EVALUATION OF MONITORING SYSTEMS FOR SEEDER SEED SPACING UNIFORMITY

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Abstract

Proper seed placement in the soil is crucial for optimal germination and initial plant growth during the seeding operation. Ideally, seeds should be positioned at a predetermined and uniform spacing and depth. However, in practice, there is often a significant deviation from the desired seed placement. Research on a seed flow detection device for seed metering systems of seeders is highly important. It ensures monitoring of the seeding rate, detects missed seeding, allows real-time reseeding during the precision seeding process, and increases overall precision seeding intelligence. Achieving a uniform distribution of seeds in a furrow maximizes the growing area for each plant and enhances yields by reducing competition among neighboring plants. Furthermore, uniform seed placement helps in weed suppression. Precision agriculture plays a crucial role in optimizing crop yield and resource efficiency, and accurate seed spacing is a fundamental aspect of this practice. This paper provides a concise overview of monitoring systems designed to ensure seed spacing uniformity in seeders, addressing the challenges associated with traditional methods and highlighting the advancements in technology. The review encompasses various sensor technologies, including optical, piezoelectric, radio wave, and computer vision-based systems, which enable real-time monitoring of seed placement during the seeding process. The integration of these monitoring systems with seeders allows for instant feedback and adjustment, minimizing the risk of uneven seed distribution. The synthesis of information from recent studies and technological developments underscores the significance of continuous research and innovation in monitoring systems for achieving optimal seed spacing uniformity in modern agriculture.

Keywords: *seeder, seed metering, seed detection, sensor, high-speed camera*

1. INTRODUCTION

Ensuring seed spacing uniformity is a pivotal aspect of evaluating seeder performance, as it directly influences crop yields and intra-specific competition [1]. The even distribution of seeds not only maximizes individual plant space but also hinders weed growth by preventing gaps. Precision seeders, designed for crops like maize or sugar beet, have been developed to meet the demand for precise seed spacing; however, their applicability is constrained to larger row spacings due to cost considerations. For cereals, conventional seed drills employing volumetric metering by fluted or studded rollers are predominant, resulting in a more random distribution of seeds. Enhancing seed distribution uniformity holds potential benefits, particularly in increasing cereal yields. This review explores methods for optimizing the longitudinal distribution of seeds, with a focus on evaluating seed spacing.

Regarding the indicators for the seeding operation, the measurements to control and evaluate 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 Seed mapping constitutes a strategic data source to have information on the quantitative and/or qualitative aspects of the planting operation [2]. While traditional field and soil bin measurements are commonly used to assess seed drill performance, these measurements are susceptible to various factors such as seed-bed quality, post-sowing weather conditions, plant emergence efficiency, volunteer plants, and inherent seed drill performance issues. Digging up planted seeds for measurement, while comprehensive, poses challenges in locating small seeds without disturbing their positions, and the time required for such assessments is a considerable limitation [3]. Some researchers propose different seeding parameter monitoring systems [4, 5].

Seed spacing on a sticky belt test stand offers an alternative, mitigating factors like seed bounce and roll with the aid of oil on the belt. However, limitations persist, including the restricted length of the belt, manual measurement time, and the risk of seed sliding or bouncing, especially at high belt speeds [6]. In response to these challenges, contemporary sensor technologies have emerged, encompassing optical, electromagnetic, piezoelectric, and computer vision-based systems. This review aims to introduce and evaluate some research and papers, including these modern technologies carried out by research team scholars from Akdeniz University, Vytautas Magnus University, and the National Institute of Industrial Technology (Argentina), providing an in-depth discussion of their results in the context of monitoring systems for seeder seed spacing uniformity.

2. STICKY BELT TEST STAND

The sticky belt test stand is a commonly used method by researchers to test seed spacing for different seeder configurations [7]. In this method, the seeder unit is placed on a moving belt that is covered with a sticky material, often grease, to prevent seeds from bouncing or rolling. The belt is then stopped and seed spacing measurements are manually recorded. Karayel further explained that by minimizing seed bouncing or rolling, the grease on the belt helps to obtain more accurate results (Fig. 1) [8].

