Non-contact laser spectroscopy for plant discrimination in terrestrial crop spraying

Kaveh Sahba, Sreten Askraba and Kamal E. Alameh

Western Australia Centre of Excellence for MicroPhotonic Systems, Electron Science Research Institute, Edith Cowan University, 100 Joondalup Drive, Joondalup 6027 Australia
k.sahba@ecu.edu.au, s.askraba@ecu.edu.au, k.alameh@ecu.edu.au

http://comps.ecu.edu.au

Abstract: The early development of a novel micro-photonic based sensing architecture for use in selective herbicide spraying systems performing non-contact spectral reflectance measurements of plants and soil in real time has been described. A combination module allows three laser diodes of different wavelengths to sequentially emit identically polarized light beams through a common aperture, along one optical path. Each exiting beam enters an optical structure which generates up to 14 parallel laser beams. A pair of combination modules and optical structures generates 28 beams over a 420mm span which illuminates the plants from above. The intensity of the reflected light from each spot is detected by a high speed line scan image sensor. Plant discrimination is based on analyzing the Gaussian profile of reflected laser light at distinguishing wavelengths. Two slopes in the spectral response curves from 635nm to 670nm and 670nm to 785nm are used to discriminate different plants. Furthermore, by using a finely spaced and collimated laser beam array, instead of an un-collimated light source, detection of narrow leaved plants with a width greater than 20mm is achievable.

OCIS codes: (300.6360) Spectroscopy, laser; (120.0280) Remote sensing; (150.3040) Industrial inspection; (200.4560) Optical data processing

References and links

1. N.Z. Wang, F.E.Dowell, Y.Sun, D.E.Peterson, "Precision agriculture – a worldwide overview," Computers and Electronics in Agriculture, **36**, 354-376 (2002).
2. J. Sinden, et. al., "The economic impact of weeds in Australia," Technical Series # 8, Cooperate Research Centre for Australian Weed Management, February 2004.
3. NTech Industries, "WeedSeeker: Concept," http://www.ntechindustries.com/concept.html.
4. N.Z. Wang, F.E.Dowell, Y.Sun, D.E.Peterson, "Design of an Optical Weed Sensor Using Plant Spectral Characteristics," ASAE Trans., **44**, 409-419 (2001).
5. Wang, N.Zhang, F.E.Dowell, Y.Sun, D.E.Peterson, "Testing of a Spectral-based Weed Sensor," American Society of Agricultural Engineers (2000).
6. J. Beck and T. Vyse, "Structure and method for differentiating one object from another object," U.S. Patent 5 296 702, March 22, 1994.
7. J. Beck and T. Vyse, "Structure and method usable for differentiating a plant from soil in a field," U.S. Patent 5 389 781, February 14, 1995.
8. W. L. Felton, "Commercial progress in spot spraying weeds," in Brighton Crop Protection Conference - Weeds, British Crop Protection Council (1995), **3**, 1087-1096.
9. P.S Thankabail, E. A. Enclona, M. S. Ashton, B. Van Der Meer, "Accuracy assessments of hyperspectral waveband performance for vegetation analysis applications," Remote. Sens. Environ., **91**, 354-376 (2004).
10. H.D Young, Statistical treatment of experimental data, McGraw-Hill Book Company, Inc., 1962.

#75285 - $15.00 USD Received 21 September 2006; revised 20 November 2006; accepted 25 November 2006

1. Introduction

There is a high demand in the precision agriculture arena for a selective vegetation discriminator device with the ability to differentiate between various plants [1], especially at the typical traveling speeds of farming vehicles (eg 35 km\h). This would allow the mounting of a series of sensors onto a vehicle spanning the boom width, scanning a crop field for weeds or other sought after plants and subsequently either spraying herbicide or recording the relevant plant location. This is an ideal approach compared to the traditional practice of blanket spraying a paddock throughout the cultivation cycle which leads to losses in the quality of both soil and crop yield, and financial turnover after harvesting for the farmer [2].

Current precision spraying technology [3] lacks selectivity in that it considers everything but soil as a spray target. Before scanning the field, the device is calibrated by scanning a sample of the field's soil. Once the reflected intensity reading of the soil scan is recorded, any object in the field which does not have the same intensity reading will be sprayed upon – the object does not even necessarily have to be a plant.

