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PORTABLE WIRELESS YIELD MONITORING SYSTEM FOR RICE COMBINE

Azmi Yahya, Oh Yun Ju, Maryam Mohd Isa[1], and Samsuzana Abdul Aziz,

Department of Biological and Agricultural Engineering, Faculty of Engineering, Universiti Putra Malaysia, 43400 Serdang, Selangor DarulEhsan , Malaysia
[1] Department of Computer and Communication Systems Engineering , Faculty of Engineering, Universiti Putra Malaysia, 43400 Serdang, Selangor DarulEhsan , Malaysia.
Email: azmiy@eng.upm.edu.my

ABSTRACT

A simple, portable, and rugged instrumentation system has been successfully developed and field demonstrated to monitor, measure and record the harvested crop yield and selected machine performance parameters for any rice combines of any makes and models. The complete system comprises of ultrasonics sensors located at the header to measure crop cutting width, microwave solid flow sensor and microwave moisture sensor at the clean grain auger to measure the flow rate and moisture content of the cleaned grains going into the clean grain tank, electromagnetic detector on the grain elevator drive shaft to monitor the grain elevator rotational speed and a DGPS receiver on the console roof to indicate the combine travel speed and geo-position in the field. All measured parameters were made to display in-real time on the touch panel screen of the embedded system on-board the combine for the interest of the combine operator and also made to display in-real time on the monitor of the toughbook at the on-ground base station for the interest of the system controller. Static calibrations on the individual sensors showed excellent measurement linearity having R^2 values within 0.9839 to 1.000 ranges. The wireless communication between the embedded system and the toughbook could be sustained to a maximum distance of 140m apart. Site specific variability maps of crop yield, grain moisture content, combine cutting width, combine traveling speed, combine field capacity, and combine field efficiency within the harvested area could be produced from the data obtained with the instrumentation system using any GIS software.

***Keywords**: Grain Harvesting, Yield Monitoring, Paddy Mechanization, Precision Farming, Wireless Data Transmission*

INTRODUCTION

Yield mapping system installed on combine harvester provides information to precisely define the crop yield variability within a harvested area. Much work have been carried out in United States and Europe on the development and successful use of yield monitor for grain crop other than rice combines[1,2, 3 and 4]. Some work have also been carried out in Japan to develop yield monitor specifically for rice on typical local rice combine [5 and 6]. However, the rice combines from Japan were found to be unsuitable for Malaysian paddy fields because of their low overall productivity and durability. The overall cutting width of the combine is incompatible with the typical local paddy field size and the overall construction of the combine is not robust enough to work in the local paddy field terrain. The combine that are generally used in the major rice schemes of Malaysia are the imported salvage units from Europe that has been reconditioned to be used for rice and modified to adapt to the local paddy field size and terrain.

Earlier attempt was made to develop a special dedicated and complete instrumentation system on-board a 168 kW@2100 rpm diesel engine New Holland TC 56 rice combine [7]. The developed instrumentation system was used to monitor, measure and record on real-time and on-the-go, the harvested crop yield, crop moisture content and combine harvester field performances at sub meter accuracy with the combine's latitude and longitude positions in the field. The monitored grain parameters include yield, moisture content and temperature of grain that goes into the clean grain tank while the field performance includes cutting width, cutting height, actual travelled speeds, theoretical speed, pitch and row angles, fuel consumption, drive shaft torque, field capacity and field efficiency. However, this system was very complex and required both the cables and sensors to be permanently installed on the combine. Due to the complexity in its design, the initial setting up and diagnosis on the system were very elaborate, tedious and time consuming. Furthermore, during operation it required a system controller to be in the operator console together with the operator of the combine harvester. Generally, the space inside the operator console of any combine was very limited and the presence of another system operator would give much disturbance to the combine operator during the harvesting operation in the field. Lastly, the complete system cannot be easily transferable to a different combines either of the same or different makes and models.

Currently, there is no simple, portable and rugged instrumentation system that could be directly used on any rice combine to monitor, measure and record on real time the harvested crop yield and crop moisture content. There has been a challenge to develop an accurate real-time and on-the-go monitoring system for the flow rate and moisture contents of the cleaned grain from the grain elevator into the grain tank of the combine. Furthermore, the measurement modes for the grain flow and grain moisture content by using the impact-type flow sensor and capacitance-type sensor respectively on the combines has been widely reported by previous researchers to be low in accuracy. The force measurement by the impact-type flow sensor is very much dependent on both trajectory and hitting intensity of the grain mass that is thrown by the grain elevator bucket as the bucket moves to the top position. Ideally, all the grains that is thrown by the grain elevator bucket should hit the surface of the impact plate in order for the sensor to register the actual grain flow. Any changes on the position of the impact-type flow sensor relative to the top elevator sprocket would affect the hitting trajectory of the grain and the hitting intensity of the grain mass [8]. The dielectric properties measurement by the capacitance-type sensor depends very much on the good and consistent electrical contact of grain mass with the sensing plates of the sensor. Ideally, all the grain mass that passed through the sensing plates should be moving at optimum flow rate and the flowing grain mass should be at constant bulk density, temperature and chemical composition structure in order for the sensor to register the actual grain moisture content.

This study emphasizes the design, calibration and demonstration of a simple, portable and rugged instrumentation system on-board the rice combine harvester capable of measuring, monitoring and recording on-real time the harvested rice yield while accomplishing the harvesting operation in the paddy field. The designed system is simple in operation, easily to install, portable, and transferrable to other combine harvester of different makes and models. It is also rugged and reliable to be employed in the most adverse harvesting operating conditions in the field. Relevant sensors in the developed instrumentation system was used to measure accurately the combine cutting width, combine grain elevator rotational speed, combine travel speed and position, instantaneous crop yield, grain flow and grain moisture content. The new complete instrumentation system uses wireless communication between the data acquiring unit on-board a combine harvester and the data control and storage unit at the ground base station. Such a system could be operated without requiring an additional system controller on the combine harvester during the harvesting operation. The system controller on the ground does all the controls in the operation of the instrumentation system for the required measurements. This adopted system would give better flexibility on the controls of the combine harvester by the combine operator and on the controls of the complete instrumentation on-board the combine harvester by the system controller. The communication between the data acquiring, control and storage unit is more flexible than the traditional wired network. The setup time of the complete system has been significantly reduced. The measured signals from the data acquiring unit could be easily transmitted across a distance. Thus allowing the data control and storage unit to be positioned at any convenient location in the field.

