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RESEARCH ARTICLE

Design and Performance Evaluation of a Novel Variable Rate Multi-Crop Seed Metering Unit for Precision Agriculture

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ABSTRACT Seed planters with the conventional ground wheel and chain-gear driven seed metering units suffer from several limitations, such as the inability to plant seeds at variable rates, high missing rates at faster travel speeds, and higher down-times due to the intricacy of the manual discs replacement procedure for planting a different type of crop seed. Therefore, an apt solution to overcome these significant limitations is to: (a) replace the ground wheel and chain-gear based disc driving mechanism with a drive-by-wire system that comprises motors and sensors for variable rate planting and (b) incorporate a two-level adjustment of the applied negative pressure in the vacuum chamber for two different types of seeds, and (c) design seed metering unit that can plant multiple types of crops without any use of multiple discs. This paper presents the design and working of a novel variable rate multi-crop pneumatic seed metering unit that addresses the limitations of conventional seed planters. Laboratory tests were carried out on our proposed metering unit for maize and soybean seeds at varying rates in compliance with travel speeds. Experimental evaluation of the developed metering unit was performed on a lab test bench in terms of accuracy, average miss counts, and average multiple counts at various rotational speeds. The experimental results proved that our developed multi-crop seed metering unit performed significantly better than the conventional seed metering units by obtaining the average miss-count of 5.4 seeds, average multiple-count of 2.5 seeds, and coefficient of variation in spacing (precision) of 0.34 inches for a set of travel speeds of 2 km/h to 4 km/h.

INDEX TERMS Electric seed metering unit, multi-seed planting, seed planter, seed planting control, variable rate planting.

I. INTRODUCTION

As underpinned by the global demographic trends; the world's population is growing. It is expected to hit the nine billion mark by the end of 2050, according to the United Nations Population Division report titled, "World Population Prospects 2019: Highlights", published in 2019 [1]. Moreover, the Agriculture Food and Agriculture Organization (F.A.O.) of the United Nations, in their report titled "Global Agriculture Towards 2050", highlights that feeding a world population of 9.8 billion people in 2050 would require raising the overall food production by up to 70 percent [2]. The additional amounts of food needed in the coming decades will likely have to be produced mainly through yield increases rather than the expansion of cultivated lands. These estimated population projections and the prevailing state of food production are harbingers of the increasing risks of food insecurity and shortage, especially in developing

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countries like Pakistan. Therefore, efficient and resilient agricultural practices must be adapted to better handle the perceptible forthcoming crisis of food scarcity in the future. Agricultural growth and sustainability cannot be achieved by expanding areas of arable land but by adopting approaches and utilizing advanced technology-driven farming machines to improve farm productivity and yields, such as [3], [4], [5], [6], and [7]. In variable-rate planting, seeds are planted according to the varying field requirements instead of the indiscriminate broadcast planting. Using imprecise seed spacing and planting rates result in poor plant population and thereby lower crop yields and unnecessary, yet avertible, financial loss. The farmers in Pakistan do not comply with the optimal seed planting standards primarily due to the lack of advanced application equipment to achieve precise seed planting rates.

The conventional seed planters driven by the ground wheel with chain and sprocket system have several limitations, such as (a) non-uniformity in seed spacing that emanates due to wheel slippage as a result of low wheel traction on farmlands having uneven topography [8], (b) no control over planting rates (of the row units individually as well as the entire planter collectively) due to the direct dependency of the metering disc's rotational speed on rolling speed of the planter's wheel that drives the metering unit, (c) imprecise planting with high missing rates at faster travel speeds due to lack of any synchronization mechanism of the applied negative vacuum pressure with the metering disc's rotational speed (increasing or decreasing) [9], and (d) higher undesired down-times that incur due to the procedural complexity involved in manually changing the discs when a planter is required to plant a different type of crop seed.

Therefore, to curb these issues associated with conventional seed planters, there is a dire need to develop smart precision seed metering units by combing traditional knowledge with modern technologies. In the commercially available wide variety of seed metering units, the pneumatic type metering units are the most commonly used because of their advantages, such as lower seed injury rates and comparatively better performance [10]. Pneumatic seed planters perform seed planting with vertical seed discs and negative pressure generated in the vacuum chamber of the seed metering unit.

This study presents our novel multi-crop pneumatic seed metering unit that aims to overcome the shortcomings mentioned above. Our developed seed metering unit replaces the disc driving mechanism of the metering unit with a drive-by-wire system that comprises electric motors and sensors. Seed planting rates of the individual row units can be varied by regulating the speed of the seed metering disc of each row via a closed-loop feedback control system based on desired seed rate and given tractor speed. The developed metering unit can plant multiple crops via the same disc, eliminating the cumbersome process of manually changing the discs or other parts.

Moreover, in recent years agriculturalists have started adopting multi-hybrid seed planting technique for higher yields in which two or more hybrids of the same crop are planted in different zones of the same field depending on the soil's previous yield performance. This requires seed planters to have separate housings for the different seed hybrids inside the seed hoppers, and have metering units that can adapt to and dispense different types of seeds in the desired manner on the go [11]. Our advanced seed metering is one step forward to unlocking the potential of such planting approaches. The major technical contributions of this study are multifaceted and include:

1. Design and development of a novel multi-crop seed metering unit that can plant different sizes and shapes of seeds without changing the discs or other parts.
2. Variable-rate dispensing of seeds is achieved by varying the tractor speed while maintaining the seed to seed distance constant.
3. Replacement of the ground wheel and chain-gear disc driving mechanism with an electric system that comprises motors and sensors for variable-rate planting.

This paper is further divided into five sections. Section 2 discusses the related work. Section 3 presents the methodology and working of the developed system. An experimental evaluation of the system with results and discussions is presented in Section 4. Section 5 finally concludes the paper.

II. LITERATURE REVIEW

Researchers have conducted in-depth studies on seed metering systems for seed planters. Precision seed planters rely on advanced techniques to effectively overcome the limitations of conventional seed planters and provide effective control over seed planting rates, inter-row, and intra-row seed spacing, and seed depth. A detailed overview of the various types of precision maize seed planters used and developed is presented in [12], [13], [14], and [15].

He et al. [16] developed an electrically driven seed meter for a precision seed planter to overcome the limitations of the chain and ground-wheel-driven planters. The speed of the seed metering disc was controlled via a proportional-integral-derivative (PID) control system. A four-row seed planter was tested in the field at two different travel speeds. The results obtained showed improvement in the quality of feed index, miss index, and precision index values compared to the conventional systems. A QFI value of 98.62 and 97.09 percent was achieved at speeds of 8.6 and 13 km/h. He et al. [17] presented a variable-rate seed planting system that could control the individual rows independently. The system comprised a controller area network (CAN), a GPS receiver, a locally available seed planting controller, a seed metering system, DC motors, and an android tablet. The developed system was tested and validated at different travel speeds and GPS frequencies. The compensation algorithm for seeding lag demonstrated promising results in the seeding lag distance. It was also found that the tractor's travel speed and GPS frequency impact the seeding lag distance. The work was continued further, and field trials were presented in [18]. Cay et al. [19] developed an electro-mechanical seed metering system for a single seed planter. The system could vary the seed planting rates according to the tractor speed obtained via speed sensors. The developed system was tested at different vehicle speeds, i.e., 5, 7.5, and 10 km/h, and the results were compared to the performance of seed planters with conventional seed metering units. The seed spacing values obtained via actual experiments were closer to the theoretical values. The developed system was tested and improved further in [20]. Liang et al. [21] presented an electrically driven precision seed metering system for maize crops to overcome the issues of non-uniform seed planting distances caused by wheel slippages in wheel-driven seed meters. The system presented is composed of a seed metering disc driven by an electric motor. The results obtained for the electric seed metering unit were compared with the conventional seed meters, and the authors reported no significant differences in seed planting quality. Still, they suggested motor-driven metering systems to be more feasible. Jafari et al. [22] presented a direct-current electric variable-rate seed planting system for a uniform grain drill. The system is composed of a direct current motor with a fixed-ratio gearbox, speed sensors, i.e., rotary encoders for measuring the rotational speed of the drive wheel and the DC motor, a GPS, a pulse-width-modulation based motor speed controller. Tests were performed at different seed planting rates, and the response of the system was measured. The results obtained showed that the response time for a change in planting rates from high to low was 5.2 seconds, and low-to-high was 7.4 seconds.

