Development of an unmanned ground vehicle for seed planting

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ABSTRACT

As global population growth intensifies the demand for sustainable food production, the application of robotics to agriculture emerges as a promising solution. This research focuses on the design, development, and deployment of an unmanned ground vehicle for seed planting, also known as a robotic seed planter. The robotic seed planter automates seed planting processes, offering advantages such as increased accuracy, reduced labour requirements, and optimal resource usage. Parametric Technology Corporation (PTC) Creo was used for the structural design, Proteus 8.14 for the circuitry design, and Arduino IDE 2.0 with Visual Studio Code for the programming. The design incorporates seed metering and drilling mechanisms guided by intelligent systems. Results show exceptional accuracy in seed placement (94%), operational efficiency, and adaptability to diverse conditions, with energy consumption relatively low. The planter is equipped with a web application for remote monitoring and control. The application is hosted on one of the microcontrollers and WebSockets protocol is utilized for inter-microcontroller communication. It offers an auto mode for automated planting and Manual mode for easier manoeuvrability. The findings of this study demonstrate the robotic seed planter's transformative impact on precision agriculture, providing a glimpse into the future of efficient and sustainable farming operations.

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1. INTRODUCTION

The field of robotics has advanced significantly, with applications spanning various industries. One such application is in agriculture, where global food demand is challenging traditional farming practices [1]. It is projected that by 2050, we will need to double our current food production capacity [2]–[4], therefore this paper focuses on developing a robotic seed planter, an unmanned ground vehicle automating seed planting to enhance precision and efficiency.

In the olden days, seeds were scattered by hand and then harrowed, this is imprecise, slow, and inefficient [5], [6]. The Robotic Seed Planter represents a paradigm shift in traditional seed planting methods by integrating mechatronics with precision agriculture, offering benefits like increased accuracy, reduced labour requirements [6], optimized resource use [7], [8], and lower operating costs [9]. At its core, the robotic seed planter integrates intelligent systems and sensors, that analyse soil conditions, and ensure precise seed placement and consistent spacing for improved crop yields and resource efficiency [10], [11].

Successfully implementing this precision agriculture technology, especially for small-scale operations, involves considering mechanical design, advanced sensing, control systems, and efficient navigation algorithms [12]–[15]. Adaptability is also a factor that hinders the wide use of robotic seed planters. When flexibility is necessary, re-configurable robots are a concrete solution, but suffer the need to be physically disassembled and re-built to adapt to plant species or task requirements [16]. This adaptability is crucial for the technology to be widely adopted and to have a significant impact on global food production.

Liu *et al.* [17] optimized a vacuum seed metering device by employing the principle of negative pressure to pick up and precisely dispense single seeds, minimizing waste and ensuring accurate seed placement. This innovative system provides farmers with precise control, optimizing seed spacing and addressing challenges like overlapping or gaps between seeds, leading to improved planting accuracy and increased crop yield across various crops.

Javidan and Mohamadzamani [18] addressed the crucial aspects of efficient path planning and obstacle avoidance by developing an autonomous seed planter. This planter incorporated an obstacle avoidance and row detection algorithm based on ultrasonic sensors, demonstrating successful straight-line navigation at different speeds. The accurate implementation of ultrasonic sensors enhanced overall performance, emphasising the efficiency of the planting process. Notably, the planter showcased a commitment to energy sustainability, utilizing solar power with photovoltaic panels and managing power usage through ultrasonic sensors and a microcontroller.

Ghalazman *et al.* [19] explored the integration of precision agriculture technologies with robotic seed planters, conceiving a modular seeding robot equipped with a seed selector and planter mechanism. The robot uses remote sensing data to identify areas with diverse crop health or nutrient deficiencies, enabling it to adjust seed placement, fertilizer application, and other agronomic practices. This synergy between technology and agriculture optimizes crop growth and yield.

In the area of weed management, Zhang *et al.* [20] and De Baerdemaeker [21] provide a comprehensive review of current robotic approaches, incorporating computer vision with traditional machine learning and deep learning for weed detection. The emergent field of autonomous weeding robots signifies a shift towards effective weed control, reducing environmental pollution by minimizing reliance on pesticides. Various weed detection methods have been developed, and most weed management robots are currently in various stages between research and commercial applications.