MATERIALS AND METHODS

General Features of the Instrumentation System

Figures1 and2 illustrate the main components that make-up the developed instrumentation system for measuring and monitoring combine travel speed, combine cutting width, combine elevator rotational speed, combine geo-position, the flow and moisture content of the clean harvested grain by the combine. The detail functions of the related components within the developed instrumentation system are summarized in table 1.

A special housing box was constructed to keep the National Instrument Compact Rio 9004 embedded system with NI 9221 I/O module, National Instrument touch panel component (TPC2016), Trimble AgGPS 132 DGPS receiver, two evaluation units for the SWR Solid Flow flow sensors and SWR M-Sens 2 moisture sensor. The TPC 2016was flush mounted on front wall of the box with its LCD screen exposing outside. The CompactRIO cRIO-9004 embedded system is a portable rugged industrial computer which is designed for the field applications. It is made up of a controller unit having 195 MHz processor, 512 MB of non-volatile compact flash storage,64 MB DRAM memory, one 10/100BASE-T Ethernet port, one RS232 serial port and eight slots embedded chassis for the for I/0 Modules.

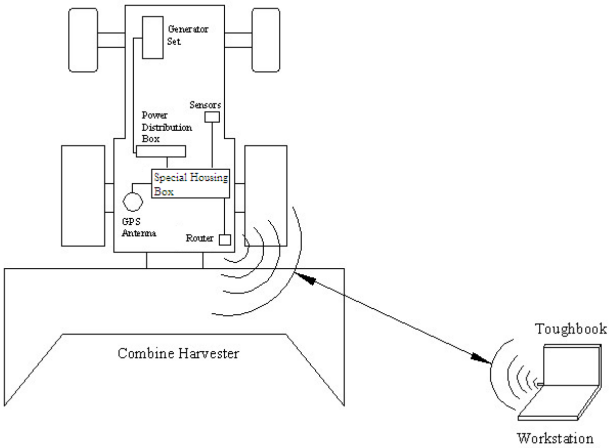


Fig 1: Simplified diagram of the complete instrumentation system.

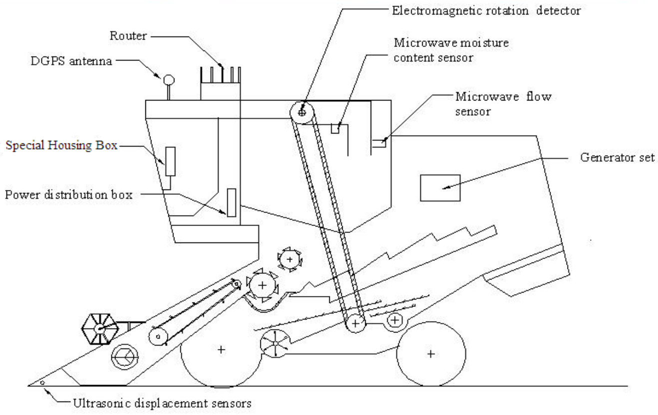


Fig 2: Locations of the various units of the instrumentation system.

Table 1. Detail functions of the respective units of the instrumentation system.

Name of Component	Function
National Instrument CompactRIOcRI-9004 embedded system with NI 9221 I/O module	Controls the acquisition,conditioning and processing the measured signals from the sensors and DGPS receiver
National Instrument TPC2016	Displays the measured data to the combine operator.
Panasonic CF-19 toughbook with in-house National Instrument LabVIEW8.6 software	Controls the acquisition, display and saving the measured data.
D-link DIR-655 router with 3 D-link ANT24-0700 antennas and a D-link DWA-140 USB adapter	Provides wireless communication between the embedded system and the toughbook.
Trimble AgGPS132 DGPS	Measures the geo-position of the combine harvester in the field.
Omron EP4A-LS200-M1-N ultrasonic displacement sensors	Measures the cutting width of the combine during harvest.
ONO SOKKI MP-810 electromagnetic rotation detector	Measures the rotational speed of the combine grain elevator
SWR M-Sens 2 moisture sensor and evaluation unit	Measures the moisture content of clean grain going into the grain tank.
SWR SolidFlow flow sensor and evaluation unit	Measures the flow of clean grain dropping into the grain tank.
HONDA EU20i generating set with the power distribution box on board	Provides the input power to run the individual units within system.

The NI 9221 I/O module with 8 analog inputs having individual input range of ± 60V and maximum sampling rate of 800 kS/s was mounted on the second slot of the compact RIO embedded chassis. Only five out of the eight analog input channels in the module were used for interfacing the available measurement sensors.

The R232 serial port (COM) and Ethernet port of the controller unit were respectively connected to the DGPS receiver and WAN port of the D-link DIR-655 router. The TPC2016 is a portable rugged industrial touch panel component that is used with the earlier mentioned embedded system. The unit has a 5.6 inch and 320 X 240 maximum revolution TFT LCD touch screen, a416 MHz Intel XScale processor, 64 MB SDRAM, 64 MB Storage memory, one 10/100 Base-T Ethernet port, two USB ports, two RS232 ports, and one RS485 port. The Ethernet port of the TPC was connected to one of four LAN port of the D-link DIR-655 route. This special housing box was located close to the diver in the operator console of the combine harvester (see figure 3).

Fig. 3: Location of the special housingbox.

The D-link DIR-655 router with 3 D-link ANT24-0700 antennas and Trimble AgGPS 132 DGPS antenna were fixed on the operator console roof using special magnetic supports. The Honda EU20i generating set was fixedat the rear left side of the combine while the power distribution box was located behind the driver seat in the operator console so that it was at close vicinity to the special housing box. The two units of Omron EP4A-LS200-M1-Nultrasonic displacement sensors were located at each sides of the combine header to measure the cutting width of combine during harvesting operation. The ONO SOKKI MP-810 electromagnetic rotation detector was directed coupled to the drive shaft of the grain elevator unit of the combine. An elbow chute unit was located right at the end of the clean grain auger to receive the grains that flow out into the clean grain tank. The SWR M-Sens 2 moisture sensor was positioned at the bottom of the horizontal portion of the elbow shape chute unit while the SWR Solid Flow flow sensor was positioned at the side of the vertical portion of the elbow shape chute unit.
The measured data from the embedded system was wirelessly transferred through the router on-board the combine to the receiver adaptor on the toughbook at the ground workstation (see figures 3 and 4).

Fig. 4: Monitoring measured parameters at the ground base station.