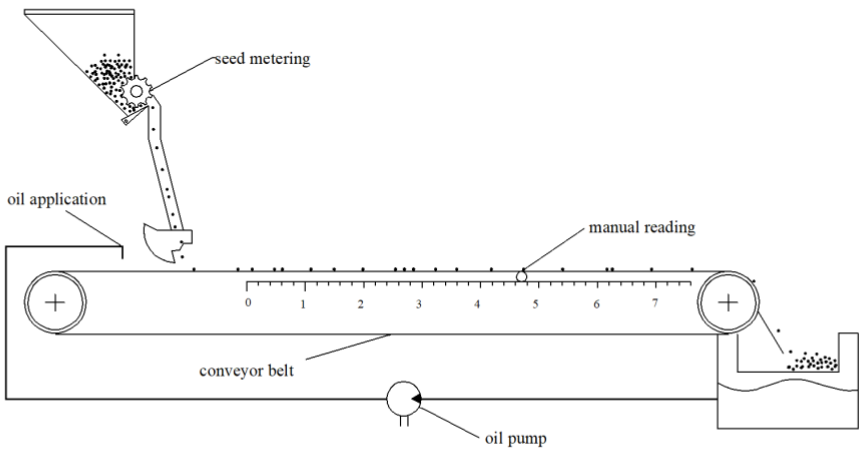


Fig. 1. Seed spacing measurement on sticky belt test stand [9]

Onal and Onal created a computerized measurement system (CMS) along with a sticky belt test stand to examine seed spacing distribution uniformity in the laboratory [10]. The CMS hardware consisted of a high-precision optical mouse, a laser pointer, and a notebook computer (Fig. 2).

This system used optical laser technology, which was a new method to determine seed spacing distribution. The CMS stored seed coordinate data, which was input using a simple user interface, and sent the data to Microsoft Excel for further statistical analysis. The results of this study confirmed that the sticky belt test stand and CMS combination can be used instead of a digital caliper and steel tape measure to obtain accurate and fast quantitative evaluations of seed spacing uniformity in the laboratory.

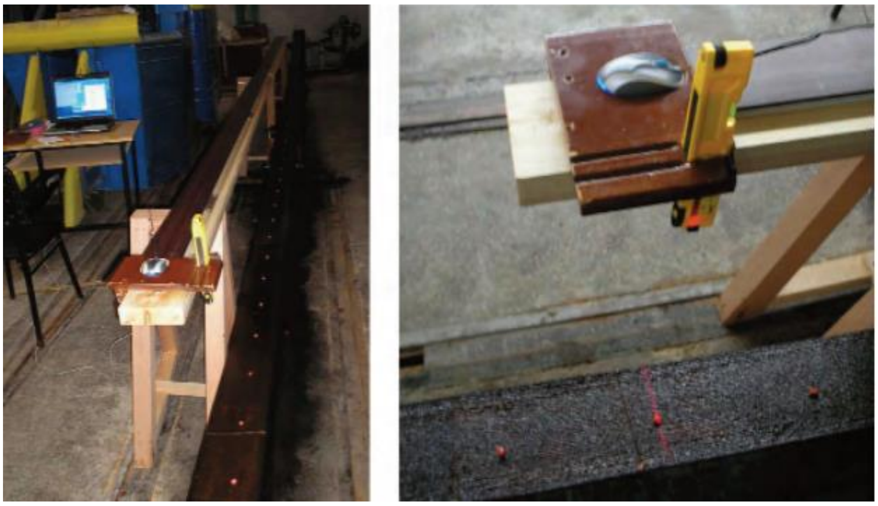


Fig. 2. Computerized measurement system along with a sticky belt test stand [10].

3. SEED SPACING MEASUREMENT TECHNOLOGIES

Different technologies have been developed for in-row seed spacing measurement systems instead of sticky belt test stands, as stated by Nardon and Botta [2]. To classify seed spacing measuring systems for the seeders, a new conceptual proposal has been suggested based on indirect and direct measurement methods. Indirect methods measure seed spacing before the seed reaches the soil, while direct methods measure seed spacing with the seed located in the furrow. Indirect methods can be classified into optical and non-optical seed sensors, while direct methods involve the open or closed furrow. Table 1 provides a detailed overview of these two methods and their subcategories.

