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Ladybug: An Automated Cultivation Robot for Addressing the Manpower Shortage in the Agricultural Industry

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ABSTRACT

The agricultural sector is projected to need more labor as a result of declining interest in careers within this domain. Despite the escalating demand for agricultural goods, previous endeavors to mitigate this challenge through the deployment of robotic prototypes have encountered hindrances such as issues pertaining to automation, adaptability to varying tasks, and the financial burdens associated with development. To address this exigency, we have developed an automated cultivation robot utilizing advancements in the Internet of Things (IoT), Image Processing, and Artificial Intelligence (AI) for seeding in pots. The robot demonstrates the capacity to sow seeds in 257 pots per hour, accomplish a mission within 12.53 minutes, traverse at a velocity of 360 meters per hour, and seed pots at a rate of 13.37 seconds per pot. It possesses an operational duration of approximately two hours, completing nine cycles and seeding 486 pots on a single charge. Notably, the robot exhibits a mission success rate of 1.00 and a seeding accuracy 0.78. Moreover, it features an adaptable workspace and a lightweight frame weighing 20 kg, rendering it a cost-effective solution for mass production.

Article information:

Keywords: Agricultural Robot, Scalable Robot, Scalable Cultivation, Greenhouse Robot, Autonomous Cultivation, Internet of Things, Image Processing

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1. INTRODUCTION

In the 20th century, developed countries saw a remarkable 80% [1] reduction in their farming workforce due to technological advancements. Automation has played a vital role in enhancing agricultural machinery's efficiency, reliability, and precision, thereby reducing the need for human intervention [2]. However, horticulture still requires skilled workers to enhance the overall output further.

The absence of workers in the agricultural sector is causing various problems, worsened by the trends of increasing farm sizes, decreasing numbers of farmers, and the growing environmental impact of food production. To address these issues, there is a need for even more efficient agricultural practices [3], and intelligent machines can help increase productivity in conventional farming [4], where farmers manually conduct crop cultivation and management. Although implementing robotics and automation requires a more costly specialized workforce and equipment, it can significantly improve agricultural productivity. Skilled machine operators are required to handle the robots and generally need more compensation for the higher initial cost. As the number of farms decreases, the average age of the agricultural workforce also increases, making it essential to make this profession more attractive to the younger generation [5, 6]. Despite the challenges of using robotics and automation in farming operations, reducing tasks performed under harsh conditions and improving the quality of life for farmers can make the profession more appealing.

Automating agricultural applications and production is more challenging than industrial applications. In stable and replicable environments, industrial applications deal with simple, repetitive, and well-defined tasks. On the other hand, agricultural production involves managing complex and highly variable environments [7, 8], making it necessary to use advanced technologies. Additionally, agricultural

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production involves live produce susceptible to environmental and physical conditions such as temperature, humidity, gas, pressure, abrasion, and acceleration [9]. That means gentle, accurate, and often complicated handling operations must maintain satisfactory quality during transportation from the production site to consumers.

As a result, replacing human resources with machines or automation in fruit, vegetable, and flower growing and similar production tasks, such as trellising, harvesting, sorting, and packaging, is challenging. These tasks are still performed manually, making manual staffing a significant cost component in field operations, accounting for up to 40% of the total cost [10].

Technological advancements have revolutionized traditional farming methods in recent years, increasing efficiency, productivity, and sustainability in modern agriculture. As the world's population grows, optimal land use becomes more urgent, making exploring innovative solutions that can enhance cultivation processes is essential. Developing and implementing an automated cultivation robot designed for precise seed sowing has become crucial to achieving this goal. Traditional seed-sowing methods often rely on manual labor, which can be time-consuming and prone to errors, resulting in inconsistent plant growth and reduced yields. However, we can overcome these limitations with automation and robotics and achieve unparalleled accuracy and productivity. Hence, the main objectives of this study are two-fold: (I) To create a self-operating cultivation robot that can efficiently plant seeds in pots, utilizing advanced technologies like Image Processing, Artificial Intelligence, the Internet of Things, and precision mechanics to tackle the labor scarcity in the agricultural sector. (II) To construct a versatile cultivation robot that can adapt to varying workspaces, possess a lightweight structure, be economically feasible to produce with minimal costs, and scale up or down as required.

2. RELATED WORKS

Over the past decade, there has been an increase in autonomous robotic innovations and technologies in agriculture [11]. However, while large-scale farming automation is available, few technologies and products still allow for personal to medium-scale farming automation.

Neha *et al.* [12] developed and tested a seed-seeding robot called Agribot. The robot is controlled by an Arm 7 microcontroller and an Open Loop Control System. It has 4 DC motors for driving, 2 DC motors for controlling the V-shaped arm movement, and a set of IR sensors for navigation. The robot is equipped with a water pump and seed-sowing machine. The prototype was used to automate the seeding of four crops: cotton, corn, soybeans, and wheat. The study focused on three essential factors: the length of sowing, sowing depth, and the distance between rows of plants. The tests were carried out on wet ground, with the robot's movement distance ranging from 4 cm to 8 cm and 2 cm to 3 cm, respectively, according to theoretical values. Agribot allowed for determining row and column spacing for the four plants in the system. Due to the short distance between crops, the robot can efficiently cover the distance between them. It can also measure parameters on the planted area. The robot's operation is more accurate, easy to use, and less complicated in mechanical and technical design. Thanks to its simple navigation system, the robot is also more miniature in size and lower in cost compared to general tractors. Although this prototype may have some flaws, it can be addressed by designing a mechatronic system and adding a new control system.

Batista *et al.* [13] created a robot called RIRRIG, which uses Cartesian coordinates to assist agricultural production. The robot has been installed at the Agricultural Science Center of Universidade Federal do Ceará in Fortaleza, Brazil. Agricultural machinery can be costly, making it difficult for farmers to purchase and use it. The RIRRIG robot was designed to improve production quality while keeping development costs low. RIRRIG makes it easier for farmers to find materials and equipment locally. The robot has a 50 × 20 mm metal structure that is 1.20 mm thick. Its movement in the x, y, and z axes is controlled by a DC motor connected to a shaft, a worm gear, and a plastic gear set. Sensors and electronic devices manage the movement, and the data is stored on a Secure Digital Card (SD Card) with an Arduino Mega 2560 installed with Python firmware. When the robot reaches designated points, it releases water to water the plants. The RIRRIG robot was designed to be simple and cost-effective so that farmers could use it without difficulty. It has been found that robots can help reduce farmers' stress, eliminate labor shortages, and reduce the work that causes health problems for farmers. The construction cost of the robot is low, at US$ 538.

Belforte *et al.* [14] developed an automatic robot for spraying chemicals inside greenhouses for agricultural purposes. They collaborated with Italian researchers to create this robot using simple and readily available materials to keep the costs low. The robot has a mechanical and kinematic design with 3 Degrees of Freedom (DOF) for easy installation. The system can use different end-effectors or tools to increase its DOF. It consists of 3 joints powered by a 12-volt DC motor with Pulse Width Modulation (PWD). The control units use PXI-8170 and PXI-7344 boards. The control code was developed using LabView 6 with IMAQ and Flexmotion Libraries. A JAI S3200 was installed on the second connector to provide a Simple Vision System for accurate operation under specified conditions. This system has to inspect and count objects. The work area is rectangular, and the robot arm moves perpendicular to the movement of the pallet on which the potted plants are placed. The robot will not move. In the study, the experiment was divided into two tasks. The first task was to spray pesticides under the leaves, which is the pests' habitat. The spray nozzle must be positioned accurately and sprayed with fine mist to be effective. The second task was to put fertilizer into the pot, with the amount of fertilizer pellets being determined in advance to suit the specific plant needs. Research conducted at the Centro Regionale di Sperimentazione e Assistenza Agricola (CeRSAA) in Albenga, Italy, found that the prototype robot had a chemical spraying speed of 7 plants per minute and a fertilizer application rate of 8 pots per minute on average. The prototype robot can achieve speeds of around 400 - 500 plants per hour, which still needs to be improved for commercial production.

