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Opto-electronic Sensor System for Laboratory Measurement of Planter Seed Spacing with Small Seeds

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Abstract

An opto-electronic sensor system for measuring seed spacing uniformity with different types of seeds is described in this paper. It consisted of a rectangular photogate block (124 × 92 mm) with 24 phototransistors (diameter, 3 mm) receiving light beams from 24 light emitting diodes (diameter, 3 mm) opposite them, a digital input/output board in a personal computer, and power supplies. The opto-electronic system was tested by comparing seed spacing measurements obtained from the opto-electronic system with measurements of the same seed spacings obtained from a grease belt test stand. The tests were conducted with different types of seeds including regular-pelleted (diameter, 3.8–4.5 mm), mini-pelleted (diameter, 3.2–4.0 mm), and medium-encrusted sugar beet seeds (3.2-3.6 mm in diameter by 1.8–2.6 mm in thickness), and pelleted chicory seeds (diameter, 2.8–3.3 mm). Results showed that the adjusted opto-electronic seed spacings were not significantly different from the same seed spacings measured with the grease belt test stand. The opto-electronic sensor system worked well to obtain 508 seed spacings with regular-pelleted and mini-pelleted sugarbeet seeds and pelleted chicory seeds. The opto-electronic sensor system missed two seeds and detected two "phantom" seeds out of 170 seed spacings with the medium-encrusted sugarbeet seed.

1. Introduction

Uniform seed spacings are important, particularly to crops such as sugarbeet, because seed spacing uniformity has been demonstrated to be a significant factor in affecting production costs and yield. With uniform spacing, the sugarbeet roots can grow to maximum size and fill the row space, without being pushed out of the row. Uniform spacing also results in uniform root size which in turn reduces harvest loss, leading to a potential increased sugar yield.

A wide variety of measures have been used to quantify planter performance with regard to plant spacing.[1–6] Some tests have used performance measures involving distance between plants in the field. Other tests have used performance measures involving distance between seeds on a grease belt test stand.[7, 8] A few tests have used performance measures involving distance between seeds planted into soil.[9]

Field measurement of plant spacings can be used to evaluate planter seed spacing capability, but the spacing data obtained may not be a true representation of the planter performance. Plant spacing data may include effects from seed-bed preparation quality, weather conditions after planting, plant emergence efficiency and volunteer plants, as well as effects from planter performance. Planter performance factors include variability around the target drop points (drop error), multiples and misses from the metering mechanism, and seed bounce and roll.

Seed spacings on a grease belt test stand are also influenced by the same factors above, except that seed bounce and roll are typically minimized by the grease on the belt, and plant factors such as emergence and volunteer plants are no longer a concern.[9] Limitations of the grease belt system include the length of the belt which limits the consecutive seed spacing data that can be obtained, the time required to manually measure the seed spacings and enter the data into a computer, and the concern that seeds may still slide or bounce on the grease belt, particularly at high belt speeds.[10]

Seed spacings measured by digging up seeds after they have been planted would include all the planter performance factors, including those in the seed spacing data from a grease belt test stand, as well as seed bounce and roll in the furrow. However, once planted, it is difficult to dig and locate small seeds such as sug-

arbeet, without disturbing their location. An additional major limitation of this method consists primarily of the time required to dig and locate the seeds and measure the seed locations.

Electronic sensors or planter monitors such as those manufactured or developed by DICKEY-john Corporation, Big John, and S. I. Distributing Company were reviewed by Kocher, *et al.*[10] These sensors detect when a seed passes, but not where it passes. As a result no information on the front-to-back location of the seed passage relative to the planter is obtained. These sensors are used with computers measuring the time interval between seed drops. The time interval multiplied by the planter travel speed gives an estimate of the seed spacing, but this estimate does not include information regarding the front-to-back location of seed drop events, which can significantly affect the accuracy of the seed spacing estimates.[10]

An opto-electronic seed spacing evaluation system that measured time intervals between seeds and detected front-to-back location of seed drop events relative to the planter was developed to rapidly determine planter seed spacing uniformity in the laboratory at the University of Nebraska–Lincoln.[10] The opto-electronic system was tested with three planter configurations at simulated planter travel speeds of 3.2 and 8.7 km/h. The information on the front-to-back location of seed drop events relative to the planter significantly improved the electronic seed spacing measurements in all cases. Seed spacing measurements obtained using the opto-electronic system determining time intervals between seeds and front-to-back locations of seed drop events relative to the planter were strongly correlated (average correlation coefficient $r = 0.951$) with the same seed spacing measurements obtained using the grease belt test stand.

