Grain flow rate sensing for a 55 kW full-feed type multi-purpose combine

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Abstract: Real time sensing of crop yield is critical for a successful implementation of precision agriculture. Yield monitoring system is an optional component of a 55 kW multi-purpose combine harvester, developed in Korea, for both domestic and global markets, especially Asian countries where field sizes are relatively small. The aim of the present study was to fabricate and evaluate the performance of a grain flow sensor suitable to the mid-sized full-feed type combine for rice, soybean, and barley. Firstly, commercially available non-contact type sensing modules (optical, ultrasonic, laser, and microwave modules) were chosen for alternative candidates, to be further tested in a laboratory bench. Through the laboratory tests, the ultrasonic module was selected as a potential approach and the performance was improved by increasing the number of modules and their layout. Finally, the improved grain flow sensor was evaluated during field harvesting operation. Field tests with the improved grain flow sensor showed a good potential for rice (R^2=0.85, *RMSE*=126.14 g/s), soybean (R^2=0.78, *RMSE*=43.87 g/s), and barley (R^2=0.83, *RMSE*=37.39 g/s). Further research would be necessary for improvement and commercialization, through various signal processing and field tests under different field and crop conditions.

Keywords: precision agriculture, combine harvester, yield monitoring system, sensor, grain flow rate
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1 Introduction

Development of combine harvesters that could maintain high field efficiency for various major food crops, such as rice, barley, and soybean, has been an issue in many countries[1]. Mechanization of dryland crop production operations is required especially in Asian countries. For example, as of 2014, mechanization level of dryland crop harvesting in Korea was only 13.3%. Recently, there has been a growing demand for full-feed type, mid-sized, and multi-purpose combine harvesters suitable to both domestic (i.e., Korea) and foreign (i.e., Asian countries such as Japan and China) markets with similar crop and field conditions.

Precision agriculture (PA) is a strategy to optimize cultivation input and crop yield based on the variability in site variables related to field and crop status, using a multidisciplinary new technology. PA has been well established and adopted by farmers, especially in the USA and European countries where field sizes are relatively large. Although the concept of PA has also drawn interest in Asian countries and various studies have been conducted, commercialization and farmer adoption of relevant technologies has been limited[2]. Recently, the Korean agricultural machinery manufacturers have been developing PA-related technologies to secure global competitiveness against with new foreign machinery.

Crop yield monitoring system is one of the fundamental components for a successful PA and has been commercialized as an optional unit of combine harvesters. Yield monitoring systems collect crop yield data in real time, during combine harvesters traveling in the fields. Generally, a yield monitoring system is composed of a grain flow sensor, a grain water content sensor, a cutting width sensor, a travel speed sensor, and a location sensor (e.g., GPS) to calculate crop yield (t/hm^2) on the point-by-point basis[3]. Yield map is a graphical representation of geo-referenced grain yield so that variability of the yield can be identified. Farmers may change the production inputs and pursue direct profits based on the information identified from the yield maps[4,5]. The performance of a yield monitoring system and yield map is strongly affected by hardware components (e.g., sensor accuracy), data processing technique (e.g., filtering)[6], and operational condition (e.g., delay time from cutting to sensing).

Among the hardware components, grain flow sensing is critical for an accurate yield calculation. The reported grain flow rate principles can be divided into two types: contact type and non-contact type. In many cases, contact type uses load cells or potentiometers to sense the weight or impact force of grains thrown from the clean grain elevator. An impact-type grain yield sensor was fabricated using a load cell and mounted at the end of grain elevator, and the average and maximum errors were 2% and 3.5%, respectively[7]. The error could be reduced by filtering the vibration noise of the combine[8]. In case of the Japanese application, the load cell was installed at the end of the grain elevator or under the grain tank to measure and accumulate the weight of the falling rice grains[9,10]. Grain separation loss was also monitored by measuring the force of the falling grains, with

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error levels less than 12% under the field conditions[11,12]. To measure the weight of citrus, a dynamic weighing system was developed and installed on the end of the hydraulic arm. Laboratory and field tests showed satisfactory results with errors less than 5%[13]. The load cell was also applied to a potato yield monitoring, with a margin of error of 2%-3%[14], and a light weight (<100 g) dried-persimmon sorting system, with an accuracy of 94.79%[15].

