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Development and performance assessment of a DC electric variable-rate controller for use on grain drills

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ABSTRACT

Site-specific crop management is a technology that modulates the application rate of field inputs such as seeds, fertilizers, and herbicides based on the needs of each management zone within a field. There are two methods available for changing the seeding rate in fluted-feed-roll type seed drills: (1) changing the active feed-roll length and/or, (2) changing the seed meter drive shaft speed. A possible method to develop a variable-rate seeder is to add a controller to a conventional grain drill which can change the speed of the seed meter drive shaft on-the-go. This was explored in the present study with the following main objectives: (a) to design a DC electric variable-rate controller to change a grain drill from a uniform to a variable-rate seeder, and (b) to determine the response time of the system. A motor control circuit was designed which used the output signals of two encoders as feedback. The system was consisted of: (1) a DC motor with a fixed-ratio gearbox, (2) encoders for sensing the rotational speeds of the grain drill drive wheel and the motor, (3) a GPS receiver, (4) a pulse-with-modulation (PWM) DC motor controller, and (5) a laptop. Dynamic tests were conducted at application rates of 87.5 (low) and 262.5 (high) kg ha^{-1}. Sigmoid equations were best fitted to the transition data from low-to-high and high-to-low seeding rates. Our findings showed that the response times of low-to-high and high-to-low transition rates were 7.4 and 5.2 s, respectively.

1. Introduction

Site-specific crop management aims at balancing agricultural inputs such as seeds, fertilizers, and herbicides to match the requirements of specific soil fertility levels and/or landscape positions. Moisture content and fertility are the most important field variables whose variations affect optimum seeding rate in the field. Given that fertility and/or moisture may be variable within a field the optimal seeding rate may also be variable. Clearly, maximizing yield calls for optimal seeding rates in the various field areas (Taylor et al., 2006). In site-specific crop management, the geographical information system (GIS) is used to prepare a seeding rate map for the field, which is uploaded into a computer prior to the planting. The controller of the agricultural machines changes the application rates of the planter at each management zone within a field using the predefined prescription map and positioning information generated by a differential global positioning system (DGPS) receiver.

One possibility for obtaining variable application rates is to add a controller to the conventional agricultural machines that are normally used for applying inputs uniformly (Robert et al., 1992). It is, therefore, important to note that a retrofit kit would be desirable for updating existing grain drills to variable-rate status in cases where viable seeding unit already exists but the variable-rate option is required. The process of changing the application rate while the seeder is traveling across the field depends on the dynamic response of the controller, and therefore can be, accompanied by some misapplication (Bahri, 1995). The severity of this misapplication depends upon the characteristics of the metering controller in switching from one rate to another. A decisive factor in this regard is the control system's response time that should be reduced to a minimum by selecting appropriate control system components.

Depending on the type of metering mechanism used in a grain drill, two methods are commonly available to change the seeding rate: (a) changing the active feed-roll length, and/or (b) changing the seed meter drive shaft speed. Bahri (1995) developed a simple operated open-loop control system to vary the seeding rate on-the-go by changing the feed-roll length, and thus modifying a conventional grain drill to a variable-rate seeder. The control system consisted of a battery, on-off control switches mounted inside the tractor cab, and an electrical linear actuator attached to the meter adjustment lever. It was reported that the response time of the control system averaged 5.6 *s* for a 20 kg ha^{-1} rate increase. The presence of seeds in the feed rolls prevented the free movement of the metering mechanism inside the metering cup for a decrease in application rate input command. This finding

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suggested that changing active feed-roll length is not a feasible method for varying the seeding rate on-the-go.

There are two control systems available for changing the seed meter drive shaft speed; namely position and speed control systems. Maleki et al. (2008) used a pneumatic seeder with an infinitely variable gearbox equipped with an electrical linear actuator to develop a variable-rate fertilizer in which the linear actuator was used to adjust the gearbox ratio. An interface program was developed using LabVIEW (Laboratory Virtual Instrumentation Engineering Workbench) programming to initiate the electrical actuator. The actuator adjusted the flow-rate in interval steps of $5\,\mathrm{kg\,ha^{-1}}$. Similarly, Tola et al. (2008) developed a variable-rate granular fertilizer by the use of an air seeder with a fluted-feed roller and an infinitely variable gearbox. The speed of fluted-feed roller was adjusted by positioning the gearbox lever. The setting lever was adjusted using a DC motor and a linear gauge. To measure fertilizer output, an incremental encoder was used in an experimental hopper to detect the incremental rate of the fertilizer depth inside the hopper. The control system response to step changes in the target fertilizer rate at a predetermined intervals was within the range of 0.95–1.9 s.

Bahri (1995) also developed another open-loop control system using a rheostat to control the speed of an electric motor driving the seed meter drive shaft. The response times varied from 3 to 9 s depending upon the rate change magnitude. It was reported that the control system performed well for rate increases and decreases. The open-loop control system eliminates the need for feedback signal and the feedback-based command signal correction. Inaccuracy is due to the inability of the system to dynamically adjust for changes in load as a result of actuator aging or other operating conditions. In contrast, the feedback signals in a closed-loop control system are compared with command signals to calculate application rate errors. The error, in turn, is used to adjust the command signal. The mechanical controller, thus, moves closer to the target rate and the error approaches zero (Anderson and Humburg, 1997). Kim et al. (2008) built a prototype granular applicator which consisted of a controller, a boom with a pneumatic conveying system and a DGPS receiver. The controller received the DGPS signal, calculated the current working speed, read from a previously developed prescription map, and controlled the metering motor speed using the pulse-with-modulation method. In this research a matrix pan was used to determine the transition seeding rate parameters. The response time ranged from 1.5 to 3 s. In another research, Yu et al. (2006) built a prototype variable-rate applicator for granular fertilizer. It was fabricated with a F/G servo system and discharger. Control performance and discharged characteristic of the control system were evaluated by a test rig. In both of the above experiments, researchers built a prototype granular applicator with a closed-loop control system.

