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Development of a Computerized Measurement System for in-Row Seed Spacing Accuracy

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Abstract: The aim of this study was to develop a computerized measurement system (CMS) combined with a sticky belt test stand for examining in-row seed spacing distribution accuracy. For this purpose 8 performance parameters were selected for precision seeding: mean seed spacing, the standard deviation, the multiples index, the miss index, the quality of feed index, the precision, the population index, and the coefficient of precision (CP-3). The CMS hardware consisted of a high precision optical mouse coupled with a laser pointer and a notebook computer. The use of optical laser technology is a new method for the determination of seed spacing distribution. The CMS stored seed coordinate data, which was input using a simple user interface, and sent to the data to Microsoft Excel for further statistical analysis. The results obtained from this study confirm that the combination of a sticky belt test stand and CMS can be used instead of a digital caliper and steel tape measure to rapidly and correctly obtain quantitative evaluations of seed spacing uniformity in the laboratory.

Key Words: Computerized measurement system, sticky belt test, seed spacing accuracy, precision seeding

Sıra Üzeri Tohum Dağılım Düzgünlüğü İçin Bilgisayar Destekli Ölçme Sistemi Geliştirilmesi

Özet: Bu çalışmanın amacı, tek dane ekimde sıra üzeri tohum dağılım düzgünlüğünü belirlemede kullanılmak üzere, yapışkan bant deney düzeni ile kombine edilmiş, bilgisayar destekli ölçme sistemini (CMS) geliştirmektir. Bu amaçla, tek dane ekim için, ortalama tohum aralığı ve standart sapması, ikizlenme indeksi, boşluk indeksi, besleme kalitesi indeksi, ekim hassasiyeti, popülasyon indeksi ve tohum konumu doğruluk derecesi (CP-3) gibi sekiz ölçüt veya performans parametresi seçilmiştir. Bilgisayar destekli ölçme sistemi (CMS)'nin donanımı, bir dizüstü bilgisayarı ve lazer ışınlı işaretleyici ile birleştirilmiş, yüksek duyarlıklı optik fare'den oluşmuştur. Tohum konumunun ölçülmesi için bilgisayar destekli ölçme sisteminde optik lazer teknolojisinin kullanılması, yeni bir uygulamadır. Bilgisayar destekli ölçme sisteminin yazılımı, basit bir ara yüz kullanarak, tohumların koordinat bilgilerini depolayacak ve daha ileri istatistiksel değerlendirmeler için Microsoft Excel'e gönderecek şekilde düzenlenmiştir. Bu çalışmadan elde edilen sonuçlar, yapışkan bant deney düzeni ile kombine çalışan bilgisayar destekli ölçme sisteminin (CMS), sayısal kumpas veya çelik metreye göre, laboratuarda sıra üzeri tohum aralığı düzgünlüğünün daha çabuk ve doğru bir şekilde belirlenmesinde kullanılabileceğini göstermiştir.

Anahtar Sözcükler: Bilgisayar destekli ölçme sistemi, yapışkan bant testi, tohum aralığı düzgünlüğü, tek dane ekim

Introduction

Precision seeders are designed to sow seeds one at a time in a furrow with predetermined spacing. A wide variety of measurement techniques have been used to quantify seeder performance, with regard to seed/plant spacing (Thomson, 1986; Brooks and Church, 1987). Some tests have used performance measures involving distance between plants in the field. Önal (1975) analyzed in-row plant distribution accuracy by measuring the distances between plants in the field. In that study plant distribution along the row was sampled to roll band paper by a mechanical plant spacing recording device. Punched

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roll band paper was then evaluated with an electronic classification device fitted with an opto-electronic sensor.

A limited number of tests have used performance measures involving the distance between planted seeds (Panning, 1997). Seed spacing measured by digging up seeds after they have been planted includes all the planter performance factors, including those in the seed spacing data obtained from a grease belt test stand, as well as seed bounce and roll in the furrow. Nevertheless, once planted small seeds are difficult to locate and dig out, such as those of the sugar beet, without disturbing their location. An additional major limitation of this method is the time required to locate and dig out the seeds, and measure seed locations. It is a common practice to check spacing accuracy in the laboratory using a sticky belt test stand (Önal, 1981, 1987; Kachman and Smith, 1995). With the sticky belt technique, sticky grease is placed on a board that is pulled under the drop tube. The grease smeared on the belt, having sufficient thickness, prevents seed bounce and roll, as each seed that exits the seeder is captured. Seed spacing on the sticky belt can then be assessed, either manually or by an automatic counter, though manual assessment is time consuming and troublesome work (Burema et al., 1980; Önal, 1987; Karayel et al., 2004).

In order to qualify the accuracy of precision seeders, seed spacing distribution is obtained using a sticky belt test stand or on opto-electronic sensor system (Lorenz, 1959; Müller et al., 1994). An opto-electronic system can be used instead of a sticky belt test stand to rapidly obtain quantitative evaluations of seeder performance, in terms of spacing uniformity, with an effective diameter of about 3 mm or larger (Kocher et al., 1998). Software analyzes the data and outputs numerical and graphical (histogram of seed spacing) results. Results indicate that seed spacing measurements obtained using an opto-electronic system are strongly correlated with spacing measurements obtained using a greased belt test stand. On the other hand, it was reported that there are 2 limitations to the use of opto-electronic systems. First, the photogate used with this experiment includes 5-mm diameter LEDs and photo-transistors. Seeds with an effective diameter less than about 3 mm have not consistently blocked enough of the light beam to reliably trigger the photo-transistors. The second limitation relates to detection of multiple seeds passing through the photogate at the same time. This could occur if 2 small seeds fit into 1 plate cell and are dropped from the seeder at the same time. If 2 seeds fall side by side across the row, 1 seed would be traveling in the shadow of the other, and so no additional photo-transistors would be able to detect the additional seed. Yet, Lan et al. (1999) reported that an opto-electronic sensor system with 3-mm diameter LEDs and phototransistors worked well for obtaining 508 seed spacing for regular-pelleted and mini-pelleted sugar beet seeds, and pelleted chicory seeds. The opto-electronic system missed 2 seeds and detected 2 “phantom” seeds.

