Design, development and field evaluation of a map-based variable rate granular fertilizer application control system

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Abstract: Site-specific application of agricultural chemicals including granular fertilizers is an effective way of resource saving and environmental protection. The objective of this research was to develop and to evaluate the performance of a map-based variable rate row crop granular fertilizer placement system. The applicator system consists of an AVR microcontroller for controlling the driving step motor of the fertilizer metering screw and a ground driven wheel integrated with a rotary encoder for the applicator displacement and speed measurement. Initially, the applicator was calibrated in laboratory to derive a relationship among the step motor speed, the input frequency, and the rate of fertilizer application as a function of metering screw rotational speed. Laboratory evaluation included measurement of the lag time while changing the application rate from low to high and vice versa. In the field tests, a factorial experiment with a split-split design was used to investigate the effects of fertilizer type (urea and triple super phosphate), applicator forward speed (3, 6 and 9 km/s) and application rate (75, 125 and 175 kg/ha) on precision of application rate (the percent of deviation between actual and target rates). The results showed that the forward speed and the application rate both had significant effect on precision of application rate, while fertilizer type had no significant effect. The precision of application rate decreased when forward speed and application rate were increased.

Keywords: precision agriculture, travel speed, fertilizer type, application rate

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1 Introduction

Precision agriculture is an emerging technology for improving crop production inputs like fertilizer, herbicide, seed, etc. on a site-specific basis to optimize crop production based on in-field variability to reduce waste, increase profits and maintain the quality of the environment (Morgan and Ess, 2003). Farmers practicing precision farming may experience the enhanced quality and quantity of their products due to better adjustment of production inputs to crop needs. Paz et al. (1998) showed that reduction in N-fertilizer consumption along with higher yield is accessible by implementing variable rate application. The increase of the rate of fertilizer generally increases the crop yield up to an optimum level, but extra fertilizer is less utilized or mobilized (Tola et al., 2008). Granular fertilizers need to be delivered at the prescribed application rates to accomplish the desired outcome of correcting within-field variations in plant nutrients (Swisher, Borgelt and Sudduth, 2002).

Variable–rate technology (VRT) used in conjunction with the global positioning system (GPS) has become a common practice implemented by precision agriculture (PA) practitioners (Fulton et al., 2005). The VRT appears to provide a method for improving input use efficiency by applying near–optimum rates based on local soil conditions and crop requirements. This reduction of over–application and under–application of inputs enhances productivity and profitability while reducing environmental impacts. There are two basic methods for implementing variable-rate application (VRA): Map-based VRA and Sensor-based VRA (Morgan and

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Ess, 2003). Map-based VRA systems adjust the application rate of a crop production input based on information contained in a digital map of field properties, while sensor-based VRA systems use data from real-time sensors to match inputs to the needs of the soil and crop. For variable rate application of fertilizers, map-based methods are favored over the sensor-based ones due to the lack of sufficient sensors for real-time monitoring of soil and crop conditions. The technology for VR fertilization should be able to minimize over- and under-fertilization. A granular VR fertilizer application system has to apply the right amount of fertilizer on different field spots according to the available soil fertility (Maleki et al., 2008) maps. Various studies have shown that there is high variability of soil nutrients even in small areas of a field (Dhillon et al., 1994; Raun et al., 1998; Mouazen et al., 2007a, b). Hence, fertilizer application should be adapted to treat as small an area as possible to meet the field requirements successfully. Therefore, VR fertilizer application needs to involve the use of fertilizer drills rather than centrifugal spreaders because the aim should be the accuracy of placement rather than treatment width (Maleki et al., 2008).

A review of the available literature revealed that most of the VR fertilizer application studies have focused on granular or liquid fertilizer spreaders rather than fertilizer placement drills. Therefore, the objective of this study was to develop and evaluate the performance of a map-based variable rate row crop granular fertilizer placement system.

2 Materials and methods

2.1 Granular fertilizer application system

A multi-flight granular material metering screw as designed by Jafari (1991) was used as a variable rate fertilizer applicator. A 12 V, 2 A step motor (Model: 103H7123) made by Sanyo Denki, Japan was used as the power unit for driving the screw applicator. An assembly of a small scale fertilizer hopper and metering screw mounted on a frame (Figure 1) was used for both laboratory and field tests.

For incremental measurement of the discharged granules during the laboratory tests, an electronic weighing scale was developed by using a single point loading type full bridge load cell made by BCM Sensor Company of Belgium with the nominal capacity of 5 kg. The weighing data was measured at 1,000 Hz sampling rate and sent to a data logging computer.

