DEVELOPING AN AUTOMATIC PRECISION SEEDING UNIT (APSU) FOR POT SEED PLANTING
/
تطوير وحدة زراعة آلية دقيقة لزراعة البذور في الأصص

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ABSTRACT

This research aims to develop an automatic precision seeding unit (APSU) for planting seeds in pots inside greenhouses. The study evaluated three seed suction nozzle diameters (0.5, 1.0, and 2.0 mm) and four types of seeds (Armenian cucumber, pepper, turnip, and okra). The key performance indicators involved the number of seeds captured per stroke, total time for seeding one pot, and deviation relative to the pots' centers. The results showed that a nozzle diameter of 1.0 mm was the most effective for okra and Armenian cucumber seeds, resulting in average yields of 1.0 and 1.46 seed(s) per pot, respectively. The 0.5 mm nozzle showed optimal performance for pepper and turnip seeds, achieving 1.33 and 1.46 seeds per pot, respectively. The average time for seeding one pot, including all three stages, is approximately 35 seconds. These findings endorse the improvement of productivity and accuracy in automated greenhouse seeding, furthering precision agriculture as a state-of-the-art technological strategy.

الملخص

تهدف هذه الدراسة إلى تطوير وحدة زراعة بذور آلية دقيقة قادرة على زراعة البذور في الأصص داخل البيوت المحمية. تم إجراء التجارب على ثلاثة أقطار مختلفة لفوهات الشفط وهي 0.5، 1.0، و2.0 مم وأربعة أنواع مختلفة من البذور وهي: القثاء، الفلفل، اللفت، والبامية. وتم تقييم أداء وحدة الزراعة من حيث عدد البذور الملتقطة في المشوار الواحد، اجمالي الوقت المستغرق لزراعة أصيص واحد، والانحراف بالنسبة لمنتصف الاصيص. أظهرت النتائج أن قطر فوهة الشفط 1.0 مم كانت الأكثر فعالية لبذور البامية والقثاء، حيث كان متوسط عدد البذوز الملتقطه 1 و1.46 بذرة لكل أصيص على التوالي. بينما أظهرت فوهة الشفط ذات القطر 0.5 مم أداءً مثاليًا لبذور الفلفل واللفت، حيث كان متوسط عدد البذور الملتقطه 1.33 و1.46 بذرة لكل أصيص على التوالي. وكان متوسط الزمن اللازم لزراعة أصيص واحد، بما في ذلك المراحل الثلاث، هو حوالي 35 ثانية. ومن ثم، تدعم هذه النتائج تحسين الإنتاجية والدقة في الزراعة الآلية داخل البيوت المحمية، مما يعزز الزراعة الدقيقة كاستراتيجية تكنولوجية متقدمة.

INTRODUCTION

The agriculture sector currently suffers from a labor shortage; thus, utilizing agricultural automation technologies presents an effective solution to mitigate reduced labor supply (*Abo-Habaga et al., 2022*; *Amin et al., 2024a*; *Amin et al., 2024b*). The primary goal of creating an agricultural automation robot is to minimize labor needs and improve food quality. This agricultural robot tackles significant obstacles farmers face, such as monitoring crop quality in real-time and performing tasks like plowing, seeding, spraying, harvesting, and fruit picking (*Bu et al., 2020*). The quality of sowing in mechanized processes is heavily reliant on the efficiency of sowing equipment, potentially impacting crop yield (*Maleki et al., 2006*; *Urbaniak et al., 2008*). For instance, the Agro-Bot is an autonomous robot with a combined seeding and watering system and a solar panel, making it a self-sufficient option for farming in remote areas. The Farmer Bot system offers information via internet connectivity, enhancing adaptability and remote accessibility; the Agro-Bot presents a workable substitute for conventional farming methods (*Khandelwal et al., 2017*). Various automation and technologies, ranging from basic integrated circuits to advanced microcontrollers, micro-computers, sensors, and Internet of Things (IoT) applications (*Abdelmotaleb et al., 2015*; *Loukatos et al., 2021*), have been utilized in agriculture through smart farming technologies (SFT) to facilitate data acquisition, analysis, evaluation, and precision application (*Balafoutis et al., 2017*a), resulting in notable economic, environmental, and labor benefits (*Balafoutis et al., 2017b*; *Balafoutis et al., 2020*). However, these applications are primarily found in large-scale farming, with limited efforts toward small-scale, automated urban agriculture.

Data acquisition tasks are supported by the advancement of computer vision techniques and the availability of various sensory data sources (*Ardiansah et al., 2021*; *Brisco et al., 2014*; *Reyns et al., 2002*), while data analysis and evaluation are prevalent in agricultural research (*Nash et al., 2009*; *Iosif et al., 2023*). These strategies apply to seed planting, seed mapping, re-seeding, weed mapping, pesticide spraying, and irrigation. The operation of air-suction seed metering devices encompasses seed loading, conveyance, and discharge to guarantee precise seed distribution and optimal planting efficiency. For seeds with high sphericity, such as pea, soybean, rapeseed, and Panax notoginseng, the preferred method of planting involves air-suction seed-metering devices, known for their consistent and effective performance (*Tang et al., 2023*). The suction force is a pivotal element in these devices, combining multiple forces, particularly the drag force, which is vital for determining seed attachment to the suction hole (*Li et al., 2021*).

This study aims to develop an automatic precision seeding unit (APSU) for pot-location detection within a greenhouse to prevent pot omission and ensure accurate planting depth, using distance sensors to optimize depth while enabling three-directional movement with a seed suction nozzle for precise, single-seed placement per pot.

MATERIALS AND METHODS

The automatic precision seeding unit (APSU) manufacturing process and trial experiments were conducted in 2024 at the Department of Agricultural Engineering, Faculty of Agriculture, Mansoura University, Egypt. The APSU comprises hardware systems and software systems.

Hardware systems

The automatic precision seeding unit (APS) comprises the following components: (1) an information collection unit, including the camera, auxiliary equipment, and sensor group; (2) control unit, comprising the central control unit; (3) moving unit for movement in the X-Y directions; and (4) seeding unit, comprising the air source control device, a set of seed suction nozzles of different diameters, and an angularly adjustable seed box (Fig. 1).

