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Real-World Deployment of a Dynamic Selective LASER Weeding System Using Multispectral Imagery

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ABSTRACT

The use of chemical treatments for weed control is increasingly challenged by weed resistance, regulatory restrictions on chemicals and the risk of soil and water contamination that can pose health hazards. Chemical weed treatments are unsustainable, prompting exploration of alternative methods such as boiling water, electrocution and directed fire. However, these approaches are limited: water-based treatments require a reliable water supply in the field, and electric or fire-based methods pose additional environmental risks. This work proposes a targeted light amplified stimulation of emission by radiation (LASER) treatment and selective spraying system integrated with automatic weed identification. The system, mounted on the rear of a tractor, utilises a bispectral imaging setup to distinguish weeds from crops. Close-to-crop weeds are automatically selected for LASER treatment, whereas a selective sprayer targets other weeds with a glyphosate globule. This integrated system approach is named 'Hyperweeding'. The results demonstrate successful separation of row crops from weeds, achieving a contamination-free crop with a significant reduction in glyphosate usage, and effectively treating weeds at speeds of 0.1 $m{\cdot}s^{-1}$.

1 | Introduction

Selective weeding strategies have proven to be efficient for future farming weed management [1]. Intrarow weeding, which is technically challenging but significantly increases yield, has attracted considerable research attention over the past decade. Light amplified stimulation of emission by radiation (LASER) weeding, a thermal method for nonchemical weed management, is particularly promising within selective weeding strategies for targeting weeds within crop rows (e.g., intrarow weeds) [2].

One of the many weed control methods that have developed over the decades is the hoe, which has evolved into the automatic cycloid hoe, allowing for automated intrarow weeding [3, 4]. However, hoeing can disturb the soil, potentially redistributing weed seeds without ensuring that they are eliminated, and it may negatively impact the topsoil quality [5]. Other methods, such as salting, burning, electrocution, meristem cell rupture and photosynthesis overload, have also been explored [6]. Burning, electrocution and meristem cell rupture typically affect only the top part of the weed, with heat dissipating into the ground, leaving the roots to potentially regrow.

The use of glyphosate offers a systemic approach to weed control, as the herbicide is absorbed through the leaves and translocated down to the roots, effectively killing the weed. Alternatively, Diquat damages leaf tissue through desiccation and can prevent photosynthesis. However, chemical treatments are likely to contaminate edible crops and leach into watercourses [7]. Recent advances have included efforts to control glyphosate formulation using 'globulisation' to ensure it adheres to the weed leaves without spattering, thereby minimising crop or soil contamination through precise, targeted application [8].

Raising the temperature in plant cells with LASERs which lead to cell wall rupture has shown efficacy, especially when focused on the meristem. Mathiassen et al. [9] compared the effect of two LASER wavelengths, whereas a photochemical approach, which damages the Photosystem II (PSII) reaction within the cell at 680 nm is extensively studied in Ref. [10], including optimising variables such as exposure time, LASER power and spot size to manage the energy dosage.

To achieve selective, dynamic and autonomous LASER weeding treatment, three primary challenges must be addressed: (1) high-speed and low-cost plant identification, (2) optimising the LASER weeding process (including LASER selection, targeting position and treatment duration) and (3) achieving high-speed, high-precision LASER manipulation.

Precise LASER beam control is critical for effective and efficient LASER treatment, and various manipulation techniques have been explored in the literature. One approach used a two-axis deflection device, comprising two galvanometer-controlled mirrors and a focus lens. Nadimi et al. [11] developed an autonomous LASER weeding system using this approach, simulating weed targeting on conveyors. Building on this design, Rakhmatulin and Andreasen [12] developed a cost-effective LASER weeding device and tested it on couch grass mixed with tomatoes. Although these deflection devices offer high precision and are widely used in additive manufacturing, they require a stable setup, which is challenging to maintain in uneven, dynamic field environments. Additionally, in practical field conditions, dust and smoke generated during weed treatment can significantly interfere with mirror reflection and lens deflection, thereby reducing the LASER beam's pointing and focus accuracy.

