TESTING AN ONLINE SPREAD PATTERN DETERMINATION SENSOR ON A BROADCAST FERTILIZER SPREADER

T. E. Grift, J. W. Hofstee

ABSTRACT. *An alternative method for fertilizer spread pattern determination was developed based on predicting where individual fertilizer particles land on the ground, in contrast to the traditional method of collecting the particles in bins (ASAE Standard S341.2).*

A small broadcast granular fertilizer spreader (Lowery 300) was equipped with an optical sensor designed to measure the velocity and diameter of individual fertilizer particles shortly after they leave the impeller disc. The measured velocity and diameter of individual particles were input into a ballistic model that predicted where particles land on the ground. A total of over 1000 landing spots revealed the spread pattern.

The results have shown that the optical sensor is capable of automatically determining the spread pattern of a fertilizer spreader on the fly. The sensor could be a key component in the development of uniformity–controlled fertilizer application systems.

Keywords. *Granular fertilizer, Spread pattern, Optical sensor, Calibration, ASAE Standard S 341.2.*

In the early 1990s, the Dutch government expressed concern about the quality of fertilizer spread patterns and potential negative effects on the environment. It announced the intention to require bi–annual performance testing of spreaders, using the traditional "collection tray" method (*ASAE Standards*, 1999). The sheer number of spreaders (around 60,000 at the time), along with the limited number of workable days due to weather constraints, would require construction of a considerable number of large and costly indoor test facilities.

As an alternative, Hofstee et al. (1994) proposed a "predict" rather than a "collect" method. This method no longer uses collection of fertilizer material in bins but instead predicts where the material lands on the ground using a ballistic model. The model inputs are the measured velocity and diameter of particles just after they leave the impeller disc. Accumulation of a large number of predicted landing spots results in a spread pattern.

The sensor that measures the initial velocity and diameter of the particles was developed by Grift and Hofstee (1997). It is an optical device that is capable of accurately measuring velocities and diameters of fast–moving small objects. It is inexpensive, and because of its fully digital electronic design, robust and reliable.

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The sensor was originally designed to work in a measurement booth in which any type of spreader could be calibrated. Under these laboratory conditions, two perpendicular velocity vectors and two associated major axes were measured. The resulting velocity vector was computed as the vector sum of the two perpendicular velocity vectors, and the particle diameter was computed as the mean of the two major axes. In addition, in the measurement booth configuration, the whole sensor was moved in a pattern. After each completed scan cycle (a semicircle around the spreader), the sensor was moved upward until the whole spreading zone was scanned.

The arrangement as presented in this article is a simplified version of the laboratory arrangement, intended for use on a spreader during field operations. The sensor was not moved up and down but mounted at a constant height, such that the measurements took place in line with the impeller disc. The velocity vector was measured in a single radial direction, and the measured particle "diameter" was computed as a single major axis of the particle. Although the information from the field test is limited compared to the laboratory version, it is sufficient to determine the shape and relative mass distribution of a spreader.

Many researchers have described the acceleration behavior of particles on a vane (Cunningham, 1962; Cunningham and Chao, 1967; Inns and Reece, 1962; Patterson and Reece, 1962), as well as aerodynamic behavior (Mennel and Reece; 1963; Pitt et al., 1982). Olieslagers et al. (1996) integrated a selection of the previous models into a complete model that predicts the landing positions of fertilizer particles in relation to the shape and position of the orifice opening, particle behavior on the disc, as well as the trajectory through the air. His model predictions were validated with the traditional collection tray method. The sensor as described here could be used as a more direct validation tool because it measures an intermediate prediction result, the exit velocity of the particles from the disc.

By mounting the sensor permanently on a spreader, the user can obtain a real–time prediction of the spread pattern by having the sensor complete one or more cycles (semicircles) around the spreader. The sensor may be a key factor in the development of feedback–controlled fertilizer equipment with which a high–quality spread pattern can be produced without calibration or adjustments by the operator.

The objective of this study was to test the performance and feasibility of an optical sensor designed to automatically determine granular fertilizer spread patterns in the field.

