AgriEngineering

Article

Development and Evaluation of a Laser System for Autonomous Weeding Robots

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Abstract: Manual weed control is becoming increasingly costly, necessitating the development of alternative methods. This work investigates the feasibility of using laser technology for autonomous weed regulation. We developed a system utilizing a laser scanner to target and eliminate weeds, which was first tested using a pilot laser for accuracy and performance. Subsequently, the system was upgraded with a high-power fiber laser. Experimental results demonstrated a high weed destruction accuracy with real-time capabilities. The system achieved efficient weed control with minimal environmental impact, providing a potential alternative for sustainable agriculture.

Keywords: laser; autonomous weed control; fiber laser; image processing; agricultural technology

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Citation: Czymmek, V.; Völckner, J.; Hussmann, S. Development and Evaluation of a Laser System for Autonomous Weeding Robots. *AgriEngineering* **2024**, *6*, 4425–4441. https://doi.org/10.3390/agriengineering6040251

Academic Editor: Simone Pascuzzi

Received: 9 October 2024
Revised: 14 November 2024
Accepted: 18 November 2024
Published: 22 November 2024

1. Introduction

Organic farming has increasingly sought to minimize the use of chemical herbicides, responding to both environmental concerns and consumer demand for cleaner food products [1]. This shift necessitates the development of effective non-chemical weed control methods [2]. For example, at present, the weeding regulation on carrot fields in organic farming is done by hand. This manual weed control is very expensive. Our cooperation partner Westhof Bio GmbH in Germany for example spends over 190,000 EUR per year for manual weed elimination by human workers [3]. Furthermore, it is more and more difficult to find workers for this task. Due to the high level of component wear in mechanical weed control, research into alternative methods and innovative approaches such as laser-based weed control systems are required.

Laser weeding, an emerging technology, offers a precise, non-chemical method for weed control by using focused laser beams to damage the cellular structure of weeds, effectively killing them without disturbing the soil or affecting nearby crops. Early research demonstrated the potential of using CO_2 lasers for weed control [4], with significant weed mortality achieved under controlled conditions [5]. Subsequent studies explored the use of different diode lasers to optimize the effectiveness of laser weeding systems in various crop environments [6,7]. In [8], the effect of different laser wavelengths was investigated using four different laser systems: a gas laser (CO_2, 10,600 nm, qcw—quasi-continuous-wave), a fiber laser (Tm, 1908 nm, qcw), a diode laser (InGaAs, 940 nm, cw—continuous wave), and a solid-state laser in frequency-doubled mode (Nd:YAG, 532 nm, pulsed). The laser wavelength strongly influenced the thermal coupling and the minimum lethal doses. Even with comparatively low efficiency, the CO_2 laser system still had the lowest energy demand. To summarize, it can be said that the energy requirement for weed control with the laser is around 20% compared to flaming, assuming a weed density in the row between the crops of 50 plants per 1 m^2 and a requirement of 50 kg of propane gas per 1 ha. Effective weed control was possible up to a growth around the two-leaf stage.

Recent advancements in laser technology, particularly the development of fiber lasers, have enhanced the feasibility of laser weeding systems. Fiber lasers offer greater efficiency and precision compared to traditional CO_2 lasers, making them more suitable for integration into autonomous platforms. These lasers have been shown to effectively target and eliminate weeds with minimal energy consumption, making them ideal for sustainable agriculture applications [9].

In addition to the technological advancements in laser systems, the integration of real-time image processing and artificial intelligence (AI) has significantly improved the accuracy of weed identification and targeting. Convolutional neural networks (CNNs), for example, have been successfully implemented in weed detection systems, enabling real-time classification and targeting of weeds in complex field environments [10,11].

This study aims to develop and evaluate a laser-based weed control system integrated into an autonomous robotic platform. The system is designed to offer a cost-effective and sustainable alternative to manual weed control in organic farming. By leveraging the precision of fiber lasers and the power of AI-driven image processing, this research seeks to address the current challenges in weed management and contribute to the broader goal of reducing chemical inputs in agriculture.

2. System Design and Development

2.1. System Requirements

The development of a laser-based weed control system requires a detailed understanding of the agricultural environments in which it will operate. Specifically, the system must address the variability in crop types, weed species, and field conditions. For instance, the system must be capable of distinguishing between closely related weed species and crops that have similar physical characteristics. Furthermore, the system must function effectively under different environmental conditions, such as varying light levels, soil types, and moisture content. Environmental conditions, such as fog and extreme temperature fluctuations, can influence the optical system by scattering the laser beam or reducing image clarity. These conditions may necessitate real-time adjustments to the system's settings to maintain accuracy and efficiency in weed detection and elimination. In Figure 1, our developed multi-track automated weeding robot is shown. The robot is driven by solar power. A diesel generator is used to power the modular weeding units. The pressure tanks are required for the weed removal tools.