Measurement strategy		Sensor Characteristics
Indirect method	Optical-type seed sensors	Infrared (IR) optical-type
		Digital fibre
		Laser
	Non-optical-type seed sensors	Line scan camera
		Machine vision (image processing)
		High-speed camera
		Capacitive
		Hall-effect
		Piezoelectric
		Radio wave
		Acoustic
		Inductive proximity
Direct method	Open furrow	Camera
	Closed furrow	X-Ray or Ground-penetrating radar

Table 1. Measurement strategy for seed spacing measurement systems [2].

Karayel et al. developed a high-speed camera system to assess the uniformity of seed spacing and the velocity of seed fall [9]. The system is comprised of three main components: a high-speed digital camera for recording the passage of seeds, a motion analyzer for image analysis, and a computer for data processing and monitoring. The system was capable of recording motion up to 40,500 frames per second and storing up to 24,576 full frames and up to 393,216 partial frames in electronic memory to be replayed for instant viewing. The system's electronic triggering features made it easy to capture unpredictable events. The 256x256 pixel sensor produced sharp images with 256 levels of grey, and the system's high light sensitivity reduced the need for supplementary lighting. In order to obtain acceptable resolutions of the seeds, a frame rate of 750 frames per second was selected for this research, so the time between successive images was 0.00133 seconds. For image processing, Optimas version 6.2 software was used.

The system's performance was compared to a sticky belt test stand, which served as a reference (Fig. 3). Identical seed patterns of wheat and soybeans were evaluated simultaneously using both methods. The seed drill's metering rollers' speed was set at 10, 20, 30, and 40 rpm, and the seed drill's speed was simulated at 1 m/s. The high-speed camera system accurately obtained the seed spacing and velocity of fall of seeds in all tests with wheat and soybean seeds, without missing any seeds (Figs. 4-5).

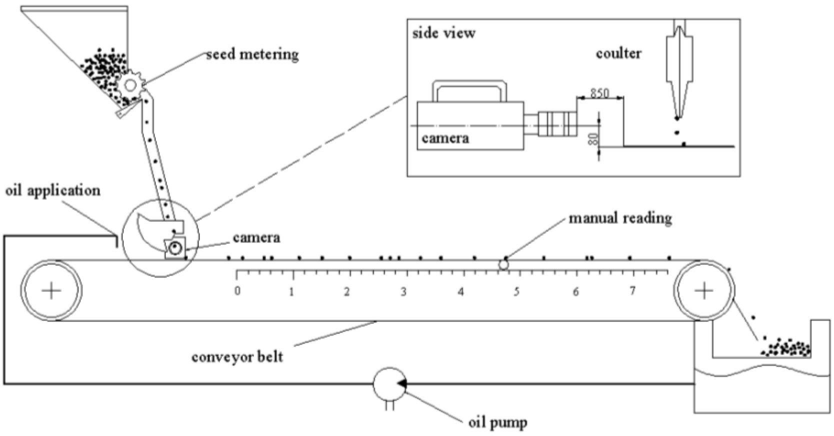


Fig. 3. Seed spacing measurement on sticky belt test stand with high-speed camera system [7]