MATERIALS AND METHODS

A Lowery 300 broadcast spreader was chosen for testing purposes, mainly because the round shape of the hopper allowed for easy mounting of the sensor and scanning of the whole spreading zone in line with the impeller disc. Before testing, the spreader was adjusted to a horizontal orientation. The spreader has two gates through which the fertilizer material is fed onto the impeller disc. Both of these gates were set to 4, which, according to the manufacturer specifications, should result in a spread width of 12.2 m. The hopper was filled half full with ammonium nitrate fertilizer, and the PTO speed was set to 540 rpm. During the spreading, the sensor was allowed to make three complete cycles, during which a total of about 1000 measurements were obtained. These were stored in a computer for off–line analysis.

FIELD TESTING CONFIGURATION

The sensor arrangement as used in field testing is shown figure 1. The sensor was mounted vertically with a horizontal bar that connects to a bearing in the center of the impeller. It was moved around the spreader rim with two motors and rubber friction wheels. End switches were used to automatically alternate the direction of travel of the motors at the end of the cycle. In the center of the spreader, underneath the impeller, a 12–bit absolute angle encoder (AG 612 WKRP 4096 GRAY, Max Stegmann GmbH, Donaueschingen, Germany) was mounted, which measured the angle of the sensor relative to the center of the impeller.

The sensor mounting configuration implies that only the radial component of the particle's velocity vector is measured, as is shown in the top view of figure 1. One effect of this is that the measured spread pattern is rotated around the center of the impeller, assuming that all particles have the same angle of emanation with respect to the impeller disc. A second effect is that the true velocity is always higher than the one measured, which means that the system is pessimistic in predicting the spread width. The latter error is non–linear since the relationship between velocity and landing position is non–linear.

In future research, the sensor could be used to measure the mean angle between the radial and tangential velocity components. This could be done by turning the sensor along its vertical axis and determining the angle at which the maximum particle velocities are observed.

OPTICAL SENSOR

The optical sensor as developed by Grift and Hofstee (1997) is shown figure 2. The heart of the system is formed by two arrays of infrared photo sensors called "OptoSchmitts" (Honeywell SDP 8601). Each OptoSchmitt is an

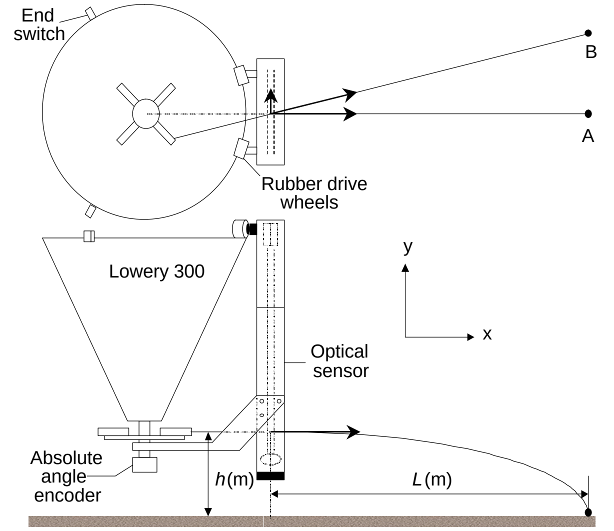

Figure 1. Optical sensor for predicting landing spots of fertilizer particles.

optical on/off switch. When sufficient light is received, the output becomes active (high), and when the light beam is blocked, the output becomes inactive (low). The digital nature of the OptoSchmitts makes the sensor very robust; it will continue to work even under severe contamination levels. If the contamination level becomes so high that no sufficient light is received, then the whole sensor will shut down rather than introduce a gradual error into the measurements, as is the case with analog measurement systems.

The two arrays are each built from 30 OptoSchmitts mounted side by side. All 30 OptoSchmitts in an array are connected in a single logical AND function, which results in the array output becoming low when either of the OptoSchmitt outputs becomes low. This means that a particle can pass away from the centerline of the light beam and still be detected. The width of the light beams is about 2 cm in the detection zone.

