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DESIGN, FABRICATION, AND EXPERIMENTAL INVESTIGATION OF SCREW AUGER TYPE FEED MECHANISM FOR A ROBOTIC WHEAT DRILL

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Highlights

- An auger type feed mechanism was designed for a robotic wheat drill, and a laboratory investigation was carried out.
- To avoid seed blockage, the recommended screw auger pitch must be at least 150% of the maximum seed dimension.
- The performance of the feed mechanism was influenced by auger speed, vibration, and slope.
- This study delivered a bulk feed mechanism for wheat drilling, which can be easily scaled and adopted by small autonomous vehicles or mobile robots.

Abstract. *Cultivating the arable, highly sloped hills and uneven terrain is challenging and unsafe with large agricultural machines. Therefore, a fleet of small Autonomous Ground Vehicles (AGV) was proposed to farm sloped or uneven terrain. The fleets need a robotic grain drill operating on varying slopes, and the success of the fleet depends on the performance of the robotic seeder or grain drill. The feed mechanism is the heart of the seeder, and its design and performance influence the plant population and crop yield. In this study, an auger-type feed mechanism was designed and fabricated for robotic wheat drilling. Feed mechanisms with augers having three different pitches were developed as per the ASABE standards. The developed feed mechanism was investigated in a laboratory setup for flow rate and flow uniformity in accordance with ISO standards. The predictor variables were auger type (pitch), auger rotational speed, vibration, and slope. The auger flow rate for flat slopes was a linear function of auger speed and varied from 30 g/min to 170 g/min. The coefficient of variation (CV) for flow rate ranged from 2 to 10%. The CV was within the acceptable limits, which was an excellent indicator of the bulk feed mechanism's flow uniformity. The feed mechanism performance was influenced by vibration and slope.*

However, the auger flow rate remained constant for vibration frequencies of 0, 6, and 14 Hz, suggesting that the feed mechanism was vibration-proof and can tolerate the vibration frequency up to 14 Hz. The flat, downhill (descending), and uphill (ascending) slope levels did not affect the feed mechanism performance. However, the side slopes (right and left slope) significantly affected the feed mechanism flow rate but did not affect the flow uniformity. The study delivered a feed mechanism for a sloped-ground prototype seeder, which can be easily scaled and adopted by small autonomous vehicles or mobile robots.

Keywords. *Flow rate, flow uniformity, multi-robot, screw auger, robotic seed drill, seed rate.*

INTRODUCTION

A continuously growing global population and escalating food, fiber, and fuel demands were the major drivers of agriculture cropland intensification and expansion to achieve global food security (Zabel *et al*., 2019). In cropland intensification, advanced tools and techniques improve crop resource use efficiencies to boost crop production on existing land (Robertson and Doran, 2013). In contrast, cropland expansion brings new land under cultivation by either clearing grasslands, or, forests or bringing unsuitable marginal land under cultivation. The pace of cropland expansion was accelerated in recent decades, and it was estimated that global cropland area increased by 9%, that was 101.9 ± 45.1 Mha, between 2003-2019 (Potapov *et al*., 2022). In the United States, the rate of cropland expansion was over 404.6 thousand ha per year between 2008 and 2016 (Lark *et al*., 2020). Some parts of the Great Plains (US) have uncultivated rolling hills, steep grasslands, and uneven terrain often characterized as marginal land (Badgujar *et al*., 2022a). The excessive steepness of marginalized grasslands, hills, and uneven terrain precludes crop cultivation with conventional agricultural equipment. Land steeper than 6° is challenging and unsafe to cultivate, and accidents involving large tractors killed over 120 farmers per year in the U.S., mainly from roll-overs (Great Plains Center for Agricultural Health, 2014). Solving this technical impediment to slope farming could significantly expand the agricultural land to boost sustainable food production. It is estimated that a sustainable expansion of wheat production to these steep grasslands and uneven terrain would almost double the land area used for this crop from current 4% to 7% in the Great Plains region.

Mobile robots and small autonomous ground vehicles were being employed to perform repetitive agricultural tasks with human assistance/intervention and have the potential to become prime candidates for outdoor agriculture in the near future. Therefore, a fleet of small Autonomous Ground Vehicles (AGV) was proposed to drill wheat on the highly sloped grassland, hills, and uneven terrain (Badgujar *et al*., 2022). The drilled wheat crop is for cattle grazing and will not be harvested for grain. A self-propelled robotic wheat drill (two rows & row spacing of 30.4 cm) dispersing the controlled amount of seeds on marginalized grasslands is the critical component of multi-AGV fleet operation. The success of a multi-AGV fleet largely depends upon the wheat drill performance. The feed mechanism is the heart of the grain drill, and its performance influences the optimum plant population and determines the crop yield. Fluted rollers are the most common feed mechanism employed on conventional grain and fertilizer drills for bulk metering. The construction, operation, and control of the fluted roller feed mechanism are relatively simple and easy. It has a flute roller periphery, and each flute acts as a seed pocket. The seeds were filled in pockets and released at the seed outlet with fixed velocity. The action of discharging seeds, pocket by pocket, results in loss of seed uniformity and uneven flow pattern. Multiple studies reported that discontinuous batch flow was the major constraint of the fluted roller feed mechanism (Jafari, 1991; Maleki *et al*., 2006, Huang *et al*., 2018). In fluted roller fitted grain drills, farmers often opt for an increased seeding rate to ensure a better yield per unit area, which results in either the loss of costly seeds or undesired plant population (Guler, 2005).

The screw conveyors or multi-flight augers have been extensively employed in bulk material handling in agriculture, chemical, processing, construction, and other industries. Jafari (1991) first studied the applicability of a multi-flight screw auger as a feed unit for grain drills. The study fabricated the nine types of screw augers varying in dimensions and tested them for bulk metering on fifteen kinds of bulk material, including common seeds and hollow spheres. A grain flow rate equation as a function of screw auger operational, constructional parameters, and seed properties was developed based on dimensional analysis. The study established design and construction guidelines for the screw auger as the grain drill feed mechanism. Maleki *et al*., (2006) developed twelve types of screw augers varying in auger dimension as a metering unit for a wheat grain drill and compared the seed distribution uniformity of the multi-flight auger against the fluted roller. The study found that the auger mechanism had more uniform discharge characteristics than the fluted type. The seed uniformity coefficient was also significantly higher for the auger unit than for the fluted roller. They tested the screw auger having outside diameter of 50 mm and 70 mm to the maximum speed of 30 rpm, so currently, the auger performance at a higher speed was unknown.