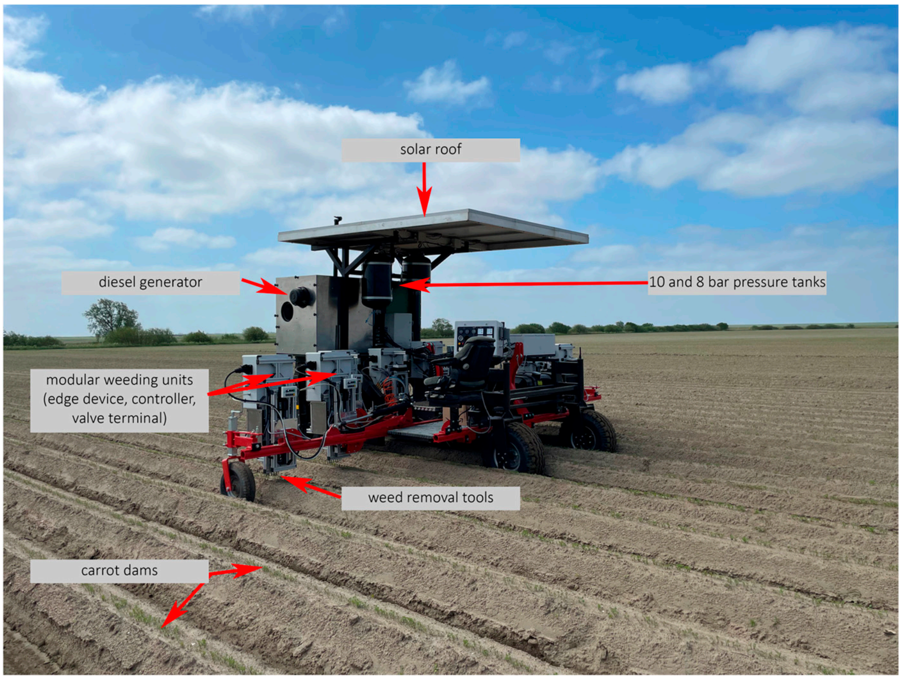

Figure 1. The multi-track weeding robot on a carrot field of our cooperation partner Westhof Bio GmbH in Friedrichsgabekoog, Germany.

The platform's mobility and navigation capabilities must be robust enough to handle irregular terrain while maintaining the precision necessary for effective weed control. Autonomous navigation systems, such as GPS and inertial measurement units (IMUs), are integrated into the platform to ensure accurate path following and obstacle avoidance.

A key requirement is the system's ability to operate at a commercially viable speed while maintaining high accuracy in weed destruction. This necessitates a laser system with rapid response times and an image processing system capable of real-time analysis. The target weed destruction time is set at 36 ms per weed, which aligns with the operational speed of 1 km/h.

The natural conditions influence the approach to destruction. Carrots are grown in a ridge culture. These ridges run parallel across the field at a distance of 75 cm. The dams have a trapezoidal structure with a height of 15 cm and a top width of 12 cm. The dam structure is shown schematically in Figure 2. The system must only work on a long, 12 cm wide track. The right side shows this working area with the points from above. The dimensions given are approximate values; the actual value may deviate from these due to several factors such as erosion due to wind and rain.

Figure 2. Typical structure of the carrot dam with on-top view.

The sowing method for carrots makes weed control more difficult, as the seed is spread as a scattering, which means that the positions of the carrot seeds and weeds are randomly distributed. This means that every weed must first be recognized for destruction. This can either be done manually by a human or via a computer with a camera. Shortly before the crop sprouts from the ground, the weeds are removed. This initially kills all the plants on the dams, which means that at the time of weeding, weeds and crops are approximately the same size. Depending on the stage of growth, the robot shown in Figure 1 with the destruction units is used approximately 10 days after sowing. The aim of weeding is to ensure that as many of the planted crops as possible bear fruit. The presence of weeds close to a crop leads to a battle between the two for nutrients and water. As soon as the crop plant reaches a certain size, weeding is no longer necessary because the roots of the crop plant are deep enough in the soil and overshadow the weeds. The crop plants are sown at a density of 150 seeds per running meter. Around 100 to 120 of these will grow out and the rest will die for various reasons. The reason for this can be the presence of weeds, a short distance between the crops, or poor weather conditions. The weed density on the dam surface per meter varies greatly due to natural conditions such as temperature and humidity. However, it is usually between 50 and 150 pieces. Many different weeds occur in the field, making it impossible to specialize in one particular species. Commonly occurring species are knotweed and chamomile, which make up a large proportion of the weeds. The size of the weeds is very small as a result of the weeding and early destruction. Figure 3 shows an illustration of different weed types and soil conditions. The size of the individual leaves is rarely larger than 2 mm × 4 mm. If these weeds are not destroyed, they can grow to a height of up to 1.5 m horizontally or upwards.

Figure 3. Illustration of common weed types found in organic carrot farming, including knotweed and chamomile.

2.2. Analysis of Existing Technologies

There are currently several companies and research groups working in the field of autonomous weed control. Almost all projects and companies are looking at destruction using a laser. For example, the companies Weedbot [12] and Carbon Robotics [13] offer commercially available units. Depending on the type of utility plant, the mechanical structure, laser power, and control system can differ greatly. Both companies make their products available for the processing of carrots. This makes it possible to establish a good reference for the unit to be developed, as it will initially be used for carrots and later for other crops.

The systems offer to either drive autonomously or be pulled by a tractor. As Carbon Robotics claims a higher speed and better accuracy for its unit, the system is discussed in more detail below. Accuracy and speed are the two most important factors in terms of cost-effectiveness. With a speed of 1.6 km/h, the robot from Carbon Robotics can process up to two hectares per hour. To do this, it is equipped with 30 CO_2 lasers, which have an output of 150 W and a shaft length of 10.6 m. These make it possible to destroy up to 55.5 weeds per second. This means that one laser destroys approx. two weeds per second, resulting in a destruction time of around 500 ms per weed. With 12 high-resolution cameras, the system has a destruction rate of 99%, and only 1% of useful plants are destroyed [13].

In addition to these two companies, there are others, such as Escarda Technologies [14]. However, they do not yet provide any information about the systems, except that these are also laser weed control systems with artificial intelligence for weed detection. The schematic structure of all systems is very similar. Pictures are taken with a camera and an artificial intelligence recognizes the weeds. The computer then controls the laser, which destroys the weeds. No information is known about the type of laser beam guidance used by the companies. However, there is another robot prototype that uses a delta robot to position the laser [15]. In all of these developed systems, the laser is not continuously active. It is triggered only when a weed is detected in the system's field of view, preventing continuous heating of the soil and minimizing the risk of drying or damaging the upper soil layer. This approach ensures that energy is conserved and the impact on the surrounding environment is minimized.

In summary, there are currently several companies offering commercial automated systems for weeding carrots and other crops. These rely on CO_2 lasers, reach a maximum speed of 1.6 km/h, and have an accuracy of approx. 1 mm. Further systems from other companies are also under development.

