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# 입제비료 살포기의 출구조절에 의한 균일도의 분석과 제어

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# Analysis and Control of Uniformity by the Feed Gate Adaptation of a Granular Spreader

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## Abstract

A method was proposed which employed control of the drop location of fertilizer particles on a spinner disc to optimize the spread pattern uniformity. The system contained an optical sensor as a feedback mechanism, which measured discharge velocity and location, as well as particle diameters to predict a spread pattern of a single disc. Simulations showed that the feed gate adaptation algorithm produced high quality patterns for any given application rate in the dual disc spreader. The performance of the feed gate control method was assessed using data collected from a Sulky spinner disc spreader.

The results showed that it was always possible to find a spread pattern with an acceptable CV lower than 15%, even though the spread pattern was obtained from a rudimentary flat disc with straight radial vanes. A mathematical optimization method was used to find the initial parameter settings for a specially designed experimental spreading arrangement, which included the feed gate control system, for a given flow rate and swath width.

Several experiments were carried out to investigate the relationship between the gate opening and flow rate, disc speed and particle velocity, as well as disc speed and predicted landing location of fertilizer particles. All relationships found were highly linear ($r^2 > 0.96$), which showed that the time-of-flight sensor was well suited as a feedback sensor in the rate and uniformity controlled spreading system.

**Keywords :** Variable rate application, Uniformity control, Precision agriculture, Optimal pattern, Coefficient of variation

## 1. Introduction

The application of dry granular materials such as fertilizers, herbicides, and pesticides has been traditionally performed with equipment that was intended for constant application rates. The quality indicators of granular applicators are the application rate, in kg per hectare and the uniformity, expressed as a percentage. The desired application rate is chosen by the farm manager and depends on the crop, its growth stage, soil and environmental conditions. The uniformity is usually expressed in a statistical coefficient of variation (CV), the standard deviation of the (simulated) overlapped spread pattern divided by the mean. The spread pattern uniformity (CV) is ideally close to zero (which would imply perfect uniformity) but in practice, it can deviate significantly from zero. Reasons are inferior spreader designs, such as the single disc spreader, poorly adjusted spreaders, unfavorable weather conditions, and human error. Uneven application can lead to over dosage, causing material wastage, burnt crops, and potential environmental hazards, which can be seen in the field in the form of 'streaks' (Helms et al., 1987). Under application can lead to nitrogen deficient plants

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and limited growth.

In ground-based application predominantly spinner disc spreaders are used. Spinner type spreaders are attractive because they can cover large areas effectively; they are simple in design, reliable, inexpensive, robust, and require little maintenance. They can produce a good pattern for constant application rates if properly overlapped and calibrated. An alternative, developed in recent years, is pneumatic application where the granular material is transported through air tubes and delivered to dividers. A comparison in performance of spinner type spreaders and pneumatic spreaders is given in Fulton et al. (2004).

Fulton et al. (2001) performed a large-scale investigation on the rate and uniformity of a spinner type spreader using the ASAE 341.2 standardized collection tray method. The spreader was started at a low application rate of 56 kg/ha, which was gradually increased to the maximum rate of 168 kg/ha. The resulting spread pattern changed from a desirable Gaussian (bell shape) at the low application rate to an M-shape at the medium setting to a very undesirable W-shape at the highest application rates. M-shapes and W-shapes make producing a uniform overlapped pattern virtually impossible and have a devastating effect on the pattern robustness (Grift, 2000). Other effects on spread pattern uniformity of a spinner type spreader are spinner height and PTO speed (Parish, 2002a), as well as spreader fill level (Parish, 1999a). Parish (2002b) confirmed the flow rate effect on spread pattern uniformity. Kweon and Grift (2006) developed feed gate adaptation method using an optical sensor to eliminate uniformity variability and showed the method is capable of producing high-quality patterns for any given application rate in simulations.

The studies by Fulton, Parish and Kweon have shown that the spinner type spreader is not directly suited for Variable Rate Application of fertilizer unless the drop location of the particles can be adjusted in real time. Such adjustments are present in some spreaders, such as in the Vicon Rotaflow design. A Rotaflow spreader contains control levers for application rate setting as well as uniformity setting by varying the drop location of the material through rotating the gates about the centers of the discs.

In the Rotaflow design, the gate adjustments are made manually during calibration tests. This research aims to replace this manual adjustment by a feedback-controlled system that automatically finds the correct gate angle setting for any chosen application rate at an optimal uniformity.

The objectives of this study were to evaluate the performance of the feed gate adaptation algorithm developed by Kweon and Grift (2006) using a dual disc spreader type test bed, and to develop a generic platform which allows implementing feed gate control algorithms.

## 2. Materials and Methods

The first step in studying the effect of fertilizer mass flow on the spread pattern was to simulate the particle trajectories after being dropped from a segmented gate, which opens tangentially with respect to the disc center.

Figure 1 shows the dimensions of a segment orifice gate described by $r_b$ and $r_e$, the inner and outer radii of the segment, $\phi_d$ is the segment gate angle which controls the flow rate, and $\phi_o$ is the position of the segment orifice gate with respect to the travel direction (the right rotation is signed as a positive angle, and the left rotation is signed as a negative angle from the travel direction).

