Han et al., (1996) measured combine cutting width using a bitmap method, finding an average error of 19.4% and maximum error of 45.8%.

Summary and Conclusions

Yield monitoring systems have been commercially available for the last three decades for various crops, including grain crops, forage crops, root crops, and citrus. During this period, the performance of individual components and overall systems has been significantly improved. The main harvested grains crops have been rice, wheat, corn, barley, and grain sorghum. A review of research trends related to grain crop yield monitoring sensors provided the following useful information:

(1) Various approaches have been taken and various set-up configurations have been used with grain flow sensors. In most cases, the flow sensors were either mass flow or volume flow measurement types, and were mounted at the clean grain elevator head. Mass flow sensors used weighing, force impact, or radiometric approaches. Volume flow sensors were either paddle wheel type or optical type. In some cases, optical type flow sensors were mounted in the middle of the clean grain elevator, and weighing type sensors were mounted under the grain tank. Other tested approaches include corn population counting at early stages or before harvesting using optical light beams and photodiodes, spring-loaded mechanical rods, and machine vision.

(2) Grain moisture content must be measured, in order to correct the grain flow according to the reference moisture content. Grain moisture content has in most cases been measured using capacitive sensors, although microwave and near-infrared reflectance approaches have been tried in some cases. Generally, moisture content sensing has been done at the grain transportation auger or in the middle of the clean grain elevator. Cutting width sensing is necessary to calculate the instantaneous harvesting area if the cutting width is not constant. Ultrasonic distance sensors have in most cases been used for cutting width measurement.

The variety in the reviewed yield monitoring sensors could be due to crop variety and cultivation practices, harvester specifications, and economic limitations. An individual selecting a suitable approach for a target crop and harvester should consider these factors. The performance of each type of sensor would not be universal. For example, grain flow sensors are influenced by machine vibration and field slopes. Sensor types and mounting locations should also be carefully selected to produce accurate yield mapping through real-time and post-processing of the yield measurement data.

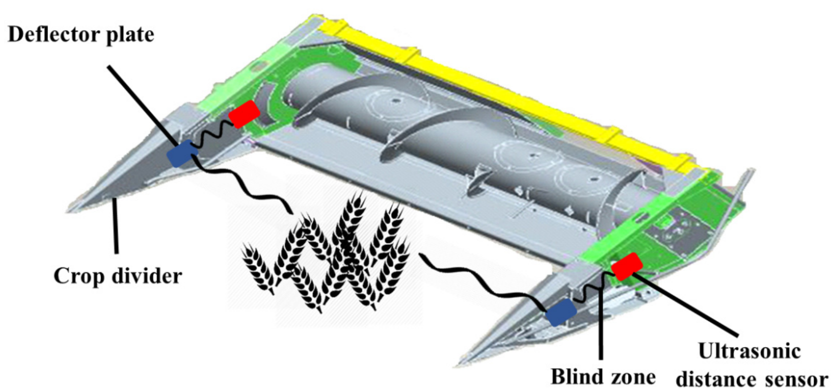

Figure 4. Diagram of a cutting width sensing concept using ultrasonic distance sensing modules.

Conflict of Interest

The authors have no conflicting financial or other interests.

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