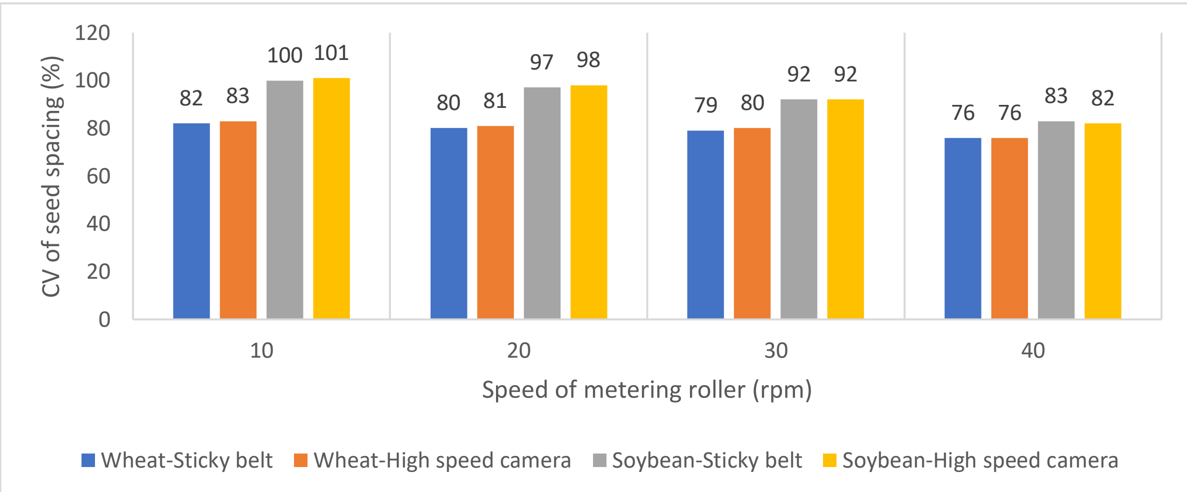


Fig. 4. Comparison of coefficient of variation of seed spacing obtained from the high-speed camera system and from sticky belt test stand [9]

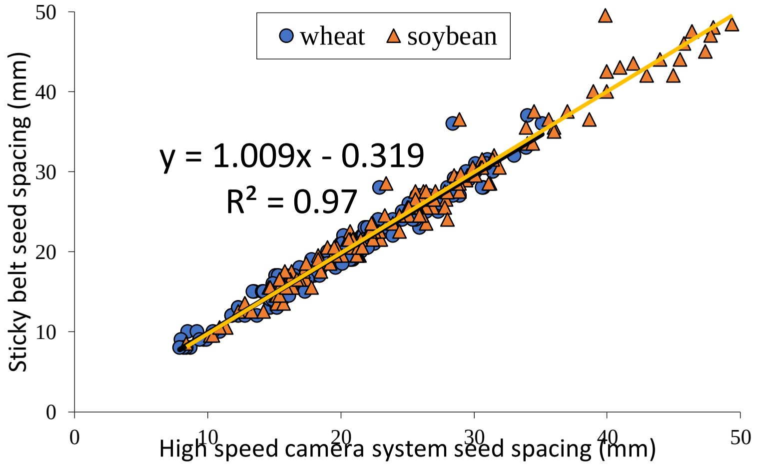


Fig. 5. Correlation of seed spacing measured with a high-speed camera system with spacing measured on the sticky belt [9].

Karayel et al. measured the falling speeds of the seeds from the seed tube to the soil/furrow using a high-speed camera system (Table 2). They found that more seeds in the seed tube result in more seed-to-seed contacts and loss of kinetic energy, and consequently, a decrease in the velocity of the fall of seeds. Because of the fewer seeds in the seed tube at the lower speed of the metering roller, differences between velocities of fall of seeds were increased as few seeds struck the wall of the seed tube. The velocity of the fall of a seed is a contributing factor to the bouncing and rolling of the seeds in the furrow [9].

Speed of metering roller (rpm)	Mean velocity of fall of seeds (m/s)
Wheat	
10	1.71
20	1.51
30	1.28
40	1.20
Soybean	
10	2.24
20	2.27
30	1.83
40	1.75

Table 2. The velocity of seeds' fall measured by a high-speed camera system [9].

Karayel compared the advantages and disadvantages of optical sensors and high-speed digital camera measurement systems to determine seed distribution uniformity of seeders (Fig. 6) [11]. The measuring system with optical sensors consists of three main parts. These are photodiodes that detect seeds, a microcontroller for image analysis, and a personal computer. Photodiodes that emit infrared light (IRED) are used as transmitters and receivers in the optical sensor. Each time the seeds interrupt the straight path between the receiver and the transmitter, the electrical response of the receiver photodiode changes. 40 transceiver diode pairs were placed in the experimental setup with optical sensors along two axes. The receiver and transmitters are mounted alternately so that the sensors are connected as close to each other as possible. Thus, the blind spots between infrared rays have been reduced to 0.35 mm, which allows the detection of seeds with a diameter of at least 1 mm. The micro-control unit reads the signals coming from the optical signals at an interval of 250 µs and determines which sensor detects the detected seeds. Then, the time difference between the detected seeds is transferred to a personal computer, and the row distances are calculated for the desired progress rate.

The research results showed that in experiments using soybean seeds, the seed spacings measured with both systems were not significantly different. However, in experiments using wheat seeds with a frequency of 110 seeds/s occurring in 40 min^{-1} speed of metering roller, the difference between seed spacing measurement systems was statistically significant at the 1% significance level. The study found that the optical sensor measuring system had higher measurement errors than the high-speed camera measurement system (Fig. 7).