Panning *et al.*[11] used the opto-electronic sensor system for laboratory evaluation of the seed spacing uniformity of a John Deere 71 Flexi-planter, a John Deere MaxEmerge II planter, and a Kleine Unicorn-3 planter. Each planter was operated at simulated planter travel speeds of 3.2, 5.6, and 8.0 km/h while planting regular-pelleted sugarbeet seeds with a target spacing of 15 cm. They commented that tests in the lab using the opto-electronic sensor system allowed the planter performance to be determined quickly, and with less variation than that obtained from field testing.

One limitation of the opto-electronic system mentioned by Kocher *et a1.*[10] was related to the 5 mm diameter light-emitting diodes (LEDs) and phototransistors in the photogate. Seeds with an effective diameter less than about 3 mm did not consistently block enough of a light beam to trigger the phototransistors reliably. A photogate with smaller diameter LEDs and phototransistors would likely work with smaller seeds.

The object of this research was to determine (1) whether an opto-electronic seed spacing evaluation system with smaller diameter LEDs and phototransistors would obtain the same seed spacing data as a grease belt system, and (2) whether the opto-electronic seed spacing system worked equally well for several different types of small seeds, for example, regular-pelleted, mini-pelleted, and medium-encrusted sugarbeet seeds, and pelleted chicory seeds.

2. Materials and methods

2.1. Seed

Regular-pelleted (one seed per pellet), mini-pelleted, and medium-encrusted sugarbeet seeds, and pelleted chicory seeds were used in this study. The specification for the diameter of regular-pelleted sugarbeet seed is between 3.8 and 4.6 mm, which is US industry practice. Mini-pelleted sugarbeet seed (diameter, 3.2–4.0 mm) is smaller than regular-pelleted sugarbeet seeds. Medium-encrusted sugarbeet seeds (3.2–3.6 mm in diameter by 1.8–2.6 mm in thickness) are irregular in shape and their thickness was the smallest dimension of the seed used in this study. The European pelleted chicory seeds used in this study have a diameter specification of 2.8–3.3 mm.

2.2. Grease belt system and planter

A grease belt test stand described by Kocher *et al.*[10] was used to test the "potential" seed spacing of a John Deere MaxEmerge II planter in this study (product names and model numbers are given for descriptive purposes only and do not imply endorsement over similar products). This particular test stand (Figure 1) had a 13-cm wide belt with a 3.36 m long horizontal viewing surface. The unit was equipped with a multi-speed drive arrangement to provide a range of belt surface speeds from 3.2 to 9.7 km/h, relative to the stationary planter mechanism, and a range of seed spacings on the belt. Sufficient oil (80 W gear oil) was added to the top surface of the belt to "capture" the seed without rolling or bouncing of the seed on the belt surface. We estimated the error of the spacing measurement on the grease belt to be less than 0.5 cm.

The seed drop tube used with the planter was a custom-made, straight metal tube. This metal tube had straight side walls tapering to bottom opening dimensions of 1 cm wide and 0.6 cm front-to-back. This metal tube was installed on the planter in a vertical orientation with a bottom discharge height the same as for a standard John Deere sugarbeet tube. The straight metal tube
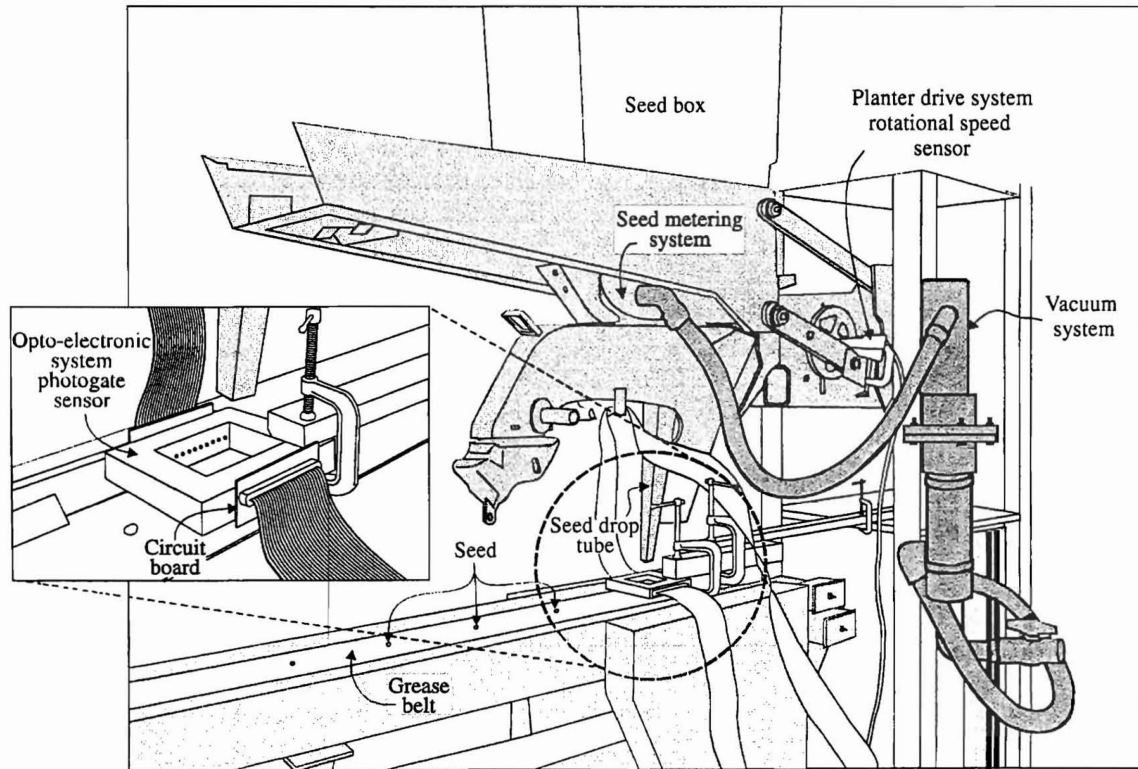
Figure 1. John Deere MaxEmerge II planter with the straight metal seed tube (disk openers and press wheel removed) mounted over the grease belt and with the opto-electronic sensor system in place for simultaneous measurement of seed spacing using both systems.