FarmBot is an open-source farming platform developed by Aronson [15]. It is designed for small-scale automatic farming and operates in a Computer Numerical Controlled (CNC) manner. It can move in the x, y, and z axes to perform tasks such as planting, watering, weeding, and area inspection. It uses linear motion and motor encoders to control navigation and localization while traveling on tracks and in the gantry. The system is equipped with a Raspberry Pi running FarmBot OS, which processes, makes decisions, and controls the operation of the sensor set and motors. The prototype has a working area of 1.5×3 meters, defined as a maximum cultivation area of 4.5 square meters, supporting the height of plants not exceeding 1 meter. The main structure is assembled from an aluminum profile and plastic and installed on a planting plot framed with rectangular wooden panels on a level surface. It has three tools installed on end-effectors to perform different tasks: seed injector, watering nozzle, and cutter/shredder. A web application runs on cloud service to control and customize work settings through a web browser to select seeds, planting positions, and control operations. Although, it has some limitations regarding time and energy loss during work. FarmBot is caused by having to move the end-effector to the tools head bay to change working tools every time a switch in work duties is required, which results in unnecessary movement. It must be moved back to the starting reference point instead of being able to continue working. In addition, there are scalability limits when the size of the farm changes. It includes defining the points of Motion Guides on the farm to control the work. Therefore, a smooth and level space is required during installation to structure the Motion Guides so they work correctly, precisely, and efficiently.

Athukorala *et al.* [16] have developed an automatic robot, SAASbot, to assist in tomato farming operations. The robot is designed to adapt to different farm sizes and perform various tasks such as planting, watering, fertilizing, and weeding. Its design is presented in the "Cost Effective" issue with an end-effector that can be rotated, reducing unnecessary robot movements and switching work duties. The SAASbot is mounted on a mobile platform that uses four Mecanum wheels and a 3-axis CNC Mechanism. It is 92 centimeters wide, 106 centimeters long, 108 centimeters high, and weighs 24.8 kilograms. The CNC structure is meant to be used in farming operations under the workspace, which is 55 centimeters x 65 centimeters. From testing, it has been found that the SAASbot can run for an average maximum time of 1 hour at full use on a 2,200 mAh battery with a planting speed of 90 plants per hour. However, SAASbot still has limitations that do not allow it to work effectively on regular ground or in other environments. It is required to work on rubber tracks assembled into a grid covering the cell to define the robot's workspace. The errors found during testing were an x-axis error of 3.1 millimeters, a y-axis error of 4.5 millimeters, and a positioning error of 0.26 degrees.

Li *et al.* [17] have developed a Seedbed, an open-source robot that boasts a variety of functions for managing seedbed planting on a large scale in agricultural production facilities. This intelligent and networked robot has a modular design and can perform seeding, irrigation, weeding, and light supplementation through neural networks. It is highly cost-effective and versatile, operating independently with a 3 DOF gantry mechanical structure powered by a synchronous belt stepping motor. The design integrates advanced Image Processing technology, including camera calibration and the MobileNetV2-SSD target detection algorithm, which results in a 94% accuracy in weed recognition. Additionally, the robot employs IoT functionality based on ESP8266 and Arduino technology, which allows it to upload environment parameters in real time via MQTT protocol for analysis. The high-precision neural network model based on the MobileNetV2-SSD model, along with training using 200 weed crop images, enables efficient recognition of weeds. With its rich functionalities, high performance, and suitability for promotion, this design is ideal for use as a production unit in large-scale facilities, boosting space utilization and efficiency in agricultural production.

Nahal [18] utilizes a closed-loop control system derived from CNC machines that navigates planting stages using CAD land files and marked planting points, improving efficiency and relieving engineers of repetitive tasks. Its primary goal is to enhance the quality of life and address basic human needs, particularly in areas affected by forest fires or human activities. Notably, Nahal incorporates servo motors for enhanced movement precision and a controller with a G-code map reading mechanism, allowing for simplified control software design and sensor feedback integration. A feedback mechanism ensures accurate planting and watering, overcoming limitations observed in previous seedling planting robots related to control complexity, energy supply, and seedling capacity. Additionally, Nahal is energy-efficient, utilizing a combination of batteries and a diesel generator for prolonged operation. It can plant and water approximately 150 trees per hour using easily replaceable seedling trays, making it a versatile and efficient tool for large-scale seedling planting initiatives.

3. ROBOTIC DESIGN AND DEVELOPMENT

In order to facilitate the widespread integration of robotic technologies within agricultural practices, these solutions must be both economically viable and readily accessible. It necessitates a focus on developing lightweight designs that can be easily maneuvered by human operators while concurrently adhering to cost-effectiveness criteria that are attainable for farmers belonging to middle-class or lower-income brackets. The Ladybug project encompasses two distinct platforms: the Manipulator Robot platform, which is responsible for the control of the end-effector utilized for planting operations, and the Mobile Robot platform, which is tasked with navigating and traversing the plantation area. The design concepts underlying these platforms are elucidated in Fig.1 and 2, respectively.

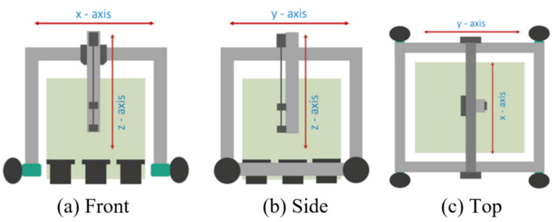


Fig.1: *Design Concept of Ladybug.*

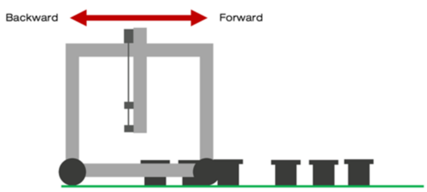


Fig.2: *The Ladybug's Movement.*

In designing the Ladybug frame, our main priority was to ensure that scalable mobile robots could maintain contact between all wheels and the ground while also being able to move freely in any given situation. It was crucial to achieving optimal flexibility in a greenhouse environment. We built structures with four Mecanum wheels attached to the robot frame to accomplish this. These wheels are free to move and can all be controlled individually in speed and direction. We also incorporated four planetary-geared motors with encoders for motion to enable the robot to move around quickly in greenhouse fields. This design allows for high precision and efficiency. The wheel module can be seen in Fig.3. The main structure of the robot frame is made of aluminum profile 6063-T5 material, which is strong enough to ensure stability while transporting heavy loads that could affect position control accuracy. The material is lightweight and easily cut and assembled into different shapes. It can support up to 120 kilograms per meter vertically and 30 kilograms horizontally. The total weight of the robot frame is about 20 kg, which is low enough to prevent any harm to the soil's structure.

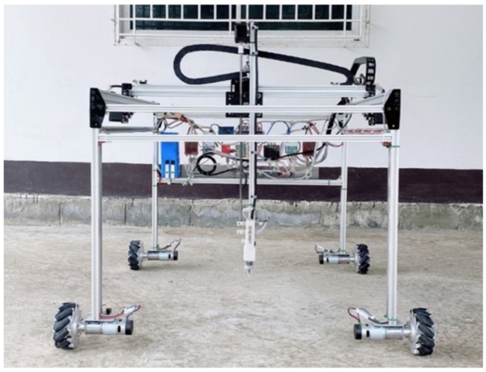


Fig.3: *The Ladybug Prototype.*

Ladybug Robot development is based on Robot Frameworks [19, 20] and consists of three parts: Motion Systems, Perception Systems, and Action Systems.

