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Prospective study of the technology for evaluating and measuring in-row seed spacing for precision planting: A review

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Abstract

Corn is the most cultivated and consumed cereal in the world. The overall objective of this review was to study the methodologies to measure and evaluate the in-row seed spacing for precision planting as well as to determine the technological alternatives that would allow obtaining information about seed mapping for corn crop planting in precision agriculture applications. As a conceptual synthesis about the electronic measurement system, there are two strategies for determining in-row seed spacing in the precision planting. Indirect methods correspond to the measurement before the seeds reach the furrow, while direct methods correspond to the measurement with the seeds placed in the furrow. The indirect measurement strategy is the most widely used in research publications and commercial planter monitors. Within this method, the seed spacing measurement systems use optical or radio wave type seed sensors. Corn seed counting accuracy through electronic measurement systems with optical-type seed sensor is at least 96%. The microwave seed sensor is used commercially by a few companies whose technologies are patented. The direct measurement strategy is under development and requires further research. The main limitation of these technologies is the seed detection in the furrow, which limits the planter travel speed and the equipment cost. The conceptual proposal for the term 'seed mapping' is to provide integrated and geo-referenced information on in-row seed spacing and depth for precision planting.

Additional key words: corn; seed sensor; seed mapping; planter monitor; precision agriculture.

Abbreviations used: A (quality of feed index); CP3 (coefficient of precision); CV (coefficient of variation); D (multiples index); Δt (time interval between seeds); Dp (diameter of the drive pulley); ds (displacement speed of belt or brush in seed delivery device); DV (dot value); e (error); g (gravity acceleration); GIS (geographic information system); GNNS (global navigation satellite system); GPR (ground penetrating radar); H (seed falling height from seed meter to the furrow); IR (infrared); L (distance from seed sensor to at the bottom of the seed delivery device); LD (planting length); M (Miss index); MES (measurement electronic systems); n (pulley rotation speed of the seed delivery device); P (precision); PA (precision agriculture); ps (planter travel speed); RFID (radio frequency identification); RTK-GPS (real-time kinematic-global positioning system); rw (row spacing); SD (standard deviation); SF (smart farming); ss (in-row seed spacing); SSMES (seed spacing measurement electronic system); SSVV (seed spacing variability value); tc (seed's falling time between the bottom of the seed delivery device and the furrow); W (planter working width); xref (theoretical seed spacing); Y (vertical height of the seed sensor-furrow).

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Introduction

Corn is the most cultivated and consumed cereal in the world, with a production of more than 1,000 million tons and a harvested area of almost 200 million hectares in 2016 (García-Lara & Serna-Saldivar, 2019). The planting operation is one of the most important tasks undertaken by corn producers. It should result in a plant stand with the desired density that emerges quickly and uniformly. Plant spacing uniformity and emergence rate are the characteristics most commonly used by producers to evaluate planter performance (Staggenborg *et al.*, 2004). Other planting factors influencing corn stand establishment include seed spacing, uniform seed depth, seed quality, planter speed, insects, diseases, desired seeding rates and optimum soil environment for rapid germination and uniform emergence, including soil water and temperature (Lauer & Rankin, 2004); variable-rate seeding, multi-hybrid planting and machinery should also provide high performance under different field and operating conditions (Virk *et al.*, 2019).

Precision Agriculture (PA) only takes into account in-field variability, while Smart Farming (SF) goes further by basing management tasks not only on location but also on data, enhanced by context and situation awareness, triggered by real-time events (Wolfert *et al.*, 2014). Fountas *et al.* (2006) mentioned that farmers need to think systematically about their information needs and costs, alternative sources, and the value of information by identifying what information needs to be collected before making decisions. In this sense, Saiz-Rubio & Rovira-Más (2020) mentioned a common way to manage field data displayed on maps and culminated with a practical solution using Geographic Information System (GIS) software.

Regarding the indicators for the planting operation, the measurements to control and evaluate in the precision planting are the uniform in-row seed spacing and seed depth. However, many times this control is not performed, or is only partially performed, due to the time required and the tedious work of the measurements. It may also be susceptible to human errors. Concerning seed mapping, it has not been studied and discussed in the research works. This map constitutes a strategic data source to have information on the quantitative and/or qualitative aspects of the planting operation.

This review can contribute to a conceptual synthesis of the methodologies for evaluation and measurement to determine the performance of the precision planter. In this sense, technology can provide tools for monitoring and reporting planting data, making corrections in real time if required, being able to use this information in the context of PA or SF to improve decision-making with the GIS-type software. The main aims of this work were to review: 1) methodologies to evaluate precision planting; 2) technologies for in-row seed spacing measurement system for the precision planter; and 3) the systems that allow to obtain corn 'seed mapping' in the planting operation for PA or SF.

Methodologies to evaluate seed spacing uniformity for precision planter's performance

Planter performance factors include variability around the target drop points (drop error), seed failure, multiple seeds falling at the same time, seed bouncing and rolling in the furrow, and in-row seed movements when covered with soil (Panning *et al.*, 2000). Singh *et al.* (2005) mentioned that the planter performance depends on the seed spacing uniformity in the furrows, which is difficult to measure in the field due to soil cover after planting.

These measured seed spacing data and descriptive statistics can be used for planter performance evaluation. These statistical indicators are arithmetic mean, standard deviation (SD), and coefficient of variation (CV). Regarding these indicators, Kachman & Smith (1995) concluded that the use of mean value and SD is not an appropriate summarized method to evaluate precision planting performance.