All the measured data by the embedded system was made to display on the TPC 2016for the interest of the operator on the combine. Concurrently, all the measured data received by the toughbook was also made to display on the monitor screen of the toughbook for the interest of the controller at the ground base station and subsequently stored inside the hard disk of the toughbook. Both theTPC 2016on the special housing box and the monitor of toughbook were programmed using Lab view Program to display the universal time coordinated (UTC) time, local time, latitude, north/south (N/S) indicator, longitude, east/west (E/W) indicator, position fix, satellites used, horizontal dilution of precision (HDOP), altitude, DGPS station ID and checksum of DGPS system, left crop position distance, right crop position distance, combine cutting width, grain flow, instantaneous crop yield, total grain, combine elevator rotational speed, grain moisture content and combine travel speed. The saved data in the hard disk of the toughbook were in ASCII format and these data could be retrieved using Microsoft Office Excel, Notepad or WordPad for the purpose of post processing the measured data.

All the available sensors in the instrumentation system were successfully calibrated in the laboratory. Figures 5 to 8 present the calibration graphs obtained with their corresponding calibration equations for the respective sensors.

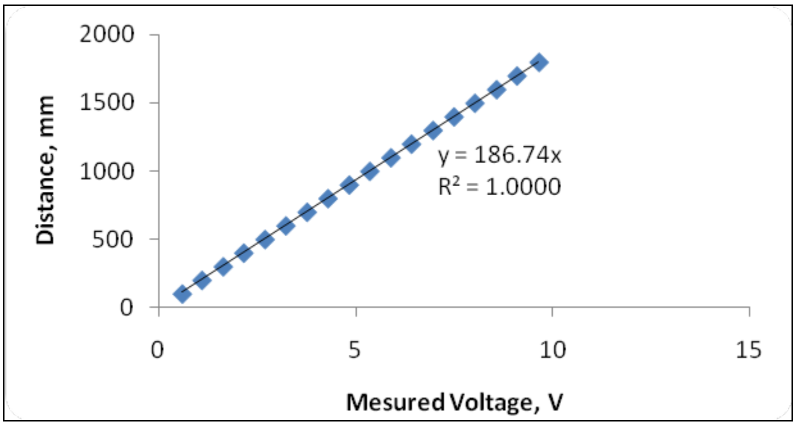


Fig. 5:Calibration graph for ultrasonic displacement sensor.

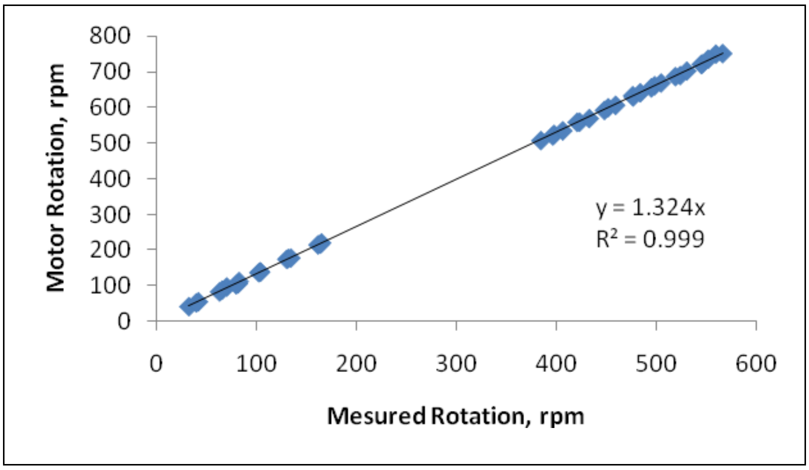


Fig. 6:Calibration graph for electronic rotation detector.

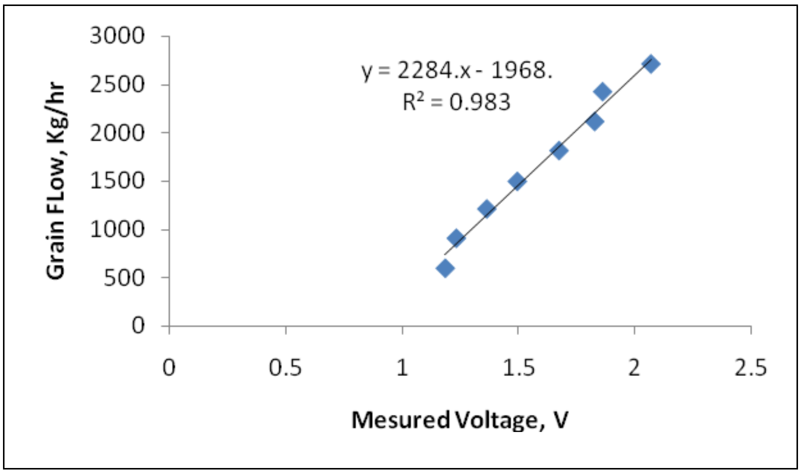


Fig. 7: Calibration graph for microwave solid flow sensor.

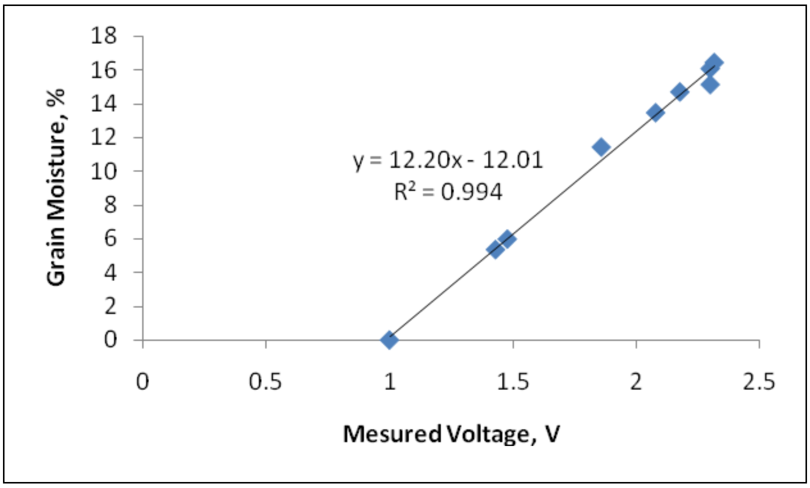


Fig. 8:Calibration graph for microwave moisture sensor.

Field Demonstration of the Instrumented Combine

Field demonstration test on the developed instrumentation on-board a combine was performed during a field harvesting operation of a two paddy plots owned and managed by the Rice Seed Processing Center under the Department of Agriculture at Sungai Burong, Tanjong Karang, Selangor. The aim of the test was to check the functionality and reliability of the developed instrumentation system on-board the combine during the actual harvesting operation. The combine was set to harvest lot T0 and followed by lot T1 on the same harvesting day. During the harvesting operation, every time the grain tank of the combine has reached to its full load capacity, the operator would drive the combine to the field side to unload harvested grains into a lorry. After completing the unloading operation, the operator would drive back the combine into the field to continue the harvesting operation from the point where the harvesting operation was stopped in the field. The harvesting operation continued with the second half of lot T0, starting with the first half of lot T1 and finishing with the second half of lot TI.

