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Photonic-based spectral reflectance sensor for ground-based plant detection and weed discrimination

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Abstract: A bench prototype photonic-based spectral reflectance sensor architecture for use in selective herbicide spraying systems performing non-contact spectral reflectance measurements of plants and soil is described and experimental data obtained with simulated farming vehicle traveling speeds of 7 and 22 km/h is presented. The sensor uses a three-wavelength laser diode module that sequentially emits identically-polarized laser light beams through a common aperture, along one optical path. Each laser beam enters a multi-spot beam generator which produces up to 14 parallel laser beams over a 210mm span. The intensity of the reflected light from each spot is detected by a high-speed line scan image sensor. Plant discrimination is based on calculating the slope of the spectral response between the 635nm to 670nm and 670nm to 785nm laser wavelengths. The use of finely spaced and collimated laser beam array, instead of an un-collimated light source, allows detection of narrow leaved plants with a width as small as 12mm.

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References and links

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1. Introduction

Due to the increased economic pressure in the agriculture industries, it is now crucial to develop and adopt new technologies that maximize the productivity and profitability of farms. Currently, farmers either spot-spray crops by hand or blanket-spray a field. Hand spraying is labour-intensive and time-consuming. Blanket spraying wastes herbicide, reduces crop yields and increases chemical loads on ecosystems. An automatic real time weed detection device, where detection and treatment are performed at the same time, can yield considerable reduction in herbicide used for weed control [1, 2]. To the authors' knowledge, the only commercially available device for weed control uses two light emitting diodes (LED) with wavelengths in the red and near-infrared bands to illuminate the field [3]. The divergence of LED illumination causes weak side lobes in the radiation pattern which require a minimum leaf size of 40mm for detection. The device is calibrated by scanning a sample of the field's soil, and once the reflected intensity reading of the soil scan is recorded, only brown-from-

non-brown discrimination can be achieved. The inability of this LED-based weed sensor system to discriminate between weeds and crops (green-from-green) limits its application in precision agriculture.

Using more wavelengths at points in the spectrum where plants show different optical characteristics in terms of reflected intensity allows more precise plant discrimination. Hyperspectral analysis of weeds and crops has been carried out from satellite and aerial platforms, and recent results show that for classifying 5 predetermined weed species, the overall accuracies increased from 56% for 3 bands, to 72% for 7 bands, to 90% for 13 bands, to 98% for 22 bands. For classifying 6 crop species, the overall accuracies increased from 48% for the 3 bands, to 81% for 7 bands, to 87% for 13 bands to 90% for 22 bands [4]. Figure 1 shows typical measured reflectance spectra for leaves of skeleton weed (*Chondrilla juncea*). The physiological differences between plant species are evident in the spectral region from 400nm to 800nm. The prototype weed control sensor described in this paper is capable of limited plant discrimination (“green from green”) using laser sources at three selected wavelengths within this region [5]. Experimental results are shown for detection of green leaves of *Spathiphyllum* at simulated vehicle speeds of 7 and 22 km/h.

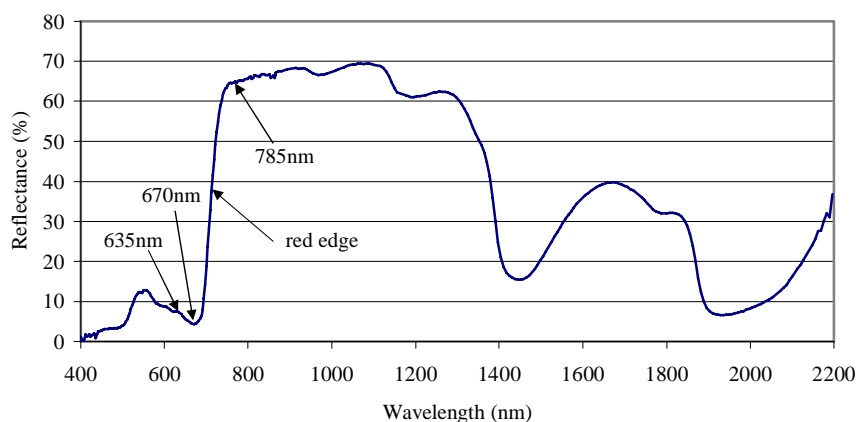


Fig. 1. Typical measured reflectance spectrum of leaves of skeleton weed. In general the variations in the reflectance between 550nm and 800nm can be used to discriminate between different plants.

2. Sensor description

The weed control sensor is comprised of a laser combination module, a multi-spot beam generator and a line scan image sensor. Figure 2 gives a high-level conceptual design for the sensor architecture where a leaf, stem or soil spot is sequentially illuminated by laser beams of different wavelengths. Discrimination is achieved by recording and processing plant reflectance data for each wavelength. Sample illumination and image sensing are synchronized by computer software developed to control the weed sensor and perform data processing. When a target plant is detected a signal is generated which can be used to trigger a spray unit or record coordinates from a global positioning system (GPS). This provides a means to only apply herbicide to weeds within the field. Weed location mapping may be used to monitor weed distribution or for treatment of difficult to control weeds such as skeleton weed at a later date.

