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A study on precision seeding with a robotic planter

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Abstract

Uniform spatial seed placement is essential for achieving optimum crop establishment and yield. Conventional seeding methods are labor-intensive, time-consuming, and energy-demanding, with limited capability for precise seed placement at predetermined locations. To address these limitations, a robotic precision planter was developed at the Division of Agricultural Engineering, ICAR-Indian Agricultural Research Institute (IARI), New Delhi, with the objective of achieving accurate and uniform seed placement through robotic integration. A computer program was developed in C++ to control the planting operation. The performance of the robotic planter was evaluated at three operating speeds and three crop geometries using maize (*Zea mays* L.) under both laboratory and field conditions. The planter successfully performed precision seed placement at different crop geometries and operating speeds. The highest planting accuracy was achieved at the medium operating speed of 200 mm s⁻¹ under both laboratory and field conditions. Among the tested crop geometries, 20 × 20 cm resulted in the most accurate seed placement, with the lowest deviation from the predetermined planting points in both laboratory and field experiments. Increasing the operating speed from 200 to 250 mm s⁻¹ resulted in greater variation in seed placement, particularly with changes in crop geometry. Under field conditions, missing seed placement ranged from 0 to 5.71%, whereas multiple seed placement ranged from 5 to 9%. The average germination percentage of maize seeds sown using the robotic precision planter was 90%, indicating satisfactory planting performance. Overall, the developed robotic precision planter demonstrated promising potential for accurate and uniform maize seed placement and may contribute to the advancement of automated and precision planting technologies in modern agriculture.

Keywords: Robotic planter, Precision planter, Maize planter, Robotics

Introduction

India supports approximately 17% of the world's population on only 2.4% of its geographical area, placing considerable pressure on its agricultural resources and food production systems. Agriculture remains a major component of the Indian economy, contributing approximately 18% to the national GDP during 2020–2021 and providing livelihoods to more than half of the country's population (MSPI, 2021; Mehta *et al.*, 2014). According to the third advance estimates, India's total food-grain production was projected at approximately 305.44 million tonnes during 2020–2021, comprising about 148.4 million tonnes during the *kharif* season and 157.1 million tonnes during the *rabi* season (Anonymous, 2021) ^[1]. However, continued population growth, declining availability of natural resources, and increasing demand for food necessitate sustained improvements in agricultural productivity. Enhancing both production and resource-use efficiency is therefore essential for ensuring future food security.

Farm mechanization plays a critical role in increasing agricultural productivity, reducing dependence on manual labour, improving timeliness of operations, and enhancing input-use efficiency. Despite its importance, the overall level of farm mechanization in India remains relatively low, estimated at approximately 40–45%. Electro-mechanical sources account for nearly 90% of the total farm power available in Indian agriculture. The extent of mechanization varies considerably among agricultural operations, with approximately 42% mechanization in soil working and seedbed preparation, 29% in seeding and planting, 34% in plant protection, and 37% in irrigation (Tiwari *et al.*, 2019) ^[22]. These figures indicate considerable scope for technological advancement, particularly in seeding and planting operations.

Seeding is one of the most critical operations in crop production because the spatial arrangement

of plants directly influences crop establishment, inter-plant competition, resource utilization, and ultimately yield. Traditional seeding and planting practices, including dibbling, dropping seeds behind a plough, opening furrows using hand hoes, and manually placing seeds, continue to be used in many parts of India (Rakesh, 2022) ^[12]. Such practices are labour-intensive, time-consuming, and require considerable human or animal effort. Although manually operated, animal-drawn, and tractor-operated seed drills and planters have substantially reduced labour requirements, many conventional systems still have limitations in achieving accurate seed placement at predetermined locations.

Mechanical seeders and planters have been developed to improve operational efficiency; however, their performance can be affected by several factors, including missed seed placement, multiple or excessive seed delivery, ground-wheel slippage and skidding, chain and sprocket vibration, variations in seed-metering performance, and fluctuations in seed spacing. These limitations can result in non-uniform plant populations and irregular crop geometry, thereby reducing the efficiency of land, water, nutrients, and other production inputs. Improvements in seed-metering mechanisms and planting control systems are therefore essential for achieving higher levels of precision in agricultural operations.

Robotics-based precision planting represents a promising technological approach for overcoming several limitations associated with conventional mechanical planting systems. Robotic planters can integrate programmable control systems, precision seed-metering mechanisms, sensors, and automated movement to place individual seeds at predetermined locations. Precision planting can reduce seed scattering and unnecessary seed use, improve uniformity of intra-row and inter-row spacing, and minimize seed displacement or bouncing during placement (Domier, 1991; Leela & Saravana Kumar, 2019; Soyoye *et al.*, 2020) ^[4, 8, 20]. Such systems also provide opportunities to customize planting geometry according to crop requirements and field conditions.

The integration of robotics and computer-controlled planting mechanisms is particularly relevant to modern agriculture, where precision, timeliness, and efficient utilization of inputs are increasingly important. A robotic precision planter capable of accurately controlling seed placement and crop geometry could contribute to improved crop establishment while reducing seed wastage and dependence on manual labour. Therefore, the development and evaluation of robotic precision planting systems for crops such as maize (*Zea mays* L.) have considerable significance for advancing mechanization and precision agriculture in India.

The adoption of automation and robotics in agriculture is influenced by several socioeconomic and technological factors, including labour costs, educational level, workforce skills, innovation capacity, occupational safety, efficient utilization of agricultural resources, and prevailing cultural and socioeconomic conditions. Compared with conventional heavy agricultural machinery, small and specialized agricultural robots can offer several advantages, including reduced soil compaction, lower energy consumption, and improved operational efficiency. Agricultural robots have the potential to reduce dependence on manual labour, shorten the time required for field operations, and improve the precision and consistency of agricultural tasks. However, agricultural robotic systems are technically complex because they require the integration and synchronization of multiple subsystems, including mechanical components, actuators, sensors, control units, navigation systems, and

software. Intelligent control systems are essential for coordinating these components and ensuring that the robot performs its intended operations accurately. The development of autonomous field robots has therefore focused on improving operational speed, energy efficiency, navigation, sensing, guidance accuracy, and communication technologies. Technologies such as wireless communication and the Global Positioning System (GPS) have further expanded the potential for autonomous agricultural operations. Despite these advances, the practical deployment of robots for diverse agricultural field operations remains challenging because of variations in soil conditions, terrain, crop geometry, weather, and operational requirements.

One of the major challenges associated with robotic planting systems is achieving precise actuator movement, particularly during individual seed placement. The accuracy of seed placement is influenced by both hardware and software components, including actuator response, control algorithms, sensor inputs, and programmed movement sequences. Furthermore, embedded control programmes must be appropriately configured according to crop characteristics and planting geometry to ensure reliable operation under different field conditions. Consequently, the movement of the actuator must be precisely synchronized with the desired inter-row and intra-row spacing to achieve uniform crop establishment.