Non-contact type uses optical, ultrasonic, microwave, X-ray, capacitive[16], or laser modules to estimate the volume of grains passing through the sensing area or space. Low-energy X-ray was used for indoor tests to measure grain flow rates of 2-6 kg/s flow, with a correlation coefficient of 0.99. For greater flow rates, a greater X-ray energy was required, and the grain water content (15%-20%) had almost no influence on the measurements[17]. Optical sensors were applied for cotton yield monitoring, but dust degraded the performance. By installing an air box, the error was reduced from 10.7% to 4.4%[18]. In other tests, error level of optical sensors could be reduced by an air-jet device, and the reduced error was 4.4% when compared with hand counts[19]. Experiments were conducted to measure grain flow using 4 different sensing approaches (i.e., load cell, potentiometer, capacitance sensor, and optical photo sensor). The results showed that the load cell method yielded the best coefficient of determination (R^2=0.94), while the optical sensor also gave a favorable performance (R^2=0.91)[20]. When the optical photo sensor was applied to the grain elevator, the errors were 4.0%±3.3%[21]. Solid particle flow rate was measured by installing electrostatic and capacitance sensors on the constant flow tube and the errors were 3%-8%[22]. When an ultrasonic module was applied to measure airflow, the results showed a high accurate performance (R^2=0.99) in a flow range of 8-12.25 m/s[23].

Due to the system requirements specific to the target application, direct adoption of commercial yield monitoring systems developed for different crop and field conditions may not appropriate. In a study where a grain yield monitoring system developed in USA was applied to a Korean 2 m wide rice combine harvester in a 30 m by 100 m field, two major problems were reported[2]. First, sensing range and resolution of the load cell type grain flow rate sensor were not feasible. Grain combine harvesters in USA mostly have swath widths over 10 m and travel at speeds relatively higher than the rice combines in Korea and Japan. Consequently, the grain flow rates (t/hm^2 or g/s) of the Korean small-sized rice combines would be much lower than those of USA large-sized grain combines. Second, the delay time issue may cause a significant amount of data loss. Delay time consists of three components: 1) sensing delay from the time of plant cutting to the time of sensor measurement of grain flow rate; 2) start delay, i.e. the required time for the sensing value to be stabilized (i.e., transient stage); 3) and stop delay, i.e. the required time for the sensing value to be decreased due to no harvesting. Among these components, sensing delay can be reduced by the selection of a better sensing location. When grain flow rate is measured at the end of a clean grain elevator, the sensing delay time would be about 12-15 s[24]. In many cases, the data affected by these delay times are removed; therefore, the delay time needs to be minimized for small-sized fields (e.g., 30 m by 100 m). In our study, to minimize the effects of delay time issue, the space below the threshing sieve case was chosen as the sensing location.

This study is a part of an overall project aiming to develop a grain yield monitoring system for a 55 kW full-feed type small-sized (i.e., 2 m cutting width) multi-purpose combine harvester suitable to Asian small-sized fields. The aim of this study was to develop a grain flow rate sensor through laboratory and field tests.

2 Materials and methods

2.1 Sensor modules tested

Through a market survey, commercially available non-contact type sensing modules were selected to investigate the potential as grain flow sensor candidates. Three sensors (i.e., optical array, microwave, and laser) were relatively expensive units fabricated to measure particle flow rate. The other two sensors (i.e., ultrasonic and optical) were relatively cheaper modules. Based on the manufacturer's information, the optical array sensor with 192 optical modules for the detection of grain particles was selected as the target reference.