was used with the stationary planter operating over the moving belt at a surface speed (simulating a planter travel speed) of 3.2 km/h.

The planter was positioned over the grease belt (Figure 1) with the upper horizontal surface of the belt positioned to correspond with the vertical distance between the bottom of the seed tube and the bottom of the seed furrow in normal planting conditions. The photogate was positioned under the seed tube and above the grease belt so there was no contact between the photogate and the oil and seeds on the belt. The photogate was attached to the planter stand to minimize relative motion between the planter and the photogate.

2.3. Opto-electronic system hardware and software

The centerpiece of the opto-electronic system hardware was a photogate consisting of 24 pairs of near-infrared (NIR) LEOs (model, EG and G VACTEC GaAs VTE3322LA) and phototransistors (model, EG & G VACTEC NPN VTT3323LA), as shown in Figure 2. The LEOs and phototransistors had a narrow beam angle of ± 10° and were formed in a molded Long T-1 plastic package. The photogate was a rectangular cast acrylic plastic piece 12.4 cm long, 9.2 cm wide, and 2.5 cm high. An opening 9.6 cm long by 6.4 cm wide

was machined in the middle of the block for seed passage. Twenty-four holes with a diameter of 3 mm and spaced at 4 mm centers were machined in one row on each side of the photogate for the photocells. Each phototransistor was located directly opposite a LED to close a photoelectrical loop. LEOs and phototransistors were placed alternately in each row to eliminate interference between each channel and the channels directly adjacent to it, on either side. With the ± 10° beam angle and the width of the photogate block, some light from an LED shone on the phototransistors two holes on either side of the phototransistor directly across from the LED. For example, some light from the LED for channel 15 was received by the phototransistors for channels 13 and 17, while the main portion of the light from this LED was received by the phototransistor for channel 15.

Each phototransistor circuit output was connected to a channel of a digital input/output (I/O) board in a personal computer. The status of each I/O channel (high or low) indicated whether a seed was blocking the light beam from its LED or not. The voltage output from each phototransistor channel could be adjusted with a variable resistor as described by Kocher *et al.*[10] The input/output board in the computer changed its output (from 1 to 0) when the output voltage from a phototransistor
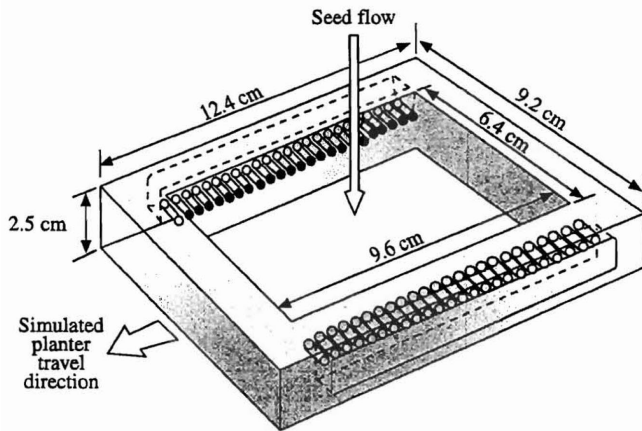
Figure 2. Sketch of the opto-electronic system photogate sensor. Twenty-four holes with 3 mm diameter were on each side of the photogate for the LEDs and phototransistors.