Another major drawback in research conducted thus far regarding spectral discrimination is the use of tungsten halogen flood lamps or light emitting diodes (LEDs) to illuminate the vegetation from above [4, 5]. The divergence of LED illumination causes weak side lobes in the radiation pattern. This means that there is little chance of a fine weed leaf being detected if it does not fall in the most concentrated area of LED illumination due to weak backscattered light.

Finally, current commercial devices use only two wavelengths in the red and near infrared bands to illuminate vegetation [3, 6 - 8]. By using more wavelengths at points in the spectrum where plants show different optical characteristics in terms of reflected intensity, more precise discrimination can be accomplished. Hyperspectral analysis of weeds and crops has been carried out from an aerial platform, and 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 [9]. Figure 1 shows a typical reflectance spectrum for a green leaf and some key wavebands which could be used for discrimination. This proof-of-concept is demonstrated in this paper, whereby projecting laser light of three wavelengths and properly processing the reflected intensity data, four plants and one soil can be easily distinguished from one another.

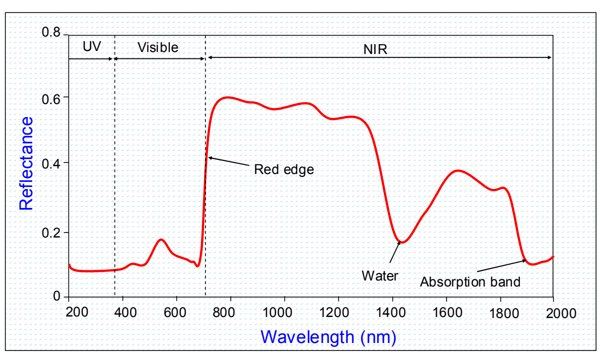


Fig. 1. Typical reflectance spectrum of a green leaf. Variations in the reflectance of the 'red edge' between 650nm and 800nm can be used to discriminate between different plants.

A custom designed combination module guides three collimated and equally polarized laser beams of different wavelengths through the same optical path. Each outgoing beam then

 Received 21 September 2006; revised 20 November 2006; accepted 25 November 2006

enters an optical structure which produces a laser spot array with fine spatial resolution. All outgoing beams are parallel and aligned. This approach is favorable as each of the three wavelength-specific spot arrays makes a common optical footprint on the vegetation surface. Therefore, each intensity reading corresponds to the same spatial point on the soil, stem or leaf. Also, projecting an array of collimated laser diode beams with a Gaussian profile gives a much higher and equal concentration of intensity over the radiation pattern, as opposed to LED illumination. This is the first reported sensor structure for plant and soil classification based on laser light spectroscopy.

2. Materials and methods

This stage of the sensor's development sees the major hardware mounted into a single housing unit interfaced to a personal computer (PC). The architecture includes a laser combination module, optical structure for multi-beam generation, collecting lens and a charged coupled device (CCD) image sensor. The software controls laser sequencing and data acquisition from the image sensor. Figure 2 gives a high-level conceptual design for the developed sensor architecture, where a leaf, stem or soil spot is sequentially illuminated with light beams of different wavelengths. Discrimination is achieved by recording and comparing plant reflectance properties for each wavelength.

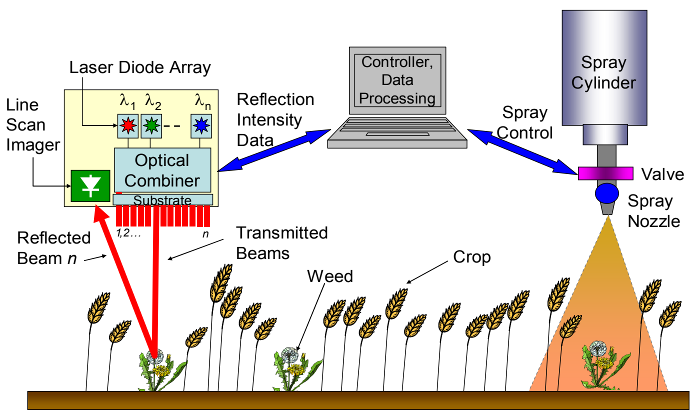


Fig. 2. The sensor will emit light at varying wavelengths along one optical path, striking the same spot on the leaf, stem or soil. Processing of the digitally recorded reflected light signal for each wavelength will determine plant or soil identification and hence a strike signal is sent to the spray valve accordingly.