Planter performance is generally assessed using parameters such as uniformity of row and plant spacing, missing and multiple seed indices, operating speed, time required for planting, and the quantity of seed placed per unit area. These parameters directly influence plant population, crop establishment, resource competition, and ultimately crop productivity. Therefore, accurate control of seed placement is a fundamental requirement for precision planting systems.

Several researchers have explored robotic technologies for improving autonomous agricultural operations. In an autonomous seeding robot, a caterpillar-track drive system can facilitate movement over uneven and undulating terrain, while a magnetometer can assist navigation and improve directional accuracy through proportional-integral control (Srinivasan *et al.*, 2017). Similarly, a solenoid-based actuator assembly can be incorporated into the seed-metering mechanism to facilitate controlled and equidistant seed placement. Reddy and Babu (2018) reported the development of an automatic seed-dispensing attachment for agricultural robots, demonstrating the potential of robotic platforms to perform multiple operations, including seeding, irrigation, and tillage. These developments highlight the potential of integrating automated seed-metering, navigation, and control systems to improve the precision and versatility of robotic agricultural machinery.

Zabiyullah *et al.* (2018) developed an autonomous agricultural robot for precision seeding with the objectives of reducing labour requirements, saving time and energy, and improving crop productivity. The system was based on the concept of precision agriculture, in which crop-specific planting requirements were incorporated into the robotic platform to achieve appropriate seed placement. A four-wheeled autonomous agricultural robot prototype was developed specifically for seed-sowing operations and controlled using an LPC2148 microcontroller. The robotic system was programmed for sowing four major crops, namely cotton, maize, soybean, and wheat, with crop-specific row and intra-row spacing incorporated into the control system. The robot successfully navigated the field and maintained the programmed distances between crop rows and planting positions, demonstrating the

potential of autonomous robotic systems for precision seeding. In Japan, an automated system for seedling production and transplanting was developed for vegetable cultivation, with the objective of improving the efficiency and consistency of nursery and transplanting operations (Osamu, 1996). Although these developments demonstrated the potential of automation in agricultural planting, relatively few studies have comprehensively evaluated the deviation between the actual seed placement and the predetermined planting positions under different crop geometries and operating conditions. Therefore, the present study was undertaken to develop and evaluate a robotic precision planting system capable of accommodating different crop geometries while minimizing deviation from the desired seed-placement positions. The study also aimed to assess the effect of operating speed and crop geometry on planting accuracy under laboratory and field conditions.

Material and methods

In the present study, precision seeding using a robotic planter was evaluated under different forward operating speeds and predetermined crop geometries. The investigation comprised laboratory testing of the robotic planter, determination of optimum operating parameters for developing the Arduino-based control programme, and field evaluation of its precision

seeding performance using maize (*Zea mays* L.) as the test crop. The robotic planter, developed at the Division of Agricultural Engineering, ICAR–Indian Agricultural Research Institute (IARI), New Delhi, was employed for seed placement. The system was designed to accommodate different crop geometries and operating speeds while controlling seed placement in the longitudinal, lateral, and transverse directions.

Accurate feedback compensation is essential for minimizing deviations between the programmed and actual seed-placement positions. Variations in actuator response, travelling speed, and field conditions can otherwise result in irregular spacing and deviations from the predetermined crop geometry. Therefore, the present study focused on optimizing the control parameters and evaluating the performance of the robotic planter to achieve accurate and uniform seed placement. The ultimate objective was to develop a precision planting system capable of accommodating different crop geometries while maintaining minimum deviation from the desired seed-placement positions.

Robotic Planter

A robotic precision planter developed (Fig.1) at the Division of Agricultural Engineering, ICAR-IARI, New Delhi with different major components and specifications (Table.1), was used for the present study.



Fig 1: Robotic planter developed by ICAR-IARI, New Delhi

Table 1: Specifications of the robotic planter

Specifications	Values
Total Weight of the Robotic Planter	460 kg
Total dimension of the planter per block (Length(m) × Width(m) × Height(m))	1.55 × 1.80 × 1.25
Distance between two tires (m)	1.05
Total no. of punching for plantation of a block	Row to row: 5 (Distance between each plant is 20 cm) Plant to plant: 6 (Distance between each plant is 20 cm) Total no of plants: 5 × 6 = 30 Nos.
Total time is taken for the completion of one block	3 min 40 Seconds (previous data) 3 min (after modification of movement control)
Total charging time for battery	70Ah 4 Nos. battery in 4 hours

An Arduino Mega 2560 development board was used as the primary control unit for operating the robotic planter at different forward speeds and coordinating the sowing operation. The board is based on the ATmega2560 microcontroller and provides 54 digital input/output pins, 16 analog input channels, 15 PWM outputs, and four hardware UART serial communication ports. The controller was programmed to coordinate the movement of the robotic platform and the seed-placement mechanism according to the predefined planting geometry and operating speed.

A Raspberry Pi 3 single-board computer was incorporated into the system to provide computational and communication capabilities. It is equipped with a 64-bit quad-core processor and supports wireless communication through integrated Wi-Fi and Bluetooth, facilitating communication with peripheral and control systems. The combination of the Arduino controller and Raspberry Pi provided the computational and control infrastructure required for the operation of the robotic planter.

Stepper motors were employed to provide precise control of the robotic platform and planting mechanism. A stepper motor is an electromechanical actuator that converts electrical pulses into discrete angular movements, allowing accurate control of position and speed. The robotic planter was equipped with six DW86HS82 stepper motors for steering control along the X- and Y-axes, four NEMA 34 stepper motors for traction, and one NEMA 23 stepper motor for operating the seed-dibbling mechanism along the Z-axis. This configuration enabled independent control of steering, traction, and seed placement.

The robotic planter was equipped with DM860H stepper motor drivers for controlling the different motors. The drivers were allocated to steering, traction, and planter operations, including the X-, Y-, and Z-axis movements. The DM860H is a digital stepper motor driver based on a digital signal processing control algorithm designed to provide smooth motion, stable torque output, and improved motor control. Compared with conventional stepper motor drivers, the system provides reduced operating noise and heat generation and smoother motor movement, which are advantageous for precision positioning applications.

Worm and planetary gear mechanisms were incorporated into the robotic planter to meet the torque requirements of steering and traction systems. The worm-gear mechanism was used for steering because of its ability to provide high torque and self-locking characteristics, thereby helping maintain the desired steering position. The worm gear had a reduction ratio of 30:1 and was integrated with a motor having a rated torque of approximately 46 kg-cm. A planetary gear mechanism was used

for the traction system to provide the torque required for movement of the robotic platform. The planetary gear had a reduction ratio of 5:1 and a rated torque capacity of approximately 200 kg-cm.