Figure 1 Fertilizer hopper and metering screw assembly used for laboratory and field tests

A floating ground-driven wheel as shown in Figure 2 was used for accurate measurement of tractor displacement and ground speed during the field tests. A solid rubber tire mounted on a steel rim, rather than a commonly used pneumatic tire, was used to eliminate the errors associated with variations of inflation pressure on speed measurement. The floating arm of the wheel was equipped with a suspension spring and a shock absorber to ensure constant ground contact and to dampen fluctuations due to natural unevenness of field surface. The rotation of ground wheel was transmitted by a flexible cable to an incremental encoder (Model E50S8) made by Autonics® Company to generate electrical pulses proportional to the wheel angular displacement.

2.2 Electronic control system

An AVR micro controller model ATMEGA16 was used as the main controller for desirable control of the fertilizer metering system and data acquisition. For reduction of any interference in the operation of the main controller during the starting of the step motor, an ATMEGA8 micro controller was connected as a slave to the main controller through a SPI connection. This micro controller acted independently in controlling the

Figure 2 Two views showing the components of ground-driven wheel used for measurement of tractor travel speed and displacement.

rotational speed of the step motor. Code Vision AVR software and C programming language were used for writing the required programs. In Code Vision software, terminal media was used for visualization and storage of the input data to the computer.

For calculation of tractor displacement, direction and velocity, the number of pulses generated by the rotary encoder were counted and analyzed by the main controller. The operator used a sound alarm to provide more accurate speed control. The designed circuit has the capability of mounting a LCD monitor for observing all of the system data.

A MOSFET transistor (No. IRF 540) was used to generate the required voltage for driving the stepper motor. An AD7730 analog to digital converter was used to amplify the load cell voltage. The main controller and the stepper motor driving circuit board are shown in Figure 3.

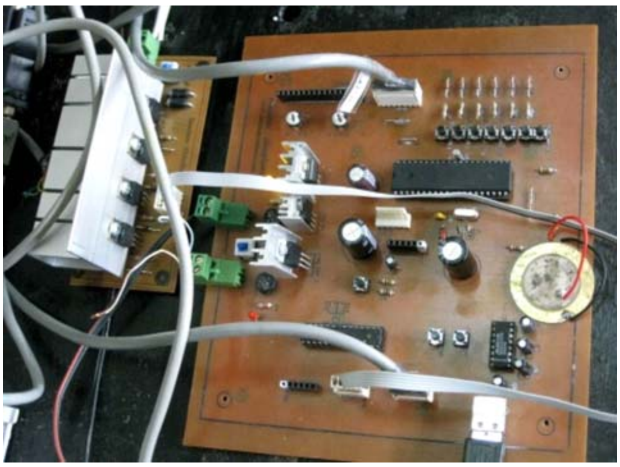

Figure 3 The main controller and the stepper motor driving circuit board

A process diagram of the fertilizer applicator microcontroller is shown in Figure 4. At the first step, the distance traveled and the speed of the fertilizer applicator is computed. Then, by comparing the fertilizer application map data, stored as a 3-dimentional matrix (planting row x distance traveled on each row x application rate) stored in EEPROM memory with the calculated position and speed, the required stepper motor revolutions is computed and the result is sent to Atmega8 microcontroller via SPI port. While traveling on a row, after a certain displacement and entering a new application zone, the fertilizer rate changes according to the application map. By passing over parallel and side-by-side planting rows, the whole field is covered. Therefore, at the headlands, the new planting row

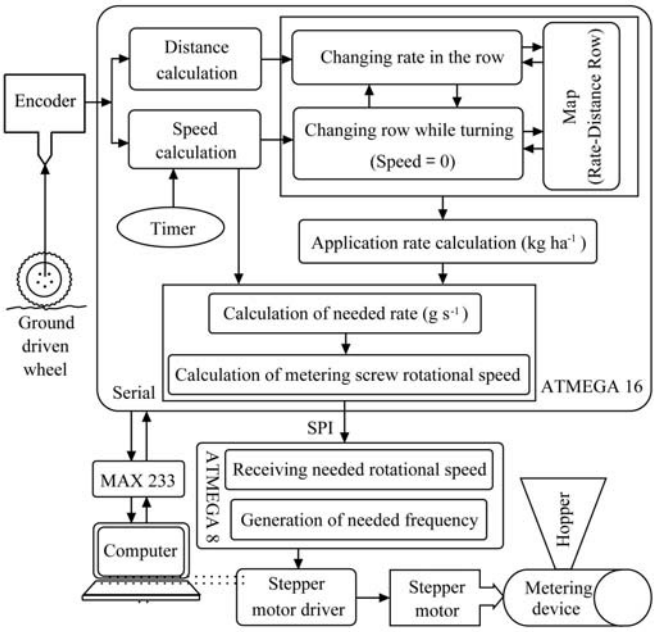

Figure 4 Process diagram of the applicator controlle

specifications given by the application map should be recognized by the controller. The controller software using the encoder data accomplished this task.