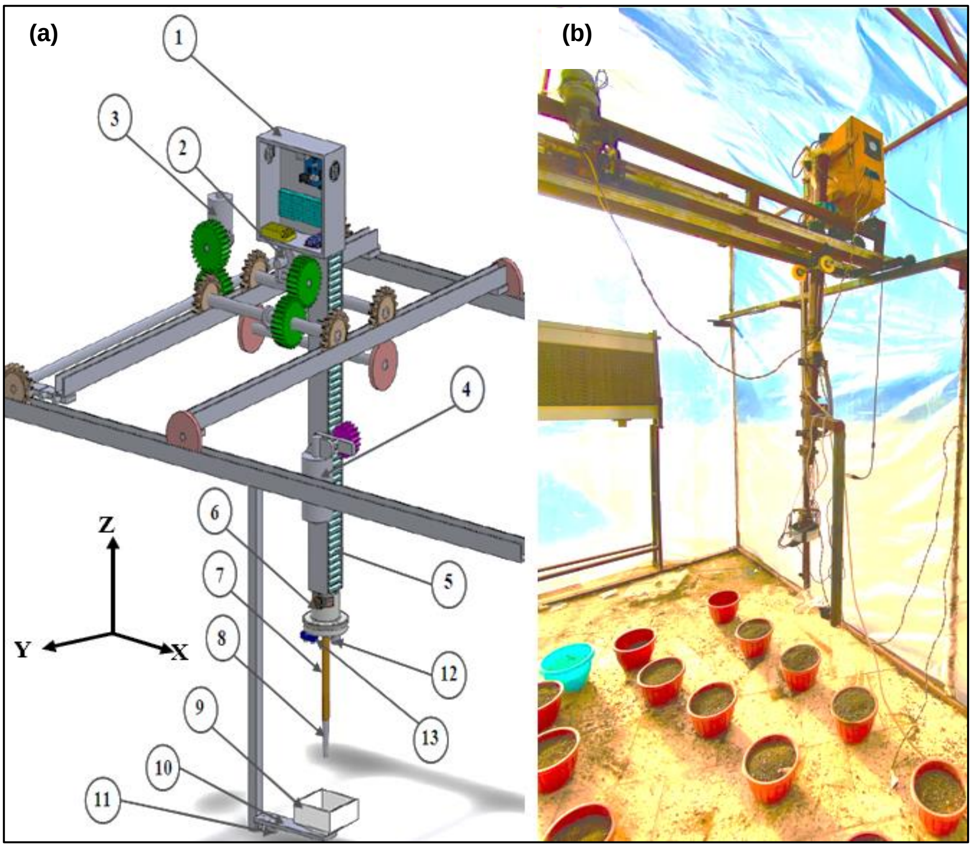


Fig. 1 – Layout and components of the automatic precision seeding unit (APSU): (a) 3D diagram, and (b) operation of the APSU inside the greenhouse

1 – Control box; 2 – Y-axis motor; 3 – X-axis motor; 4 – Z-axis motor with pinion gear; 5 – Rack; 6 – Seed suction motor; 7 – Seed suction pipe; 8 – Seed suction nozzle; 9 – Seed box; 10 – Seed box holder; 11 – Servo motor; 12 – Camera; 13 – Ultrasonic sensor

Information collection unit

The Logitech C270 Pro Stream camera was used in this study. It features a 720p HD resolution at 1280 × 720 pixels, with a maximum frame rate of 30 frames per second (fps) and a fixed-focus lens providing a 60-degree field of view. The camera supports high-definition (HD) 720p and captures images up to three megapixels. It was mounted vertically below the air suction motor, covering the image acquisition area of the planting pot, and was connected to the control unit to initiate operation. A distance sensor was used to adjust the gap between the planting nozzle and the seeds in the seed box, ensuring accurate planting depth and preventing interference between moving parts during the motion signaling process.

For accurate soil penetration depth, three HC-SR04 ultrasonic sensors were used to determine the planting arm position in the X, Y, and Z directions. Powered by a +5V DC supply, these sensors have a current below 2 mA, an operating current of 15 mA, an effective angle of less than 15°, and a measurement range of 2 to 400 cm with a resolution of 0.3 cm. They feature a measurement angle of 30°, a pulse trigger width of 10 µS, dimensions of 45 × 20 × 15 mm, and an approximate weight of 10 g. Built for robustness, they operate within a temperature range of -20°C to +70°C, making them suitable for various environmental conditions.

Control unit

The control unit consists of a PC, an Arduino Uno (AVR), a Raspberry Pi 4 Model B powered via a USB Type-C power supply delivering 5V at 3A, a 24V-10A power supply for appropriate voltage, a 2-channel and 1-channel relay module, and peripheral circuits. The primary function of this unit is to collect sensor signals to send to the PC, receive data processed by the PC, and transmit it to the Arduino. The Arduino distributes these signals across 14 channels to enable individual relay control.

Moving unit in the X-Y directions

A moving unit operates in the X-Y directions, with X-axis motion driven by a DC motor featuring a 55 mm diameter spur gear, 29 teeth, and a drive shaft with three spur gears. A 60 mm middle gear connects to the motor gear, flanked by two side gears with a 60 mm diameter and a 33 mm pitch. The Y-axis motion is also driven by a DC motor with specifications similar to the X-axis motor but with an 8 mm gear pitch and a length of 180 cm (Fig. 2).

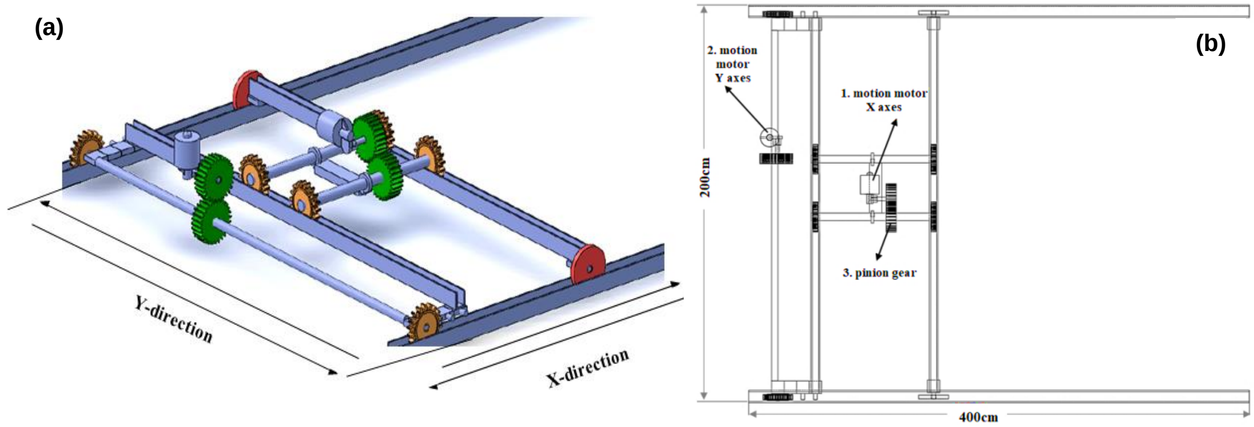


Fig. 2 – 3D view of the X- and Y-axis motion (a) and layout of the X- and Y-axis motion directions (b)

Seeding unit

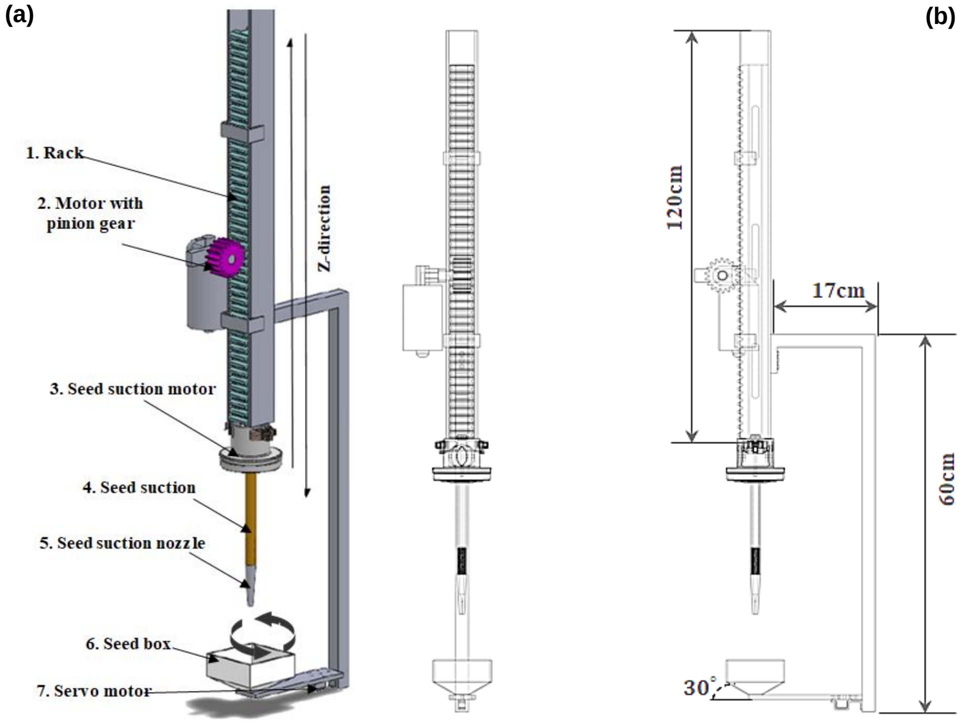
The seeding unit includes Z-axis motion that is driven by a DC motor with a 23 mm diameter pinion gear, 14 teeth, and an 11 mm pitch aligned with a rack of 120 cm length and 2 cm width. The planting arm (PA) comprises three main components: the seed suction motor, suction pipe, and seed suction nozzle (Fig. 3).

