Development of a High-Throughput UGV System for Precision Weed Detection and Control Using Speckle Imaging and UV-C Irradiation

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A paper from the Proceedings of the
16th International Conference on Precision Agriculture
21-24 July 2024
Manhattan, Kansas, United States

Abstract.

Effective weed management is a longstanding challenge in agriculture, with significant implications for crop yields, environmental sustainability, and economic viability. Conventional weed control practices, such as blanket herbicide application, raise concerns about environmental impact, development of herbicide resistance, and non-target effects on beneficial organisms. This paper proposes a novel precision agriculture approach that integrates speckle imaging and UV-C radiation for targeted weed detection and control, offering a potentially sustainable and eco-friendly solution. The proposed system employs a coherent light source and lens-less camera to capture and analyze speckle patterns generated by light scattering from plant surfaces. Advanced image processing algorithms distinguish weeds from crop plants based on their unique speckle signatures, stemming from differences in surface characteristics like texture, roughness, and moisture content. Once weeds are detected, the system selectively applies UV-C radiation to the identified locations using strategically positioned UV-C light sources. UV-C exposure inhibits plant growth and development by damaging cellular structures, providing a targeted weed control mechanism. The speckle imaging and UV-C lighting components are integrated into an autonomous ground robot platform, enabling precise navigation and targeted application of weed control measures. Potential benefits of the proposed approach include reduced herbicide usage, minimized environmental impact, eco-friendly weed control, decreased herbicide resistance development, and increased crop yields. However, challenges exist, such as developing robust image processing algorithms, optimizing UV-C exposure parameters, ensuring precise navigation, addressing safety concerns, and evaluating long-term ecological effects. Comprehensive field trials will be conducted to assess the system's performance, including weed detection accuracy, weed control effectiveness, crop yield impact, and environmental impact assessment. Continuous optimization, scalability analysis, and commercialization efforts are planned to refine the system and promote its widespread adoption in sustainable agricultural practices.

Keywords.
Precision Agriculture, Weed Control, Speckle Imaging, Weed Detection, Sustainable Farming.

The authors are solely responsible for the content of this paper, which is not a refereed publication. Citation of this work should state that it is from the Proceedings of the 16th International Conference on Precision Agriculture. Salem, M. A. & Rabia, A. H. (2024). Potato Disease Detection Using Speckle Imaging and Deep Learning. In Proceedings of the 16th International Conference on Precision Agriculture (unpaginated, online). Monticello, IL: International Society of Precision Agriculture.

Introduction

Effective weed management is a critical challenge in agriculture, with significant implications for crop yields, environmental sustainability, and economic viability. Conventional weed control methods, such as blanket herbicide application, often raise concerns about environmental impact, herbicide resistance, and non-target effects on beneficial organisms. This paper proposes a novel precision agriculture approach that combines speckle imaging and UV-C lighting for targeted weed detection and control, potentially offering a more sustainable and eco-friendly solution.

Background and Related Work

Weed Detection Techniques

Various techniques have been explored for weed detection, including computer vision, spectral analysis, and machine learning approaches. However, these methods often face challenges in accurately distinguishing weeds from crops, especially in early growth stages or under varying environmental conditions.

Speckle Imaging

Speckle imaging is a technique that analyzes the interference patterns created by coherent light scattered from rough surfaces (Dogan, et al. 2021). It has been successfully applied in various fields, such as material characterization (Salem, Elshenawy and Ashour 2023), surface metrology, and biomedical imaging. The unique speckle patterns generated by different surface textures and structures hold the potential for distinguishing weeds from crop plants based on their distinct surface characteristics.

UV-C Radiation for Weed Control

UV-C radiation, with wavelengths between 200-280 nm, has been shown to have detrimental effects on plant growth and development. Exposure to UV-C can damage cellular structures, DNA, and disrupt various physiological processes in plants. Previous studies have explored the use of UV-C for weed control, demonstrating its potential as an environmentally friendly alternative to chemical herbicides (Udugamasuriyage, Kahandawa and Tennakoon 2024).