Borja et al. [23] presented a mechatronic solution for modifying a local seed metering system. A stepper motor drove the seed metering disc, and a camera observed the rotational speed of the seed metering disc. The vision-based control system detected empty holes on the seed metering disc and adjusted the seed planting rate to compensate for any seed miss encountered. The results obtained showed that the control system could function well in the speed ranges of 2 to 6 km/h. Zahra et al. [24] conducted tests for evaluating the seed spacing uniformity of maize and castor seeds via a pneumatic seed planter at four different pressures and two different speeds ranging from 3 to 4.5 km/h and 6 to 8.5 km/h. The experimental setup consisted of a high-speed camera and a conveyor system on which seed fell from the seed meter. Vibrations encountered in actual field conditions were also simulated to depict field conditions. The results recorded revealed that non-uniformity in seed spacing is greatly affected by the speed at which the seed falls and hits the surface of the furrow. It was also reported that increased vacuum pressure levels also decrease the seed's falling speeds at low operational speeds. Mangus et al. [25] conducted experiments to measure the seeding accuracy of electric seed metering system using high-speed cameras and image processing. Several scenarios of machine operation were identified that impact the seed planting accuracy. The planting tests were carried out under varying sowing speeds that vary from 0 km/h to 16 km/h. The average singulation rate of 98.45% was achieved for a uniform increase in speed. However, the error nearly becomes doubled with fast accelerations and deceleration.

Singh et al. [26] carried out studies on pneumatic seed metering device for different crops, established the relationship equation between pressure and crop characteristics, and optimized the parameters of sucking holes. They carried out an experiment on cotton and obtained the best operating parameters of the seed metering device. Xue et al. [27] studied the influence of rotational speeds of pneumatic seed metering device on the seeding effect. Field tests were carried out on soybean and maize, and the relationship between rotational speeds of the seed metering device and the seeding effect was obtained. Jing et al. [28] presented an electro-hydraulic downforce control system for dealing with the uneven seed germination and soil compaction issues related to the varying soil conditions in a field using a four-row pneumatic seed planter. According to the soil condition, the downward force applied on the gauge wheel was controlled via a closed-loop Proportional-Integral-Derivative (PID) control algorithm. Experiments were performed in fields with tilled land and non-tilled land at a driving speed of 8 km/h. The results showed that the proposed downforce control system enabled better control overseeding depth than the conventional spring-based depth adjustment mechanism. An improvement of 1.05 to 2.23 percent in terms of consistency in seeding depth was reported.

A trend towards adaptation of agricultural precision technologies can be observed in most of the planting systems presented in the literature herein, but none of these systems have yet introduced and tested seed metering units that can plant different seeds types. Moreover, the seed metering units, in literature, that can plant different seed types require manual replacement of the discs for each seed type, unlike our proposed seed metering unit.

III. SYSTEM DESCRIPTIONS AND METHODOLOGY

The working and description of our developed seed planting system is explained in the following sections: (a) a seed metering unit, (b) a vacuum system, (c) a closed-loop PID control system, (d) calibration of seed metering unit, and (e) performance evaluation parameters.

A. SEED METERING UNIT

A seed metering unit is deemed to be the heart of a seed planter. The SMU comprises several parts and assemblies. It includes seed discs, a disc locking mechanism, a seed singulation mechanism, a seed picking and delivery mechanism, and a disc driving mechanism. The design factors considered and the working of these components and mechanisms are described in detail in the following subsections.

1) SEED DISCS

The seed metering unit comprises two discs, one disc on the seed chamber side and the other on the vacuum chamber side. The vacuum chamber disc (VCD) has three groups of holes. Each group further comprises 12 holes distributed radially in an alternating pattern along the circumference of a circle having a radius of 123.5 mm. Therefore, the vacuum chamber disc has cumulatively 36 holes, as shown in Figure 1(a). On the other hand, the seed chamber disc (SCD) has only one group consisting of 12 holes, and gear teeth along its circumference, as shown in Figure 1(b). The indented profile of each hole serves to reduce the combined cross-sectional width of the two discs to get a better hold of seeds via the negative pressure applied across the holes. Currently, in this research work, we used group 3 and group 2 holes for maize and soybean, respectively. To eliminate misalignment risks due to backlash phenomena, the holes on the SCD are formed by sliding a circle along an arc that subtends an angle θ about the center of the SCD. Moreover, the SCD has a sectional cut in which the VCD sits. The two discs are mounted co-axially and thus share a common axis of rotation. The VCD is permanently attached through fasteners to the shaft of the DC motor, whereas the SCD is kept free to rotate via a ball bearing mounted on the main shaft.

2) DISC LOCKING MECHANISM

The seed metering unit has two locking systems for both discs. One locking system uses a ratchet and pawl mechanism which is responsible for locking the SCD with the VCD upon the rotational motion of the VCD. A circular cylindrical hub with an internal cogwheel gear is attached to the SCD via fasteners. This cylindrical hub also houses the ratchet and pawl mechanism which is permanently fastened with the VCD through the main shaft. For load distribution, i.e., the applied torque, the ratchet uses four pawls that are loaded with springs and are engaged simultaneously with the teeth on the cogwheel gear. The other ends of the pawls are pivoted via a pin to the ratchet wheel. Both discs get locked in the clockwise rotation due to the ratchet-pawl locking system, which forces them to rotate together.

The second locking system uses a pinion that engages with the teeth on the circumference of the SCD as shown in Figure 2(a). The main purpose of this locking system is to change the seed hole type. In counterclockwise rotation, the SCD gets locked by the pinion, and the VCD (fastened to the main shaft) rotates and adjusts to another hole group/type. The pawl slides over the sloped edge of the teeth of the internal gear in counterclockwise rotation and, therefore, allows the VCD to rotate. A spring is attached to the pawl and the ratchet wheel that compresses as the pawl passes through the tip of the gear teeth.

The maximum angle through which the VCD can rotate until the pawl engages with the internal gear teeth and thereby enforces rotation of the SCD is calculated by dividing 360° by the total number of teeth. The internal cogwheel gear has 36 engagement points; thus, its maximum angle of engagement is equal to:

$$\text{Angle of Engagement} = \frac{360^\circ}{P.O.E} = \frac{360^\circ}{36} = 10^\circ \tag{1}$$

3) SEED SINGULATION

An adjustable seed singluator, shown in Figure 2(b), removes the double seeds that may get attached to a single hole. The singulator comprises three circular notched edges, A, B, and C, that engage with seed holes in different proportions radially along the path of holes/seeds.