For corn crop planting, Lázaro *et al.* (2005) concluded that SD levels below 5 cm did not produce grain yield loss and that the relationship between SD plant spacing and grain yield loss is not linear. On the other hand, a study by Nielsen (2001) evaluated the effect of plant spacing variability, SD treatment from 5.1 to 30.5 cm, on grain crop yield. The results of that field research indicated that about 62 kg/ha are lost for each centimeter increase in the SD of the plant-to-plant spacing. Regarding operating variables in the field, Staggenborg *et al.* (2004) indicated that corn yield decreased at a rate of 93.7 kg/ha per km/h as the planter speed increased from approximately 7.2 to over 11.3 km/h.

Another methodology for evaluating seed spacing uniformity is the Standard ISO 7256/1 (1984). It is based on the theoretical seed spacing (xref). This value assumes that there are no missing, multiple or variant seeds, and its value is a planter manufacturer's specification. With this value, the intervals for determining the multiple index (D), the missing index (M) and the quality of the feed index (A) are defined. For the calculation of these indicators it is necessary, from each measurement of the seed spacing, to determine to which interval it corresponds. The sum of the three indexes is equal to 100%. The precision (P) indicator of the Standard differs from the usual CV in that it uses the xref as the denominator instead of the sample mean. Another difference is that in the numerator the SD corresponds to the uses of the seed spacing data included in the interval corresponding to the A index. The standard of making at least 250 seed spacing measurements to evaluate planter performance is mentioned.

Another methodology based on xref is called coefficient of precision (CP3) for planter performance. Panning *et al.*

Table 1. Measurement strategy for in-row seed spacing measurement system in precision planter (Lab or/and Field).

Measurement strategy		Sensor characteristics	Seed/s	References
Indirect method	Optical-type seed sensors	Infrared (IR) optical-type	pelleted sugar beet	Kocher *et al.*, 1998
		Digital fiber	corn chickpea rape	Barut & Yiğit, 2008 Hajahmed *et al.*, 2011 Ding *et al.*, 2016
		Laser	corn	Meng *et al.*, 2016
	Non-optical-type seed sensors	Line scan camera	cotton	Alchanatis *et al.*, 2002
		Machine vision (image processing)	corn	Li & Lin, 2006
		High-speed camera system	wheat, soybeans	Karayel *et al.*, 2006
		Capacitive	corn	Zhou *et al.*, 2012
		Hall-effect	-	Goldman *et al.*, 2013
		Piezoelectric	corn	Huang *et al.*, 2013
		Radio wave-type (microwave)	-	Sauder & Plantamura, 2014
		Acoustic	corn, pelleted tomato, wheat	Karimi *et al.*, 2015
		Inductive proximity	-	Tolón Becerra *et al.*, 2016
Direct method	Open furrow	Seed-firming wheel (rolling on seed)	part of a tuber, corn, etc.	McCloskey, 2018
		High-speed camera (image)	corn	Badua *et al.*, 2019
	Closed furrow	X-Ray technique	barley, rape, soybeans	Campbell & Baker, 1989
		Ground penetring radar	corn	Mapoka *et al.*, 2018

(2000) mentioned that the interval for CP3 is determined only with the seed spacing value within, xref ± 1.5. The CP3 value (in %) can be calculated as the ratio between the number of measurements within the interval and the total number of measurements of seed, or plant, spacing.

A variant of the calculation of the indicators used in the ISO Standard methodology is the one mentioned by Ding *et al.* (2016), who used the method based on the GBT/6973-2005 Standard (China) but with the 'standard time' of the metering seeds instead of xref. The standard time is calculated by an equation using the variables of the seed meter rotation speed and the seed plate holes number of the seed meter.

Some authors have mentioned quantitative and qualitative indicators for the evaluation of precision planting. Gil & Carnasa (1996) considered that any seed placed at a distance of ± 20% of xref will produce a viable plant with a non-negative effect on yield. On the other hand, Weirich Neto *et al.* (2015) concluded that it is convenient to adopt corn planting as acceptable when the A-index value is above 90%. Kachman & Smith (1995) mentioned that a practical upper limit to the P-indicator value is 29%, which would indicate that the entire seed sp acing is evenly distributed within the target range. However, Yazgi & Degirmencioglu (2014) mentioned qualitative performance criteria based on quantitative indicators to evaluate precision planters. By using D, M and A indexes (in %), it is possible to classify planting as Very Good, Good, Moderate and Insufficient.

Seed spacing measurement technologies for precision planter in the laboratory and in the field

Karimi *et al.* (2015) mentioned that the sticky belt test stand is a method commonly used by researchers as a reference technique to test seed spacing for each planter configuration. The planter unit is placed on the moving belt covered with an adhesive material, usually grease, so that impacted seeds remain in the grease. The belt is then stopped and seed spacing measurements are recorded manually (Alchanatis *et al.*, 2002). Panning *et al.* (2000) reported that seeds can bounce or roll and that the grease on the belt can minimize this. The authors concluded that laboratory test methods could be useful in the planter with poor seed metering uniformity. The results of laboratory and field tests could be used to improve planter performance.