Peskett sheds light on the innovative partnership between human operators and collaborative robots, like John Deere's ExactShot. Collaborative robots, or cobots, work together to optimize efficiency and flexibility in seed planting operations [22]. This collaboration reduces costs for farmers while strategically avoiding feeding unwanted weed seeds, marking a significant advancement in agricultural technology [23].

Several challenges exist for seeding robots, such as the working speed being a critical factor for precision seeding, requiring individual calibration for each robot [13]. Given the existing literature, most research in this field revolves around proposed models or prototypes based on theoretical analysis. However, these are often miniature versions of the actual machine. In our approach, we undertake a two-phase development process for the robotic seed planter: hardware assembly (involving mechanical and electrical components) and software development (designing operational logic). This integrated approach ensures a balanced and functional device, merging physical components with digital instructions. Our research focuses on advancing the robotic seed planter by integrating a precise seed metering mechanism, drilling mechanism, and distance measurement system to ensure accurate seed placement and optimal distribution. The seed metering mechanism involves a DC-geared motor, transmitting rotatory motion via a chain to two metering discs, facilitating controlled seed release for accurate placement, while the drilling mechanism employs three DC-geared motors: two for drilling and one for retracting the drills. Employing geared motors enhances torque, enabling effective handling of robust seeds and challenging soil conditions. In summary, our research transcends theoretical models, concentrating on refining key components for optimal performance. By addressing the intricacies of seed metering, drilling, and distance measurement, we strive to develop a robotic seed planter that excels in accuracy, efficiency, and adaptability, marking a significant advancement in agricultural automation.

2. METHOD

The development of this robotic seed planter involves two main phases: hardware assembly, which includes mechanical and electrical components forming the physical structure, and software development, where the operational logic is designed. These two phases work together to create a balanced and functional device, integrating physical components with digital instructions. The hardware assembly ensures the robustness and durability of the device, enabling it to withstand various environmental conditions. On the other hand, the software development phase ensures the precision and efficiency of the seed planting process, making the device a reliable tool for modern agriculture.

2.1. Materials
2.1.1. Mechanical components
- **Auger ground digging screw**

This screw, shown in Figure 1, plays a vital role in efficiently drilling holes for planting crops or trees. With a spiral blade of various sizes and compatibility with different soil types, it ensures precision and adaptability in the seed-planting process. Moreover, the Auger Ground Digging Screw’s design allows for easy attachment and detachment to the robotic seed planter, enhancing the device’s versatility and ease of maintenance.

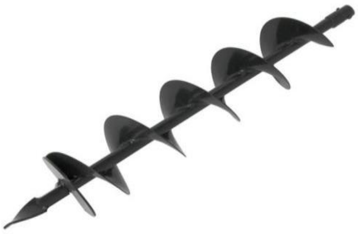

Figure 1. Auger ground digging screw

- Mechanical bearings

These components play a pivotal role in constraining relative motion and reducing friction between moving parts, contributing to the overall efficiency and smooth operation of the planter. An example is shown in Figure 2. Mechanical bearings are designed to be durable and withstand the rigors of continuous operation, thereby extending the lifespan of the robotic seed planter. Furthermore, their modular design allows for easy replacement, ensuring minimal downtime for maintenance and repairs.

Figure 2. Mechanical bearing

- Sprocket

Utilized for power transmission, the toothed design, pitch compatibility, and varied sizes of the sprocket make it fundamental, ensuring effective and controlled transfer of rotational motion. Figure 3 shows an example of a sprocket. The sprocket’s robust construction ensures longevity, even under the strain of continuous operation. Additionally, its compatibility with various chain sizes allows for flexibility in the design and functionality of the robotic seed planter.

Figure 3. Sprocket

2.1.2. Electrical components

– ESP 32 Module

ESP32 is a powerful SoC microcontroller with integrated Wi-Fi 802.11 b/g/n, dual-mode Bluetooth version 4.2 and a variety of peripherals [24]. It forms the core of the planter's electronic system. Providing computational power, wireless connectivity, and extensive input/output options, it enables seamless communication and control. Two ESP32 microcontrollers are used; one is shown in Figure 4.

Figure 4. ESP32 microcontroller

– Hub motor

This motor, an in-wheel motor, is integrated into the wheel hub and contributes to improved efficiency, regenerative braking, and enhanced overall performance. Two hub motors are used, as shown in Figure 5. The hub motor’s compact design and lightweight allow for more space on the robotic seed planter for additional components and reduce the overall weight. Moreover, the use of two hub motors provides better control and stability, ensuring precise movement and operation of the device.