Table 1 Major specifications of the non-contact type sensing modules selected for laboratory tests

Sensing module	Specifications	
 Optical array sensor	Manufacturer	Banner, USA
	Model	Array high resolution
	Output voltage /V	0-10
	Measurement range/mm	163-1951
	Frequency/GHz	20
	Size/mm	35×35×980
	Number of optical module	196 ea
	Price/$	7000
 Microwave sensor	Manufacturer	WADECO, Japan
	Model	MWS-DP-3-24V
	Output current/mA	0−10
	Measurement range/mm	0−15 000
	Frequency/GHz	24
	Size/mm	114×114×170
	Price/$	800
 Laser sensor	Manufacturer	Banner, USA
	Model	LE550
	Output voltage/V	0-10
	Measurement range/mm	100-1000
	Frequency/kHz	12
	Size	17×34×34 mm
	Price/$	400
 Ultrasonic module	Manufacturer	DAS, Korea
	Model	UDS-10A
	Output voltage/V	0-5
	Measurement range/mm	300-60 000
	Frequency/kHz	40
	Size/mm	15×15×25
	Price/$	40
 Optical module	Manufacturer	Autonics, Korea
	Model	BX15M-TDT
	Output voltage/V	0-5
	Measurement range/mm	0-15 000
	Frequency/kHz	6
	Size/mm	10×40×47
	Price/$	34

2.2 Test Bench and indoor evaluation

Selected commercial sensing modules were tested in the laboratory. As mentioned above, the location below the sieve case screen, where grains would fall after threshing, was selected for sensor attachment. A test bench was constructed considering the size of the combine under development (Figure 1). To simulate the grain flow during harvest, the grains were fed from the top of the test bench. Test levels of grain flow were selected considering the cutting width (i.e., 2 m), travel speed (i.e., about 1.5 m/s), and planting density of crops. Tested grain flow rates were 50-300 g with a 50 g interval for soybean and barley, and 1150-1300 g with a 50 g interval for rice. Each test was repeated 3 times.

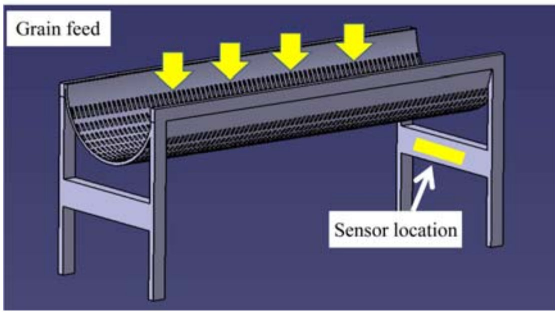
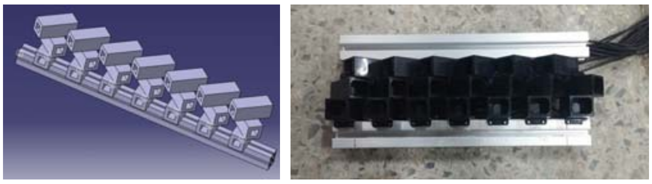


Figure 1 Schematic diagram of the tech bench constructed for laboratory tests

2.3 Prototype fabrication

Based on the results of the laboratory tests on the bench, the ultrasonic module was selected for flow rate sensing of rice, barley, and soybean. The performance of the ultrasonic module with 4 units was not acceptable from the initial tests. Based on a literature review, however, accuracy improvement was expected to be enhanced through the increased number of the modules and their layout[25]. The number of the modules was increased to 12 and 20. Through preliminary tests, the ultrasonic modules were attached in 3 directions to cover the falling grain space: forward at the bottom layer, 45° left at the middle layer, and 45° right at the top layer (Figure 2). Figure 3 shows the prototype sensor mounting location between the threshing sieve case and the horizontal grain auger in the developed combine.



a. Drawing b. Photo

Figure 2 Sensor prototype

2.4 Field Tests

Field tests were performed in 2015 in a South-East area of Korea (rice field, 35.542°N, 128.467°E; barley and soybean fields, 35.426°N, 128.781°E). The sizes of the rice, soybean, and barley fields were about 0.8 hm^2, 0.5 hm^2, and 1.2 hm^2, respectively. The measured average grain water contents were 24.7%, 18.6%, and 16.3%, and grain flow rates were 1148.14 g/s, 398.45 g/s, and 272.98 g/s, for the rice, soybean, and barley, respectively.

