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Vision-guided Height Adaptive Micro Spraying Rover for Precision Agriculture

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Abstract: This study examines a pesticide spraying system that adapts to the height of the plants. A depth sensor and a spraying system with several nozzles at various heights in a vertical direction are part of the system. An automatic guided vehicle (AGV) is equipped with the full system. Plant recognition and plant height computation are essential for the system with fixed nozzle height in order to conduct precision spraying or automatic targeting. Since the plant height has been determined, the planned system will open one or more of the spraying system's nozzles. A plant height-adaptive pesticide spraying system based on a video sensor to handle the plant's shape is suggested as a solution to the plant height-adaptive problem. The spraying system's open or closed state is optimized for various plants with varying heights, and both the depth and color data of the figure are collected and examined. Numerous experimental findings have shown that the suggested system is regarded as well.

Keywords: Depth sensor, height-adaptive, precision spraying, automatic guided vehicle, Machine vision.

1 INTRODUCTION

The increasing demand for sustainable agricultural production has intensified concerns regarding excessive pesticide usage, environmental contamination, and food safety risks. Long-term pesticide applications significantly influence soil erosion processes and chemical mobility within agricultural ecosystems, thereby affecting watershed stability and environmental health [1]. In addition, agricultural insecticides have been identified as major contributors to global surface water contamination, highlighting the urgent need for improved pesticide management strategies and efficient application techniques [2]. Precision spraying has emerged as an effective solution for minimizing pesticide consumption while maintaining crop protection efficiency. Environmentally friendly spraying techniques enable selective chemical application based on crop requirements, thereby reducing chemical drift and unnecessary exposure to surrounding ecosystems [3]. Recent developments in agricultural robotics have further strengthened the implementation of selective spraying systems capable of disease-specific treatment through automated sensing and control mechanisms [4].

Advancements in intelligent sensing technologies and adaptive control systems have enabled the integration of machine-based perception into agricultural operations. Vision-guided robotic spraying platforms are capable of detecting plant characteristics and adjusting spraying parameters dynamically according to crop geometry and environmental conditions [6]. Close-range precision spot-spraying techniques supported by aerodynamic spray coverage optimization further enhance pesticide targeting accuracy in robotic agricultural applications [7]. Recent studies have demonstrated that coordinated motion control combined with machine vision significantly improves spraying accuracy in controlled agricultural environments by enabling real-time plant detection and adaptive targeting [8]. Comprehensive reviews on agricultural spraying robots have highlighted the importance of integrating sensing technologies, automation, and intelligent control strategies to improve pesticide application efficiency and sustainability in precision agriculture systems [9]. Machine vision-based precision spraying control systems developed for orchard environments have shown promising performance in detecting crop structures and enabling adaptive spray control using image-based decision mechanisms [10].

Furthermore, integrated crop protection technologies combining unmanned aerial detection, adaptive mixing strategies, and intelligent spraying platforms have demonstrated improved efficiency in pesticide usage and environmental protection [11]. Literature studies on robotic pesticide spraying systems also emphasize the growing importance of height-adaptive spraying mechanisms capable of adjusting nozzle operation according to plant geometry for improving spray utilization efficiency and reducing chemical wastage [12]. Vision-guided height-adaptive spraying systems represent an effective approach for achieving selective pesticide application by automatically detecting plant height and controlling nozzle activation accordingly. Depth sensing technology enables accurate extraction of plant structural information, supporting real-time adjustment of spray height and improving application precision. Integration of depth sensors, image processing techniques, and automated guided vehicles enables intelligent pesticide delivery systems capable of responding dynamically to variations in crop height and spatial distribution, thereby improving spraying efficiency and supporting sustainable precision agriculture practices.

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2 SYSTEM DESCRIPTION AND DATA PROCESSING

The vision-guided height-adaptive micro spraying rover operates based on the principle of selective pesticide application through plant height detection using depth sensing and image processing techniques. The system integrates a depth sensor, RGB camera, embedded controller, and vertically arranged spray nozzles mounted on an automatic guided vehicle platform to enable adaptive pesticide spraying according to plant height variations. Sensor-acquired data are processed to extract plant structural information required for precise spray control decisions. The integration of sensing and actuation mechanisms enables intelligent adjustment of spraying height, thereby improving pesticide utilization efficiency and reducing unnecessary chemical exposure to surrounding areas.