Changing a conventional fluted-feed-roll type seed drill to a variable-rate seeder requires adding some variable-rate controllers. Alternative designs of the controllers could be used to obtain the variable-rate seeding. If the grain drill, for instance, had an infinite gear ratio, it would be possible to change the seeding rate on-the-go by controlling the position of the gear shift lever. A variable-speed belt drive could also be used to change the seed meter drive shaft speed. This mechanism may consist of two pulleys with variable pitch diameters, thus providing a variable ratio between the two pulleys. As the belt length is fixed, decreasing the diameter of one pulley results in a corresponding increase in the diameter of the other. Moving two half-pulleys could give an extensive range of ratios (Huffmeyer, 2003). Multiple sprockets could be also mounted between the metering mechanism and the drive wheel of the grain drill to obtain different seeding rates. All the sprockets mounted on the seed meter drive shaft are normally idle. One of the sprockets on the shaft, however, may be locked at each time step by a magnetic clutch depending on the seeding rate demanded (Drummond, 2002). Other type of controller would be one that transfers the rotational speed of the grain drill drive wheel to the sun gear of a planetary gearbox and to connect the seed meter drive shaft to the carrier. In order to change the rotational speed of the metering mechanism, the rotational speed of the ring gear could be varied with the addition of an electric motor. In order to damp out load variations, the seed meter drive shaft speed could be used as a feedback in a closed-loop control system (Landphair, 2005).

Using DC motor is an alternative approach that has some advantages and deserves to be explored. Therefore, the objective of the present study was to: design a DC electric variable-rate controller for an existing grain drill which will enable the seeding rate of wheat to be varied on-the-go benefiting farmers in developing countries who do not have access to the technology available in developed countries and obtain its response times when seeding rate changes from high-to-low or vice versa.

2. Material and methods

2.1. Seed specifications

In this study, wheat seed (*Triticum aestivum* L.) with purity and germination percentages of 99% and 98% were used. The bulk density and 1000-seed weight were $800\,\mathrm{kg\,m^{-3}}$ and 43.5 g, respectively. The moisture content was measured at 7.8% wet basis.

2.2. Grain drill specification

In this experiment, a Hassia grain drill (model no. DU100) with 19 planting rows was used whose metering mechanism was of the external straight fluted-feed-roll type. The metering mechanisms were located on a seed meter drive shaft. The drill row spacing was 16 cm. The power for the seed meter drive shaft was provided by drive wheels via sprockets and chain to the gearbox. The gearbox with the cam and a follower mechanism using a one-directional ball-bearing made it possible to adjust the metering mechanism for different seeding rates at a constant ground speed.

2.3. Design specification

In this study, a DC motor with a fixed-ratio gearbox was used to rotate the seed meter drive shaft directly. Changing the rotational speed of the motor was accomplished by a DC motor speed control drive. Due to the independence of the seed meter drive shaft speed from the forward speed of the grain drill, a feedback from the grain drill drive wheel speed was obtained. In order to have a closed-loop control system and to compensate for load changes, an encoder was used to sense the rotational speed of the grain drill seed meter drive shaft (Fig. 1).

Upon the selection of the controller design, the different components of the system were specified. For this purpose, a torque meter was used to measure the torque of the seed meter drive shaft, which read 10 N m. The maximum wheat seeding rate and tractor speed were assumed to be $350\,\mathrm{kg\,ha^{-1}}$ and $10\,\mathrm{km\,h^{-1}}$, respectively. A maximum rotational speed of 50 rpm was thus obtained for the seed meter drive shaft. The power required for the rotation of the shaft was determined to be 52.3 W. A DC motor was selected to change the seed meter drive shaft speed. DC motors commonly have high rotational speeds, for which reduction gearboxes are required to obtain appropriate rotational speeds. For the present study, a worm type gearbox with a reduction ratio of 1:40 was selected. Given the low efficiency of the worm gearbox, a 250 W, 24-V electrical scooter motor with a maximum current of 13.5 A was chosen. The motor was a permanent magnet DC type with 4 poles. The maximum motor torques at rotational speeds of

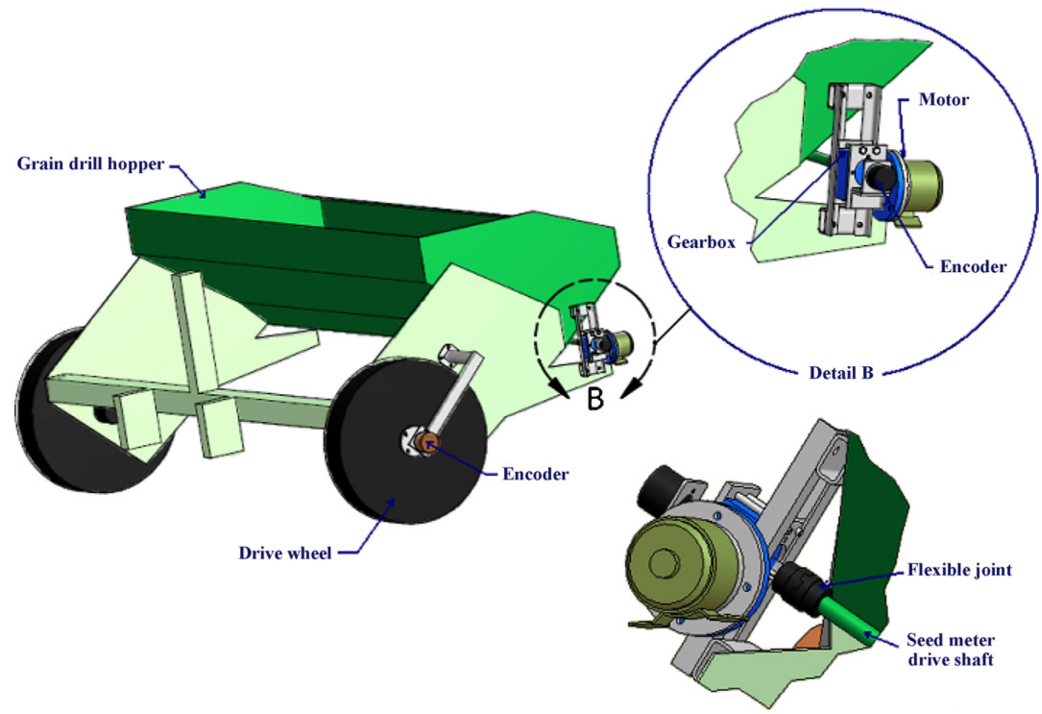

Fig. 1. A DC motor with fixed-ratio gearbox was used to change the rotational speed of the seed meter drive shaft of a grain drill.