For each field, 9 sub-sectors were prepared for 3 crops with 9 replications (Figure 4). The size of the sub-sectors was 2 m by 20 m for barley and 2 m by 10 m for rice and soybean. The tested speeds were in the range of 1.0-1.7 m/s and the average speed was about 1.4 m/s. To minimize the effects of combine vibration, a low pass filter with a cutoff frequency of 100 Hz was used for the grain flow rate sensor measurements. The calibrated sensor output and manually measured values were compared.

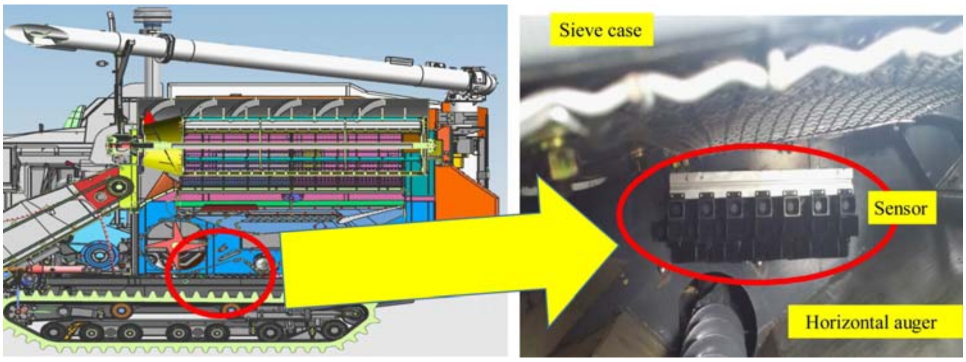


Figure 3 Photo showing the sensor mounting location under threshing sieve case

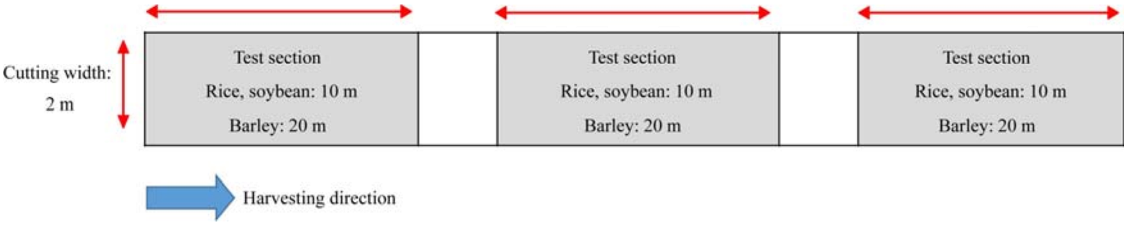


Figure 4 Diagram showing the sub-sections prepared for field test

3 Results and discussion

3.1 Laboratory Tests for Sensor Comparison

Table 2 shows results of the laboratory tests of sensor comparison. The performance of the each sensor was similar for the tested crops. The optical array sensor, microwave sensor, and laser sensor data provided statistically significant linear regression models (p<0.05), while those for the ultrasonic and optical modules were not statistically significant. Performance of the optical array and microwave sensors were very good with the coefficients of determination above 0.93. Except the optical array sensor, the results were based on single or 4 modules. Multiple sensors would be necessary to cover the whole width of the threshing sieve, therefore low-cost and small-sized sensor (i.e., ultrasonic sensor) was selected for further investigation.