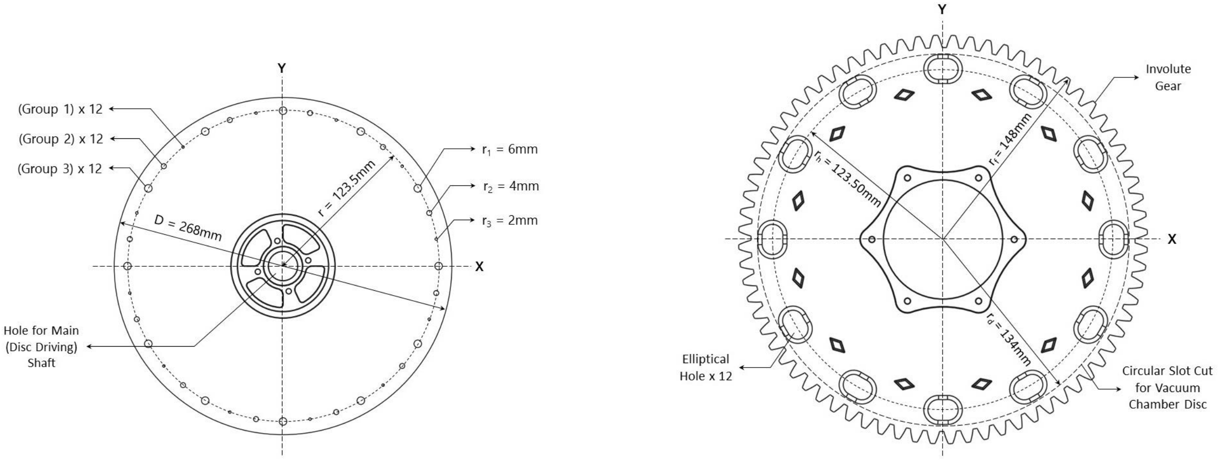
A rotating knob placed outside the seed chamber body and a sliding pin connection allows the user to adjust the singulator at three different positions. Each adjustment position provides a different range of hole coverage, as illustrated in Table 1. The adjustment positions 1, 2, and 3 sets the singulator position such that the three-lobed edges of the singulator provide coverage of either 0, 25, 50, or 100% to each hole that it encounters. The rotation of the knob via a screw mechanism lowers or raises the singulator and therefore adjusts its position in accordance with the hole group on the disc that is being desired to be used.

4) SEED PICKING AND DELIVERY MECHANISM

The seeds are gradually poured out in to the seed chamber of the metering unit via a seed hopper, as shown in Figure 3(a) which is composed of two parts. The base part of the hopper, attached to the metering unit via M4 screws, is made of mild steel. The upper part, which serves the purpose of pouring and storing the seeds, is a box-shaped container made up of acrylic sheet. It has an opening window having 100 x 150 mm dimensions (length and width, respectively). The seed carrying capacity of the seed hopper is 2500 cm^3. The seeds from the seed chamber are then picked by attracting them through the holes in the disc with the negative pressure generated by the vacuum system. The seeds are taken and consequently released into the delivery tube by cutting the vacuum supply at the discharge area of the seed meter, i.e., the point where seeds are dropped into the outflow tube.

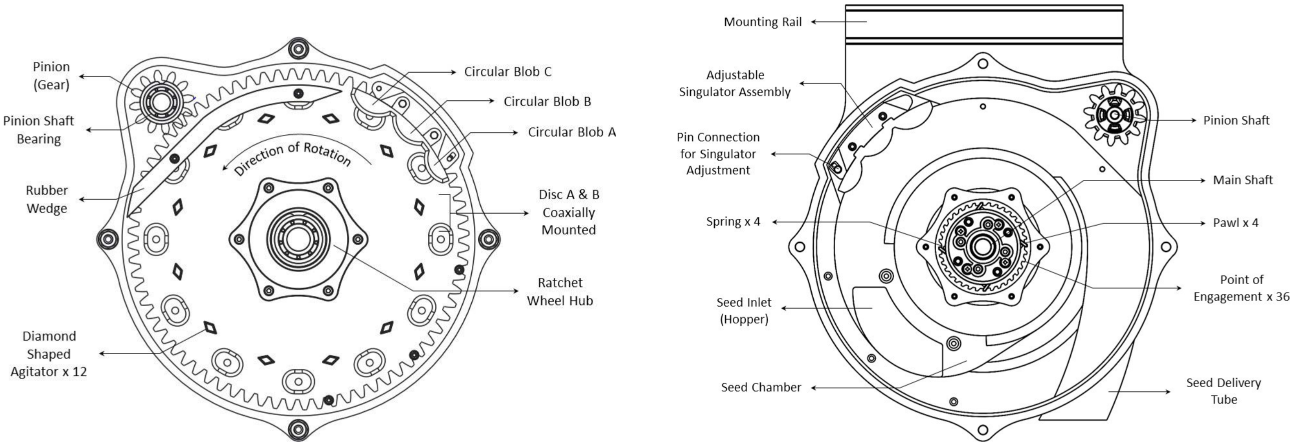
5) SEED DISC DRIVING MECHANISM

In conventional seed planters, a ground-driven wheel and a combination of several gears generally serve to transfer motion to the seed discs. Our developed seed metering unit uses a brushed DC motor to drive the seed discs. The speed of the metering discs is synchronized with the tractor speed. A closed-loop PID control system regulates the discs' speed according to the reference seed meter disc speed. This reference speed of the seed meter is synchronized with the tractor speed. A rotary encoder measures the speed of the seed metering disc which is used as a feedback. An LCD screen is used to set the desired seed to seed distance, and display the information of tractor speed, the synchronized reference seed meter disc speed and the actual speed of the seed metering disc. Moreover, planters commonly have separate seed metering units for each crop row; therefore, our developed metering unit can be mounted on the main



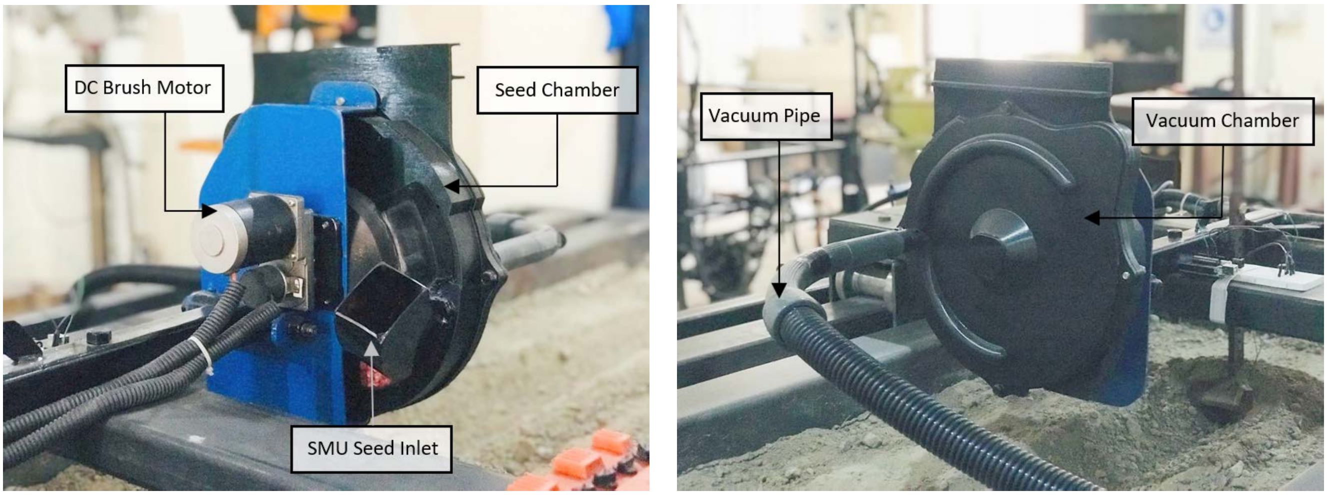
(a) Vacuum Chamber Disc **(b)** Seed Chamber Disc

FIGURE 1. Seed Metering Unit Discs.



(a) Vacuum Chamber Internal Assembly **(b)** Seed Chamber Internal Assembly

FIGURE 2. Internal assembly of the seed metering unit.