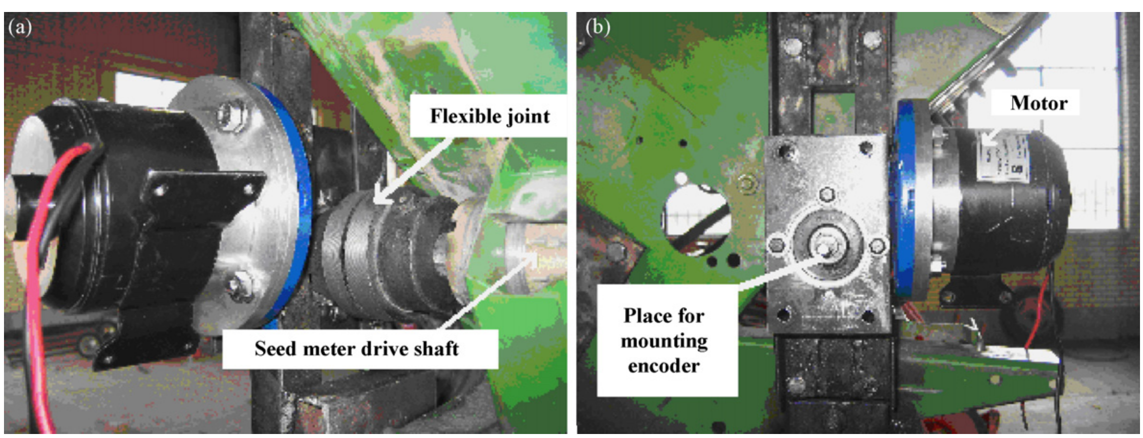

Fig. 2. Different views of DC motor and flexible joint mounted on the grain drill seed meter drive shaft.

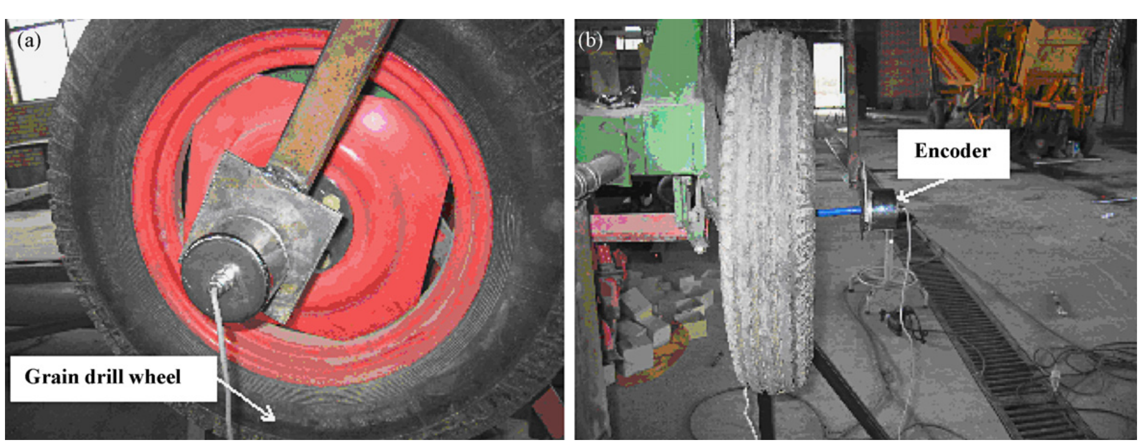

Fig. 3. Different views of grain drill wheel encoder.

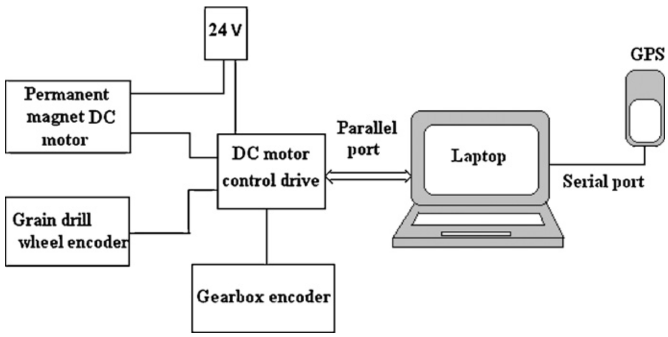

Fig. 4. A simplified flow diagram of the variable-rate application controller.

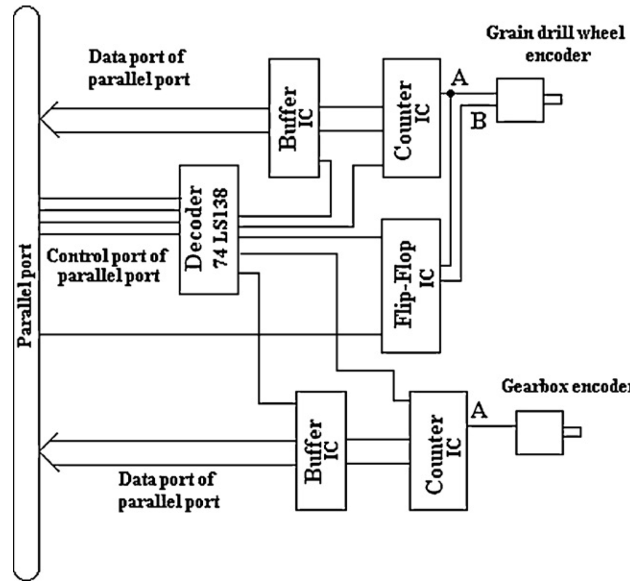

Fig. 5. Schematic circuit for reading the two encoders.