A problem that occurred during the development of the optical detector was the small size of the fertilizer particles compared to the size of the OptoSchmitts (5 mm width). A small particle could be missed completely by "slipping through" two adjacent OptoSchmitts. This problem was solved by magnifying the shadow of the particle by a factor of 8 using a converging/diverging lens combination, similar to a slide projector principle.

The velocity and diameter measurement principle is shown in figure 3. The particle velocity (*v*), assumed constant during the passage, was computed by dividing the distance between the light layers (*b*) by the time difference between event 1 (particle just blocking layer 1) and event 2 (particle just blocking layer 2). In formula form:

$$v = \frac{b}{\Delta t_f} \qquad (1)$$

where

v = particle velocity (m s^{-1})
b = distance between the two light layers (m)
Δt_f = time difference between passage events of layer 1 and 2 (s)

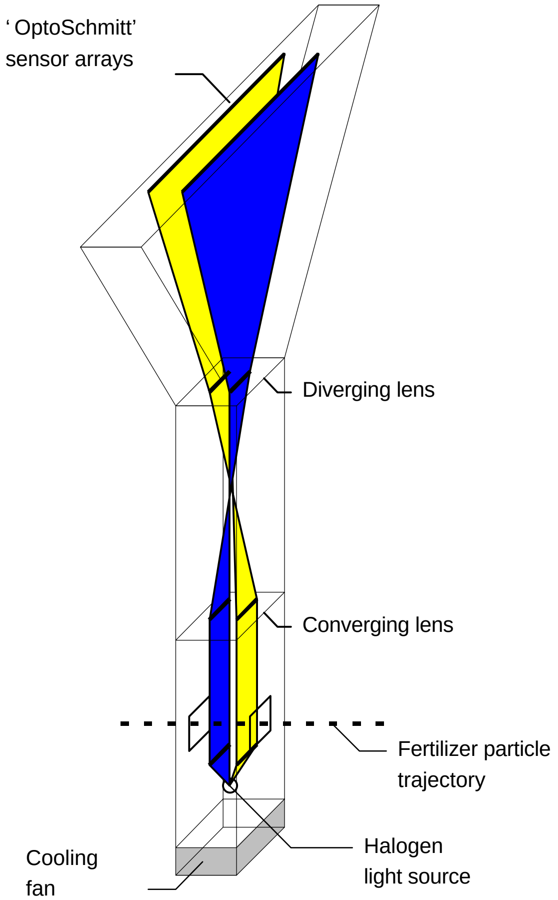

Figure 2. Principle of the optical sensor.

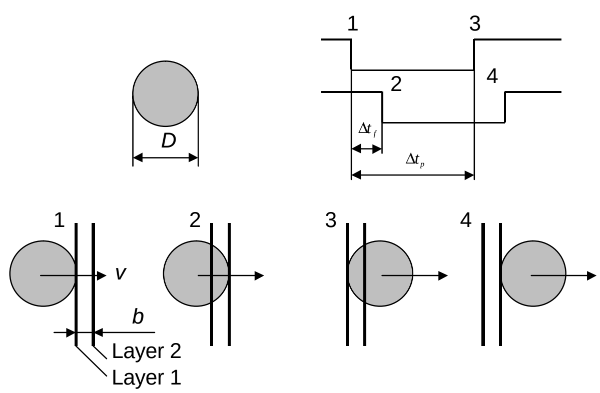

Figure 3. Particle passing light layers in optical sensor.

The particle diameter (D) was computed by multiplying the velocity by the total time during which a particle blocks light layer 1 (from event 1 to event 3) or:

$$D = v\Delta t_p = b\frac{\Delta t_p}{\Delta t_f} \tag{2}$$

where

- v = particle velocity (m s^{-1})
- b = distance between the two light layers (m)
- Δt_f = time difference between particle passage events of layer 1 and 2 (s)
- Δt_p = total time a particle blocks either light layer (s)

The time differences ($\Delta\tau_f$ and $\Delta\tau_p$) were measured using a counter/timer board (model TC1024, Real Time Devices, Inc., State College, Pa.) and stored for off–line processing.