3.1 Motion Systems

In this phase, we analyze the Ladybug's movement and review previous studies on a mobile robot platform. The platform encompasses both holonomic and non-holonomic locomotion [21]. Our analysis and findings guide the design and development of the movement system of the autonomous and scalable cultivation robot. We pay particular attention to the following details:

1) To create a movement system for a holonomic locomotion robot using a DC motor, the motor's speed is controlled by supplying electricity at intervals. The voltage polarity determines the rotation direction, and the system uses the H-Bridge drive principle and Mecanum wheel [22-24] to control the motor. The Mecanum wheel has a roller mounted at a 45-degree angle, which supports surrounding rotation and requires four independent electrical signals to operate [25]. The four-wheel operation is used as a system controller. Refer to Fig.4 for the Mecanum wheels setup.

The robot can perform three types of operations with its Mecanum wheels. Type 1 is when all four wheels rotate in the same direction, allowing the robot to move forward and backward like regular wheels. Type 2 is a diagonal operation where two sets of opposite wheels rotate in the same direction, causing the robot to move sideways. Type 3 is self-rotation, where the Mecanum wheels rotate in a specific pattern, enabling the robot to rotate smoothly and evenly.

2) To test the movement of the Mecanum wheels, we can send an electrical signal to the Motor Driver Board. This board controls all four gear motors using Pulse Width Modulation (PWM) according to the conditions outlined.

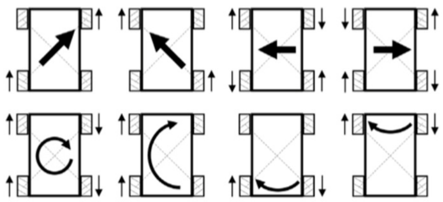


Fig.4: *Standard Operation Pattern as Reference for Control of Mecanum-wheeled Robot (MWR) [25].*

3.2 Perception Systems

Ladybug is equipped with a Perception System that relies on data from a camera and sensors on its frame to determine its movement and task performance. These images and information received from the devices control the robot's actions [26]. To achieve this, Raspberry Pi and Raspberry Pi Camera Module work together in Image Processing and execute commands via serial communication to control the actuator. The robot's recognition system uses Image Processing and Artificial Intelligence to detect circular pots within a plantation. The Hough Circle Transform (HCT) technique [27-29] shown in Fig.5 is utilized to detect circles captured by the camera in grayscale images. The system then extracts features from the image and votes to determine the shape of objects. The pixel value is converted to millimeters to obtain the actual size of the objects.

Fig.5: *Detection of Pots and Determination of Centroids Using HCT.*

To effectively employ the circle detection function, it is imperative to specify the argument value in HoughCircles() to customize its behavior. The Hough Circles function takes three mandatory and five optional arguments. The first argument specifies the image in which the circles are to be detected. This image must be converted to grayscale before processing. The second argument determines the method of detecting circles, which can be either HOUGH_STANDARD for classic detection or HOUGH_PROBABILISTIC for probabilistic detection when the image has a long linear segment, HOUGH_MULTI_SCALE to include multilevel variables in the classic Hough Transform, or HOUGH_GRADIENT and GRADIENT_ALT for other available methods. The third argument represents the ratio of accumulator resolution and image resolution, where a ratio of 1 indicates that the cumulative and image resolutions are the same. A ratio of 2 means that the cumulative resolution of the image, in width and height, is halved for the HOUGH_GRADIENT_ALT method. A recommended ratio is 1.5. The fourth argument specifies the minimum distance between the centers of two circles. The fifth argument is a parameter specific to the first method (HOUGH_GRADIENT and HOUGH_GRADIENT_ALT), used as the threshold for edge detection using the Canny technique. The sixth argument is a parameter specific to the second method (HOUGH_GRADIENT), which calculates the circle's center for HOUGH_GRADIENT_ALT. The sixth argument represents the perfectness value for the circle. The seventh argument is the minimum value of the circle radius, while the eighth argument is the maximum radius of the detected circle. By carefully selecting the arguments and their respective values, the HoughCircles() function can accurately detect circles in an image.

Ladybug utilizes the Raspberry Pi Camera Module to accurately locate the pot's position in both the x and y axes. It employs an ultrasonic sensor to determine the z-axis distance between the pot and the seed injector, thus creating a reference point at the center for seed planting. The MCU-Cam [30-31] is programmed to control its movements and decision-making using barcode tags, as depicted in Fig.6. With a frame rate of 60 per second. It can swiftly detect and scan robot symbols in just 1/60 s or 16.7 ms. The MCU-Cam can recognize small barcodes but only detect values between 0 and 15 [32], representing the barcode's identification code. As demonstrated in Fig.7, the Ladybug's decision-making system determines how it reacts to each barcode. Lastly, it can reach a maximum speed of 40 miles per hour while also being capable of detecting lines and intersections.

Barcodes serve as directional indicators for Ladybug, guiding it toward each cell accurately. These barcodes are affixed to the floor at the cell's perime-

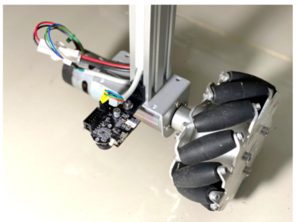


Fig.6: *The MCU-Cam has been Implemented to Track the Ladybug's Motion.*

ter, allowing the MCU-Cam, positioned above the Mecanum wheel, to detect them. These indicators are programmed to convey specific commands to the robot, including forward, backward, rightward, leftward, and end of task. The robot's motion is synchronized with Image Processing to detect the presence of containers, ensuring its movement remains precise and dependable, surpassing the detection capabilities of a single MCU-Cam camera.

Fig.7: *The MCU-Cam Uses a Barcode on the Ground to Control the Ladybug Robot's Movements.*

3.3 Action Systems

Ladybug is designed to move along three axes, x, y, and z, and is controlled to make the machine plant crops. The gantry robot is the model used, like an overhead crane. It can move linearly (Prismatic) on the perpendicular axis, making it ideal for limited spaces. The robot's aluminum profile end-effector moves to designated x, y, and z-axis positions on the planting field's pot. It is lightweight and can be installed on various structures based on the work's needs. The sliding actuator is driven by a stepper motor, an electric motor that rotates 360 degrees continuously by a pulse signal. The machine moves in small steps, either 1, 1.5, 1.8, or 2 degrees, depending on the motor structure, to ensure precise positioning. Three sets of stepper motors control movement on each axis except for the z-axis, where the lead screw is necessary due to the planting head's operation. Precision and resistance are essential for the z-axis movement to withstand the impact of the seed injector against the soil inside the pot, which can damage the equipment and cause misalignment.

A seed injector has been designed to plant seeds in pots, and its design prototype is shown in Fig.8. The injector acts as a seeding planting head that stores seeds in a tube, thereby reducing the planting time

Fig.8: *The Ladybug's Seed Injector.*

by eliminating the need to return to the seed tray to collect seeds for each pot. Instead, the planting head moves to the center of the pot and pierces the soil using the tube before releasing the seeds from the seed collection tube. This results in a 50% reduction in work time.

3.4 Communication System

Ladybug has an Internet of Things system to monitor the greenhouse environment while a robot works autonomously. The technique comprises three sensor units: (I) MCU-3001 (OPT3001) ambient light sensor, which measures light intensity in Lux within a range of 0.01 to 83,000. (II) BME-680 low-power gas, pressure, temperature, and humidity sensors, which measure temperature (in Celsius), humidity (as a percentage of air humidity), air pressure (in hPa), and air quality (in mΩ). (III) The Quectel UC20-G device is capable of HSPA+ /WCDMA and supports traditional 3G GSM/GPRS/EDGE communication. It also includes a Global Positioning System (GNSS Receiver Module) for determining location using the built-in GPS satellite system.

The data collected from the three modules depicted in Fig.9 is transmitted in real-time through the mobile network's High-Speed Packet Access Plus (HSPA+), leveraging the Internet of Things MQTT protocol. This data is then published on the MQTT Broker on cloud computing. The information controls the robot's operation and can be accessed on different platforms, including computers, tablets, and smartphones.