The literature survey suggested that the screw auger was an alternative to the fluted roller as a feed mechanism in grain drills. Different augers were developed for bulk metering of grains and tested against varying operational settings, mostly auger rotational speed. However, robotic grain drill operation on sloped and uneven terrain is challenging and introduces a unique variable that has not been previously considered in the literature. In conventional grain drills, an engine-powered tractor provides sufficient drawbar pull to operate a heavy grain drill equipped with a passive tillage tool for furrow opening. In contrast, AGVs are lightweight, often weigh less than 200 kg, and do not have drawbar pull and downforce for furrow creation with passive tillage tools. Therefore, actively powered tillage tools were a suitable option for furrow opening. Powered tool or blade assemblies generate vibration as the tool cuts the grasses, soil and encounters rocks. These induced vibrations would affect the feed mechanism performance, such as seed flow rate and flow uniformity (Boydas and Turgut, 2007). Hence, the feed unit performance must be tested against the varying vibration levels. Moreover, a robotic drill has to operate on continuously varying sloped or uneven terrain up to 20° (downhill, uphill and side slope). The feed unit inclination would affect the seed flow in the metering unit and its performance; hence, it was essential to assess the feed mechanism performance on varying slope inclination.

This study aimed to design, fabricate, and investigate an auger type feed mechanism for wheat drilling on sloped and uneven terrain. The specific objectives of the study were to (1) design and fabricate an auger feed unit for a robotic wheat seed drill and, (2) investigate the developed feed mechanism performance at varying speed, vibration, and slope inclination. The feed mechanism would be incorporated into the prototype robotic grain drill.

MATERIALS AND METHODS

SEEDER DESIGN & FABRICATION

Physical characteristics of seed

The seed dimension such as length, width, and thickness were essential in designing the auger groove and seeder dimensions. The bulk density of seed affects the seed flowability in the auger groove, and test weight (thousand seed weight) was required to compute the auger flow rate in gram/min. This study selected the wheat seed variety called "Zenda" without seed treatment. This seed variety was primarily grown in the Kansas region (U.S.A). The physical characteristics of wheat, such as dimensions (length, width, and thickness), seed weight, and bulk density, were measured as per the procedures mentioned in Badgujar *et al.,* (2018) from a randomly selected seed batch. Measured characteristics were presented in Table 1.

Table 1. Physical characteristics of wheat seed used in the study.

Length (mm)	Width (mm)	Thickness (mm)	Thousand seed weight (g)	Bulk density (kg/m^3)
6.02 ± 0.34	2.99 ± 0.20	2.67 ± 0.19	31.6	811-809

Auger Design Parameters

The physical characteristics of wheat seeds were considered for the auger design. The ASABE Standard: EP389 (2019) was followed for the auger design and explained as follows.

Inside diameter (d): Nominal auger diameter selection depends upon the drive shaft diameter. A six mm diameter drive shaft (D-shaft) was used to drive the auger, resulting in an auger inside diameter of nine mm with a 1.50 mm wall thickness.

Flighting strip width: The strip width was the depth of the groove which accommodates the seeds. The depth and width of the groove must be greater than the maximum seed dimension for free movement of seed particles inside the auger groove (Maleki *et al*. 2006). Length was the maximum dimension of wheat, and the observed average length was 6.02 mm. Therefore, the strip width of 7.60 mm was selected, which was 25% greater than the maximum seed dimension.

Outside diameter (D): The auger size was specified by the auger flight outside diameter. The outside diameter was determined by adding two times the strip width to the inside diameter (*d*), which resulted in an outside diameter of 24.2 mm. The length of the auger was 65 mm, and this auger length did not allow the auger to self-discharge when not in motion on flat and side slopes up to 11°.