Mathematical Model

The ballistic model used to predict the landing position of the fertilizer particles is shown in equation 3:

$$\ddot{x} = -K\dot{x}\sqrt{\dot{x}^2 + \dot{y}^2}$$
$$\ddot{y} = -K\dot{y}\sqrt{\dot{x}^2 + \dot{y}^2} - g \tag{3}$$

where

- x = horizontal distance (m)
- y = vertical distance (m)
- g = gravitational acceleration (m s^{-2})

The set consists of two coupled non–linear ordinary differential equations and was initially reported by Mennel and Reece (1963). There are two measured inputs, velocity and particle mass (computed using the measured diameter), and four parameters: (1) initial launch height (measured before testing), (2) density of air, (3) true density of the fertilizer particle, and (4) the q factor, a material–specific constant. The factor K was defined as:

$$K = \frac{3}{8} C_D \rho_{AIR} \frac{1}{\rho_P q R_P} \tag{4}$$

where

- C_D = drag coefficient of sphere (1)
- ρ_{AIR} = density of air (kg m^{-3})
- ρ_P = density of particle (kg m^{-3})
- R_P = radius of particle (m)
- q = correction factor ($0 < q < 1$) (1)

The factor K was assumed to be constant, since the drag coefficient (C_D) is virtually constant for high Reynolds numbers (high velocities), especially for non–spherical particles that introduce a turbulent flow regime at lower Reynolds values. The initial conditions of the model were as follows:

$$\begin{aligned} x(0) &= 0 \\ \dot{x}(0) &= measured \\ \ddot{x}(0) &= 0 \\ y(0) &= measured \\ \dot{y}(0) &= 0 \\ \ddot{y}(0) &= 0 \end{aligned} \tag{5}$$

where x represents the horizontal direction and y the vertical direction.

The ballistic model, as presented here, is only valid for a sphere. Since a fertilizer particle, due to its shape and texture, would have a longer flight time than a perfectly smooth sphere, it was treated as a smaller sphere (which would also have a longer flight time) by multiplying the diameter by a correction factor q ($0 \leq q \leq 1$). This factor was retrieved from fall tests performed in earlier research reported by Grift et al. (1997). The q factor value was estimated to be 0.87 because the shape and texture features of ammonium nitrate fertilizer are comparable to calcium ammonium nitrate (CAN), which was tested in the research mentioned.

The landing spots of fertilizer particles were computed in advance by solving equation 3 using MatLab (1999) for an expected range of diameters (1 to 5 mm) and velocities (2 to 40 m/s). The advantage of this method is that the landing position of each particle can simply be retrieved from interpolation of an *a priori* computed "landing matrix" rather than by solving the differential equations for every measurement in real time. The landing matrix values depend on the initial launch height (a constant), the true density of the fertilizer particles and the q factor (both material constants), as well as the density of air. For practical use, matrices must be available for a known initial launching height, a certain material, and air density. The model parameters used for the computation of the landing positions are given in table 1. The overall shape of the landing matrix is shown figure 4.

Material

The material used in the test was ammonium nitrate, purchased from a local supplier. The diameter distribution was obtained by measuring the maximum and minimum major axes of 1000 particles with a slide micrometer and taking the mean as the diameter. Figure 5 shows the diameter histogram of 1000 particles, where the mean was 2.18 mm and the standard deviation 0.38 mm.

Results and Discussion

The diameter distribution of the ammonium nitrate fertilizer particles, measured by the optical sensor, is shown in figure 6. The mean is close to the true mean (2.13 mm versus 2.18 mm), but the standard deviation is larger (0.53 mm versus 0.38 mm). The main reason for the difference is defocus in the sensor. This error occurs when particles pass the sensor away from the optical focal point (compare a slide being out of focus in a projector) and is caused by the non–coherent light source used in the sensor design. Another factor may be that some particles are broken on the impeller disc, resulting in more smaller diameter particles. Overall, the same skewed diameter distribution can be recognized.

Table 1. Initial conditions for solving ballistic model equations.