All the measured data by the instrumentation system during the harvesting operation was saved in ASCII format in the hard disk of the toughbook. These data files were retrieved by using Microsoft Excel program in the laboratory for post processing. Rearranging, trimming, and calculating tasks were conducted on the data using the spread sheet programs of Microsoft Excel. Rearrangement of the data was done by using the spreadsheet program to prepare the data file in the format required for statistical analysis and map plotting. Trimming of the data was done manually in the spreadsheet program to delete the presence of unnecessary outliers in the data set. Some of the measured parameters were used to generate the required secondary parameter based on calculation from its standard formula. SAS 9.1 software was employed to analyze the distribution and the t-test on the measured parameter data set. Finally, ArcGis9.2 software was employed to individually plot map of these measured parameters to visually illustrate their spatial variations within the harvesting areas. The GIS coordinate system in the data set was used from longitude and latitude format measured by Trimble AgGPS 132 DGPS. The data set was used to create the maps of instantaneous crop yield, combine cutting width, combine travelled speed, field capacity, combine elevator rotational speed and grain moisture the respective field lots. A polygon feature was created and digitized as a boundary to the map of the field plot using the Arc Catalog menu of the software. The data was interpolated geostatistically by Krigging technique based on the suggested variogram parameters that were derived from geostatistical analysis. The purpose of this interpolation was to produce a surface of predicted value in order to identify the surface coverage or spatial distribution of the combine parameters and grain parameters. Graph model and values were used for the Krigging process. During the Krigging process, the range map in the layer properties was set to natural break to give 3 distinct range classes.

RESULTS AND DISCUSSIONS

The complete instrumentation system was able to monitor and store all the required measured attributes in the demonstration field test done with the combine. Throughout the test duration, the embedded system, DGPS, router and all sensors within the instrumentation system functioned perfectly. The demonstration test conducted was able to fulfil the objective of checking both the operational and robustness of the instrumentation system under the actual harvesting operation with the combine in the paddy field. The wireless data transmission between the embedded system on-board the combine and the tough book at the base station could be sustained to a maximum distance of 140 m. As such, the wireless coverage is wide enough for a typical paddy field plot of 200 m width and 60 m length having the base station located on the field banks somewhere at the middle width of field plot.

Each of the field lots that was used in the demonstration test has a layout dimension of 118 m length by 91 m width and a total area of 1 .08 ha. Lot T0 is located right at the corner boundary of the tertiary canal while lot T1 is located besides lot T0 having one of its width srunning in parallel with the tertiary canal. A bank runs in the middle of the lots to give two equal size sub plots. As for lot T1, a mid drain furrow runs parallel to the middle bank in each sub plots to further divide the sub plot into two sub sub-plots. The adopted field machine patterns by the operator in operating the combine for the two lots are indicated in the combine tracking maps. For lot T0, the combine was set to follow a circuitous round corners pattern around the boundaries for two complete rounds and followed with a headland pattern from boundaries to finish harvesting the middle area of the first sub plot. The same field machine pattern was adopted in the second sub plot of lot T0. For lot T1, the combine was set to operate in the similar field machine pattern as in lot T0 with the only difference that the operations were repeated for the four sub sub-plots in lot T1(see figures 9 and 10).

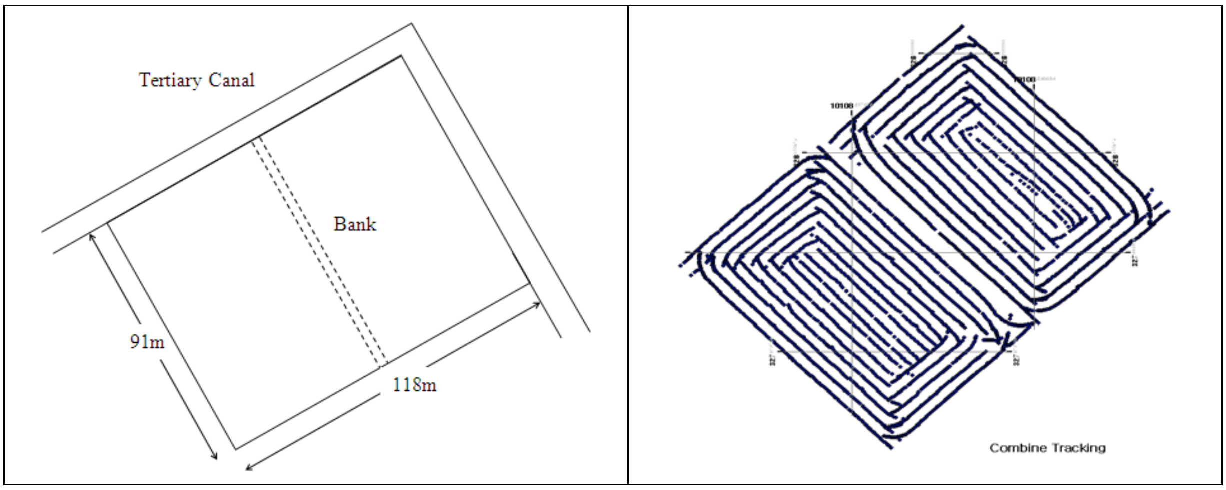


Fig. 9: Field layout and combine tracking map for lot T0.

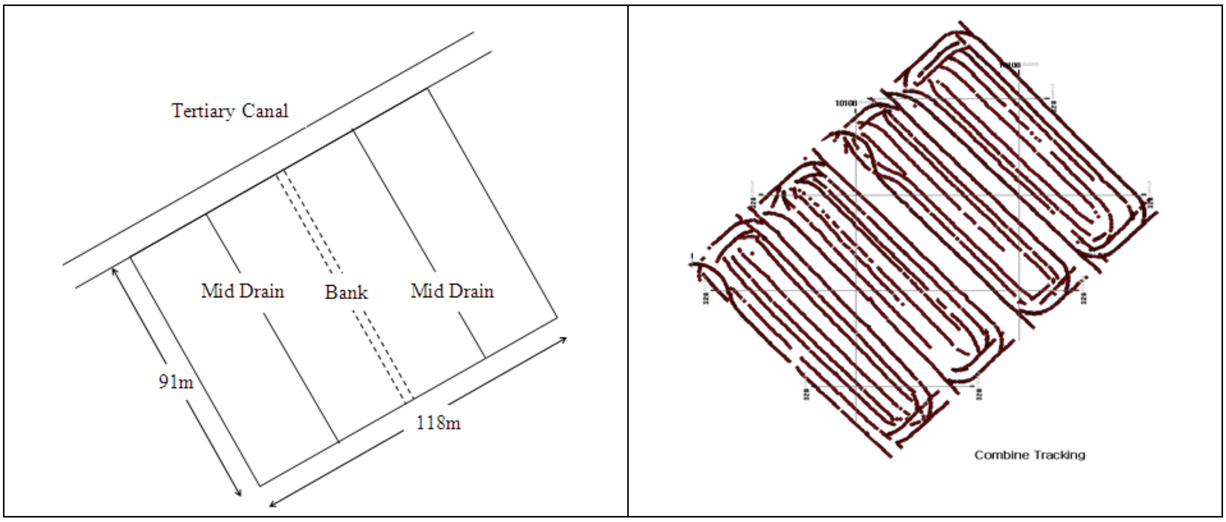


Fig. 10: Field layout and combine tracking map for lot T1.