Different technologies have been developed for in-row seed spacing measurement systems. According to the available technologies, a new conceptual proposal could

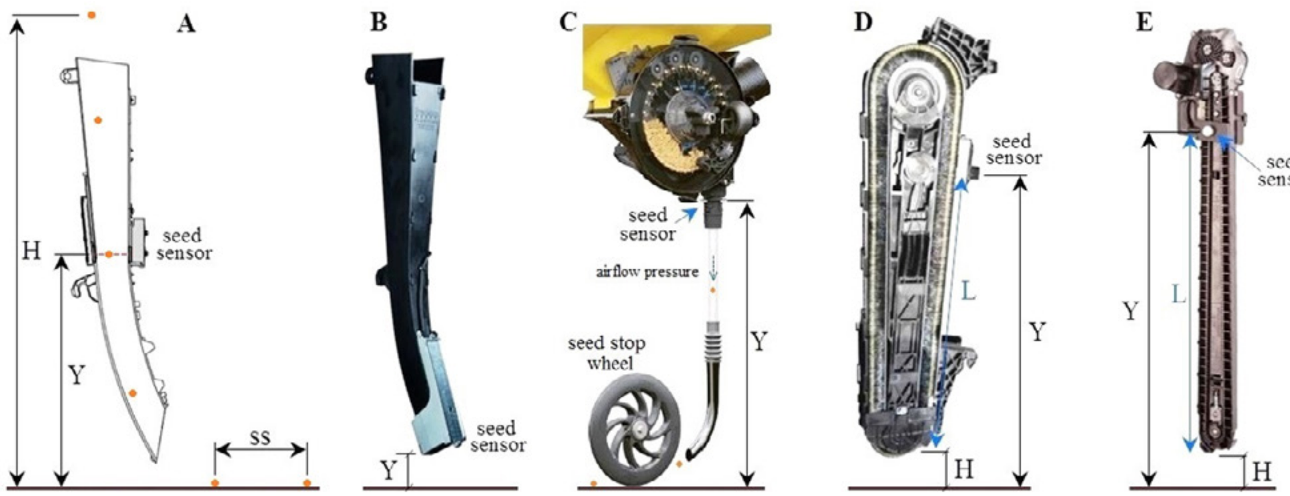

Figure 1. Different options for seed delivery to the precision planter: (1) seed tube with (A) optical-type seed sensor (adapted from Liebich *et al.*, 2017); (B) radio-wave seed sensor (Precision Planting, 2022); (C) optical-type seed sensor (Väderstad, 2021); (2) seed delivery device with (D) brush belt (Deere, 2015) and (E) flight-type belt (Precision Planting, 2017) and optical-type or radio wave seed sensors. H: seed drop height from the seed meter (not shown) to the furrow. L: distance from the seed sensor to the bottom of the seed delivery device. ss: in-row seed spacing. Y: vertical height of the seed-furrow sensor.

be mentioned to classify seed spacing measuring systems for the precision planters. The proposal is based on two methods, indirect and direct measurement (Table 1).

The indirect methods consist of measuring seed spacing before the seed reaches the soil, *i.e.,* the furrow. The direct methods consist of measuring seed spacing with the seed located in the furrow. The measurements strategies for the indirect methods could be classified into optical and non-optical seed sensors. While that, the direct methods measurement strategies involve the open or closed furrow.

As for non-optical type seed sensor technology, Karimi *et al.* (2015) mentioned that acoustic signals are generated by seed impact and evaluate seed spacing. Mapoka *et al.* (2019) reported that a typical acoustic sensor is composed of a transmitter and a receiver, which contain a piezoelectric material responsible for generating and receiving sound waves at frequencies below 20 kHz, infrasound, and above 20 kHz, ultrasound. Badua *et al.* (2019) mentioned the technique of overlapping images using common points to create a single image with a field of view to measure seed spacing. Mapoka *et al.* (2019) related that ground penetrating radar (GPR) is a high-frequency electromagnetic signal and consists of a transmitter and receiver antennas. The reflected signals per seed are received by the GPR receiver as a function of time.

Optical-type seed sensor technology is based on the use of the visible or non-visible electromagnetic spectrum to detect the passage of seeds. Seed monitoring systems with infrared (IR) optical-type sensor are the dominant commercial technology in the electronic equipment for planter monitors. This system allows the planter operator to monitor and diagnose problems during precision planting. Shearer & Pitla (2014) mentioned that there are two technologies most commonly used in seed monitoring systems. One is IR optical-type sensors that detect seed shape and another is microwave seed sensors that detect the seed mass using high-frequency radio waves.

There are three alternative seed delivery concepts for the singular seed meter on the precision planter. As shown in Fig. 1, these are typical seed tubes in which seed falls by gravity only (Fig. 1A-B), gravity and pressurized air movements (Fig. 1C) and seed delivery with brush belt or flight belt (Fig. 1D-E). The first alternative (Fig. 1A-B), showed two technologies, optical IR barrier and radio wave types seed sensors, respectively.

For optical-type seed sensor, Kumar & Raheman (2018) indicated that IR technology is better due to higher accuracy, small size, lower power consumption, low cost, and simple control of input/output signals. Sauder & Plattner (2006) mentioned that, as for the photoelectric seed sensor, when a seed passes between the light emitting source and the light receiver the light beam is interrupted and detected. The planter monitor processes signals to determine the seeds number or seeding rates, as well as monitors the time between seeds (pulses) to determine seed spacing (Sauder & Plantamura, 2014). Körösi *et al.* (2019) mentioned that optical-type seed sensors can be classified into two groups according to the control scheme of the sensor light sources. The first group includes seed sensors in which the light sources operate continuously and with a constant light intensity over time. The second group includes seed sensors in which the intensity of the light sources is controlled by periodic signals (Fig. 2). The number of light sources and detectors is selected depending on the specific location of the application, the shape and dimensions of the detection zone in the seed tube.