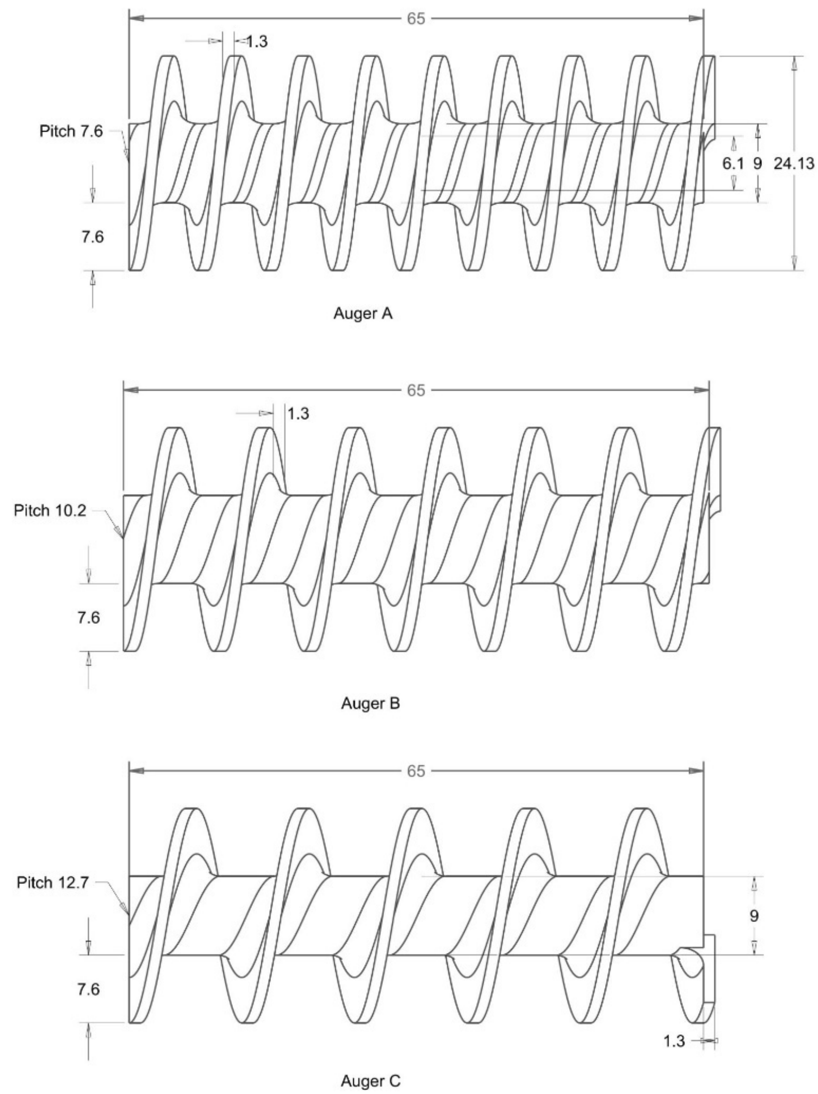

Figure 1. Augers with three different pitches were developed in this study. Figure shows only left-hand augers (All dimensions in mm).

Pitch of flighting (P): The width of the auger groove was defined by the auger flighting pitch. It was the distance parallel to the shaft axis of one revolution of the flight strip around the center shaft. To prevent seed blockage, the pitch should be greater than the sum of seed width and length (Maleki *et al*. 2006). Three different augers pitches were used. The selected pitches were 7.60 mm, 10.20 mm, and 12.70 mm, which resulted in an auger with nine, seven, and five flights, respectively, as shown in Figure 1. The seeder included both right-hand and left-hand flighting augers. The width and depth of the groove influenced the amount of seed discharge (flow rate) in addition to auger rotational speed. The strip thickness was 1.30 mm. In this study, three types of augers with varying pitch and flights were developed and shown in Figure 1. The augers were fabricated with a 3D printer (F410, Fusion3 3D Printers, Greensboro, NC, US) using Thermoplastic Polyurethane (TPU) filament. TPU was a flexible and durable material that would significantly reduce seed damage compared to a hard-plastic material. The flexible material auger flights did not move relative to a point on the shaft while metering wheat, so the effective pitch and strip width were not affected.

Auger housing: The housing was a rectangular box shape. The augers were fitted into the hollow auger housing with 1.5 mm clearance, less than the seed thickness which prevented seed entrapment between auger flighting periphery and the auger housing. The auger housing was 3D printed with a durable hard plastic filament called Acrylonitrile Butadiene Styrene (ABS). The seeder housing was fitted into a readily available and standard aluminum U-channel section with a fixed hole pattern (Actobotics U-channel, Servocity, Winfield, KS, US). An adjustable rectangular seed entrance was located between the bottom of the seed hopper and the top of the housing. Each auger had an independent exit hole for seed discharge located at the bottom, as shown in Figure 2. Each exit hole had a seed discharge tube, one on the left and one on the right (Figure 2). The U-channel accommodated two auger housings, in which the right-hand and left-hand flighting augers were fitted. The left-auger housing was made of transparent acrylic material. This see-through housing allowed direct observation of seed particle behavior, blockage, and seed flow. The right auger housing was ABS plastic filament and did not allow for seed flow observation. These different housing material types had relatively different surface roughness; therefore, their flow rate was recorded separately, i.e., LH and RH. A gravity seed hopper was attached to the top of the auger housing. The hopper and other seed parts were 3D printed with ABS plastic filament.

Drive assembly: A six mm diameter drive shaft (D-shaft) was used to drive the two augers. The 3D-printed augers were press fit on the driveshaft, and a separating wall was placed in between these augers. The high torque D.C stepper motor (Nema 23, OMC Corporation Limited, Nanjing City, China) was fixed to one end of the U-channel and connected to the D-shaft with a coupler. At the other end of the U-channel, a rotary encoder (755A Nema, Encoder products company, Sagle, ID, USA) was mounted onto the drive shaft, which measured the auger rotational speed. As desired, the motor speed was controlled by a stepper motor driver (DM542T, OMC Corporation Limited, Nanjing City, China). The auger shaft was supported on three bearings; one was at the center and two at the ends.