There are two functional tests available: In the first pattern, data from MCU-3001 BME-680 and UC20-G sensors, installed on the robot, published using the MQTT protocol over the HSPA+ (3G) system of Advanced Info Service (AIS) to the CloudMQTT provider's MQTT Broker. The measured parameter data from each sensor's environment is sent to defined topics. In the second pattern, the robot subscribes to the information of the topic named "status" with MQTT protocol through the internet network on the HSPA+ (3G) system of Advanced Info Service (AIS) from the MQTT Broker of the service provider CloudMQTT. This information is used to control the work of actuators.

Below are the detailed assessment conditions:

1. The publish function covers eight topics: temperature, humidity, pressure, altimeter, air quality,

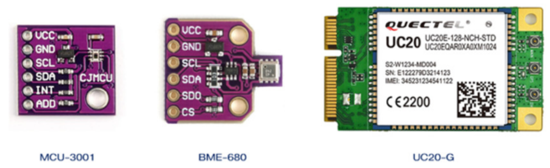


Fig. 9: *Types of Sensors Utilized for Research Purposes.*

light, latitude, and longitude.

2. The topic for the subscribe function is "status."

3. The publisher function has three units: Cultivation Robot, Computer, and Smartphone.

4. Similarly, the subscriber function has three units: Cultivation Robot, Computer, and Smartphone.

5. The payload size for all the functions is 16 bytes.

3.5 Robot Firmware

Ladybug's software development and structure design are concurrent and divided into two platforms, as illustrated in Fig.10. The Raspberry Pi platform captures images of plantation pots using Python, applies the Hough Circle Transform technique with OpenCV to detect and locate the center of the pots, and sends the position values (x, y, and z) to the Arduino board via serial communication. It also facilitates communication within the Internet of Things and controls robot movement. Meanwhile, the Arduino platform controls the distal device's three axes (x, y, and z) using a stepping motor and the seed injector for sowing. It also measures various environmental parameters, including temperature, humidity, air quality, air pressure, altitude, ambient light, and the robot's position (latitude and longitude) through sensors installed within the robot structure.

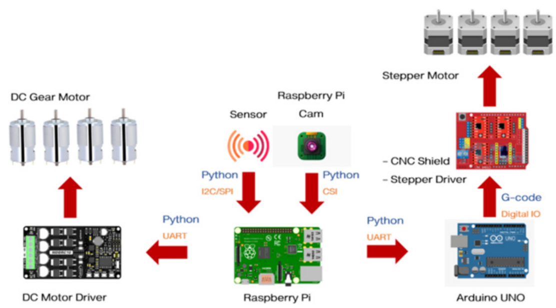


Fig. 10: *Interoperability Model for Hardware.*

The flow diagram in Fig.11 depicts the design process for creating robotic algorithms. Firstly, the software installs the robot in the test environment and initiates an initialization process to set the software variants to their default values. The system then verifies the serial connection between the Raspberry Pi board and Arduino and between Raspberry Pi and the Motor Driver. The system then connects to the AIS's GSM 3G network to establish contact with the MQTT Broker. In case of connection failure, the system makes further attempts. Once the connection is based, the sensor unit connected to the Internet of Things system provides various environment parameters, which the system reads and publishes to the MQTT Server. Lastly, the system awaits a signal from the MQTT Broker to control the robot through subscription, thus completing the process.

Regarding the hardware component, the control system shall thoroughly inspect the limit switch for each drive system's three axes. This inspection aims to verify whether the end-effector's drive unit has reached the home position, indicated by the limit switches x, y, and z being pressed. Suppose any axis has not reached this position. In that case, the system will issue a command to the end-effector's drive unit to return to the home position, which serves as the system's reference point for operation.

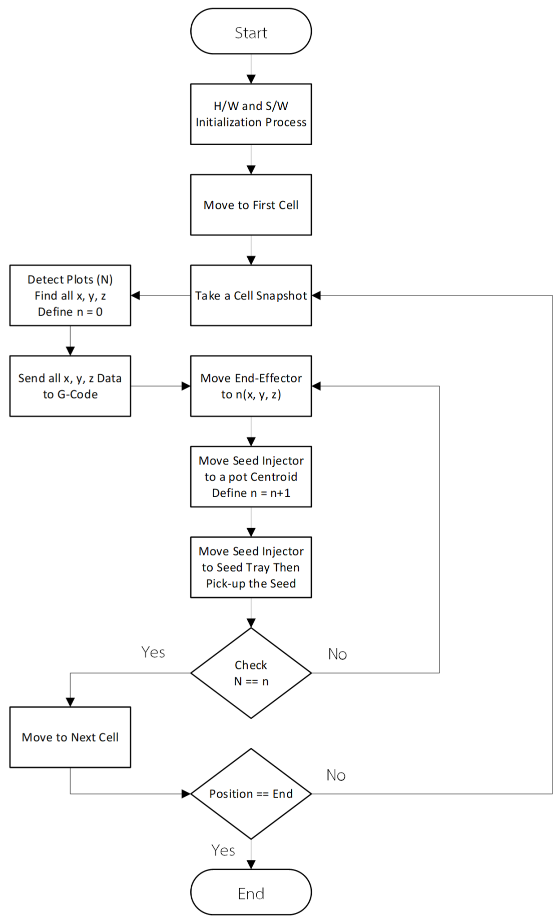


Fig. 11: *The Flow Diagram of Ladybug Algorithm.*

Once Ladybug reaches the first cell planting plot, it will begin its journey. Upon covering the first cell area, Ladybug will capture an image to identify the pots in the cell. The image will be analyzed to extract various parameters, including the total number of pots and the coordinates of each pot's center point, or centroid, using the HTC technique. In addition, Ladybug's ultrasonic sensor will measure the height between pots and Ladybug's seed injector, represented by the z coordinate. These values will be saved as N and n(x, y, z), respectively, where n(x, y, z) denotes the coordinates of the pot.

The next step is initializing n to 0 and transferring all values to the Arduino to control the two stepper motors responsible for movement in the x and y planes. The end-effector will then move to the position n(x, y, z) with n set to 0 for the first time. The stepping motor controlling the z-axis will lower the seed injector so the seeds can be sown onto the pot's center. Finally, the value of n will be incremented by setting n equal to n+1 before moving the end-effector to the subsequent position.

To ensure that all pots within a cell are planted, the N and n values are compared for equality. If they are not equal, the robot will repeat the planting process until all pots are planted. Once N and n are equal, the robot will use the MCU-Cam to read the barcode tag on the cell's perimeter. This tag contains specific commands that direct the robot's movement, such as forward, backward, rightward, and leftward. The robot will then determine its next direction based on the instructions provided by the tag.

As Ladybug proceeds to the following cell, it will diligently scan for the "End of Task" barcode to determine whether the work has been completed. Without the barcode, the system will seamlessly revert to the beginning of the work process by taking another cell snapshot. Conversely, if the barcode is detected, the control system will promptly signal the robot to halt its operations.

4. EXPERIMENT SETUP

Ladybug tests in a simulated environment. The test area, depicted in Fig.12, comprises round black pots, each with a diameter of five inches. These pots are placed in two plots, 50 centimeters wide and 150 centimeters long, and are positioned side-by-side with a gap of 50 centimeters between them. The robot commences from the start point on the left side of Cell-1 and moves towards Cell-1 to locate the pot, determine its center, and sow seeds into it. The robot repeats this process at Cell-2 and every subsequent cell until it reaches Cell-6. A barcode system has been implemented to facilitate Ladybug's movement between adjacent cells on the following plot. It has been placed precisely along the boundary between neighboring cells, such as Cell-3 and Cell-4, to signal the robot to move to the right. As the robot moves to the next cell, the MCU-Cam identifies the command barcode, and the camera detects the presence of pots in the cell. At this point, Ladybug initiates the seeding process again and completes the task before proceeding. The robot is programmed to stop when the MCU-Cam detects a barcode that means the end point of the plot.