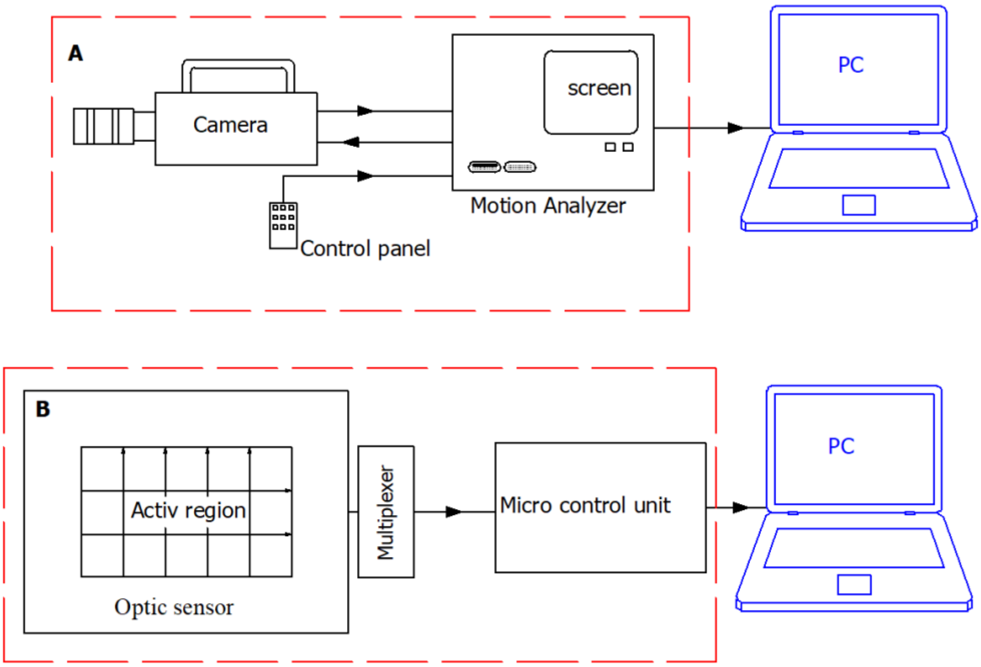
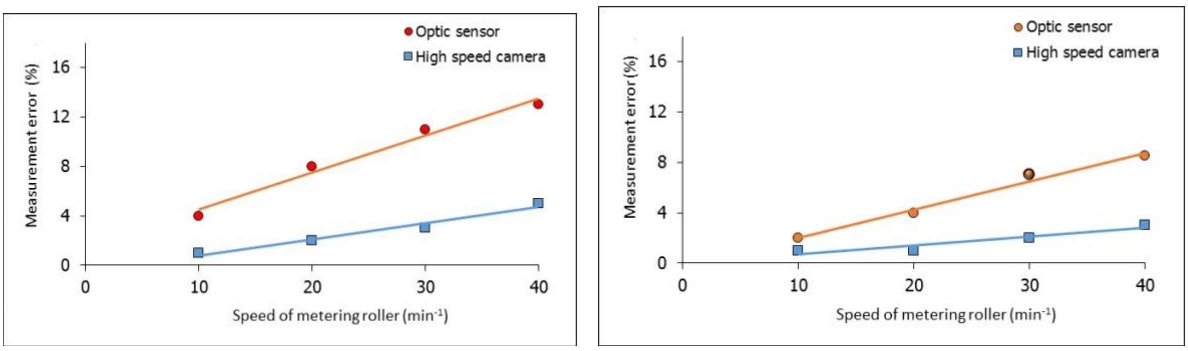


Fig. 6. Optical sensor (A) and high-speed digital camera (B) measurement systems, compared by [9].



wheat soybean

Fig. 7. Measurement error comparison of optic sensor and high-speed camera systems

Infrared sensors are commonly used to detect the passage of seeds. Nardon and Botta have stated that for optical-type seed sensors, IR technology is more accurate, smaller in size, consumes less power, is cost-effective, and has simple control of input/output signals [2]. On the other hand, Rossi et al. have mentioned that photoelectric seed sensors work by detecting the interruption of the light beam when a seed passes between the light emitter and receiver [12]. The seed monitor processes signals to determine the number of seeds or seeding rates, as well as monitors the time between seeds (pulses) to determine seed spacing. Optical-type seed sensors can be classified into two groups based on the control scheme of the sensor light sources. The first group comprises seed sensors with light sources that operate continuously with constant light intensity over time. The second group comprises seed sensors with light sources whose intensity is controlled by periodic signals. The number of light sources and detectors is selected depending on the specific location of the application, the shape, and the dimensions of the detection zone in the seed tube. These sensors can be placed in the seed tube, as shown in Fig. 8.