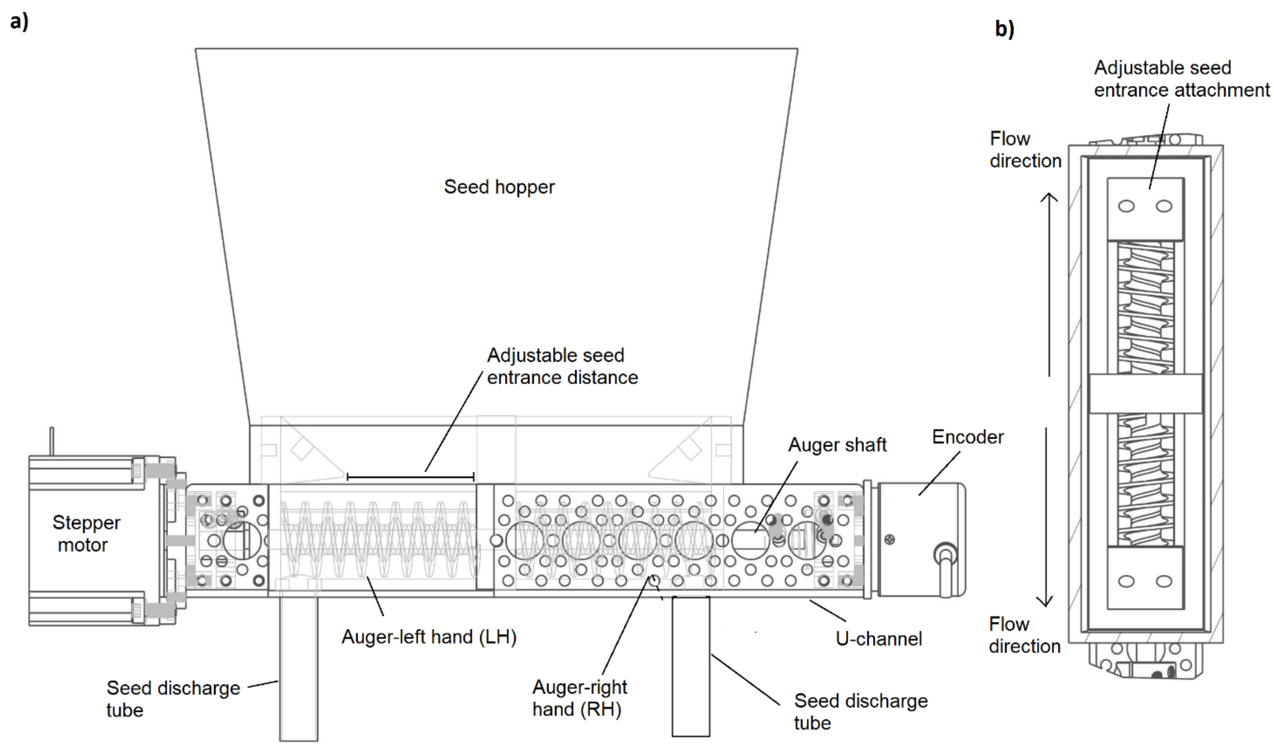

Figure 2. a) Schematic diagram of the feed mechanism showing the main components b) Top cross-sectional view of the auger housing.

EXPERIMENTAL INVESTIGATION

Experimental variables

The study included the four predictor variables (n=4), and their levels were listed in Table 2. The three different types of augers described above were investigated. Each revolution of the auger flight moved a theoretical volume of material. The auger rotational speed was varied from 10 to 70 rev/min with an 10 rev/min increments. The vibration levels (frequency and amplitude) were decided based on the acceleration data collected from the prototype robotic grain drill during field operation. The source of vibration was motor rpm, soil cutting action of blades, and field irregularities. The collected acceleration data was transformed to the frequency domain from the time domain by applying the Fast-Fourier Transform (FFT). Figure 3(a) showed the actual observed acceleration, the vibration frequency was randomly distributed, and there was no dominant frequency observed. However, we noticed the frequency peaks around 6, 22, and 35 Hz. Therefore, we attempted to generate the vibration of frequency around 6 Hz (level 2), 14 Hz (level 3), and 23 Hz (level 4) with higher amplitude, as shown in Figure 3(b), 3(c), and 3(d). Vibration level 1 included no vibration. The robotic grain drill would be traversing the varying sloped terrain on an uphill, downhill, and side slopes. Hence, the metering unit slope levels included the flat, ascending (uphill), descending (downhill), and side slopes (right slope and left slope). The slope magnitude (11 deg) was decided in accordance with ISO 7256/2 (1984; Table 2).

The experimental design was divided into two separate procedures, which significantly reduced the number of experiments. Both of the experimental design procedures implemented the Split-Split Plot design. The treatment structure of the first study was arranged in a 3 x 7 x 2 factorial manner with three levels of auger pitch (types A, B, C), seven levels of speed (10, 20, 30, 40, 50, 60, and 70 rev/min), two levels of location (left hand auger, right hand auger) and five replications. In the first design, auger types were randomly assigned to whole plots, then different levels of speed were randomly assigned to subplots within the auger type. Both locations were assigned to each subplot. The total number of experimental units for main plots was 15, for subplots was 105, and for sub-sub-plots was 210. The optimal combination of auger type and speed were fixed according to the application needs (desired flow rate) from the first experiment. The selected auger and speed combination were further studied in the second experimental design to check the influence of vibration and metering unit inclination on flow rate. The treatment structure of the second study was arranged in a 5 x 4 x 2 factorial manner with five levels of slope (flat, asc., desc., left slope, and right slope), four levels of vibration (level 1, level 2, level 3, and level 4), two levels of location (left-hand auger and right-hand auger), and five replications. In the second design, different slopes were randomly assigned to whole plots, then different levels of vibration were randomly assigned to subplots within the slope. Both locations were assigned to each subplot. The total number of experimental units for main plots was 25, for subplots was 100 and for sub-sub-plots 200. For these two studies, analysis of variance tests were conducted to determine if there were any significant difference among the treatment means. All tests were conducted at the 0.05 significance level. The Holm-Tukey multiple means comparison test was used to determine which means were significantly different. Statistical analysis was executed via Statistical Analysis Software (SAS version 9.4; Cary, NC).

Table 2. Experimental variables under the study.

Predictor				
Auger types	Speed, rev/min	Vibration, Hz	Metering unit slope, deg	Response
Auger A	10, 20,	Level 1 (none)	Flat	Flow rate (g/min)
Auger B	30, 40,	Level 2 (6 Hz)	Ascending slope (11)	Flow uniformity
Auger C	50,	Level 3 (14 Hz)	Descending slope (11)	
	60,	Level 4 (24 Hz)	Side slope to the left (11)	
	70		Side slope to the right (11)	