2600–2850 rpm were in the range of 0.84–0.92 N m. Using the combination of the motor and the gearbox, the rotational speed of the seed meter drive shaft could be adjusted in the range of 0–65 rpm. This range was appropriate for planting a variety of seeds. The rotational speed of the seed meter drive shaft was monitored by an encoder (Model no. E50S-2500-3-2-24; Autonics Co., Korea)[1] mounted on the gearbox shaft (Fig. 2) which was powered by a 12–24 V supply. It produced 2500 pulses for each revolution of the seed meter drive shaft. In order to install the motor on the seed meter drive shaft, the rotation of the shaft was first made independent of the drill drive wheels. The grain drill wheel speed was monitored by an encoder (Model no. ISE-200-5V; Tabriz Paguh Co., Iran) mounted on the grain drill wheel (Fig. 3) which was powered by a 5 V supply and produced 200 pulses per revolution. The second encoder was used to determine the grain drill speed in indoor tests due to not having GPS signal. A laptop was used for data collection and post-processing analysis regarding the research objectives.

Some components of the variable-rate (VR) control system such as the laptop and grain drill wheel encoder could be omitted in the commercial version of the system. Therefore, by omitting these components, the VR controller could be manufactured with lower costs and could be more affordable for the farmers in the developing countries.

2.4. Control system

The VR control system detected the drill position from the GPS and the grain drill wheel speed from the encoder mounted on the drive wheel. The grain drill position and velocity data were then compared with reference data already stored in the computer, which represent the amount of seeds per unit area for each specific location (prescription map). From this, the appropriate rotational speed of the seed meter drive shaft was determined. Instant rotational speed of the seed meter drive shaft in each location was compared with the desired value to issue an appropriate (8-bit) instruction to the motor control circuit via a parallel port (Fig. 4). Therefore, the drive circuit command signal was a value between 0 and 255 (8-bit). The control system was composed of the signal processing unit, the control unit, and the control software.

2.4.1. Signal processing unit

The function of the signal processing unit is to send the information to the control unit. This unit was required for reading data from the two encoders to get the grain drill drive wheel speed and the rotational speed of the motor and also to determine the direction of rotation in the grain drill wheel encoder. A 12-step CMOS 4040 IC was used to count the encoder pulses. A set of two ICs was used for each encoder to read a sum of 14-bit pulses. A 74LS245 IC was used as a buffer or separator in the encoder reading circuit. To determine the direction of the grain drill drive wheel, the two signal lines from the grain drill wheel encoder were connected to the 74LS374 IC with 8 flip-flops. A 74LS138 IC was used to decide which data had to be transferred to the data line of the parallel port (Fig. 5).

2.4.2. Control unit

Fig. 6 shows the block diagram of the rotational speed control system for the grain drill seed meter drive shaft. To reach the target speed on the DC motor as quickly as possible and to maintain it, the control system for the DC motor used a PID controller and an encoder to provide the feedback signal of the rotational speed. PID coefficients could be changed through the interface program. An 8-bit number was sent to the parallel port to issue instructions to the motor. A PWM (pulse-width-modulation) pulse was then generated by the microcontroller in proportion to the input. An output pin from the microcontroller was used to turn the MOSFET directly. This circuit was a low side drive type. A 74LS373 IC which has 8 data latches was used to latch data on the microcontroller (Fig. 7).

2.4.3. Control software

The interface program was written in Visual Basic to control grain drill seeding rate on-the-go. Data, consisting of position and seeding rate, could be inputted manually or by a text file (Fig. 8). In the first part of the dialog box, tractor location and tractor forward speed were received as hexadecimal values from the GPS under the NMEA protocol. The software was received the data and translated them for display. The second part was exhibited appropriate seeding rate, grain drill drive shaft speed, wheel speed, width, and travel direction. In the third part, there were possibilities for motor calibration and seeding rate estimation for each revolution of the metering mechanism under various conditions. In the fourth part of the dialog box, an automatic option was shown. By selecting this option, the software was asked for the map in text format. Additionally, the software automatically was logged the trajectory path, speed, and seeding rate to a text file.

[1] Mention of trademark, proprietary product, or vendor is for information purposes only. No endorsement implied.

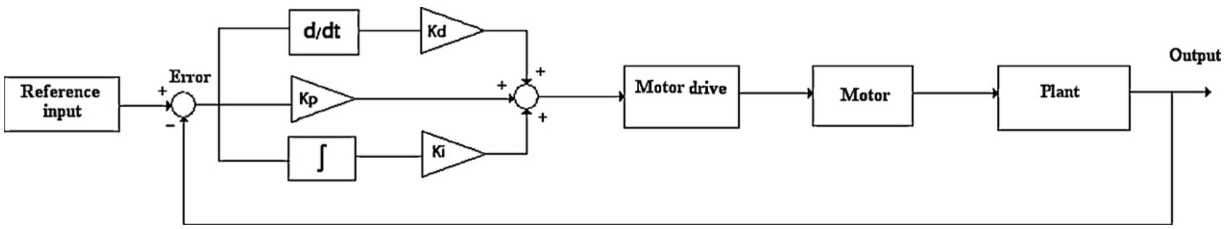

Fig. 6. Block diagram for speed control system of the grain drill seed meter drive shaft.

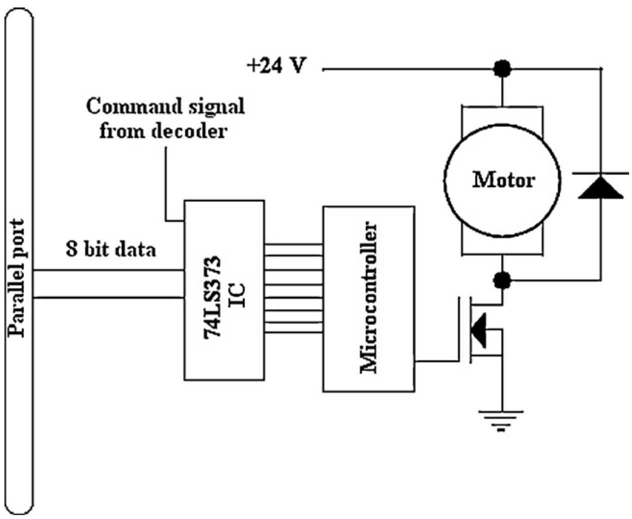

Fig. 7. Schematic of DC motor control speed circuit.