2.1. System Working Principle

The operating principle of the proposed spraying system is based on detecting plant presence and estimating plant height using depth and color information captured through the vision sensor. The automatic guided vehicle moves along the crop rows while continuously capturing image data. The sensing module identifies plant regions and extracts depth values corresponding to plant structures. Based on the detected plant height, appropriate combinations of vertically arranged spray nozzles are activated through controller-generated signals. This adaptive activation mechanism ensures that pesticide spraying is performed only within the required height range of crop foliage, thereby improving spraying precision and minimizing pesticide wastage. Fig.1 shows the system operation principle.

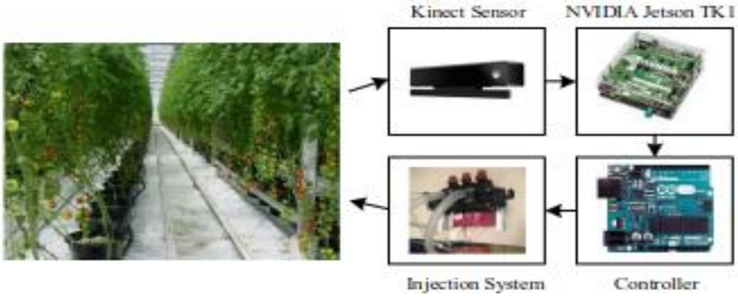

Fig. 1. System Operation Principle

2.2. Sensor Introduction and Calibration

Plant height detection is performed using a depth sensing module that integrates an RGB camera and an infrared-based depth measurement unit. The sensing system captures both color images and depth images simultaneously to enable accurate plant identification and height estimation. The RGB camera provides visual information required for plant region extraction, while the depth sensor generates distance measurements corresponding to plant surfaces. The captured depth and color images are transmitted to the processing unit through a high-speed communication interface for further analysis. Since the RGB camera and depth sensor operate from slightly different physical positions, calibration procedures are required to determine intrinsic sensor parameters and relative pose alignment between sensing components. Sensor calibration improves measurement accuracy by correcting geometric inconsistencies between color and depth image coordinates. Fig. 2 shows the schematic diagram and front view of kinect.

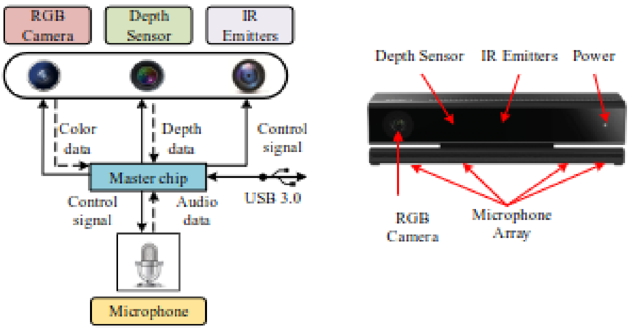

Fig. 2. Schematic Diagram and Front View of Kinect

2.3. Depth Data Acquisition

Depth information obtained from the sensor is used to estimate the distance between the sensing unit and plant surfaces for calculating plant height. The measured depth values vary with changes in object distance and may exhibit nonlinear characteristics when represented in pixel-based depth format. A relationship between measured depth values and actual distance is established through calibration analysis to improve measurement accuracy. Experimental observations indicate that depth sensing accuracy decreases gradually as the distance between the sensor and plant increases. However, the sensor provides sufficient precision within the operational range required for crop height estimation and adaptive spray control applications. Fig. 3 shows the depth data conversion.