(a) 3D Printed Seed Chamber Internal Assembly and Motor Drive System **(b)** 3D Printed Vacuum Chamber Internal Assembly and Vacuum Line

FIGURE 3. 3D printed seed metering unit.

TABLE 1. **Hole area coverage by singulator positions.**

Position	Blob Edge	Hole Area Coverage (%)		
		Group 1	Group 2	Group 3
1	A	0	0	0
	B	25	0	0
	C	50	25	0
2	A	25	0	0
	B	50	25	0
	C	75	50	25
3	A	50	25	0
	B	75	50	25
	C	100	75	50

TABLE 2. **Calibrated vacuum pressure for maize and soybean seeds.**

Seed Type	Speed (km/h)	Minimum Pressure (KPa)	Optimum Pressure (KPa)
Maize	2	0.8	1.28
	4	0.9	1.40
Soybean	2	1.0	1.6
	4	1.0	1.6

structural frame of the planter underneath individual hoppers for each row. The electric drive system provides individual control over each row, and therefore the seed rate can be changed in each row unit individually.

B. VACUUM SYSTEM

The seed picking is primarily based on negative pressure generated by the vacuum system. As the experiments were conducted in the laboratory, an impeller-based vacuum machine was used for creating negative pressure in the vacuum chamber of the SMU via a vacuum line, as illustrated in Figure 3(b). Since the required vacuum levels depend on the type/size of the seed, therefore, two-level calibrated negative pressure values are determined experimentally each for a separate seed type. The procedure involves reducing the speed of the vacuum pump while recording the value of negative pressure from the 3 kPa until it reaches to a minimum value at which the hole of the SMU disc cannot hold the seed. This minimum value of negative pressure is added with its 60 percent value to get the required negative pressure value for each type of seed at different SMU speeds. Table 2 shows the results of the experiment conducted to determine the optimum value of negative pressure.

C. CLOSED LOOP PID CONTROL FOR SPEED REGULATION

A complete block diagram of the system is shown in Figure 4. The speed of the seed metering discs is controlled and varied via a closed-loop PID control system based on desired seed-to-seed distance and given tractor speed. For adjusting/setting the hole/disc according to a particular seed type, the motor is rotated counterclockwise through a specified predetermined angle to co-axially align the holes (group) of the desired seed type on the VCD to the holes on the SCD. The disc rotates and takes the entrained seed towards the seed delivery tube. A singulator singulates any multiple seeds on the way before being released in the tube. The rotational speed of the seed metering disc is varied via a closed-loop feedback control system based on desired seed to seed distance and given tractor speed. Synchronizing the disc's rotational speed with the tractor's travel speed helps the metering unit achieve the desired seed spacing (seeding rate) for the respective seed type. Moreover, the feedback from a rotary encoder is utilized for regulating the metering disc's speed, and thereby the seeding rate, in response to any changes in the tractor's travel speed.

D. CALIBRATION OF SEED METERING UNIT

The rate of seed distribution is performed directly by the seed metering unit. This seed rate depends on the SMU discs' angular speed, ω_{smu}, which would vary accordingly with the vehicle's angular speed ω_t and a fixed predetermined value of seed-to-seed distance d_{ss}. The relation between the required angular velocity SMU and the vehicles's angular velocity is given by equation (2),

$$\omega_d = f_c K_{smu} \omega_t \tag{2}$$

where K_{smu} is the angular velocity coefficient that determines the required relative angular speed. This relative angular speed acts as a reference for the actual SMU discs' angular speed. Whereas f_c is the correction factor that accounts for any offset error in the desired seed-to-seed distance d_{ss}. This offset error that may appear during execution is due to the uncertainty in measuring physical parameters like the vehicle's wheel radius R_t and the amount of flatness caused by the load on the tires. The value of f_c may vary, such that $0 < f_c < 2$. The linear velocity of the vehicle is given by equation (3),

$$v_t = 2\pi R_t \omega_t \tag{3}$$

whereas seed discharge rate R_{seed} is given by,

$$R_{seed} = n_h \omega_d \tag{4}$$

where n_h is the number of holes in the disc for seed picking. For a specific value of vehicle's linear velocity, v_t and seed discharge rate, R_{seed} the seed-to-seed distance, d_{ss} is given by equation (5),

$$d_{ss} = \frac{v_t}{R_{seed}} \tag{5}$$

$$d_{ss} = \frac{2\pi R_t}{n_h K_{smu}} \tag{6}$$

$$K_{smu} = \frac{2\pi R_t}{n_h d_{ss}} \tag{7}$$

This value of angular velocity coefficient is used to determine the required theoretical (tracking) angular velocity of SMU, which would be used as a reference velocity for regulating the actual SMU velocity in a closed-loop control system.

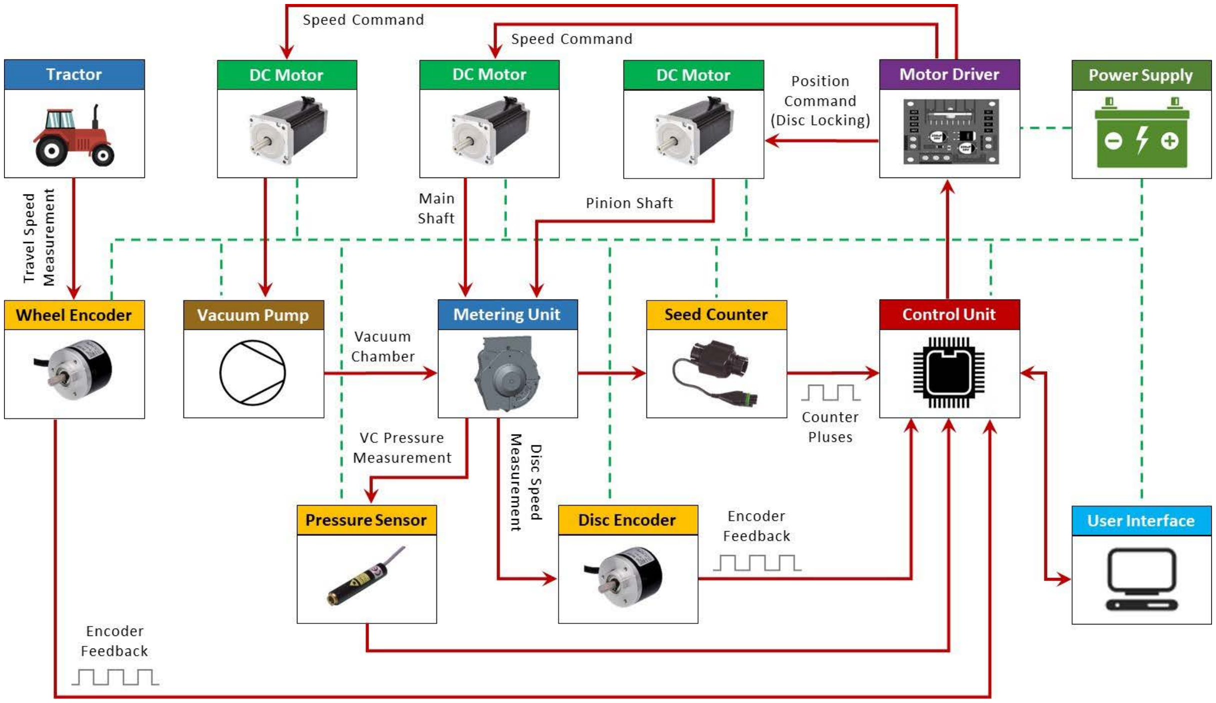


FIGURE 4. Block diagram of the complete system.