In this research, the performance of a robot is evaluated based on two aspects: its capabilities and behaviors in a simulated environment that replicates natural conditions. The evaluation includes meeting specific requirements for materials, equipment, codes, conditions, and time spent on actual experiments. Surveillance is used to observe experimental results to ensure realistic outcomes when evaluating the robot's performance. The robot's efficiency is evaluated using various metrics, including velocity, accuracy, duration, and success rate.

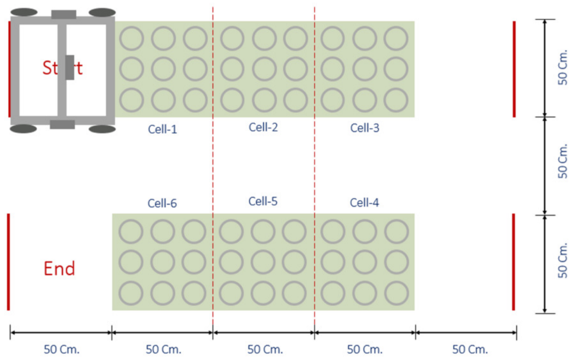


Fig.12: *The Testing Environment for the Robot's Operation.*

Velocity is determined by how quickly the robot moves from one point to another at a given time. Accuracy is calculated by analyzing how accurately the robot plants seeds in the designated area, considering an acceptable error rate. Mission duration refers to the time it takes for the robot to move from the starting point to the planting field, detect pots, process data, and sow seeds into each pot. The process is repeated until all pots have been accounted for; at this point, the robot stops. Lastly, the mission success rate represents the percentage of pots in which the robot successfully plants seeds compared to the total number of pots in the field.

To determine the effectiveness of the robot prototype, we used evaluation criteria. The accuracy of its sowing measured the success of the robot prototype. The robot's planting head should place seeds correctly within a 20% discrepancy from the center of the pot at a 70 mm position within the green area, as shown in Fig.13. It is considered unsuccessful if the robot fails to sow, moves to the wrong location, or places seeds outside the pot with a discrepancy of over 20%.

5. RESULTS AND DISCUSSION

5.1 The Motion System of Ladybug

Initially, a control system was designed and developed for a horizontal robot. The prototype is a Cartesian robot that moves on the x-axis, allowing it to move along the length of the greenhouse, followed by the width and vertical motion. It is a lightweight

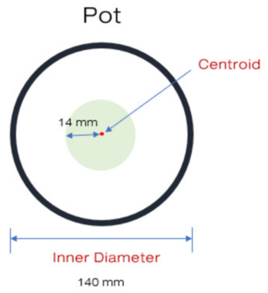


Fig.13: *The Proper Placement of Seed Sowing in the Pots Based on the Testing Conditions.*

and rust-proof aluminum profile that is easy to assemble. After the assembly, holes were drilled in the four corners of the frame to fix the motor gear and wheels. It was placed on a surface to check the system's balance, and a water level measuring device was used. The movement of the Ladybug was tested, and it was determined that the designed structure was sturdy and capable of effectively supporting weight.

A gantry robot was designed to supplement the Mobile Robot. Before subjecting the robot prototype to natural surface testing, it underwent a simulation test of the rotation of all four motor gears. It was done to reduce the possibility of failure and damage to the robot's structure.

During the testing phase, the Ladybug robot underwent a simulation of the rotation of all four motor gears. The primary objective of the testing was to minimize the risk of failure and damage to the robot's structure before being tested on a natural surface. The experiment demonstrated that the Mecanum wheel drive system robot could move freely in all directions. It was achieved by installing a roller set at a 45-degree angle, which enabled the robot to move in any direction by rotating all four wheels separately. The roller had alternating tilts on each side of the Mecanum wheel, and the wheel axles were parallel to the diagonals of the robot's structure, resulting in linear motion. The Ladybug robot's movement was effectively controlled by changing the rotation speed and the wheel's direction with a high-resolution encoder in the gear motor, closed-loop motor controllers, and PID control loops on a microcontroller in the Motor Driver Board.

The Mecanum wheel boasts an unparalleled ability to maneuver in any direction. However, compared to conventional wheels, it may be slower and pricier. Additionally, it requires sophisticated programming and maintenance due to roller wear. While it excels in restricted areas, it may present challenges when navigating obstacles due to its larger turning radius and increased noise generation.

The Ladybug robot is based on the working model of the gantry robot. It is designed similarly to an overhead crane and operates linearly on the x-axis, y-axis, and z-axis. The system is powered by four sets of stepper motors, including one set for the x-axis, two for the y-axis, and one for the z-axis drive (as illustrated in Fig.14). Three limit switches for the x-axis, y-axis, and z-axis serve as End Stops, setting the home point during system start-up. These limit switches protect the stepper motors from malfunctioning and damaging the mechanical system, preventing mechanical work. The x and y-axes use a Belt Driven System with the Step/mm value set to 80.00, while the z-axis uses a Lead Screw Driven System with the Step/mm value set to 400.00. Table 1 summarizes the testing results for linear movement in all three axes of the Ladybug. A short distance (100 mm) was instructed to move forward and backward in the forward and backward directions. The experimental results demonstrate that the drive system of both the x, y, and z axes can move in the correct direction without shaking and is stable. The accuracy of the x-axis and y-axis sets was noted to have different tolerances, although they use the exact Belt Driven System. This difference can be attributed to the number of stepper motors used to drive the belt.

Table 1: *The Results of the Testing for Linear Movement in All Three Axes of Ladybug.*

Axis	Average	Precision
x-axis	103.20 mm	0.968
y-axis	105.35 mm	0.946
z-axis	110.90 mm	0.891

The z-axis in the Ladybug robot uses a Lead Screw Driven System as a low-cost alternative to the Ball Screw Driven System. However, this system has a flaw related to the backlash, which is the free distance that occurs during the rotation of the spiral shaft. Backlash can cause inaccurate movements, decreased precision, and increased vibration, especially in pick-and-place operations or machining processes. To rectify this, an Anti-Backlash Nut Block can be used, which prevents the lead screw from slipping during operation. The nut block uses a dual-thread design, offsetting opposing threads on the nut to absorb backlash when engaging with the lead screw. It also integrates a spring mechanism to preload the threads, ensuring continuous backlash compensation, even in high-speed applications. Additionally, it offers adjustability, enabling fine-tuning of the preload and compensating for backlash according to specific application requirements and Ladybug robot characteristics. These components enhance precision, stability, and overall performance by reducing or eliminating backlash, facilitating smoother, more accurate movements, minimizing vibrations, and extending the system's lifespan.

Ladybug improves upon past research projects, such as IRRIG, CeRSAA, and Seedbed, by offering greater flexibility in expanding the workspace. In

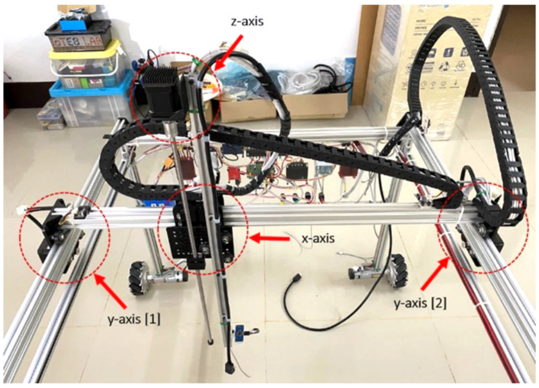


Fig.14: *Linear Motion Controller for Robot Prototypes.*

contrast, FarmBot and Seedbed had a limited work area, while SAASbot only allowed adjustments to the work area size through a rubber sheet cover rail, which created a grid table to determine the scope of work in advance.

5.2 The Perception System of Ladybug

Ladybug's sensing system utilizes Image Processing to identify pots within a plot. Instead of using real-time video images, we take snapshot photographs of the planting plot using the Raspberry Pi Camera Module (as shown in Fig.15) to conserve system resources and avoid slow processing times on the Raspberry Pi platform. We locate each pot, draw a contour around it, and count the number of pots. Then, we use the Image Processing data to accurately calculate the pot's position along the x-axis and y-axis, which enables us to sow seeds precisely. To achieve this, we use the Hough Circle Transform technique written in Python with OpenCV to convert the image's pixel system coordinates to a reference point for the center of the actual pot in millimeters.