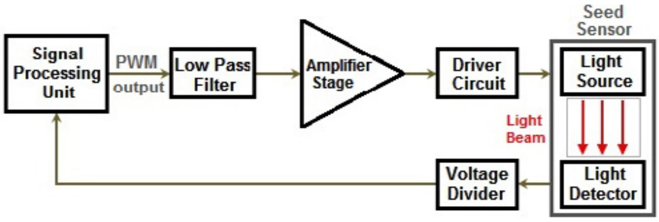

Figure 2. Conceptual block diagram of the sensitivity adjustment system for seed sensor (adapted from Körösi *et al.*, 2019). PWM: pulse width modulation.

The methodology used to estimate in-row seed spacing with strategic indirect measurement is calculated using the following equation:

$$ss = \Delta t * ps + e \quad (1)$$

where ss: in-row seed spacing, Δt: the time interval of consecutive seeds measured at the seed sensor, ps: planter travel speed, and e: error. The measuring system consists of a sensor for each seed tube to calculate the seed time interval (Δt) and a sensor to measure the ps. These signals are processed in the planter monitor together with the GPS signal to geo-referenced data. To calculate the error (e) of seed spacing is the actual measured value minus the calculated or estimated value. Goldman *et al.* (2013) mentioned that the processor, planter monitor, could use a setting based on time parameters to improve the accuracy of seed spacing measurement in the furrow. As for the adjustment parameter, Klenin *et al.* (1986) mentioned that the time required for the seed to reach the furrow is seed residence time in the seed tube multiplied by an empirical factor (1.05 to 1.15).

Therefore, an alternative to the adjustment parameter is the time (tc) to reach the seed in the furrow given by the free-fall equation. Result of the equation of uniformly accelerated motion, with approx. vo = 0,

$$tc = \sqrt{(2 * H/g)} \quad (2)$$

where tc: seed falling time between the bottom of the seed delivery device and the furrow (s), H: distance in vertical direction of seed falling (m), and g: gravity acceleration (9.81 m/s^2).

For the case of the planter with the seed delivery device, the seed sensor is located at the top (Fig. 1D-E). From that seed detection, the time required for the seed to reach the bottom of the furrow could be considered as the sum of two times. The first section-time corresponds to the seed being transported the distance (L) in the seed delivery device. The second section-time (tc) corresponds to the seed falling by gravity in the furrow. The estimation of the total time (tt) can be calculated as

$$tt= (L/ds) + tc \quad (3)$$

where: L, distance from the seed sensor to the bottom of the seed delivery device; ds, displacement speed of the belt or brush on the seed delivery device. The term (L/ds) is the travel time for the seed to reach the bottom of the delivery device. The ds (m/s) can be calculated with the equation

$$ds = (\pi * n * Dp)/60 \quad (4)$$

where: n, pulley rotational speed of the seed delivery device (rpm); Dp, diameter of the driving pulley (m).

Some limitations have been mentioned in the use of the technology with IR optical-type seed sensors. Kocher *et al.* (1998) mentioned that seeds with an effective diameter of less than about 3 mm have not consistently blocked enough light beams to trigger the phototransistors reliably. While St Jack *et al.* (2013) reported that if two seeds fall next to each other, the IR light beam from the sensor would only be cut once and multiple seeds would be incorrectly recorded as a single seed. Liebich *et al.* (2017) developed a seed sensor in which light is emitted from the diodes transversely to a receiving axis of the sensor receiving unit, bundled through the perforated screens. The light guided into the straight triangular prism-shaped reflector element is deflected by total reflection to form a light band of parallel light beams inside the seed tube with flat intensity. On the contrary, Wilhelmi *et al.* (2014) developed a seed sensor provided with at least one emitter and several light receivers. The seed size and shape can be inferred from the number of trajectories blocked by the receivers in the array that are cut in each direction and the time it takes for the seed to pass through the seed detection plane in the seed tube.

Steffen *et al.* (1999) evaluated in the laboratory the influence of two corn seed coatings on the accuracy of a commercial planter monitor, and the authors concluded that one of them undercounted seeds by almost 4.6%. Tevs *et al.* (2018) mentioned that, during field operation, a layer of dust can accumulate on the sensor optical windows, causing the light from the emitters to refract in unpredictable directions, so that seed counts are doubled or not detected. On this, Kjartanson (2014) indicated that during the planting operation dust is stirred up and this can generate a seed-like signal resulting in a false count.