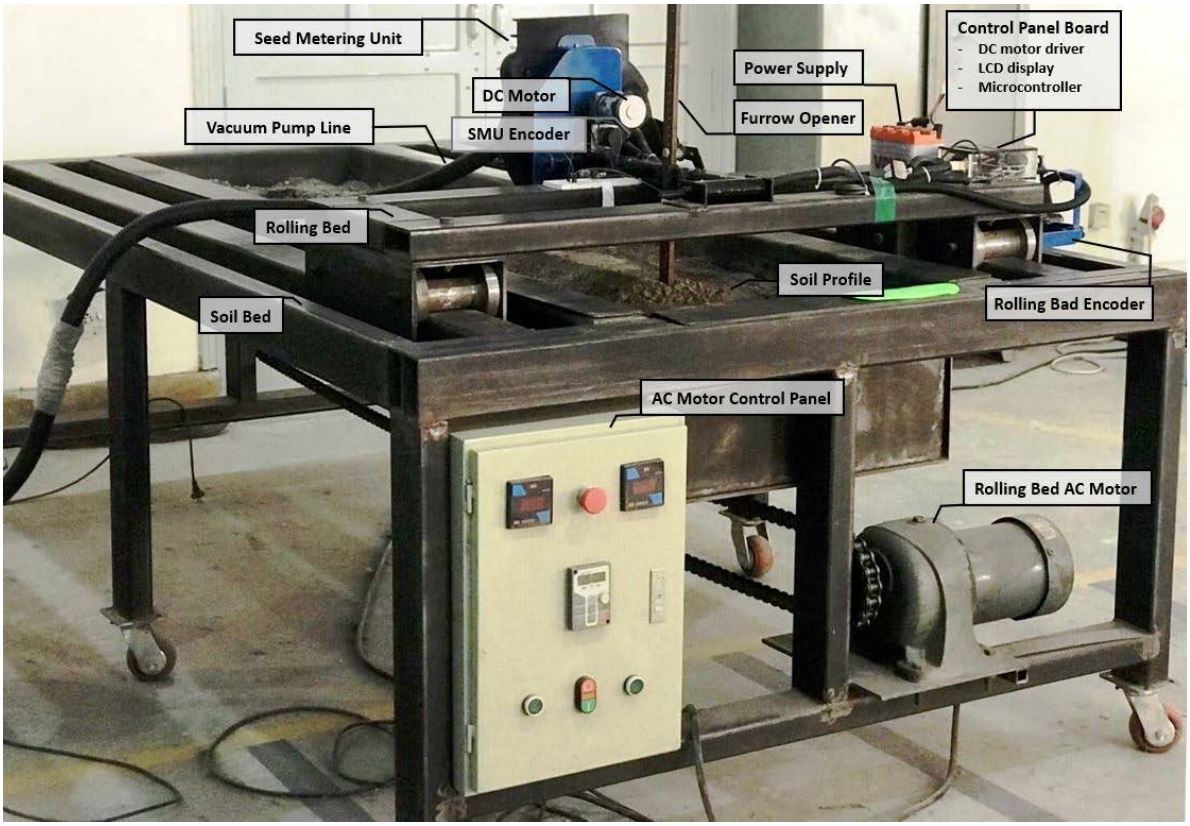


FIGURE 5. Experimental setup.

E. PARAMETERS FOR PERFORMANCE EVALUATION

Missed Seed Count, is the number of seeds missed by the disc holes that passes through a fixed number of revolutions.

Multiple Seed Count, is the number of more than one seed picked by a single hole of the disc that rotates for a set number of revolutions. The *Multiple Seed Count* is further divided

TABLE 3. **Singulator calibration for optimum response.**

Hole Group	Knob Position	Hole Area Coverage (%)			Actual Seed Count
		Blob A	Blob B	Blob C	
Hole 1 for Maize	1	0	25	50	126
	2	25	50	75	111
	3	50	75	100	96
Hole 2 for Soybean	1	0	0	25	119
	2	0	25	50	96
	3	25	50	75	92

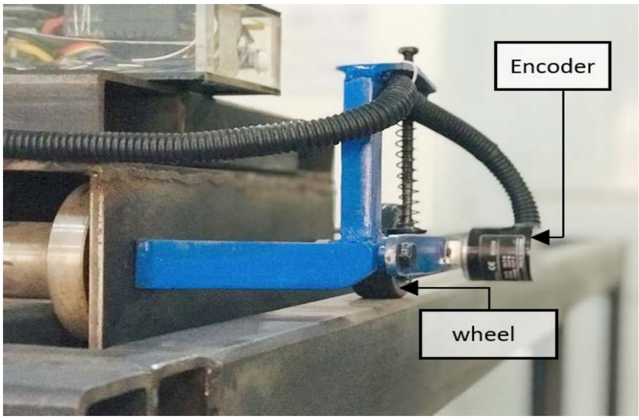


FIGURE 6. **Rolling bed encoder and wheel unit.**

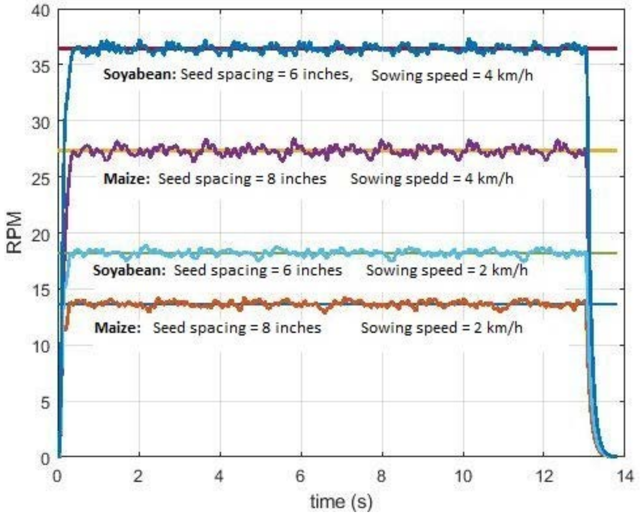


FIGURE 7. **PID controller-based SMU speed tracking.**

into *Double Seed*, *Triple Seed*, and *Quadruple Seed Count* that accounts for the double, triple, and four seeds picked by a single hole of the disc, respectively. *Single Seed Count* determines the numbers of single seeds picked by a single hole of the disc for a set number of revolutions. Precision in spacing I_p is a measure of the variability (coefficient of variation) in spacing S between seeds after accounting for variability due to both multiples and misses, and is given by equation (8),

$$I_p = \frac{S_d}{S} \tag{8}$$

where, S_d is the standard deviation of the spacing more than half but not more than 1.5 times the set spacing S in inches.

Control variable, ω_{smu} is the angular speed of the SMU discs. The SMU uses a DC motor to regulate its speed at which it is required to discharge the seeds in the field. This seed discharge rate depends on the angular speed of the vehicle's wheel. Therefore, the PID controller uses the error information between the relative angular speed, ω_d and the actual angular speed of the SMU, ω_{smu}.

$$e = \omega_d - \omega_{smu} \tag{9}$$

Where ω_d is the desired angular speed calculated by using equation (2). The actual angular speed ω_{smu}, is measured from the encoder value mounted on the SMU.

IV. EXPERIMENTAL EVALUATION

Real-time experimental tests are performed on a laboratory test bench for maize and soybean seeds for evaluating planting accuracy of the seed metering unit.

A. EXPERIMENTAL SETUP

The complete experimental setup is shown in Figure 5. The test bench consists of a soil bed, rolling bed, and a soil tank. The soil bed is a rectangular shaped metal frame having a length of 6 m and a width of 2.5 m. It has two inner beams upon which the rolling bed rolls horizontally across its length. Between these two beams, a soil tank of length 6 m, width 0.8 m, and depth 0.4 m is placed for measuring and analyzing the sowing seeds placed in the soil profile by the SMU.