Proposed Approach

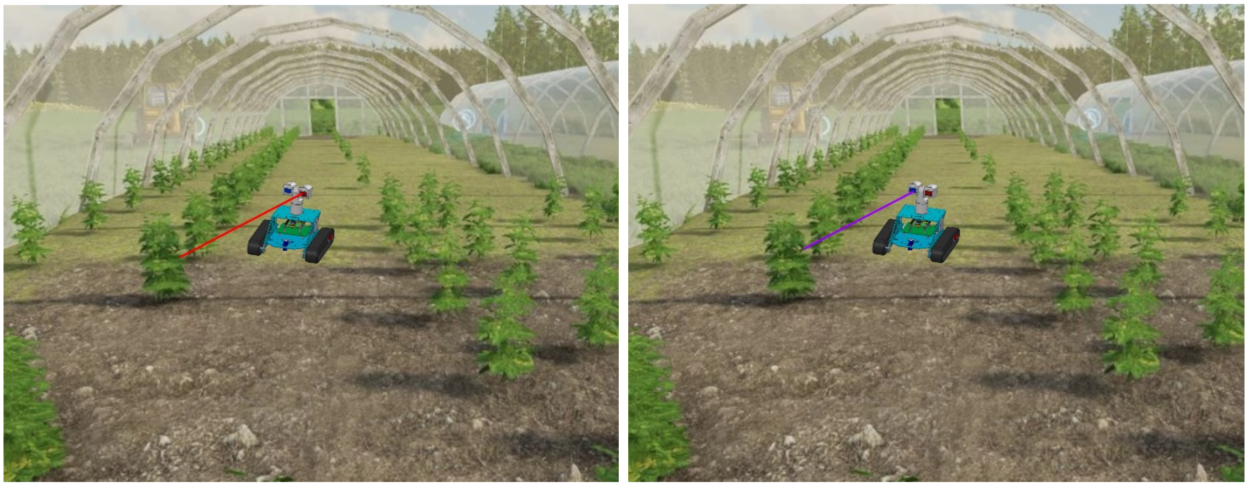
The proposed precision agriculture application integrates speckle imaging and UV-C lighting into a ground robot platform for targeted weed detection and control. The system comprises the following key components:

Speckle Imaging System

A coherent light source, such as a laser, illuminates the crop field. A high-resolution camera captures the resulting speckle patterns generated by the interaction of light with the plant surfaces. Advanced image processing algorithms then analyze these speckle patterns to differentiate weeds from crop plants based on variations in surface characteristics, including leaf texture, roughness, and moisture content. Figure (1-a) presents a simulation of this approach. The proposed weed detection and control system leverages a two-part unit: a UV-C LED weed control system for targeted elimination and a laser-speckle-based plant detection system for real-time weed identification.

UV-C Lighting System

Once weeds are detected, the system selectively applies UV-C radiation to the identified weed locations using strategically positioned UV-C light sources as shown in Figure (1-b). The intensity and duration of UV-C exposure can be carefully controlled to maximize weed control efficacy while minimizing potential harm to crop plants.



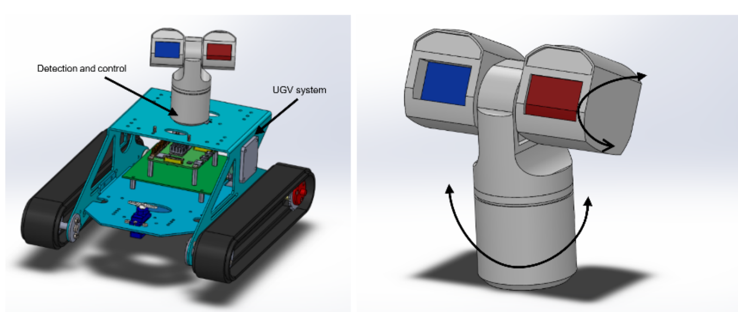
(a) (b)