Conventional market frame light barriers produce a 1-dimensional beam grid with individual receiver diodes that are connected in parallel; therefore, seeds that drop simultaneously cannot be registered individually. Moreover, the high speed of seeding machines results in considerable measurement errors. In order to determine the dropping point, a light-barrier with a 2-dimensional beam grid was developed with receiver diodes connected in serial (Köller et al., 1997). This system facilitates the precise determination of the X-Y coordinates at which individual seeds pass the light barrier; measuring error was 4%, with a 100-Hz reliable seed frequency level and minimum seed diameter of 1 mm.

As the trajectories of seeds falling from the planter are not the same, seed distances obtained from seed trajectories do not represent actual seed spacing. The trajectories of falling seeds could be different as the release angles of seeds from the seed discharge device are not the same; therefore, the front-to-back location approach is required to estimate the seed drop location using seed trajectories. The measurement error of electronic sensor systems with front-to-back location relative to the seeder is 0.14 cm by 15 cm target seed spacing and 4.8 km h^{-1} travel speed (Kocher et al., 1998).

Some studies were carried out using precision balance or camera systems for determining seed spacing distribution in the laboratory. During such tests the precision balance was placed directly under the feed unit and the material that flowed from the feed roll was weighed continuously and cumulatively by a precision balance, and the data were transmitted to a PC. Flow rate (g s^{-1}) and flow evenness (CV, %) were determined for each roll (Güler, 2005). The results showed that measuring inaccuracy of the opto-electronic measurement system was higher than that of the camera system (Karayel, 2007).

Although opto-electronic systems are costly and include complex hardware and software, they can fail in particular conditions, as mentioned above; therefore, a measurement system was conceived for the rapid and accurate evaluation of in-row seed spacing distribution.

The aim of the present study was to develop a computerized measurement system (CMS) in order to determine equidistance seed spacing distribution on a sticky belt, based on 8 performance parameters: mean seed spacing, the standard deviation, the multiples index, the miss index, the quality of feed index, the precision, the population index, and the coefficient of precision (CP-3).

Materials and Methods

Seeds

Hybrid maize (AG 9241) and delinted cotton seeds (Deltapine 388) were used; seed specifications are given in Table 1.

Sticky Belt Test Stand and Precision Seeder

A sticky belt test stand was coupled with the CMS. The sticky belt test stand had a 15-cm wide leader belt with a horizontal viewing surface that was 11 m long. The test unit was equipped with a multi-speed drive arrangement to provide a range of belt surface speeds, ranging from 1.8 to 7.2 km h^{-1}, relative to a stationary seeder mechanism. In order to provide the theoretically correct seed spacing, the seed planting mechanism was driven by another multi-speed drive arrangement. Special care was taken to ensure synchronization of the travel speed associated with the peripheral speed of the seed plate and the sticky belt speed. Grease oil was smeared on the top surface of the belt to capture seeds as they were released from the seeder, without the seeds rolling or bouncing on the belt surface (Figure 1a). Preliminary tests showed that the greased surface of the leather belt captured the seeds at sticky belt speeds below 2 m s^{-1}.

The precision seeding unit used for these tests was a Gaspardo (Italy) model ST. The ST pneumatically operated vacuum-type precision seeder had a ground-driven wheel that transferred motion to the vertical seed plate with a combination of available gears. The height of the seed drop was 8 cm. Details of the sticky belt tests are given in Table 2.

Computerized Measurement System (CMS) Hardware and Software

The CMS hardware consisted of a high precision (1000 dpi) optical mouse coupled with a laser pointer and a notebook computer. The optical mouse (Microsoft Optical Mouse 3000) used a USB cable extension (5 m) and was affixed to a wooden guidance apparatus, which enabled only 1-dimensional movement on the polished ply-wood along the sticky belt (as shown in Figure 1a). The line laser pointer was installed on the guidance apparatus so that the laser beam fell perpendicular to the sticky belt (Figure 1b). The distance between the mouse and sticky belt was set at 40 cm for ergonomic purposes. Preliminary tests showed that seeds with a diameter larger than 1 mm (i.e. canola seeds) could be seen by using contrasting colored grease on the sticky belt. The laser beam ensured precise alignment between the optical mouse and the seeds under indoor conditions. Light meter (Lutron model Lx-1108) measurement during the tests showed that there were no difficulties seeing the laser line on the sticky belt with illumination below 720 lux. Under the laboratory conditions, units of illumination along the sticky belt were measured between 67 and 264 lux. It was impossible to work under direct sunlight. In order to conduct the test in the laboratory, it is necessary to move the mouse along the sticky belt. If the laser beam falls

Table 1. Specifications of the seeds used in this study.