channel dropped to 1.40 ± 0.02 V or lower. Adjustments to the output voltage were made when there was nothing in the photogate to block the light from the LEDs to the phototransistors. The output voltage from each phototransistor channel was adjusted to 1.70 ± 0.02 V for the regular-pelleted and mini-pelleted sugarbeet seeds. The output voltage from each phototransistor channel was adjusted to 1.65 ± 0.02 V for the pelleted chicory and medium-encrusted sugarbeet seeds to increase the sensitivity of the opto-electronic sensor system for the smaller seeds.

Kocher *et al.*[10] indicated regular-pelleted sugarbeet seeds with phototransistor outputs adjusted to 1.70 ± 0.02 V could block enough light to indicate a maximum of two adjacent phototransistors were blocked simultaneously. The opto-electronic sensor system could be used with larger seeds, but this would require modification of the data-acquisition program to adjust the maximum number of adjacent phototransistors that could be blocked by one seed.

A Hall-effect switch was fixed in place on the planter frame so that it was triggered by magnets attached to a rotating part of the planter drive unit. This was used to measure the simulated forward speed of the planter. The output from the Hall-effect switch was connected to a counter on the digital I/O board in the computer. A 3.58 MHz clock on the digital I/O board provided a time base for timing the intervals between seed drops, and converting magnet count to planter speed. Data recorded as each seed interrupted light to a phototransistor included the time, which I/O channel(s) had been triggered, and the count of magnets that had passed the Hall-effect switch. The seed detection section of the data acquisition program was written in assembly language so the scan rate for the photogate (all 24 channels read during each scan) was a minimum of 8 kHz. The pro-

gram included an 8 ms time interval after detecting a seed, before the next one could be detected. With a maximum spacing error of ± 0.4 cm from the hole spacing for the LEDs and phototransistors, combined with a maximum timing error of ± 1 scan (1.25×10^{-4} s/scan) multiplied by the maximum belt (simulated planter travel) speed of 9.7 km/h, the total maximum seed spacing error was ± 0.44 cm. Additional details on the hardware and software were presented in Kocher *et al.*[10]

2.4. Calibration procedure

The metering mechanism for this planter consists of a vertical plate that rotates in a vertical plane parallel to the direction of travel. The seed bin feeds seed to the left side of the plate with the seed cells also on the left side of the plate. In the bottom of each seed cell is a small hole (approximately 1 mm diameter), drilled through to the right side of the plate. These holes allow the pneumatic vacuum (about 10 cm of water) applied through a manifold on the right side of the plate to pull seeds into the cells and hold them there while the plate rotates. The manifold is shaped so that it does not extend over the lower front quarter of the seed cell plate. A star wheel on the right side of the plate in this lower front quarter of the seed plate pushes a protruding point of the star wheel through the small hole in each seed cell to positively eject the seed from the cell into the top of the seed drop tube. The seed drops down the seed drop tube and out the bottom, into the furrow.

The planter was set to space seeds at 9.7 cm while traveling at 3.2 km/h (metering plate speed of 12.4 rpm) in this study. This low speed was within the manufacturer's recommendation, and allowed the planter to operate at a very high performance level for testing the opto-electronic sensor system. Three types of plates were used because of different seed sizes. One seed plate (John Deere part no. A43066) was used with the regular-pelleted sugarbeet seeds. With the same planter and plate operating under the same conditions, Kocher *et al.*[10] determined ISO multiples and miss indices of 0.4 and 0.2%, respectively. Another seed plate (John Deere part no. H136445) was used with the mini-pelleted and medium-encrusted sugarbeet seeds. Yet another seed plate (John Deere part no. A51712) was used with the pelleted chicory seeds. The seed plates had 45 cells and some cells were filled with hot glue to force consistent, easily recognized misses. The pattern was the same as in Kocher *et al.*[10] with three consecutive seed holes filled followed by 10 consecutive seed holes left open, two consecutive seed holes filled followed by 20 consecutive seed holes left open, and one seed hole filled followed by 9 consecutive seed holes left open. This arrangement gave a triple miss, a double miss, and a single miss, with

known seed drop opportunities between them, that were readily recognized visually on the grease belt. This technique was used to allow a match to be made between each seed spacing measurement from the grease belt with the same seed spacing measurement from the opto-electronic system.