2.1 Laser combiner

One unique design feature is the ability to illuminate the plant or soil under inspection with varying wavelengths. This has been achieved this with a custom-built, triple wavelength laser diode combination module, where each beam of a differing wavelength emits through the same aperture. The laser module contains three laser diodes of different wavelengths appropriately aligned with two free-space beam combiners. This produces three collimated and overlapped laser beams with the same polarization angle. The output beam diameter of each diode is 4mm. The combined three beams propagate from the module through a single aperture as shown in Fig. 3. The laser diode sequencing is controlled by an eight channel digital output device interfaced to a computer via a universal serial bus interface (USB). The sequencing frequency can be controlled and the optical output power of each diode can be adjusted by the laser driver trim-pot.

#75285 - $15.00 USD Received 21 September 2006; revised 20 November 2006; accepted 25 November 2006

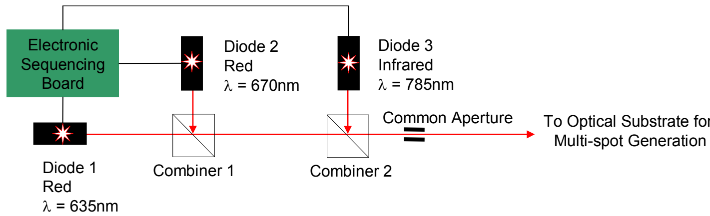
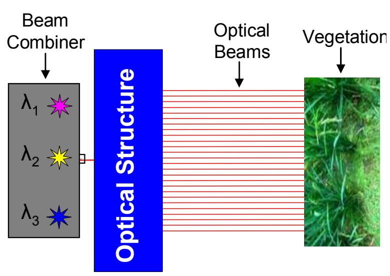


Fig. 3. Laser beam combination.

2.2 Multi-spot generation

A "black box" optical structure, shown in Fig. 4(a), has been devised for multiple laser spot generation, with adjustable spacing. The structure can generate up 14 spots from a single laser beam exiting the beam combiner. A 15mm spatial resolution exists between the spots. This fine spacing allows the detection of plants which are very narrow stemmed or leaved. An example is the noxious Chondrilla juncea, a.k.a Skeleton Weed. Figure 4(b) shows a spot array projected onto an experimental screen holding a leaf over background soil.

An advantage of using the optical structure for spot generation is the consistent alignment of the generated beams, regardless of the movement of the whole sensor housing. This stability is especially important when scanning along rugged terrain where the vertical sensor-plant distance may vary rapidly.



(a)

(b)

Fig. 4. (a) Multiple beam projection. (b) Resulting spot array projected onto an experimental screen holding a leaf over background soil.

Figure 5 shows the measured optical power for each spot at each wavelength, projected from a pair of optical structures.

2.3 Capturing reflectance

An image sensor with 1024 pixels and $14 \times 14\mu$m pixel size is used to detect the intensities of the light reflected from various spots. This image sensor is interfaced to a PC using a Gigabit Ethernet connection and is capable of operating at a very high frame rate of up to 68 kHz, which is ideal of for scanning at the speed of a farming vehicle traveling at about 35 km/h. The imaging data is measured in 12-bit digital form.

The image sensor is placed behind an appropriate C-mount lens assembly with adjustable iris, zoom and focus to properly capture the reflected light from the spot array. Figure 6 illustrates plotted intensity data recorded by the image sensor in digital numbers (DN) for 3 spots projected from the optical structure at each wavelength a towards a Spathiphyllum leaf.

#75285 - $15.00 USD Received 21 September 2006; revised 20 November 2006; accepted 25 November 2006