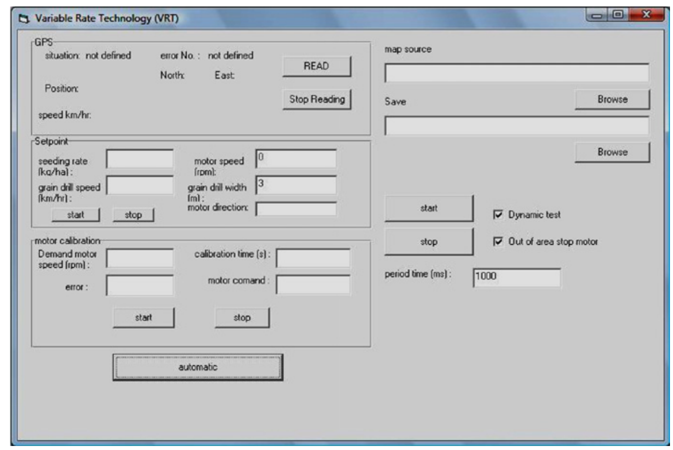

Fig. 8. Dialogue box for user interface to control program.

2.5. Evaluation of the variable-rate grain drill

2.5.1. Calibration of the grain drill

Laboratory tests were conducted at the Agricultural Machinery Workshop of the Isfahan University of Technology. Before mounting the VR controller, calibration of the grain drill was conducted on a test rig. Two rotational speeds of 16 and 23 rpm were selected for the seed meter drive shaft. Speeds of 2.5 and 3.6 km h^{-1} were chosen for the movement of the test rig.

2.5.2. Evaluating time response characteristics of the variable-rate grain drill

The rate response characteristics (delay and transition times) for the VR seeder were obtained using the collection pan matrix (Shearer et al., 2005) and following the same test protocol outlined by Fulton et al. (2001) for granular VRT applicators. This was the only procedure available for evaluating variable-rate granular material application accuracy which we had to use for our VR seeder. The variable-rate grain drill was evaluated by seeding wheat (Fig. 9). The tests conducted to determine seeding variations for the two different conditions of fixed and variable-rates consisted of: (1) seeding at a low fixed rate (87.5 kg ha^{-1}), (2) seeding at a high fixed rate (262.5 kg ha^{-1}), (3) variable seeding rate (low-to-high transition), and (4) variable seeding rate (high-to-low transition). Each of these four tests was conducted with three replications and therefore, a total number of 12 tests were performed. To gather the seeds from each grain drill outlet, a plastic cover of 12 m long and 3 m wide was first extended on the workshop floor. Then, twelve gathering boxes of 10 cm × 14 cm × 14 cm evenly spaced by 1 m were placed along each of the 7 outlets which did not lie along the tractor or the grain drill wheel tracks (Fig. 10). Each test was conducted after 40–50% volume of the drill hopper was filled with the seed

Fig. 9. (a) Variable-rate grain drill for seeding wheat, and (b) view of the collection pan matrix.

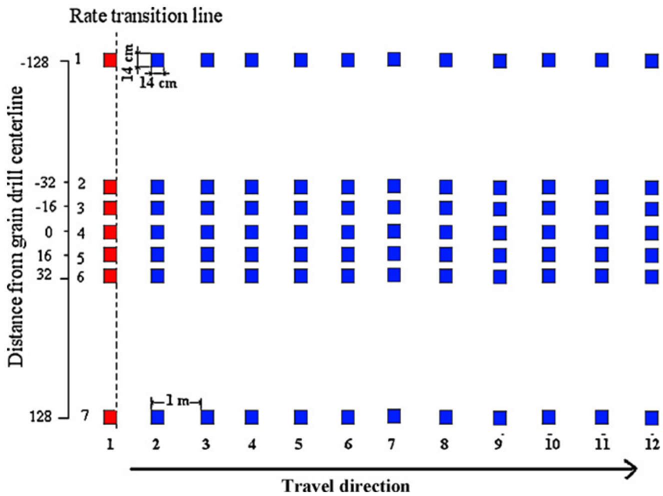

Fig. 10. Collection pan matrix and rate transition line.

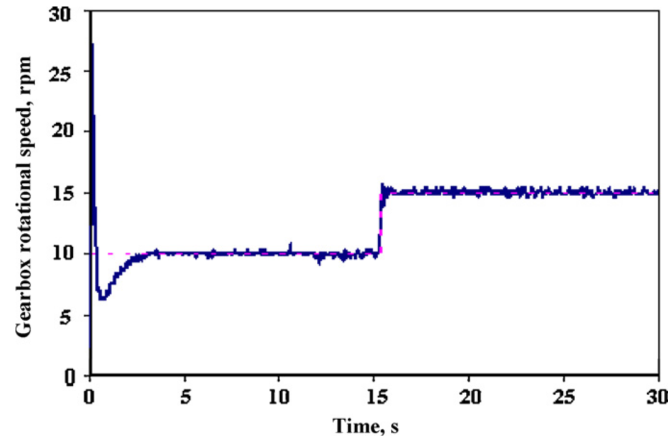

Fig. 11. Response of the control system to a step function input. ▬▬▬, response; ■ ■ ■, command. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)

(ASAE S341.2). The discharge tubes were fastened up higher than normal to pass easily over the collection pans. To determine the response time, the change rate command was sent to the control system once the first row of the gathering boxes was passed.

A high targeting wheat seeding rate of 350 kg ha^{-1} was selected to show the capability of the system. Two seeding rates of 25 and 75% of the maximum seeding rate were selected as the low and high values (87.5 and 262.5 kg ha^{-1}), respectively, and the forward speed was set to 1 m s^{-1} (Shearer et al., 2005).