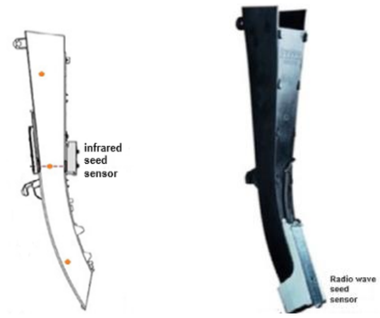


Fig. 8. Placement of the infrared and radio wave seed sensors in/on seed tube [2, 4].

Rossi et al. have developed an algorithm that is specifically designed for seed-passage detection through a linear array of one-dimensional sensors, which are perpendicular to the seed passage. The proposed algorithm uses object detection in binary images, utilizing run-based connected component labeling. This method is easily implementable on a microcontroller and allows for real-time use. A U-shaped aluminium frame was equipped with infrared sensors (phototransistor receivers) placed at equal intervals. Fig. 9 provides a top view of the setup, showing that the sensors are separated by 4 mm and have a diameter of 3 mm. Two infrared emitters are positioned in front of the sensors, with a 20 mm gap between them, while the distance between the emitters and receivers is 200 mm [12].

The use of infrared sensors makes this method non-invasive, low-cost, robust to various environments and allows for a high sampling frequency. However, the method has a disadvantage in that measurements of the infrared sensors can be altered by smoke, dust, reflective, or very dark surfaces. To demonstrate the effectiveness of the methodology, experiments were conducted with different seeding scenarios at the Instituto Nacional de Tecnología Industrial (INTI), using a pneumatic seeder with its seed tube and a high-speed camera. Three types of seeds (corn, soybean, and sunflower) and two different seeding speeds were used in the experiments. As the error of undetected seeds for soybeans at a high dosage rate was higher, a similar behaviour is observed in the accuracy values: in this case, the accuracy is lower, with values between 96% and 98%. In all other cases, the accuracy is above 99%, except for isolated cases with values between 98% and 99% (Table 3).

Although there has been substantial research on seed detection using infrared sensors, this study is unique in its implementation of a technique of searching for objects in binary images from infrared sensor signals. The errors of the method presented in this study are similar to those in the literature. However, the authors suggest that errors can be reduced in future work by improving the spatial resolution of the phototransistors and using two linear arrays of sensors at 90° to generate a three-dimensional binary array with the third dimension along the time axis.

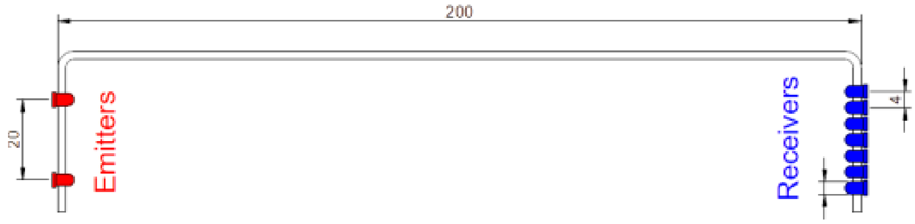


Fig. 9. Infrared sensor and main dimensions of the sensor array [10].

Seed	Speed	
	6 km/h	12 km/h
	Accuracy (%)	
Corn	100	100
Soybean	99.5	97
Sunflower	100	99.5

Table 3. Accuracy percentage of infrared sensor [10]