The pot detection system detected all four pots in each experiment throughout the testbed simulation. However, Table 2 revealed a slight variance in the seeding point location between each test and the reference position. On average, the Hough Circle Transform's sensitivity and calibration resulted in a 1.68 percent error in the x and y coordinates. The lighting conditions in the testing environment affected the system's edge detection, causing the position to shift or the size to fluctuate. It was evident in the contour of the detection effect. Fig.16 provides an example of the system detecting a slight error, even when it detected the same set of pots at the exact location several minutes apart.

Throughout the development stage of Ladybug, we carried out additional tests to assess the accuracy and efficiency of its pot detection system. We conducted these Tests using various pot arrangements, as depicted in Fig.17. These tests aimed to identify any possible limitations in the detection process.

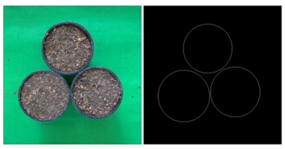
Table 2: *The Error and Precision of Ladybug's Pot Detection System.*

	Axis	% Error	Precision
Pot 1	x	0.96	0.990
	y	0.39	0.996
Pot 2	x	0.74	0.993
	y	2.24	0.998
Pot 3	x	7.58	0.997
	y	0.89	0.991
Pot 4	x	0.45	0.993
	y	0.15	0.998

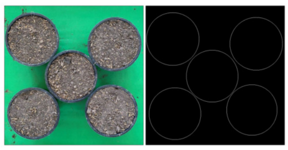
Fig.15: *The Sensors for the Perception Part are Installed on the Z-axis.*

(a) The first result. (b) The second result

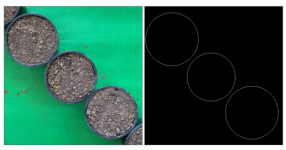
Fig.16: *There was a Discrepancy Detected during Pot Testing.*



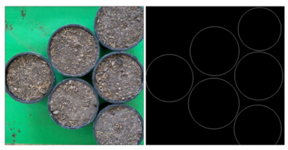
(a) 3 pots (detect 3 pots)



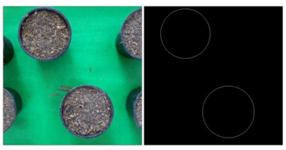
(b) 5 pots (detect 5 pots)



(c) 5 pots (detect 3 pots)



(d) 6 pots (detect 6 pots)



(e) 6 pots (detect 2 pots)

(f) 6 pots (detect 5 pots)

Fig.17: *The Effect of Pot Detection when Arranged in Different Configurations.*

The location of the pot is a crucial factor that affects the detection process. If the camera fails to capture the entire composition of the pot due to its placement, the detection system will not be able to identify its presence in the image. For the detection to be accurate, the pot's cross-sectional area must be at least 50%, and its center should be visible in the picture. Additionally, to enhance the detection system's accuracy, a line can be drawn from the center point to the edge of the pot with a radius of r.

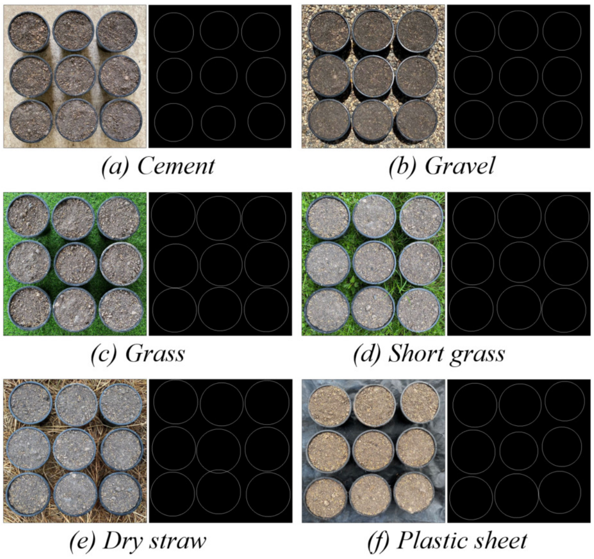


Fig.18: *Results of Pot Detection when Placed on Various Surfaces.*

The ability of the cognitive system to detect the number of pots can be affected by the placement of the pot, according to a test conducted in Fig.18. Detection accuracy can be improved if the area where the pot is placed has a different color or contrast from the pot itself. However, there may be slight differences in the actual size and position of the layout due to variations in pixel intensity.

Furthermore, light intensity may affect the quality and clarity of images captured by Ladybug in the workspace. The appearance of objects in photos could also differ depending on the light spectrum in the area. It is essential to comprehend the spectral features of the light source to ensure precise image analysis. Techniques like multi-angle imaging or polarization filtering can help mitigate the effects of shadows and glare. It must adjust to changes in lighting conditions due to significant variations in light levels and spectral composition to maintain dependable performance. Controlled lighting systems that employ LED lighting on the robot frame can optimize perception conditions. Furthermore, it can use other sensors, such as LiDAR or infrared, and image-based perception.

5.3 The Action System of Ladybug

The seed injector, or the planting head, is responsible for placing the seeds into the pot. It uses a drop-head design to store the seeds in the tube. The linear actuator's shank then pushes the seeds into the pot at the sowing point, making moving back and forth to the seed tray unnecessary, ultimately saving time. Once the sowing is complete, the linear actuator moves back to its original position, and the spring on the drop head pushes it back to its original position, preventing the seeds from spilling out.

Here are the four steps to follow while using the seed injector, as shown in Fig.19:

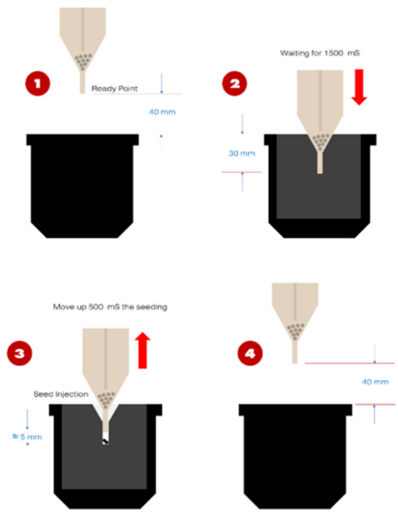


Fig.19: *The Process of the Seed Injector at Work.*

1. Begin by moving the seed injector towards the center of the pot on the x and y axes. Then, lower the z-axis until it reaches the ready point, 40 mm above the pot's mouth. To locate this position, use the ultrasonic distance sensor.

2. Next, move the seed injector down by 65 mm, the distance between the ready point and the seed injector's tip. Wait for 1,500 milliseconds to allow the soil to settle around the tip.

3. Lift the seed injector's tip above the pot once the soil has stabilized. Be sure it goes within the hole's mouth pressed into the pot, then command the linear actuator to move the metal rod forward by 10 millimeters. Immediately move the linear actuator backward to prevent the seeds from spilling out, allowing the sowing rod springs to push the sowing rod back to its original position.

4. Finally, move the seed injector to the seeding position's height. Wait for the following command to move to the next pot's x and y coordinates for sowing seeds.

The seed injector control system was tested, and it was found that the robot successfully planted seeds in every pot. However, the number of seeds planted per pot varied between 2 and 4, with an average of

2.20 seeds per pot. This seeding rate is appropriate if the seed germination rate is 90% or higher. The inconsistency in the number of seeds planted can be attributed to the seed injector mechanism, designed for 2mm diameter seeds. As a result, the planting process could be more consistent due to the different shapes and sizes of seeds available in the market. This limitation is a natural factor that cannot be controlled.

Ladybug's seed injector boasts higher efficiency than robots like FarmBot, SAASbot, and Seedbed. Its ability to avoid returning to the seed tray at the reference point for seed collection sets it apart. It is made possible by the seed injector's seed storage cylinder, which effectively minimizes time wastage.