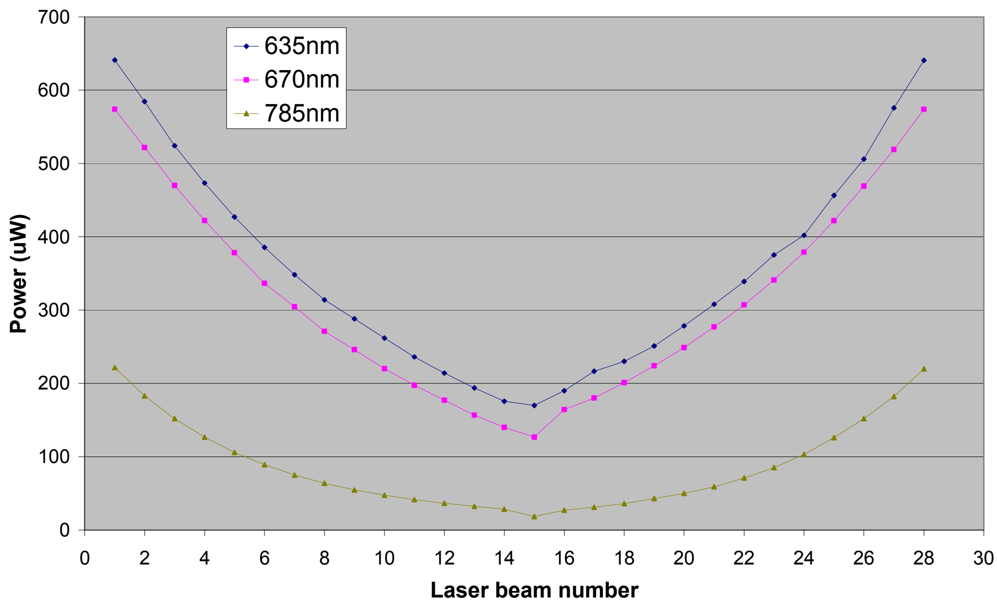


Fig. 5. Measured optical power for each spot projected from two adjacent cavities at each wavelength.

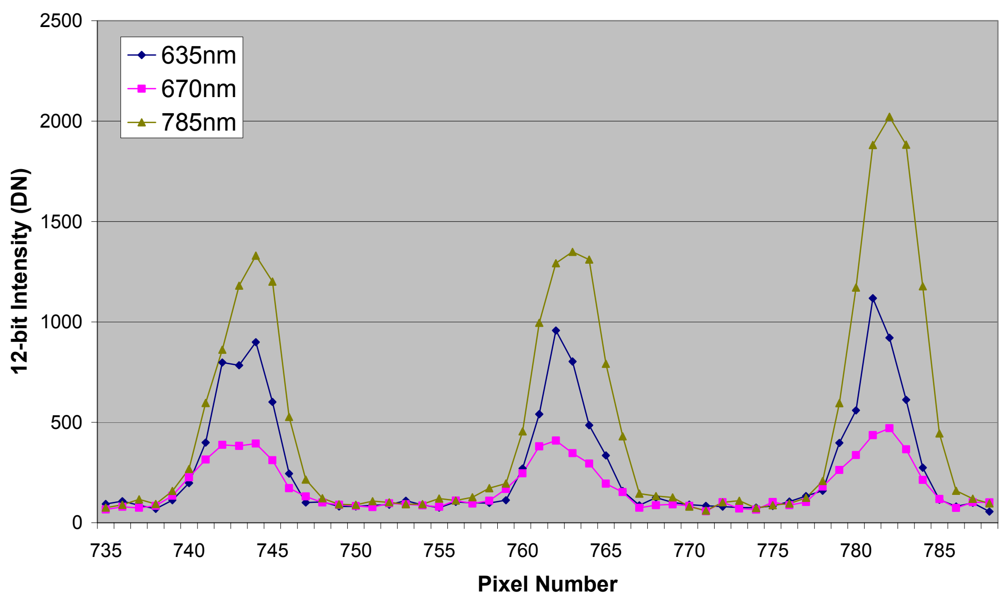


Fig. 6. Gaussian intensity profile of three spots striking a green leaf recorded by a line scan imager.

2.4 Acquisition process

The acquisition process uses the synchronization of the image frame grabbing and the laser sequencing. The laser sequencing is commenced at a desired frequency (i.e. each diode is turned on and off in sequence at an appropriate frequency).

#75285 - $15.00 USD Received 21 September 2006; revised 20 November 2006; accepted 25 November 2006

After the desired wavelength from a specific laser has been turned on, the image sensor grabs a single frame containing the Gaussian intensity profile of the spot array falling on the plant or soil under inspection. The peak intensity value of each spot is extracted and used for calculating the spectral characteristics. If this optical signature matches that of a pre-recorded weed, then an 'on' signal is sent to the spraying unit. A logic flow diagram describing this process is shown in Fig. 7. These steps form one acquisition cycle and are started at once using one software trigger.