Seeds	Seed dimensions (mm) ($\bar{X}_i \pm S_e^{**}$) Length (a)	Width (b)	Thickness (c)	Sphericity* K (%)	Seed mass (g/1000 seeds)
Hybrid maize (AG 9241)	11.5 ± 0.18	8.6 ± 0.18	6.9 ± 0.15	76.6	437.0
Delinted cotton seed (Deltapine 388)	8.5 ± 0.11	4.9 ± 0.11	4.3 ± 0.07	66.1	74.2

$K^{*} = (a,b,c)^{1/3}/a \times 100$ (Mohsenin, 1970), $^{**}(P < 0.05)$

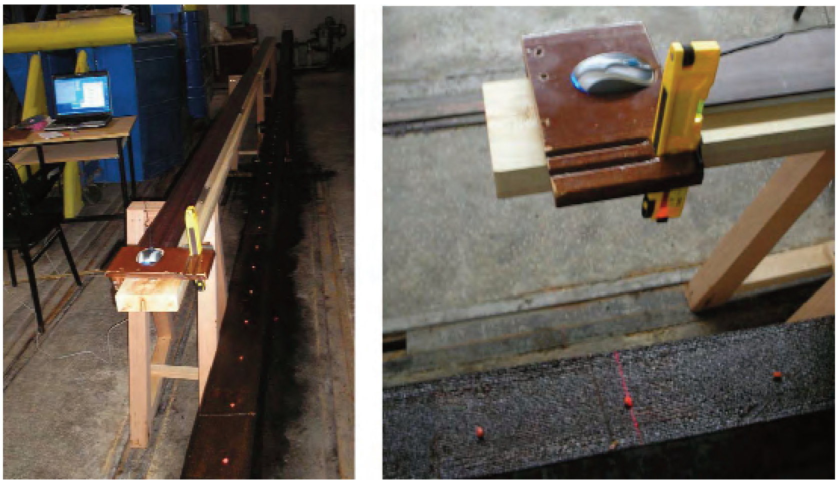


Figure 1. The CMS (a), sticky belt, mouse, mouse guide, and line laser source (b).

Table 2. Details of the sticky belt tests.

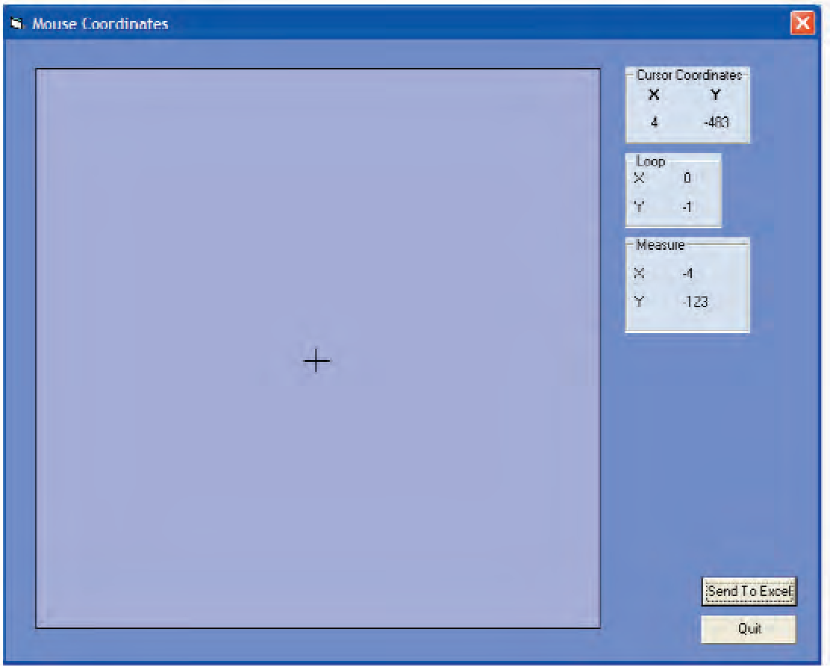
Single seed planting unit	Seeds	Target seed spacing (cm)	Travel (belt) speed (m s^{-1})	Seed plate			Vacuum Pressure (kPa)
				Diameter (cm)	Hole diameter (cm)	Number of Holes (k)	
ST	Cotton	5-10	1.0-1.5-2.0	19	3.5	72	6.3
Model	Maize	20	1.0-1.5-2.0	19	4.5	26	6.3

over a seed, the operator must click the mouse button, which stores the coordinate of the seed; therefore, special software was developed for this system in Microsoft Visual Basic.

The CMS software can be divided into 2 parts. The first was written in Microsoft Visual Basic. The program stores seed coordinate data using a simple user interface and sends the data to Microsoft Excel for further statistical analysis (Figure 2). In order to store the coordinate data, the mouse pointer was restricted to an area on the screen. Once the mouse pointer reached a border, it was programmed to continue from the opposite border to ensure a measuring distance larger than the notebook's display area. Because the software was sensitive to mouse movement, the program was controlled by the keyboard. At the end of the test seed distribution data was exported automatically by starting Microsoft Excel, in which the statistical analysis of the test results was programmed in VB Macros (Figure 3), according to the theory explained below.