Comparing the performance of the optical array sensor and optical module, we hypothesized that the increase of the number and proper layout of the modules would improve the results. The performance of the optical module with 4 units was very poor (R^2: 0.03-0.11; *RMSE*: 77.07-84.21 g/s), while that of the optical array sensor with 196 units was fairly good (R^2: 0.95-0.96; *RMSE*: 6.41-9.78 g/s). Optical module was relatively cheap (34 USD), and the array sensor used 196 modules (7000 USD). It was also noted that the ultrasonic module showed better results (R^2: 0.03-0.11; *RMSE*: 77.07-84.21 g/s) than the optical module. In this study, therefore, we assumed that the performance of the ultrasonic module could be improved with the increase of the number of modules and the layout.

Table 2 Results of the laboratory tests for sensor comparison

Sensor module	Grain	R^2	*RMSE*/g·s^{-1}	*p*-value
Optical array sensor (196 units)	Rice	0.95	9.78	<0.05
	Soybean	0.96	7.55	<0.05
	Barley	0.96	6.41	<0.05
Microwave sensor	Rice	0.93	20.19	<0.05
	Soybean	0.95	20.60	<0.05
	Barley	0.93	49.01	<0.05
Laser sensor	Rice	0.86	26.37	<0.05
	Soybean	0.88	23.80	<0.05
	Barley	0.81	30.55	<0.05
Ultrasonic module (4 units)	Rice	0.29	70.75	0.29
	Soybean	0.32	70.23	0.31
	Barley	0.22	72.86	0.29
Optical module (4 units)	Rice	0.11	77.07	0.39
	Soybean	0.04	84.21	0.75
	Barley	0.03	82.44	0.61

3.2 Performance Improvement of Ultrasonic Module

As shown in Table 3 and Figure 5, the performance of the ultrasonic module was considerably improved with the increase of the number of modules. When the number of modules increased from 4 to 20, coefficients of determination and RMSE values improved from 0.29 and 70.75 g/s to 0.86 and 34.13 for rice, from 0.32 and 70.23 g/s to 0.90 and 29.69 for soybean, and from 0.22 and 72.86 g/s to 0.88 and 22.23 for barley, respectively. Figure 5 shows that the linear pattern of the data became clearer with the module number increase. In particular, the slope increased from 0.25 to 0.88, indicating that the slope would get closer to 1 with a greater number of modules.

3.3 Field Tests of the Prototype

Overall, field test results were acceptable; however, the performance was relatively worse than that observed in the laboratory tests. In the field tests, coefficients of determination decreased from 0.86-0.90 to 0.78-0.85, and the RMSE values from 22.23-34.13 g/s to 37.39-126.14 g/s, depending on the crops. It should be noted that the data points were located fairly along the 1:1 line, and the slopes were in the range of 0.83-1.22 (Figure 6).

The performance degradation and slope increase would be due to vibration and dusts during the combine harvest operation. Although laboratory and field tests showed a favorable performance, the sensor should be improved for commercialization and practical implementation. To improve the sensor performance, further research should be performed. A possible approach would include a change of the module number and layout, data filtering (e.g., low-pass) to minimize the vibration and dust influence, long-term operation, and various field conditions.

Table 3 Test results of the ultrasonic modules with different numbers

Grain	Number of modules	R^2	RMSE/g·s^{-1}
Rice	4	0.29	70.75
	12	0.57	58.37
	20	0.86	34.13
Soybean	4	0.32	70.23
	12	0.68	48.15
	20	0.90	29.69
Barley	4	0.22	72.86
	12	0.51	63.46
	20	0.88	22.23

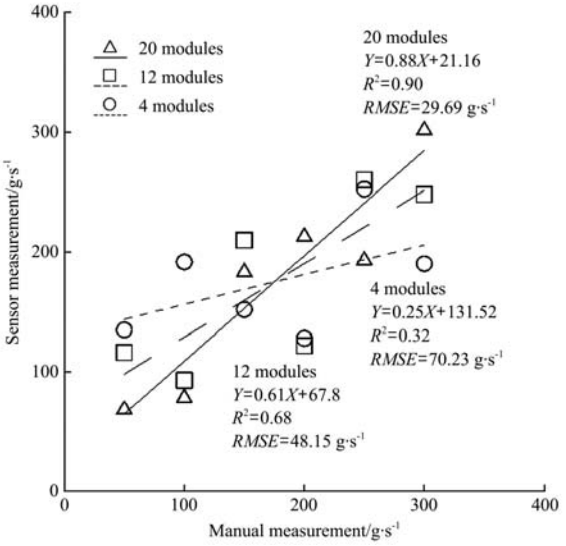


Figure 5 Results of the ultrasonic module with different module numbers for soybean