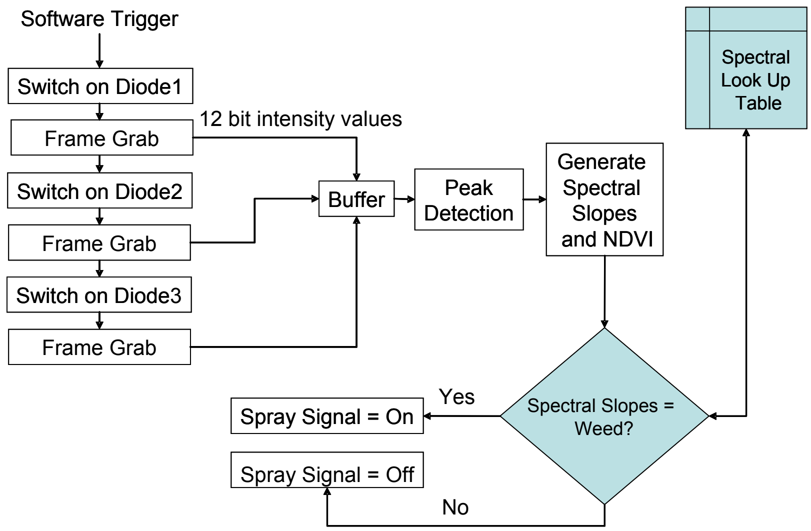


Fig. 7. Flow chart for a single acquisition cycle. This cycle must be completed before the farming vehicle has traveled 4mm – the spot diameter of the projected beam. This is to ensure each of the three frames grabbed is from the same spatial points on the plant or soil.

2.5. Discrimination method

Our method for discriminating between various plants is based on analyzing the slopes in the spectral response between the three wavelengths used. The two slope values, S_1, and S_2, are defined as:

$$S_1 = \frac{R_{635} - R_{670}}{\lambda_{670} - \lambda_{635}} \tag{1}$$

$$S_2 = \frac{R_{785} - R_{670}}{\lambda_{785} - \lambda_{635}}, \tag{2}$$

where:

$$R_\lambda = \frac{I_\lambda}{P_\lambda}. \tag{3}$$

λ_n is wavelength value of the used laser diode expressed in nanometers. R_λ, I_λ, and P_λ are the reflectance value, the maximum recorded reflected intensity in DN, and the maximum measured optical power for the considered spot at the laser wavelength λ, respectively. The average values of $S_{1,2}$ for the total number of beams striking the same leaf are stored in a look up table. This is done for all three wavelengths, producing an average S-value for each plant, for both slopes. Soils can be easily identified by the Normalized Difference Vegetation Index (NDVI), defined as:

$$NDVI = \frac{R_{785} - R_{670}}{R_{785} + R_{670}}. \tag{4}$$

3. Results and discussion

Four sample plants have been used to trial the proof-of-concept apparatus in the laboratory. These were Spathiphyllum, Dianella, Pelargonium and Dieffenbachia. As house plants, they were selected for their ability to survive in an indoors environment. Each plant is first characterized with a visible – near infrared commercially available CCD spectrometer. The spectral response of each plant's leaf is shown in Fig. 8.