An alternative approach employs serial mechanisms (SMs), specifically several 2-degree-of-freedom (DoF) SMs, which have been designed to simulate static LASER weeding by manoeuvring a class-I LASER beam in laboratory settings, emulating static LASER weeding [13]. Recognising the dynamic advantages of parallel mechanisms (PMs), Wang et al. [14] proposed a LASER weeding manipulator based on a novel 4-DoF PM, providing 2-DoF rotation and 2-DoF translation mobility, and some of these methods have advanced to field trials involving continuous positioning and tracking [15].

Image processing for weed and crop identification is covered extensively in the literature. More recently, deep learning techniques have been implemented with accurate results [16]. Nevertheless, classical machine learning techniques have also been implemented, and are still relevant due to their lower computational burden compared to deep learning approaches [17]. Weed recognition is achieved using active shape models [18], which have been demonstrated to recognise overlapping leaves, and those which are close to the crop, whereas meristem positions are detected to an accuracy of 3.5 mm, and stereo vision is used to identify plant height and the unevenness of the soil. An active learning system for weed species recognition has been used in Ref. [19], and crop and weed are distinguished using a spectral reflectance differential. A normalised difference vegetation index (NDVI) spectral signature identifies the weeds, and a variety of classifiers are used: one-class, support vector machine (SVM), auto-encoder, mixture of Gaussians (MOG) and self-organising map (SOM). In a review of autonomous weed control [20], a variety of automatic recognition algorithms are compared: biological morphology, shape fit and active shape recognition. Occlusion problems are compensated using the watershed algorithm; and some methods use the spectral characteristics of colour alone with green chromacity (G/R + G + B) (G: green; R: red; B: blue), hyper-spectral imaging and visual texture analysis. However, it is be noted that the focus of this work is not on the weed detection approach, but rather that weed detection is one of the stages of development, and other techniques might be implemented.

From the above, gaps still remain in active weed control, especially with deployment. This work proposes the development, testing and deployment in the field of a self-contained LASER and targeted glyphosate weed treatment system with its own power supply, which can be attached to a manual or autonomous vehicle and meets the rigorous safety specifications of LASER management. Several novel features include that this system has been tested in a field of commercially grown crops, a bispectral lighting is applied for background removal, and a gimbal is developed to improve the guiding of the LASER.

This paper is organised as follows. Section 2 covers an overview of the hardware, including the levelling system, LASER gimbal and imaging unit. Section 3 covers an analysis of the bispectral vision recognition techniques and LASER targeting for optimal treatment. Section 4 covers the results of LASER frequency, dwell times, static and dynamic tests and Section 5 covers the cost and power implications for commercial considerations.

2 | Hardware System Overview

The main components are listed in Table 1 whereas Figure 1 shows the principle of operation of the system. The system is enclosed in an opaque metal hood, and plants are illuminated with a bispectral light source. This is sensed by the camera, and a computer processes the image, defining the weed area to treat. A gimbal is operated to guide a LASER beam using a fibre optic cable, and the LASER is pulsed to treat the weed. Figure 2 shows snapshots of the deployed system. A laptop computer processes the visual information provided by the multispectral vision unit and controls the position of the LASER beam through the LASER manipulation unit (gimbal) as the vehicle is traversing the field. The entire system is enclosed in an opaque metallic box with overlapping flanges. The purpose is to protect people from stray LASER light reflected from reflective objects on the ground, to keep out external light and to protect the components inside. Each of the stages shown in Figures 1 and 2 will be explained in detail in the following sections.

2.1 | MultiSpectral Vision Unit

Plant species have particular spectral frequencies where light will cause the leaf to reflect in a manner unique to that species. By using this spectral fingerprint, a bispectral vision unit is implemented in this work for crop identification. Three main components are included in this unit: a computer, a mono-camera (PointGrey, Grasshopper 3, GS3-U3-41C6M-C, with a wide angle lens, Fujinon CF12.5HA-1) and lighting rig capable of switching

TABLE 1 | Weeding system parameters.