Ding et al. used fiber-optic sensors to monitor the performance of seed metering devices for small-sized seeds such as rapeseed. They found that the fiber-optic sensors are expensive, and the hardware cost for real-time monitoring of the six-row precision seeder is higher than the cost of the seeder itself [13, 14, 15]. This greatly limits the application and popularization of seeding rate or seeding quality monitoring for rapeseed and other small-sized seeds. Among the seed monitoring systems, the photoelectric sensor has advantages such as high sensitivity, easy signal processing, low cost, and high detection accuracy. However, it is sensitive to dust, fertilizer residues, and other factors and requires enhanced protection and regular maintenance [16, 17]. The acoustic-electric sensor is not sensitive to dust interference and can detect seed damage when combined with artificial neural networks [18]. However, it is susceptible to noise interference and requires strengthened sound insulation and anti-noise measures [18, 19]. The piezoelectric sensor has a simple structure, high sensitivity, and high signal-to-noise ratio (SNR). In addition, it can be used under harsh conditions, such as dust and vibration. However, the current piezoelectric sensors are mostly used to detect blockages in the airflow conveying and seed tube, and research and applications for high-speed flow detection are limited. Bourges et al. proposed a precision pneumatic seed meter test bench, in which an electric motor carries out the rotation of the meter plate [20]. Seeds are detected with a piezoelectric sensor attached to an impact plate to evaluate a precision pneumatic seed meter using the ISO 7256-1 standard indices [21]. The time differences between each seed detection are proportional to the longitudinal spacing between seeds in the furrow. In contrast with other laboratory methodologies, such as sticky belts, impact plate simplifies the analysis and allows more prolonged evaluation tests. Compared to infrared sensors, a piezoelectric microphone can easily be attached to a plate with biface tape and directly wired to a computer’s audio input without the need for electronic circuitry. However, the signal shape is not a simple pulse and a specific detection method is required.

As previously mentioned, piezoelectric sensors are simple to install, but their signal processing is more complex than photoelectric sensors. Therefore, Rossi et al. evaluated a seed passage detection system by considering four signal processing algorithms, using an impact plate with a piezoelectric microphone (sensor) to improve the signal processing ability of the piezoelectric sensor [22]. This impact sensor is part of a precision pneumatic seed meter test bench owned by the National Institute of Industrial Technology of Argentina, which is used to evaluate local industries’ precision meters. Any contribution to improving the seed detection capacity results in better evaluation capabilities for precision meters and the potential to accelerate the research, development, and innovation processes of the planters and the industry of agricultural parts. The novelty of the study was the application of a new algorithm for efficient signal analysis, leading to improved seed detection. The algorithm did not involve iterative loops and processes the signal straightforwardly using simple computations such as additions, multiplications, maximum values, and if-else statements. As a result, it can be implemented in small microcontrollers, thus enhancing the effectiveness of piezoelectric sensors in seed flow monitoring. The performance of the new algorithm was compared to two other algorithms, and the system was validated using a high-speed camera system.

The performance of the tested algorithms was compared using corn, soybean, and sunflower seeds at simulated forward speeds of 6 and 12 km/h. Based on the experimental results, the algorithm presented in this work (VTPD-AM) and the algorithm developed by Ozbek et al. [23] achieved the highest seed monitoring accuracy (over 97%) (Table 4). The advantage of the VTPD-AM algorithm was that it can be implemented on microcontrollers for real-time applications. In all cases, the percentage of undetected seeds increased with the increase in the seed flow rate.

Method	Seeds		
	Corn	Soybean	Sunflower
	Accuracy (%)		
Ozbek	99.0	99.0	100.0
Palhiskar	97.8	88.0	98.0
VTPD	99.0	98.0	92.0
VTPD-AM	99.0	99.0	100.0

Table 4. Detection accuracy of the piezoelectric sensor with VTPD-AM algorithm at the forward speed of seeder of 6 km/h [22]

Rossi et al. designed and tested a fast and high-precision piezoelectric detection system using steel, acrylic, medium-density fiberboard (MDF), fiberglass, and autoclaved aerated concrete (AAC) as plate materials [24]. The results demonstrated that fiberglass exhibited the highest measurement accuracy, exceeding 95%, in detecting soybean, corn, and sunflower seeds (Table 5). The findings of this study contribute to the development of more efficient and accurate methods for testing and detecting the seeding performance of precision seeders. Using fiberglass as a plate material for piezoelectric impact sensors is a promising approach to improving seed detection accuracy and ensuring the quality of seeding operations.

Material	Seeds		
	Corn	Soybean	Sunflower
	Detection accuracy (%)		
AAC	99.5	96.5	98.1
Fiberglass	**99.5**	**96.7**	**99.5**
Steel	99.0	95.7	99.5

Table 5. Percentage of detection accuracy of the piezoelectric sensor for each plate material for simulated forward speeds of 12 km/h [24].