2.3 Laboratory test and evaluation

For calibration of the metering screw revolutions with the stepper motor input frequency, the elapsed time for 100 revolutions of the driving motor at various input frequencies were determined by using an odometer and a stopwatch. Then, using the calibration data, the number of revolutions per minute was related to the driving frequency. The result was programmed in the stepper motor controller in order to generate the proper frequency for the desired motor speed.

As any specific frequency in micro controller for driving the stepper motor is generated by application of delay between pulses, the required delay time for obtaining different levels of stepper motor rotational speed was measured and recorded.

By accurate weighting of the amount of granular fertilizer discharged during one-minute intervals at different motor speeds, a calibration curve between the motor speed and material discharge rate was derived.

For determination of the delay time due to sudden change of fertilizer discharge rate, the load cell readings at each millisecond were recorded during an interval in which the discharge rate was suddenly changed. By passing two separate best fit lines over the load cell data pertaining to before and after the change of discharge rate (discarding the data points during the transition zone), the intersection point of the two lines was determined. The difference between the actual time of triggering the change and coordinate of the intersection point on the time axis was considered as the estimated delay time.

2.4 Field evaluation tests

Calculation of traveled distance: by calculating the mean values of generated pulses by the encoder of the ground wheel passing ten times over a 30 m test track, the calibration factor for conversion of pulses to traveled distance was calculated (315.85 pulses/m).

Evaluation of the VR applicator performance: in order to evaluate the performance of the VR applicator in field conditions, continuous arrays of collecting buckets made from canvas fabric, were made and installed along the planting rows as shown in Figure 5. Each collecting unit acting as a patternator for measuring the applicator discharge rate was 30 m long and 0.25 m wide and was subdivided into sixty 0.5 m long buckets.

The accuracy index was the percent of applicator error in the amount of discharged fertilizer compared to the target value as calculated by the following formula:

$$\text{Applicator Error (\%)} = ((\text{Target weight} - \text{Discharged weight}) / \text{Target weight}) \times 100$$

Figure 5 Arrays of patternators made of canvas for measuring the discharge rate of fertilizer along each planting row. Each array was made up of thirty 50 cm long, 25 cm wide buckets

2.5 Experimental design

A factorial experiment with split-split plot design was used for conducting the field evaluation tests and statistical data analysis was performed by using SPSS package. The main factor was fertilizer type (two levels: triple super phosphate and urea), the sub-factor was travel speed (three levels: 3, 6 and 9 km/h) and the sub-sub-factor was application rate (three levels: 75, 125 and 175 kg/ha). According to the experimental design, the application map was written as a 3-dimensional matrix and it was saved in controller memory through the computer interface. During the field tests, the fertilizer applicator mounted on a MF285 tractor applied the test fertilizers according to the application map as read by the controller. The discharged fertilizer was collected in the patternator buckets as shown in Figure 6.

Figure 6 Collection of test fertilizers in the patternator buckets along the experimental plots during the field trials

3 Results and discussion

3.1 Laboratory tests

Calibration of the metering screw: The best-fit line relating the rotational speed of the stepper motor driving the fertilizer applicator metering screw to its input signal frequency is shown in Figure 7.

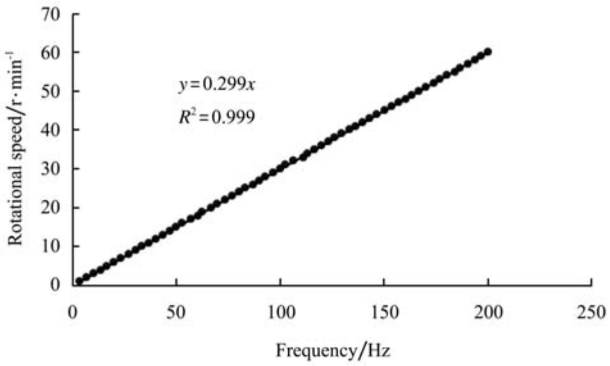

Figure 7 Calibration curve relating stepper motor rotational speed with input frequency

Calibration of delay time in pulse generation with stepper motor rotational speed: the equation of best-fit regression cure relating the required delay time for pulse generation to the motor rotational speed of the stepper as shown in Figure 8 was derived and it was entered into the micro controller algorithm.