Two sealed lead-tin (PLT) battery power units were installed on opposite sides of the robotic planter to supply electrical power to the control, drive, and planting systems. The battery units provided a nominal voltage of 48 V. The batteries required approximately 4 h for charging, with a rated capacity of 70 Ah. The distributed placement of the battery units also helped accommodate the power requirements of the robotic platform while maintaining an appropriate weight distribution.

Development of embedded program

The control programme for autonomous planting was developed using the C++ programming language and implemented through the open-source Arduino Integrated Development Environment (IDE). Preliminary observations of the robotic planter, including the operating characteristics of the stepper motors, actuator response, and pulse-width modulation (PWM) requirements, were used to determine the appropriate control parameters. Based on these parameters, a microcontroller programme was developed to coordinate the movement of the robotic platform and seed-placement mechanism according to the selected crop geometry.

The embedded programme was designed to provide flexibility in adjusting planting geometry and operating speed. Accordingly, the programmed parameters could be modified to accommodate different row spacing, intra-row spacing, and forward speeds, thereby allowing the robotic planter to be adapted to the requirements of different crops. The design and operating values obtained during the preliminary evaluation of the robotic planter were incorporated into the control algorithm to improve the accuracy of seed placement.

For systematic operation, the embedded control programme was organized into three functional subsets. These subsets controlled the major operational sequences of the robotic planter, including movement, positioning, and seed-placement functions. A series of predefined commands was incorporated into the programme to facilitate operation and modification of the robotic planter according to experimental requirements. The overall control sequence followed these functional subsets during autonomous planting, as illustrated in Fig. 2.

The workflow of the microcontroller program was given in Fig 3 and a description of constants in the flowchart was given in Table 2.

Table 2: Details of constants used in a program flowchart

Crop geometry	P = distance between two plants (cm)	n = number of cycles varies according to the spacing	m = number of rows
20cm × 20cm	20cm	4	6
15cm × 15cm	15cm	6	8
10cm × 10cm	10cm	9	11
60cm × 20cm	60cm	1	6

The program algorithm was designed concerning the BLUs (the basic length unit) obtained by the preliminary test study on the robotic planter. Stepper motors were tested at different speeds. For the particular number of input pulses, displacement in the

stepper motor was observed. The BLU per pulse was calculated for transverse, longitudinal-forward, and backward axis movements, z-axis, steering, and traction.

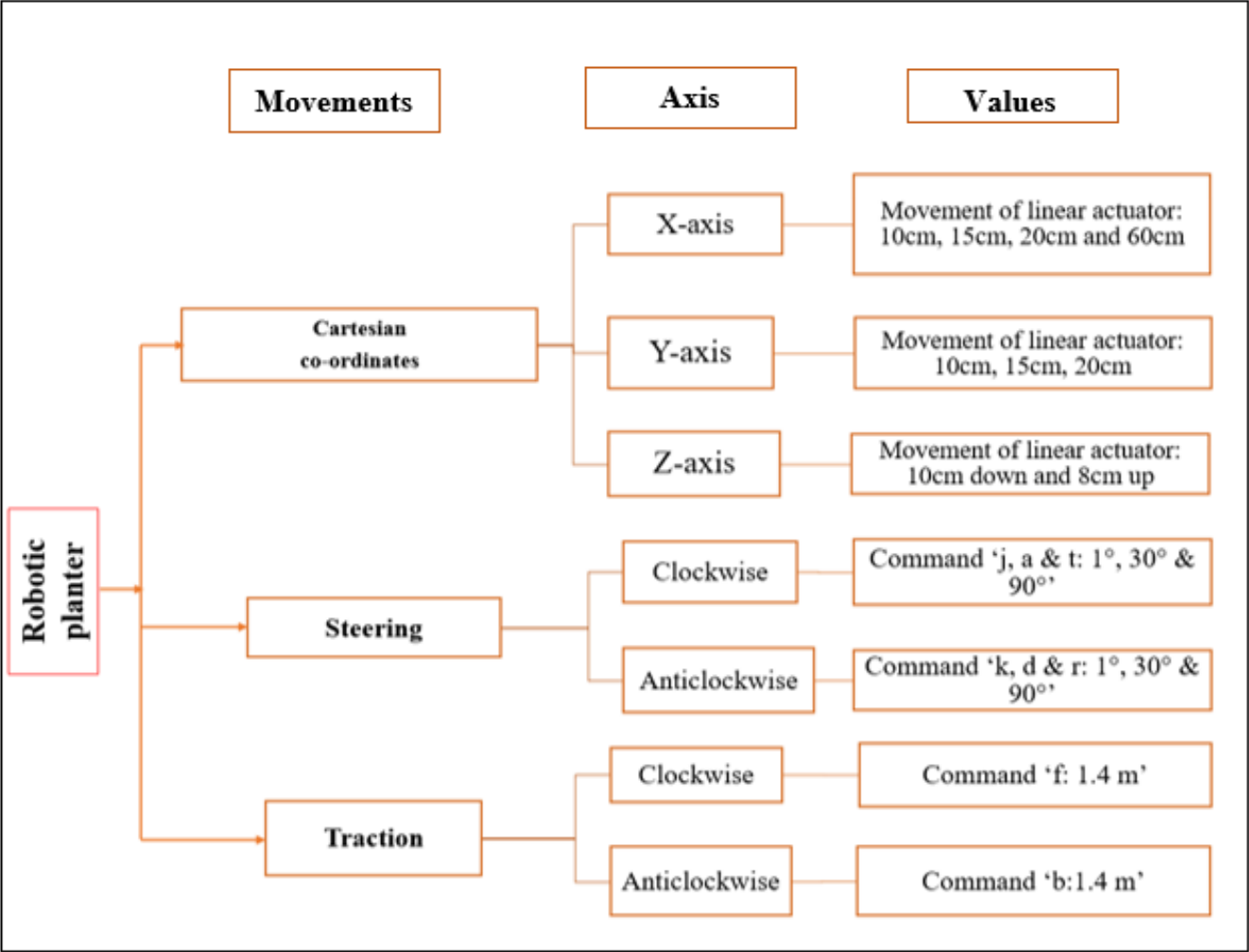


Fig 2: Sub-sets of embedded program

The developed code was uploaded on the microcontroller from Arduino software; further, it was connected to the planter operating system through raspberry Pi 3. Every planter operation, such as planting, steering, forward and backward movement, etc., was controlled by controlling commands to the planter through Wi-Fi. Hence a graph paper of 5m×2m size was used (Fig. 3a). To mark planting points on graph paper. The planter was operated for each crop geometry-speed combination (Table 2) by modifying the developed code as required.