Figure 1. A Simulation for the proposed weed detection and control system, (a) on the left side shows a simulation for the robot in a greenhouse during the detection process using the laser speckle imaging technique, while the image in the right (b) illustrates the control process by a UV-C LED

Ground Robot Platform

The speckle imaging and UV-C lighting systems are integrated into an autonomous ground robot platform, enabling precise navigation and targeted application of weed control measures. The robot can be programmed to follow pre-defined paths or utilize real-time sensor data for adaptive path planning, ensuring comprehensive coverage of the crop field.

The unmanned ground vehicle (UGV) system depicted in Figure 2(a) utilizes a mobile robot platform equipped with a sensor suite for obstacle detection and weed identification. A high-resolution camera mounted atop the UGV captures visual information about its surroundings. Alongside the camera, a laser source generates a coherent beam for speckle imaging, a technique that differentiates plants based on variations in surface characteristics. This non-intrusive method allows for real-time weed detection and distinction from desired crops, as illustrated in Figure 2(b). Figure 2(b) displays a separate 3-degrees-of-freedom (DOF) positioning unit that integrates the laser speckle sensor and UV-C LEDs for targeted weed control.



(a) (b)

Figure 2. The proposed autonomous ground robot platform with the laser speckle imaging and weed control system. (a) shows a 3D model for the robot platform, while (b) is the laser pointing system has a 3 DOF and consisting of a mount for the laser and UV-c LEDs and the speckle imaging camera.

Potential Benefits and Challenges

Benefits

- Precise weed detection and targeted control, reducing herbicide usage and minimizing environmental impact.
- Non-destructive and non-invasive weed detection method, without the need for complex image processing algorithms.
- Eco-friendly weed control approach, leveraging the natural weed-suppressing properties of UV-C radiation.
- Potential reduction in herbicide resistance development due to targeted application.
- Increased crop yields and improved agricultural sustainability.

Challenges

- Developing robust image processing algorithms for accurate speckle pattern analysis and weed detection.
- Optimizing UV-C exposure parameters for effective weed control while minimizing potential harm to crop plants.
- Ensuring precise navigation and positioning of the ground robot for targeted UV-C application.
- Addressing potential safety concerns related to UV-C exposure for human operators and non-target organisms.
- Evaluating the long-term effects of UV-C exposure on soil health and other ecological factors.

Future Work

To further develop and validate the proposed approach, several key research directions are envisioned:

System Development and Integration

Designing and constructing the speckle imaging and UV-C lighting systems, as well as integrating them into a suitable ground robot platform, will be a critical first step. This will involve hardware and software development, sensor calibration, and extensive testing.

Field Trials and Evaluation

Comprehensive field trials will be conducted to assess the system's performance in real-world agricultural settings. Key evaluation metrics will include weed detection accuracy, weed control effectiveness, crop yield impact, and environmental impact assessment.

Optimization and Refinement

Based on the field trial results, the system will undergo continuous optimization and refinement to improve weed detection accuracy, UV-C exposure efficiency, and overall system performance. This may involve refining image processing algorithms, adjusting UV-C parameters, and enhancing navigation and positioning capabilities.

Scalability and Commercialization

Efforts will be made to explore the scalability and commercialization potential of the proposed system, addressing challenges related to cost-effectiveness, user adoption, and integration into existing agricultural practices.

Conclusion

The proposed precision agriculture application leveraging speckle imaging and UV-C lighting presents a promising approach for sustainable and targeted weed control. By combining innovative technologies, this system aims to minimize herbicide usage, reduce environmental impact, and promote efficient and eco-friendly agricultural practices. While challenges exist, addressing them through rigorous research and development efforts could lead to significant advancements in precision weed management and contribute to the overall sustainability of modern agriculture.

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