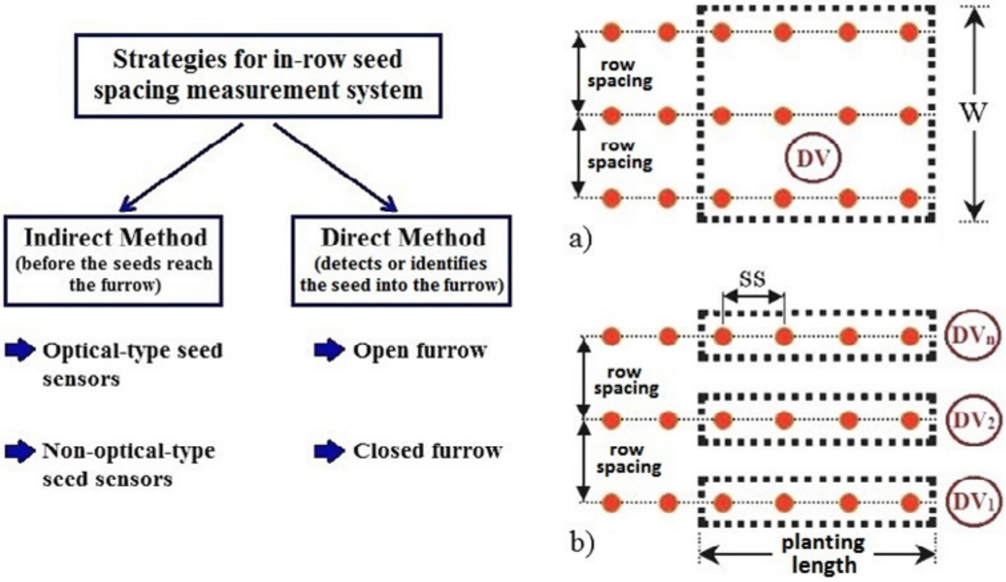

Figure 3. Conceptual synthesis to classify the measuring strategy for seed monitoring in precision planter (left). Data architecture alternatives for the seed mapping (right). a) dot value (DV) with quantitative data of the planting (seeding rates per sampled area); b) dot value for row 1, 2,…, n (DV1, DV2,…, DVn) with quantitative and qualitative data, obtained from the measurement of the in-row seed spacing (ss).

If a puff of dust with 95% transmissivity travels through the IR optical-type seed sensor with a passage time similar to that of a seed the result will be a signal virtually indistinguishable from that produced by a falling seed. To the above, Kostić *et al.* (2018) mentioned that the sensitivity of the IR optical-type seed sensor should be properly adjusted to avoid erroneous seed reading induced by external light sources, i.e. sunlight or ambient light. On the above problem, a solution by Körösi *et al.* (2019) proposed an IR optical-type seed sensor whose sensitivity is automatically regulated (Fig. 2) depending on the given circumstances and, in case of excessive dust trouble problems, an alarm signal is provided to indicate the need for sensor cleaning. The sensor signal is modulated by a square pulse of constant frequency. Seed detection is performed by examining the distortion of the detected signal on the receiver side.

In the case of the seed meter device with seed falls by gravity, Sauder & Plattner (2006) mentioned that factors like sensor holes may act as catch points when the seed drop in the seed tube; manufacturing tolerances of the seed tube or sensor elements and improper installation can affect in-row seed spacing. Deere (2007) used a translucent seed tube that allows the seed sensor to be mounted completely outside of the seed tube, and eliminates the need for seed sensor holes.

Considering the current trend of increasing travel planter speed, in which the rotational speed of the seed meter is increased, it is necessary to consider planting performance. Moody *et al.* (2003) used two seed sensors in the seed tube, one at the top and another in the bottom, to evaluate seed spacing. These authors concluded that the largest component of seed spacing variability was introduced over the top seed sensor, possibly due to variations in seed exit speed of the meter. In this sense, Virk *et al.* (2019) mentioned that the results of field data analysis suggested that seed meter performance starts to degrade at higher meter speeds (>35 rpm) indicated by higher CV values (>30%) for seed spacing. On the other hand, Kostić *et al.* (2018) determined in the laboratory that seed meter rotation speed had the most significant effect on seed spacing deviation, followed by corn seed varieties.

The term microwave is defined as an electromagnetic radiation between radio waves and infrared waves in the electromagnetic spectrum having frequencies between 300 MHz and 300 GHz and wavelengths between 1 m and 1 mm (The American Heritage Dictionary, 2020). About this technology, Shearer & Pitla (2014) mentioned that given the dusty environment of the planting operation, the radio wave-type sensors perform better as they are not prone to dust and can accurately differentiate between single and double seeds. Itagi *et al.* (2018) reported that sensors with this technology were able to count with accuracy higher than 99% and with high seeding rates over 100 seeds/s.

Tables 2 and 3 show the state of the art in measurement technologies for the indirect method. These could be classified as optical and non-optical seed sensor technologies. Also, the methodologies for evaluating the corn seed planting in the laboratory (Lab) and field tests are mentioned. These results refer only to corn seeds since other seeds were used in some of these investigations. Three groups can be identified to increase the system performance order: (i) quantitative measurement technologies where only seed counts can be determined; (ii) electronic measurement systems (MES) to evaluate the planting performance through the D, M and A indexes, as indicated in the ISO 7256/1 and GBT/6973-2005 standards; these MES are used with different sensors, capacitive, piezoelectric or IR optical-type; and (iii) electronic seed spacing measurement system (SS-MES) to measure in-row seed spacing; these use different technologies evaluated in laboratory conditions through a belt test stand with or without adhesive material on the surface to retain the seeds.

Information about seed mapping

Having the planting information arranged in the form of a geo-referenced seed map, together with other sources of soil and crop information, would reduce uncertainty in decision-making. Therefore, seed mapping contributes to data collection and management to support decision-making within GIS to support sustainable agriculture. In addition, the equipment involved in this technology allows improving the planting operation in real time.

In terms of sustainable agriculture, the use of seed mapping could be reducing the planting equipment passes number in no-till or conventional tillage systems. This leads to a reduction in soil compaction and, consequently, favors soil conservation. It is important to note that compaction of agricultural soils is a serious problem worldwide that produces not only reduced crop yields, but also leads to increased greenhouse gas emissions, groundwater pollution and increased fuel consumption of agricultural machines as indicated by Antille *et al.* (2019) and Botta *et al.* (2022).

The dot map on the yield map represents an average value (kg/ha) for each data point collected by the yield monitor. This area is determined by the header working width of the grain harvesting machinery and the sampling frequency. Therefore, the length of each dot will depend on the travel speed of the machine and the sampling frequencies, which are intervals generally on the order of 1, 2, or 3 seconds at the harvesting machinery operator choice. This method that does not differentiate between intra- and in-rows of the crop yield data has a certain degree of uncertainty for the analysis stage with GIS-type software. Therefore, other sources of information, *e.g.* seed mapping, are required.