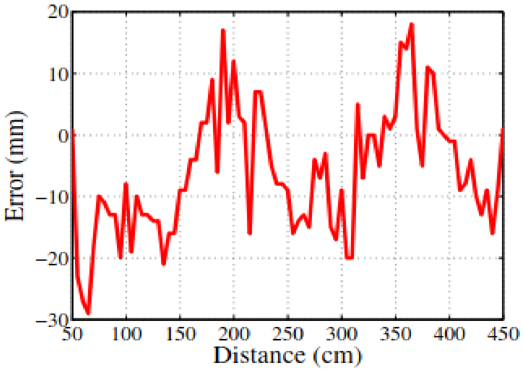

Fig. 3. Depth Data Conversion

2.4. Color Data Processing

Color image processing is performed to identify green plant regions required for accurate plant height estimation. The captured RGB images are first resized to reduce computational complexity during processing operations. Fig. 4 shows the color data processing.

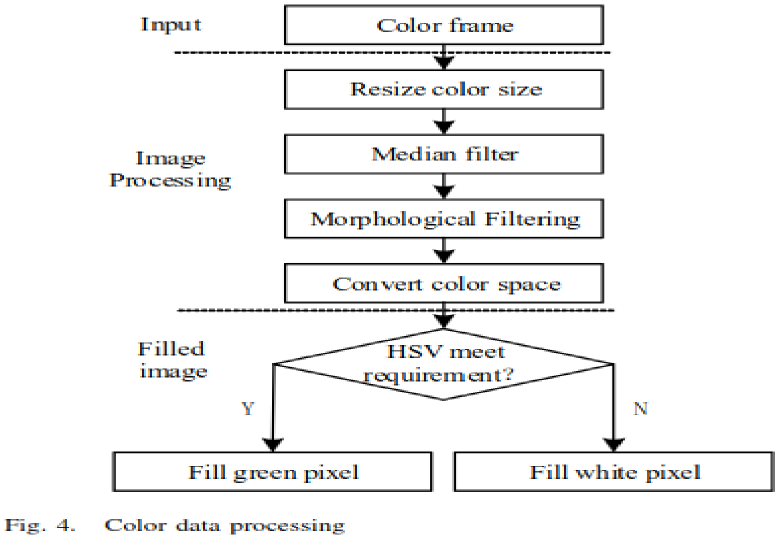

Fig. 4. Color Data Processing

Noise components present in the captured images are removed using median filtering techniques to improve image clarity. Morphological image processing operations such as erosion and dilation are applied to eliminate small unwanted artifacts and enhance plant region boundaries. Since RGB color representation provides limited discrimination capability for vegetation detection under varying illumination conditions, the color information is converted into HSV color space to improve segmentation performance. Threshold values corresponding to hue, saturation, and brightness components are applied to identify green vegetation regions within the captured image Fig. 5 shows the fill green image. The segmented plant regions are further processed to determine contour boundaries and center locations required for extracting corresponding depth information from the depth image. The extracted plant region depth values are then used for estimating plant height and enabling adaptive spray nozzle control based on vegetation geometry detected by the sensing system.