Parameter	Detail
Crop type	Lettuce grown in 'plugs', both green and red (gem)
Camera	Grasshopper 3, GS3-U3-41C6M-C
Lighting	Red and NIR
Image processing	Open computer vision library
Gimbal	5 R-RPM, dynamixel 64-AT motors
LASER	50 W class IV thulium, 1940 nm, 5 mm beam width
Weed eradication intra-row	With LASER, 0.5 s dwell
Weed eradication inter-row	Switchable spray matrix

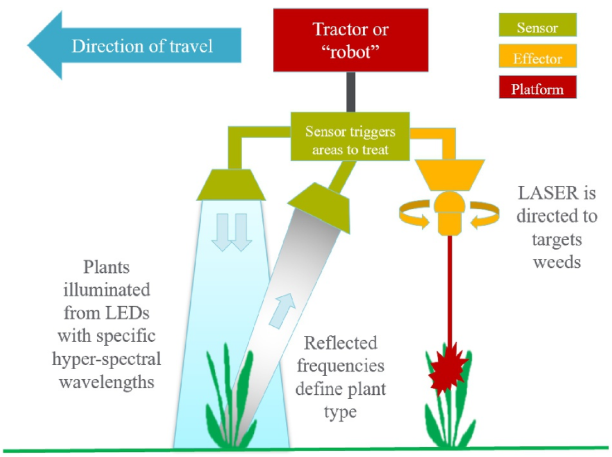

FIGURE 1 | Principle of operation.

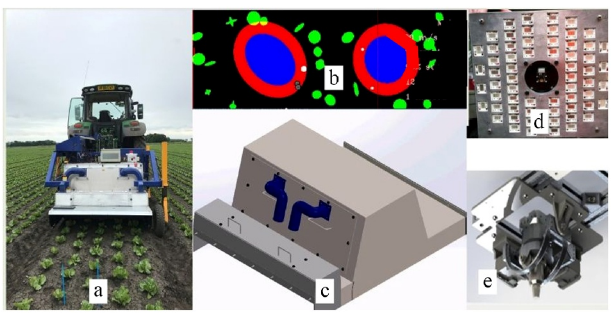

FIGURE 2 | Laser system overview: (a) system in the field towed by a tractor; (b) augmented image showing crop in blue, the close-to-crop area ideal for LASER treatment in red and weeds in green; (c) hood enclosing system; (d) bispectral light source of red and NIR; (e) gimbal LASER guide.

two frequencies of: red at a wavelength of 650 nm and near infrared (NIR) at a wavelength of 850 nm provided by Justar Electronic Technology Co. LTD controlled with a customised Teensy [21] microcontroller board. To highlight anything that is a growing crop or a weed and separate them from the background of soil and other items, including chaff, stones and flint, a combined light of two frequencies is used, with each wavelength activated separately. The high-resolution monochrome camera, which is sensitive in the infrared region, is used to acquire images. Images are collected first by applying a red light source and then immediately followed by a NIR light source. The processing algorithm will be explained in the software system overview section.

2.2 | Laser Manipulation Unit

To achieve the dynamic intrarow LASER weeding, a novel gimbal is designed based on a 2-DoF PM [22]. The full system of five revolute joints (5 R-joints) rotational parallel manipulator (RPM) is shown in Figure 3. The two motors (Dynamixal 64-AT) are mounted on a fixed base as the actuated joints, whereas the beam collimator is connected to the moving platform as the end-effector. It is worth noting that a unique ring guide mechanism (RGM) is proposed in this design, which can provide a large 1-DoF rotation range, allowing the beam collimator and its cable to pass through, as well as preventing possible interference between the manipulator and the cable. The connecting links and the base can also provide the physical constraints to avoid the beam collimator from pointing the LASER upwards. Therefore, this novel gimbal design can meet both the large bending radius requirement of the power cable and the centre of mass (CoM) of the beam collimator to be coincident with the common point of all the rotation axes, as well as a safety requirement in utilising a high-class IV level LASER. As a further safety precaution, the LASER is only active when a weed is recognised and being treated.