3. Laser Selection and Hardware Integration

The technical principles relevant to the project are outlined and explained below. The focus is placed on laser technologies, as these form the main part of this work.

3.1. Laser Selection

First, the general operation of a laser is described, and then the types of lasers considered for this application are discussed. A laser consists of three main components. An active laser medium, in which photons are generated with a pump source, and a resonator, which amplifies the generated laser power. In the case of stimulated radiation emission, an electromagnetic radiation field interacts with the particle. This interaction occurs when the energy of the radiation matches the transition energy required for the particle to move from one energy state to another [15].

The transition energy of the particle is transferred to the electromagnetic wave and the particle returns to the lower energy state. During this process, the original wave is amplified without any changes to its frequency or phase. To achieve an amplification of the laser beam, a population inversion must be present in the active laser medium. This means that more particles are present at a higher energy level than at a lower energy level. In this scenario, the stimulated electromagnetic wave is not absorbed by the particles in the lower energy state, allowing it to pass through and contribute to the amplification process. It is not possible to generate an occupation inversion without an external energy input [16].

The methods for achieving population inversion vary depending on the active laser medium. For example, optical pumping uses photons to excite atoms or molecules to higher energy states. The pumping system uses two different energy levels of the particles, and excitation can also occur through electron discharge in a gas laser, where electrons of specific energy are used to pump the laser medium [17]. The use of a pump system, which only uses two different energy levels, is not possible, as the forward and reverse reactions are identical, and therefore no occupation inversion can be established. This is the case because the excitation mechanisms also allow the particles to discharge again. Four-energy level systems are therefore usually used. In these, only one transition is used for stimulated emission, the other two occur through non-radiative processes [18].

To generate a highly directional beam, a resonator is used which gives the radiation a preferred direction in the laser-active medium. The structure of the resonator influences the divergence, the beam diameter, and the intensity distribution of the laser beam [19]. There are many different lasers with different properties. These differ mainly using different laser-active media. Several characteristic parameters are used when comparing lasers. The most important properties are the wavelength of the generated radiation, power, operating mode, efficiency, and beam divergence. The beam profile indicates the energy distribution in the cross-section of the laser beam, which can follow a Gaussian distribution, be evenly distributed, or be largely at the edge [20]. In this work, we focused on two types of lasers—CO_2 and fiber lasers—and compared them to determine which is best suited for our application.

3.1.1. Fiber Laser

In a fiber laser, a laser fiber forms the active laser medium, from which the name is derived. This consists of a glass fiber in which the active core is doped with rare earth ions. The doping material determines important properties of the laser, such as the emitted wavelength. The pump radiation in the pump core is continuously absorbed in the laser core. This allows the generation of single-mode laser radiation using multimode pump radiation [21].

The absorption of the pump radiation in the laser core is relatively low in fully concentric double-core fibers. This structure increases the energy transport from the pump core into the active core. The resonator of a fiber laser is formed by two fiber Bragg gratings (FBG). These are formed by a periodic variation of the refractive index in a glass fiber. The rectified wavelength of an FBG depends on the period of the grating Λ and the effective refractive index n_{eff} of the fiber. For a single-mode glass fiber, the wavelength is calculated using Formula (1). An FBG therefore works like a wavelength-selective mirror in the glass fiber [22].

$$\lambda_B = 2 \times \Lambda \times n_{eff} \quad (1)$$

Only a certain frequency is reflected. This means that only this wavelength is used for amplification in the active laser medium. This enables very narrow-band laser operation.

3.1.2. CO_2 Laser

With a CO_2 laser, a gas rather than a solid is used as the active laser medium. In the case of a CO_2 laser, carbon dioxide is used as the active laser medium. In this gas, the laser transition does not take place between the energy states of electrons, but between vibrational energy levels of the molecules. A CO_2 molecule can perform three different vibrations. The energy in the molecular vibrations is quantized and can therefore only assume discrete values. Due to the displacement of charges during oscillation, the molecule acts as an antenna and can thus absorb or emit electromagnetic radiation. Due to these properties, the vibrational states of the molecule are used as energy levels for the stimulated emission. The most frequently occurring energy state of the CO_2 emits a wavelength of 10.6 μm [17].

3.2. Laser Energy Absorption of Plants

When a laser beam is absorbed by a plant, the energy of the laser beam is taken up by the plant. The absorbed energy leads to the heating of the plant. The penetration depth of the beam depends on the wavelength of the radiation. The mid-infrared radiation (MIR radiation) of a CO_2 laser is absorbed at the surface of the plant and can cause burns there. In contrast, shorter near-infrared radiation (NIR radiation) penetrates deeper into the plant tissue and causes damage there [23]. The damage to the plant from heating occurs through the denaturation and aggregation of proteins. As a result, the permeability of the cell membrane increases, leading to its destruction. The direct influence of heat also harms the plant by drying out the tissue. Lethal damage to cells begins at a temperature of 55°C [24]. With low energy input, the energy is insufficient to destroy the plant. At medium energy levels, cell destruction and evaporation of cell water occur, resulting in the wilting of the plant. When the energy input is high enough, the plant is burned and thus destroyed. Insufficient energy is therefore not effective, as it does not lead to the wilting of the plant. Likewise, too high an energy input is inefficient, as the increased energy and time investment do not provide a direct benefit for the destruction.

The energy required to destroy a weed depends on other factors. The growth stage, the position of the laser, the size of the laser spot, and the type of weed also have an influence on the lethal energy required. The influence of these parameters was investigated in [25]. The required laser energy in joules for a 95% probable lethal damage was determined. Two different weeds were used in the experiment, the millet (*Echinochloa crus-galli*, ECHCG) and the bent-back amaranth (*Amaranthus retroflexus*, AMARE). Millet is a monocotyledonous plant, and amaranth is a dicotyledonous plant. For both, the growth stage was varied. The results show that the lowest energy is required for a small beam diameter, a high degree of coverage, and the smallest growth stage. The laser beam used in these tests had a diameter of approximately 1.5 mm, ensuring precise targeting of small weed leaves. It is also noticeable that the dicotyledonous plant requires on average less energy for destruction than the monocotyledonous plant. The energies required range from 25 J to 278 J. The probability of destruction as a function of the energy used follows a normal distribution [4]. As a result, beyond a certain destruction probability, increasing the energy input is no longer efficient, as it would lead to a reduction in travel speed.