Figure 5. Hub Motors

– 3-phase BLDC brush-less motor controller PWM with hall motor sensor

This controller connects the hub motor to the planter's microcontroller, providing precise control over speed, direction, and commutation. Two separate controllers are used for the two hub motors; one is shown in Figure 6. The use of separate controllers for each hub motor allows for independent control, enhancing the maneuverability and responsiveness of the robotic seed planter. Furthermore, the integration of the Hall motor sensor in the controller ensures accurate motor positioning, contributing to the precision and reliability of the device’s operation.

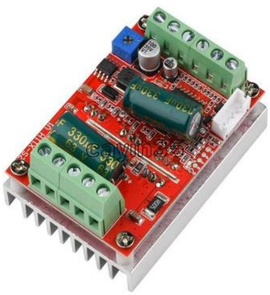

Figure 6. PWM hub motor controller with hall motor sensor

– Geared motor

The windshield wiper motor, shown in Figure 7, functions as a key electrical component. With features like variable speeds, park position, and a control mechanism, it powers the metering and seeding mechanisms as well as the rear wheels. The geared motor's variable speeds allow for adaptability in different planting scenarios, ensuring optimal performance. Additionally, the control mechanism provides precise control over the seeding process, contributing to the overall efficiency and accuracy of the robotic seed planter.

Figure 7. Geared motor

– Limit switches

Essential for automation and control systems, the limit switch, shown in Figure 8, detects the presence or absence of objects and determines the position of moving parts within the planter. Limit-switch sensors are input-output devices that switch operating states in reaction to the crossing of a threshold value of their input [25]. They contribute to safety, precise positioning, and efficient operation in various applications.

Figure 8. Limit switch

– DC power supply

The power supply is a 36-volt battery pack, a combination of three 12-volt DC batteries, used to power the microcontrollers and motors. The DC power supply's compact design allows for efficient use of space within the robotic seed planter, contributing to its portability. Moreover, the use of a battery pack ensures that the planter can operate independently, making it suitable for remote and off-grid locations.

2.1.3. Software design

The web application, constructed with HTML, CSS, JavaScript, and C++, is hosted on a microcontroller using ESPAsyncWebServer, with WebSockets used for inter-microcontroller communication. Instructions entered by the farmer on the interface are transmitted from the server microcontroller to the planter's microcontroller via WebSockets. Calculations for locomotion and planting operations are executed using C++ on the planter's microcontroller, which automatically implements received instructions after calculations. The planter updates the server microcontroller, which, in turn, reflects real-time progress on the web application for the farmer to monitor. Two ESP32 microcontrollers are used; the SERVER for hosting the web application and the BRAIN for executing planting operations.

2.2. Construction

2.2.1. Circuit design and block diagram

The block diagram provides a visual representation of the system's architecture, illustrating the flow of information and control signals between different components. This aids in understanding the overall operation of the robotic seed planter and facilitates troubleshooting and optimization of the system. Figure 9 shows the block diagram of operation of the robotic seed planter. Figure 10 shows the circuit diagram of the robotic seed planter. The circuit design provides a detailed view of the electrical connections and pathways, facilitating a deeper understanding of the planter's electrical system. It also serves as a valuable reference for troubleshooting and modification, ensuring the planter's electrical components function optimally and safely.