The summarised descriptive statistics for the measures attributes for the two lots are shown in table 2. The mean differences for all the measured attributes between the two lots as indicated in table 3 were found to be highly significant at 1% probability level.

Table 2. Descriptive statistics of dataset from lots T0 and T1.

Statistical Parameter	Field Lot	Attributes					
		Combine Cutting Width, mm	Grain Moisture Content, %	Instant.Crop Yield, t/ha	Combine Elevator Rotational Speed,RPM	Combine Travel Speed, km/hr	Combine Field Capacity, ha/hr
No of Samples	T0	5654	5654	5654	5654	5654	5654
	T1	4681	4681	4681	4681	4681	4681
Mean	T0	3301.76	21.86	6.01	218.24	1.76	0.57
	T1	3240.91	20.02	5.64	219.97	2.12	0.67
Median	T0	3325.56	21.37	5.86	218.40	1.68	0.54
	T1	3306.73	19.90	5.40	220.34	2.12	0.66
Mode	T0	2274.03	20.27	5.96	217.45	1.24	0.50
	T1	2298.77	19.53	3.72	210.18	1.51	0.64
Std Deviation	T0	514.62	2.16	2.238	9.23	0.52	0.16
	T1	697.88	0.90	2.09	10.73	0.54	0.16
Std Error Mean	T0	6.84	0.03	0.03	0.12	0.01	0.01
	T1	10.20	0.01	0.03	0.16	0.01	0.01
Maximum	T0	4151.35	29.11	11.98	249.32	3.20	1.17
	T1	4152.03	25.79	12.00	260.13	3.47	1.23
Minimum	T0	1077.18	16.22	0.77	180.76	0.38	0.09
	T1	940.49	14.74	0.88	181.75	0.59	0.14
Skewness	T0	-0.77	1.34	0.29	-0.19	0.43	0.41
	T1	-0.43	0.60	0.47	-0.12	0.03	-0.07
Kurtosis	T0	0.49	1.57	-0.26	0.26	-0.76	-0.08
	T1	-1.08	3.33	0.09	-0.07	-1.14	0.11
Coefficient Variation	T0	15.59	9.91	37.24	4.23	29.57	28.68
	T1	21.53	4.50	37.02	4.88	25.67	24.44
D:Normal	T0	0.0744	0.1477	0.0345	0.0137	0.102	0.0676
	T1	0.1421	0.1405	0.0491	0.0159	0.0779	0.0201
Prob>D	T0	0.01	0.01	0.01	0.01	0.01	0.01
	T1	0.01	0.01	0.01	0.01	0.01	0.01

Table 3 .T-test of measured attributes betweenlots T0 and T1

Attribute	Mean Values		T Test			Percent Different
	Lot T0	Lot T1	Variance	T Value	Prob>|t|	T0 vs T1
Combine Cutting Width, mm	3301.76	3240.91	Unequal	4.95	0.0001	+1.84
Grain Moisture Content, %	21.86	20.02	Unequal	57.39	0.0001	+8.40
Instantaneous Crop Yield, t/ha	6.01	5.64	Unequal	8.70	0.0001	+6.18
Com. Elevator Rotational Speed, RPM	218.24	219.97	Unequal	-8.66	0.0001	-0.79
Combine Travel Speed, km/hr	1.76	2.12	Unequal	-34.01	0.0001	-20.36
Combine Field Capacity, ha/hr	0.57	0.67	Equal	-29.54	0.0001	-16.61

The mean instantaneous crop yield of lot T0 was 6.18% higher than lot T1 while the mean combine field capacity of lot T0 was 16.61% lower than lot T1. The conditions of the field and crops in lot T0 were quite wet because of the morning light rain when harvesting operation started. However, the field conditions was slightly better and the crop conditions were drier as the weather turned sunny in the afternoon when harvesting operation was conducted on lot T1. This explains why the mean grain moisture content for lot T0 was 8.40% higher than lot T1. The mean combine travel speed in lot T0 was 20.26 %lower than in lot T1 because of the wet ground conditions in lot T0.Even though, the combine mean cutting width in the harvesting operation for lot T0 was 1.84% higher than T1, the combine field capacity for the lot was still lower than that for lot T0. This was due to the fact that the magnitude of increase in combine travel speed had prominent effect than the magnitude of decrease in the combine cutting width on the final computed value for the combine field capacity. The mean combine elevator speed of lot T0 was only 0.79% higher than that of lot T1. The correlation between measured combine elevator rotational speed and measured flow of the grain coming out from the auger was computed to be 0.010 which indicates that there was no significant effect on the combine elevator rotation speed on the flow of the grain coming out from the grain levelling auger at the top of the combine grain elevator. Thus, it also indicates that the slated bar conveyor of the grain elevator was able to continuously receive and transport the grains that were delivered by clean grain auger at bottom of the combine grain elevator. In other words, the current operating handling capacity of the combine grain elevator was able to cope with the delivering capacity of the clean grain auger or the overall crop handling capacity of the combine for the harvesting operation. Normally, if these operational conditions were not met, the operation of the clean grain auger could be choked and ultimately the whole operations within the combine could be stalled. Also, the correlation between measured combine elevator rotational speed and measured grain moisture content was computed to be -0.191 which indicates that there was no significant effect on the combine elevator rotational on the grain moisture content measurement by the moisture sensor.

The dominant distribution range for instantaneous crop yield was the higher intermediate range of 5.1 to 7.5 ton/ha which respectively covered for 66.86 and 70.07% of the total area of lots T0 and T1(see figure 11 and table 4).