Quantity	Symbol	Value	Unit
Initial height	h	0.35	m
Gravitational acceleration	g	9.81	m s^{-2}
Density of air	ρ_{AIR}	1.2	kg m^{-3}
True density of fertilizer particles	ρ_P	1100	kg m^{-3}
Drag coefficient of sphere	C_D	0.4	1
Correction factor	q	0.87	1

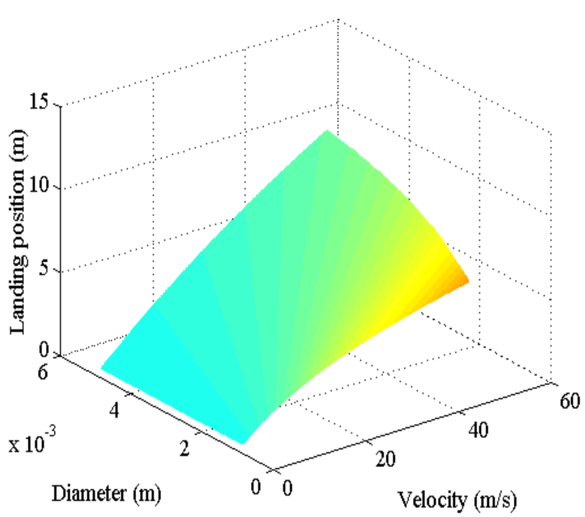

Figure 4. Landing matrix, solution of ballistic model for particle diameter and velocity ranges.

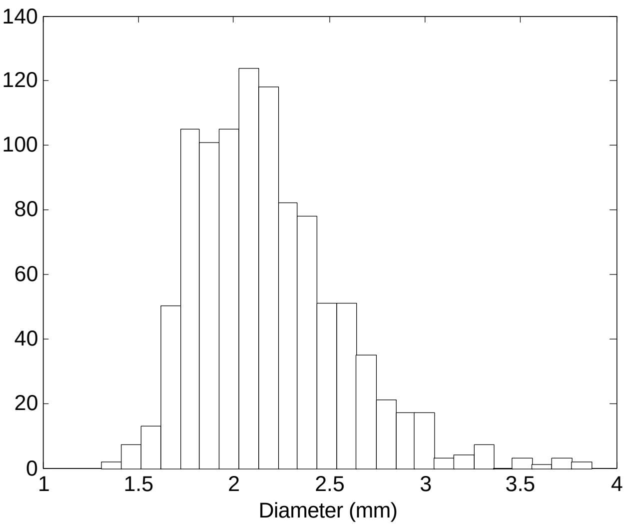

Figure 5. Histogram of true diameters of 1000 ammonium nitrate fertilizer particles.

The measurements as a function of horizontal launch angle are presented in figures 7 through 9. Note that in all figures, the plot is rotated, such that the line of travel of the tractor would be north–south. In addition, all plots contain a solid line through the data points, which indicates the mean. This line was computed by taking the mean values for 5° angle increments.

Velocity Profile

The measured velocities of 832 particles are presented in figure 7. The solid line indicates the mean velocity (19.78 m/s). Note that the sensor only measures the radial velocity component, which means that the true velocity could

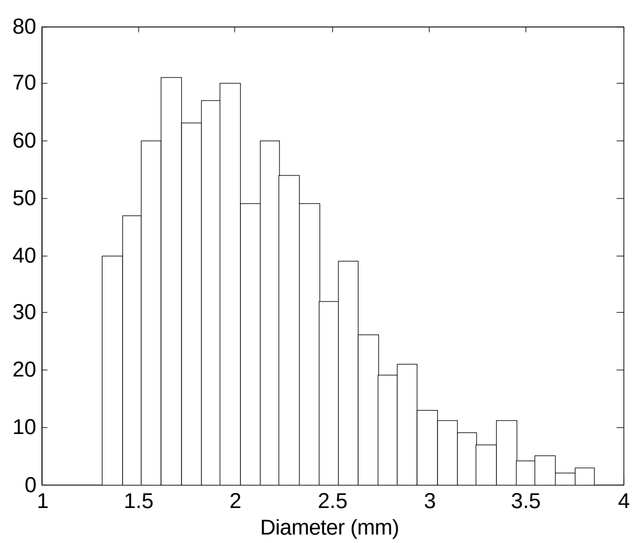

Figure 6. Histogram of measured diameters of 832 ammonium nitrate fertilizer particles.

be slightly higher when particles pass at an angle in the horizontal plane.