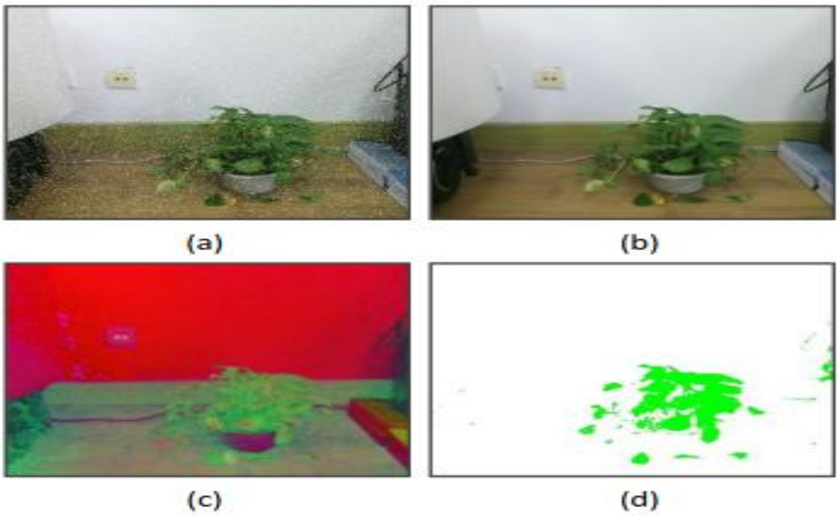

Fig. 5. Fill Green Image

3 PLANT HEIGHT MEASUREMENT

Accurate estimation of plant height is an essential requirement for implementing height-adaptive pesticide spraying in precision agriculture systems. Plant height measurement in the proposed system is performed using depth information obtained from the integrated vision sensor mounted on the automatic guided vehicle platform. The sensing unit combines RGB image data with depth measurements to extract spatial information corresponding to crop structures during rover movement along the cultivation path. Each vision sensor operates within a predefined field of view that determines the observable spatial region during image acquisition.

The horizontal and vertical viewing angles of the sensing module define the measurable coverage area for vegetation detection. Using the depth values obtained from the sensing module, the actual distance between the plant surface and the sensor is determined. This distance information is then used together with pixel-based plant height measurements extracted from the processed image to estimate the real-world plant height. The plant height estimation process begins with identification of the vegetation region through color segmentation in HSV space. After detection of the plant region, contour extraction techniques are applied to determine the boundary and center position of the detected vegetation structure. The vertical extent of the plant region within the captured image frame is calculated in pixel units and used as the basis for computing the actual plant height using geometric relationships derived from sensor viewing parameters.

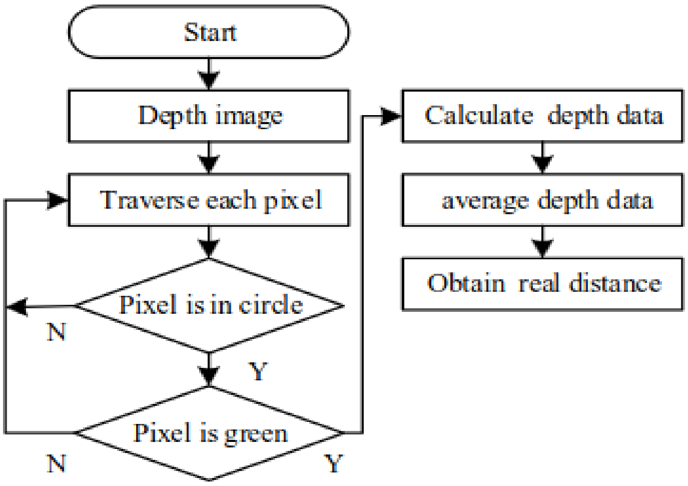

Fig. 6. Depth Data Processing

Since depth measurements vary slightly from actual distances due to sensing limitations and environmental conditions, multiple height observations are collected continuously while the rover moves along the crop row.

These repeated measurements improve reliability by reducing the effect of random sensing variations. The height value with the highest occurrence probability within the observation sequence is considered as the final estimated plant height. The estimated plant height information is transmitted to the control module for activating appropriate combinations of vertically arranged spray nozzles. This height-based adaptive spraying mechanism ensures that pesticide delivery is limited only to the required crop canopy region, thereby improving spray utilization efficiency and supporting selective pesticide application in precision agriculture environments. Fig. 6 shows the depth data processing. Fig. 7 shows the plant height measurement.

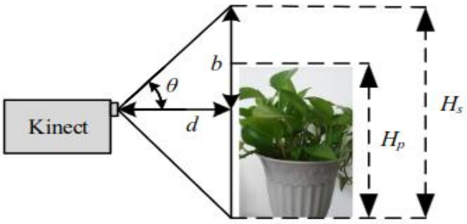

Fig. 7. Plant Height Measurement

4 SPRAY CONTROL SYSTEM

The spray control system represents one of the most critical components of the height-adaptive pesticide spraying rover, enabling selective pesticide delivery based on plant height information obtained from the sensing module. The system operates through coordinated interaction between the depth sensing unit, embedded controller, solenoid valve assembly, and vertically arranged spray nozzles mounted on the automatic guided vehicle platform. The primary control signals required for spray regulation are generated by the Arduino-based controller. These control signals determine the activation and deactivation of solenoid valves connected to individual spray nozzles positioned at different vertical levels along the spraying column. The vertical arrangement of spray nozzles allows pesticide application to be adjusted according to variations in crop height detected during rover movement along the field.