3.3. System Architecture of the Laser Unit

The laser chosen for this system is a 50 W Thulium fiber laser from Futonics Laser GmbH, Katlenburg-Lindau, Germany [26], operating at a wavelength of 1940 nm. This specific wavelength was selected due to its high absorption in plant tissues, which is essential for the effective destruction of weeds. The energy absorption properties of the Thulium fiber laser are particularly suited for agricultural applications, as the wavelength is absorbed efficiently by water in the plant cells, leading to rapid heating and cellular destruction.

Fiber lasers offer several advantages over traditional CO_2 lasers, which have been used in earlier weed control systems. CO_2 lasers, operating at a wavelength of 10.6 μm, require more power and have a bulkier design. While they have a higher absorption coefficient for certain plant tissues, their larger size and lower energy efficiency (around 10%) make them less practical for mobile, field-based applications. In contrast, fiber lasers have a compact form factor, are more energy-efficient (up to 30%), and are more robust, requiring less maintenance due to fewer optical components [27]. These factors make the Thulium fiber laser a better fit for integration into the autonomous weed control platform.

For this prototype, a 50 W model was selected to investigate the feasibility of weed destruction. This power level is sufficient for initial tests, with the possibility of scaling up to higher-power lasers in the future to increase weed destruction speed. Models with up to 250 W are available for Thulium fiber lasers, and CO_2 lasers can reach up to 500 W, but the 50 W model balances energy consumption with the required power for efficient field operation.

In summary, the Thulium fiber laser was selected for its superior energy efficiency, compact design, and ability to deliver precise, high-energy pulses required for weed destruction. The laser control system is designed to ensure fast and reliable operation, making it suitable for integration into the mobile autonomous platform for field-based weed control.

4. Software Development and Image Processing Methods

4.1. Image Processing and Plant Detection

In [10,11,28], we already published our results for the weed detection and different image processing techniques. This is critical to the system's ability to distinguish between crops and weeds in real time. The process begins with image capture using high-resolution cameras. These images are then preprocessed to enhance contrast and remove noise, making it easier for the neural network to accurately classify plants.

The segmentation process is particularly important in fields with dense weed coverage or overlapping plant canopies. The CNN used in this system has been trained on a large dataset of labeled images, allowing it to achieve high accuracy even in challenging conditions. After segmentation, the system classifies each plant as either a weed or a crop. The classification results are then used to generate bounding boxes around the weeds, which are sent to the laser control unit for targeting. The entire process is optimized to run in real time, ensuring that the system can operate at the desired speed without sacrificing accuracy. The proposed method was able to detect the weeds in real time at up to 56 FPS, with a modified YOLO approach, which is an important feature for the development of modern smart farming applications. A lower precision was accepted in favor of a higher calculation rate of about 56 FPS. The best average precision of 75.07% was achieved at 18.65 FPS and an input size of 832 $\times$ 832 pixels. The detection speed can be adjusted to the application's accuracy requirement to maximize the detection speed. The proposed method shows that it is flexible and robust.

4.2. Laser Control and Targeting

The laser control system is designed to deliver precise pulses to the target areas identified by the image processing unit. The microcontroller, which manages the laser unit, calculates the exact coordinates for laser targeting based on the bounding boxes generated during the image processing phase.

One of the key challenges in laser control is ensuring that the pulses are delivered with the correct energy and duration to effectively kill the weed without damaging nearby crops. The system dynamically adjusts the laser's power and pulse duration based on the size and type of the weed, as well as the environmental conditions. Therefore, the laser is controlled using an analog interface, which minimizes delays in laser emission. This is critical for real-time weed targeting, as any delay could result in missed targets or damage to surrounding crops. The analog control method was chosen over digital options due to its lower emission delay.

The control system uses an operational amplifier to increase the 3.3 V output from the used edge device (NVIDIA Jetson Xavier, Santa Clara, California, USA [29]) to 7.6 V, which is required to operate the laser at a maximum power of 50 W as shown in Figure 4. The operational amplifier is configured as a non-inverting amplifier, and the voltage increase is achieved by adjusting the ratio of resistors in the circuit.

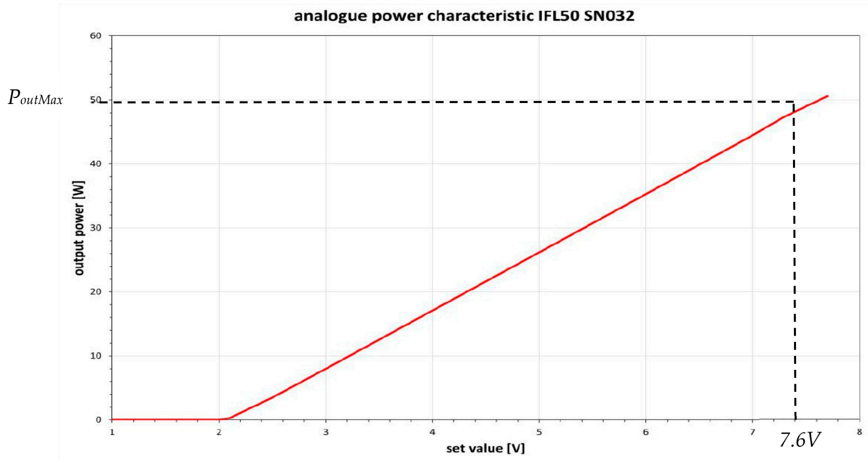

Figure 4. Analog power characteristics of the laser [26].