Figure 2 shows the simulated particle trajectories for gate angle of 15 deg and 50 deg representing the minimum and maximum segment angle, respectively. As the segment angle increases, the flow onto the disc increases in the disc's rotational direction, affecting the pattern's left side in

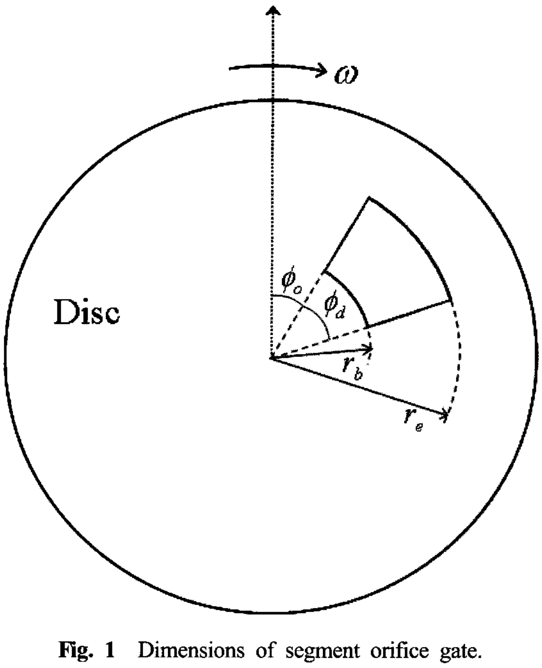

**Fig. 1** Dimensions of segment orifice gate.

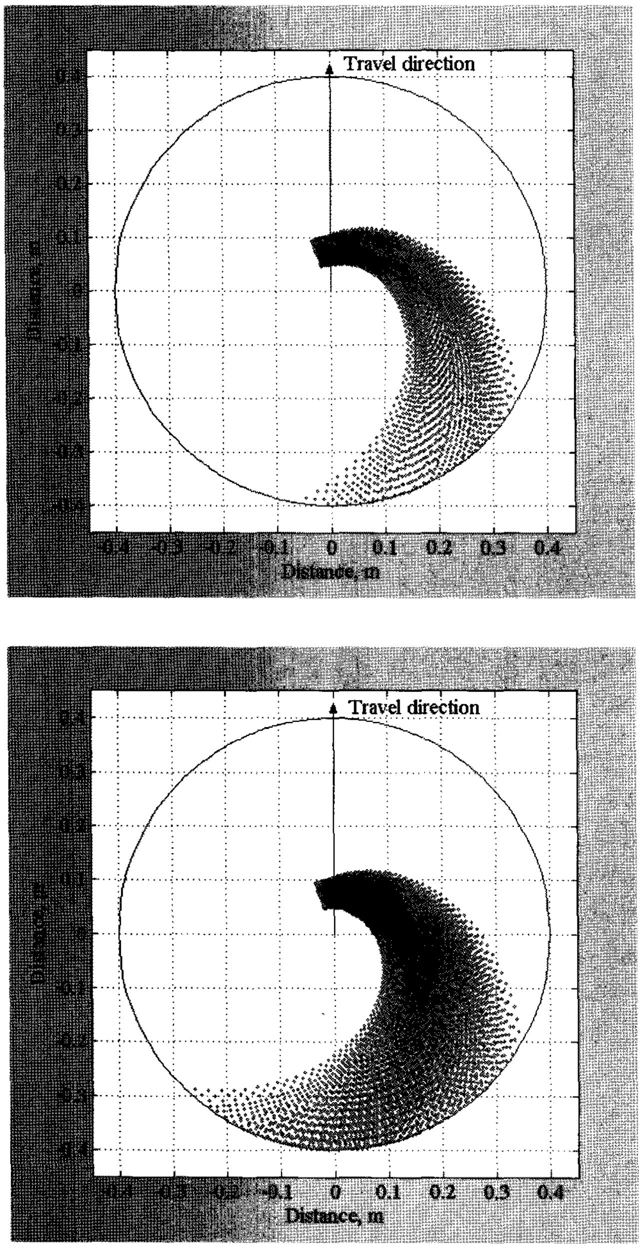

**Fig. 2** Identical particle flows on a disc with gate angle of 15 deg (left) and 50 deg (right).

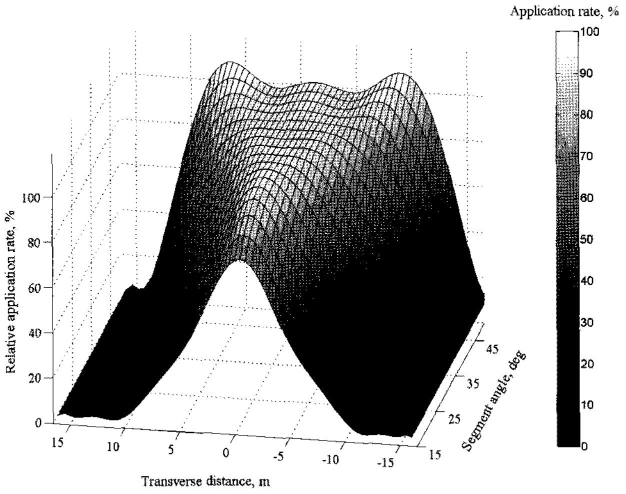

**Fig. 3** Simulated transverse spread pattern from dual discs showing an ideal Gaussian at a low flow rate of 15 deg segment angle and an M-shape at a high flow rate of 50 deg segment angle (Kweon and Grift, 2006).

the field. The second opposing disc is assumed to have the same characteristics in the mirror direction. The disc and particles characteristics used in this simulation were: the disc rotational speed = 1000 RPM; the disc radius = 0.4 m; $r_b = 0.05$ m; $r_e = 0.1$ m; $\phi_0 = -20$ deg; the friction coefficient of the vane = 0.2, and the friction coefficient of the disc = 0.2. For simplicity, identical spherical particles were assumed accelerated along a straight radial vane on a flat disc to comply with the model from Inns and Reece (1962). The particle positions corresponding to the segment orifice gate area were generated by a stepwise increase of 5 mm and 2.5 degrees for the particle initial drop location and angle on the disc, respectively.