The laboratory experiment and performance evaluation of the robotic planter were conducted according to the experimental plan presented in Table 3, with the overall experimental workflow illustrated in Fig. 3. At the beginning of each test, the robotic planter was positioned at the designated starting point, after which the planting unit was lowered and the marker mechanism was activated to mark the programmed seed-placement positions on the paper surface. Observations were recorded for both forward and reverse movements of the robotic planter at the selected operating speeds, as shown in Fig. 3b.

The same experimental procedure was repeated for each of the selected crop geometries by varying the operating speed according to the experimental treatment. The time required by the robotic planter to complete the marking operation in both forward and reverse directions was recorded for each treatment. These observations were used to assess the effect of operating speed and crop geometry on the performance and positioning accuracy of the robotic planting system.

The deviation of the linear actuator from the programmed Cartesian coordinates was determined by measuring the actual distance between successive marked points. The distance between adjacent points within a row was considered the plant-to-plant spacing, whereas the distance between adjacent rows was considered the row spacing. These measurements were taken manually from the marked paper surface, and the corresponding observations were recorded for subsequent statistical analysis. The deviations between the programmed and observed positions were used to quantify the precision and uniformity of the robotic planter, as illustrated in Fig. 4.

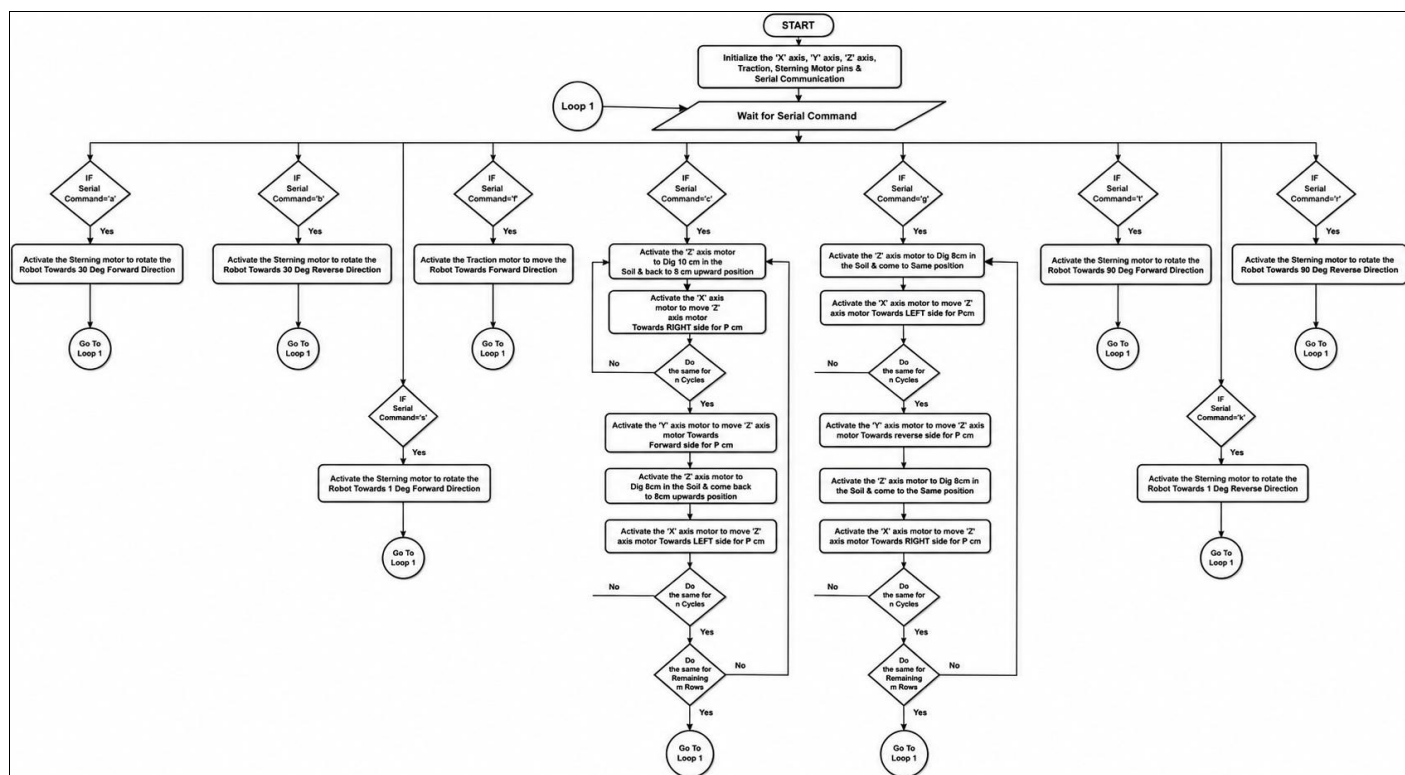


Fig.3: Flow chart for developed arduinoprogram

Table.3: Selected speeds for different crop geometry

Crop geometry	Stepper motor speed (mm/s)		
	Slow	Medium	High
20 cm × 20 cm	133	200	250
15 cm × 15 cm	133	200	250
10 cm × 10 cm	133	200	250
60 cm × 20 cm	133	200	250



Fig.3: (a) Laboratory testing setup using graph paper (b) Marking done by the robot on paper

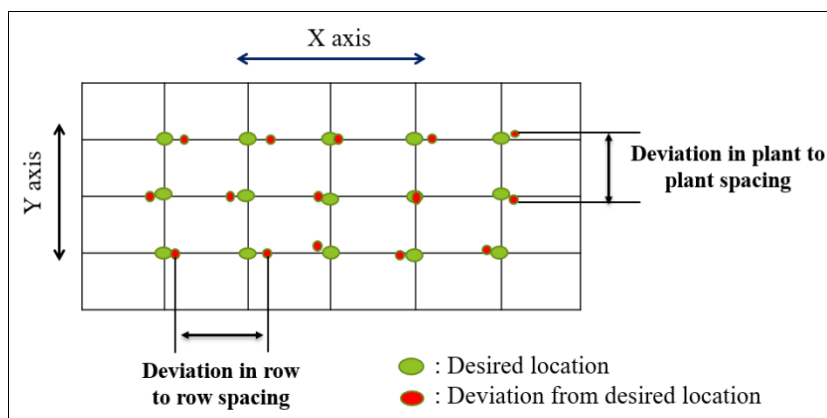


Fig 4: Deviation obtained from the desired placement

The reduced crop geometry yields larger deviation values with the increased speed of seed placement. In comparison to all the reactions between spacing and speed, levels 1-2 (20cm*20cm and 200mm/s) were found best with the least deviation

observations but deviations exist in all cases (Fig.5 and Fig.6). Thus, slight modifications were required to incorporate into the developed program to use the program in the field condition.