An important part of destroying weeds with a laser is guiding the laser power to the weeds. The laser beam in the system is controlled and deflected using a scan head, which enables the laser to cover a two-dimensional surface area for weed destruction. The scan head utilizes a mirror-based system where two orthogonal mirrors are driven by a galvanometer to continuously move the laser beam across the surface. The operation of the scanner is shown in Figure 5. The scanner used in this study has a beam divergence of 0.1 mrad, achieves a beam diameter of approximately 1.5 mm, and can process an area of approximately 21 cm × 21 cm when positioned 40 cm above the ground, with a positioning speed of up to 2000 mm/s at a height of 1 m.

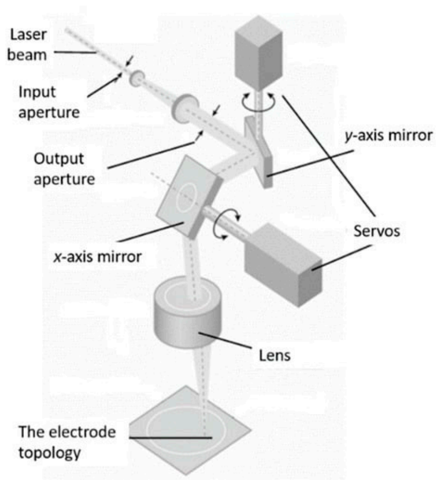

Figure 5. Structure of a laser scanner [30].

The scanner is controlled via the XY2-100 protocol, which transmits the X and Y coordinates as 16-bit data words. The protocol allows for data transmission speeds of up to 2 Mbit/s, equating to 100,000 coordinates per second. The signal path requires four data channels for X and Y coordinates, a clock signal, and a sync signal, resulting in eight physical connections due to differential transmission. The scanner reads data at the falling edge of the clock signal, and transmission terminates when the parity bit is present and the sync signal goes low [31].

In terms of software implementation, the control system is developed in C++ to translate image coordinates into scanner coordinates for precise control. The coordinates are converted into the scanner's format, and 32-bit variables are used to represent the X and Y data channels. A parity check ensures data integrity during transmission, and the conversion process adjusts for the scanner's requirements, ensuring accurate laser targeting.

A Jetson Xavier is used to generate the necessary signals to control the laser scanner. This implementation leverages Xavier's GPIO pins, eliminating the need for additional hardware and keeping the system's complexity low. Signal generation occurs in a separate thread operating in freerun mode, ensuring continuous operation without interruption. Signal control is handled by a dedicated class with two key functions: an update function that writes coordinate transfers to the GPIO pins and a function that calculates the data to be transmitted. The system uses a ping-pong buffer to allow new data to be calculated while the current data is being transmitted, improving efficiency and reducing delays.

Due to the protocol's requirement for differential signals, an RS-485 differential line driver is used to convert single-ended signals into the necessary differential format. This setup allows for stable, high-frequency transmission of control signals to the scanner.

During testing, the Jetson Xavier achieved a maximum clock rate of 1.9 kHz, allowing data transmission at 95 Hz. While this rate is lower than the maximum permitted by the protocol (2 MHz), the system maintained correct transmission despite some fluctuations in signal speed. The limited speed of the GPIO pins, however, affects the ability to steer the laser quickly enough for high-speed operations, which could pose a constraint in scenarios requiring rapid scanning and targeting.

Safety is also a critical consideration in the design of the laser control system. The software includes multiple fail-safes to prevent accidental laser activation, ensuring that the laser only acts when it is correctly aligned with a weed. Additionally, the system continuously monitors the platform's speed and position to maintain precise targeting even as the platform moves through the field.

4.3. Calibration Development

In order to accurately target and destroy weeds, the system must convert the image coordinates of the weed-bounding boxes into the corresponding laser scanner coordinates. This is achieved through a calibration process using a pilot laser, which is visible via the camera, allowing the high-power laser's path to be traced and aligned. The pilot laser is closely aligned with the main laser's optical path, ensuring that any calibration or adjustments made with the pilot laser directly correspond to the operational behavior of the main laser. This alignment minimizes discrepancies between the two systems.

4.3.1. Coordinate Transformation

The camera and laser scanner operate in two-dimensional coordinate systems that can be shifted and scaled relative to each other. To simplify the calibration, the mechanical setup ensures that there is no rotation or tilt between the two systems, leaving only scaling and translation factors to be determined. The calibration process involves identifying two points with known coordinates in both systems. By moving the scanner to two different positions in the camera's field of view, the corresponding coordinates in both the image and scanner coordinate systems are recorded. These points are then used to calculate the scaling factor and translation between the systems. The scaling factor, which defines the relationship between the distance in the camera image and the distance in the scanner system, is calculated as:

$$\mathrm{SF_x} = \frac{\mathrm{Scanner2_x} - \mathrm{Scanner1_x}}{\mathrm{Image2_x} - \mathrm{Image1_x}} \tag{2}$$

where:

- $\mathrm{SF_x}$ is the scaling factor for the x-axis.
- $\mathrm{Scanner1_x}$ and $\mathrm{Scanner2_x}$ are the x-coordinates of the two points in the scanner coordinate system.
- $\mathrm{Image1_x}$ and $\mathrm{Image2_x}$ are the x-coordinates of the same points in the image coordinate system.

Similarly, the scaling factor for the y-axis can be computed using the same approach. The translation, which accounts for the displacement of the origins of the two coordinate systems, is calculated using:

$$\text{ScannerBase}_x = \text{Scanner1}_x - \text{Image1}_x \times \text{SF}_x \tag{3}$$

This equation gives the X-coordinate of the upper-left corner of the camera's image field in the scanner coordinate system. A similar calculation is performed for the Y-axis. Once the scaling factor and translation are known, any image coordinate can be transformed into a scanner coordinate using

$$\text{ScannerCoord}_x = \text{ScannerBase}_x + \text{ImageCoord}_x \times \text{SF}_x \tag{4}$$

This equation converts the X-coordinate from the camera image to the corresponding scanner coordinate. ImageCoord_x represents the x-coordinate of the detected weed in the camera's image coordinate system. The same method is used for the Y-coordinate. However, due to differences in angles and heights between the scanner and camera, the accuracy of this conversion can be affected by height differences. If the distance to the ground changes significantly, recalibration is required. Alternatively, periodic recalibration can be performed to account for variations in plant height.