It is clear from the simulation that the varying mass flow has a pronounced effect on the discharge location of the particles and consequently, on the resulting spread pattern.

The second step was simulating the trajectories of particles in air. Figure 3 shows the simulated spread pattern of a dual disc spreader where the pattern from a single disc (Fig. 2) was combined with a mirror image pattern from the second disc (Kweon and Grift, 2006). The landing locations were computed using a ballistic model (Mennel and Reece, 1963), which accepted the simulated discharge velocity and location as well as the particle diameter as inputs.

Grift (2000) claimed that the most desirable spread pattern is Gaussian shaped and indeed the pattern at a low flow rate is similar in Figure 3. However for higher flow rates, the pattern becomes severely distorted to an undesirable M-shape at the maximum gate angle (maximum flow rate). In this figure, the maximum application rate at the 50 deg segment angle was considered as 100% relative application rate.

A feed gate adaptation algorithm, which was based on simulating the overlapped spreading pattern for a large number of gate settings and judging the quality of the pattern, was developed using three uniformity control criteria (Kweon and Grift, 2006).

The feed gate adaptation method has shown that the M-shape effect can be avoided by finding the optimal gate settings according to the three criteria.

## A. Implementation of Feed Gate Adaptation Algorithm

In the feed gate algorithm development, the inputs for the ballistic model, which predicted the landing locations, originated from simulating particle trajectories on a disc, resulting in discharge velocities, locations and particle diameters. In the validation, these values are obtained from a sensor, developed by (Grift and Hofstee, 1997) who used it to predict the spread pattern of a single disc fertilizer spreader (Grift and Hofstee, 2002). In the center of the sensor, a 12-bit absolute angle rotary encoder (AG 612 WKRP4096 GRAY, Max Stegmann GmbH, Germany) was mounted, which measured the angle of the sensor relative to the center of the disc.

To evaluate the feed gate adaptation algorithm, a half section of a Sulky spreader was used, fitted with a flat disc with straight radial vanes (Fig. 4).

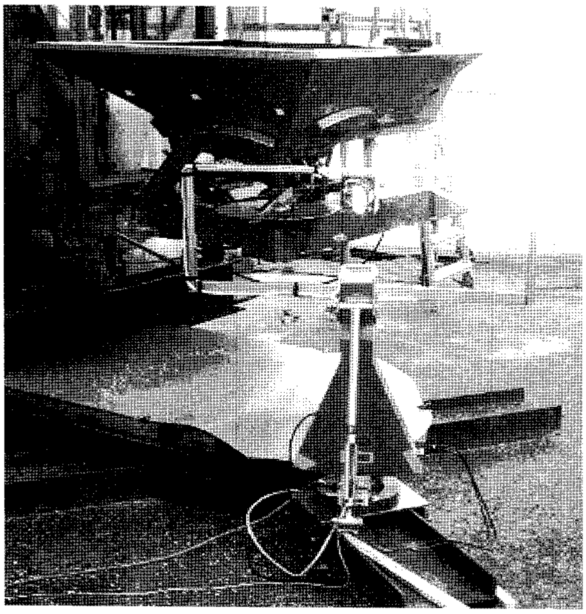

**Fig. 4** Test bed for feed gate adaptation validation.

## B. Development of Generic Experimental Arrangement

To implement the feed gate adaptation control, a generic experimental arrangement was developed at Cemagref, Montoldre, France (Fig. 5). This arrangement allows for experimentation with varying spinner speeds, varying particle drop locations, different gate types and materials.

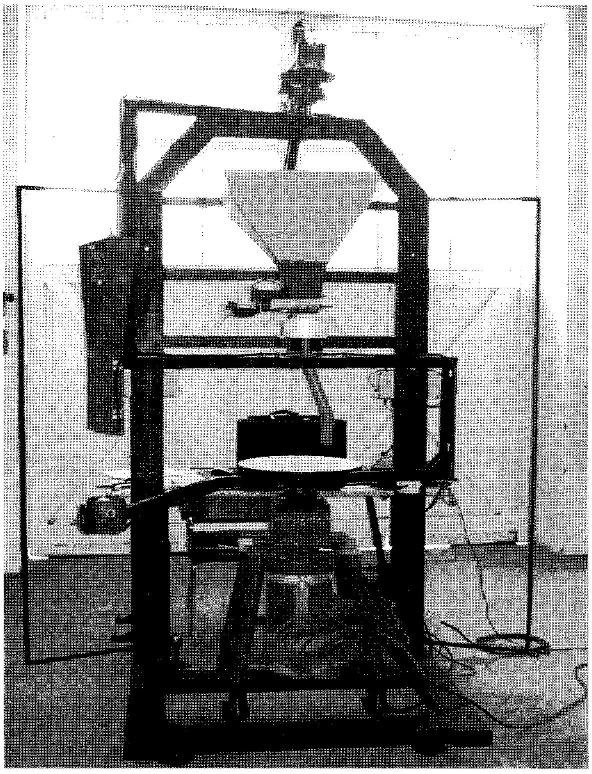

**Fig. 5** Photo of the generic experimental arrangement.

The optical time-of-flight sensor used to obtain spread patterns is an integral part of the design. To prevent particles from hitting the sensor, the light source was detached from the sensing element, such that the particles had an unobstructed path.