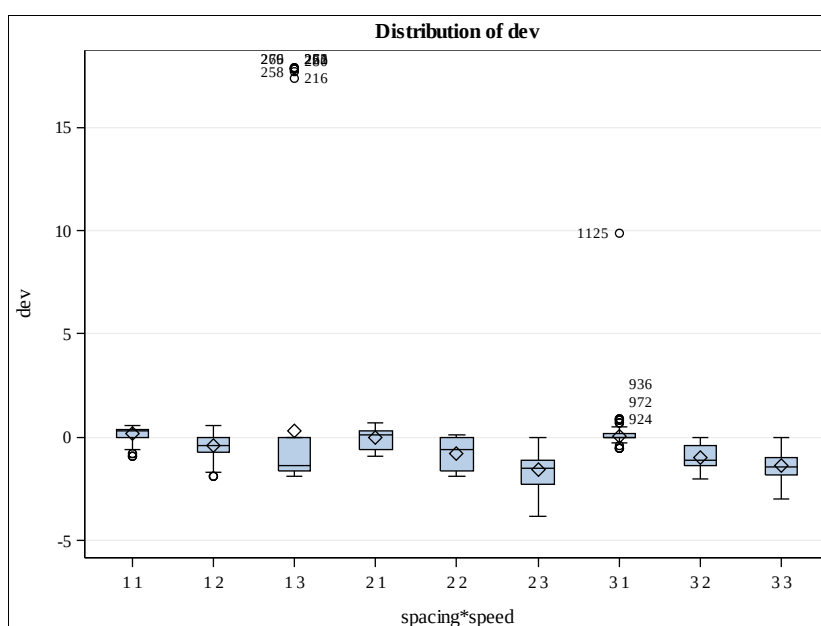


Fig.5: Plant- to- plant distance condition

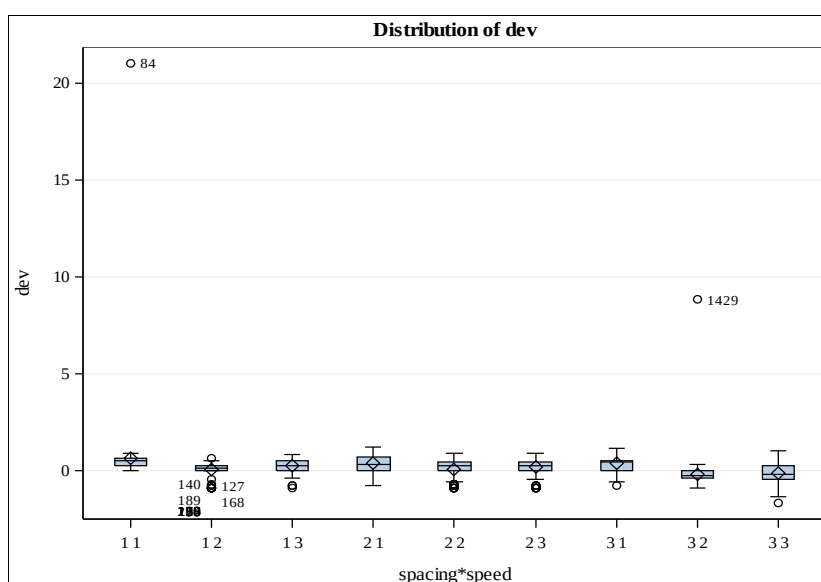


Fig 6: Row -to -row distance condition

Field evaluation of Robotic planter with developed embedded program

The program code was developed using Arduino software to obtain the desired crop geometry by providing the required number of steps per revolution to run the stepper motor on the planter. Laboratory experiments were conducted using the developed code. The observations obtained showed deviations in the crop geometry. Based on the laboratory observations, the modifications were made in the developed code to control the

deviations in seed placement by reducing the number of steps provided to the stepper motor.

The modifications in the code were done by reducing the required number of steps by 2 numbers. Thereby the deviations were controlled in the field condition (Fig.7 and Fig 8). Deviation in the field condition was slightly lesser as compared to the laboratory condition in both plants to plant and row to row category. Thus slight modifications in the code could help to control the deviation in seed placement.