2.5. Measurement procedure

The planter, grease belt, and opto-electronic system combination with a simulated planter travel speed of 3.2 km/h was run eight times each with regular-pelleted sugarbeet seeds, mini-pelleted sugarbeet seeds, pelleted chicory seeds, and medium-encrusted sugarbeet seeds. The planter and grease belt were started and run for 30 s or so to reach steady operating conditions before the opto-electronic system was signaled to start collecting data. As soon as the opto-electronic system signaled that it had collected all the data for 25 consecutive seeds, the grease belt and planter were stopped manually as quickly as possible. A tape measure was stretched out beside the seeds on the grease belt and the seed locations determined. The easily recognized pattern of misses and seeds on the grease belt (from the pattern of plugged holes in the seed plate) was compared to the seed spacing data from the opto-electronic system to match the seed spacings from the opto-electronic system with the same seed spacings as measured using the tape measure on the grease belt. Each time the planter/grease belt/opto-electronic system was run, it yielded 18–24 seed spacings for which the different spacing measurements could be compared. This occurred because the reaction time for stopping the grease belt was slow enough that several of the 25 seeds for which the opto-electronic system had colleted data were already off the end of the belt before the grease belt could be stopped for manual measurement of the seed spacings on the belt.[10]

2.6. Spacing adjustment

In normal usage, the opto-electronic sensor system would be used by itself (without the grease belt) with the sensor placed at the furrow-base height. However, for the tests described in this paper, the opto-electronic sensor could not be in the same horizontal plane as the viewing surface of the grease belt, as both systems were operated simultaneously to allow comparison. In addition, the LEDs and phototransistors in the photogate were soldered to printed circuit boards, and the presence of these circuit boards on the side of the photogate prevented the photogate from being placed very close to the top surface of the belt (Figure 1). Consequently, a difference (error) was expected between the grease belt seed spacings and the opto-electronic system seed spac-

ings whenever a consecutive pair of seeds blocked different phototransistors because they had different trajectories in falling from the seed drop tube, through the opto-electronic sensor and onto the grease belt. The height difference between the middle of the LED and phototransistor row and the top of the grease belt was 7 cm, while the bottom of the seed drop tube was only 10.5 cm above the top surface of the grease belt. As the object of this research was to determine whether the opto-electronic system would obtain the same seed spacing data as the grease belt, the following technique was used to adjust the opto-electronic seed spacings for the elevation difference, to allow comparison with the grease belt seed spacings.

The adjustment to the opto-electronic sensor spacing to improve its representation of the seed spacing at the grease belt was developed based on projectile motion (Figure 3). The bottom of the seed drop tube was small, so the location of the seed was assumed to be at the middle of the tube. The velocity of the seed V_0 at the bottom of the tube was approximated using the conversion of potential energy at the seed release point to kinetic energy at the bottom of the seed tube:

$$V_0 = \sqrt{2gh}$$

where the height of fall h is 0.58 m and g is the acceleration due to gravity.
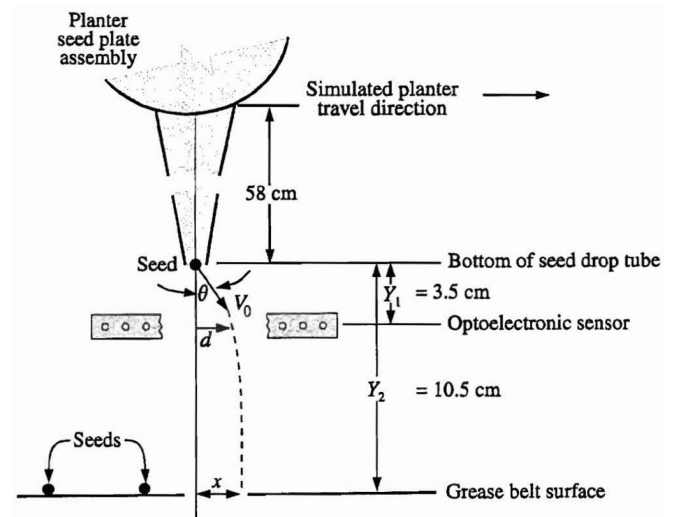

Figure 3. Side view schematic diagram showing the adjustment to the optoelectronic sensor spacing to improve its representation of the seed spacing at the grease belt. V_0 = seed velocity; θ = angle of deflection from vertical; d = horizontal translation of seed at sensor; x = horizontal translation of seed at belt; Y_1 = fall distance from bottom of seed tube to middle of sensor; Y_2 = fall distance from bottom of seed tube to belt.