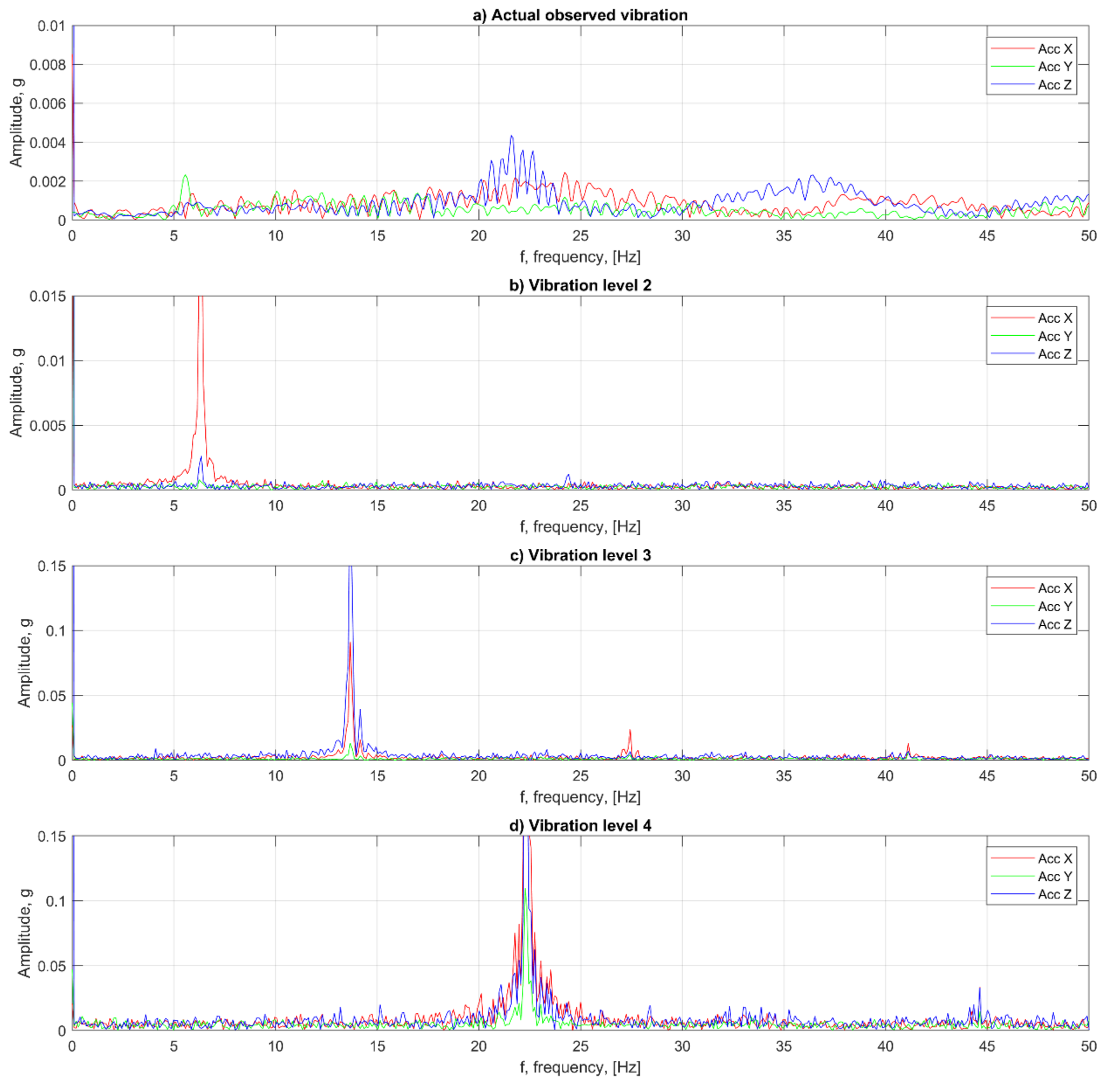

Figure 3. Actual field vibration and experimental levels of vibration. (Note: g = 9.81m/s^2)

Seeder test bench

A seeder test bench was established for feed mechanism testing, which accommodated the necessary instrumentation setup. The test bench allowed control of auger speed, measurement of seed flow rate, and setting the slope and vibration level. A microcontroller (myRio, National Instruments, Austin, TX, USA) was fitted on the test bench. The microcontroller controlled the stepper motor driver for auger speed. A straight bar mini load cell (TAL221, Sparkfun Electronics, Boulder, CO, U.S.A) with 100 g capacity was used to measure seed weight. The load cell was calibrated (static calibration), and signals were amplified to 0-5 voltage with a load cell amplifier (JY-S60, Calt sensor, Shanghai, China). The amplified load cell signals were recorded by the microcontroller. The test bench setup included the two load cells, one for the left-hand auger (LH) and the other for the right-hand auger (RH). These load cells were part of test bench but not attached directly to test bench. The inclination of the metering unit was manually adjusted with clamping attachments, and a digital protractor (Fowler high precision, Newton, MA, US) was used to measure the feed mechanism inclination. A dual shaft DC electric motor was rigidly mounted in the center of the test bench to generate varying levels of vibrations. Unbalanced center weights were attached to both shafts. As the motor rotated, the unbalanced center weights induced the test bench vibration. The vibration frequency increased with motor speed, and amplitude was adjusted to approximately 0.2 g (where g = $9.81 m/s^2$) by using weights (200g). The test bench vibration was measured with the in-built accelerometer (8 G, 12 bits accuracy) of the microcontroller. The test bench rested on a vibration isolater to reduce the vibration intensity to the ground. A LabView program was developed to control, observe and record the testing procedure.

SEEDER TESTING PROCEDURE

The testing procedure for the auger-type feed mechanism was conducted in accordance with ISO 7256/2 (1984), which specified a test method for grain drills (sowing in lines) and permitted the reproducibility of tests. The test procedure aimed to establish the flow rate and the flow uniformity of the feed mechanism under varying rotational speed, slope, and vibration levels. Briefly, the test procedure started with the gravity hopper filled with wheat seeds to a ¾th level (75 mm depth). During each run, the same hopper level was maintained to eliminate the influence of hopper fill percentage on flow rate. The wheat seeds flowing through the feed mechanism were collected in a trough (material: Styrofoam) placed over the load cell. Two troughs separately collected the seeds from each feed mechanism, i.e., left-hand (LH) and right-hand (RH) augers; called location. Since the metering unit would be installed on an AGV, which would traverse varying slope inclinations, we were interested in knowing how the auger location influenced the flow rate. The load cell cumulatively measured the weight of seeds collected on each trough at a 100 Hz sampling rate throughout each test run. Each test was conducted for a duration of 35 seconds and replicated five times as recommended by ISO 7256/2 (1984). During the test, the data from the auger speed encoder, load cells measuring seed mass, and vibration in the X, Y, Z plane were time-stamped, recorded by the microcontroller and stored in an external thumb-drive at a frequency of a 100 Hz. The microcontroller was connected to the desktop computer and the LabView program enabled real-time data visualization and control of the test. For each replication, the initial five seconds of data were discarded (initial transient phase), and the remaining 30 seconds of data with 3000 data points were used to compute the flow rate in grams per 30 seconds. The 3000 flow rate values were converted to gram per minute (g/min) for each replication, and the mean flow rate was computed. The flow rate of the left-hand (LH) and the right-hand (RH) auger feed mechanism was calculated and reported independently. The flow uniformity was represented by the coefficient of variation (CV) of flow rate and computed for both left-hand (LH) and right-hand augers (RH).