The rolling bed rolls horizontally over the two beams of the soil bed using a chain-motor drive system. The SMU and all the associated electrical components are installed on the rolling bed. A three-phase motor was operated using a Variable Speed Drive (VSD) to get a desired field velocity for the rolling bed, and consequently move the SMU horizontally to dispense the seeds over the soil bed.

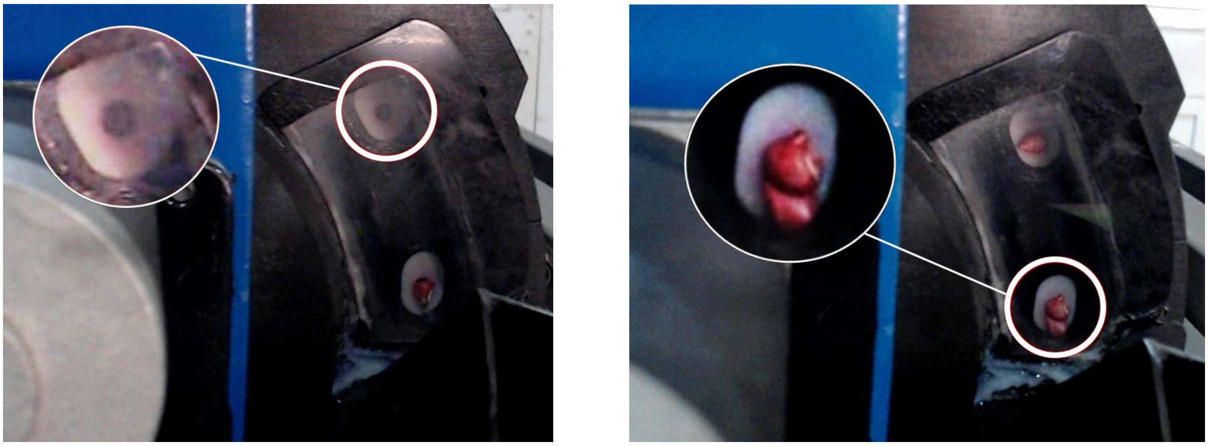
The SMU is equipped with a 12 V brushed DC motor for rotating the discs with the desired rotating speed. A 36 V and 30 A DC motor driver is used to regulate the rotating speed of the SMU by varying the input PWM signal. A 1000 PPR encoder is used to measure the angular velocity of the SMU and is used as a feedback in the control loop. All the electrical components of the planting system are powered by a 12V 50 Amp-hour power supply. A separate incremental encoder-wheel setup is installed on the rolling bed to measure the linear speed (sowing speed) of the rolling bed upon which the SMU is installed. This linear speed is represented by v_t, and is given by equation (3). The overall operating power consumption rating is approximately equal to 26.7 Watts.

B. SMU TEST RESULT AND ANALYSIS

In order to validate the overall performance of the proposed seed metering unit, two types of experiments were conducted in lab facility, i.e., static and mobile tests. Also, as a prior step,

TABLE 4. Seed metering unit precision test.

Crop	Time Duration (s)	Distance Traveled (Inches)	SMU Revolutions		Seed Count		Average Seed Distance (Inches)	Sowing Accuracy (Count Difference)
			Theoretical	Actual	Theoretical	Actual		
Maize	20	437.4	4.55	4.62	54.6	53	8.2	−1.60
	30	656.1	6.82	6.92	81.84	86	7.6	+4.16
	40	874.8	9.10	9.27	109.2	107	8.1	−2.20
	60	1312.2	13.65	13.86	163.8	172	7.6	+8.20
Soybean	20	437.4	6.02	6.19	72.01	68	6.4	+4.01
	30	656.1	9.10	9.31	109.12	106	6.18	+3.12
	40	874.8	12.14	12.24	145.60	139	6.20	+6.60
	60	1312.2	18.21	18.41	218.52	207	6.33	+21.52



(a) Seed Miss Recorded at Travel Speed of 2 km/hr

(b) Seed Double Recorded at Travel Speed of 2 km/h

FIGURE 8. Seed doubles and misses.

the singulator needed to be calibrated according to the type of seed used for sowing.

At each knob position of the singulator assembly, the SMU was operated for 10 revolutions. This procedure was repeated for maize and soybean seeds separately. The theoretical and actual counts were measured for maize and soybean seeds at each knob position of the singulator, and the corresponding results are shown in Table 3. For the singulator with the knob positioned at level 1, the difference in actual and theoretical counts was less than the results for the singulator knob positioned at 2 and 3. We therefore, operated the SMU with the singulator set at position 1 for both maize and soybean seeds for the rest of the experiments.

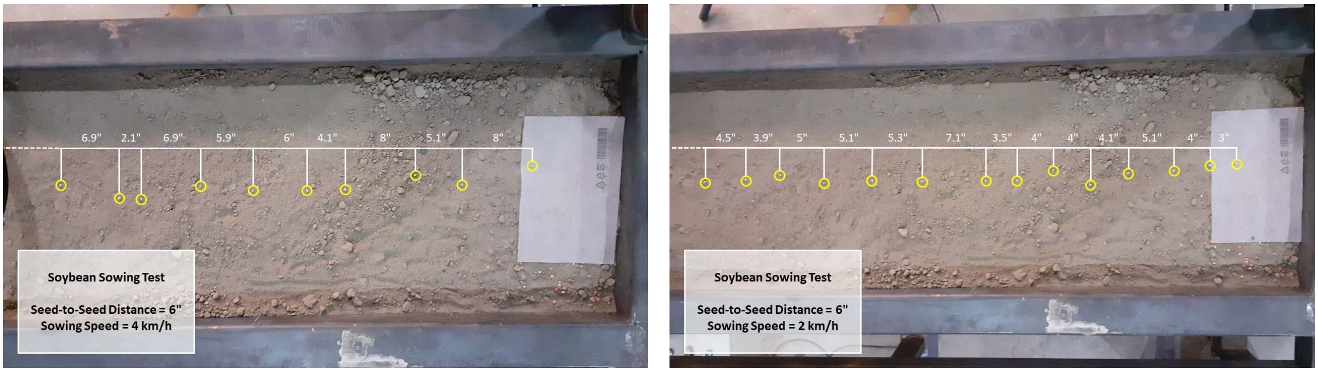
In the static experiment, the SMU was operated with the rolling bed in a rest position, and its performance was evaluated for a longer theoretical distance. The theoretical distances, i.e., the distance traveled in inches as shown in Table 4, were calculated using the vehicle's speed v_t and time duration information. A small hopper holding 1500 maize-seeds capacity was used as a seed storage tank. A seed collecting bag was used to collect the seeds at the outlet of the SMU. In the first set of experiments, the precision tests were performed by comparing the theoretical and actual seed counts for each turn of experiments. The results of the precision tests for the maize and soybean seeds are shown in Table 4. During these experiments, the vehicle's linear speed v_t was maintained at 2 km/h for both types of seeds.

FIGURE 9. Three maize seed doubles at 4 km/h sowing speed and 8 inches seed spacing.