5.4 Communication System with IoT

The Internet of Things setup is designed to measure a greenhouse environment's parameters while an automatic planting robot operates. The system consists of three sensor units: an ambient light sensor for measuring light intensity and low-power gas, pressure, temperature, and humidity sensors for measuring air quality, temperature, humidity, and air pressure. It utilizes the Quectel UC20-G device, which uses GSM communication and features a built-in GPS GNSS receiver module that enables it to determine the user's position from the GPS satellite system.

The process begins by gathering environmental data from three modules. These modules update the data every 5 seconds and transmit it in real-time through the MQTT protocol. The information is then transferred to the internet using HSPA+ on the GSM 3G mobile phone network to be published and subscribed to topic information at the MQTT Broker. The MQTT Broker Server, named driver.cloudmqtt.com, is installed in the cloud computing system at `https://www.cloudmqtt.com`. The status information from the computer and smartphone is published on the "status" topic to the MQTT Broker Server on Amazon Web Services.

On the other hand, the planting robot is subscribed to the "status" topic to receive a payload from the MQTT Broker. This payload is utilized to operate the actuators responsible for managing the planting robot's tasks. Moreover, the payload shows comprehensive information on the dashboard, as depicted in Fig.20. The dashboard system of the Ladybug robot displays environmental data collected by the robot. It consists of four sets of gauges that display temperature in Celsius, relative humidity in percentage, air quality value in mega-ohms (mΩ), and light intensity in Lux. The dashboard also shows air pressure in hPa units and GPS coordinates for the robot's location in latitude and longitude. All data on the dashboard is updated automatically when the robot publishes the information to the MQTT Broker. Furthermore, the dashboard features three buttons that can be used to control the robot's actuator, allowing the user to turn the light on/off or send an alarm. These commands will be published to the MQTT Broker, which will forward them to the robot through a topic named "status."

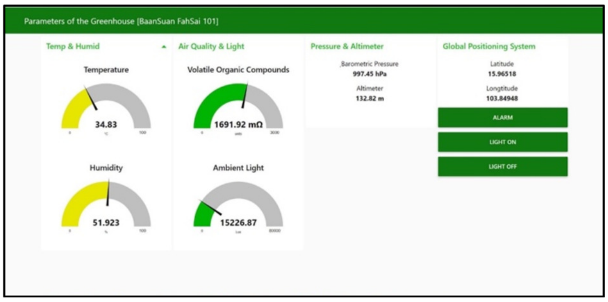


Fig.20: *The Dashboard Shows the Information that the Robot has Transmitted.*

Based on the findings in the experiment, it is possible to publish and subscribe to a topic in real time using the MQTT protocol on CloudMQTT's WebSocket UI system. The operation was tested on a web browser and an MQTT client, as shown in Fig.21, on a mobile device running iOS, specifically an Apple iPhone 11 Pro Max. The robot's sensors accurately published and subscribed to environmental data during testing. The number of published and subscribed topics was also found to be correct. Notably, the robot operated on a GSM 3G network located approximately 3 kilometers away from the repeater station. Despite the low speed of 384 Kbps – 3 Mbps, there were no operational errors. The MQTT protocol is designed to send and receive data quickly due to its small header size, low resource usage, and power efficiency. Additionally, it is an event-driven system that can receive information anytime topics are published.

Once the tests on subscribing and publishing topics are completed, it is time to test Ladybug's control over the Internet of Things. The control is established through an MQTT Client. The client creates a button that can handle three functions of the robot:

1. The "Beep" button commands the robot to send an alarm signal.

2. The "LED light" button commands the robot to turn on the installed LED light.

3. The "LED off" button instructs the robot to turn off the installed LED lighting.

This test monitors the control results via serial console with Putty. The robot's operation is observed after pressing a button in the MQTT Client.

The experiment involved testing the control of a robot using the Internet of Things System. The robot had an accuracy value of 0.96, with only two instances of control failure. Upon control failure, pressing the control button again caused a delay before the robot resumed working. The serial console revealed that the failure was caused by the Quectel UC20-G losing connection to the GSM 3G network before attempting to reconnect. Therefore, the robot could not receive the published topic data, resulting in a delay in the order due to the network connection attempt.

Fig.21: *Testing the Subscription and Publication of Data through the Mobile Application.*

The publish and subscribe test results for the topic showed that the system operates efficiently and accurately. The experimental results of the robot control test via the Internet of Things emphasize the need for the robot's hardware to verify its connection to the GSM network. The hardware must check its connection status before executing any commands and automatically reconnect if any loss of connection occurs.

In contrast, the Internet of Things robot control test relies on commands from the MQTT Client on the user's smartphone instead of the robot's hardware. Therefore, the MQTT Client must be aware of the connection status of the Quectel UC20-G on the robot and only serve as an intermediary to relay commands from the user to control the robot.

5.5 Performance Evaluation of Ladybug

During the experiment, the efficiency of the Ladybug robot was tested in a simulated environment like Fig.22. The setting consisted of two plots, each having six cells with nine black, round, 5-inch pots. The robot started its task from the first cell on the left and proceeded to detect the pots. Once detected, it calculated the center of the pots and planted the seeds in them. After sowing all the seeds in the pots of the first cell, the robot moved on to the second cell, detected the pots, found the midpoint, and planted the seeds. This process continued until the robot reached the sixth cell. The system automatically stopped working when the sensor detected that the robot had reached the endpoint.

Fig.22: *Testing the Functionality of Ladybug in a Simulated Field for Planting.*

(a) Side-view *(b) Top-view*

Fig.23: *Injecting Seeds into Pots Using a Seed Injector.*

Based on the experimental data, we plotted the x and y position values in Fig.24 to evaluate the efficiency of the sowing process. The sowing location should be within the small circle, which has a tolerance of ±20% from the center of the pot at 70 mm. This criterion determines the success of the robot's sowing capabilities. Any seeds sown outside the circle indicate a failure on the robot's part to plant successfully.

The test results indicate the distance between the pot's center and the seed injector's center that's inserted into the soil surface in each pot. This evaluation determines whether the seed injector successfully sows the seeds in each pot. The robot's planting head must move to the pot's position and sow the seeds with a discrepancy of ±20% (or no more than ±14 mm) from the center of the pot, according to the evaluation criteria. Therefore, any pot's spacing in the test result table larger than ±14 mm will be considered an unsuccessful sowing.

The test data showed that the robot completed the task successfully in each work cycle. Moreover, the seed was sown in pots across all six cells in the Testbed. The graph in Fig.25 depicts the results of successfully sowing seeds in each mission, with an average of 39 pots planted successfully and an accuracy rate of 0.72.