Evaluation of the Seed Spacing Distribution

A number of measures based on the theoretical spacing of the seeder were defined by the International Organization for Standardization, as ISO Standard 7256/1-1984E (ISO, 1984). These measures include the quality of feed index, multiples index, miss index, and precision. In addition of these values, the population index and the coefficient of precision (CP-3) were used. In the present study target spacing was determined based on the planter drive rotational speed and transmission ratio, and used as a theoretical spacing (Z_t). A typical histogram of the precision seeder's seed spacing is given in Figure 4, in which Z_t, Z_{tot}, and Z_m values are the target (theoretical) seed spacing, mean seed spacing of the entire seed distribution, and mean seed spacing of the main seed distribution, respectively. Both Z_t- and Z_{tot}-based evaluations of seed distribution provide valuable data concerning in-row seed spacing accuracy. Z_t, Z_{tot}, and Z_m values are approximately the same when multiples and miss indexes are low. With the software developed for the

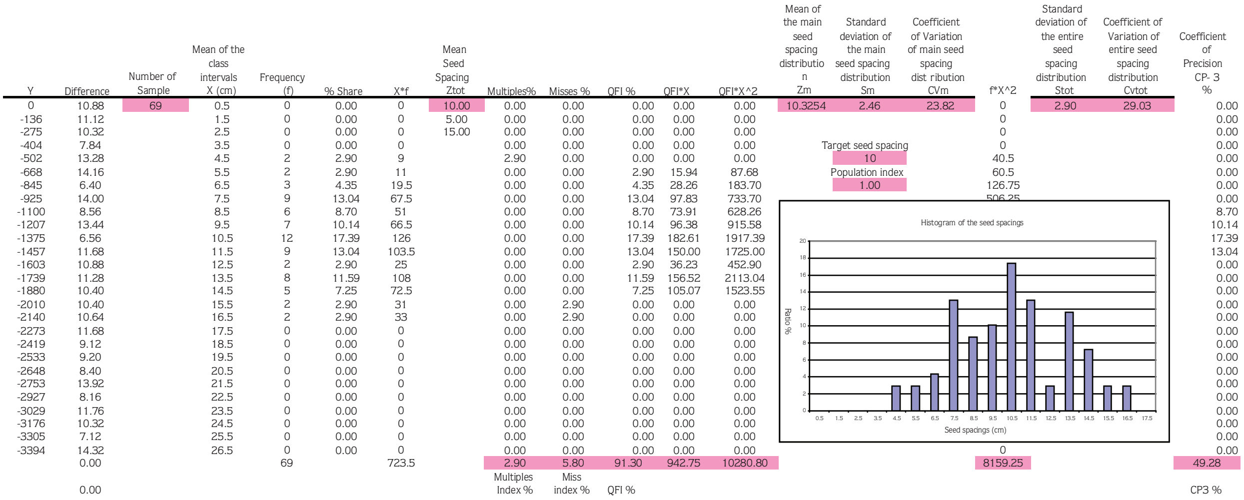


Cursor Coordinates
X 4
Y -483

Loop
X 0
Y -1

Measure
X -4
Y -123

Figure 2. The user interface of the Visual Basic software.



Y	Difference	Number of Sample	Mean of the class intervals X (cm)	Frequency (f)	% Share	X*f	Mean Seed Spacing Ztot	Multiples%	Misses %	QFI %	QFI*X	QFI*X^2	Mean of the main seed spacing distribution Zm	Standard deviation of the main seed spacing distribution Sm	Coefficient of Variation of main seed spacing dist ribution CVm	f*X^2	Standard deviation of the entire seed spacing distribution Stot	Coefficient of Variation of entire seed spacing distribution Cvtot	Coefficient of Precision CP- 3 %
0	10.88	69	0.5	0	0.00	0	10.00	0.00	0.00	0.00	0.00	0.00	10.3254	2.46	23.82	0	2.90	29.03	0.00
-136	11.12		1.5	0	0.00	0	5.00	0.00	0.00	0.00	0.00	0.00				0			0.00
-275	10.32		2.5	0	0.00	0	15.00	0.00	0.00	0.00	0.00	0.00				0			0.00
-404	7.84		3.5	0	0.00	0		0.00	0.00	0.00	0.00	0.00		Target seed spacing		0			0.00
-502	13.28		4.5	2	2.90	9		2.90	0.00	0.00	0.00	0.00		10		40.5			0.00
-668	14.16		5.5	2	2.90	11		0.00	0.00	2.90	15.94	87.68		Population index		60.5			0.00
-845	6.40		6.5	3	4.35	19.5		0.00	0.00	4.35	28.26	183.70		1.00		126.75			0.00
-925	14.00		7.5	9	13.04	67.5		0.00	0.00	13.04	97.83	733.70				506.25			0.00
-1100	8.56		8.5	6	8.70	51		0.00	0.00	8.70	73.91	628.26							8.70
-1207	13.44		9.5	7	10.14	66.5		0.00	0.00	10.14	96.38	915.58							10.14
-1375	6.56		10.5	12	17.39	126		0.00	0.00	17.39	182.61	1917.39							17.39
-1457	11.68		11.5	9	13.04	103.5		0.00	0.00	13.04	150.00	1725.00							13.04
-1603	10.88		12.5	2	2.90	25		0.00	0.00	2.90	36.23	452.90							0.00
-1739	11.28		13.5	8	11.59	108		0.00	0.00	11.59	156.52	2113.04							0.00
-1880	10.40		14.5	5	7.25	72.5		0.00	0.00	7.25	105.07	1523.55							0.00
-2010	10.40		15.5	2	2.90	31		0.00	2.90	0.00	0.00	0.00							0.00
-2140	10.64		16.5	2	2.90	33		0.00	2.90	0.00	0.00	0.00							0.00
-2273	11.68		17.5	0	0.00	0		0.00	0.00	0.00	0.00	0.00							0.00
-2419	9.12		18.5	0	0.00	0		0.00	0.00	0.00	0.00	0.00							0.00
-2533	9.20		19.5	0	0.00	0		0.00	0.00	0.00	0.00	0.00							0.00
-2648	8.40		20.5	0	0.00	0		0.00	0.00	0.00	0.00	0.00							0.00
-2753	13.92		21.5	0	0.00	0		0.00	0.00	0.00	0.00	0.00							0.00
-2927	8.16		22.5	0	0.00	0		0.00	0.00	0.00	0.00	0.00							0.00
-3029	11.76		23.5	0	0.00	0		0.00	0.00	0.00	0.00	0.00							0.00
-3176	10.32		24.5	0	0.00	0		0.00	0.00	0.00	0.00	0.00							0.00
-3305	7.12		25.5	0	0.00	0		0.00	0.00	0.00	0.00	0.00							0.00
-3394	14.32		26.5	0	0.00	0		0.00	0.00	0.00	0.00	0.00				0			0.00
	0.00			69		723.5		2.90	5.80	91.30	942.75	10280.80				8159.25			49.28
	0.00							Multiples Index %	Miss index %	QFI %									CP3 %