2.3 | Hyperweeding System Supporting and Levelling Unit

The lasing system is powered by 48 V batteries with a capacity of 110 A·h, and the LASER output is 50 W with 10% efficiency. It therefore utilises 500 W during operation (10.4 A). The LASER operates for 0.5 s during treatment, and the gimbal takes on average 125 ms to track to a point (giving a total treatment time of 0.625 s). The 50 W class IV Thulium LASER has the ability to adjust the power using a PWM control input. It produces a 5 mm diameter parallel beam with a Gaussian distribution pattern. The wavelength of light is specified to be 1940 nm, which is chosen as being the most effective for treating weeds by rupturing the cell walls due to water absorption and heating. The beam collimator is connected by a flexible fibre optic cable, which is manipulated to aim at the chosen weeds. Since the LASER beam has to exit the enclosure to treat the weeds, the downwards-facing side of the enclosure has to be open. The outdoor LASER system is designed with flanges that block the LASER from escaping and a ring of proximity safety sensors. This has a warning system, emergency-stops and the required signage to enable it to be classed as LASER-safe complying to EN60825 [23]. To mitigate the risk of the LASER light escaping, it was stipulated that the enclosure had to be close to the ground to stop any stray reflections from shiny objects in the soil, such as flint. The growing medium of the crop, which is peat, is known to be flammable and potentially slow-burning for years underground. Calculations involving the power output combined with the maximum dwell time are performed to ensure that combustion cannot occur, and the control programme ensures that the dwell limit is not exceeded.

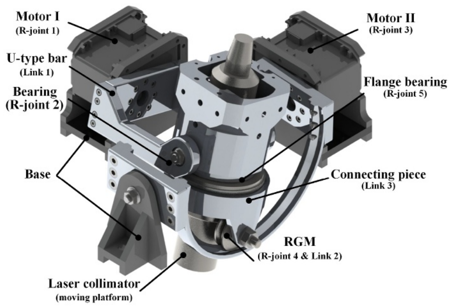

FIGURE 3 | A 2-DOF 5 R-RPM based LASER manipulation unit.

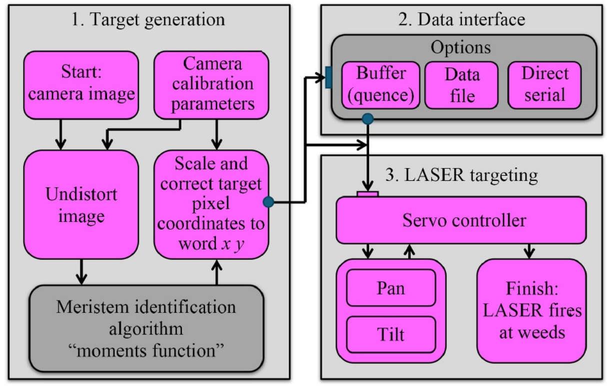

FIGURE 4 | Block diagram of the software system.

3 | Software System Overview

The software system comprises several interconnected components, as depicted in Figure 4. During the target generation stage, the camera captures an image that is subsequently undistorted and scaled to $[x, y]$ coordinates. Weeds are identified, and the meristem detection algorithm maps these into a memory buffer within the data interface section, as shown in Figure 4. During the LASER targeting stage, the system reads the points from the buffer. If the coordinates fall within the LASER's operational range, controlled by the gimbal, the pan and tilt mechanisms are actuated to align with the coordinates and track them dynamically as the weeds move in the $[x, y]$ plane.

3.1 | Target Generation

A single monochrome camera equipped with two active lighting frequencies—red and NIR—is used as shown in Figure 5. Healthy plants absorb red light while reflecting NIR, and this is used to distinguish living matter from the ground using the soil adjusted vegetation index (SAVI) formula [24] as

$$I = \frac{(I_{\text{NIR}} - I_{\text{red}})(1 + L)}{I_{\text{NIR}} + I_{\text{red}} + L}. \quad (1)$$

where I_{NIR} and I_{red} are the pixels from the two images taken by the NIR and the red lighting, respectively, L is the soil correction factor set at 0.5 and I is the corresponding image pixel value. A threshold value of $I > 0.15$ is applied to determine living matter. This system outperforms RGB imaging as it improves the separation of living matter over dry straw, wood shavings, yellowing leaves, wet soil and shadows. This approach is proven to segment both red lettuce (Gem) and green crop.