The seed suction nozzle assembly consists of three cone-shaped air-suction nozzles with hole diameters of 0.5, 1.0, and 2.0 mm. The first nozzle, with a 0.5 mm hole diameter, is made of Teflon, while the other two are from steel. All nozzles have a standardized total length of 25 mm, including a 15 mm external thread length with a 10 mm diameter.

The suction pressure values were obtained through measurements conducted with three different nozzle sizes (2.0 mm, 1.0 mm, and 0.5 mm), resulting in recorded pressures of -0.20 bar, -0.16 bar, and -0.12 bar, respectively.

The suction pipe is fabricated from steel and has a length of 23 cm with an outer diameter of 2.25 cm. The lower part of the pipe features an internal thread for attaching diverse cone-shaped air-suction nozzles (Fig. 4).

The seed box, designed for sowing seeds in pots, is constructed from acrylic with dimensions of 133.92 × 125.92 × 80 mm (length × width × height), a thickness of 2.5 mm, and a slope angle of 30º. A carbon fiber seed box holder, measuring 20 cm in length and 4 mm in thickness, provides sturdy support. The MG946R metal gear servo motor was predominantly chosen for its high-angle precision. In contrast, the seed box was continuously rotated at a 90-degree angle by a standard electric motor when power was supplied, while the servo motor was halted after its instructed rotation was completed and awaited the following command.



Elevation Side view

Fig. 3 – 3D view of the Z-axis motion of the PA motion (a) and elevation and side views of the PA (b)

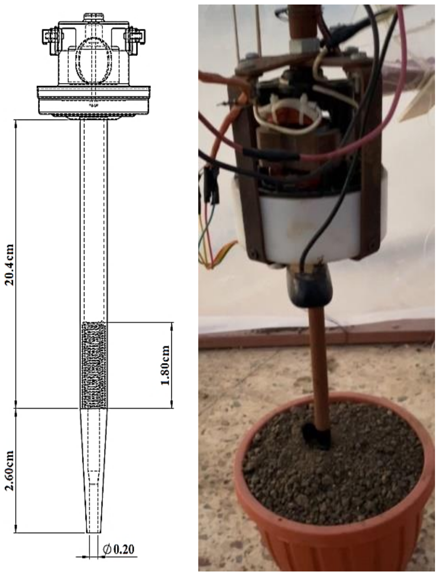


Fig. 4 – Suction-seeding pipe of PA

Software systems

This section outlines the methodologies for image acquisition, image processing, identification and positioning of plant pots, data management, and control of the precision seeding mechanism, encompassing tasks related to image analysis, data processing, and mechanical adjustments. An Arduino microcontroller was utilized for signal distribution and program execution. Figure 5 presents the software system flowchart after initialization.

Image acquisition

The Python script conducts real-time circle identification via a webcam feed, utilizing the OpenCV library for image processing and circle detection. The circle coordinates are transmitted to an Arduino using a serial link. Figure 6 presents a depiction of an image obtained using the industrial camera. If circles are identified, they are outlined in green with red centers on the frame. The center coordinates of each circle are converted to strings and transmitted to the Arduino via the serial connection.

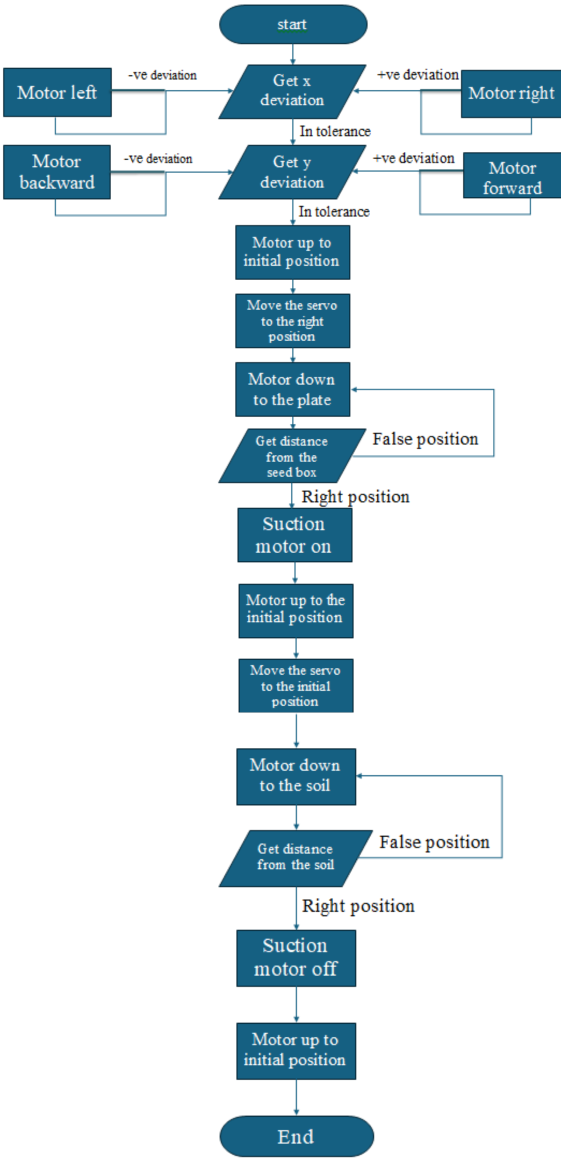
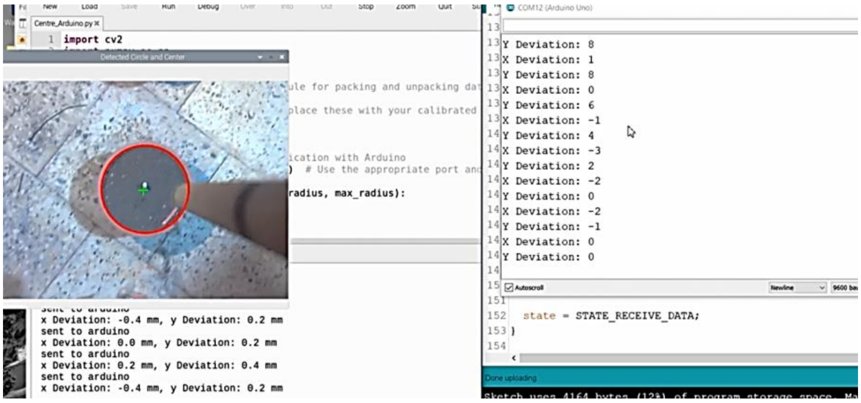