4.3.2. Image Processing for Laser Dot Identification

The position of the pilot laser in the camera image is essential for calculating the coordinate transformation. A dedicated class for image analysis processes the camera images and identifies the laser dot through a thresholding method. The laser point is identified by applying a threshold to the color channels of the image, focusing on the green channel (since the pilot laser is green). The thresholding process converts the image to a binary format where pixels are either "on" or "off". For the green laser, the threshold function evaluates whether the value of the green channel is above a set threshold, while the values of the blue and red channels remain below their respective thresholds. The pixel is considered part of the laser point if:

$$\text{Threshold}_{\text{green}} > 210, \text{Threshold}_{\text{blue}} = 0, \text{Threshold}_{\text{red}} = 0 \tag{5}$$

This method isolates the bright green laser dot from other elements in the image. Additionally, a brightness threshold can be used by calculating the grayscale value of each pixel:

$$\text{Vgray} = \text{Vblue} \times 0.144 + \text{Vgreen} \times 0.587 + \text{Vred} \times 0.299 \tag{6}$$

However, the color-based thresholding method was found to be more effective in identifying the green laser dot. The system applies morphological operations (erosion and dilation) to remove small artifacts, such as soil particles or stones, from the image. The erosion process reduces the size of white areas in the binary image, removing noise, while the subsequent dilation restores the laser dot's shape. Once the image is processed, the X and Y coordinates of the remaining white pixels (the laser dot) are averaged to determine the laser point's position. This position is then used for calibration, ensuring the camera and laser coordinates are correctly aligned. Finally, the image analysis class provides the option to display the binary image after processing to verify the correct identification of the laser point, allowing for a visual check of the calibration process.

4.4. Tracking Development

A tracking algorithm is developed to connect the bounding boxes of weeds across successive frames, allowing the system to keep track of which weeds have already been processed by the laser. Since weeds may still be recognized by the classifier shortly after being treated, the algorithm prevents the system from unnecessarily reprocessing them, thus saving time and energy. The tracking process relies only on the properties of the bounding boxes, such as the coordinates of the top-left and bottom-right corners, rather than the actual image data. This simplification reduces computational overhead and allows the system to operate with a higher refresh rate, enabling more efficient tracking of weeds in real time.

The tracking algorithm begins by receiving the bounding boxes generated by the classifier. Any boxes that do not fully contain weeds or are only partially visible in the camera's field of view are discarded to avoid inaccurate classification. The algorithm then checks whether the weed in each bounding box has been previously tracked by comparing it to an array of stored weeds. If a match is found, the coordinates are updated. If the weed is new, its data is added to the array.

Since the classifier may not detect a weed in every frame, the algorithm keeps track of the number of frames since each weed was last recognized. A maximum threshold is set based on the travel speed of the platform, frame rate, and the camera's field of view. In this case, the threshold is calculated as 13 frames, using the formula:

$$\text{Frames} = 0.12\ \text{m}/(0.277\ \text{m/s}) \times 30\ \text{Frames/s} = 13\ \text{Frames} \tag{7}$$

Weeds that have not been detected for more than this number of frames are deleted from the array. After pruning old data, the system identifies the next weed to be processed. It selects the bounding box with the highest Y-coordinate (closest to the edge of the camera view), ensuring it prioritizes the weed that will soon leave the camera's field of view.

5. Experimental Results and Performance Evaluation

The system was tested by mounting it on our autonomous field robot illustrated in Figure 1 with adjustable wheels, allowing it to navigate various field conditions. The initial tests were conducted without using laser power, relying only on the pilot laser to verify the system's functionality and safety.

5.1. Initial Testing with Pilot Laser

The first tests used the pilot laser to confirm the accuracy of calibration, coordinate conversion, and laser spiral generation. These tests were conducted on static, printed test weeds. The main objective was to verify the intersection of the laser's spiral with the weed, as this is critical to ensure proper energy input for effective weed destruction. The accuracy of the system was evaluated by recording the pilot laser's movement with a camera, superimposing the images, and marking the laser points. The analysis showed some positioning errors, particularly at the edges of the image, due to the non-linear distance between scanner coordinates. This resulted in slight shifts in the spiral center when the weed was located at the edges of the image, compared to the center. Fluctuations in the size and position of the bounding boxes for stationary weeds were also observed, which could lead to parts of the plant being outside the processed area.

Figure 6 shows the same image of a weed but with different sizing red bounding boxes. These fluctuations were attributed to small classification inaccuracies and resulted in different center stages. The system's tracking and laser tracing functionality were further tested during movement. Re-lasering (reprocessing) of already destroyed weeds was rare and mainly caused by misclassification. Tests were conducted at different speeds (100, 200, and 300 cm/s). At 300 cm/s, tracking accuracy decreased, leading to some weeds being missed. At 200 cm/s, the system performed almost error-free. During testing, the system missed approximately 2.5% of weeds at a speed of 200 cm/s. This rate increased to 5% when the speed was increased to 300 cm/s, indicating a slight trade-off between speed and accuracy. Finally, the pilot laser successfully tracked and destroyed test weeds, demonstrating the system's expected behavior. The results showed that the system was capable of targeting and eliminating weeds with an accuracy of 1 mm, well within the required precision for effective weed control.