The disc carrier can be fitted with an arbitrary disc, conical or flat with radial or pitched, curved or straight vanes. To control the speed of the disc, an electric motor (LS100, Leroy-Somer, France) and a motor speed controller (Altivas 18, Telemecanic, France) were used, which allow rotational velocities up to 2500 RPM. To rotate the sensor a DC motor (P16, Crouzet Co., France) and gears with a reduction ratio of 1:40 were used. The rotational speed of the sensor was set to 0.5 RPM. A 12-bit absolute encoder (AG 612 WKRP 4096 GRAY, Max Stegmann GmbH, Germany) was attached to the top of the axis of the rotating sensor to provide the discharge angle of the particles passing the sensor.

To reduce the influence of the flow rate change on the spread pattern, a PVC tube was used with a rectangular sliding edge gate with a size of 40 mm × 80 mm. The flow rate can be controlled by changing the position of the feed gate with a linear actuator, which has a potentiometer as feedback sensor (Electrak 1, Warner linear, USA). The PVC tube can be rotated by a RC servomotor (S3305, Futuba Co., USA), which controls the drop location.

The generic experimental arrangement contains the following components:

1. A feedback sensor that predicts the spread pattern behind the spreader
2. Actuators that control the gate opening (flow rate) as well as the particle drop location on the disc
3. An algorithm that finds the gate setting which optimizes the spread uniformity of the spreader
4. A communication network which interfaces the sensors, actuators and control hardware

Table 1 and Figure 6 show the specification and the control system of the experimental arrangement.

The particle velocity, diameter and discharge angle information were obtained from the optical sensor and encoder using a Timer board (PCI 6602, National Instruments Co.) under control of LabVIEW® (National Instruments Co.) Based on these data, a MatLab® program simulated pattern overlaps for a given swath width and subsequently generated signals to control the fertilizer drop location. Finally, actuators moved the position of the drop tube according to the set point. Several micro-controllers were used to bridge communication as well as generating pulses and output voltages to control actuators. PIC18F458 (Microchip Inc.) with Controller Area Network (Etschberger, 2001) functionality were chosen, since these allow future integration of the system with existing CAN buses on off-road equipment. Figure 7 shows a photo of the control system with three micro controllers, a laptop computer as well as two actuators.

**Table 1** Specification of the experimental arrangement

| Item | Specifications |
|---|---|
| AC Electric motor for disc speed control | 230 V, 60 Hz, three phase, 2.2 KW |
| Motor speed controller | speed control up to 2500 RPM |
| Electric motor for sensor rotation | DC 12 V, 10 W |
| Reduction gears | reduction ratio of 1:40 |
| Rotary encoder | 12-bit absolute gray code |
| Linear actuator | DC 12 V, Max. stroke length : 150 mm |
| RC servo motor | Speed : 0.20 sec/60°,<br>Torque : 8.9 kg-cm at 6V |

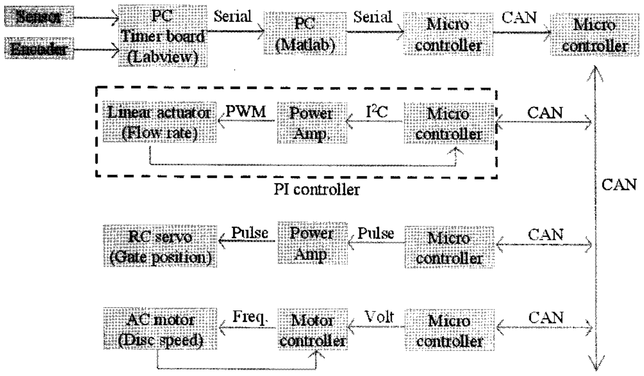

**Fig. 6** Control loop of the generic experiment arrangement.

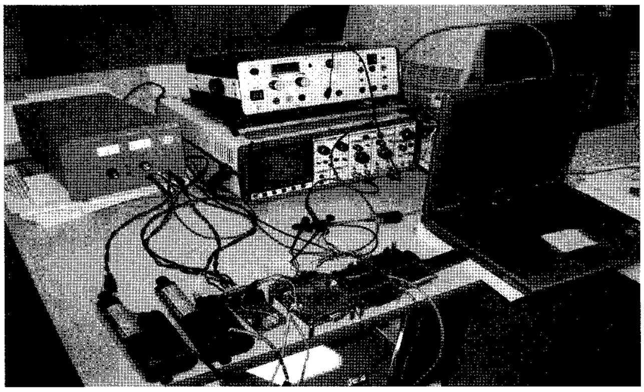

**Fig. 7** Photo of the linear actuators controlled by the micro-controllers through a CAN bus.

## C. Spatial Optimization of Fertilizer Application in the Field

Virin et al. (2005 and 2006) suggested an optimization technique, by which optimal parameters of a spreader can be obtained, based on a spatial distribution model developed in several researches (Colin, 1997; Olieslagers, 1997). Since the control loop needs to start with initial values for the gates preferably without using the time-of-flight sensor and spreading fertilizer in a stationary location, this optimization method can be used.

The spread pattern model shown in Figure 8 is characterized

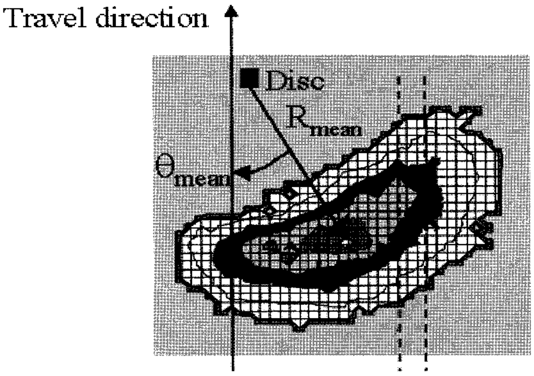

**Fig. 8** Mean radius and mean angle in a spatial distribution.

by its mean radius and mean angle (Virin et al., 2005). The mean radius ($R_{mean}$) defines the distance between the disc center and the spread center and the mean angle ($\theta_{mean}$) is the angle between the travel direction and the straight line passing through the disc center and the spatial distribution.