Fig. 5 – Flowchart of software system



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import cv2
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place these with your calibrated
ication with Arduino
)  # Use the appropriate port and
radius, max_radius):
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x Deviation: -0.4 mm, y Deviation: 0.2 mm
sent to arduino
x Deviation: 0.0 mm, y Deviation: 0.2 mm
sent to arduino
x Deviation: 0.2 mm, y Deviation: 0.4 mm
sent to arduino
x Deviation: -0.4 mm, y Deviation: 0.2 mm
```

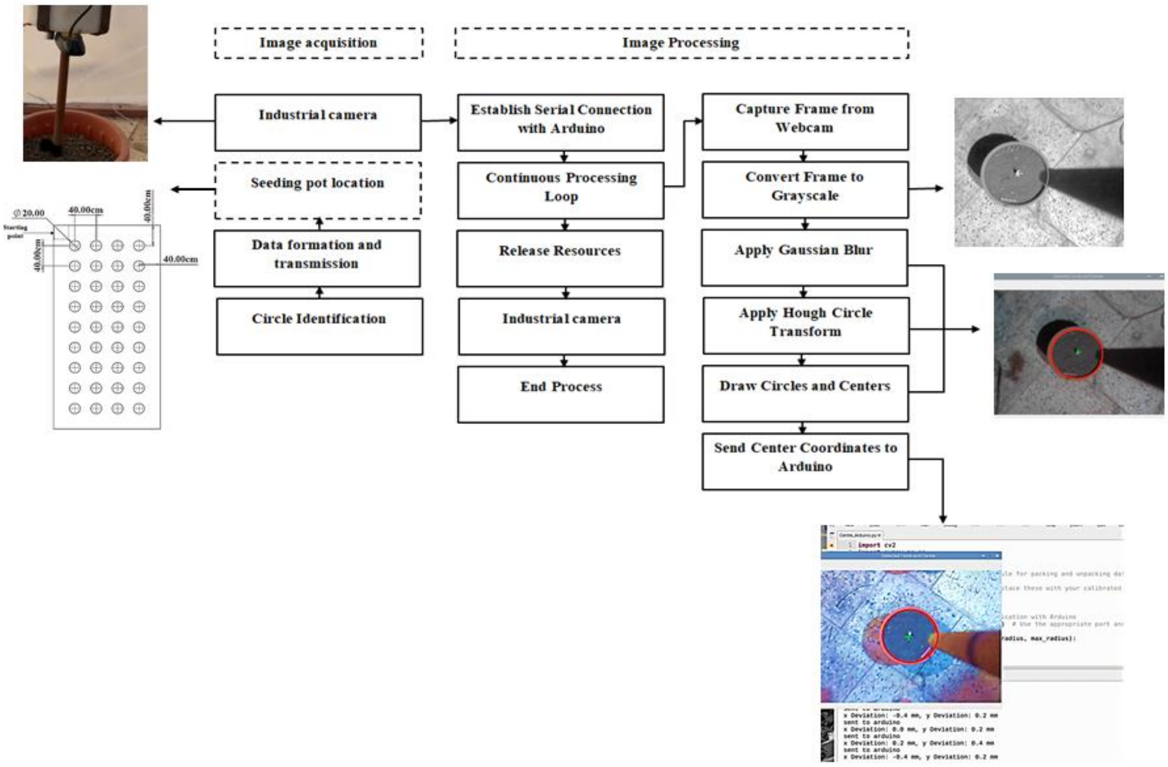
```
Y Deviation: 8
X Deviation: 1
Y Deviation: 8
X Deviation: 0
Y Deviation: 6
X Deviation: -1
Y Deviation: 4
X Deviation: -3
Y Deviation: 2
X Deviation: -2
Y Deviation: 0
X Deviation: -2
Y Deviation: -1
X Deviation: 0
Y Deviation: 0
```

```
  state = STATE_RECEIVE_DATA;
}
```

Fig. 6 – Drawing circles and sending coordinates

Image processing

The captured frame was converted from BGR color format to grayscale to simplify processing. A Gaussian blur was then applied to the grayscale image to reduce noise and enhance circle detection accuracy. Finally, the Hough Transform was used to identify circles in the blurred grayscale image (Fig. 7).



```
x Deviation: -0.4 mm, y Deviation: 0.2 mm
sent to arduino
x Deviation: 0.0 mm, y Deviation: 0.2 mm
sent to arduino
x Deviation: 0.2 mm, y Deviation: 0.4 mm
sent to arduino
x Deviation: -0.4 mm, y Deviation: 0.2 mm
```

Fig. 7 – Image processing

Controlling the seed planting automation

The Arduino system governs various motors and a servo motor by following instructions through serial communication (mySerial). It controls motor movements, planting actions, and sensor data by utilizing different states and functions to automate the planting procedure—controls motors based on deviations (x_deviation and y_deviation). Modify motor orientations and statuses according to discrepancies received from Raspberry Pi.

Controlling a suction motor

The Arduino sketch manages a suction motor connected to pin 8 of the Arduino board. The motor activates for half a second, followed by a two-second off period, continuously cycling through this pattern in the loop() function. Modifying the timing in the delay() functions will alter the motor's duration on and off. Upon reaching the intersection of the circle's radii (showing the planting point), the APSU starts the planting process. Initially, the seed box moves using a servo motor until it reaches a 90-degree angle, positioning it directly beneath the planting column. The suction motor responsible for seed collection is then activated. According to measurements from the ultrasonic sensor, the APSU moves downward in the Z direction until it reaches the seed box, which is positioned 31 cm below the maximum height. It picks up the seed and then moves upward in the Z direction to the maximum height until the seed box returns to its original position (Fig. 8).

Ultrasonic distance measurement

This Arduino sketch utilizes an ultrasonic sensor connected to pins A0 (trigger) and A1 (echo) to measure distances. It continuously reads distances, filters out invalid measurements, and displays the valid distance readings on the Serial Monitor (Fig. 9). The distance range and timing can be adjusted based on specific sensor characteristics and application requirements. Based on these readings, the arm plants seeds at the required depth.

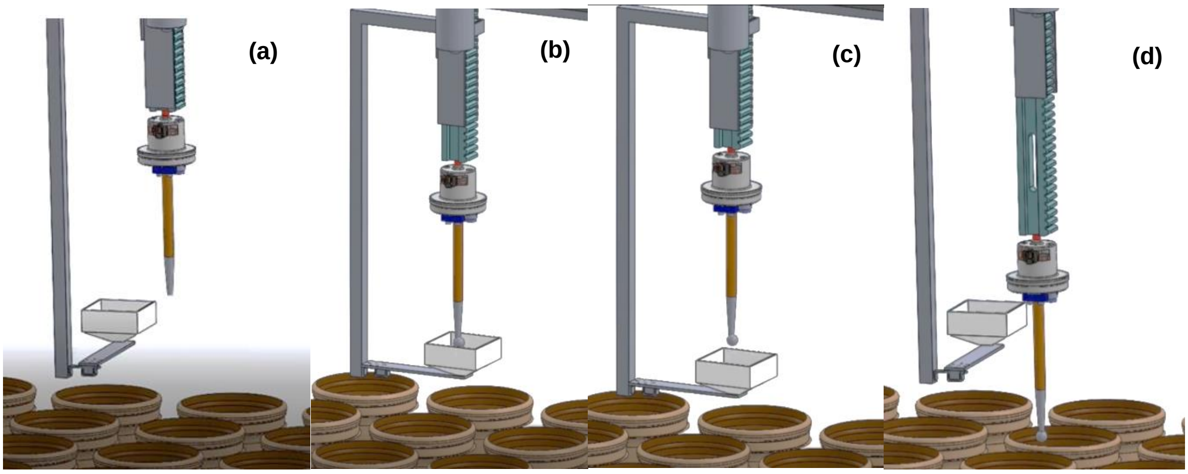
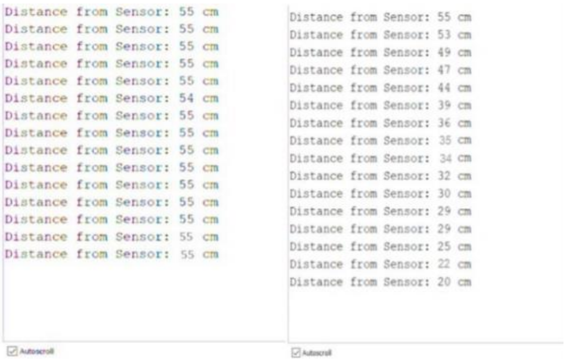


Fig. 8 – The process of picking up the seed from the rotating seed box, beginning at the starting position (a), followed by a downward vertical movement (b), then an upward vertical movement after suctioning the seed (c), and finally a downward vertical movement to place the seed in the pot after a 90° rotation by the servo motor (d)