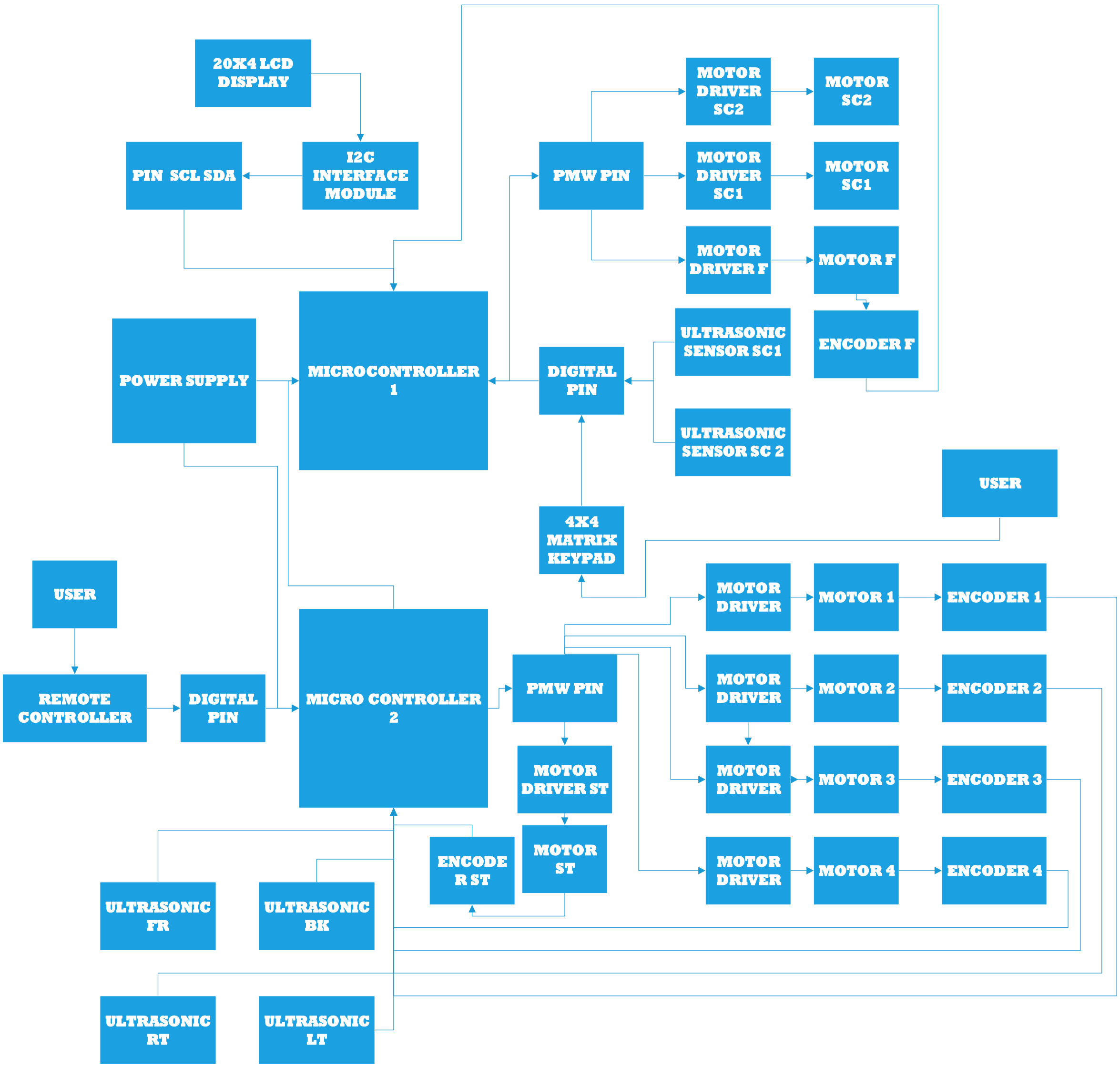

Figure 9. Block diagram

2.2.2. Theoretical calculations

– Locomotion between planting points

The time taken for locomotion between planting points is crucial as it directly impacts the overall efficiency of the planting process. By optimizing this time, the planter can achieve a balance between speed and accuracy, ensuring that each seed is planted correctly while minimizing the total planting time. These calculations are then inputted into the software for operation.

Diameter of Rear Wheels=40 cm=0.4 m

Circumference of Rear wheel=$2\pi\ (d\ \div\ 2) =\ 125.7\ cm = 1.257\ m$ (per revolution)

Diameter of Front Wheels=24.7 cm=0.247 m

Circumference of Front wheel=$2\pi\ (d\ \div\ 2)$=77.82=0.778 m (per revolution)

Seed spacing for maise seed is approx. 13 cm=0.13 m

RPM of rear wheels=90 rpm

Speed, S, in centimetres per second (cps) is (1).