Figure 3. Output of the statistical analyses performed in Microsoft Excel using VB Macro programming (as an example: Z_t-based evaluation, CMS test 4, Table 4).

CMS, evaluation is initially based on the Z_{tot} value. Total seed spacing uniformity, and multiple and miss indexes, therefore, are calculated according to the Z_{tot} value; however, Z_t-based evaluation can also be computed by entering the Z_t value instead of the calculated Z_{tot} value in the program developed for Excel.

Three different seed spacing groups, according to Z_t, can be classified in Figure 4, and 3 indexes can be defined:

I. The multiples index is the percentage of spacing that is less than or equal to half of the theoretical seed spacing, and indicates the percentage of multiple seed drops (0 to $\leq 0.5\ Z_t$).

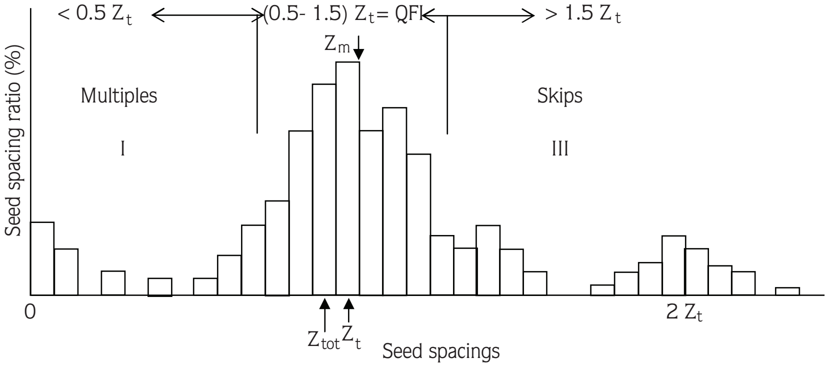


Figure 4. A typical histogram of seed spacing obtained with a sticky belt test stand.

II. Quality of feed index (acceptable seed spacing, QFI, %) is the percent values with a seed spacing within the range from bigger than 0.5 times the theoretical seed spacing to equal or smaller than 1.5 times the theoretical seed spacing. Quality of feed index is calculated by subtracting miss and multiples indexes from 100, and indicates the percentage of single seed drops ($> 0.5\ Z_t$ to $\leq 1.5\ Z_t$).

III. The miss index is the percentage of spacing greater than 1.5 times the theoretical seed spacing and indicates the percentage of missed seed locations or 'skips' ($> 1.5\ Z_t$).

Precision is the coefficient of variation (CV_m) of the spacing that is classified as singles after omitting the outliers that consist of misses and multiples (CV of the main seed distribution curve, II). Seed spacing uniformity of the main seed distribution (II), known as precision, is expressed by the coefficient of variation (CV, %):

$$CV_m = \frac{S}{Z_m} \times 100 \qquad (1)$$

where S is the standard deviation of the main seed distribution and Z_m is the mean seed spacing of the main seed distribution curve (II). Standard deviation (S) can be calculated by Equation 2 from the histogram of the seed spacing (Düzgüneş, 1963).

$$S = \sqrt{\frac{\sum_{i=1}^{k} f_i X_i^2 - \frac{\left(\sum f_i X_i\right)^2}{\sum f_i}}{\sum^{k} f_i - 1} - \frac{c^2}{12}} \qquad (2)$$

where X_i is the midpoint of the i^{th} class values, f_i is the frequency of i^{th} class, $\sum_{i=1}^{k} f_i$ is the sum of the frequencies, and $c^2/12$ is the Sheppard's correction. In the present study, c class width was equal to unity and was neglected. ISO Standard 7256/1-1984 uses a population standard deviation. The standard deviation for the data of a sample is defined with N-1; replacing N represents a better estimate of the standard deviation of a population from which a sample is taken (Spiegel, 1961). Fisher (1948) preferred N-1 instead of N; however, for more than 100 variants the difference between 2 results is not significant.

The population index is the deviation from the theoretical population and is expressed as a decimal number (Z_{tot}/Z_t). The planting population decreases in plate-type and some vacuum-type metering units (i.e. population index < 1), as the speed increases over the recommended seed-plate speed (Breece et al., 1975). This problem is caused by the seed plate rotating too fast for the seeds to be properly caught by the cells. As the speed of the seed plate decreases to below the recommended value, the planting population increases (i.e. population index > 1).