To determine the response time in transition from high-to-low or vice versa, sigmoid equation should be fitted to the data. The most important factor in seeding rate fitting is the use of a unique regression function for both increasing and decreasing rate transitions to simplify the fitting process. The following sigmoid equation was fitted to the transition data from low-to-high and high-to-low rates:

$$\hat{y} = a + \frac{b}{1 + e^{(cx-d)}}$$

where, $\hat{y}$ = application rate, a = initial application rate, b = rate change increment (difference between the initial and final rates), c/d = the abscissa of the inflection point, and x = distance.

The start and end points are defined using a 5% settling time. This corresponds to a 5% and 95% change in the overall rate transition. A 5% settling time was used in view of the small-scale variability (noise) in the observed data. The delay distance was determined as the difference between the location of the initiation of rate change and the location at which there was a 5% change in the initial application rate (Shearer et al., 2005).

3. Results and discussion

3.1. Grain drill calibration

Results showed that for a constant test rig speed, the seeding rate was changed proportional to the seed meter drive shaft speed. For a constant speed of seed meter drive shaft, the seeding rate linearly decreased as the speed of test rig increased. Coefficients of variation (CV) of 5 evaluated outlets were in the range of 17% to 51%. Outlet 1 which was adjacent to the side wall of the seed hopper had the largest CV value.

3.2. Time response

Fig. 11 shows the response of the control system to a step function input. Because the input values (0–255) were discrete

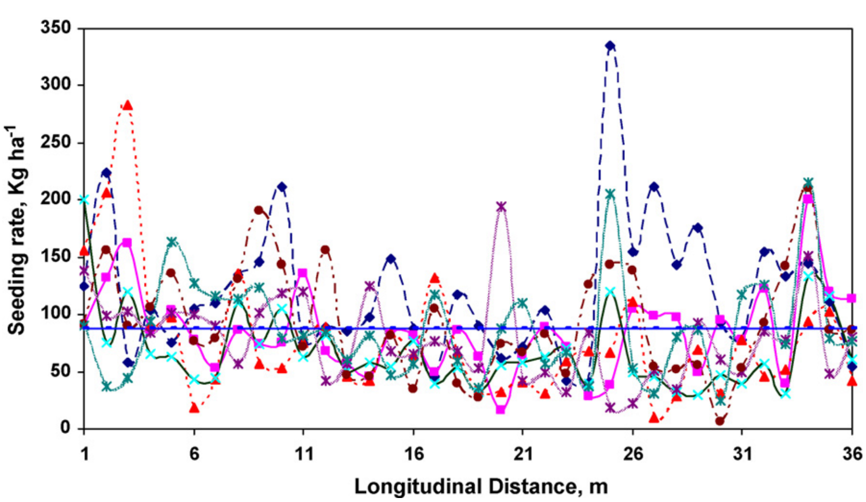

Fig. 12. Variation in seeding rate with distance. Thirty six consecutive data from 3 replications which were collected from the pan matrix for a fixed application rate of 87.5 kg wheat ha^{-1} at 1 m s^{-1} working speed. , outlet 1, , outlet 2, , outlet 3, , outlet 4, , outlet 5, , outlet 6, , outlet 7, , adjusted application rate of 87.5 kg ha^{-1}. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)

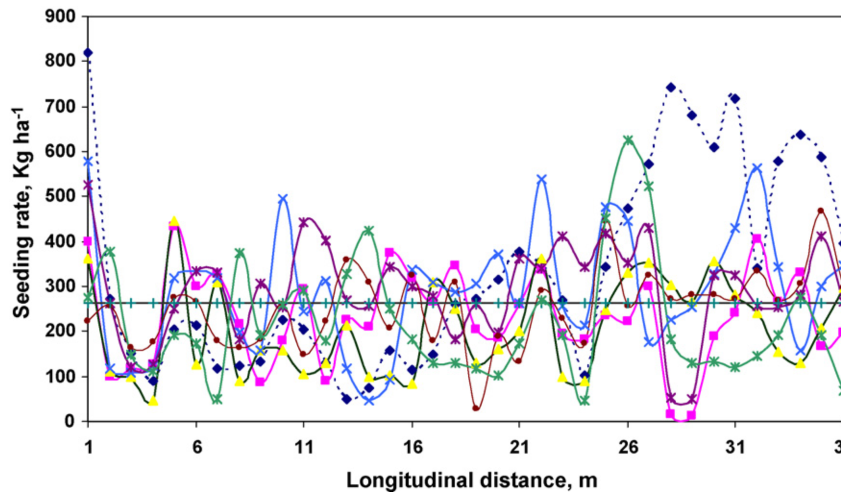

Fig. 13. Variation in seeding rate with distance. Thirty six consecutive data from 3 replications which were collected from the pan matrix for a fixed application rate of 262.5 kg wheat ha^{-1} at 1 m s^{-1} working speed. , outlet 1, , outlet 2, , outlet 3, , outlet 4, , outlet 5, , outlet 6, , outlet 7, , adjusted application rate of 262.5 kg ha^{-1}. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)

numbers, there was an oscillation about the demand response. This response was appropriate to control the variable-rate grain drill. Figs. 12 and 13 present variation in seeding rate with distance for the fixed application rate of 87.5 and 262.5 kg ha^{-1}, respectively. Seed distribution and seeding accuracy were directly affected by many factors such as systematic errors associated with machine calibration, deviation from straight line tracking, and discharge tube deviation from its normal form. Variation in seeding rate with distance for the fixed application rate of 87.5 kg ha^{-1} appeared to be more uniform than for the fixed application rate of 262.5 kg ha^{-1} with some irregularities. These irregularities are expected from the higher seeding rate. By increasing the seeding rate, more seeds were trapped in the deformed discharging tubes. Outlets 4 and 1 had maximum irregularity. Outlet 1 was placed at the end of the grain drill hopper and was more greatly affected by the tractor deviation from straight tracking. Outlet 4 was placed in the middle of the grain drill hopper and its discharge tube had the most trapped seeds because of its deformed shape.