Three spray nozzles are mounted vertically along the side structure of the automatic guided vehicle with uniform spacing between adjacent nozzle positions. The total structural height of the spraying assembly enables pesticide delivery across a defined vertical range suitable for typical crop canopy heights encountered in precision agriculture environments. Depending on the measured plant height, different combinations of solenoid valves are activated to ensure that pesticide spraying is restricted only to the required vegetation region. When no vegetation is detected within the sensing range, all solenoid valves remain in the closed state to prevent unnecessary pesticide discharge. When plant height falls within the lower detection range, only the lowest-positioned nozzle is activated. Fig. 8 shows the node installation diagram.

For medium-height vegetation ranges, the lower and middle nozzles are activated simultaneously to provide adequate canopy coverage. When taller vegetation is detected within the upper spraying range, all three vertically arranged nozzles are activated to ensure complete coverage of the crop height profile. This adaptive nozzle activation strategy enables efficient regulation of spray height according to real-time vegetation measurements obtained from the depth sensing system. The selective activation of solenoid valves reduces pesticide wastage, improves spray targeting accuracy, and supports environmentally responsible pesticide application practices within precision agriculture operations.

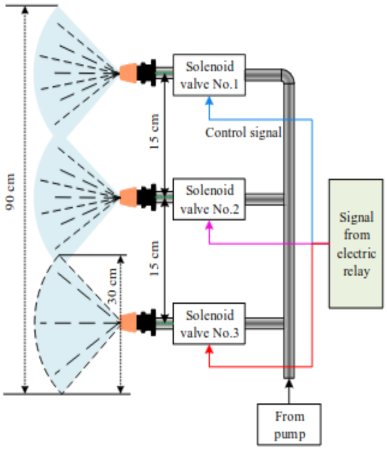

Fig. 8. Node Installation Diagram

5 EXPERIMENTAL VALIDATION

Experimental validation was performed to evaluate the effectiveness of the proposed height-adaptive pesticide spraying system in automatically controlling spray nozzle activation based on detected plant height. The validation process focused on verifying plant height detection accuracy and confirming appropriate nozzle operation corresponding to different vegetation height ranges. The experimental setup consisted of a height-adaptive pesticide spraying platform mounted on an automatic guided vehicle structure. The main components of the system included a DC motor for platform movement, a vision sensor for acquiring plant height information, three solenoid valves for controlling nozzle activation, a pesticide storage tank, and a pumping mechanism responsible for supplying pesticide to the spray nozzles. The sensing unit continuously provided vegetation height information to the controller, which generated corresponding control signals for activating the appropriate nozzle combinations.

5.1. Experimental Setup

To validate the height detection capability of the system, three plants of different heights were positioned at a distance of approximately 1000 mm from the sensing unit. The selected plant heights for evaluation were approximately 230 mm, 510 mm, and 810 mm. During rover movement, the sensing system continuously measured plant height values for each vegetation sample. Multiple measurements were recorded for each plant to evaluate the reliability and consistency of height estimation under operational conditions. Each plant height was measured repeatedly during traversal, resulting in approximately 80 observations per plant. These repeated measurements enabled statistical verification of sensing accuracy and ensured reliable estimation of vegetation height under dynamic operating conditions.

5.2. Experimental Results

The final plant height estimation was determined based on the most frequently occurring measurement value obtained from the observation set. This maximum probability-based selection approach reduced the influence of sensing variations and measurement noise present during height detection. The most probable measured height corresponding to the first plant was approximately 235 mm with a likelihood value of 78%. Similarly, the second plant height was estimated at approximately 540 mm with a likelihood value of 68%, and the third plant height was estimated at approximately 780 mm with a likelihood value of 68%. The measurement results demonstrated that the sensing module provided acceptable accuracy for plant height estimation within the operational spraying range of the system. Fig. 9 shows the height statistics for first plant.