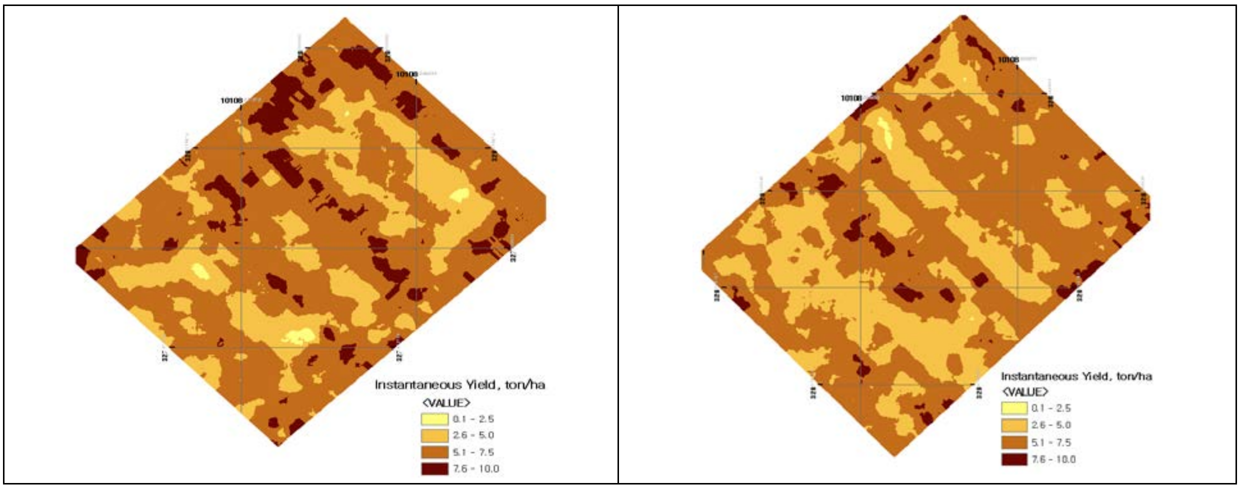


Fig. 11: Instantaneous crop yield maps for lots T0 and T1.

Table 4 . Instantaneous crop yield distributions for lots T0 and T1.

Instantaneous Crop Yield, ton/ha	Percent. of Total Area	
	Lot T0	Lot T1
0.1 – 2.5	0.35	0.11
2.6 – 5.0	20.35	23.37
5.1 – 7.5	70.42	66.86
7.6 – 10.0	8.88	9.66

The plotted maps were able to show the variations in the instantaneous crop yield within the lots and at the same time able to indicate which area locations within the individual lots having low yields for any possible remedial in-situ agronomic actions to be taken to improve the crop yield of the field plot for the next coming growing season. The possible causes of low crop yield at the identified area location might be due to low soil nutrient content, low plant populations, low percentage of crop emergence, high field losses on crops due to disease or pest, high pre harvest lost on crops due to lodged plants, and high grain losses due to machine action during harvesting. Even though there were significant differences in both instantaneous crop yield distributions and mean instantaneous crop yield values between lot T0 and T1, it was not part of the objective of this field test to determine the causes of such differences. This was because there was no monitoring and controls done throughout the growing period of the planted crops in the two field plots. These field plots were selected only for the purpose of running the demonstration test on the developed instrumentation system on-board a combine in an actual field harvesting operation.

The most dominant distribution range for grain moisture content was the lower intermediate range of 20.1% to 22.5% or lot T0 and the lower moisture range of 17.6% to 20.0% for lot T1 which respectively covered 52.44% and 65.36% of the total area for lots T0 and T1 (see Figure 12 and Table 5).

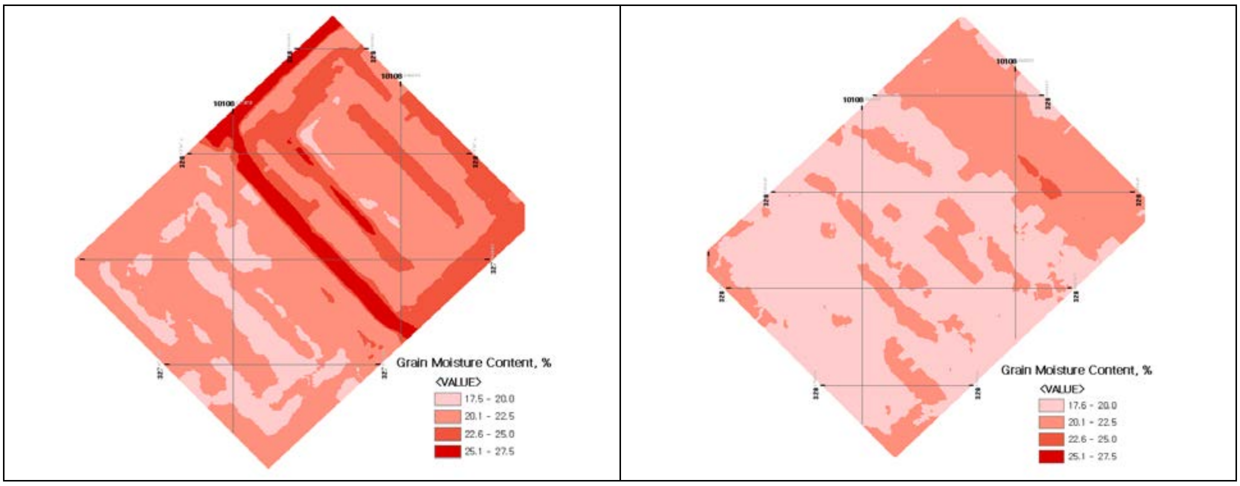


Fig. 12:Grain moisture content maps for lots T0 and T1.

Table 5:Grain moisture content distributions for lots T0 and T1.

Grain Moisture Content, %	Percent. of Total Area	
	Lot T0	Lot T1
17.6 – 20.0	10.24	65.36
20.1 – 22.5	52.44	34.37
22.6 – 25.0	22.70	0.27
25.1 – 27.5	14.62	0.00

The measured grain moisture content from lot T0 was generally higher than the measured grain moisture content from lot T1. Harvesting operation with the combine started on the first sub plot of lot T0 immediately after the slight rain shower had stopped. Thus, the crop condition within the field plot was a bit wet when it was harvested by the combine. The harvesting operation on lot T1 was conducted right after the completion of the harvesting operation on lot T0. The crop condition for lot T1 at the time of harvesting by the combine was a bit dry because the crops had been subjected to natural sun drying in the open field while waiting to be cut at the later stage of the day. The distribution pattern of grain moisture content does not visually show any possible related trend with the distribution patterns of other measured attributes maps.

Throughout the harvesting operation, the combine was consistently set to be operating at the upper cutting width range of 3501 to 4100 mm for 58.95%and 55.74% of the total area for lots T0 and T1 (see figure 13 and table 6).