```
Distance from Sensor: 55 cm
Distance from Sensor: 55 cm
Distance from Sensor: 55 cm
Distance from Sensor: 55 cm
Distance from Sensor: 55 cm
Distance from Sensor: 54 cm
Distance from Sensor: 55 cm
Distance from Sensor: 55 cm
Distance from Sensor: 55 cm
Distance from Sensor: 55 cm
Distance from Sensor: 55 cm
Distance from Sensor: 55 cm
Distance from Sensor: 55 cm
Distance from Sensor: 55 cm
Distance from Sensor: 55 cm
```

```
Distance from Sensor: 55 cm
Distance from Sensor: 53 cm
Distance from Sensor: 49 cm
Distance from Sensor: 47 cm
Distance from Sensor: 44 cm
Distance from Sensor: 39 cm
Distance from Sensor: 36 cm
Distance from Sensor: 35 cm
Distance from Sensor: 34 cm
Distance from Sensor: 32 cm
Distance from Sensor: 30 cm
Distance from Sensor: 29 cm
Distance from Sensor: 29 cm
Distance from Sensor: 25 cm
Distance from Sensor: 22 cm
Distance from Sensor: 20 cm
```

Fig. 9 – Ultrasonic readings and its height above the soil surface

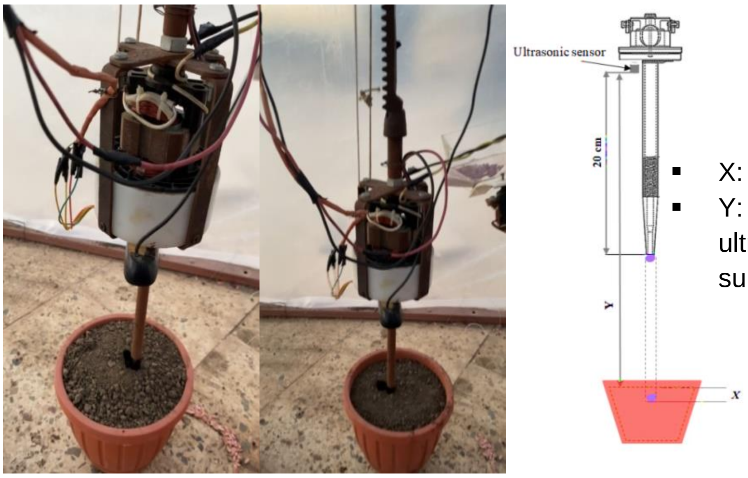
Planting depth

The program was used for planting seeds in soil, relying on an ultrasonic distance sensor to measure depth. Variables like Servo_ANG and Servo_ANG_RE were assigned to set the servo motor's motion angles for seed placement. During the Put_Seeds() process, continuous checks were made on the distance (Dis_Z) to ensure accurate seed placement. The program can be adjusted to regulate planting depth by modifying conditions in functions like GetSeeds() and PutSeedsInSoil() to meet specific agricultural tasks.

The ultrasonic sensor is 20 cm from the suction pipe's end and varies in distance from the soil's surface (Fig. 10). Next, the planting depth is computed using Eq. (1).

$$Y = 20 - X \tag{1}$$

where Y represents the distance between the ultrasonic sensor and the soil surface [cm], *20* represents the suction pipe [constant height], and X denotes the planting depth [cm].



- X: Planting depth
- Y: Distance between the ultrasonic sensor and the soil surface

Fig. 10 – Determining planting depth

Time to complete the planting process

Each pot has a diameter and height of 20 cm. Thirty-six pots are arranged in an 8 m² area, with 9 pots placed longitudinally and 4 pots placed transversely, each spaced 20 cm apart. The distance between the pot edges and the greenhouse structure is 30 cm in all directions. The required planting time for this greenhouse was determined according to Eq. (2):

$$= (N \times (T_P + T_R)) + T_T + Turnaround\ time \tag{2}$$

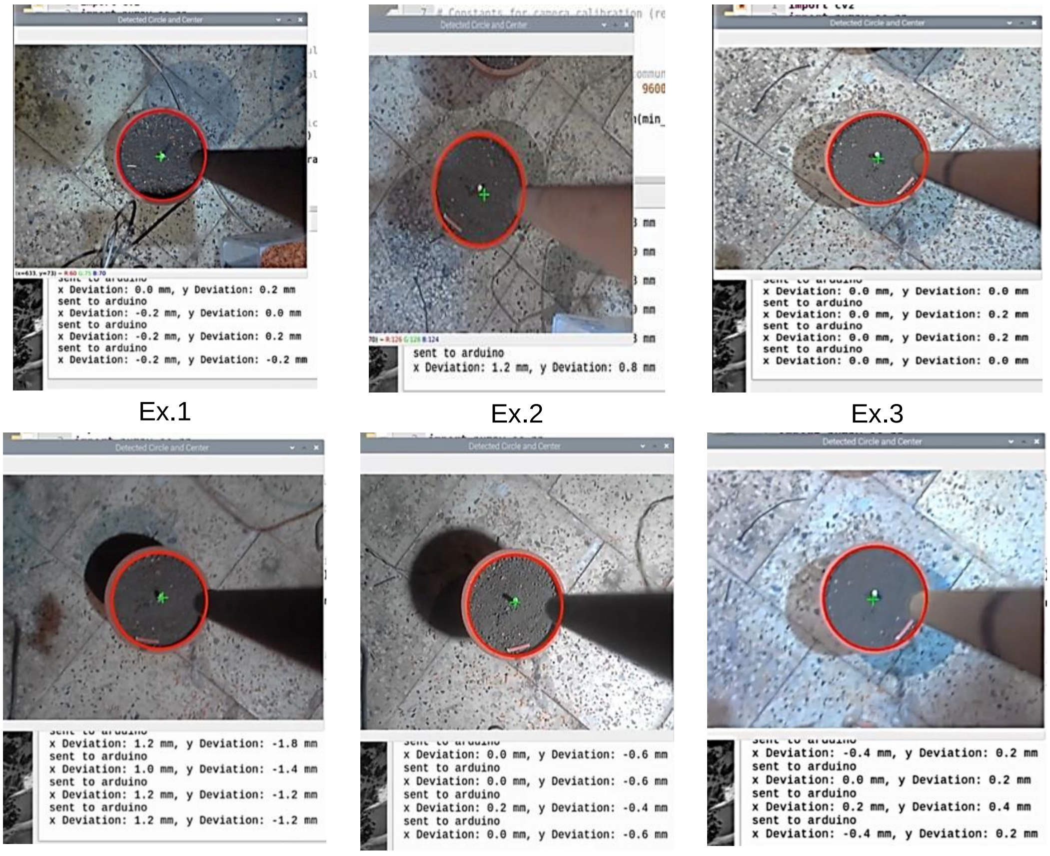
$$= (36 \times 30) + (8 \times 4 \times 5) + (3 \times 5) = \frac{1255}{3600} = 0.35\ h$$

where *N* denotes the number of pots, T_p denotes the planting time [sec], T_R represents the resting time [sec], and T_T implies the transit time [sec].

RESULTS AND DISCUSSION

Camera deviation relative to the pots' centers

The code begins by including the SoftwareSerial library, which facilitates virtual serial communication on the Arduino. It then defines variables for storing deviations in the X and Y axes and processing incoming data. Figure 11 represents the precision and variability of the positioning system. Minimal deviations, ranging from -1.2 mm to 1.2 mm, were observed, demonstrating effective alignment control. Experiments 3 and 5 showed no deviation on the X-axis. Experiment 3 achieved accurate alignment in both X and Y directions, while Experiment 5 demonstrated a minor deviation in the Y direction (-0.6 mm). In the X direction, negative deviations of -0.2 mm and -0.4 mm were noted in Experiments 1 and 6, respectively, along with slight shifts in the Y direction. Experiment 2 showed the most substantial positive deviations in the X (1.2 mm) and Y (0.8 mm) axes, showing a significant shift from the central position. Experiment 4 showed a positive deviation of 1.2 mm in the X direction and a notable negative deviation of -1.2 mm in the Y direction, suggesting angular displacement. Despite the overall precision, adjustments may be needed to enhance accuracy because of the deviations observed in Experiments 2 and 4. These deviations might be because of mechanical discrepancies, limitations in the control system, or systematic inaccuracies. Enhanced calibration and more precise control algorithms have the potential to minimize these deviations and improve alignment with the pot centers.



Ex.1