The distance d was known by the difference between the location of the phototransistor directly under the bottom of the seed drop tube, and the phototransistor channel blocked as the seed passed through the opto-electronic sensor. The known fall distance Y_1 between the bottom of the seed drop tube and the middle of the opto-electronic sensor allowed use of the uniformly accelerated motion equation

$$Y_1 = V_0(\cos(\theta)t_1 + 0.5\, gt_1^2 \tag{1}$$

and solving for the realistic (positive) time t_1 for this portion of the fall gives

$$t_1 = \frac{-V_0\cos\theta}{g} + \sqrt{\left[\frac{V_0\cos\theta}{g}\right]^2 + \frac{2Y_1}{g}} \tag{2}$$

where θ is the angle of deflection from the vertical. The horizontal portion of the projectile motion at the constant horizontal velocity $V_0 (\sin\theta)$ is

$$d = V_0(\sin\theta)t_1 \tag{3}$$

Solving this expression for t_1 and substituting it in Equation (2) gives the following equation:

$$\frac{2Y_1}{g} = \frac{2d\cos\theta}{g\sin\theta} + \frac{d^2}{V_0^2\sin^2\theta} \tag{4}$$

which was solved (using an iterative technique) for θ.

Once the angle θ was determined, the time t_2 for the seed to fall distance Y_2 from the bottom of the seed drop tube to the grease belt was determined:

$$t_2 = \frac{-V_0\cos\theta}{g} + \sqrt{\left[\frac{V_0\cos\theta}{g}\right]^2 + \frac{2Y_2}{g}} \tag{5}$$

and the horizontal distance x traveled by the time the seed reached the grease belt was calculated as

$$x = V_0(\sin\theta)t_2 \tag{6}$$

The adjustment to the opto-electronic seed spacing from the trajectory of this seed in falling to the grease belt was made as follows:

$$S_a = S_0 + (x - d) \tag{7}$$

where S_a is the opto-electronic seed spacing adjusted for the seed fall trajectory and S_0 is the seed spacing measured at the opto-electronic sensor.

A program was written using the analysis outlined above to adjust the opto-electronic seed spacing measurements to obtain opto-electronic seed spacing data theoretically adjusted to the grease belt elevation. Because of the differences in seed trajectories, the adjustments to seed spacing were frequently as large as 1.5 cm, and reached a maximum of 3.8 cm. The adjustments

closely resembled increments of 0.77 cm as seed trajectories changed from seeds passing by one phototransistor to seeds passing by the next one. As the position of each seed measured by the opto-electronic sensor system could have been in error by about half this increment, the seed spacing, involving the position of two seeds, could have been in error by one full increment, or ± 0.77 cm. The adjusted opto-electronic system seed spacings were compared with spacings measured using the grease belt for all the spacings from all the test runs for the regular-pelleted, mini-pelleted, and medium-encrusted sugarbeet seeds, and pelleted chicory seeds.

2.7. Data analysis

Each test run with the grease belt and opto-electronic sensor system yielded 18-24 seed spacings, and each spacing was measured using two different methods. One measurement method involved using a tape measure with the seeds on the grease belt. The other method involved using the opto-electronic system with spacings calculated from the time intervals between seed drop events and front-to-back location of the seeds as they passed through the photogate, relative to the planter, and the trajectory adjustment to the grease belt elevation.

The planter/grease belt system was set to give the smallest possible seed spacings (target spacing was 9.7 cm). The artificially induced misses (induced by plugging planter plate holes) generated spacings of about 19, 29, and 39 cm. These spacings were included in the analyses to allow comparison of seed spacing measurements obtained from the grease belt and the opto-electronic sensor system over a wider spacing range than just the minimum target spacing possible with the planter/grease belt system.

Seed spacing errors were calculated by subtracting each seed spacing obtained using the grease belt from the corresponding adjusted spacing obtained using the opto-electronic system. The variance of these errors was calculated for each test run for each seed type. An ANOVA test was used to see if variances were the same for all seed types (regular-pelleted, mini-pelleted, and medium-encrusted sugarbeet seeds, and pelleted chicory seeds). A regression analysis was used to compare the seed spacings from the grease belt with the corresponding adjusted spacings from the opto-electronic system for the regular-pelleted and mini-pelleted sugarbeet seeds, and pelleted chicory seeds. If the linear model fit the data well (coefficient of determination r^2 close to 1), and the intercept was zero, and the slope was unity, then the adjusted opto-electronic seed spacings were not significantly different from the grease belt seed spacings.

3. Results and discussion

3.1. Differences among seed types

The opto-electronic system worked well in obtaining the seed spacing data. Of the 508 seed spacings with the regular-pelleted and mini-pelleted sugarbeet seeds and pelleted chicory seeds, the opto-electronic sensor system did not miss any seeds, nor detect any extra "phantom" seeds. A few problems were encountered with the seed spacing data obtained from the opto-electronic system with the medium-encrusted sugarbeet seed. The opto-electronic system missed two seeds that were seen on the grease belt, and counted two "phantom" seeds that were not seen on the grease belt.