Figs. 14 and 15 present the transitional response of each outlet for low-to-high and high-to-low rate changes, respectively. The graphs of transitional response of each outlet for these application rates demonstrated that the control system of the grain drill changed the seeding rate in transition zones thoroughly. All the transitional behavior could be seen over this small distance (a 12-m traveling distance). The next step was to model the variable-rate application process shown in Figs. 14 and 15. Equidistant widthwise rows from the beginning to 10th row of the collection pan were averaged to create 10 widthwise data to represent the rate change dynamics. Variable-rate parameters such as distance for rate transition and delay distance for each rate change (high-to-low or low-to-high) are presented in Fig. 16. The start and end points were defined using a four-parameter sigmoid function.

Fig. 16a shows that the delay distance in transition from low-to-high is −0.5 m, which means that it was started with a rate higher than 87.5 kg ha^{-1}. The rate start and end points were placed at −0.5 and 6.84 m, respectively, to give a rate transition distance of 7.38 m.

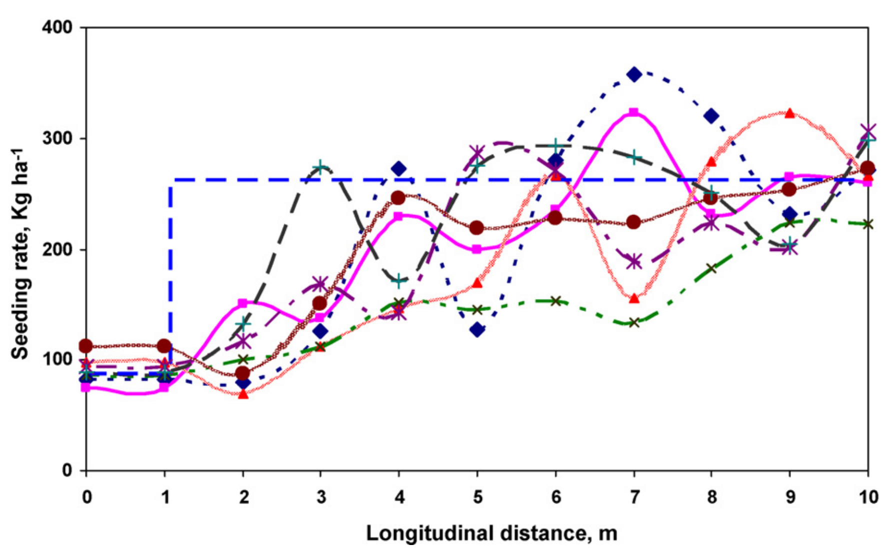

Fig. 14. Transitional response of each outlet (data were collected from the pan matrix for a low-to-high rate change (from 87.5 to 262.5 kg ha^{-1}) at 1 m s^{-1} working speed where the change rate command was sent to the control system after passing the first row of the gathering boxes). , outlet 1, , outlet 2, , outlet 3, , outlet 4, , outlet 5, , outlet 6, , outlet 7, , step input. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)

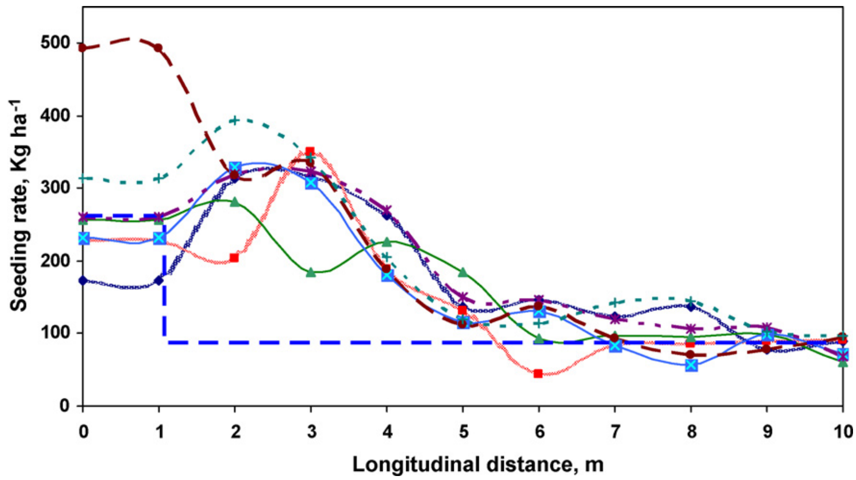

Fig. 15. Transitional response of each outlet (data were collected from the pan matrix for a high-to-low rate change (from 262.5 to 87.5 kg ha^{-1}) at 1 m s^{-1} working speed where the change rate command was sent to the control system after passing the first row of the gathering boxes). , outlet 1, , outlet 2, , outlet 3, , outlet 4, , outlet 5, , outlet 6, , outlet 7, , step input. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)

Based on the tractor speed, the response time of the variable-rate system in transition from 78.5 to 262.5 kg ha^{-1} was 7.4 s. Fig. 16b shows that the delay distance in transition from high-to-low is 2.7 m. Rate transition start and end points were placed at 3.5 and 6.2 m, respectively, and the rate transition distance was set to 5.2 m. Consequently, given the tractor speed of 1 m s^{-1}, the response time of the variable-rate system in transition from 262.5 to 78.5 kg ha^{-1} was 5.2 s. The increase in response time for the low-to-high rate change as compared with the high-to-low rate change was due to the increase in motor torque demand because the motor should increase its torque; hence, more time was required to switch to the new transition rate.