RESULTS AND DISCUSSION

INFLUENCE OF ROTATIONAL SPEED

In the first experiment, the three types of auger performance were investigated in terms of flow rate and flow uniformity (CV) as a function of rotational speed. For all augers tested in the study, the flow rate was a linear function of speed. The flow rate of the left-hand auger (A_{LH}, B_{LH}, C_{LH}) and right-hand auger (A_{RH}, B_{RH}, C_{RH}) were closely followed the slope line, as shown in Figure 4(a). The increased auger pitch increased the flow rate; therefore, significantly higher flow rates were observed for augers B and C than for auger A. A few seeds lodged longitudinally in the auger groove (width) for auger A, as shown in Figure 5. Therefore, it was recommended that the auger pitch be at least 150% of the maximum seed dimension to avoid seed lodging. The CV of right-hand augers (A_{RH}, B_{RH}, C_{RH}) and left-hand augers (A_{LH}, B_{LH}, C_{LH}) varied from 2-12% and 2-6 %, respectively (Figure 4(b)). These CV values were well within acceptable limits for the bulk feed mechanism. Guler (2005) reported that a CV of less than 5% was considered "Very Good," and a CV between 5-10% was regarded as "Good." The CV of right-hand augers was relatively higher than left-hand augers. This could be explained by different auger housing materials (ABS plastics [LH] and acrylic material [RH]) and their surface roughness. The lower CV was reported at a higher speed (above 50 rpm). At lower speed (less than 40 rpm), the augers flow was not uniform, seeds were discharged pocket by pocket, and a series of discrete steps resembling the staircase was observed, as shown in Figure 6.

The statistical analysis of flow rate in the first experiment showed there was no significant three-way interaction among auger type, speed and location ($P = 0.278$). Also, no significant two-way interaction was observed between auger and location ($P=0.070$). However, auger × speed and speed × location two-way interactions were significant ($P < 0.01$).

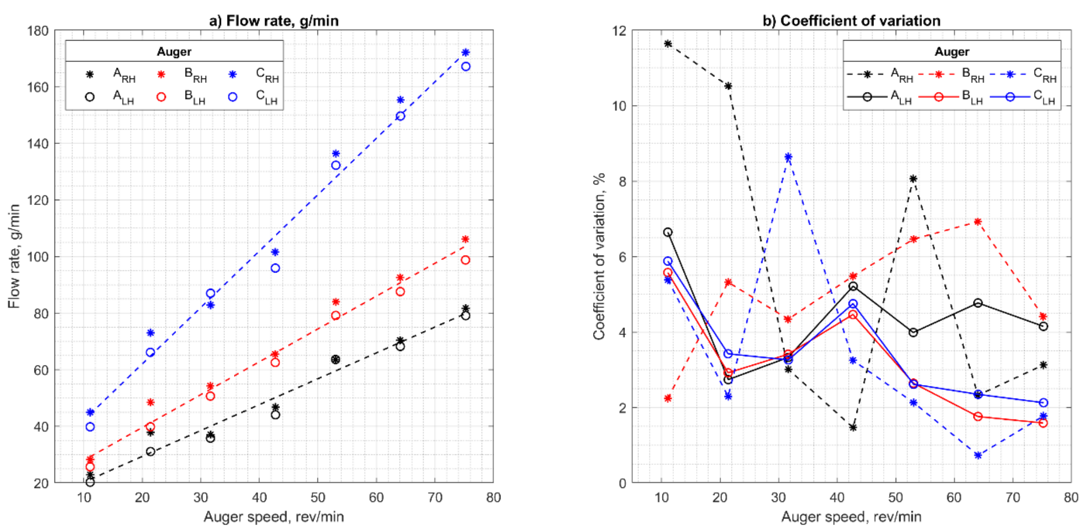

Figure 4. Influence of auger speed (rev/min) on a) auger flow rate (g/min) and b) Coefficient of variation.

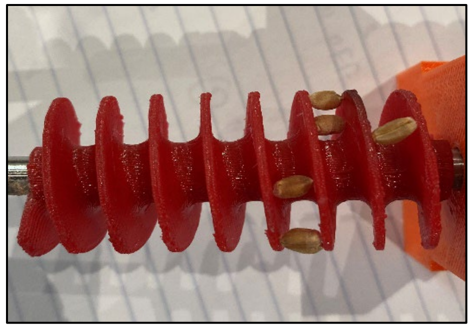

Figure 5. The seed blockage was observed in auger A during the test period.

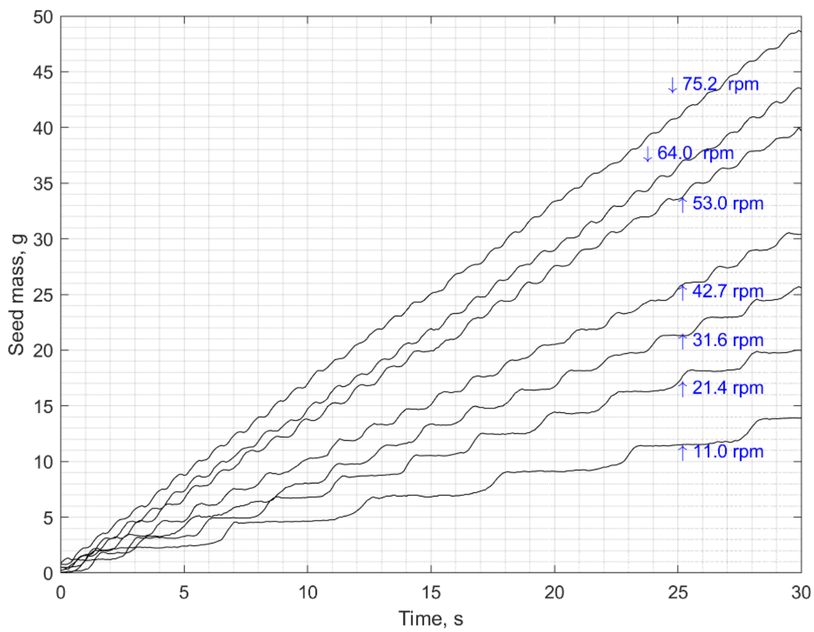

Figure 6. A seed discharge pattern in the first experiment observed with LH auger B during the test period.