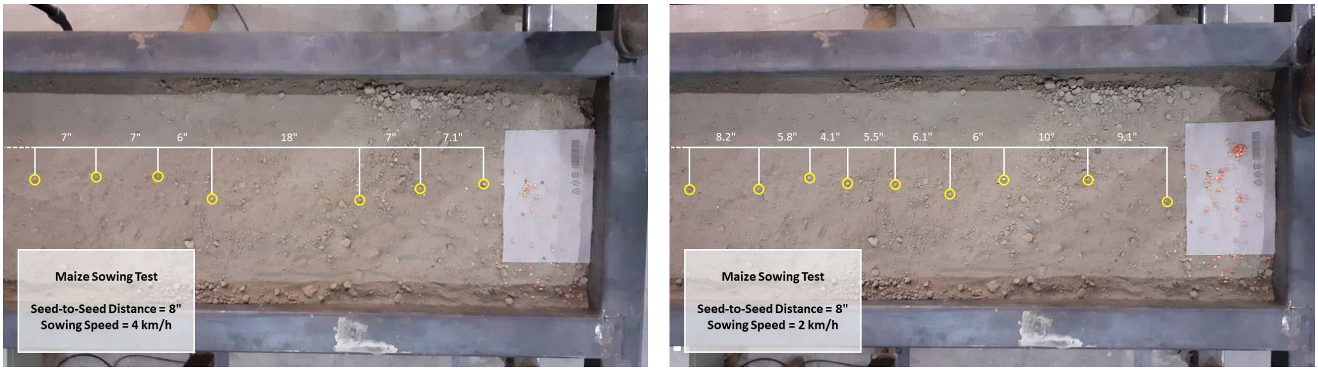
Seed-to-seed distance of 8 inches was considered for the maize, and 6 inches for the soybean. The theoretical seed counts were calculated from the SMU's desired angular velocity ω_d (maintained for a series of different time durations i.e., 20, 30, 40, and 60 seconds). This desired angular velocity of SMU was calculated using the vehicle's angular velocity ω_t that was calculated from equation (3), and the angular velocity coefficient K_{smu} that was calculated using equation (7). Using the vehicle's linear speed v_t and the desired angular speed of SMU ω_d (maintained for a series of

TABLE 5. Effect of speed on the sowing performance.

Crop	Tractor Speed (km/h)	Seed Count		Miss Seed Count	Multiple Seed Count			Seed Spacing Variation Coefficient (I_s)
		Theoretical	Actual		2x	3x	4x	
Maize	2	81	84	2	13	5	3	0.25
	4	163	155	12	7	3	0	0.57
Soybean	2	109.1	97	8	4	0	0	0.17
	4	218	142	71	0	0	0	0.38



(a) Soybean Sowing Test at 4 km/h (b) Soybean Sowing Test at 2 km/h



(c) Maize Sowing Test at 4 km/h (d) Maize Sowing Test at 2 km/h

FIGURE 10. Maize and soybean sowing tests.

different time durations), the vehicle's total traveled distance and the total numbers of SMU revolutions are determined respectively, as shown in Table 4. The fact that there are n_h seed picking holes arranged along the circumference of the seed disc, the total number of theoretical seed counts is equal to the to total number of theoretical revolutions multiplied by n_h.

In order to measure the actual output performance of the SMU, the PID controller was designed to regulate the actual angular velocity of SMU ω_{smu} by tracking the calculated desire angular velocity of the SMU ω_d. The actual total number of SMU revolutions is measured using the SMU encoder for a series of different time durations. The actual seed counts are measured by counting the numbers of ejected seeds from the outlet of the SMU.

To change the seed hole size i.e., to shift from one hole group type to another hole group, the DC motor is used to rotate the vacuum chamber disc relative to the seed chamber disc. As the teeth on the pinion gear are meshed with the teeth on the SCD, the pinion blocks rotation of SCD by applying electric braking via the second DC motor attached to the pinion shaft. This helps in achieving the desired hole shift for the required seed type.

It can be seen in the precision tests that maize seed, with a sowing speed of 2 km/h and 8 inches seed-to-seed distance, shows 94% accuracy. Also, the desired seed-to-seed distances for both seed types were achieved within the acceptable range of variations. However, the accuracy decreases as the seed-to-seed distance decreases for the soybean seed. This decrease in seed-to-seed distance accounts for the increase in the angular speed of the SMU. Because of this increase in the SMU's angular speed, the miss-count rate increases as shown in Table 4.

In the mobile experiment, the maize and soybean seeds were used to examine the sowing quality in a single row of the soil bed. The sowing was performed through a single row in a series of experiments, carried out for each type of seed separately. The sowing was performed at 2 km/h and 4 km/h rolling bed speed. As shown in Figure 6, the rolling bed uses a rotary incremental encoder and a wheel that roles over the soil bed to measure the angular velocity of the rolling bed (vehicle), ω_t and using equation (2), the reference angular velocity for SMU is calculated. The SMU control unit then uses the PID controller to track the reference angular velocity. The corresponding angular velocities response of the SMU for planting the maize and soybean seeds are plotted in Figure 7. The difference in angular velocities is due to the required different seed-to-seed distances.

The SMU has a transparent window through which the rotating disc carrying seeds can be seen. A video recording camera was put in front of the window to record any miss and multiple counts of seeds, as illustrated in Figure 8.

The numbers of observed multiples counts and miss-counts of seeds recorded in the videotape were counted and listed in Table 5. As shown in Figure 9, the doubles for maize seeds are observed and highlighted with a zoomed-in circle. The seeds are considered double if the corresponding distances between two subsequent seeds is less than half of the required set seed spacing. In the case of maize seeds, the set seed spacing of 8 inches was considered. Therefore, three doubles of 2.1, 1.2, 1.3 inches were observed for the maize seed with the sowing speed of 4 km/h.

In Table 5, the effect of the singulator on seed multiples can be seen for maize seeds at a sowing speed of 2 km/h. The numbers of doubles, triples, and quadruples are reduced to a single seed per hole. It is evident that the actual seed count is very much close to the theoretical seed count. However, with the increase of sowing speed to 4 km/h, the desired angular velocity of the SMU increases. Because of this increase in SMU's velocity, the miss-counts increases, and accordingly the values of higher multiples-counts of seeds decrease. In Figure 10, the actual seed-to-seed distance can be seen for maize and soybean. In Figure 10(b) and (d), the desired seed-to-seed distance for soybean and maize were maintained at 6 and 8 inches respectively for a 2 km/h sowing speed. In Figure 10(a) and (c), the sowing speed was increased to 4 km/h and the corresponding actual seed-to-seed distances for soybean and maize seeds were measured, respectively.

V. CONCLUSION

This paper presents a novel variable rate multi-crop pneumatic seed metering unit that can plant different types of seeds at variable rates. The developed metering unit can plant different crop seed types without any need to change the discs or other parts. Experimental evaluation of the developed metering unit on a lab test bench proved that our developed multi-crop seed metering unit offers better performance and efficiency than the conventional seed metering units. Moreover, our proposed seed metering unit is a step forward to advanced planting techniques such as (a) multi-crop planting in which two or more than two different types of crop seeds can be planted in different areas of the same field, and (b) multi-hybrid planting in which two or more than two hybrids of the same type of crop can be planted in different areas of the same field. The accuracy of the proposed SMU has shown a maximum of 2 miss seeds for 11 meter sowing distance. Also, the error in seed-to-seed distance was maintained within less than half of the set seed-to-seed distance. The future study intends to incorporate the metering unit presented in this study with hoppers that have separate housings for different types of hybrids or seeds with an electrically actuated cut and supply seed delivery system. The miss seed rate could be reduced by regulating the vacuum pressure according to the SMU's angular speed.

REFERENCES

[1] N. Alexandratos and J. Bruinsma. (Jun. 2012). *World Agriculture Towards 2030/2050: The 2012 Revision*. [Online]. Available: http://www.fao.org/3/aap106e.pdf and http://www.fao.org/3/a-ap106e.pdflt and http://ageconsearch.umn.edu/record/288998

[2] U. Desa, *World Population Prospects 2019: Highlights*, vol. 11. New York, NY, USA: United Nations Department for Economic and Social Affairs, 2019, p. 125.

[3] A. Khadatkar, S. M. Mathur, K. Dubey, and V. Bhusanababu, "Development of embedded automatic transplanting system in seedling transplanters for precision agriculture," *Artif. Intell. Agricult.*, vol. 5, pp. 175–184, Jan. 2021.