Based on the detected height values, appropriate combinations of spray nozzles were activated automatically according to predefined control rules implemented within the controller. When vegetation was not detected within the sensing range, the spray flow rate remained at 0 L/min, indicating that all solenoid valves remained in the closed condition. When plant height was detected within the lower height range around 235 mm, only one nozzle was activated, resulting in a flow rate between approximately 1.3 and 1.5 L/min. When plant height was detected around 540 mm, two spray nozzles were activated simultaneously, producing a flow rate of approximately 2.3 L/min. Fig. 10 shows the height calculation for first plant.

When plant height reached approximately 780 mm, all three spray nozzles were activated, producing a flow rate of approximately 2.4 L/min. The experimental observations confirmed that the system successfully detected plant height and automatically activated appropriate nozzle combinations according to vegetation height variations. These results demonstrate the effectiveness of the height-adaptive spraying mechanism in achieving selective pesticide delivery and improving spraying efficiency in precision agriculture applications.

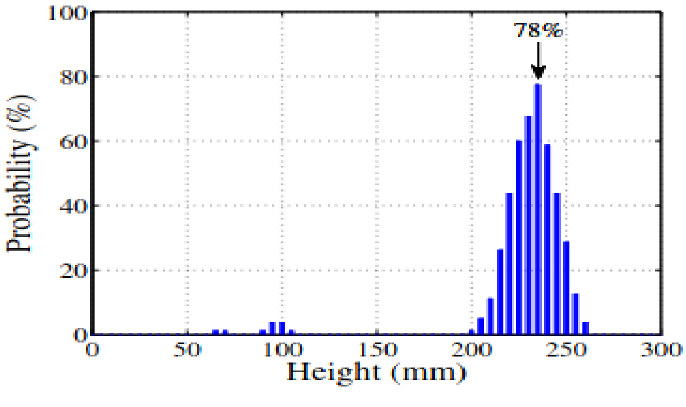

Fig. 9. Height Statistics for First Plant

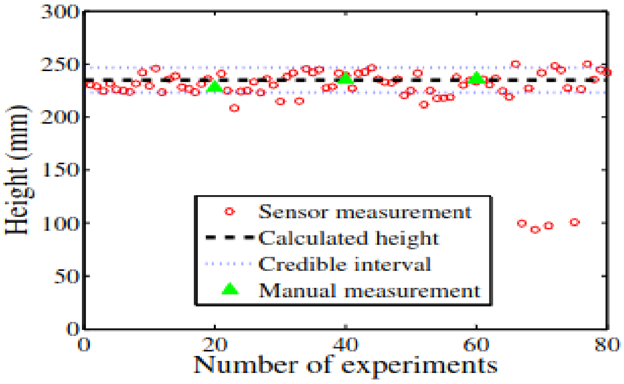

Fig. 10. Height Calculation for First Plant

6 CONCLUSION

A vision-guided height-adaptive micro spraying rover for precision agriculture has been presented to improve pesticide application efficiency through selective and intelligent spray control. The system integrates a depth sensing module, RGB image processing, and an automatic guided vehicle platform to detect plant height accurately and activate appropriate spray nozzles based on vegetation geometry. The adaptive control strategy enables selective pesticide delivery by adjusting spraying height according to real-time crop measurements, thereby reducing unnecessary chemical usage and minimizing environmental impact. Experimental validation confirmed that the sensing module successfully estimated plant height within acceptable accuracy limits and enabled automatic regulation of nozzle activation corresponding to different plant height ranges. The results demonstrated improved spray utilization efficiency and reliable operation under varying vegetation conditions. The proposed approach supports sustainable agricultural practices by enhancing precision spraying performance and reducing pesticide wastage. Future improvements may focus on integrating advanced sensing techniques and autonomous navigation strategies for large-scale field deployment.

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ETHICS STATEMENT

This study did not involve human or animal subjects and, therefore, did not require ethical approval.

STATEMENT OF CONFLICT OF INTERESTS

The authors declare that they have no conflicts of interest related to this study.

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