```
x Deviation: 0.0 mm, y Deviation: 0.2 mm
sent to arduino
x Deviation: -0.2 mm, y Deviation: 0.0 mm
sent to arduino
x Deviation: -0.2 mm, y Deviation: 0.2 mm
sent to arduino
x Deviation: -0.2 mm, y Deviation: -0.2 mm
```

Ex.2

```
sent to arduino
x Deviation: 1.2 mm, y Deviation: 0.8 mm
```

Ex.3

```
x Deviation: 0.0 mm, y Deviation: 0.0 mm
sent to arduino
x Deviation: 0.0 mm, y Deviation: 0.2 mm
sent to arduino
x Deviation: 0.0 mm, y Deviation: 0.2 mm
sent to arduino
x Deviation: 0.0 mm, y Deviation: 0.0 mm
```

Ex.4

```
x Deviation: 1.2 mm, y Deviation: -1.8 mm
sent to arduino
x Deviation: 1.0 mm, y Deviation: -1.4 mm
sent to arduino
x Deviation: 1.2 mm, y Deviation: -1.2 mm
sent to arduino
x Deviation: 1.2 mm, y Deviation: -1.2 mm
```

Ex.5

```
x Deviation: 0.0 mm, y Deviation: -0.6 mm
sent to arduino
x Deviation: 0.0 mm, y Deviation: -0.6 mm
sent to arduino
x Deviation: 0.2 mm, y Deviation: -0.4 mm
sent to arduino
x Deviation: 0.0 mm, y Deviation: -0.6 mm
```

Ex.6