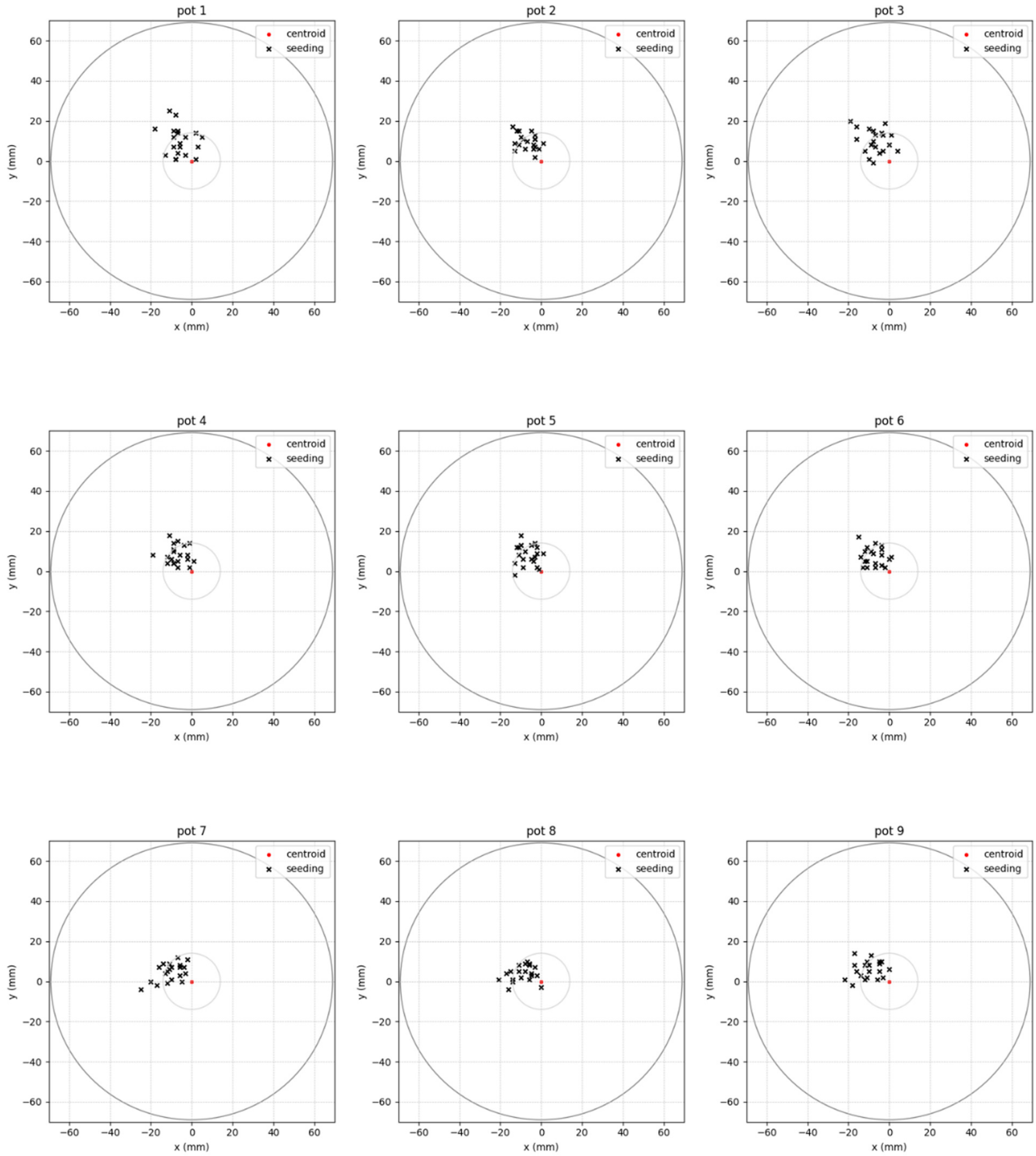


Fig.24: *The Result of Injecting Seeds into Pots by Ladybug.*

Fig.26 displays a graph that shows the robot's duration on missions. On average, each mission, including the seeding process, lasts for 12.53 minutes. The robot takes around 13.37 seconds to sow each pot and can sow approximately 257 pots per hour. The robot's velocity is 6 meters per minute or 360 meters per hour. The mission duration value keeps increasing according to the experimental results obtained during cycles 6-8 and 14-16. The battery voltage level decreases from 11.9 V to 10.1 V, which reduces the electricity supply efficiency to the stepper motor and gear motor. Charging the battery is necessary to prevent any damage. The prototype robot can also run for about two hours with a full load on a 30,000 mAh Lithium-Ion battery before the average voltage drops below 9 V.

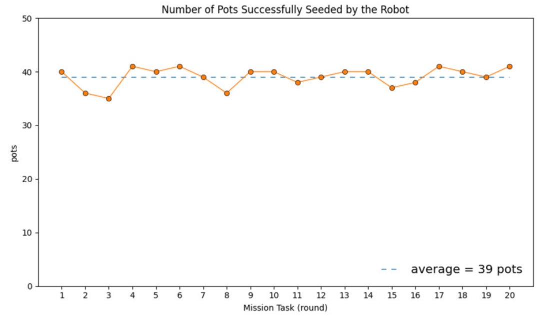


Fig.25: *The Number of Pots Successfully Planted by Ladybug During its Mission.*

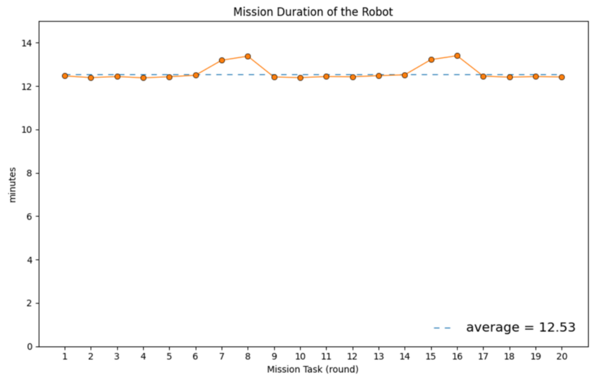


Fig.26: *The Ladybug's Time to Complete its Mission in Each Round.*

6. CONCLUSION

This article introduces Ladybug, an automated cultivation robot that offers a cost-effective, lightweight, and compact solution to modern farming challenges. Weighing 20 kg, Ladybug is equipped with Mecanum wheels, enabling it to move in any direction and operate efficiently, even in small spaces. Our system utilizes Image Processing and Artificial Intelligence to enable scalable autonomous planting, which can handle changes in the number of pots or modifications to the placement and diameter of pots. We developed a methodology that uses the Hough Circle Transform (HCT) algorithm and AI refinement to identify pots accurately. Before analysis, we employed pre-processing techniques such as grayscale conversion, noise reduction, and contrast adjustment to enhance image clarity. The HCT algorithm identified circles based on edge information, with parameters tailored to match the expected pot size. False positives were eliminated through a Rule-based filtering process, and overlapping circles were identified by proximity grouping. The robot relied on the MCU-Cam to scan barcodes on the ground in each cell to ensure it moved to the correct position. Ladybug uses a seed injector as a planting head, reducing the need to return to the seed tray to pick up seeds and resulting in a 50% reduction in work time. The robot can sow 257 pots in an hour and complete a mission in 12.53 minutes while moving at 360 meters per hour, taking only 13.37 seconds to sow seeds in one pot. Ladybug can operate continuously for up to two hours, perform nine cycles, and seed 486 pots on a single charge, boasting a mission success rate of 1.00 and a seeding accuracy 0.78. Real-time monitoring of the environment's parameters, including temperature, humidity, air quality, ambient light, pressure, altimeter, and robot positioning (latitude and longitude), is possible. Actuator control is enabled through the Internet of Things System on the GSM 3G network using the MQTT protocol.

There are limitations to consider. Mecanum wheels are great for maneuverability but can be complex, prone to vibration and slippage, and require intricate control. Belt-driven systems offer smooth, high-speed operation but might struggle with high loads or require complex tensioning mechanisms. Lead screw-driven systems provide precise positioning but can be slower and susceptible to wear and tear. Image Processing is helpful for perception, but it can be hampered by factors like inconsistent lighting, object occlusion, and limited recognition capabilities, affecting the robot's ability to understand its environment accurately.

Our future goal is to develop a multitasking robot named Ladybug II that can water, fertilize, analyze plants, eliminate weeds, and spray pesticides. To ensure efficient navigation, we will equip it with an advanced system that uses AI and LIDAR to avoid obstacles. Additionally, we will create a station dock mechanism to monitor the robot's resource status in real time, ensuring it operates within predetermined limits. The robot will autonomously return to the dock station for recharging and refilling.

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AUTHOR CONTRIBUTIONS

Conceptualization, A.T. and S.K.; methodology, A.T.; software, A.T.; validation, S.K. and C.J.; formal analysis, A.T.; investigation, M.N.; data curation, A.T. and M.N.; writing—original draft preparation, A.T.; writing—review and editing, A.T. and S.K.; visualization, A.T. and M.N.; supervision, S.K. and C.J.; funding acquisition, A.T. All authors have read and agreed to the published version of the manuscript.

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