The two seeds the sensor missed were believed to have presented their smallest axis to block the light between LEDs and phototransistors, and also to have fallen in the middle between the axes of two adjacent channels. This would have resulted in the minimum cross-sectional area to interrupt the light from LEDs to phototransistors in the photogate sensor. It is unlikely the missed seeds were doubles, because the multiple channels of the photogate sensor allow it to readily detect multiple seeds that drop in a front-to-back arrangement. As noted by Kocher *et al.*,[10] multiple seeds in a side-by-side arrangement would be the most difficult for the photogate sensor to detect. The missed seeds had spacings to the nearest seed of 2.5 and 1.3 cm on the grease belt indicating it was unlikely that they fell through the photogate in a side-by-side arrangement. One double that was detected by the photogate sensor during these tests had spacings to the nearest seed of 0.2 cm measured on the grease belt, and 1.4 cm measured by the opto-electronic sensor system (without adjustment for the elevation difference between the grease belt and the photogate sensor). These observations suggested that the missed seeds likely resulted from the medium-encrusted sugarbeet seed size being smaller than the minimum seed size (at least along the minor diameter) that could be reliably detected with the photogate sensor.

The two "phantom" seeds were believed to have been the result of the adjustment of the output voltage for all the phototransistor channels to 1.65 ± 0.02 V to increase the sensitivity of the sensor for the smaller seeds. In general, increasing the sensitivity of photo-electric proximity sensors like those used in the photogate sensor, also increases the risk of false triggering. The data show that in each case, "phantom" seeds were the result of the opto-electronic sensor system indicating two seeds had passed through the sensor at the same time. For the first "phantom" seed occurrence, the opto-electronic sensor system indicated that seeds were present at channels 15 and 17. For the second "phantom" seed occurrence, the opto-electronic sensor system indicated that seeds were present at channels 13 and 15. For each of these "phantom" seed occurrences, one seed is believed to have fallen through the photogate with the seed's major diameter perpendicular to the light paths between the LEDs and phototransistors, in an orientation to block the most light, and in the middle between the axes of two channels. As an example for the first "phantom" seed occurrence, one seed could have fallen in the middle between channels 16 and 17. The light from the LEDs for channels 16 and 17 would have been blocked to the phototransistors for channels 16 and 17. With the sensitivity of the system increased for the medium-encrusted sugarbeet seeds, enough light from the LEDs for channels 16 and 17 would have been blocked from the phototransistors for channels 18 and 15, respectively, to indicate these channels were blocked as well. With channels 15 through 18 blocked, the data acquisition software would have reported that two seeds were present simultaneously, at channels 15 and 17.

It is unlikely that the "phantom" seeds were a result of insects flying through the photogate as the data were obtained on March 25 and 26, 1997. At this time of year it is still winter in Nebraska, and the likelihood of insect flight activity is very low. The most likely reason for the "phantom" seeds is the adjustment to increase the sensitivity of the opto-electronic sensor system for the smaller seeds.

The total number of seed spacings in the eight test runs with medium-encrusted seed was 170. The spacings for the missed seeds and the "phantom" seeds were removed from the seed spacing data set for the medium-encrusted seed before the statistical analyses were performed. The missed seeds and "phantom" seeds indicated that the medium-encrusted seed size was likely smaller than the minimum seed size that could be reliably detected with the opto-electronic system.

The analysis of variance, of the variances in seed spacing errors, among seed types is shown in Table 1. No differences were detected among the variances of the seed spacing errors for the regular-pelleted, mini-pelleted, and medium-encrusted sugarbeet seeds, and the pelleted chicory seeds (Table 1).

3.2. Opto-electronic system and grease belt comparison

The seed spacing data for the regular-pelleted and mini-pelleted sugarbeet seeds and pelleted chicory seeds were pooled into one data set of 508 seed spacings, as the ANOVA showed no differences among the variances of the errors for these seed types. The regression analysis with each seed spacing measured from the grease belt as a function of the corresponding adjusted seed spacing measured from the opto-electronic system

Table 1. Analysis of variance, of the variances of seed spacing errors, for regular-pelleted, mini-pelleted, and medium-encrusted sugarbeet seeds, and pelleted chicory seeds with a planter travel speed of 3.2 km/h. Note that the seed spacing data for the medium-encrusted sugarbeet seeds in this analysis were edited to remove the spacings for the two known missed seeds, and the two known "phantom" seeds