$$S = (rpm \div 60) \times diameter\ of\ rear\ wheels\ (cm) \times \pi \qquad (1)$$
$$S = (90 \div 60) \times 40 \times \pi = 188\ cps$$

$$Distance\ covered = Speed \times Time \qquad (2)$$

The time taken, T, to cover a seed spacing distance of 13 cm is

$$13 = 188 \times T$$

Therefore,

$$T = 13 \div 188 = 0.069\ seconds\ (approx. 7\ milliseconds)$$

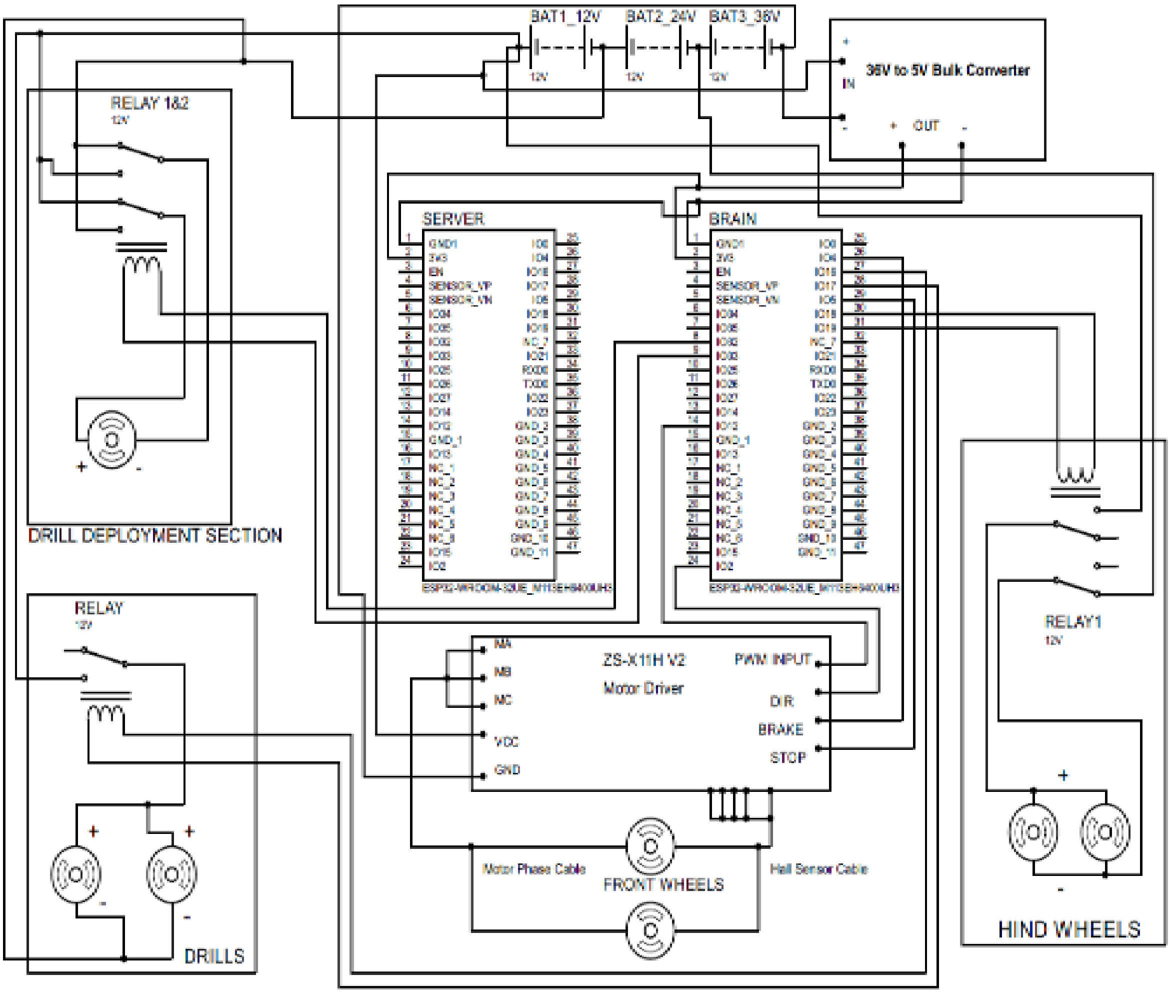

Figure 10. Circuit design

– Drilling

The drilling process is a critical step in the operation of the robotic seed planter, as it prepares the soil for the placement of the seeds. The planter's drilling mechanism is designed to create holes of a consistent depth and diameter, ensuring that each seed is planted at the optimal depth for germination. Furthermore, the drilling process is automated and synchronized with the planter's locomotion, allowing for precise placement of holes at predetermined intervals. Assume a force of 300 N is needed to bore the soil, then a motor of torque 30 kg/in (minimum) is needed. The required depth of the bored holes is 5.1 cm, 1 inch=2.54 cm; and 5.1 cm=2 in.