The variables for the optimization method are defined as follows :

$m(t) \in \mathbf{R}$, mass flow rate for right disc
$d(t) \in \mathbf{R}$, mass flow rate for left disc
$\rho(t) \in \mathbf{R}$, mean radius for right disc
$\xi(t) \in \mathbf{R}$, mean radius for left disc
$\varphi(t) \in \mathbf{R}$, mean angle for right disc ($R_{mean}$ in the Figure 8)
$\psi(t) \in \mathbf{R}$, mean angle for left disc ($\theta_{mean}$ in the Figure 8)

According to simplifying assumptions by (Colin, 1997; Olieslagers, 1997), the spread pattern ejected by the right and left discs, $q_r$ and $q_l$, are two-dimensional Gaussians, given by following equations.

$$q_r(x,m,\rho,\varphi) = \frac{m}{2\pi\sigma_r\sigma_\theta} e^{\frac{(-r-\rho)^2}{2\sigma_r^2} + \frac{(-\theta-\varphi)^2}{2\sigma_\theta^2}} \tag{1}$$

$$q_l(x,d,\xi,\psi) = \frac{d}{2\pi\sigma_r\sigma_\theta} e^{\frac{(-r-\xi)^2}{2\sigma_r^2} + \frac{(-\theta-\psi)^2}{2\sigma_\theta^2}} \tag{2}$$

where, $x$ is coordinate in the field; $r$ is corresponding radius vectors of the spread pattern; $\theta$ is corresponding angle vectors of the spread pattern; $\sigma_r$ and $\sigma_\theta$ are the standard deviations for radius and the angle of the spread pattern, respectively. The applied mass flow rate during spreading is determined by Equation (3).

$$m = (Q^* \times W \times S) / 600 \tag{3}$$

where: $m$ is the mass flow rate (kg/min); $Q^*$ is the prescribed application rate (kg/ha); $W$ is the working width (m); and $S$ is the speed of tractor (km/h). The total spatial distribution $q_{tot}$ can be written as follows:

$$q_{tot}(x, M(t), R(t), \Phi(t)) = q_r(x, m(t), \rho(t), \varphi(t)) + q_l(x, d(t), \xi(t), \psi(t)) \tag{4}$$

where: $M = (m(t), d(t)) \in \mathbf{R}^2$; $R = (\rho(t), \xi(t)) \in \mathbf{R}^2$; $\Phi = (\varphi(t), \psi(t)) \in \mathbf{R}^2$

The actual application rate $Q$ for a single driving path can be calculated as:

$$Q(x, M, R, \Phi) = \int_0^T q_{tot}(x,M,R,\Phi)dt \tag{5}$$

If $Q^* \in \mathbf{R}^2$ is the prescribed application rate, the optimization function $F$ can computed by minimizing the following function in Equation (6)

$$F(M, R, \Phi) = \int_\Omega [Q(x,M,R,\Phi) - Q^*]^2 dx \tag{6}$$

where, $\Omega \in \mathbf{R}^2$. For the actual optimization, the optimization toolbox of Matlab® was used.

## 3. Results and Discussion

### A. Validation of Feed Gate Adaptation Algorithm

Figure 9 shows the predicted fertilizer landing positions by angle obtained from the time-of-flight sensor and the rotary encoder in the Sulky half section, for a mass flow of 10 kg/min, using Ammonium Nitrate fertilizer. From this figure, it is clear that the pattern of a single disc is severely skewed, but this does not imply that the transverse pattern of the dual disc spreader is poor. The transverse pattern of

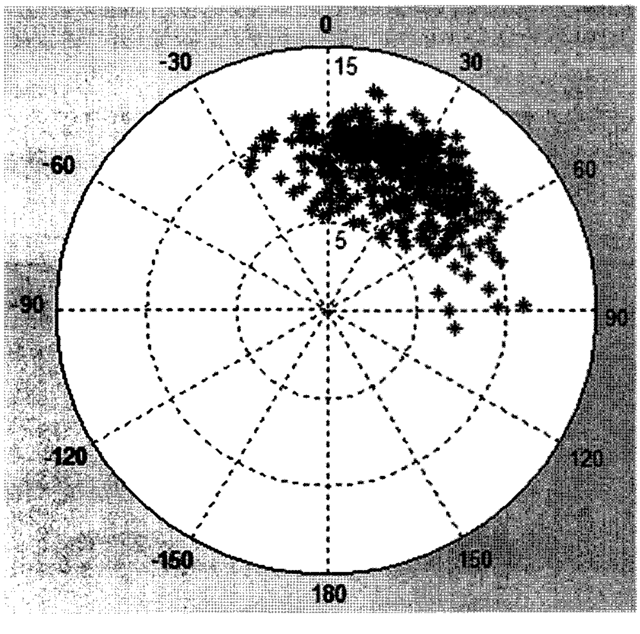

**Fig. 9** Predicted fertilizer-landing positions by angle produced by Sulky half section at a mass flow rate of 10 kg/min using Ammonium Nitrate fertilizer.