Calibration of motor speed with material discharge rate: The calibration curves relating fertilizer metering screw rotational speed with material discharge rate for urea and triple super phosphate (TSP) fertilizers are shown in Figure 9 and Figure 10, respectively.

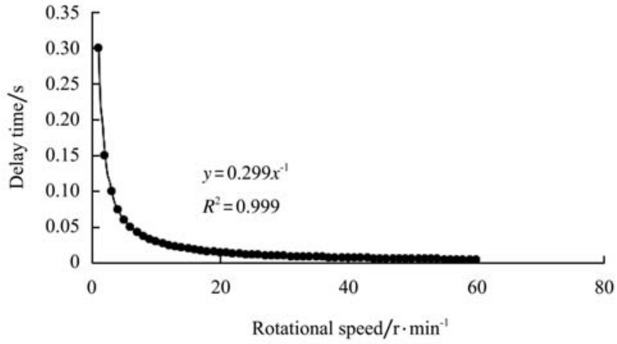

Figure 8 Calibration curve relating the required delay time in pulse generation with stepper motor rotational speed

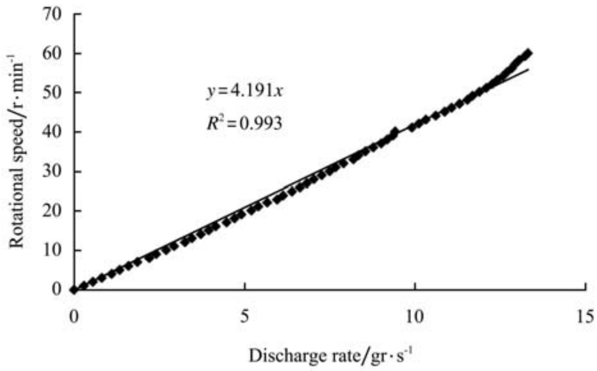

Figure 9 Calibration curve relating stepper motor rotational speed with discharge rate of urea fertilizer

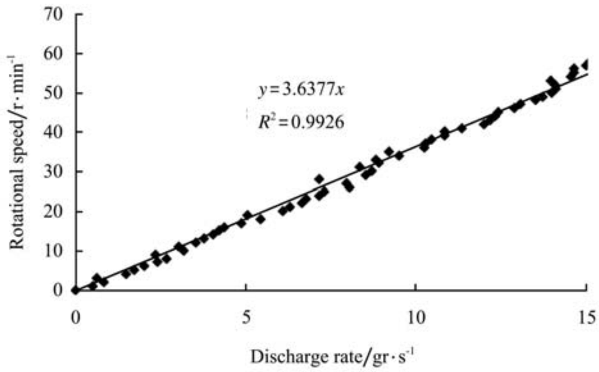

Figure 10 Calibration curve relating stepper motor rotational speed with discharge rate of triple super phosphate (TSP) fertilizer

Applicator delay time at sudden change of discharge rate: the difference between the actual time of triggering the change and the coordinate of intersection point on the time axis of Figure 11 and Figure12, was calculated as the delay time (in seconds) for changing the motor speed from 10 to 50 rpm and from 50 to 10 rpm for increasing or decreasing the discharge rate, respectively. The results (Figure 13) indicate that the delay time is significantly greater (p<0.01) when the discharge rate is changed from a lower to a higher value (0.22 s) than changing from higher to lower value (0.15 s). This could be attributed to the inertial effect of fertilizer mass as well as the rotational inertias of stepper motor rotor and metering screw. There was a significant difference (p<0.05) between the delay times of two fertilizer types which could be the result of the higher flow ability (lower angle of repose, 20.2° compared to 22.7°) of urea compared to TSP.