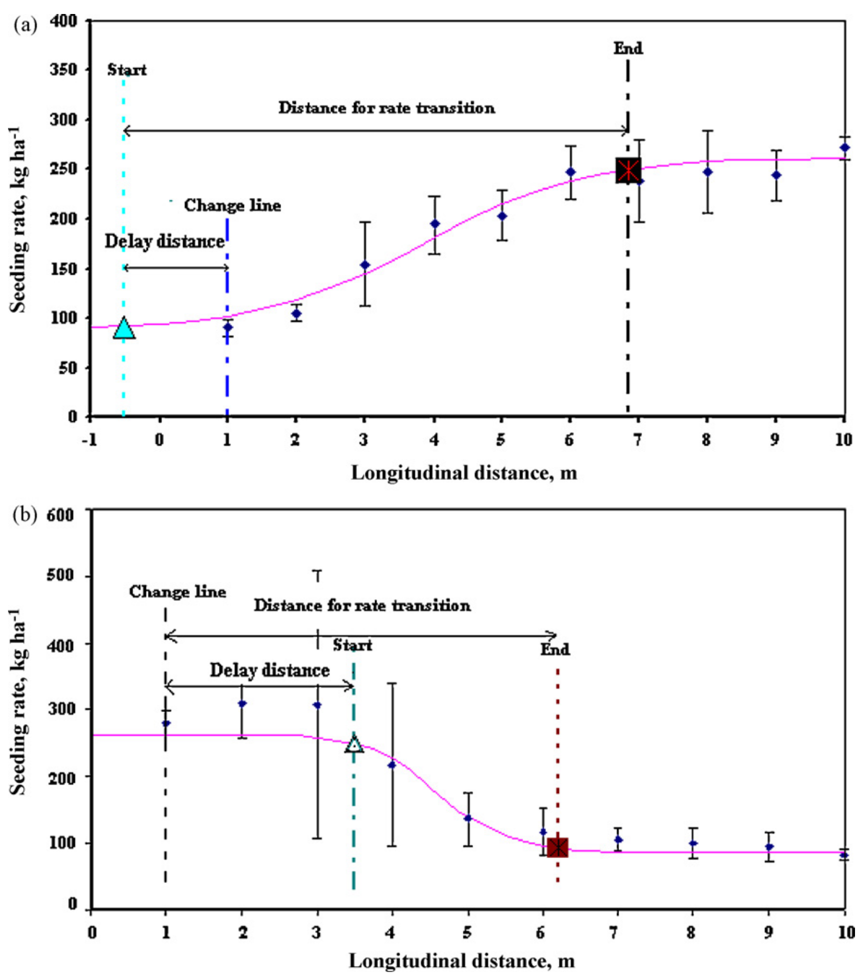

Fig. 16. (a) Low-to-high and (b) high-to-low rate Sigmoid graphs.

Table 1
Sigmoid equation parameters for fitted curve to each outlet for rate change from high-to-low.

Sigmoid equation parameters	Outlets number							Mean of outlets
	1	2	3	4	5	6	7	
a	262.5	262.5	262.5	262.5	262.5	262.5	262.5	262.5
b	−175	−175	−175	−175	−175	−175	−175	−175
c	−1.7	−2.996	−1.098	−24.06	−1.71	−21.64	−2.988	−2.293
d	−8.587	−12.75	−5.18	−96.26	−8.897	−86.81	−13.07	−10.58
R^2	0.7034	0.7941	0.8867	0.8656	0.8656	0.6461	0.6902	0.91

Table 2
Sigmoid equation parameters for fitted curve to each outlet for rate change from low-to-high.

Sigmoid equation parameters	Outlets number							Mean of outlets
	1	2	3	4	5	6	7	
a	87.5	87.5	87.5	87.5	87.5	87.5	87.5	87.5
b	175	175	175	175	175	175	175	175
c	−1.54	−0.9779	−1.011	−0.4112	−1.034	−2.056	−23.03	−0.8364
d	−5.413	−3.331	−4.933	−3.006	−3.709	−6.706	−47.11	−3.213
R^2	0.4639	0.8031	0.7765	0.8632	0.6069	0.8479	0.6982	0.96

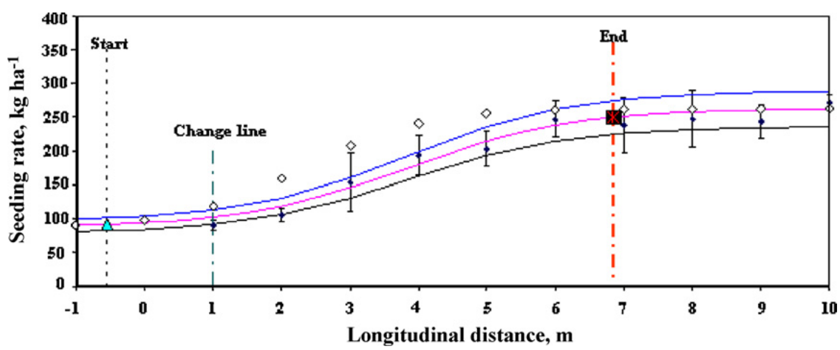

Fig. 17. Example of seeding rate change dynamics for 87.5–262.5 kg ha^{-1}. ✚, Observed; ▬, Fitted; ▬, 90% CI; –, 90% CI; ◇, Predicted. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)

Tables 1 and 2 show the coefficients of the fitted sigmoid equations to the rate changes (high-to-low and low-to-high) and R^2 values for the seven outlets. The *c* and *d* coefficients of all outlets were not in the same range and the R^2 values of the fitting curves for each outlet were less than the average R^2 value of the outlets. This behavior was due to the tractor deviation from straight traversing. More seeds were gathered in some boxes than the others. The *c* and *d* parameters for the first six outlets in the low-to-high transition were in the same range and their average values are −1.17 and −4.52, respectively. The predicted points using these constants are shown in Fig. 17. The predicted points are not contained within the 90% confidence interval (CI). Therefore, the equations for each of the outlets are not suitable for predicting the actual application rate.

4. Conclusions

A closed-loop control system was designed and constructed to change the seeding rate of a grain drill on-the-go. The system consisted of: (1) a DC motor with a fixed-ratio gearbox, (2) encoders for sensing the rotational speeds of the grain drill drive wheel and the motor, (3) a GPS receiver, (4) a pulse-with-modulation (PWM) DC motor controller, and (5) a laptop. Dynamic tests were conducted at application rates of 87.5 (low) and 262.5 (high) kg ha^{-1}. Sigmoid equations were best fitted to the transition data from low-to-high and high-to-low seeding rates. Response times of low-to-high and high-to-low transition rates were 7.4 and 5.2 s, respectively, while the drill operated at a travel speed of 1 m s^{-1}. The Sigmoid equations fitted to each outlet data did not predict the actual application rate. Because of large variations in results, different procedures such as a test rig may be suggested for evaluating the variable-rate seeder. In the test rig evaluation, the discharge tubes will be in their normal form and the error caused by deviation from straight line tracking will be minimized.

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