Brinkmann et al. (1980) proposed the use of a new parameter for seed spacing comparisons. This parameter, known as the 3-cm mode range, was determined to be a better representation of the ability of a precision seeder to space seeds or plants near the actual precision seeder spacing setting than using the combination of average spacing and standard deviation. The 3-cm (1.2-in) mode range provides easier visualization for comparison of precision seeders than other measures. Other researchers have also used the 3-cm mode range as a measure for evaluating precision seeder performance (Önal, 1983; Irla and Heusser, 1991; Smith et al., 1991; L'Institut

Technique Français de la Betterave Industrielle, 1994; Panning et al., 2000). They referred to it as the coefficient of precision (CP-3) or the precision of seed location (PSL). As an example, if the spacing between the seeds is 0.9 cm, 20.4 cm, 39.2 cm, 19.3 cm, 20.4 cm, 20.5 cm, 1.4 cm, 0.7 cm, and 18.6 cm, this indicates that the first 2 seeds were a double, a seed was missed between the 3rd and 4th seeds, seeds 7, 8, and 9 were a triple, and all the other seeds were planted normally. The CP-3 would include only spacings that were within ±1.5 cm of the theoretical spacing of 20 cm, so that spacings within the range of 18.5 cm to 21.5 cm would be counted in the CP-3. In this example, 5 of the 9 spacings were within this range, and so the CP-3 value would be 55.5. Irla and Heusser (1991) used the 3-cm mode range for sugar beet seed, and the 4-cm mode range for maize seed. Irla and Heusser (1991), and Önal (2006) recommended test criteria to evaluate the uniformity of precision seeders. Kachman and Smith (1995) stated that a precision of 29% would indicate that all the spacings were uniform within the target range.

Measurement Procedure for the Performance of the CMS

In order to determine the measuring deviation of the CMS, 5-cm, 10-cm, and 20-cm target spacings were traced with a flexible steel tape measure located on the sticky belt by the operator using the CMS. The mean of the measured values (Z), standard deviation (S), and standard error of the mean ($S_{\overline{X}}$) were calculated.

Methods for the Comparison of the Seed Spacing Measurement Techniques

In all, 27 tests with 1.0, 1.5, and 2.0 m s^{-1} travel speeds, and 5-, 10-, and 20-cm target seed spacing were conducted in order to compare 3 different measurement techniques. Miss index, multiples index, quality of feed index, mean seed spacing value of main seed distribution, precision, population index, and CP-3 values were calculated. One measurement technique involved using a steel tape measure with seeds on the sticky belt. In this technique, seed spacing was manually measured by the operator using a steel tape measure. With the second technique seed spacing on the sticky belt was measured by the operator using a digital caliper. Finally, with the third technique seed spacing on the sticky belt was traced using the CMS. In order to compare the 651 seed spacing values measured with the 3 techniques, regression analysis was used and coefficient of determination (R^2) values were calculated.

Methods for the Time Analysis of the Seed Spacing Measurement Techniques

In order to determine the time requirement of the 3 seed spacing measurement techniques for 5-, 10-, and 20-cm seed spacings, measuring speeds were recorded with a stop watch (s m^{-1}). The measuring cycle time for 5-, 10-, and 20-cm seed spacing was composed of 2 segments:

- Active measurement time for 250 seed spacing,
- Return time depending on the return number. Average return time for a single return was taken as 15 s.

From these values, cycle time (seconds per 250 seed spacing) was calculated. According to ISO Standard 7256/1-1984 E, minimum 250 seed spacing must be measured. Total length of the sticky belt was 12.5 m, 25 m, and 50 m for 5-cm, 10-cm, and 20-cm seed spacing, respectively. Accordingly, return numbers to complete each test were 1, 3, and 6 for 5-cm, 10-cm, and 20-cm seed spacing, respectively, when the actual length of the sticky belt was 7.5 m.

Results

Performance Analysis of the CMS

Standard deviation of the CMS for 5-cm, 10-cm, and 20-cm spacing varied by ±0.11 cm, ±0.126 cm, and ±0.199 cm, respectively (Table 3). These values are very small and are quite acceptable. The limits of the confidence intervals of the mean of the population varied by 5.00 ± 0.014 cm, 10.02 ± 0.016 cm, 20.00 ± 0.025 cm for the 95% confidence level. Coefficients of variation for 5-, 10-, and 20-cm seed spacing were 2.20%, 1.26%, and 0.99%, respectively.

Comparison of Seed Spacing Measurement Techniques

Cotton and maize seed distribution patterns were analyzed according to 3 different measurement techniques, and are shown in Table 4, in which both Z_t- and Z_{tot}-based evaluation of seed spacing distribution can be seen. Evaluation was initially based on the Z_{tot} value. Z_t-based evaluation can also be computed by entering the Z_t value instead of the Z_{tot} value in the Excel sheet.

Table 3. CMS performance.

Target seed spacing Z_t cm	Mean of the measured values $\vec{Z}$ cm	Standart deviation S ±cm	Coefficient of variation CV %	Number of seed spacing measured n	Standard error of a mean $S_{\bar{x}} = \sqrt{\frac{S^2}{n}}$	Mean of the population and confidence intervals $(P < 0.05)$ $\mu = \bar{Z} \pm t \times S\bar{x}$ cm
5	5.00	0.110	2.20	250	0.0069	5.00 ± 0.014
10	10.02	0.126	1.26	250	0.0080	10.02 ± 0.016
20	20.00	0.199	0.99	250	0.0126	20.00 ± 0.025

Table 4. Seed distribution patterns for cotton (5 cm and 10 cm) and maize (20 cm) seeds determined with CMS, digital caliper, and tape measure techniques.