– Seeding

The seeding process involves the precise placement of seeds into the pre-drilled holes. This is automated to ensure consistency and accuracy in seed distribution. The planter's design allows for adjustments to accommodate different seed sizes and types. The calculations below estimate how many seeds are dispensed per revolution of the seeding disk. Motor torque should also be 30 kg/in.

Diameter of seed feeding disk=16.5 cm
Diameter of seed feeding disk bore hole=12 mm=1.2 cm
Number of boreholes=8
RPM of motor=45 rpm
Diameter of maize seed=10 mm
So, in one revolution of the seed feeding disk, one maize seed is dispensed through the seed disk hole, resulting in the release of eight corn seeds into the seeding pipe.

– Turning at the end of each row

The turning mechanism of the planter is designed to navigate the end of each row efficiently. This ensures a smooth transition to the next row, maintaining the alignment and spacing of the planting points. The planter's turning radius and speed can be adjusted to accommodate different field sizes and shapes. The calculations below show the estimated turning angle.

R=Turning radius the vehicle has to cover
α=Angle of the turn
WB=Wheelbase (distance between the front and rear axles)

To get the turning radius,

$$R = \frac{WB}{tan(\alpha)} \quad (3)$$

To get the angle of turn, α,

$$\alpha = tan^{-1} \left(\frac{WB}{R}\right) \quad (4)$$

For a row spacing of 84 cm,

$$R = 84 \div 2 = 42\ cm$$
$$WB = 49.2\ cm$$

To determine the angle of turn of wheels, α,

$$\alpha = tan - 1 \left(\frac{49.2}{42}\right)$$
$$\alpha = 49.5\,°$$

Therefore, the wheels will have to be at an angle of 49.5 degrees for the planter to accurately turn a distance of 84 cm to begin a new row of planting.

3. RESULTS AND DISCUSSION

3.1. Results

In this study, the performance of the robotic seed planter was assessed across four rows, each containing ten holes. The robotic seed planter demonstrated a high degree of precision, with each seed accurately placed in its designated hole. The planter executed the intended operations, yielding the following results.

3.1.1. Seed spacing, metering and delivery accuracy

The robotic seed planter achieved impressive seed placement accuracy with a mere 1% average deviation from predefined spacing. In the field, the robot attained a seed delivery accuracy of about 94%. However, seed metering exhibited an average accuracy of 66.67%. Detailed metrics can be found in Table 1 for seed spacing and metering.

Table 1. Seed spacing and metering results

Row	Average seed spacing (cm)	Average deviation from the number of seeds specified per hole (3)	Metering accuracy per row (%)
1	13.2	1.3	66.7
2	12.9	1.3	66.7
3	13.1	0.9	70
4	13.2	1.1	63.3

3.1.2 Drilling depth and precision

The drilling mechanism consistently achieved a depth of 5 cm, meeting the desired planting depth. Figure 11 illustrates the uniformity of boreholes along two planting rows. This consistency in drilling depth ensures that seeds are planted at an optimal depth, promoting uniform germination and growth. Moreover, the precision of the boreholes contributes to the efficient use of space, allowing for maximum crop yield within a given area.

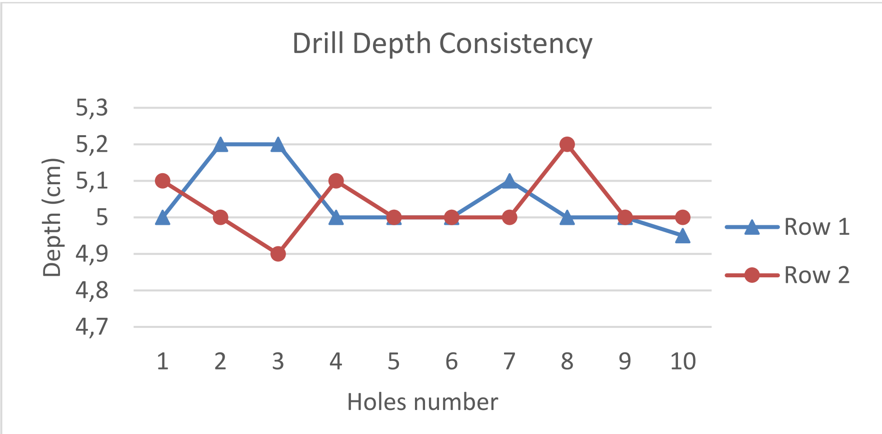

Figure 11. Graph of drill depth consistency

3.1.3. Energy consumption

The planter's energy consumption during operation averaged 0.7 kWh per planting cycle, indicating operational efficiency. However, there is room for further optimization to enhance energy sustainability. The power requirements for different operations are shown in Table 2. This level of energy consumption demonstrates the planter’s potential for use in off-grid and remote locations, where access to power may be limited.