In the case of the seed mapping, depending on the technology implemented in the planter monitor, it would allow a quantitative and/or qualitative data architecture. The first conceptual proposal consists of the seed mapping with the information in each dot containing the seeding rates value in the sampled area. This area is the planter working width (W) multiplied by the planting length (LD). As for W, it depends on the row spacing and the number of the planter row units. The length of each dot (LD) on the seed map will be determined by the planter travel speed and the sampling frequency of the planter monitor measurement system. The first case of the seed mapping, quantitative information, determines the seeds number in the sampled area. By using GPS, it allows georeferencing a dot map of the planting information to form the seed mapping.

On the other hand, the second conceptual proposal consists of generating the seed mapping with a dot value containing the in-row seed spacing (ss) data from the precision planter (Fig. 3). From the qualitative planting data, it is possible to determine the seeding rates for each row. To do this, it is necessary to obtain the seed spacing measurement in each planter row unit. From the identification of each seed, it is possible to determine the seeding rates in each row. The seed map is composed of each dot value (DV) with the seed spacing measurement at the planting length (LD) for each row. This LD will depend on the sampling methodology implemented in the planter monitor. One alternative is to use ISO 7256/1 Standard, which requires at least 250 in-row seed spacing measurements. Another alternative could be to implement the sampling frequency in a way that is compatible with the information obtained in the dot yield map. Therefore, for this case, the data architecture would be arranged along each planting row. This geo-referenced dot value data allow obtaining a qualitative and quantitative seed mapping.

In relation to qualitative seed mapping, Schweitzer *et al.* (2019) employed a planter monitor and a method in which the seed spacing variability value (SSVV) was calculated and displayed to the operator during the planting operation. This value was calculated as 1 - CV. The number of seed sensor signals, the time between each seed signal and the planter travel speed were used to determine the SSVV value.

Regarding the qualitative aspects of the indirect measurement method, Nørremark *et al.* (2007) concluded that the errors associated with plant position estimation consist of positioning sensor measurement errors, the seed displacement in the furrow, and the deviation between the plant emergence and the corresponding seed location.

A technological variant is the seed metering system with RTK-GPS, that allows a planting pattern with parallel or diamond configuration. These planting systems allow obtaining an equidistant seed spacing. Auernhammer (2001) mentioned that these approaches not only result in higher yields, but also in a more efficient use of soil water and nitrogen.

Wilson (2017) developed a system, method and apparatus to automatically collect seed-specific data for the corn crop. For this purpose, an RFID-type sensor was used with the seeds for planting. After planting with the actual seed in the soil, appropriate readers, RFID-tag, can quickly and accurately read the seed-specific data.

Final considerations

The methodology ISO 7256/1 standard has been used by many researchers and also implemented in some commer-

Table 2. State of the art for measurement technologies for indirect method with optical-type seed sensors and methodologies for evaluating corn planting.

Measurement technology	Planting indicators	Results for seed corn	References
SSMES with optical sensor	Seed spacing (calculated and manual)	From a mass flow rate of 12.8 seeds/s passing by the seed sensor, the average error in the prediction of the seed spacing tends to a constant value of 0.66 cm and an average relative error of 3.8% (SSMES vs. grease belt test stand).	Nardon, 2003
SSMES with fiber optic sensor	Seed spacing	The regression coefficient of the value of seed spacing as a result of electronic-based measurement and grease belt system was 0.7735 (Lab).	Barut & Yiğit, 2008
MES with optical sensor	Seeds number (calculated and manual)	MES is composed of a photoelectric sensor (infrared LED/phototransistor), display system, and wireless data transmission system. The system detected 96% of seeds (Lab).	Xia *et al.*, 2010
System with LS	Seeds number (calculated and manual)	The seed was detected on the seed plate of the metering device through the LS. Then the seed detected signal was transmitted to the microcomputer. The average error rate between actual and measured seeds was 0.485% (Lab).	Meng *et al.*, 2016
SSMES with optical sensor	Seed spacing (calculated and manual) ISO 7256/1	SSMES is composed of a commercial sensor and a microcontroller (Arduino). Lab test results were the R2 = 0.992; MAPE = 4.41%; and absolute deviation = 0.4 cm.	Cay *et al.*, 2017
SSMES with optical sensor	Seeding rate (calculated and manual)	Lab test results of the seeding rate showed a R2 = 0.99. The field test of the seeding rate showed that max relative error was 2.92%, and the max RMSE = 1.64%.	Yin *et al.*, 2018
MES with optical sensor	Accuracy (%)	Lab and field tests results showed that the seed detection accuracy of seeding rate quantity was 98.45%.	Liu & Yi, 2019

LS: laser sensor. MAPE: mean absolute percentage error. MES: measurement electronic systems. R2: coefficient of determination. RMSE: root mean square error. SSMES: seed spacing measurement electronic system.

cial planter monitors to evaluate precision planting. On the other hand, the value of xref could be calculated from the standard time mentioned by Ding *et al.* (2016), multiplied by the planter travel speed, but this requires further research. Despite the above, the criterion for measuring seed spacing is not standardized. Therefore, it may be necessary to define the seed geometric point to be considered as a reference in the seed spacing measurement. Another aspect that requires further investigation is the disposition of corn seeds in the furrow and its incidence on seed spacing measurements and planting depth when seedlings emerge. On the other hand, a uniform seed arrangement within the furrow with the proper position for germination could be a technological development to increase corn crop yield.