Radio wave seed sensors are a new technology that is revolutionizing seed sensing in agriculture by using radio waves instead of traditional light beams. The sensor emits high-frequency radio waves through an antenna positioned near the seed tube. These waves have the unique ability to penetrate seeds, unlike light waves used in optical sensors. As the waves pass through the seeds, their properties, like amplitude and phase, are altered depending on the seed's mass and moisture content. The antenna then receives these altered waves, which are processed by the sensor's electronics. This process involves filtering out noise and interpreting the changes in the waves caused by the seeds. Using sophisticated software, the sensor can then identify individual seeds, determine their size and spacing, and even detect any doubles (two seeds stuck together) or skips (missing seeds) based on the analyzed signal.

One of the significant advantages of radio wave sensors is their immunity to dust. Unlike optical sensors that dust particles can fool, radio waves simply pass through them, ensuring accurate seed detection even in harsh and dusty conditions. Additionally, radio waves can distinguish the difference in mass between a single seed and two seeds stacked together, a problem for traditional optical sensors. Furthermore, radio wave sensors can be mounted at the bottom of the seed tube, where seed singulation and spacing are most critical for planting accuracy. This is because dust concerns often limit optical sensors to the middle of the seed tube.

Overall, radio wave seed sensors offer a more precise and reliable way to detect and analyze seeds in a seeder compared to traditional optical sensors. This technology is still under development, but it has the potential to improve monitoring the seeding precision significantly.

Xie et al. selected three types of sensors for testing, including two infrared optoelectronic sensors and one high-frequency radio wave sensor (Fig. 8) [4]. The same monitoring system is used to test the monitoring accuracy of the three main parameters of seeding quantity, qualified rate, and missed rate. The test was carried out at five speeds and three spacing gradient levels. The results showed that the three different sensors have similar changes in the parameter monitoring of the seeding quantity relative error, the qualified rate, and the missed rate. When the seeding speed is high, and the seeding spacing is small, the change in the sensor monitoring accuracy is very obvious. The significant difference is most obvious when the speed is ≥ 14 km/h and the spacing is ≤ 20 cm.

4. CONCLUSIONS

In conclusion, the evaluation of monitoring systems for seeder seed spacing uniformity is crucial for enhancing precision agriculture practices and optimizing crop yields. Traditional methods for assessing seed distribution, such as field and soil bin measurements, sticky belt test stands, and manual assessments, are fraught with limitations, including susceptibility to external factors, time-consuming processes, and potential for human errors. This review has highlighted advancements in monitoring systems that leverage modern sensor technologies, including optical, electromagnetic, piezoelectric, and computer vision-based systems, to provide real-time and accurate monitoring of seed placement during the seeding process.

The sticky belt test stand, a widely used method, has been enhanced through the integration of a computerized measurement system (CMS) utilizing optical laser technology. This combination offers a more efficient and accurate alternative to traditional measurement tools. High-speed camera systems, such as those developed by Karayel et al., have demonstrated superior performance in assessing seed spacing and velocity of seed fall compared to sticky belt test stands. The application of infrared sensors, as presented by Rossi et al., introduces a non-invasive and cost-effective method for real-time seed-passage detection, although challenges such as sensitivity to environmental conditions persist.

Various seed spacing measurement technologies, including fiber-optic sensors, photoelectric sensors, and piezoelectric sensors, have been explored for both indirect and direct measurements. The application of photoelectric sensors, despite their sensitivity to environmental factors, remains advantageous due to high sensitivity, easy signal processing, low cost, and high detection accuracy. Piezoelectric sensors, with their simplicity, sensitivity, and adaptability to harsh conditions, show promise in improving seed detection accuracy, especially when utilizing innovative signal processing algorithms.

The presented studies demonstrate that advancements in monitoring systems, coupled with data analytics and machine learning algorithms, can contribute significantly to achieving optimal seed spacing uniformity. The integration of these technologies into precision seeders allows for instant feedback and adjustments during the seeding process, minimizing the risk of uneven seed distribution. As precision agriculture continues to evolve, continuous research and innovation in monitoring systems are imperative for ensuring sustainable crop establishment, maximizing yields, and addressing the challenges associated with seed spacing uniformity in modern agriculture.

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