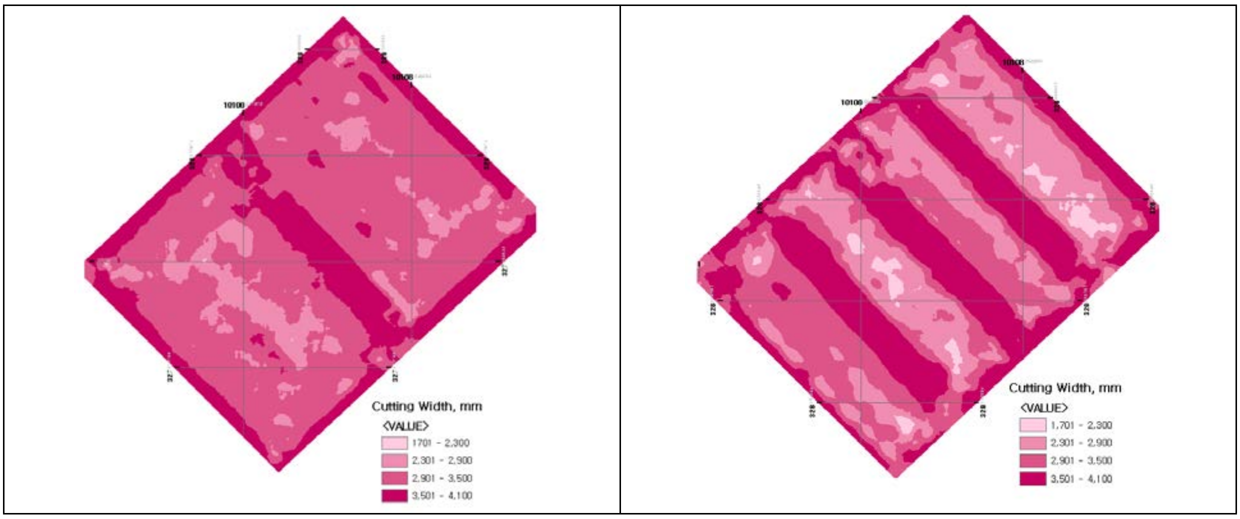


Fig. 13:.Combine cutting width maps for lots T0 and T1.

Table 6: Combine cutting width distributions for lots T0 and T1.

Combine Cutting Width, mm	Percent. of Total Area	
	Lot T0	Lot T1
1701 – 2300	0.02	1.60
2301 – 2900	5.97	15.48
2901 – 3500	35.06	27.18
3501 – 4100	58.95	55.74

The combine was operated at a greater cutting width in the beginning of the harvesting operation especially along the sub plot side perimeter boundary and at reduced cutting width as the combine moved to follow the circuitous round corners pattern around the field perimeter and with much smaller cutting width as the combine moved to follow the headland pattern at the sub plot center. The combine was dominantly operating at the lower travel speed range of 1.1 to 2.0 km/hr for 73.73% and 63.32 % of the total area in lots T0 and T1 (see figure 14 and table 7).

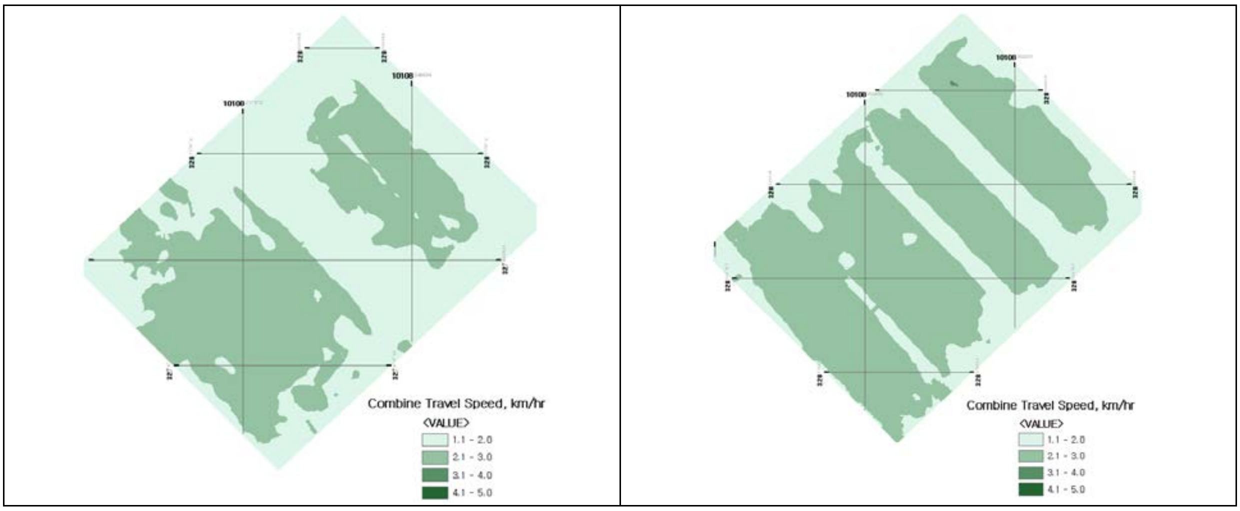
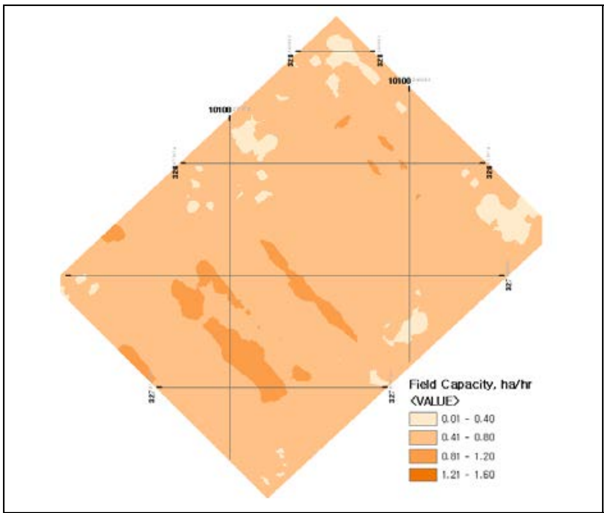


Fig. 14: Combine travel speed maps for lots T0 and T1.

Table 7: Combine travel speed distributions for lots T0 and T1.