The measured velocities were truncated in the range [15,25] m/s. The 25 m/s was the maximum velocity found, and there were a rather large number of particles (around 200) that had velocities lower than 12 m/s, quite distinct from all others shown here. These low–velocity particles must have ricocheted off the edge of the sensor's measurement orifice and passed the sensor with severely reduced momentum. In the future, the sensor will be built such that there is no obstruction to the particles, and the ricochet effect will be eliminated.

As the solid line (mean velocities in 5° angle increments) indicates, the measured velocity of the particles was virtually independent of the horizontal launch angle.

DIAMETER PROFILE

The measured diameters by angle are shown in figure 8. The diameters were truncated in the range [1.5, 4] mm. The mean value of all diameters was 2.13 mm.

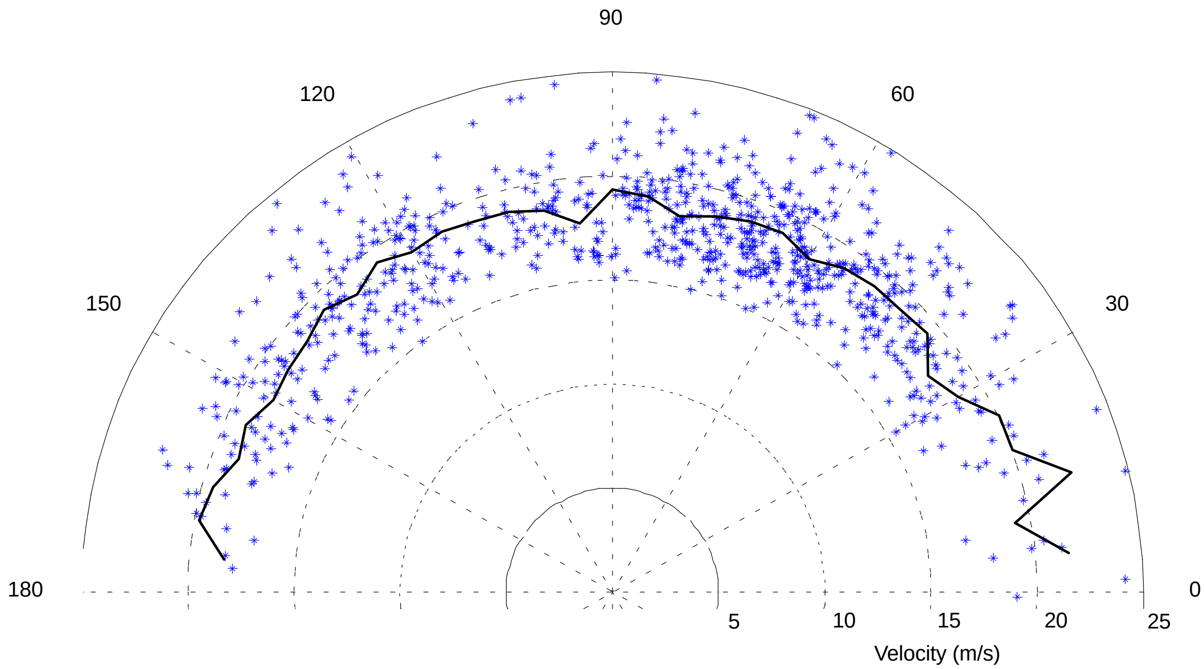

Figure 7. Measured velocities of 832 ammonium nitrate fertilizer particles.