Measuring techniques Test #	Travel speeds m s^{-1}	Z_t cm	Z_{tot} cm	Population index Z_{tot}/Z_t	Multiple index %	Miss index %	Q. feed index %	Z_m cm	Precision CV_m %	CP-3 %
CMS (1)	1.0	5	5.11	1.022	20.42	11.27	68.31	5.47	24.88	56.34
D. caliper	1.0	5	5.17	1.034	18.44	12.77	68.79	5.42	23.53	59.57
T. meter	1.0	5	4.87	0.974	20.42	7.75	71.83	5.36	26.17	58.45
CMS (2)	1.5	5	5.27	1.054	27.74	24.82	47.45	5.11	29.14	38.69
D. caliper	1.5	5	5.40	1.080	26.47	27.94	45.59	4.98	28.40	39.71
T. meter	1.5	5	5.09	1.018	29.20	24.82	45.99	5.04	29.44	38.69
CMS (3)	2.0	5	5.26	1.058	30.15	20.59	49.26	5.32	27.82	39.71
D. caliper	2.0	5	5.46	1.092	27.41	22.96	49.63	5.28	28.81	40.00
T. meter	2.0	5	5.09	1.018	33.82	19.12	47.06	5.39	27.56	36.76
CMS (4)	1.0	10	10.49	1.049	2.90	5.80	91.30	10.32	23.82	49.28
D. caliper	1.0	10	10.63	1.063	2.90	5.80	91.30	10.44	22.44	55.07
T. meter	1.0	10	10.25	1.025	4.35	5.80	89.86	10.16	22.90	50.72
CMS (5)	1.5	10	10.22	1.022	7.04	9.86	83.10	10.09	23.72	50.70
D. caliper	1.5	10	10.25	1.025	7.04	9.86	83.10	10.16	23.25	49.30
T. meter	1.5	10	9.88	0.988	8.45	5.63	85.92	10.14	23.77	47.89
CMS (6)	2.0	10	9.94	0.994	5.63	5.63	88.73	9.91	28.85	33.80
D. caliper	2.0	10	10.09	1.009	2.82	9.86	87.32	9.61	28.57	36.62
T. meter	2.0	10	9.75	0.975	4.23	5.63	90.14	9.64	28.97	36.62
CMS (7)	1.0	20	20.08	1.004	0.00	0.00	100.00	20.08	9.62	84.06
D. caliper	1.0	20	20.20	1.010	0.00	0.00	100.00	20.20	9.56	82.61
T. meter	1.0	20	19.92	0.996	0.00	0.00	100.00	19.92	10.03	81.16
CMS (8)	1.5	20	21.14	1.057	0.00	1.52	98.48	20.84	11.04	65.15
D. caliper	1.5	20	21.24	1.062	0.00	1.52	98.48	20.92	10.79	68.18
T. meter	1.5	20	20.89	1.040	0.00	1.52	98.48	20.60	11.19	71.21
CMS (9)	2.0	20	22.06	1.103	3.13	6.25	90.63	21.15	7.52	68.75
D. caliper	2.0	20	22.19	1.110	3.13	6.25	90.63	21.29	6.84	68.75
T. meter	2.0	20	21.94	1.097	3.13	6.25	90.63	21.05	7.16	68.75

Generally, it could be concluded that the performance criteria calculated by the 3 measurement techniques were approximately the same.

The cotton and maize seed spacing data obtained using the 3 measurement techniques were pooled into 1 data set of 651 seed spacings. Regression analyses were used to compare the accuracy of seed spacing values obtained with the CMS, a digital caliper, and a steel tape measure. Results indicate that seed spacing measurements obtained using the CMS were strongly correlated (coefficient of determination $R^2 = 0.9969$, $P < 0.05$) with the same seed measurements obtained using a digital caliper (Figure 5). 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 CMS seed spacing measurement was not significantly different than that of the digital caliper. Regression analysis between each seed spacing measured with a steel tape measure on the grease belt and the corresponding seed spacing measured with the CMS had a coefficient of determination (R^2) of 0.9956 ($P < 0.05$), which also indicates a strong linear relationship (Figure 6). The data shown in Figure 6 include a total of 651 seed spacings; however, it can be seen from Figures 5 and 6 that the relationship between the CMS and digital caliper had a higher R^2 value than that between the CMS and steel tape measure. The CMS can be used instead of a steel tape measure or digital caliper to obtain rapid quantitative laboratory evaluations of precision seeder seed spacing uniformity.

Comparison of Operation Time and Labor Work Analysis

Time requirements of the CMS are given in Table 5. The results show that a complete CMS measurement required 14.23, 16.63, and 22.42 min per 250 seed spacings for 5-cm, 10-cm, and 20-cm seed spacing, respectively. One person was sufficient to conduct the sticky belt test. After testing, the software we developed analyzed the data and simultaneously output the results numerically and graphically (histogram of seed spacing). Seed spacing could be measured by the CMS with 1/100-cm precision; however, digital caliper measurement required 2 persons. The time required to complete the tests with a digital caliper was 24.20, 27.58, and 28.50 min per 250 seed spacings for 5-cm, 10-cm, and 20-cm seed spacing, respectively. Seed spacing measured with a digital caliper had a precision of 1/100 cm. Measurement with a steel tape measure also required 2 persons and seed spacing was measured with 0.5-cm precision. The time required to complete the tests with a steel tape measure was 17.76, 18.84, and 22.84 min per 250 seed spacings for 5-cm, 10-cm, and 20-cm seed spacing, respectively. Additionally, the digital caliper and steel tape measure techniques required an extra 64 min to calculate the quality of feed index, multiples index, missing index, precision, population index, and CP-3 values, and to draw the histogram.