Combine Travel Speed, km/hr	Percent. of Total Area	
	Lot T0	Lot T1
1.1 – 2.0	73.73	63.32
2.1 – 3.0	26.27	36.65
3.1 – 4.0	0.00	0.03
4.1 – 5.0	0.00	0.00

The combine was operating at a slower travel speed at the beginning of the harvesting operation when cutting width was greater and later changed to faster travel speed when the cutting width became smaller as the combine moved to follow the circuitous round corners pattern around the boundary and then the headland upon approaching the sub plot center. The harvesting operation throughout the whole lot T0 was generally conducted at much slower combine travel speed than in lot T1. The distribution pattern of combine travel speed map visually shows similar trend with inverse relation to the distribution pattern of combine cutting width map to indicate that the combine was moving at lower travel speed when the harvesting operation was at greater cutting width. The combine was dominantly operating at the lower intermediate field capacity range of 0.41 to 0.80 ha/hr at 91.63% and 87.78% of the total areas in lots T0 and T1 (see figure 15 and table 8).



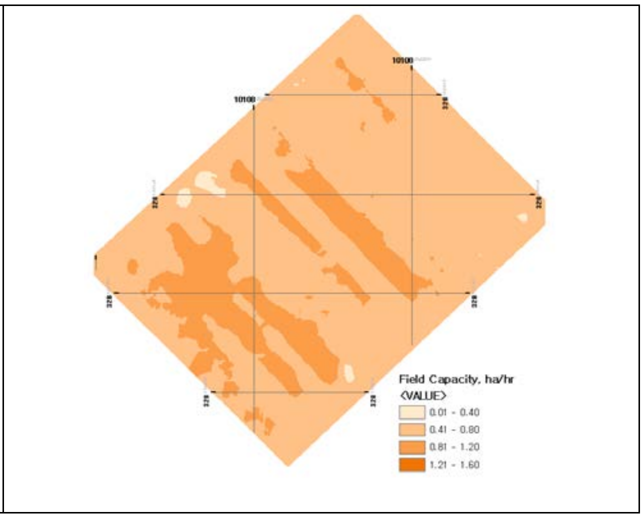


Fig. 15: Combine field capacity maps for lots T0 and T1.

Table 8 : Combine field capacity distributions for lots T0 and T1.

Combine Field Capacity, ha/hr	Percent. of Total Area	
	Lot T0	Lot T1
0.01 – 0.40	3.03	0.47
0.41 – 0.80	91.63	87.78
0.81 – 1.20	5.34	11.75
1.21 – 1.60	0.00	0.00

Harvesting operation with the combine in lot T0 was generally conducted at a lower field capacity than in lot T1. The distribution pattern of field capacity map does not visually show any possible related trends either with the distribution patterns of combine cutting width map or the distribution pattern of combine travel speed because of the collective combinational effects of travel speed and cutting width on the calculated field capacity values. Also, the combine was dominantly operating at the lowest elevator rotational speed range of 201 to 225 RPM at 98.65 and 81.89% of the total areas in lots T0 and T1 (see figure 16 and table 9). However, there were not much spread in the variations of combine elevator rotational speed for in the two field lots. Besides, distribution pattern of combine elevator rotational speed map does not visually show any possible related trend with the distribution patterns of other measured attributes maps.

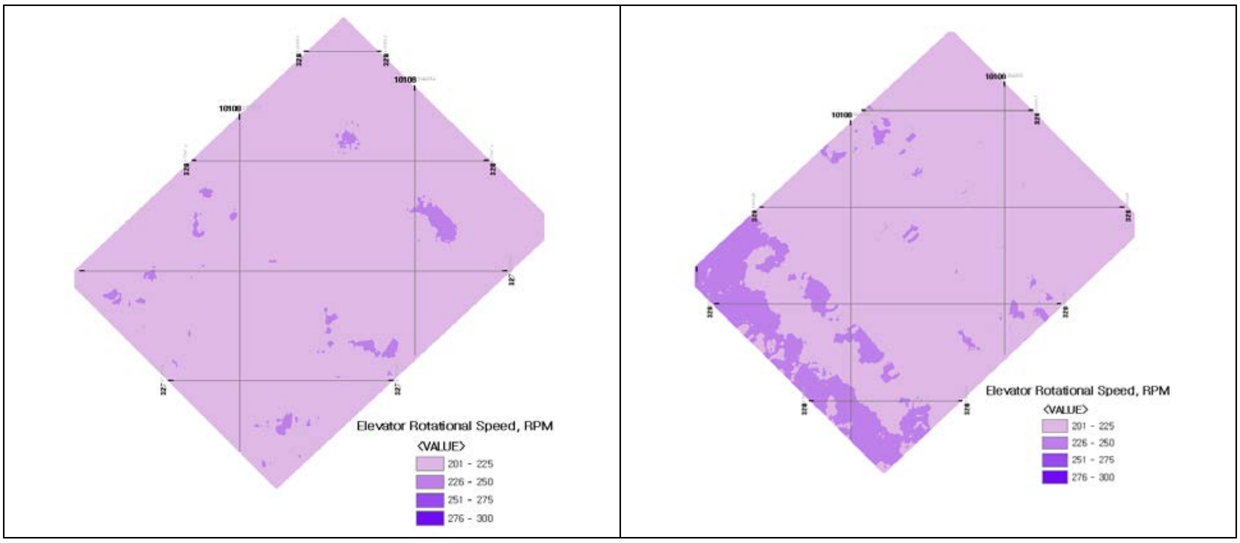


Fig. 16: Combine elevator rotational speed maps for lots T0 and T1.

Table 9: Combine elevator rotational speed distributions for lots T0 and T1.

Combine Elevator Rotational Speed, RPM	Percent.of Total Area	
	Lot T0	Lot T1
201 – 225	98.65	81.89
226 – 250	1.35	18.11
251 – 275	0.00	0.00
276 – 300	0.00	0.00

CONCLUSIONS

A reliable portable wireless yield monitoring system for rice combine had been successfully designed, developed, interfaced, calibrated, and field demonstrated. The system was able to record, display, and store the measured data on the geo-position of the combine, cutting width of combine, travel speed of combine, rotational speed of the combine grain elevator, moisture content and flowrate of the clean grain going into the combine grain tank on-real time at a sampling intervals of one second. The router with the 3 antennas that was connected to the embedded system on-board the combine were able to provide reliable wireless communication with the adaptor that was connected to the toughbook at the ground base station. The individual calibrated sensors presented excellent measurement linearity with R^2 values within 0.98309 to 1.000 ranges. Maps of combine tracking, instantaneous crop yield, grain moisture content, combine cutting width, combine travel speed, combine elevator rotational speed and combine field capacity could be easily plotted using ArcGis 9.2 software with the data obtained from the field demonstration test. The plotted crop yield map was able to show the variations of crop yield within the field plot and could indicate the area locations within the field plot which has low yield for possible remedial in-situ agronomic actions in the coming cropping season.

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