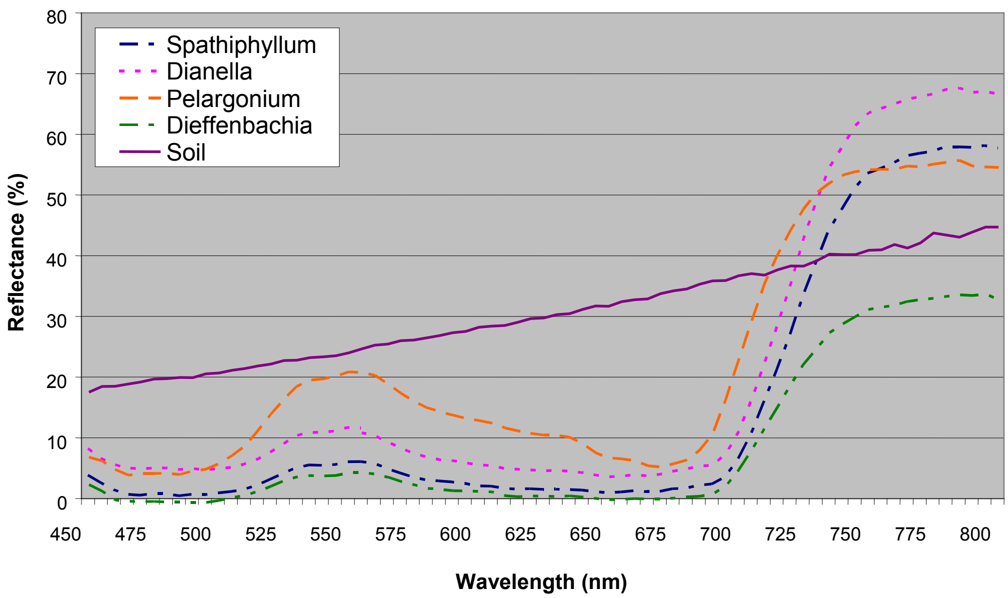


Fig. 8. Spectral response of plants and soil used for experimentation.

The specific wavelengths of 635nm, 670nm and 785nm were chosen for two reasons. Firstly, the significant spectral slopes between the plants are within the regions from 550nm to 675nm and 675nm to 785nm. Secondly, laser diodes with wavelengths within these regions and the required specifications were commercially available.

The slopes S_1 and S_2 for each plant were determined by using Eq. (1) and Eq. (2). The results in arbitrary units (a.u) are presented in Fig. 9. Each plant differs in at least one slope value, making it distinguishable. Standard deviations [10] for obtained results are presented in Fig. 10. Clearly, no simultaneous overlapping between the slopes S_1 and S_2 of the different plants is exhibited, making the discrimination between the various plants feasible. The total error in measurements is due to the dark current of the image sensor and, predominantly, the optical power fluctuation of laser diodes in time.

#75285 - $15.00 USD Received 21 September 2006; revised 20 November 2006; accepted 25 November 2006

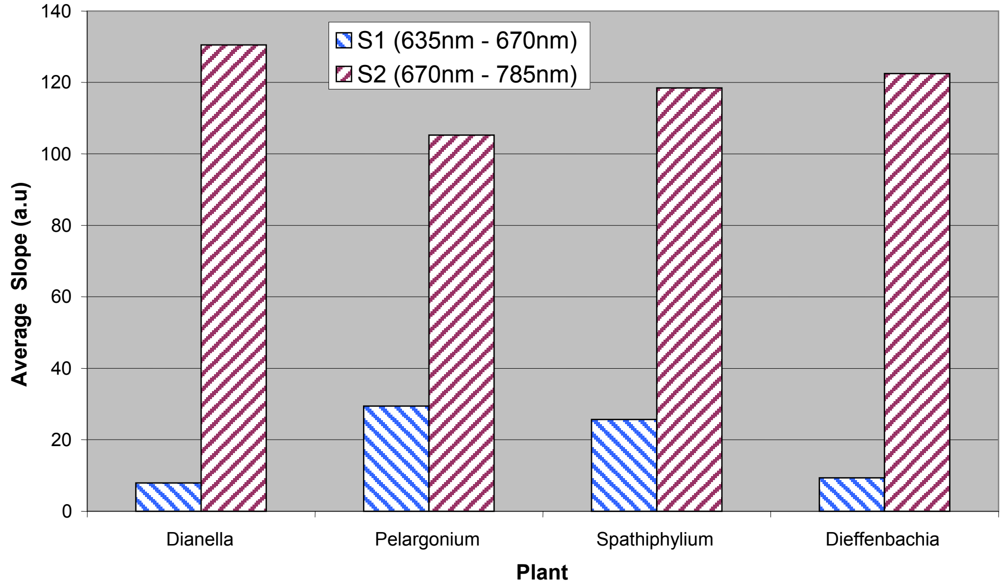


Fig. 9. Determined average slope values for the four sample plants.

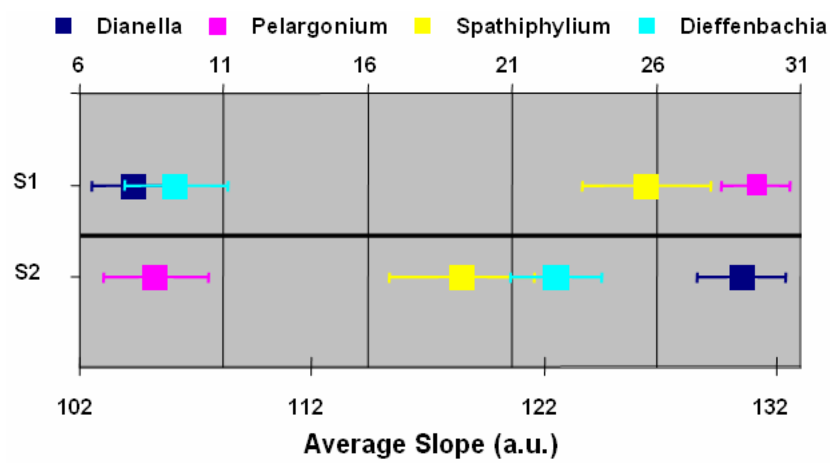


Fig. 10. Standard deviation of the mean for slopes S_1 and S_2 for the four sample plants.