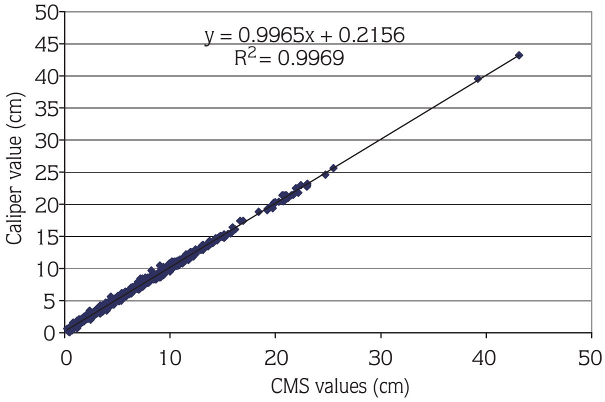


Figure 5. Comparison of 651 seed spacings measured with the CMS with those measured from the grease belt with a digital caliper. Regression analysis shows a coefficient of determination (R^2) of 0.9969 ($P < 0.05$), with a slope of 0.9965 and an intercept of 0.2156 cm.

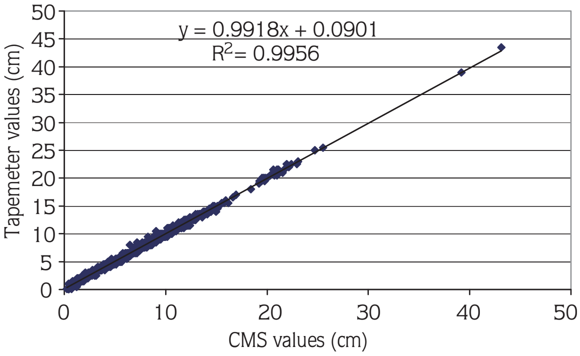


Figure 6. Comparison of 651 seed spacings measured with the CMS with those measured from the grease belt with a steel tape measure. Regression analysis shows a coefficient of determination (R^2) of 0.9956 ($P < 0.05$) with a slope of 0.9918 and intercept of 0.0901 cm.

Table 5. Time requirement and labor work analysis for CMS, digital caliper, and steel tape measure techniques (mean of 10 values).

	CMS			Digital caliper			Steel tape meter		
	Time requirement		Labor requirement	Time requirement		Labor requirement	Time requirement		Labor requirement
Seed spacing cm	s m^{-1}	Second per 250 seed spacing	minutes per 250 seed spacing (one person)	s m^{-1}	Second per 250 seed spacing	minutes per 250 seed spacing (two person)	s m^{-1}	Second per 250 seed spacing	minutes per 250 seed spacing (two person)
5	67.1 ± 1.8*	854	14.23	56.9 ± 0.7	726	24.20	41.4 ± 0.6	533	17.76
10	38.1 ± 1.8	998	16.63	31.3 ± 0.6	828	27.58	20.8 ± 0.3	565	18.84
20	25.1 ± 1.9	1345	22.42	15.3 ± 0.4	855	28.50	11.9 ± 0.2	685	22.84

* Standard error.

Discussion

The CMS described in this work successfully determined seeding machine seed spacing distribution. The standard deviation of the 250 spacings measured in the test by the CMS for 5-cm, 10-cm, and 20-cm spacing varied by ±0.11 cm, ±0.126 cm, and ±0.199 cm, respectively. Seeder travel speed, seed diameter (≤ 1 mm), and seed spacing were not restrictive parameters for the CMS. As the final positions of the seeds were on the sticky belt, misdetections of the seeds were not observed; however, Kocher et al. (1998) indicated that the measurement error for opto-electronic sensor systems with a front-to-back location relative to the seeder was 0.14 cm by 15 cm target seed spacing and 4.8 km h^{-1} travel speed. At higher speeds variation in front-to-back location of seed drops increased and at a seeder travel speed of 8.05 km h^{-1} it was impossible to detect the position of the seeds with the sensor. The high speed of seeding machines, seed diameter (< 3 mm), multiple seeds passing through the photo-gate at the same time, and phantom seeds (i.e. flying insects in the air) result in considerable measurement error (Lan et al., 1999).

Results of the present study indicate that seed spacing measurements obtained using the CMS were strongly correlated (R^2 = 0.9969, $P < 0.05$) with the seed measurements obtained using a digital caliper; however, it can be seen from Figures 5 and 6 that the CMS had a higher coefficient of determination (R^2) value than a steel tape measure. The combination of a sticky belt stand and the CMS can be used to rapidly and accurately obtain quantitative evaluations of seed spacing uniformity in the laboratory. Tests longer than the sticky belt length can also be performed by fragmenting a complete test into parts. The software we developed analyzed the data and output the results in numerical (ISO Standard indexes of quality-of-feed index, multiples index, miss index, and precision) and graphical (histogram of seed spacings) form. The developed program can also provide the results of the population index and the coefficient of precision (CP-3). The setup is designed so that the system can be used by a semi-skilled technician. The major advantage of this method is the rapid evaluation of test results (i.e. at the end of the data input). Digital caliper and steel tape measure techniques required an extra 64 min (excluding measurement time) to analyze the data and to output results in numerical and graphical form; however, the CMS required only 14.23-22.42 min, including measurement and evaluation of tests, according to seed spacing values. Therefore, the researcher was able to simultaneously check the test data to repeat the test.

Laboratory testing with a greased belt (or an opto-electronic sensor system) does not account for seed bounce or seed movement from bounce and roll in the furrow, and while being covered by soil it does not adequately predict seed spacing uniformity of seeders in the field. Field testing of seeders that perform well in laboratory tests must be undertaken to adequately determine seed spacing uniformity in the field.

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