High-Precision Laser Weeding System for Lettuce Fields

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Abstract.

The aggressive competition for resources such as sunlight, water, and soil nutrients caused by weeds severely hinders the initial developmental stages of lettuce. To tackle this agricultural issue, this study proposes a self-directed laser weed eradication system combining a compact galvanometer scanner with a deep learning recognition model. Specifically, an enhanced real-time detection architecture, termed YOLO11-GDCNet, was engineered building upon a single-stage pose estimation framework. This model integrates lightweight convolutional modules to lower computational overhead, alongside an attention-driven feature enhancement mechanism to boost the localization accuracy of weed meristems (growth points) amid intricate field environments. Empirical evaluations reveal that the designed network attains a mean average precision (mAP) of 96.9% in pinpointing weed growth centers, operating rapidly with minimal computational demands. Moreover, laboratory validations of the complete laser eradication setup yielded a weed clearance efficacy of 90.8%, while limiting inadvertent crop damage to a mere 2.5%. Ultimately, this research delivers a highly accurate, non-chemical engineering strategy for weed management in lettuce farming.

Keywords.

Laser weed eradication; Lettuce cultivation; Deep learning; YOLO11-pose; Keypoint estimation.

Introduction

The proliferation of weeds acts as a primary constraint on lettuce cultivation, actively competing for vital space and resources during the critical seedling phase (Garibaldi-Márquez et al., 2025; Picon et al., 2022). Conventional mechanical and agrochemical management techniques frequently present drawbacks, such as the potential degradation of soil health and elevated risks of environmental contamination (Wang et al., 2019; M. Zhang et al., 2025). Consequently, laser-based weed control has gained traction as a viable, chemical-free alternative, providing highly targeted suppression with negligible physical impact on crop seedlings. Effective implementation of this technology relies heavily on the precise differentiation between crops and weeds, as well as the exact spatial mapping of their locations. To this end, this research introduces an advanced deep learning model, YOLO11-GDCNet, tailored for the high-precision localization of weed growth centers. Concurrently, a complete laser elimination apparatus featuring a miniaturized galvanometer scanner is constructed to execute targeted, non-contact weed termination.

Materials and Methods

The hardware architecture of the proposed setup is primarily composed of a mobility platform, a visual perception unit, a galvanometer deflection mechanism, and the laser emission source. The perception module relies on an Intel RealSense D435i depth sensor coupled with an NVIDIA Jetson Orin NX edge computing device. The suppression module incorporates a 200 W blue laser generator, an embedded microcontroller, and an independent portable power supply.

The operational workflow of the galvanometer-guided laser framework encompasses continuous image capture, target identification, spatial coordinate conversion, and directed laser firing (Fig. 1). Initially, the D435i sensor acquires visual data from the field, which is subsequently analyzed by the Jetson Orin NX utilizing the YOLO11-GDCNet algorithm to identify weed growth centers. The three-dimensional coordinates of these targets are extracted and routed to the microcontroller unit. This embedded controller then translates the spatial data into precise mirror rotation angles for the galvanometer, accurately steering the high-energy laser beam toward the identified targets.

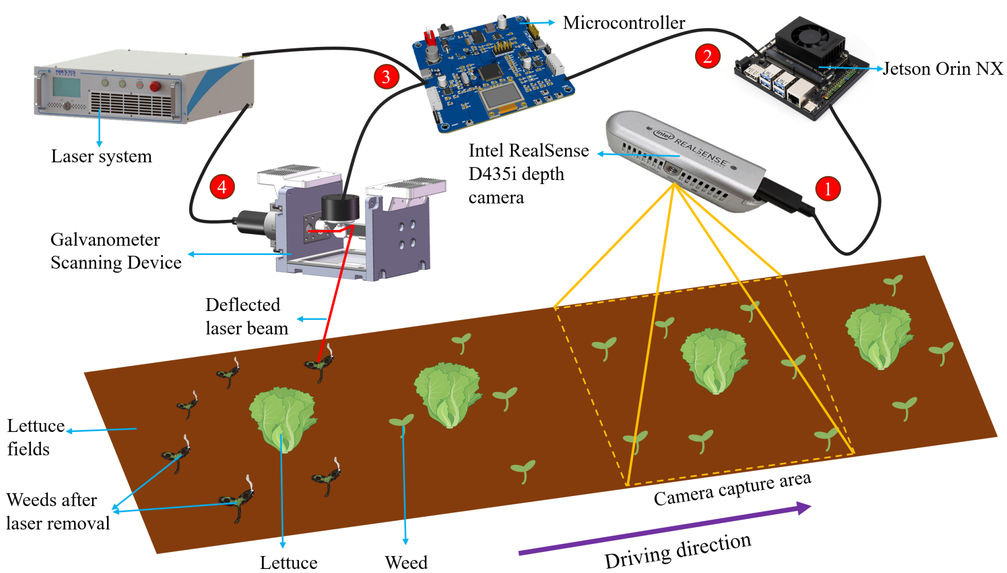

Fig 1. Overall working principle of the laser galvanometer-based weeding system.

YOLO11-GDCNet was constructed adopting YOLO11n-pose as the foundational architecture. To strike an ideal compromise between detection precision and deployment efficiency, GSConv and Dual Convolution (DualConv) blocks were incorporated, effectively lowering processing overhead while reinforcing multi-scale feature integration. Furthermore, a Convolutional Block Attention Module (CBAM) was embedded to dynamically amplify salient features against cluttered agricultural backgrounds. Training was conducted on an augmented dataset comprising 4425 images, thoroughly annotated for lettuce seedlings, whole weeds, and specific weed growing points.

Results and Discussion

YOLO11-GDCNet demonstrated superior performance in localizing weed growth centers compared to baseline models. The customized architecture recorded a mean average precision (mAP) of 96.9%, paired with 96.4% precision and 93.8% recall. In terms of computational efficiency, the model retained a highly streamlined profile, featuring a size of just 5.34 MB and 6.3 GFLOPs of computational demand, while sustaining a rapid inference rate of 95.6 frames per second (FPS).

To substantiate the operational viability of the integrated hardware-software framework, comprehensive laboratory trials were executed. Over the course of 40 replicated test cycles, the vision module accurately tracked 80 lettuce seedlings and 310 weed targets. The laser deflection unit successfully eliminated 297 weeds, translating to an impressive removal efficacy of 90.8%. Concurrently, the high spatial precision of the targeted irradiation restricted the crop injury rate to a minimal 2.5%.

Conclusion

This research successfully establishes an autonomous laser weed management solution that merges YOLO11-GDCNet vision algorithms with a nimble galvanometer scanning mechanism, facilitating eco-friendly and precise weed control in lettuce crops. The optimized neural network delivers remarkable localization accuracy, rapid inference speeds, and a lightweight footprint suitable for edge computing. Empirical testing confirms that directing laser energy specifically at weed growth points effectively neutralizes the threat while safeguarding crop health. This proposed architecture establishes a robust technological cornerstone for the future of intelligent, precision agricultural weeding.

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