Table 2. Power requirements

Operation	Power Requirement (W)
Movement	480
Drilling: Deploying and Retracting	180
Seeding	60

3.1.4. Web application performance

The web application proved effective, allowing for real-time interaction as well as remote monitoring and control with the robotic seed planter. Figure 12 displays the user interface dashboard during one of the planting tests. The user-friendly design facilitates seamless communication and control, enhancing the planter’s practicality for farmers. The different parameters that can be inputted on the web interface include crop type, soil type, seed spacing and depth, the farm area, and seed per hole. The final product, as shown in Figure 13, represents the culmination of careful design, assembly, and testing, resulting in a fully functional robotic seed planter. Its compact and robust design, combined with its precise and efficient operation, makes it a valuable tool for modern, automated agriculture.

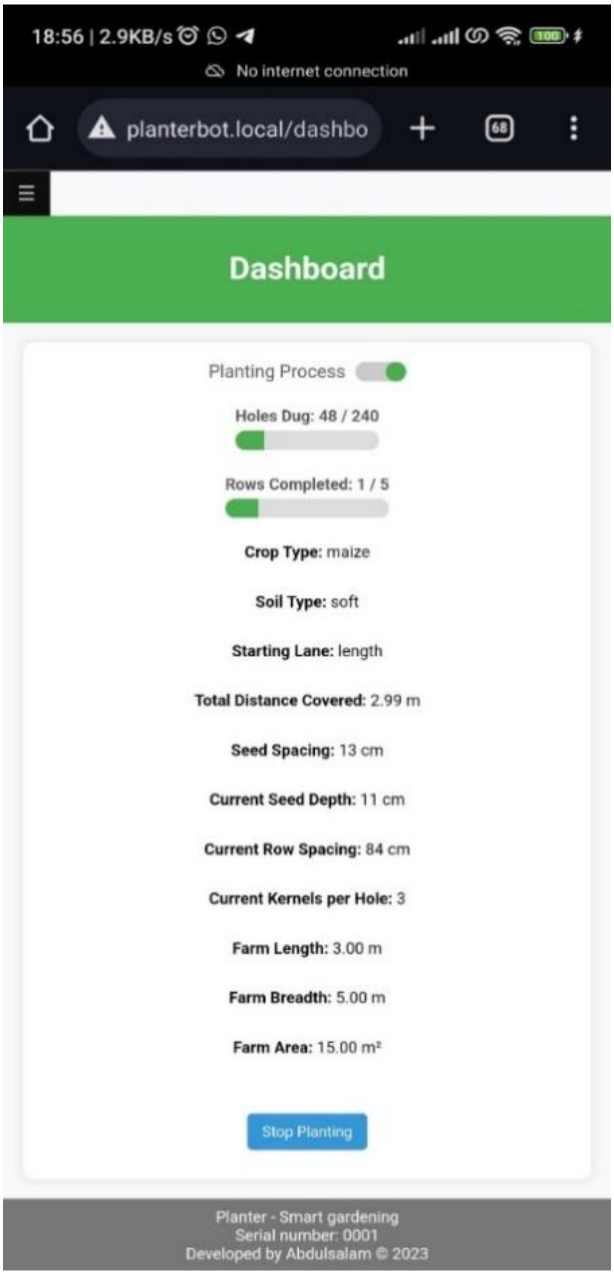

Figure 12. The web interface dashboard for the planter

Figure 13. The final product

4. CONCLUSION

The robotic seed planter has strong performance in seed planting precision, operational efficiency, and energy optimization, making it a promising option for enhancing agricultural yields and resource efficiency. The developed web application serves as a seamless Human-Machine Interface, facilitating effective interaction between the farmer and the planter. Nevertheless, scalability, energy optimization, and crop variety specificity pose challenges that require further exploration. Despite these limitations, the study provides a groundwork for future advancements in agricultural robotics.

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