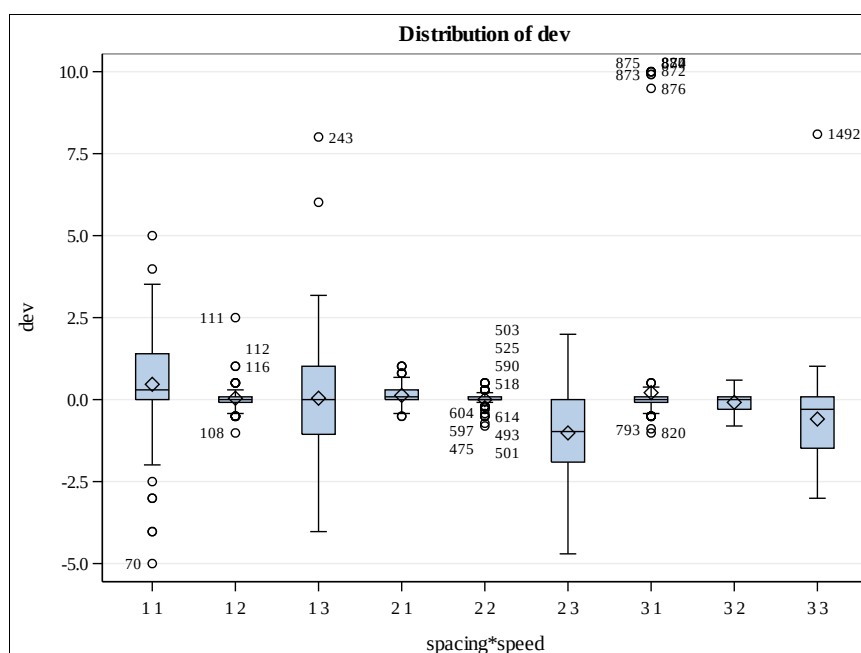


Fig 7: Plant to plant field condition

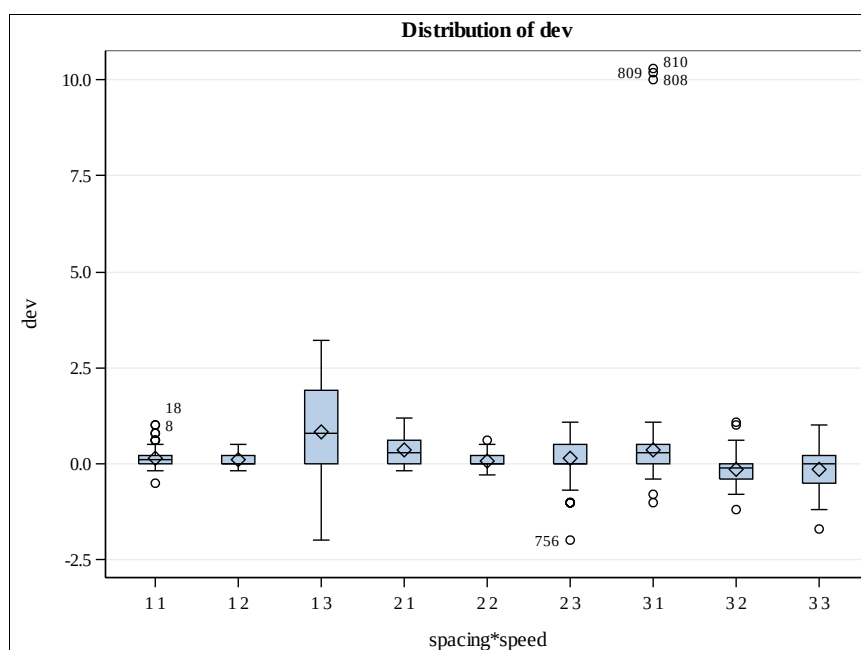


Fig 8: Row- to- row field condition

Field preparation was done using a cultivator operation twice and a rotavator once, followed by a field layout with a dimension of 19 m × 13 m. The selected field was divided into eight rows and five columns with space left for robot movement. A total of 40 blocks of size 1.75m × 1.65m were prepared (Fig. 9a). Field evaluation of the robotic planter was done at three speeds for specific crop geometries (20 cm × 20 cm, 15 cm × 15

cm, 10 cm × 10 cm, and 60 cm × 20 cm) at three different speeds (slow, medium, and high, varies with crop spacing).

Maize can be cultivated throughout the year; it can resist high temperatures (about 38°C) and rainfall. A planting spacing of 60 cm × 20 cm is commonly recommended by agronomists and adopted for maize (Sharma and Dass, 2012). Hence manual dibbling with the recommended crop spacing was also done to

compare the time and precision with the robotic planter and manual operation (Fig.9b). Field data of row- to- row and plant-to -plant spacing was collected after 20 days of sowing (Fig 9 c and d). The performance evaluation of the robotic planter, based on field data, was done for parameters, such as crop geometry, planting depth, missing, and multiple indices.

Data recorded for the laboratory and field experiments were statistically analyzed using SAS (statistical analysis software)

package to analyze the variance and interaction of the selected variables (operating speed, crop geometries). Factorial Random Block Design was used to analyze the factor effects in field conditions. The experiment had two factors each at three levels (operating speed: slow, medium, high, crop geometry: 20cm ×20cm, 15cm×15cm, 10cm×10cm) were distributed in 36 blocks to determine the best combination of operating speed and crop geometry.



Fi g9: Field evaluation (a) Planting by robotic planter (b) Manual dibbling (c) Maize crop stand (d) measurement of crop geometry

Results

The effect of selected levels of speed and crop geometry on planter performance was studied. The laboratory data obtained at different speeds and spacings in the forward and backward operation of the robotic planter were statistically analyzed. The

data was used for the design and development of the embedded program for autonomous planting for selected crop geometry, and basic length units (BLUs) were calculated to develop the embedded program (Table.4).

Table 4: Design values for the development of microcontroller code

Particulars	BLU/pulse (mm/pulse)	90° steering (No. of pulses)	Forward traction (No. of pulses for 140cm)	10cm (No. of pulse)	15cm (No. of pulse)	20cm (No. of pulse)
X_f	0.42 mm/pulse	-	-	235	352.5	470
X_b	0.43 mm/pulse	-	-	232	348	465
Y_f	0.42 mm/pulse	-	-	235	352.5	470
Y_b	0.43 mm/pulse	-	-	232	348	465
Z-axis	0.02 mm/pulse	-	-	4000	4000	4000
Steering	0.03°/pulse	3000	-	-	-	-
Traction	0.218mm/pulse	-	6400	-	-	-

Laboratory experiments

In forward movement, row-to-row measurements for 10cm ×10cm spacing, the deviation was initially less at slow speed, decreased at medium speed, and increased at high speed up to

0.55cm. But in the 20cm ×20cm and 15 cm ×15cm, the higher deviation was observed at slow speed, with lesser value for medium speed, and again greater values for high speed (Fig.10).

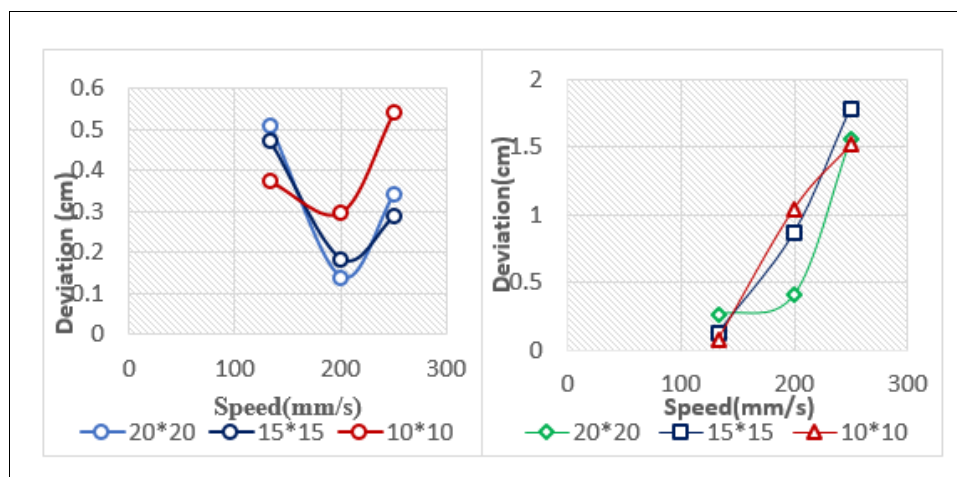


Fig 10: Deviation from desired placement with speed in (a) Row to Row (b) Plant to Plant

The deviation was high for the row-to-row measurements; for medium speed, the deviation was least; the deviation was large at high and low speeds. For forward movement plant-to-plant

measurements in lab conditions, the deviation pattern was the same for three spacings with an increase in speed. As speed increases, deviation also increased with the same pattern

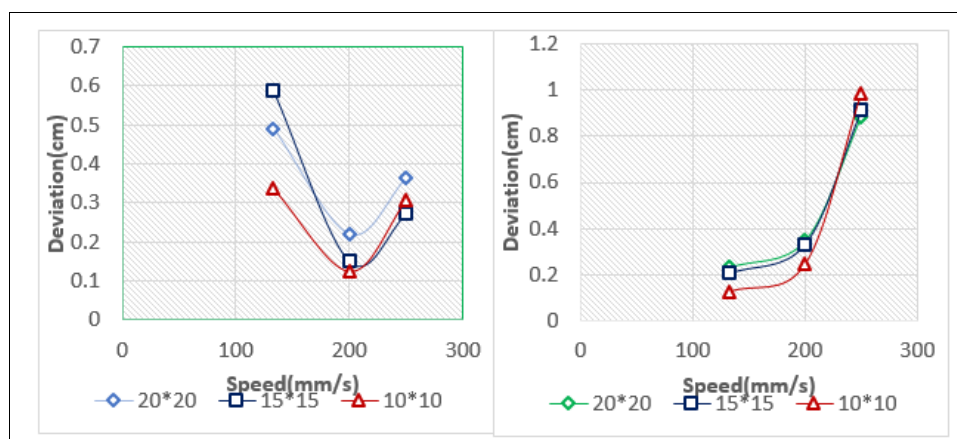


Fig 11: Deviation from desired placement with speed for backward operation (a) Row-to-row (b) Plant-to-plant

A similar trend in deviations was observed in backward operation row-to-row and plant-to-plant measurements. From row to row, measurements for three spacings at slow speed deviation was more, less in medium speed and again increased at

high speed. In plant-to-plant spacing deviation pattern for all three speeds and spacing was found similar to forward operations condition (Fig.11).