In the review, different technologies for in-row seed spacing measurement and methodologies for the precision planter evaluation have been described. A conceptual synthesis was proposed to classify the in-row seed spacing measuring systems for precision planters (Table 1). The proposed classification consists of indirect and direct methods related to the position of seed spacing measurement.

The error (e) in the in-row seed spacing estimation could be influenced by several factors, such as the vertical height of the sensor at the bottom of the furrow (Y), seed falling trajectory, seed metering performance and design, planter row unit, factors related to the planting operation, seed characteristics and measurement technology, among others. Thus, further research is needed to correct seed spacing estimates in the field. As for the seed delivery device option, it has the advantage that the seed drop height (H) is lower than that of the seed tube, and the drop time (tc) can be estimated with Eq. 2. In addition, the seed trajectories are more uniform due to the seed transport, brush or flight belt, and could decrease the error (e) for the in-row seed spacing measurement system. The main disadvantage is the higher cost compared to the seed tube. Therefore, its use is limited only to those agricultural productions where the field slope or the soil surface allow faster planting speeds, permitting to amortize the investment.

The two predominant technologies are IR optical-type and radio wave-type seed sensors, in agreement with Shearer & Pitla (2014). The first alternative is the most widespread at the research publication level and is the most widely used technology in commercial products for seed monitoring systems. The best results (Tables 2 and 3) correspond to the measurement systems with IR optical-type seed sensors, where they present values of the accuracy which show accuracy values of at least 96%. Optical seed sensors with IR technology are used in the laboratory and the field. Laboratory results indicate the coefficient of determination (R2) value of 0.99. Therefore, these SSMES

Table 3. State of the art for measurement technologies with non-optical-type seed sensors and methodologies for evaluating corn planting in the Laboratory (Lab) and/or Field tests.

Measurement technology	Planting indicators	Results for seed corn	References
SSMES with MV	Seed spacing	Seed spacing was measured for two methods by hand (sticky belt test stand) and using the MV system (image techniques). The average CV results were 15.5 and 15.6%, respectively (three speeds tests).	Li & Lin, 2006
MES with capacitive sensor	Accuracy (%) [a]	The MES average accuracy when the belt simulation planting test (4 km/h) was 94.6% in seed quantity, 93.5% in seed missing, and 88.1% in seed multiples detection. While of the average accuracy in the total seed quantity was 97.3% for a mass flow rate of 3.0 seeds/s in bench tests.	Zhou *et al.*, 2012
MES with PVDF piezoelectric film sensor	Accuracy (%) [a]	Lab test results to MES average accuracy, when mass flow rate are 5, 8.75 and 10 seeds/s, was 94.6% in seed quantity, 90.5% in seed missing, and 64.7% in seed multiples. Field test accuracy values for the different planting indicators was 95.3%, 93.3%, 75.0% for 3 km/h; 93.8%, 93.1%, 63.9% for 4 km/h; and 90.5%, 89.7%, 61.3% for 5 km/h respectively.	Huang *et al.*, 2013
SSMES with AS	Seed spacing	Typical seed patterns were positioned manually on a belt stand with different seed spacing. The R2 of gathered data from the belt system and AS in all runs was 0.988. The MAPE was 3.89%.	Karimi *et al.*, 2015
MES with capacitive sensor	Accuracy (%) [a]	Lab test results to MES average accuracy was 99.58% in normal planting, 94.20% in seed missing, and 74.21% in seed multiples detection. Field tests, was 96.90%, 95.19%, and 77.03%, respectively. While of the average accuracy in the total seed quantity was 98.20% in bench tests and 96.28% in field tests.	Qi *et al.*, 2015
Computer vision system	Seed spacing and planting depth	The system accuracy to provide a seed spacing measurement was determined by comparing the calculated spacing to the measured spacing. Overall, R^2 = 0.87 and RMSE = 0.23	Badua *et al.*, 2019

[a] GBT/6973-2005 standard. AS: acoustic system. CV: coefficient of variation. MAPE: mean absolute percentage error. MES: measurement electronic systems. MV: machine vision. PVDF: polyvinylidence fluoride. R^2: coefficient of determination. SSMES: seed spacing measurement electronic system.

allow replacing the typical belt test stand with manual seed spacing measurement.

The optical seed sensor can be placed at the top or in the center of the seed tube and requires two holes in the seed tube for the emitter and receiver. As for the number of emitter-receiver light sources of seed sensors, it depends on the manufacturer and will depend on the dimensions of the sensor and the location according to the geometry and dimensions of the seed tube. On the other hand, the microwave seed sensor is placed at the bottom and does not require holes in the seed tube. Therefore, the latter option avoids possible human errors during the mounting of the sensor in the seed tube. Both of these seed sensor technologies are available in commercial planter monitors. Regarding the IR optical-type seed sensor technology, the possible problems in seed counting with dust and differentiation of multiple seeds when passing through the sensor were mentioned. Some authors proposed different solutions to this technological problem. However, Moody *et al.* (2003), Ehsani *et al.* (2004) and Griepentrog *et al.* (2005) used optical-type seed sensors in the field and did not report the effect of environmental dust as a problem to be considered on the performance of the measurement system unlike mentioned by Shearer & Pitla (2014). Therefore, further research is needed on this topic. While the microwave seed sensor technology would not have problems with dust, further research is needed, mainly in small seed counting performance. Another topic mentioned by Sauder & Plantamura (2014) is that the rotation of nearby furrow opener disks will cause secondary magnetic fields, eddy currents, which are received by the detector, resulting in significant interference to the signal produced by the seed sensor.