Table 3. The analysis of variance for wheat flow rate from the first experiment.

Effect	df	F Value	Pr > F
Auger	2	3498.04	<.0001
Speed	6	2588.83	<.0001
Replication	4	3.78	0.0518
Location	1	84.02	<.0001
Auger × Speed	12	152.3	<.0001
Auger × Location	2	2.74	0.0705
Speed × Location	6	3.76	0.0023
Auger × Speed × Location	12	1.23	0.2787

The augers A, B, and C delivered the flow rate of around 80, 100, and 170 g/min at 75 rev/min. The

AGVs recommended operating speed varied from 1 to 2 km/hour (16.6 m/min to 33.2 m/min) on sloping terrain. The recommended wheat seed rate for cattle grazing was 120-180 seeds per meter and varied with the row spacing. The AGV traveling at one km/h (16.6 m/min) had to deliver ~2,500 seeds per min (16.6 m/min ×150 seeds/m = 2,500 seeds/min) at the seed rate of at 150 seeds/m. The 2,500 seeds weigh around 81.6 grams. The auger B operating at 55 rev/min delivered the 80 g/min seed rate. Therefore, auger B at 55 rev/min was selected to study the influence of vibration and slope in the second experiment.

On sloping terrain, the forward speed of AGV would vary as the slope varies. An established linear relationship between auger rotational speed and flow rate would be used to control the seed rate as the forward speed of AGV changes on sloping hills and uneven terrain. In a commercial application, a control algorithm for the AGV would keep track of forward speed and adjust the auger speed to change the seed rate.

INFLUENCE OF VIBRATION AND SLOPE

There was a significant three-way interaction on flow rate (Table 4). Therefore, a multiple comparison procedure was applied to check the conditional effect of vibration and slopes, and the results were presented in Tables 5 and 6, respectively. The auger flow rate remained nearly constant for vibration level 1, level 2, and level 3 for each given combination of slope and location conditions, as shown in Figure 7. However, vibration level 4 showed a significantly increased flow rate. From Figure 7 and Table 5, it can be concluded that the developed feed mechanism was vibration proof and can handle the vibration frequency up to 14 Hz (level 3). The Holm-Tukey multiple comparison test results were presented in Table 5, and a group within a column with a similar mean was assigned a similar letter. The vibration level 1, level 2, and level 3 were assigned the same letter, and a different letter was assigned to level 4 for the given slope.

The mean flow rate between flat, ascending slope (asc.) and descending (desc.) slope did not vary significantly for each combination of vibration and location, as shown in Figure 7(a) and Table 6. The flat, ascending, and descending slopes were placed in a similar group for a given vibration level (Table 6) except that the flow rate for the ascending slope was slightly higher for level 1 and LH location for level 2. However, the slope to the right (R slope) and slope to the left (L slope) showed significant differences compared to flat [Figure 7(b) & Table 6]. When the feed mechanism was inclined towards the right (R slope), the right-side auger (R $slope_{RH}$) delivered a relatively higher flow rate compared to the left-side auger (R $slope_{LH}$) and vice-versa. The gravity effect could explain this; when inclined to the right slope, the seed in the left side auger had to climb against the gravity, which reduced the flow rate, and for the right-side auger gravity helped increase the flow rate.

In short, the AGV downhill and uphill run would not influence the feed mechanism performance, that was, flow rate. However, operating the seeder on the side slope would significantly influence the performance of the feed mechanism. To compensate for the flow rates on the side slope, we recommend a separate auger drive (D.C. motor), so the seed rate of each auger was independently controlled and adjusted by a controlled algorithm. The CV was presented in Figure 8 and shows that the observed CV was less than 5%, which indicates a flow uniformity of “very good” according to Guler (2005).

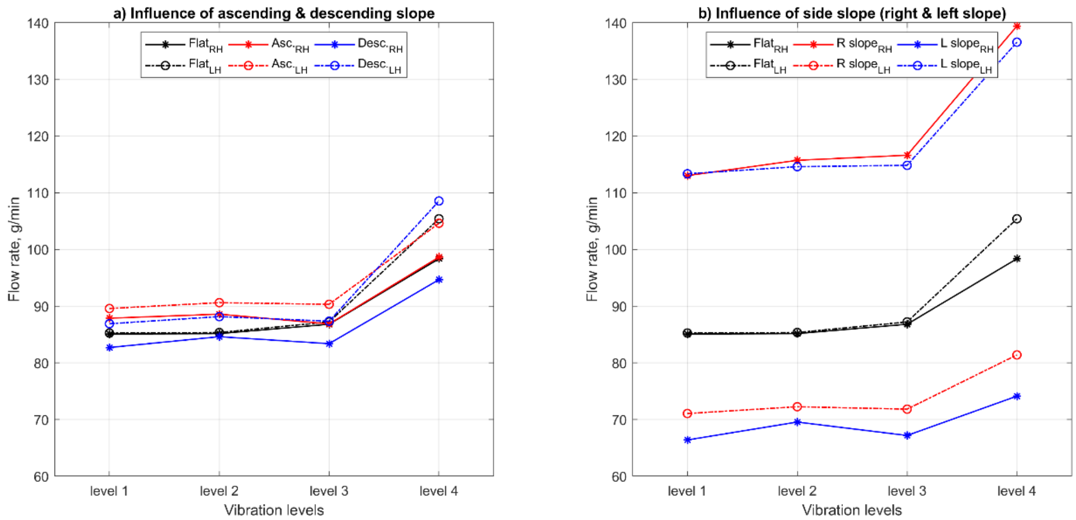

Figure 7. Influence of vibration levels on flow rate at a) flat, ascending and descending slope b) flat, side slope i.e., slope to right (R slope) and slope to left (L slope).