```
x Deviation: -0.4 mm, y Deviation: 0.2 mm
sent to arduino
x Deviation: 0.0 mm, y Deviation: 0.2 mm
sent to arduino
x Deviation: 0.2 mm, y Deviation: 0.4 mm
sent to arduino
x Deviation: -0.4 mm, y Deviation: 0.2 mm
```

Fig. 11 – Deviations in the X and Y directions relative to the pots' centers

The number of seeds captured by air suction for different seed types and seed suction hole diameters

Figures 12-15 present the number of seeds collected through air suction, categorized by suction hole diameters (0.5 mm, 1 mm, and 2 mm) and seed varieties (okra, turnip, pepper, and Armenian cucumber) across fifteen experiments. Okra seeds show consistent behavior, achieving a nearly 100% success rate across diameters, indicating they can be efficiently used with various hole sizes. Some deviations were noted in specific experiments, possibly because of alignment issues. Turnip seeds displayed greater variability; smaller diameters (0.5 mm and 1 mm) had high success rates, while the 2 mm diameter resulted in multiple seeds being captured, reducing efficiency. Pepper seeds captured mostly 1 seed at 0.5 mm, with slightly higher averages at 1 mm (2.13 seeds) and a significant increase at 2 mm (average of 12.6 seeds), indicating challenges in capturing a single seed effectively. Armenian cucumber seeds also increased in capture with larger diameters, from 1 seed at 0.5 mm to an average of 3.93 seeds at 2 mm.

Recommendations based on these findings suggest using a 0.5 mm suction hole for turnip and pepper seeds and a 1 mm hole for okra and Armenian cucumber seeds to enhance planting efficiency and reduce waste.

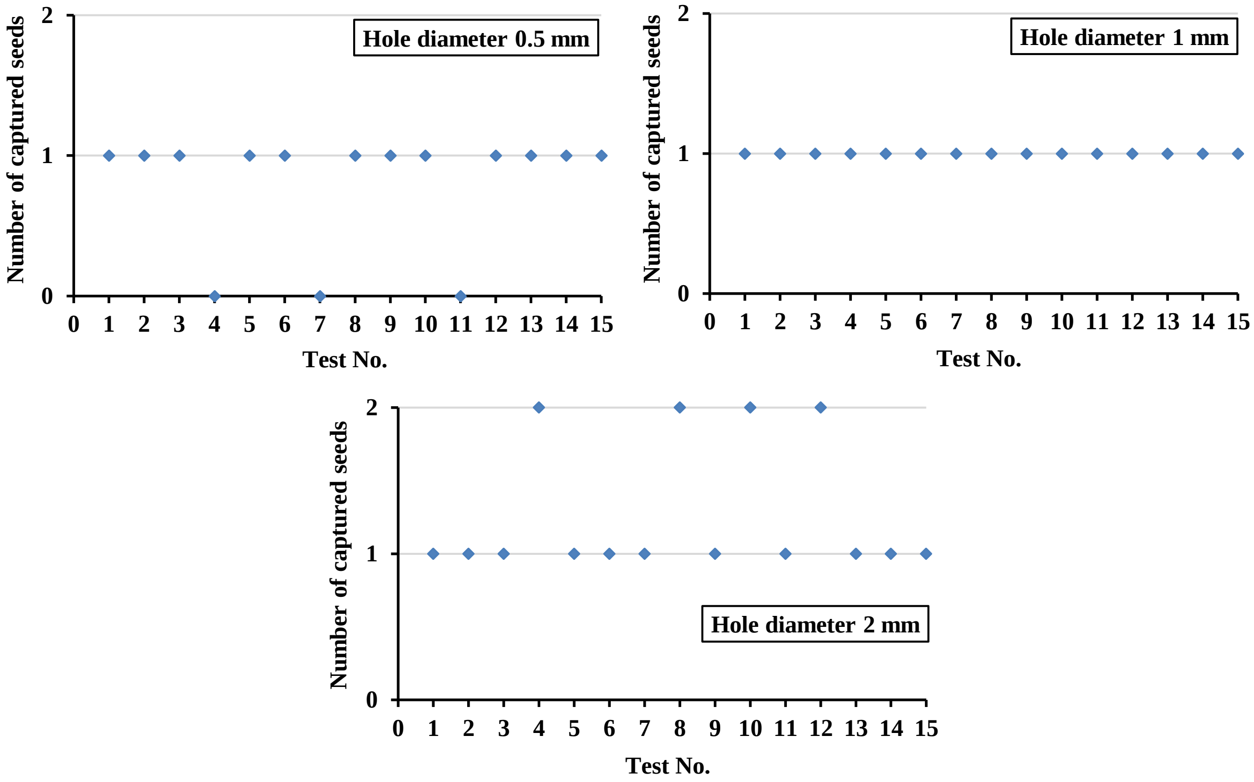


Fig. 12 – Number of captured okra seeds with suction hole diameters of 0.5, 1, and 2 mm

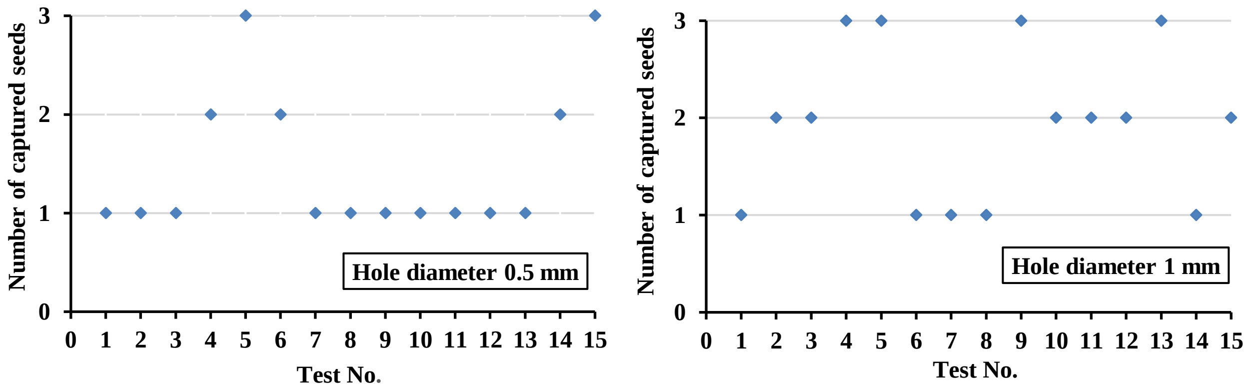


Fig. 13 – Number of captured turnip seeds with suction hole diameters of 0.5 and 1 mm

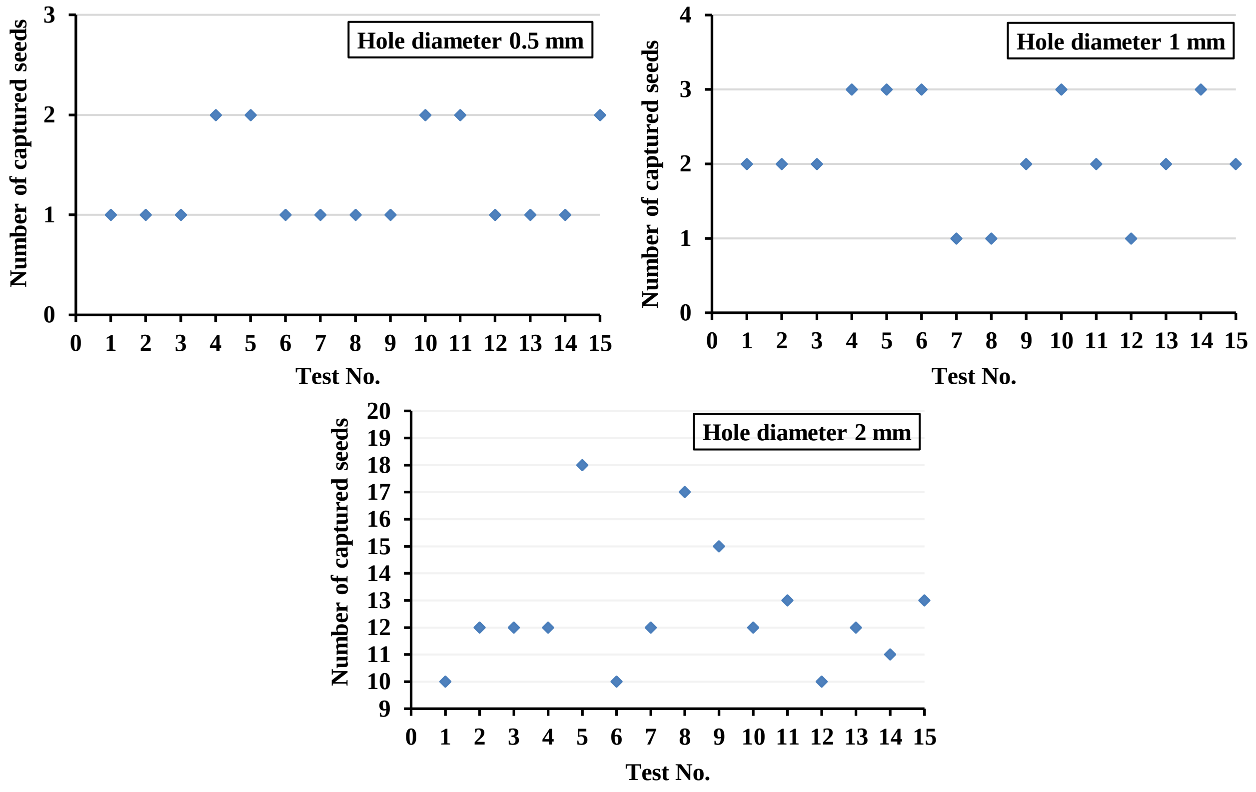


Fig. 14 – Number of captured pepper seeds with suction hole diameters of 0.5, 1, and 2 mm

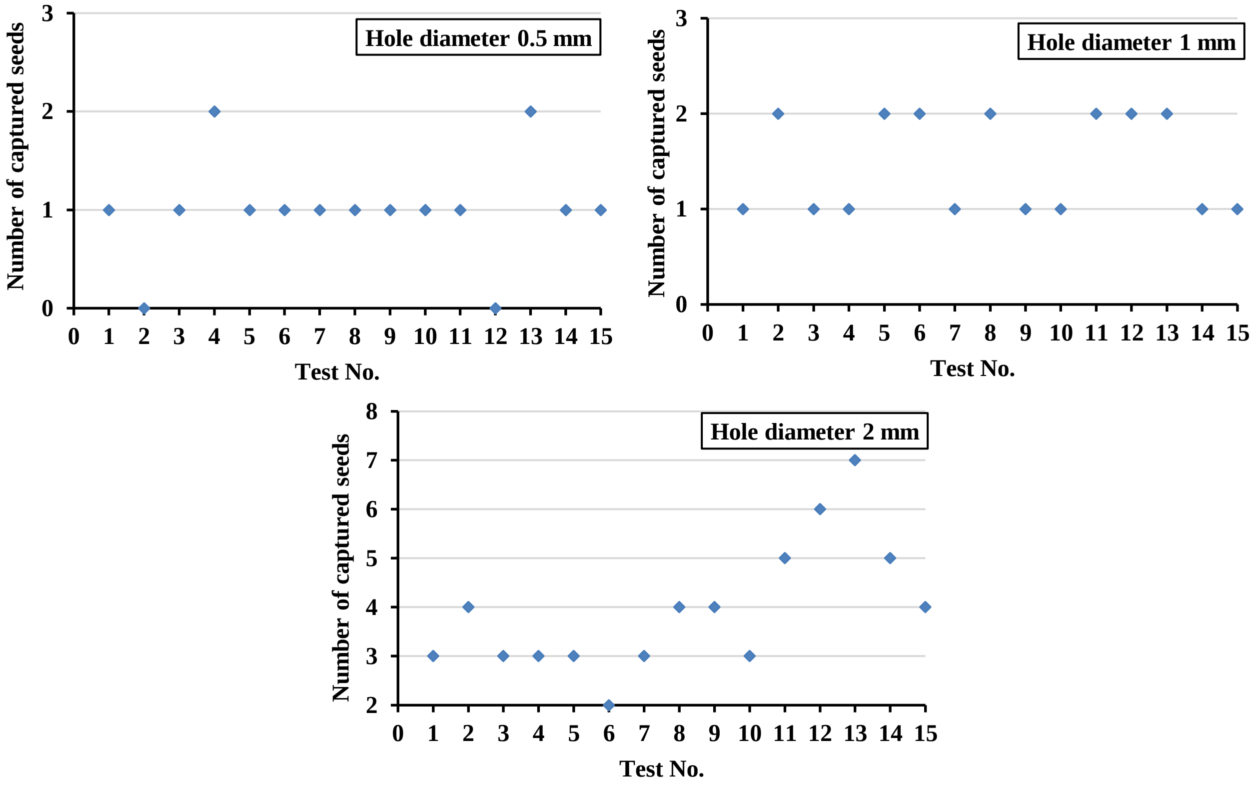


Fig. 15 – Number of captured Armenian cucumber seeds with suction hole diameters of 0.5, 1, and 2 mm

Planting depth and soil elevation

This program is intended for seed planting and employs an ultrasonic distance sensor to measure depth precisely. The planting arm adapts its elevation using reliable sensor readings to reach the predetermined planting depth of 3.0 cm. The depth was assessed at three distinct soil elevations, varying between 15 and 20 cm (Table 1). The results from nine trials exploring planting depths at varying soil elevations to maintain a target depth of 3.0 cm are presented in Table 1.

The data demonstrate how changes in soil elevation influence planting depth, which plays a crucial role in ensuring uniform seed placement and promoting optimal germination. Trials were conducted at three soil elevations: 20 cm, 18 cm, and 15 cm, showing that variations in soil elevation affect planting depth. At a soil elevation of 20 cm, the planting depth ranged from 2.5 cm to 3.2 cm, with an average of 2.9 cm. At 18 cm, planting depths varied between 2.7 cm and 3.3 cm, while at 15 cm, they ranged from 2.7 cm to 3.0 cm. The average planting depth across all trials was 2.9 cm, slightly below the target depth of 3.0 cm. The planting depth had a coefficient of variation (CV) of 8.28% and a standard deviation of approximately ±0.24037 cm. Despite variations in soil elevation, the planting technique consistently maintained a depth close to 3 cm. The results indicate satisfactory performance, although minor adjustments and calibrations could further enhance accuracy and consistency.