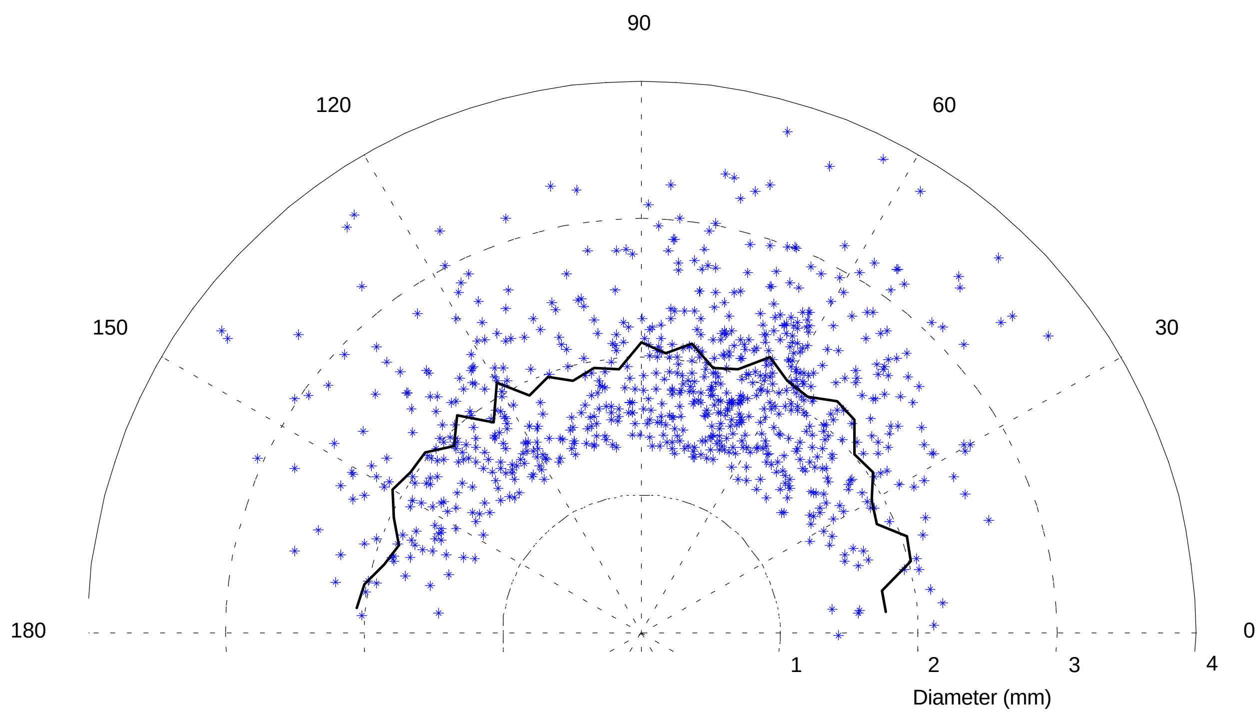

Figure 8. Measured diameters of 832 ammonium nitrate fertilizer particles.

A situation that occurs sporadically is that a particle blocks the first light layer of the optical sensor but does not block the second. This always results in a measured diameter of 0.85 mm (distance between the sensor arrays), and such measurements were discarded.

A second effect that is encountered is two or more particles passing simultaneously, which results in a diameter larger than the maximum diameter of the fertilizer particles. These measurements were discarded as well.

The minimum and maximum diameters of the particles measured by hand (1000 particles) were 1.5 mm and 4 mm, respectively. Therefore, all diameters outside of this range were considered erroneous and consequently discarded. After removal of all erroneous measurements, 832 remained.

Landing Position Profile

The landing position profile (predicted spread pattern) is shown in figure 9. As can be seen from the "landing matrix" (fig. 4), the landing position is highly dependent on the particle velocity and to a much smaller extent on the particle diameter. This is why the landing positions are grouped in a rather narrow band, similar to the velocity profile shown in figure 7. The radial landing distances range from about 3 m to 5.5 m, with a mean of 3.99 m.

Number of Particles per Angle

The diameter, velocity, and landing position plots all contain information about the number of particles by angle range. They all show that the detected number of particles is much higher in the 30° to 90° range than in the 90° to 150° range. This was unexpected, since the two gate control levers were set to the same value (4) and the spreader was adjusted to be perfectly horizontal. This particular pattern is severely skewed, and the resulting uniformity would be very low for any given swath width.

The total radial spread width of the spreader was predicted to be around 10 m, slightly lower than the manufacturer's value of 12.2 m for the flow rate setting of 4. The fact that the sensor only measures the radial velocity is assumed to be responsible for this difference.