As the hood moves across the field, the $[x, y]$ coordinates are dynamically updated based on velocity sensed through optical flow of the raw red image component. Additionally, this stores all detected weeds for database file export and provides direct serial connection access for debugging and testing. Since the two images are time-separated, a correcting pixel shift is first applied, which is dependent on the current ground speed and camera height. This coregisters the image data prior to the application of the SAVI formula. A third exposure is taken without illumination, whereby only dots produced by parallel beams from a set of four LASER pointers can be seen. This is used to determine the angle of the hood to the ground and is used to solve any parallax errors.

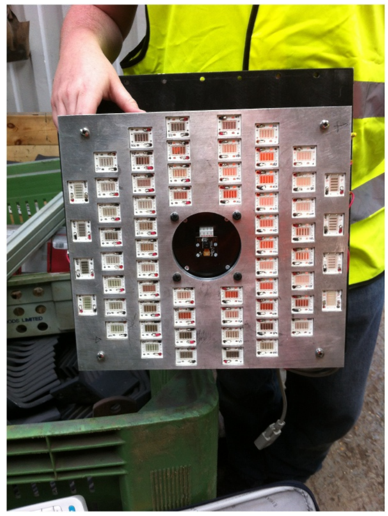

FIGURE 5 | Bi-spectral light source with central camera.

3.2 | Image Processing

The output from the initial image processing algorithms is a binary image with plant matter shown as white pixels against a black background. From this, it is necessary to perform the following actions: distinguish the crop from weeds, and find the meristem.

3.2.1 | *Distinguish the Crop From Weeds*

Mostly, the weeds in the tested areas are *Chenopodium album* (fat hen). The OpenCV vision library is utilised, and objects are represented as contours. This allows various standard operations to be performed, such as filling (which fills voids on leaves caused by specular reflection) and finding the centre of moments of shapes representing weeds. The lettuce crop is planted as plugs in a base field. This is a common method that allows the seed to sprout in a controlled environment and is routinely done before being planted into a weed-free prepared field as a small lettuce. Thus, the seedling has a head start on the weeds. The system is designed to begin operation on early-planted crops, and the crops are thus bigger than the weeds. Any object in the image over a threshold area is assigned the status of 'crop'. The threshold can be set by the operator on the graphical user interface (GUI) of the master laptop. With regular operation, the crops are consistently larger than the weeds, so the default setting does not need adjusting once set.

3.2.2 | Find the Meristem

The meristem is assumed to be at the centre of an object classified as a weed. Using OpenCV's 'moments function', the central $[x, y]$ point can be calculated. This estimate is generally within the effective diameter of the LASER beam, but occasionally a weed will be rendered as disjointed leaves if the stems are too thin. In this case, each leaf will be treated as a separate target.

3.3 | Laser Targeting

The treatment zones are visualised in Figure 6, where the blue area represents the crop, the red zone denotes 'close-to-crop' weeds for LASER treatment and confined to a narrow band of 20 mm surrounding the crop, the green items are weeds designated for spraying and the white objects are 'close-to-crop' weeds targeted for lasing. This 'close-to-crop' region is reserved for LASER treatment rather than chemical applications, keeping the crop free from chemical exposure. Due to the relatively long dwell time of 0.5 s, a complementary chemical treatment ensures comprehensive weed management away from the crop area, as the LASER gimbal does not have the capacity to track them all.

Each weed is flagged in the memory buffer as either 'close to crop' or distant. Using optical flow tracking, the system monitors the hood's movement. When a 'close-to-crop' weed coordinate enters the LASER's range, its location is transferred to a secondary memory buffer for processing, known as the 'data interface'. This secondary buffer queues targets for treatment. The LASER locks onto the target and tracks it for the 0.5 s dwell time, during which the weed could move up to 150 mm relative to the hood. Once treated, the coordinates are removed from the buffer.