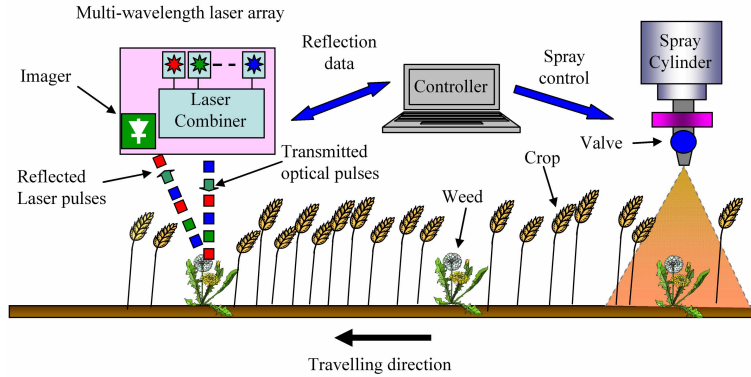


Fig. 2. Concept of laser based real-time weed monitoring and spraying sensor. Plants are illuminated with laser beams at varying wavelengths along one optical path, striking the same spot on the leaf, stem or soil. Processing of the reflected light signal for each wavelength determines plant or soil identification. When required, the control unit generates a signal to open the valve on the spray unit.

2.1 Laser combination module

The laser combination module contains three laser diodes of different wavelengths appropriately aligned with two free-space beam combiners as shown in Fig. 3. The laser module produces three collimated and overlapping laser beams with the same polarization angle propagating through a single aperture. Aligning the polarization angle for all three laser beams reduces the polarization dependence of the measured reflectance. The output beam diameter of each laser diode is 4mm.

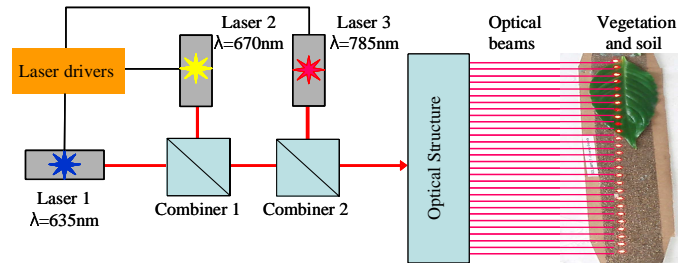


Fig. 3. Laser combination module with three wavelengths and optical structure projecting multiple laser beams onto an experimental screen holding a leaf over background soil

2.2 Multi-spot beam generator

The output from the laser combination module passes through a multi-spot beam generator for sample illumination. This device can generate a line array of up to 14 output beams at a spatial resolution of 15mm. This beam resolution allows detection of plants which are narrow leaved such as skeleton weed. The multi-spot beam array projected onto an experimental screen holding a leaf over background soil is shown schematically in Fig. 3. An advantage of using this optical structure for multi-spot beam generation is the stable alignment of the generated beams regardless of the movement of the whole sensor housing. This stable alignment is especially important when scanning along rugged terrain where the vertical sensor-plant distance may vary rapidly.

2.3 Image sensor

The intensity of the reflected light from the sample illuminated by the multi-spot beam generator is recorded by a line scan image sensor. The image sensor has 1024 pixels with area

of $14 \times 14 \mu\text{m}$, 12 bit resolution and can operate at a line rate of up to 68 kHz, limited by the required exposure time. The image sensor is placed behind an appropriate C-mount lens assembly with adjustable aperture and focus to image the reflected light from the illuminated sample. Figure 4 shows intensity data recorded by the image sensor in digital numbers (DN) for 14 spots projected onto a background screen.

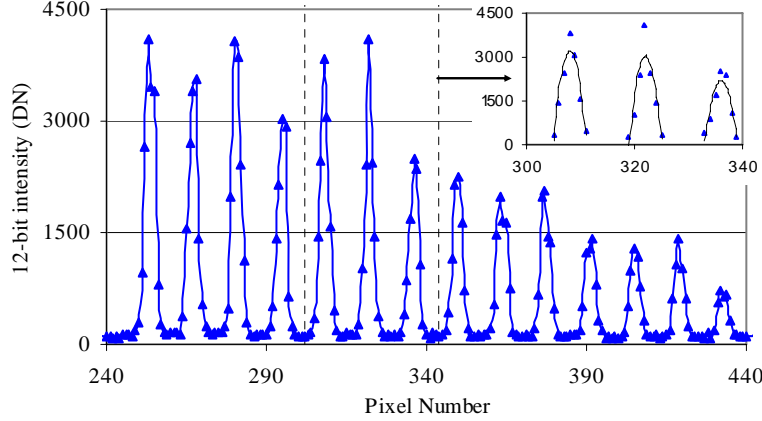


Fig. 4. Intensity profile of 14 spots illuminating a background screen recorded by image sensor. Inset shows quadratic fitting of measured intensity profile for three peaks.