[4] F. E. Nasir, M. S. Alam, M. Tufail, and M. T. Khan, "A novel pressure and flow control technique for variable-rate precision agricultural sprayer," in *Proc. Int. Conf. Robot. Autom. Ind. (ICRAI)*, Oct. 2021, pp. 1–6.

[5] X.-T. Yan, A. Bianco, C. Niu, R. Palazzetti, G. Henry, Y. Li, W. Tubby, A. Kisdi, R. Irshad, S. Sanders, and R. Scott, "The AgriRover: A reinvented mechatronic platform from space robotics for precision farming," in *Reinventing Mechatronics*. Cham, Switzerland: Springer, 2020, pp. 55–73.

[6] M. S. Alam, M. Alam, M. Tufail, M. U. Khan, A. Gunes, B. Salah, F. E. Nasir, W. Saleem, and M. T. Khan, "TobSet: A new tobacco crop and weeds image dataset and its utilization for vision-based spraying by agricultural robots," *Appl. Sci.*, vol. 12, no. 3, p. 1308, Jan. 2022.

[7] A. Pretto, S. Aravecchia, W. Burgard, N. Chebrolu, C. Dornhege, T. Falck, F. Fleckenstein, A. Fontenla, M. Imperoli, R. Khanna, and F. Liebisch, "Building an aerial–ground robotics system for precision farming: An adaptable solution," *IEEE Robot. Autom. Mag.*, vol. 28, no. 3, pp. 29–49, Sep. 2021.

[8] L. Quanwei, H. Xiantao, Y. Li, Z. Dongxing, C. Tao, Q. Zhe, Y. Bingxin, W. Mantao, and Z. Tianliang, "Effect of travel speed on seed spacing uniformity of corn seed meter," *Int. J. Agricult. Biol. Eng.*, vol. 10, no. 4, pp. 98–106, 2017.

[9] K. N. Harker, J. T. O'Donovan, R. E. Blackshaw, E. N. Johnson, G. P. Lafond, and W. E. May, "Seeding depth and seeding speed effects on no-till canola emergence, maturity, yield and seed quality," *Can. J. Plant Sci.*, vol. 92, no. 4, pp. 795–802, Jul. 2012.

[10] S. Mandal, G. V. P. Kumar, H. Tanna, and A. Kumar, "Design and evaluation of a pneumatic metering mechanism for power tiller operated precision planter," *Current Sci.*, vol. 115, no. 6, pp. 1106–1114, 2018.

[11] Kapil, B. R. Kamboj, M. L. Jat, A. Kumar, D. Kumar, H. S. Sidhu, M. K. Gathala, Y. S. Saharawat, V. Kumar, A. Kumar, and V. Kumar, "Operational manual for multi-crop zero till planter," Cereal Syst. Initiative South Asia (CSISA), Int. Maize Wheat Improvement Center (CIMMYT), Int. Rice Res. Inst.(IRRI), NASC Complex, New Delhi, India, 2012, p. 24.

[12] O. Ani, B. Uzoejinwa, and N. Anochili, "Design, construction and evaluation of a vertical plate maize seed planter for gardens and small holder farmers," *Nigerian J. Technol.*, vol. 35, no. 3, pp. 647–655, 2016.

[13] M. Sahu, V. Victor, and A. Verma, "Response of maize (Zea mays L) crop to different planting machine: A review," *Int. J. Eng. Res. Gen. Sci.*, vol. 5, pp. 1–5, Jan. 2017.

[14] J. A. L. Gomez and J. Van Loon, "Agrotechnical evaluation of manual implements for corn planting," *Revista Mexicana De Ciencias Agricolas*, vol. 9, no. 21, pp. 4258–4269, 2018.

[15] J. Van Loon, T. J. Krupnik, J. A. López-Gómez, J. Timsina, and B. Govaerts, "A standard methodology for evaluation of mechanical maize seed meters for smallholder farmers comparing devices from Latin America, sub-Saharan Africa, and Asia," *Agronomy*, vol. 10, no. 8, p. 1091, Jul. 2020.

[16] X. He, T. Cui, D. Zhang, J. Wei, M. Wang, Y. Yu, Q. Liu, B. Yan, D. Zhao, and L. Yang, "Development of an electric-driven control system for a precision planter based on a closed-loop PID algorithm," *Comput. Electron. Agricult.*, vol. 136, pp. 184–192, Apr. 2017.

[17] X. He, Y. Ding, D. Zhang, L. Yang, T. Cui, and X. Zhong, "Development of a variable-rate seeding control system for corn planters Part I: Design and laboratory experiment," *Comput. Electron. Agricult.*, vol. 162, pp. 318–327, Jul. 2019.

[18] X. He, Y. Ding, D. Zhang, L. Yang, T. Cui, and X. Zhong, "Development of a variable-rate seeding control system for corn planters Part II: Field performance," *Comput. Electron. Agricult.*, vol. 162, pp. 309–317, Jul. 2019.

[19] A. Cay, H. Kocabiyik, and S. May, "Development of an electro-mechanic control system for seed-metering unit of single seed corn planters Part I: Design and laboratory simulation," *Comput. Electron. Agricult.*, vol. 144, pp. 71–79, Jan. 2018.

[20] A. Cay, H. Kocabiyik, and S. May, "Development of an electro-mechanic control system for seed-metering unit of single seed corn planters Part II: Field performance," *Comput. Electron. Agricult.*, vol. 145, pp. 11–17, Feb. 2018.

[21] Z. Liang, D. Zhang, L. Yang, T. Cui, and Y. Hao, "Experimental study on motor driven pneumatic precision seed-metering device for maize," in *Proc. ASABE Annu. Int. Meeting*. American Society of Agricultural and Biological Engineers, 2015, p. 1.

[22] M. Jafari, A. Hemmat, and M. Sadeghi, "Development and performance assessment of a DC electric variable-rate controller for use on grain drills," *Comput. Electron. Agricult.*, vol. 73, no. 1, pp. 56–65, Jul. 2010.

[23] A. A. Borja, R. M. C. Amongo, D. C. Suministrado, and J. P. Pabico, "A machine vision assisted mechatronic seed meter for precision planting of corn," in *Proc. 3rd Int. Conf. Control Robot. Eng. (ICCRE)*, Apr. 2018, pp. 183–187.

[24] Z. Abdolahzare and S. A. Mehdizadeh, "Nonlinear mathematical modeling of seed spacing uniformity of a pneumatic planter using genetic programming and image processing," *Neural Comput. Appl.*, vol. 29, no. 2, pp. 363–375, Jan. 2018.

[25] D. L. Mangus, A. Sharda, D. Flippo, R. Strasser, and T. Griffin, "Development of high-speed camera hardware and software package to evaluate real-time electric seed meter accuracy of a variable rate planter," *Comput. Electron. Agricult.*, vol. 142, pp. 314–325, Nov. 2017.

[26] R. C. Singh, G. Singh, and D. C. Saraswat, "Optimisation of design and operational parameters of a pneumatic seed metering device for planting cottonseeds," *Biosyst. Eng.*, vol. 92, no. 4, pp. 429–438, Dec. 2005.

[27] P. Xue, X. Xia, P. Gao, D. Ren, Y. Hao, Z. Zheng, J. Zhang, R. Zhu, B. Hu, and Y. Huang, "Double-setting seed-metering device for precision planting of soybean at high speeds," *Trans. ASABE*, vol. 62, no. 1, pp. 187–196, 2019.

[28] H. Jing, D. Zhang, Y. Wang, L. Yang, C. Fan, H. Zhao, H. Wu, Y. Zhang, J. Pei, and T. Cui, "Development and performance evaluation of an electro-hydraulic downforce control system for planter row unit," *Comput. Electron. Agricult.*, vol. 172, May 2020, Art. no. 105073.

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