Source	DF	Sum of squares	Mean square	F value	Prob > F
Seed types	3	0.709	0.236	1.26	0.305
Among test runs within seed types	28	5.229	0.187		
Total	31	5.938			

Figure 4. Comparison of 508 adjusted seed spacings from the opto-electronic system with spacings measured from the grease belt for all the spacings from all the test runs for the regular-pelleted and mini-pelleted sugarbeet seeds, and pelleted chicory seeds with a planter travel speed of 3.2 km/h. The regression analysis showed a coefficient of determination (r^2) of 0.977 with a slope of 0.991 and an intercept of 0.19 cm.

had a coefficient of determination r^2 of 0.977, indicating a strong linear relationship (Figure 4). The data shown in the graph (Figure 4) include a total of 508 seed spacings. The intercept of the regression equation was 0.19 cm and the slope was 0.991. The test to determine if the intercept was significantly different from zero resulted in a t value of 2.265 with the probability of a higher t of 0.024. The test to determine if the slope was significantly different from 1 resulted in an F value of 3.687 with the probability of a higher F value of 0.026.

The opto-electronic sensor system had a maximum seed spacing error of ± 0.44 cm by itself. The adjustment for the elevation difference had a maximum error of ± 0.77 cm by itself. Of the combined maximum error (± 0.44 ± 0.77 = ± 1.21 cm), the opto-electronic system error contributed only 36%. To be sure the acceptance region for the regression parameters of the slope and intercept included 95% of the opto-electronic system errors, it would have to include all the adjustment error (± 0.77 cm) and 95% of the opto-electronic system error (± 0.42 cm) for a total acceptance region error of ± 1.19 cm. This resulted in an acceptance region (confidence interval) of 98.3%, or rejection region of 1.7% (α = 0.017). Using this confidence interval, the slope and intercept were not significantly different from unity and zero, respectively. This means that the adjusted opto-electronic seed spacings were not significantly different from the seed spacings measured on the grease belt.

3.3. Limitation

As with the sensor discussed in Kocher *et al.*,[10] seed size in comparison with LED and phototransistor size seemed to be a limiting factor. The opto-electronic system used for this project worked well with regular-pelleted and mini-pelleted sugarbeet seed and pelleted chicory seed. The two missed seeds and two "phantom"
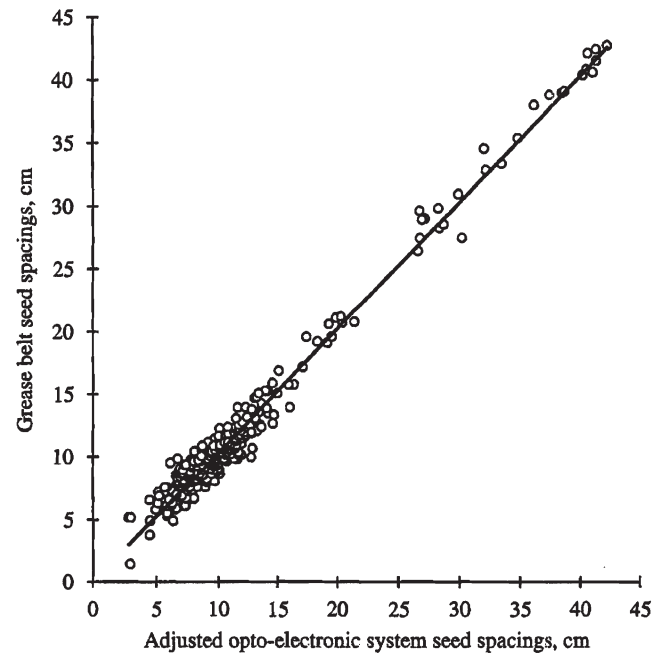
seeds noted in the data from the opto-electronic system for the 170 medium-encrusted seed spacings indicated that the medium-encrusted seed size may be slightly smaller than the minimum seed size that could be reliably detected with this system.

4. Conclusions

Within the error range caused by the elevation difference between the opto-electronic photogate sensor and the grease belt, the seed spacing data obtained from the two systems were not significantly different. The opto-electronic system can be used instead of a grease belt test stand to obtain rapid quantitative laboratory evaluations of planter seed spacing uniformity. The opto-electronic sensor system, with 3 mm diameter LEDs and phototransistors, worked well to obtain 508 seed spacings for regular-pelleted and mini-pelleted sugarbeet seeds and pelleted chicory seeds. The opto-electronic system missed two seeds and detected two "phantom" seeds out of 170 seed spacings with medium-encrusted sugarbeet seed.

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