Table 4 Performance comparison of the grain flow rate measurement

Grain	Laboratory tests		Field tests	
	R^2	*RMSE*/g·s^{-1}	R^2	*RMSE*/g·s^{-1}
Rice	0.86	34.13	0.85	126.14
Soybean	0.90	29.69	0.78	43.87
Barley	0.88	22.23	0.83	37.39

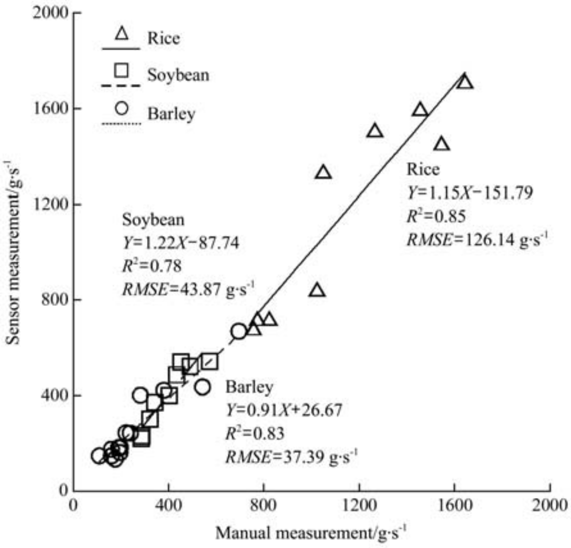


Figure 6 Results of grain flow rate measurement: after filtering (low-pass filtering with a cutoff frequency of 100 Hz)

4 Conclusions

Recently, agricultural machinery has started to adopt new technologies, such as automatic steering system, operation monitoring sensors, and control devices. For a successful implementation of precision agriculture, yield monitoring systems are becoming an important option for combine harvesters. In the present study, a non-contact type grain flow sensor was developed using an ultrasonic module and its performance was tested under laboratory and field conditions for a 55 kW full-feed type multi-purpose grain combine, to minimize the delay time effects (i.e., ideally no delay because the sensing was done right after the threshing), which is an important issue for Asian countries with their typically small-sized fields. When the sensor prototype was applied for field tests of rice, soybean, and barley, coefficients of determination were 0.78-0.85 and the RMSE values were 37.39-126.14 g/s. Although field test results showed a potential for a suitable grain flow sensor, for a successful commercialization and practical application, the prototype should be improved through various field tests and signal processing.

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[References]

[1] Kim Y K, Hong J T, Choe J S. Deflection characteristics of the rice stalk in harvesting operation by combine for multi-crops. Journal of Biosystems Engineering, 2003; 28(6): 485–490.

[2] Chung S O, Park W K, Chang Y C, Lee D H, Park W P. Yield mapping of a small sized paddy field. Journal of Biosystems Engineering, 1999; 24(2): 131–144.

[3] Chung S O, Choi M C, Lee K H, Kim Y J, Hong S J, Li M. Sensing technologies for grain crop yield monitoring system: a review. Journal of Biosystems Engineering, 2016; 41(4): 408–417.

[4] Aslan S A. Grain flow model to simulate grain yield sensor response. Sensors, 2008; 8(2): 952–962.

[5] Birrell S J, Sudduth K A, Borgelt S C. Comparison of sensors and techniques for crop yield mapping. Computers and Electronics in Agriculture, 1996; 14(2-3): 215–233.