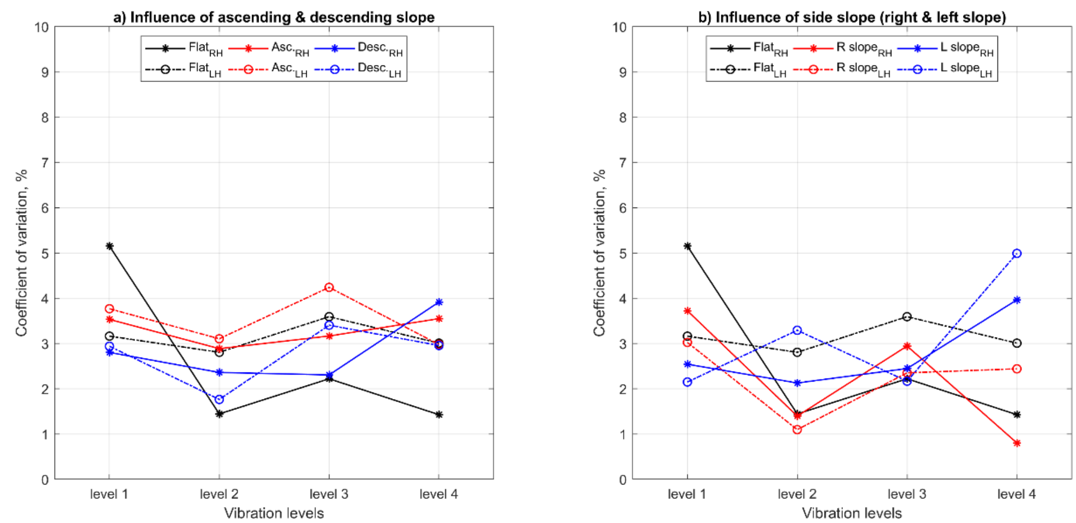

Figure 8. Influence of vibration levels on the coefficient of variation at a) flat, ascending, and descending slope b) flat, side slope, i.e., slope to the right (R slope) and slope to left (L slope).

Table 4. The variance analysis for flow rate values for wheat.

Effect	df	F Value	Pr > F
Slope	4	44.26	<.0001
Vibration	3	276.53	<.0001
Location	1	88.48	<.0001
Replication	4	2.4	0.0573
Slope × vibration	12	1.03	0.427
Slope × Location	4	2313.39	<.0001
Vibration × Location	3	11.61	<.0001

Slope × Vibration × Location	12	16.37	<.0001

Table 5. Holm-Tukey multiple comparison test for wheat flow rate (g/min) values (conditional vibration influence).

	Flat		Asc. slope		Desc. slope		R slope		L Slope	
	LH	RH	LH	RH	LH	RH	LH	RH	LH	RH
Level 1	85.27a[a]	85.10a	89.59a	87.89a	86.90a	82.71a	71.07a	113.04a	113.36a	66.41a
Level 2	85.36a	85.17a	90.63a	88.60a	88.17a	84.63a	72.27a	115.74a	114.62a	69.57a
Level 3	87.23a	86.82a	90.34a	86.87a	87.36a	83.39a	71.85a	116.64a	114.85a	67.20ab
Level 4	105.42b	98.37b	104.64b	98.66b	108.56b	94.68b	81.41b	139.41b	136.57b	74.15b

[a] Means in the same column having the same letter were not significantly different at P<0.05

Table 6. Holm-Tukey multiple comparison test for wheat flow rate (g/min) values (conditional slope influence).

	Level 1		Level 2		Level 3		Level 4	
	LH	RH	LH	RH	LH	RH	LH	RH
Flat	85.27a[a]	85.10ab	85.36a	85.17a	87.23a	86.82a	105.42a	98.37a
Asc. slope	89.59b	87.89b	90.63b	88.60a	90.34a	86.87a	104.64a	98.66a
Desc. slope	86.90ab	82.71a	88.17ab	84.63a	87.36a	83.39a	108.56a	94.68a
R slope	71.07c	113.04c	72.27c	115.74b	71.85b	116.64b	81.41b	139.41b
L slope	113.36d	66.41d	114.62d	69.57c	114.85c	67.20c	136.57c	74.15c

[a] Means in the same column having the same letter were not significantly different at P <0.05

CONCLUSIONS

In this study, a screw auger-type feed mechanism was designed, fabrication, and investigated in a laboratory setup for robotic wheat drilling. The performance of the metering device depends upon the physical characteristics of bulk material (seeds), constructional design, and operational parameters. Three different types of screw augers were developed, and a laboratory investigation was carried out on varying auger rotational speed, vibration, and slope. From this study, the following conclusions can be drawn:

- The recommended auger pitch must be at least 150% of the maximum seed dimension to avoid seed lodging in the flighting with corresponding blockage. Hence, augers B and C can be used for a grain drill operation.
- The investigation established the linear relationship between flow rate and auger rotational speed for augers operating on flat, ascending, or descending slopes, which would be essential to control

the seed rate on continuously sloping terrain as the slopes would influence the AGV forward speed.

- The auger flow rate should be determined as a function of both side slope and auger speed for proper control of seed rate on side slopes to the left (L slope), or side slope to the right (R slope).
- The coefficient of variation (CV) for flow rate for augers of sufficient pitch (augers B and C) ranged from 2 to 8%. The CV was within the acceptable limits, which was an excellent indicator of the bulk feed mechanism's flow uniformity. The CV of auger B was not affected by slope.
- The feed mechanism was vibration-proof up to a certain frequency, and its performance was unaffected for the vibration frequency up to 14 Hz.
- The study delivered a bulk feed mechanism for a sloped-ground prototype seeder, which can be easily scaled and adopted by small autonomous vehicles or mobile robots.
- The developed feed mechanism would be fitted into the prototype robotic grain drill for seeding on high sloped hills and uneven terrain.

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