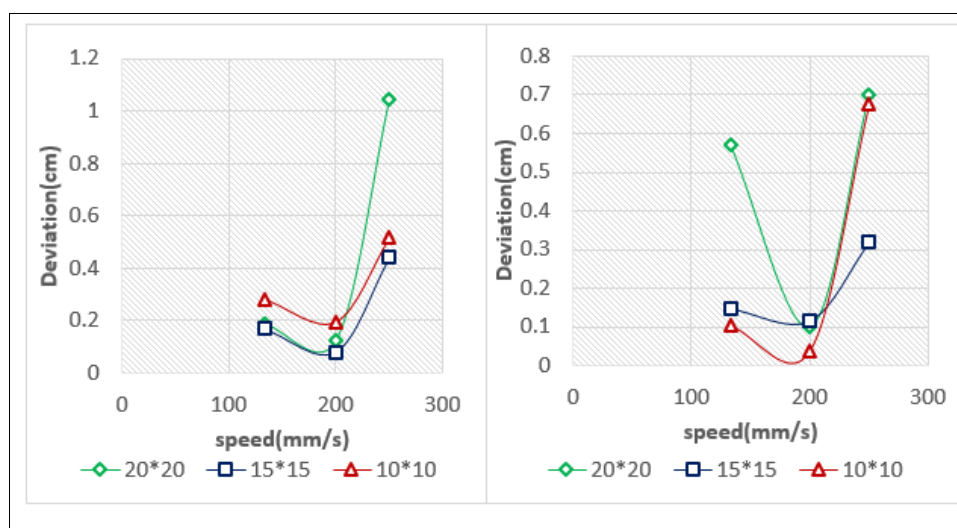


Fig 12: Deviation from desired placement with speed in-field operation (a) Row to row (b) Plant to plant

Field evaluation

Many researchers worked on precision planters' design and development but did not focus on the precision placement of seeds and deviation studies. So, this study was attentive to the precision placement and controlling the deviation in seed placement to obtain the desired crop geometry. Along with precision placement, the cartesian coordinates of the robotic planter were controlled for its operation in the field.

Row-to-row measurements for all the three spacings at medium speed deviation were the lowest, as speed increased deviation also increased. With speed reduction, the deviation was higher. In the plant-to-plant distance measurements, the deviation was lesser at medium speed for all the spacings, but the deviation increased as speed increased. The deviation pattern was alike the row- to row measurements.

Discussion

The embedded control programme was used to operate and monitor the hardware components and actuators of the robotic planter. The programme calculated the number of electrical pulses required to execute specific movements and seed-placement operations. Initially, the microcontroller-based programme was evaluated under laboratory conditions to assess the positioning performance of the robotic planter. Deviations from the programmed positions were recorded during both forward and reverse operations at different operating speeds and crop geometries.

Several factors contributed to the observed deviations, including actuator jerks, motor torque, inertial forces, and inadequate mechanical support for the planting unit. The movement of the planting unit along the X-axis was controlled through a belt-driven mechanism. During forward movement, greater belt tension increased the resistance to movement and resulted in a negative positional deviation. In contrast, during reverse movement, the force required to move the system was comparatively lower because of belt slackness, allowing relatively freer movement of the X-axis and resulting in greater positive deviation. These observations indicated that the mechanical characteristics of the belt-driven system had a direct influence on positioning accuracy.

The deviation could be reduced by optimizing the number of input pulses supplied to the stepper motor. Based on the laboratory observations, the Arduino control programme was modified by reducing the input pulse requirement, and the revised programme was subsequently incorporated into the robotic planter for field evaluation.

The distribution of positional deviations under laboratory conditions indicated that the medium operating speed of 200 mm s⁻¹ provided the most consistent performance among the three tested speeds, namely 133 mm s⁻¹ (slow), 200 mm s⁻¹ (medium), and 250 mm s⁻¹ (high). A greater number of outlying observations were recorded at both the lower and higher operating speeds, indicating reduced positioning consistency under these conditions. The medium speed therefore provided a better balance between actuator response, movement stability, and positioning accuracy.

Following laboratory evaluation, the control programme was modified to minimize positional deviation before conducting field experiments. Under field conditions, the robotic planter again demonstrated its best performance at the medium operating speed of 200 mm s⁻¹, which resulted in the lowest deviation from the predetermined planting positions for the selected crop geometry. The effects of operating speed on positional deviation were statistically significant within the 95%

confidence limits.

Greater deviation was observed at the high operating speed of 250 mm s⁻¹. At this speed, the interval between successive control pulses was reduced, potentially limiting the ability of the stepper motor to respond accurately to every pulse within the available time. Failure to register or execute some pulses can result in loss of motor steps, thereby increasing positional error. In contrast, at the medium operating speed of 200 mm s⁻¹, the required pulses were delivered to the motor with sufficient time for accurate execution, resulting in improved movement stability and lower positional deviation.

Overall, the laboratory and field evaluations demonstrated that an operating speed of 200 mm s⁻¹ was the most suitable among the tested speeds for achieving accurate seed placement with minimum positional deviation. Optimization of the embedded control programme, combined with appropriate operating speed and mechanical adjustment of the belt-driven actuator system, substantially improved the precision performance of the robotic planter. The results indicate that medium-speed operation is preferable for precision planting where accurate and uniform seed placement is the primary objective.

The spacing of 20 cm × 20 cm had a lesser deviation, whereas large deviation values were observed in 15 cm × 15 cm spacing followed by 10 cm × 10 cm spacing. The lesser spacing of crop geometries resulted in a higher deviation. It might be due to the continuous working of motors in the robotic planter. As the spacing decreased, the number of drops or planting points per particular crop geometry increased. In field testing, the robotic planter planted 35 times (one or two seeds per dropping point) in 20 cm × 20 cm spacing, 54 times in 15 cm × 15 cm spacing, and 108 times in 10 cm × 10 cm spacing. With the decrease in crop geometry dimensions, the dropping points increased, which resulted in positive or negative deviations either on the left or right side of the dropping point.