[6] Wang H, Bai X P, Liang H B. Proportional distribution method for estimating actual grain flow under combine harvester dynamics. Internat J Agric & Bioll Eng 2017; 10(4): 158–164.

[7] Koichi S, Tsuneo K A. A mini grain-yield sensor and in-situ non-linear calibration impact-by-impact sensing to compensate for its own drift and to preserve non-linearity for enhanced accuracy. ASAE Paper No. 1111161. St. Joseph ASAE, 2011.

[8] Jun J, Cong B, Liu C. Elimination of vibration noise from an impact-type grain mass flow sensor. Precision Agriculture, 2014; 15(6): 627–638.

[9] Koichi S, Kawamura T, Horio H. Impact-based grain yield sensor with compensation for vibration and drift. Journal of JSAM, 2002; 64(5): 108–115.

[10] Michihisa I, Toshikazu K, Lee C K, Mikio U, Masabiko S. Measurement of grain yields in Japanese paddy field. Soil Science and Plant Nutrition, 1999; 48(3): 293–300.

[11] Zhan Z, Lia Y, Jin C, Xua J. Grain separation loss monitoring system in combine harvester. Computers and Electronics in Agriculture, 2011; 76(2): 183–188.

[12] Liang Z, Li Y M, Xu L, Zhao Z. Sensor for monitoring rice grain sieve losses in combine harvesters. Biosystems Engineering, 2016; 147: 51–66.

[13] Crews H, Whitney J D, Salyani M, Schueller J K. Dynamic weighing to improve citrus yield mapping. 2001. ASAE Paper No. 11842001. St. Joseph ASAE, 2014.

[14] Ehlert D. Measurement mass flow of potatoes for yield mapping. Precision Agriculture, 2000; 2(2): 119–130.

[15] Lim J G, Kim G Y, Mo C G, Choi I C. Development and performance evaluation of falling-type dried-persimmon weight sorting system utilizing load cell. Journal of Biosystems Engineering, 2015; 40(4): 327–334.

[16] Kim C, Choi M, Park T, Kim M, Seo K. Optimization of yield monitoring in harvest using a capacitive proximity sensor. Engineering in Agriculture, Environment and Food, 2016; 9: 151–157.

[17] Arslan S, Feyzi I, Joseph N, Thomas G, Colvin S. Grain flow measurements with x-ray techniques. Computers and electronics in agriculture, 1999; 26(1): 65–80.

[18] Khalilian A, Wolak F J, Dodd R B, Han Y J. Improved sensor mounting technology for cotton yield monitors. ASAE Paper No. 991052. St. Joseph ASAE, 1999.

[19] Hummel J W, Drummond S T, Sudduth A K, Krumpelman M J. Sensing systems for site-specific assessment of corn plants. Proceedings of the 6th International Conference on Precision Agriculture. Madison, WI: ASA, CSSA, and SSSA, 2002.

[20] Martel H, Savoie P. Sensors to measure forage mass flow and moisture continuously. ASAE Paper No. 991050. St. Joseph ASAE, 1999.

[21] Wilkerson J B, Moody F H, Hart W E. Development and evaluation of a flow measurement device for cotton yield mapping. ASAE Paper No. 011172 St. Joseph ASAE, 2001.

[22] Li J, Kong M, Xu C, Wang S, Fan Y. An Integrated instrumentation system for velocity, concentration and mass flow rate measurement of solid particles based on electrostatic and capacitance sensors. Sensors, 2015; 15(12): 31023–31035.

[23] Raine A B, Aslam N, Underwood C P, Danaher S. Development of an ultrasonic airflow measurement device for ducted air. Sensors, 2015; 15(5): 10705–10722.

[24] Chung S O, Sudduth K A, Drummond S T. Determining yield monitoring system delay time with geostatistical and data segmentation approaches. Transactions of the ASAE, 2002; 45(4): 915–926.

[25] Dai H J, Zhao S, Jia Z, Chen T. Low-cost ultrasonic distance sensor arrays with networked error correction. Sensors, 2013; 13(9): 11818–11841.