To ensure accurate targeting, the LASER is deactivated while transitioning between targets. The high-speed gimbal movement necessitates a settling time before reactivating the LASER and commencing tracking. The gimbal is positioned slightly ahead of the next target, where it awaits the weed's arrival. Only then is the LASER activated, and tracking begins. Weeds outside the 'close-to-crop' region are selectively sprayed using a ten-nozzle system similar to a 'dot matrix' spray printer head. This system opens for 20 ms to spray weeds as they pass beneath. To avoid interference with the camera and lighting system, this spray system is mounted outside the LASER-protected hood area.

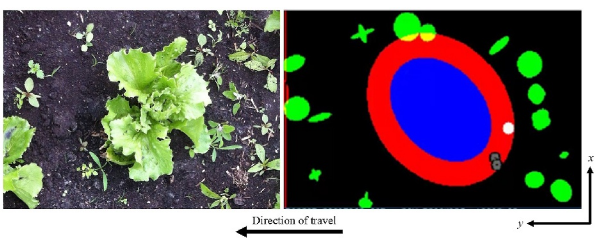

FIGURE 6 | Lettuce with weeds (left) and the target generation results after image processing.

4 | Experimental Results

4.1 | LASER Power and Dwell

The dwell time and power applied are a balance between the power required and the time to affect the weed growth. The system using 50 W for 0.5 s effectively imparts 25 J but without the use of chemicals, and thus ruptures the cell walls of the growth cells.

The system speed is limited due to the LASER power restricting the treatment time taken for each weed (0.5 s at 50 W). However, there are possibilities to increase the velocity since the equation governing energy is directly proportional to the power and time as

$$E = PT, \tag{2}$$

where P is the power in Watts, T time in seconds, and E the energy in Joules. It is the energy rather than the dwell time which ruptures the cell walls, and experiments [10] have taken place which demonstrate that the same amount of rupturing occurs by doubling the power and halving the dwell time. A more powerful LASER can reduce the treatment time by increasing the LASER power proportionally, thus increasing the maximum velocity of the hood. The area width the LASER can treat is 300 mm or one crop row width. To treat the weeds over the entire 950 mm width of the hood, the system would require four LASERs, one for each crop row and these could work in parallel, and one for each row to cover the width of the hood.

4.2 | Static Tests

This consisted of giving a desired static coordinate with a known height. The positioning test results in previous work [22] gave average errors of 0.05° in R-joint 1, 0.10° in R-joint 3 and 0.62 mm in position, respectively, which indicates that the proposed gimbal design is capable of performing desired pointing and targeting with consistently high accuracy.

4.3 | Dynamic Tests

An initial mock-up uses a conveyor in a laboratory environment with images of weeds. The conveyor is set up to simulate a ground speed of 0.1 $\mathrm{m{\cdot}s^{-1}}$, and the weed number is controlled on purpose to ensure that every weed can be treated, thus enabling us to evaluate the LASER treatment/gimbal actuation accuracy. The results in Table 2 show the results of targeting the weed centre, equating to a hit rate of 99.2%. The hit rate is only compromised by the limitation of the gimbal acceleration rather than missing identification. The weeds are treated in the order they appear in the imaging system, but an optimally calculated path will improve function, and further work will seek to optimise the path of the gimbal.

Figure 7 illustrates the field deployment of the system during outdoor trials conducted at a site in Ely, UK. The trials are carried out on Red Gem lettuce, followed by cauliflower, grown with an intrarow spacing of 300 mm. The majority of the

TABLE 2 | Weed lasing test results on a conveyor.

Row number	Treated/Total	Hit rate (%)	Total time (s)	Average weed time/weed (s)	Average positioning time/weed (s)
1	42/42	100	30.5	0.73	0.09
2	41/42	97.6	30.2	0.74	0.10
3	42/42	100	30.1	0.72	0.08

FIGURE 7 | Picture of the field trial, deployed at G's arable land facilities, in Ely, England, United Kingdom.

weeds are fat hen. The length of the treatment zone in the hood is 950 mm, with a width of 425 mm. A tractor pulls the Hyperweeding hood along the field at a steady 0.1 m·s^{-1} using its automated velocity control and driven by a human.