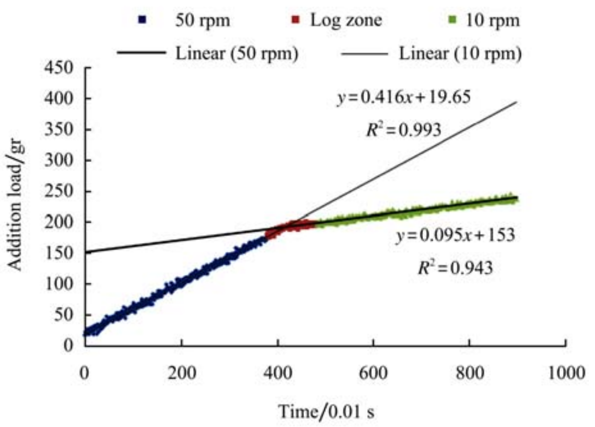

Figure 11 Intersection point of the two lines fitting the load cell data at two metering screw rotational speeds, 50 and 10 rpm, respectively

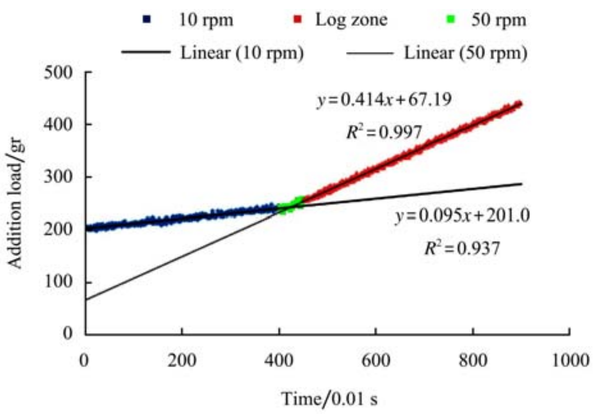

Figure 12 Intersection point of the two lines fitting the load cell data at two metering screw rotational speeds, 10 and 50 rpm, respectively

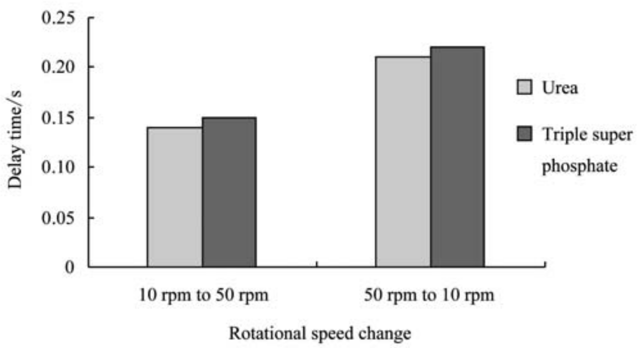

Figure 13 Mean values of applicator delay time for changing fertilizer type and discharge rate

3. 2 Results of the field tests

Analysis of variance on the field experiment data showed that the effects of applicator travel speed and application rate on accuracy of fertilizer application were statically significant, while the effect of fertilizer type was not significant.

Comparison of mean errors for the effect of travel speed as given in Table 1 shows that the percent of application error at travel speed of 9 km/h is significantly larger than the other two lower speeds of 3 and 6 km/h.

Table 1 Effect of travel speed on accuracy of fertilizer application

Travel speed/km • h^{-1}	Mean error/%
4	4.42^{b}
6	5.24^{b}
9	6.55^{a}

Notes: Means followed by the same letter are not significantly different at 5% level using LSD test.

Comparison of mean errors for the effect of fertilizer application rate, as given in Table 2 shows that the percent of application error increases with the increasing application rate. These phenomena could be attributed to several factors including the increasing transition distance from one application rate to another at higher travel speeds, incomplete filling of metering screw slots at higher rotational speeds needed for higher application rates and higher travel speeds. Two suggestions for improving the performance of the metering system include: (a) employment of an application controller with the capability of looking ahead on the application map for advanced triggering of the application rate change with increasing the travel speed. This look-ahead procedure takes into account the time required for the metering device to change a flow rate after a decision is made to change the application rate. And (b) using a larger diameter feeding screw with deeper slots in order to have larger feed rates at lower rotational speeds. The overall mean values of application rate errors for urea and TSP fertilizers were 5.36 and 5.45%, respectively. This non-significant difference indicates that the variable rate applicator performs similarly for both fertilizer types.

Table 2 Effect of application rate on accuracy of fertilizer application

Application rate/kg • ha^{-1}	Mean error/%
75	4.12^{b}
125	5.71^{a}
175	6.37^{a}

Note: Means followed by the same letter are not significantly different at 5% level using LSD test.

4 Conclusion

Field evaluation tests showed that the developed VR fertilizer applicator was successfully able to respond to the target discharge rates with small delay time and acceptable accuracy. The overall mean value of application rate error was about 5.4%. In the most extreme case (highest discharge rate and highest travel speed), the application rate error was 9% equivalent to 15 kg/ha. With some compromise in travel speed, this VR fertilizer applicator could be integrated with row crop planters and seed drills to optimize the consumption of high demand crop fertilizers based on prescription maps.

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