This review shows the need to study performance with simultaneous evaluation of both IR optical-type and microwave seed sensor technologies because there is no scientific evidence. This could provide clarity or evidence on the best performance and cost-benefit of each technology. Further research is needed on the performance of seed spacing measurement systems using planters with seed delivery devices.

Considering that the IR optical seed sensor for the corn seed control system has a 4% error in seed counting (Table 2), it is necessary to use another source of information for the variable-rate seeding control system. Therefore, it is necessary to evaluate the response time of the seed meter drive-power system considering the minimum and maximum threshold, sensitivity, of variable-rate seeding. Another topic for seed mapping is a new development that allows multi-hybrid corn to be sown according to the crop yield potential under field conditions.

The data acquisition system of the planter monitor shall record and store in the memory equipment with the geo-location data at least the time interval of consecutive seed, seed spacing, planting speed, seed meter rotation speed, gauge wheel contact on the ground, and seed meter device accelerations. From these data, the measurement system could obtain different types of maps for the planting operation.

There are two options or strategies for in-row seed spacing electronic measurement to obtain seed mapping with a monitor planter (Fig. 3). Measurements with the indirect method were taken by Upadhyaya *et al.* (2005), Nørremark *et al.* (2007), Sauder & Koch (2011) and Tevs *et al.* (2013). On the other hand, measurements with the direct method using open furrow were taken by Goldman *et al.* (2013), Landphair & Liu (2013), McCloskey (2018) and Badua *et al.* (2019), and using closed furrow by Mapoka *et al.* (2018). Finally, the proposal of Schweitzer *et al.* (2019) allows obtaining a qualitative seed planting map using descriptive statistical indicators. To georeference the planting data, RTK-GPS/GNSS-based technology is used. Contrarily, Wilson (2017) proposal would require an RFID sensor for each seed, which limits its adoption in seed mapping.

Commercial planter monitors generate seed mapping considering only the mean in-row seed spacing geo-referenced information. Therefore, it would be useful to have the seed spacing information in a deterministic and non-probabilistic way to adapt the data analysis. Considering that non-uniformity in planting depth affects corn crop yield, it is necessary to incorporate this information along with in-row seed spacing. The seed depth implementation in the seed mapping in the indirect method strategy would require using a large number of sensors to determine the relative position of the planter row unit over the furrow. Therefore, a priori, the second measurement strategy, direct method, would be the most suitable to have three-dimensional (3D) seed mapping data on the in-row seed spacing and the seed depth. On the contrary, the developments proposed by Goldman *et al.* (2013) and Landphair & Liu (2013) allow obtaining only information on in-row seed spacing.

The benefits of 3D seed mapping are not only for farmers, but also for the personnel of planting equipment manufacturing companies. Such measurement technology would reduce the time required in the evaluation phase of new products or modifications of precision planter agro-components. This seed mapping would contribute to improving the accuracy of planting data. Thus, reliable information is available and a proper analysis is performed to validate site-specific crop management strategies. In this context, Pivoto *et al.* (2018) mentioned that SF based on information and communication technologies incorporation in machinery, equipment and sensors in agricultural production systems allow a high volume of data and information. SF must be able to adapt autonomously and in real time to these changes to remain competitive in the market (Zambon *et al.*, 2019).

Conclusions

The methodologies for evaluating in-row seed spacing for planters are those using descriptive statistical indicators, and indicators based on theoretical seed spacing, xref, such as CP3, and the indices mentioned in the ISO 7256/1 Standards.

A conceptual synthesis of the measurement technology was proposed. There are two main measurement strategies for determining in-row seed spacing to apply in seed mapping. One is the indirect method, which involves measuring before the seeds reach the soil. The other is the direct method, which involves measuring with the seeds in the open or closed furrow. Each of them uses different measurement technologies and methodologies, which have been mentioned in this review.

The indirect method is the most commercially used method in the planter monitor and has a large number of studies in publications and technological developments. The seed counting accuracy through electronic measurement systems with optical-type sensors is at least 96% for corn seeds. Contrastingly, the microwave seed sensor is used commercially by few companies whose technologies were patented. Future research will be required to validate the best performance of both technologies on seed sensors. Concerning the error (Eq. 1), further research is needed to determine deterministic or statistical correction parameters or models to improve the estimation of in-row seed spacing measurement in the field.

Therefore, the direct method is under development and requires further research. The main limitations of this method are seed detection in the furrow, which limits the planting speed, and the measuring equipment cost. In addition to obtaining planting information, the system would require the completion of real-time seed monitoring to indicate to the user the possible errors during this operation, missed and multiples seeds, for their correction.

The current use of the term 'seed mapping' only contemplates geo-referenced information about in-row seed spacing, in the highest yielding planter monitor. Therefore, it would be convenient to redefine it. The conceptual proposal of the 'seed mapping' is to provide integrated and geospatial information on the location of each seed in terms of the in-row seed spacing and depth for precision planting. In this way, through this information and with the seedling emerged, it would allow to have data sources for single plant-to-plant management. This more accurate planting information will allow decisions to be made with less uncertainty in the GIS-type software. Therefore, by having a Seed Mapping, crop management information could be improved and aspects related to the operation of the precision planter user can be compared. This technology could also be useful for the planter manufacturers to evaluate the performance of a new commercial product in the experimental stage.

Authors' contributions

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