Conclusion

The development and evaluation of the robotic precision planter demonstrated the potential of robotic technology for improving the accuracy and uniformity of seed placement in agricultural operations. The system successfully performed precision planting under both laboratory and field conditions and provided flexibility in accommodating different operating speeds and crop geometries. Among the evaluated operating speeds, 200 mm s⁻¹ provided the most consistent and precise performance, with the lowest positional deviation in both laboratory and field conditions. Deviations increased when the operating speed was either increased or decreased from the optimum level, primarily because of variations in pulse execution and the resulting loss of motor steps. Crop geometry also influenced planting accuracy. The 20 × 20 cm crop geometry produced the lowest variation and demonstrated the most consistent seed placement under both laboratory and field conditions. Larger crop geometries generally resulted in lower standard deviations than closely spaced geometries, indicating improved positioning accuracy at wider planting intervals. No substantial difference in positional deviation was observed between forward and reverse movements, suggesting that the robotic system maintained comparable positioning performance in both directions after optimization of the control programme. Under field conditions, the percentage of missing seeds remained below 5.71%, which was primarily associated with the limited ability of the dibbling mechanism to generate sufficient force for consistent soil penetration and seed placement. Multiple seed placement ranged from 5 to 9%, mainly because soil adhering to the dibbling unit

occasionally interfered with the timely release of individual seeds. These observations indicate that further refinement of the dibbling and seed-metering mechanisms could improve planting accuracy and reduce missing and multiple seed placement. Overall, the findings demonstrate that the developed robotic planter can provide accurate and uniform seed placement when operated under optimized conditions. Integration of appropriate actuator control, feedback compensation, suitable operating speed, and crop-specific planting geometry can enhance the effectiveness of robotic precision planting. Such systems have considerable potential to reduce labour requirements, improve input-use efficiency, and support the adoption of precision agriculture. Further improvements in mechanical design, sensor-based feedback, autonomous navigation, and seed-metering mechanisms could enhance the reliability and versatility of robotic planters for diverse crops and field conditions.

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References

1. Anonymous. Monthly bulletin (DES), May 2021. New Delhi: Ministry of Agriculture & Farmers' Welfare, Government of India; 2021.
2. Aravind KR, Raja P, Pérez-Ruiz M. Task-based agricultural mobile robots in arable farming: a review. *Spanish J Agric Res*. 2017;15(1):1-16. doi:10.5424/sjar/2017151-9573.
3. Dhande KA, Sahu OR, Bawane MS, Jiwane AA, Chaware PS. Design and development of automatic operated seeds sowing machine. *Int J Recent Innov Trends Comput Commun*. 2017;5(2). doi:10.17762/ijritcc.v5i2.215.
4. Domier KW. Determination of the optimum seedbed conditions for canola. In: An overview of canola agronomic and varietal development research. Canola Council of Canada; 1991. p. 8-10.
5. Haibo L, Shuliang D, Zunmin L, Chuijie Y. Study and experiment on a wheat precision seeding robot. *J Robot*. 2015;2015:696301. doi:10.1155/2015/696301.
6. Haibo L, Shuliang D, Zunmin L, Chuijie Y. Study and experiment on a wheat precision seeding robot. *J Robot*. 2015;2015:696301. doi:10.1155/2015/696301.
7. Kanthane N. Modeling, design, and fabrication on automatic seed sowing device. *Int J Mech Eng Inf Technol*. 2015;3(5):1221-1247.
8. Leela C, Saravanakumar M. Development of electronically meterized maize planter. *Int J Curr Microbiol Appl Sci*. 2019;8(4):2432-2440. doi:10.20546/ijcmas.2019.804.283.
9. Siemens MC, Gayler RR. Improving seed spacing uniformity of precision vegetable planters. *Appl Eng Agric*. 2016;32(5):579-587. doi:10.13031/aea.32.11721.
10. Mehta CR, Chandel NS, Jena PC, Jha A. Indian agriculture counting on farm mechanization. *AMA Agric Mech Asia Afr Lat Am*. 2019;50(1):84-89.
11. Muley S, Kandhikar SW. Robotic vehicle for seed planting and weeding applications. *IJIRST Int J Innov Res Sci Technol*. 2017;3(12):213-216.
12. Rakesh S. Textbook on fundamentals of agronomy: principles and practices. Shashwat Publication; 2022.
13. Rao NA, Reddy PS, Raju N. Design and development of seed sowing AGROBOT. *J Emerg Technol Innov Res*. 2018;5(5):783-787.
14. Reddy, Babu. Design and development of farmer-friendly agricultural robot with automatic seed dispensing system. *Robotics, Automation & Business News Index: Asian Robotics Review*; 2018.
15. Ruangurai P, Ekpanyapong M, Pruetong C, Watwai T. Automated three-wheel rice seeding robot operating in dry paddy fields. *Maejo Int J Sci Technol*. 2015;9(3):403. doi:10.14456/mijst.2015.31.
16. Sakaue O. Development of seeding production robot and automated transplanter system. *Japan Agric Res Q*. 1996;30:221-226.
17. Senthilnathan N, Gupta S, Pureha K, Verma S. Fabrication and automation of seed sowing machine using IoT. *Int J Mech Eng Technol*. 2018;9(4):903-912.
18. Sharma AR, Dass A. Maize. In: Prasad R, editor. Text book of crop production. 2012. p. 98-136.
19. Singh RC, Singh G, Saraswat DC. Optimization of design and operational parameters of a pneumatic seed metering device for planting cottonseeds. *Biosyst Eng*. 2005;92(4):429-438. doi:10.1016/j.biosystemseng.2005.07.002.
20. Soyoye BO. Development of the instrumentation unit of a motorized precision planter. *Eur J Eng Technol Res*. 2020;5(4):403-407. doi:10.24018/ejeng.2020.5.4.1815.
21. Srinivasan Jayakrishna PV, Reddy MS, Sai NJ, Susheel N, Peeyush KP. Autonomous seed sowing agricultural robot. In: 2018 International Conference on Advances in Computing, Communications, and Informatics (ICACCI); 2018. p. 2332-2336. IEEE. doi:10.1109/ICACCI.2018.8554622.
22. Tiwari PS, Singh KK, Sahni RK, Kumar V. Farm mechanization-trends and policy for its promotion in India. *Indian J Agric Sci*. 2019;89(10):1555-1562.
23. Syed ZG, Gunasekaran R, Keerthana A, Kirubakaran P, Krishnamoorthy S, Rajeswari K. Agriculture robot for seeding and forming. *ISAR Int J Electron Commun Ethics*. 2018;1(2).