Conclusions and Further Research

The optical sensor arrangement produced an excellent indication of the relative dispersion of the fertilizer material behind the spreader. The sensor proved reliable and robust enough to be used under field conditions.

During measurement, several particles were found that showed very low velocities (lower than 12 m/s). They were assumed to have ricocheted off the optical sensor's measurement orifice edge. Their velocities were easily distinguishable from the others and consequently discarded.

The particular spread pattern produced by a single–impeller Lowery 300 fertilizer spreader was found to be severely skewed, although the two feed gates were set equally and the spreader was adjusted to perfectly horizontal. The total spread width was found to be marginally lower than the manufacturer's specifications.

For research purposes, the sensor could be used to determine the angle between the radial and tangential velocities of the fertilizer particles. This would involve rotating the sensor along its vertical axis and determining the angle at which the measured velocities are maximal. In addition, the sensor could be used as an intermediate measurement step for validation of spread pattern prediction models.

In further research, the predicted spread pattern needs to be validated using the procedure in ASAE Standard 341.3. In addition, a control system that produces uniform patterns at

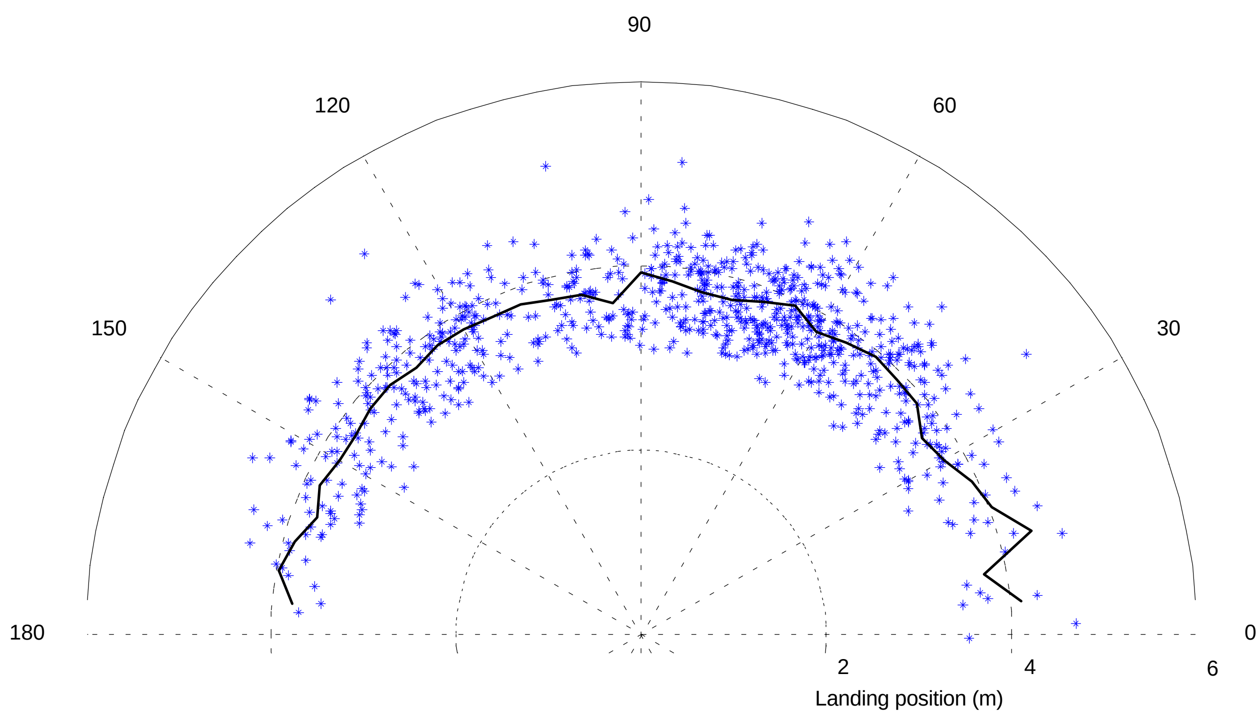

Figure 9. Predicted landing positions of 832 urea fertilizer particles.

variable rates, using the sensor as described here as a feedback mechanism, needs to be developed.

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