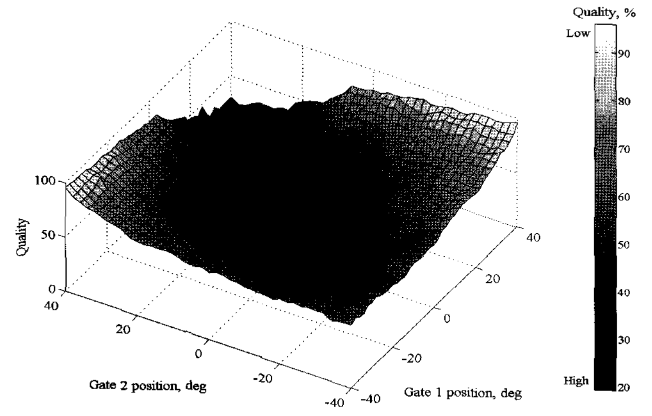

**Fig. 10** Quality map indicating a minimum value at gate 1, 2 = 14 deg.

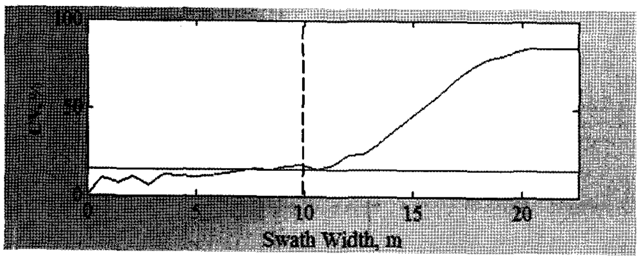

**Fig. 11** CV versus Swath width plot showing a CV of 17% at a swath width of 10 m.

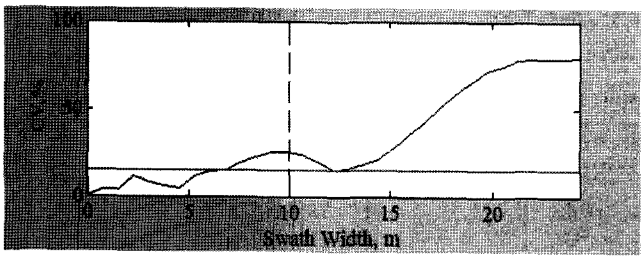

**Fig. 12** CV versus Swath width plot showing a CV of 27% at a swath width of 10 m.

the dual disc spreader was generated by adding a second mirrored pattern to the one shown in Figure 9 at a distance equal to the design of the Sulky spreader.

Figure 10 shows the quality map. The minima are found where the gate positions are equal (symmetric pattern) and the minimum is found at 14, 14 deg for gate 1 and 2 respectively.

A coefficient of variation (CV), the standard deviation of the overlapped spread pattern divided by the mean, is widely used to express the uniformity of a spread pattern. Based on a rule of thumb, a CV lower than 15% is acceptable to prevent damage to the crop at a pre-determined swath width.

The CV- Swath width plot of the overlapped pattern of the dual disc spreader as shown in Figure 11 indicates that the CV at the chosen swath width of 10 m (vertical dashed line) and a mass flow of 10 kg/min is 17%, slightly higher than 15% (horizontal straight line) which is considered acceptable. The overlaps were carried out in Back & Forth mode since it represents the worst-case scenario and is most popular (Parish, 1999b).

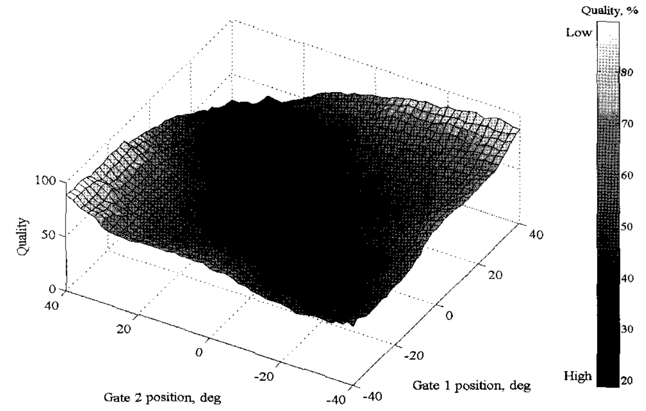

**Fig. 13** Quality map indicating a minimum value at gate 1, 2 = 8 deg.

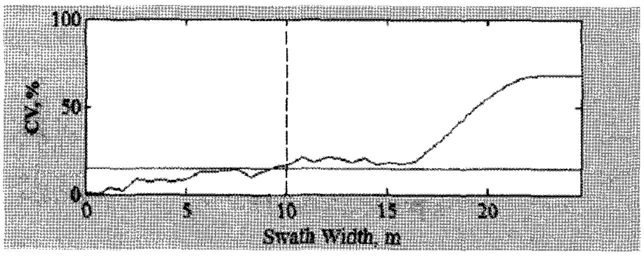

**Fig. 14** CV versus Swath width plot showing a CV of 15% at a swath width of 10 m.

The spreading run, which resulted in the data shown in Figure 9, was repeated for a increased mass flow of 15 kg/min, while keeping the gate angles constant at 14 deg. This resulted in a spread pattern, which was unacceptable, since it exhibited a CV of 27% at a swath width of 10 m as shown in Figure 12. This result confirms that the spread pattern quality is highly dependent on the mass flow and that an adaptation algorithm is needed to control the uniformity.

The feed gate algorithm was applied to the new mass flow rate of 15 kg/min and the optimal pattern was found at a gate setting of 8 deg for both gates as shown in Figure 13.

The resulting spread pattern uniformity as a function of swath width is shown in Figure 14. It is clear that the uniformity has greatly improved compared to the original 14 deg gate setting version (Fig. 12), not only locally at 10 m where the CV is 15%, but the pattern has a lower CV for a range of swath widths, which makes it more robust.