The LASER treats close-to-crop and intrarow weeds, whereas the interrow weeds are treated with a separate spot spray system. Figure 8 shows the intrarow treatment zone, which is approximately 300 mm between crops. Having a speed of 0.1 m·s^{-1} and using a 0.5 s dwell time, it could theoretically treat up to 20 weeds between the crop, and the battery would last 10 hours during this LASER operation. We have carried out a series of field trials. Only one field trial of a pass of the treatment system is reported as an example to evaluate the effectiveness of our proof-of-concept.

Figure 8 shows the treatment resulting from a pass of the treatment system. The weed density intrarow averages 25 weeds, and five remain after LASER treatment, with a success rate of 80%. The treated weeds are observed to be damaged at the meristem, which suggests no further regrowth. The system's scope is to treat lettuce planted as plugs and to apply previous research using LASERs to treat weeds in a commercial field. Weeds that are overshadowed by the lettuce leaves are undetected, but these tend to die off due to competition from the crop.

The conveyor evaluation comprises three independent runs ($n = 3$), each containing 42 weeds, giving a total of 126 targeting events. The aggregated hit rate is 99.2%, with a binomial 95%

FIGURE 8 | Results of the LASER weeding system.

confidence interval of 95.7%–99.9%. All missed treatments are attributable to gimbal acceleration limits rather than detection errors. Although the sample size is modest, the results provide a consistent indication of reliable targeting performance under controlled dynamic conditions. The field trial consists of a single pass through a commercial crop, and we are experiencing more weeds per row to be treated within the treatment zone, so the success rate is reduced accordingly, thus reflecting the exploratory nature of this prototype deployment. The intrarow weed population is dominated by fat hen, preventing a meaningful per-species breakdown. Across the trial, the intrarow density averages 25 weeds per crop spacing, of which five remain after treatment, corresponding to an observed success rate of 80% (95% confidence interval: 63%–92%). No crop damage attributable to the LASER is observed during or after the pass. As a single-pass evaluation, these results should be interpreted as a feasibility demonstration rather than a statistically powered agronomic assessment. Future work will include replicated multifield trials to quantify performance across weed species, growth stages and environmental conditions.

5 | Conclusions

The field trials demonstrate that the prototype LASER-based system provides an effective close-to-crop nonchemical weeding method. During testing, the hood advances at a conservative speed of 0.1 m·s^{-1}, selected to ensure safe operation while validating perception, targeting and control algorithms. Although this speed is not intended for commercial deployment, it enables reliable evaluation of the LASER–weed interaction. Slower traversal will increase the number of weeds treated, and future implementations can incorporate real-time weed density measurements to dynamically adjust forward speed and optimise treatment efficiency.

Manual organic weeding, typically performed using mechanical hoeing, costs approximately 1000 GBP ha^{-1} per pass and requires 2–3 d of labour. As this process is usually repeated three times per growing season, the total seasonal cost is around 3000 GPB ha^{-1}.

The prototype LASER system has a capital cost of 15,000 GPB (including 12,000 GPB for the LASER unit) and, at the prototype speed and a single-row treatment width, requires 1.27 $d \cdot ha^{-1}$ of continuous operation. Because field capacity scales approximately linearly with both forward speed and treatment width, multirow configurations offer substantial gains. For example, a four-row hood operating at 0.5 $m \cdot s^{-1}$—a conservative commercial target—would reduce the time per hectare by a factor of 20, to approximately 0.064 $d \cdot ha^{-1}$ ($\approx$1.5 $h \cdot ha^{-1}$).

This capacity is comparable to existing mechanical weeding systems while retaining the advantages of selective, nonchemical weed control. Labour availability in organic systems is increasingly constrained by rising costs, recruitment challenges and additional administrative burdens such as accommodation, insurance, pensions and sick-pay obligations. These pressures further shorten the effective payback period of automated systems. The LASER platform is inherently scalable through the addition of parallel LASER channels and wider hoods aligned with crop row spacing, and its operational characteristics make it well suited to full or near-full automation.

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Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

All relevant data are included within the article.

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