Figure 11 shows the average NDVI values for the samples plants, as well as soil, green and blue papers. It is obvious that the minimal difference in NDVI between plants and non-plants is significant – approximately 40%.

In summary, the proposed sensor is capable of differentiating green plants from other objects, including green colored material. The device can also differentiate green plants using two spectral slopes. By combining more laser diodes of varying wavelengths, further slope values can be calculated and compared. This enables more accurate discrimination between a broader range of plants.

#75285 - $15.00 USD Received 21 September 2006; revised 20 November 2006; accepted 25 November 2006

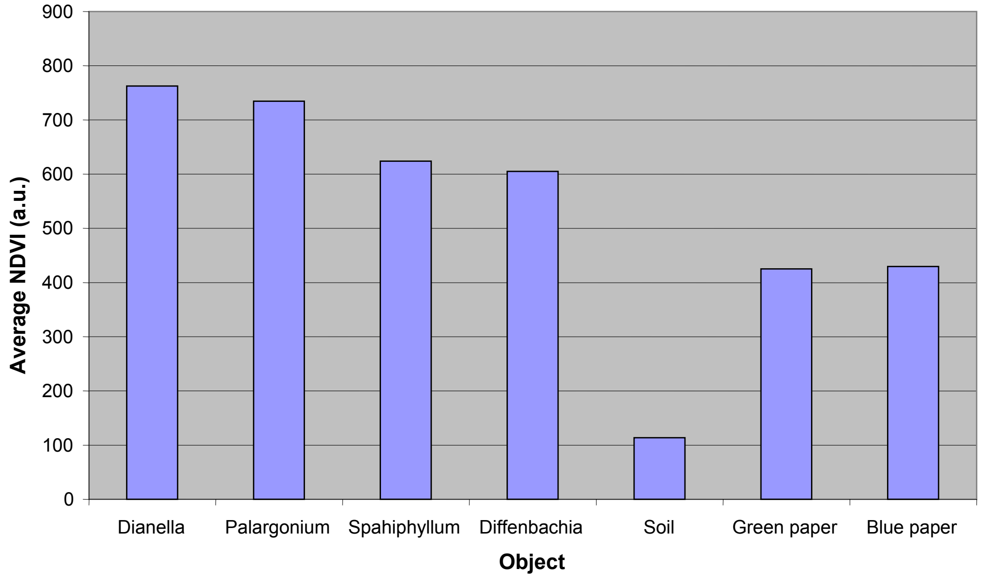


Fig. 11. Average NDVI values for the four samples plants, soil and colored paper.

4. Conclusions and future work

A novel sensing technique that implements multi-waveband laser light for obtaining spectral reflectance data has been described. Various types of plants have been illuminated with an array of collimated laser beams emitted through an optical structure integrating laser diodes, free space combiners and optical components. Limited discrimination between plants has been achieved by determining two spectral slopes defined by three wavelengths and NDVI to discriminate green plants from soil and other green and non-green objects.

By designing a laser combination module which accommodates more laser diodes of different wavelengths, a more detailed optical signature can be derived for a plant or a weed. In terms of physical parameters, research efforts will be directed at the elimination of varying ambient light and accountability for the ever-changing plant phenology which can vary between the hours of a day and affect the reflectance intensity readings. Other ambient field variables which must also be considered include soil types, ambient temperature, humidity and dust.

Potential benefits exist in exploring vegetation optical characteristics of up to 2μm since applications such as plant health inspection in terms of water absorption can use the same scanning system. This requires the implementation of a broadband image sensor.

The end goal of this research is to successfully identify and spray only weeds in all situations including the post emergent stages of crop growth.

Acknowledgments

The authors would like to acknowledge Weed Control Australia Ltd. for their support.