## B. Performance Evaluation of the Generic Experimental Arrangement

Since the feed gate and the time-of-flight sensor play an important role in the development of the experiment arrangement, key parts were evaluated individually. To test the feed gate function, a test was carried out to establish the relationship between the gate opening and the flow rate. Figure 15 shows the result in which the relationship between feed gate openings and flow rate was found to be linear with $r^2 = 0.96$.

Subsequently the time-of-flight sensor performance was evaluated under varying flow rates. For this test, the disc rotational speed was set to 800 RPM and two tests were performed at different flow rates while rotating the sensor around the spreader. Granular fertilizer of NPK 13-12-18 (13% of nitrogen, 12% of phosphorus, and 18% of potassium), which has a rather spherical shape, was used and the data of particles with a velocity lower than 20 and higher than 55 m/s, and diameter smaller than 2.0 and higher than 8.0 mm were removed since they were assumed to not have accelerated smoothly along the vane and/or to not have passed the sensor properly.

Test results showed that the change of flow rate did not affect the measurement of diameter, velocity, and landing location by the sensor; however, for higher flow rates the resulting spread pattern rotated around the disc center. Even though the PVC tube was used to reduce the variability in drop location, the spread pattern was influenced. This test confirmed that to obtain highly uniform patterns, there is a need for a feedback controlled system that uses the feed gate adaptation algorithm. Table 2 shows how the change in flow rate affects the measurements by the optical sensor.

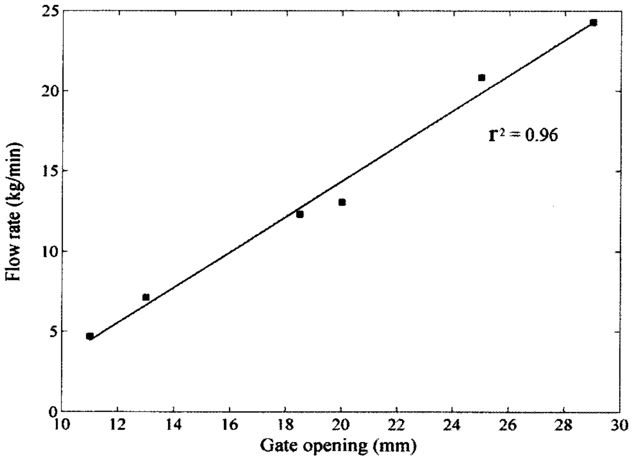

**Fig. 15** Relationship between flow rate and the opening of the rectangular sliding edge gate in the experiment arrangement.

To investigate the effect of a disc rotational speed on the measured quantities by the time-of-flight sensor, a test similar to the mass flow test, was carried out at a constant flow rate of 4.69 kg/min. Table 3 shows the influence of disc speed on the measured velocities and predicted landing locations of fertilizers. The disc speed does not affect the measurement of particle diameters significantly. This experiment shows

**Table 2** Influence of flow rate changes on measured quantities at a disc speed of 800 RPM

| Flow rate (kg/min) | Sensor rotation | Velocity (m/s) | Particle diameter (mm) | Landing distance (m) | Mean of spread pattern angle (deg) |
|---|---|---|---|---|---|
| 4.69 | Yes | 36.95 | 4.88 | 12.04 | 15.19 |
| 4.69 | No | 36.66 | 4.97 | 12.03 | - |
| 7.17 | Yes | 37.26 | 5.12 | 12.29 | 13.50 |
| 7.17 | No | 37.07 | 5.23 | 12.33 | - |
| 12.31 | Yes | 36.95 | 4.88 | 12.19 | 9.21 |
| 12.31 | No | 35.64 | 5.04 | 11.80 | - |

**Table 3** Influence of disc speed on the velocity and landing distance of fertilizers

| Disc speed (RPM) | Velocity (m/s) | Particle diameter (mm) | Landing distance (m) |
|---|---|---|---|
| 800 | 37.64 | 5.11 | 12.41 |
| 900 | 42.45 | 5.23 | 13.65 |
| 1000 | 47.74 | 4.98 | 14.44 |
| 1100 | 52.06 | 5.14 | 15.48 |

highly linear relationship between disc speed and measured particle velocity ($r^2 = 0.99$) and between disc speed and particle landing position ($r^2 = 0.99$).

## C. Gate Adaptation by Feedback Control System

To obtain initial setting parameters for the spreader system, the optimization technique shown in the previous chapter was used. In this study, only a rectangular field with a parallel driving path was considered. For the experiment, the prescribed application rate was set to 200 kg/ha, the working width was set to 10 m and the tractor speed was assumed constant at 7 km/h. After the optimization calculation, the parameters were obtained as follows:

$m$, mass flow rate for right disc, was obtained as 12.5 kg/min
$d$, mass flow rate for left disc, was obtained as 12.5 kg/min
$\rho$, mean radius for right disc, was obtained as 12.6 m
$\xi$, mean radius for left disc, was obtained as 12.6 m
$\varphi$, mean angle for right disc, was obtained as -0.7°
$\psi$, mean angle for left disc, was obtained as -0.7°