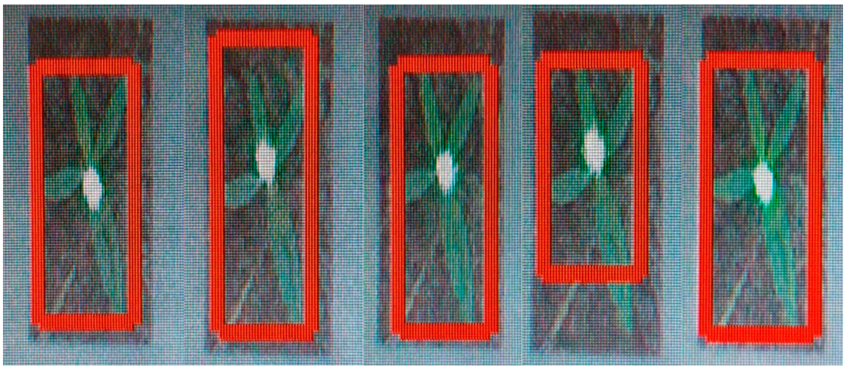

Figure 6. Illustration of the inaccuracy of the bounding boxes.

These tests also provided insights into the system's image processing capabilities, particularly the CNN's ability to accurately classify plants under different lighting conditions. The results indicated that the system could maintain high accuracy even when operating in variable lighting environments, a critical factor for field deployment.

5.2. Real-Time Capability Measurements

A critical factor in evaluating the system's performance is its real-time capability. The system captures images and performs classification at a rate of 30 Hz, meaning that the destruction process must operate within a 33.3 ms time frame per cycle to maintain this rate. The destruction time per weed directly impacts the overall frame rate, and if the processing time for a weed exceeds 33.3 ms, the system will fail to achieve real-time performance. For example, with a weed processing time of 100 ms, the system can only process one image every 100 ms, reducing the overall efficiency.

The performance of the system was tested under different configurations of exposure times and spiral segments, with five weeds present in the camera's field of view during each test. Table 1 summarizes the results of these tests, measuring the time taken for the update function. Each test varied the exposure time and spiral segments, with exposure times ranging from 10 ms to 200 ms. The system was forced to perform destruction on each function call to simulate maximum load conditions. The results show that, with exposure times of 30 ms or less, the system was able to maintain the necessary real-time frame rate of 30 Hz.

Table 1. Processing time of the update function.

Test No.	Exposure Time in ms	Revolutions	Mean Value in ms	Median in ms	Standard Deviation in ms
1	10	8	25.3	22.3	8.2
2	30	8	33.3	31.5	5.1
3	100	8	101.1	98.7	6.1
4	200	8	205.7	201.9	9.5

The destruction times, summarized in Table 2, closely matched the expected values, with a minimum destruction time of around 22 ms. This time is constrained by the number of segments in the laser's spiral and the maximum rate at which coordinates are transmitted to the scanner. Reducing the number of spiral segments would allow for faster destruction but could also lead to uneven heat distribution across the weed, reducing the overall effectiveness. Since the system requires a destruction time of no more than 36 ms to maintain a driving speed of 1 km/h, the current configuration is adequate for field operation.

Table 2. Processing time of the spiral function.

Test No.	Mean Value in ms	Median in ms	Standard Deviation in ms
1	24.5	21.5	8.2
2	32.7	30.9	5.0
3	100.4	98.1	6.0
4	205.1	201.2	9.4

Tracking performance generally took less than 1 ms per frame, though this could vary depending on weed density and travel speed. During testing, five weeds were present, and the robot was stationary. It is expected that, in real-world scenarios with higher weed densities, tracking time could increase to a few milliseconds. As long as the destruction time remains below 30 ms, the system can reliably process 30 frames per second. However, when destruction times exceed this threshold, the frame rate drops, potentially causing some sections of the field to be missed.

The minimum frame rate necessary to detect all weeds is determined by the robot's travel speed and the camera's field of view height. With a travel speed of 1 km/h and a camera height of 12 cm, the minimum required frame rate is 3 frames per second. If the frame rate falls below this, sections of the field may not be analyzed, and weeds could be missed entirely. Table 3 shows the difference in throughput times between the spiral and update functions. For all tests, a high standard deviation was observed, which can be attributed to the operating system's scheduler. This scheduler allocates system resources between different processes, occasionally causing significant delays in the destruction process and reducing the overall system performance.

Table 3. Difference of throughput times.

Test No.	Mean Value in µs	Median in µs	Standard Deviation in µs
1	738.4	599.5	628.7
2	611.1	516.1	291.9
3	630.1	490.5	604.9
4	590.4	604.9	257.4

The measurements show that the specified destruction time corresponds well with the actual destruction time. The larger the value, the less influence there is on the system load, and the specified value is achieved more accurately. However, this results in a minimum destruction time of approx. 22 ms. This value results from the number of segments of a spiral in conjunction with the maximum transfer rate of coordinates to the scanner. A reduction in the number of segments of the spiral would allow shorter annihilation times. Fewer sections also result in less even heat distribution in the weed. A destruction time of less than 22 ms is not initially required for the application, which is why this lower limit was not adjusted. It is known from the previous chapters that the destruction time must not be greater than 36 ms to achieve a driving speed of 1 km/h. The processing time for tracking is usually less than 1 ms. However, this depends heavily on the density of the weeds and the driving speed. The tests were carried out with five weeds in the image and during a standstill. It can be assumed that tracking while driving can take up to a few milliseconds with a high weed density. The system can work with 30 frames per second up to a specified destruction time of 30 ms. If a higher destruction time is required, this is no longer the case. A lower limit for the minimum number of images per second that must be processed results from the image height in the direction of travel and the travel speed, irrespective of the weed density. If there are not enough images per second, this means that areas of the dam surface are not analyzed. This means that weeds can be completely overlooked. For a travel speed of 1 km/h and an image height of 12 cm, this results in a minimum frame rate of three images per second.

6. Discussion and Future Work

The results of this study demonstrate the potential of laser-based weed control systems to provide a viable alternative to manual weeding in organic farming. The use of Thulium fiber lasers, combined with advanced image processing techniques, allows for precise and efficient weed destruction with minimal environmental impact.