Table 1

Different soil elevations with planting depth stability of 3.0 cm

Experiments	Soil elevation	Planting depth
Ex.1	20 cm	3.2 cm
Ex.2	20 cm	3.0 cm
Ex.3	20 cm	2.5 cm
Ex.4	18 cm	2.7 cm
Ex.5	18 cm	2.8 cm
Ex.6	18 cm	3.3 cm
Ex.7	15 cm	3.0 cm
Ex.8	15 cm	2.7 cm
Ex.9	15 cm	2.9 cm
Average ($\bar{X}$)		**2.9 cm**
Standard deviation (±SD)		**± 0.24037 cm**
Coefficient of variation (CV)		**8.28%**

Total time for planting

Table 2 details the overall time needed for the planting procedure, comprising three separate time spans: planting time (T_P), resting time (T_R), and transit time (T_T). Planting time (T_P) is the overall period required for the mechanical planting process, which involves the planting arm's horizontal descent and subsequent vertical motions to achieve the desired planting depth and ensure precise seed placement in the soil. The duration of this phase is estimated to be approximately 20 seconds. Resting time (T_R) refers to the period following the suction motor's deactivation and the seed's subsequent release, enabling it to embed itself in the soil at a 3 cm depth. This period is critical to ensure the correct seed penetration before advancing to the subsequent seed, and it typically endures for approximately 10 seconds. This timing was determined through conducted experiments. Transit time (T_T) refers to the period needed for transferring between pots, commencing with the initiation of the planting arm's upward movement and ending when the subsequent downward movement commences. This phase lasts approximately 5 seconds. In conclusion, the overall time (T_{To}) required for a complete planting cycle, encompassing all three elements, totals 35 seconds.

Table 2

Total time to complete the planting process

Required time	
Planting time (T_P)	**20 s**
Resting time (T_R)	**10 s**
Transit time (T_T)	**5 s**
Total time (T_{To})	**35 s**

CONCLUSIONS

An automatic precision seeding unit was developed for planting pepper, turnip, Armenian cucumber, and okra seeds. The research introduced an approach to identifying planting pot positions and calculating pot radius to assist with planting at the prescribed depth. Investigating the precision seeding device's control system and mechanical structure yielded multiple discoveries. A practical approach for identifying circles and determining positions was introduced through image processing methods such as circle detection, morphological processing, and image reconstruction, showcasing exceptional precision.

Three seed suction nozzles were meticulously crafted to function through air suction, each with dimensions of 0.5 mm, 1 mm, and 2 mm, and set at precise pressure levels of -0.2 bar, -0.16 bar, and -0.12 bar, respectively, effectively fulfilling seed suction needs. A precision seeding unit automated planting procedures, including identifying pot locations, controlling the movement of the seeding unit, managing the seed box movement, and overseeing the seed uptake and release through the suction nozzle. The planting arm achieved a depth accuracy within a coefficient of variation of ±8.28%, positioning at an average depth of 2.9 cm beneath the soil surface in contrast to the 3 cm target depth, despite fluctuations in soil height. The results illustrate the system's ability to offer a reliable solution for automated planting with consistent precision.

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