The local maxima of each peak can fluctuate by up to 20%. To reduce the fluctuations a quadratic peak fitting method is applied to each peak to determine the maximum intensity which is used in the plant discrimination process. This method is less computationally intensive than gaussian fitting which requires non-linear regression. The result of quadratic fitting is shown in the inset in Fig. 4.

2.4 Discrimination method

Plant discrimination is based on determining the slope in the reflectance at the three wavelengths used. The two slope values, S_1 and S_2 , are defined as:

$$S_1 = \frac{R_{635} - R_{670}}{\lambda_{670} - \lambda_{635}} \quad \text{and} \quad S_2 = \frac{R_{785} - R_{670}}{\lambda_{785} - \lambda_{635}}, \quad (1)$$

where λ_n is the wavelength of the laser diode in nanometers, $R_\lambda = I_\lambda / P_\lambda$ is the calculated reflectance, I_λ is the peak recorded intensity in arbitrary units and P_λ is the measured optical power for each spot generated by the optical structure (Fig. 3). The Normalized Difference Vegetation Index (NDVI) defined by Eq. (2) is used to discriminate soils and green leaves.

$$NDVI = \frac{R_{785} - R_{670}}{R_{785} + R_{670}}. \quad (2)$$

The steep slope of the red edge (Fig. 1) results in large values of the NDVI for all green plants in comparison with soil and other objects.

3. Results and discussion

The performance of the weed sensor was tested by simulating vehicle movement with leaf samples mounted on a rotating stage. This test was conducted under static conditions and at average linear velocities of 7 and 22km/h. All calculated values of S_1 , S_2 and NDVI presented in Fig. 5 are for 3cm wide *Spathiphyllum* leaves covering 4 laser beams at distances of 58cm, 69cm and 80cm from the weed sensor. Each data point is an average over 10

measurements for four laser beams illuminating the leaf. The variability of the measurements is mainly due to fluctuations in the response of the image sensor and optical power of the laser diodes in time.

Results show that there is no significant change in the calculated values of S1, S2 and NDVI for variation in the distance to the leaf sample or for simulated speeds of 7 and 22km/h. Consistency over a range of distances from the sensor is achieved by coplanar alignment of the laser modules and the image sensor. The current system is capable of conducting measurement for leaf size as small as 3cm at 22km/h. Replacing the existing control system with embedded hardware would reduce this minimum leaf size to approximately 6mm at vehicle speed of 36km/h. Previous static results, [5], showed that the weed sensor is also capable of limited discrimination of green plants. These capabilities make the weed sensor suitable for plant discrimination when mounted on a farming vehicle.

Improving the discrimination capabilities of the weed sensor is possible with the addition of lasers at other wavelengths. Physical space in the laser combination module limits the number of laser diodes which can be added as does the line rate of the camera. Up to five lasers could be used while maintaining a minimum leaf size of 6mm.

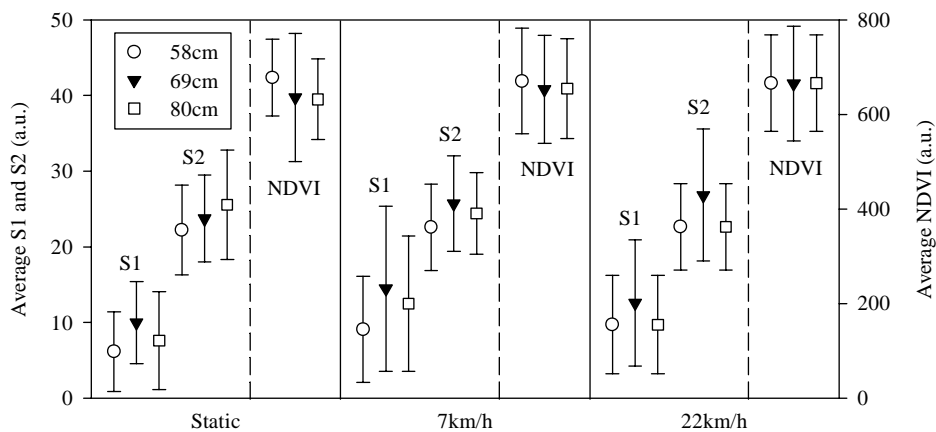


Fig. 5. Average values of S1, S2 and NDVI for static, 7km/h and 22km/h measurements of Spathiphyllum leaf at different distances. S1 and S2 are plotted against the left axis and NDVI against the right axis. circle – 58cm, filled triangle – 69cm and square – 80cm.

Conclusion

A prototype three-waveband laser optical sensor for plant discrimination has been described and tested using Spathiphyllum leaves. Plant leaves have been illuminated by an array of coplanar laser beams and reflectance properties of the leaves have been determined. Operation of the sensor at simulated farming vehicle speeds has shown that it is capable of discrimination between soil and green plants at these speeds over various distances. Future development will aim to improve the precision of the weed sensor by implementing a more appropriate image sensor and replacing the control system with embedded hardware. The addition of lasers at other wavelengths to the laser combination module will improve the plant discrimination capabilities of the current prototype weed control sensor.

Acknowledgments

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