Previous research has explored various laser technologies for weed management. Heisel et al. [20] investigated the use of CO_2 lasers, highlighting their potential in selective weed control. However, CO_2 lasers often require significant energy input and have limitations in mobility due to their size and cooling requirements. Advancements in fiber laser technology have addressed some of these challenges. Kaierle et al. [8] demonstrated that fiber lasers could effectively damage weed tissues with higher energy efficiency and compactness compared to CO_2 lasers. Our study corroborates these findings, showing that Thulium fiber lasers offer precise targeting capabilities with improved energy efficiency. The results of this study are also consistent with findings from previous research on laser-based weed control. For example, Marx et al. [4] demonstrated that CO_2 laser systems could achieve effective weed destruction at specific growth stages. Our results showed similar success but with the added benefits of higher energy efficiency and real-time performance using fiber lasers. Notably, systems like those from Carbon Robotics [13] and Escarda Technologies [14] have employed similar laser-based approaches with distinct system architectures and performance parameters. The Carbon Robotics platform uses CO_2 lasers, achieving an operational speed of 1.6 km/h with a 99% weed destruction accuracy. While this system is equipped with 30 individual CO_2 lasers to cover a broad area at high speeds, it also requires a more significant energy input, and the larger, bulkier design limits mobility. In contrast, our Thulium fiber laser system maintains a similar precision of 1 mm but does so with a single laser unit, enabling a more compact and mobile configuration suitable for a variety of field conditions. Furthermore, our system's energy efficiency is notably higher; where CO_2 lasers typically have an efficiency of around 10%, the Thulium fiber laser achieves up to 30%, allowing extended operation times with reduced energy consumption. Escarda Technologies, on the other hand, is developing an AI-driven laser system for weed control that also emphasizes high precision and real-time performance. However, limited information is available on the exact specifications of their lasers or system setup, as they are currently in prototype stages. Our work contributes further by providing experimentally validated results on processing speeds of up to 200 cm/s and real-time targeting accuracy of 30 FPS. Moreover, by opting for the fiber laser technology, our system achieves greater energy and spatial efficiency than the CO_2 lasers used in Carbon Robotics' design. This compactness enables simpler integration with autonomous mobile platforms, enhancing adaptability across various terrains and crop types—a critical advantage for precision agriculture. Thus, our system not only matches the precision standards of leading systems but also introduces substantial improvements in energy efficiency and operational flexibility. These advantages position our Thulium fiber laser-based system as a highly competitive option for sustainable weed management in organic farming, capable of reducing operational costs and ecological impact compared to existing solutions. The integration of artificial intelligence (AI) for weed detection has further enhanced laser weeding systems. Wang et al. [32] developed an AI-based recognition system capable of distinguishing weeds from crops in real-time, facilitating targeted laser application. Our system incorporates similar AI technologies, achieving real-time weed detection and precise laser targeting at processing speeds up to 200 cm/s.

While the initial testing phase using the pilot laser has provided valuable insights into the system's accuracy and functionality, future work will focus on conducting comprehensive real-field tests throughout an entire weeding season. These tests will involve deploying the laser-based weed control system across several hectares of carrot fields to evaluate its performance under real-world agricultural conditions. The goal is to assess the system's effectiveness, efficiency, and long-term reliability over the course of the growing season, considering variables such as weed density, crop growth stages, and environmental factors. We anticipate publishing a follow-up research paper based on these tests, providing detailed results and analysis from the field trials. This study will aim to further validate the system's viability for large-scale, autonomous weed control and its potential impact on reducing manual labor and herbicide use in organic farming.

Another area of future research is the development of a multi-functional platform capable of performing additional tasks, such as soil monitoring and crop health assessment. This could further enhance the platform's value to farmers by providing a comprehensive solution for precision agriculture.

7. Conclusions

This study presents the development and evaluation of a laser-based autonomous weed control system designed for organic farming. The integration of Thulium fiber lasers and AI-driven image processing has resulted in a system that is both precise and efficient, capable of operating autonomously in a variety of field conditions.

The experimental results validate the system's effectiveness, demonstrating a high precision detection of 1 mm and tracking of the weeds with real-time capabilities of 30 FPS with a maximum travel speed of 200 cm/s. As organic farming continues to grow, technologies like this will play a crucial role in reducing the reliance on manual labor and chemical herbicides, contributing to more sustainable agricultural practices.

Despite the success in controlling weeds with high precision, the system has several limitations. First, the current processing speed restricts its application in larger fields, as real-time weed detection at higher speeds can result in missed targets. Additionally, while the system is effective for small-scale testing, further improvements are necessary to ensure robustness across diverse environmental conditions, such as varying weed densities and crop types. Future work will focus on addressing these limitations by enhancing processing speed and adapting the system for broader applications in precision agriculture. We will also focus on enhancing the system's capabilities and expanding its applicability to a broader range of crops and farming environments, ultimately providing farmers with a powerful tool for precision weed management.

Author Contributions: Conceptualization, V.C., J.V. and S.H.; methodology, V.C. and J.V.; software, V.C. and J.V.; validation, V.C. and J.V.; formal analysis, V.C. and J.V.; investigation, V.C. and J.V.; resources, S.H.; data curation, V.C. and J.V.; writing—original draft preparation, V.C. and S.H.; writing—review and editing, V.C., J.V. and S.H.; visualization, V.C. and J.V.; supervision, S.H.; project administration, V.C.; funding acquisition, V.C. and S.H. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded under the AI-funding guideline ("KI-Förderrichtlinie") by the Federal State of Schleswig-Holstein in Germany.

Data Availability Statement: The data are not publicly available due to our laboratory privacy data protection.

Acknowledgments: We would like to thank our cooperation partner Westhof Bio GmbH for their many years of support.

Conflicts of Interest: Authors Vitali Czymmek and Jost Völckner was employed by the company Naiture GmbH & Co. KG, The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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