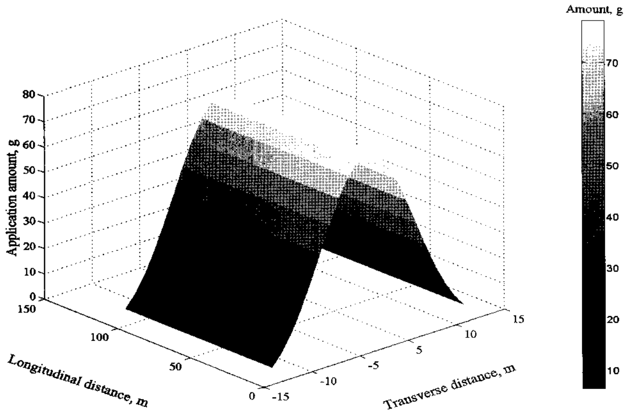

**Fig. 16** Single spread pattern generated by the parameters from the optimization method.

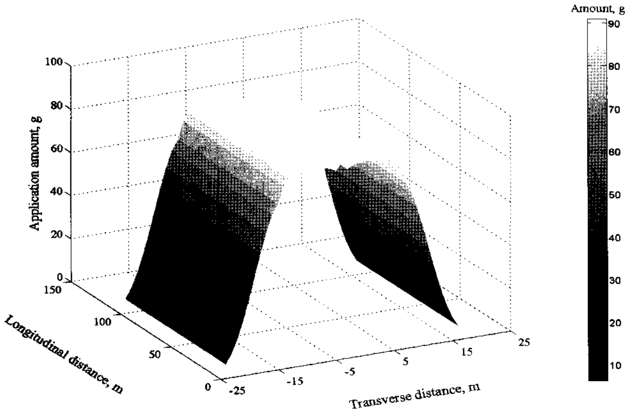

**Fig. 17** Overlapped spread pattern generated by the parameters from the optimization method (only three overlaps shown).

Using the above parameters a single transverse spread pattern and an overlapped pattern were generated using simulation as shown in Figures 16 and 17, respectively. The CV of the overlapped pattern was 3.28%.

The spreader system was initially set at a flow rate of 12.31 kg/min, a disc rotational speed of 800 RPM and a drop location of -30° to obtain a mean angle of 0° from the parameters obtained from the above optimization method.

Figure 18 shows the predicted landing positions of particles by the time-of-flight sensor. The generated pattern as a function of the spreading system is similar to the one obtained by the optimization method with a mean angle of 0° and a mean radius of 11.8 m. Using the initial setting, the feed gate adaptation was implemented, it found the optimal drop location and generated the control signal to move the gate to the desired positions. The optimal

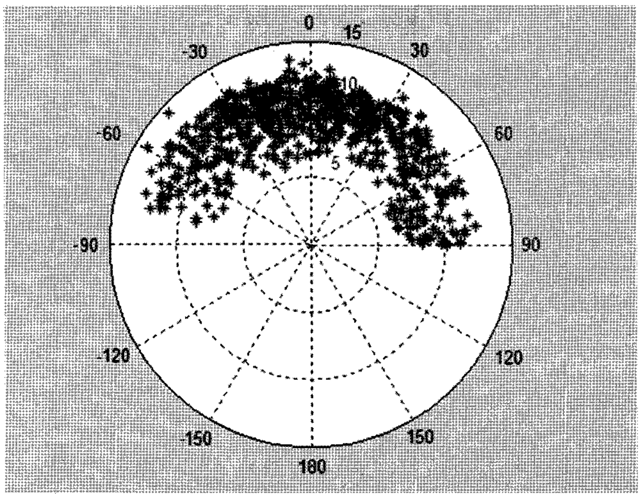

**Fig. 18** Predicted fertilizer-landing positions by initial setting obtained from the optimization method.

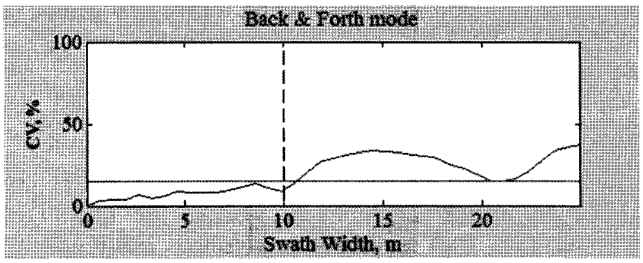

**Fig. 19** CV-swath width plot obtained from feed gate adaptation.

positions of both feed gates were found as 16°.

Finally, Figure 19 shows the CV-swath width plot of the overlapped pattern of the experimental arrangement, indicating an acceptable CV of 9% at the swath width of 10 m.

## 4. Conclusions

The objectives of this study were to evaluate the performance of the feed gate adaptation algorithm using a dual disc spreader type test bed, and to develop a generic platform which allows implementing feed gate control algorithms as well as studying fundamental particle behavior on the disc.

This paper describes the analysis and control of uniformity for a spinning disc granular fertilizer spreader. Simulations showed that it is possible to obtain highly uniform patterns by rotating the drop location of the fertilizer particles about the center of the disc. Major findings were:

(1) The feed gate adaptation algorithm tested on a Sulky half section spreader with a single flat disc with straight radial vanes produced a higher quality spread pattern with 15% CV from the original, uncontrolled pattern with 27% CV.

(2) A generic experimental arrangement was developed to control the rate and uniformity of spread patterns. Actuators were able to control the position of the gates according to the control inputs, generated by the feed gate adaptation algorithm. The experiment to investigate the relationship between the gate opening and flow rate showed highly linear ($r^2$=0.96). The test for disc speed and particle velocity, as well as disc speed and predicted landing location of fertilizers also showed both very high linear relationship ($r^2$=0.99).

(3) The feed gate algorithm was implemented by feedback control systems using initial parameter settings obtained from a mathematical optimization method for a given flow rate and swath width. The experiment result showed that the CV of the spread pattern at the chosen swath width was acceptable (9% CV).

The current approach was limited to both spinning discs rotating at identical rotational velocities. Therefore, it was valid to assume that the patterns from both discs were mirror images and the quality plots became symmetric. However, it is conceivable that in the future asymmetric patterns are required, particularly for border spreading, to avoid waterways and other environmentally sensitive areas.

In future research, the adaptive feed gate control method needs to be integrated with positioning information using GPS and field tested with multiple rate settings.

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