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Design of laser multi-beam generator for plant discrimination

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***Abstract*—Optimisation of the optical signal from the laser multi-spot beam generator employed in a photonic based real-time plant discrimination sensor for use in selective herbicide spraying systems is presented. The plant detection 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 15 parallel laser beams over a 240mm 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 685nm and 685nm to 785nm laser wavelengths. Further optimisation of the optical signal is achieved by minimising the effect of daylight background noise by implementing a custom designed optical band-pass filter. The effectiveness of this filter is experimentally demonstrated.**

***Index Terms*—Photonic sensors, remote sensing, lasers, precision agriculture.**

I. INTRODUCTION

The most widely used practice in agriculture industries for weed control is still the spraying of the entire field with selective herbicides at different times in the cultivation cycle. Significant concerns have been raised over threats to consumer safety and the environmental damage that results from widespread agricultural use of herbicides. Furthermore, the growing phenomenon of crop resistance to herbicides and the spiraling costs of weed management continue to place increasing pressure on the ability of farmers to maintain profitability. The economic cost of weed management is a smaller return at harvest time as a result of outlay on herbicide and labour, reduction in yield and loss of productive growing land. There are also environmental costs from the increased chemical load on ecosystems and social costs due to the additional time required to manage weeds. Despite implementation of alternative methods of weed control including physical removal, crop rotation strategies and mechanical separation, herbicides remain the most widely used form of weed control and this is unlikely to change in the short to medium term. An automatic real time weed detection system, where weed detection and treatment are performed at the same time, can yield considerable reduction in the amount of herbicide used for weed control [1, 2]. To the authors' knowledge, the only commercially available device for weed control uses Light Emitting Diodes (LED) with two wavelengths in the red and near-infrared bands to illuminate the field [3]. The inability of this LED-based plant sensor system to discriminate between weeds and crops (green-from-green) limits its application in precision agriculture. Typical measured diffuse reflectance spectra in the visible region for Guinea Grass (*Panicum maximum*) leaves are shown in Fig. 1. Comprehensive spectral measurements show that the physiological differences between plant species are evident in the spectral region from 400nm to 800nm. The prototype weed control sensor described previously [4, 5] uses 635nm, 685nm and 785nm laser sources and it is capable of limited plant discrimination ("green from green"). Using more wavelengths at points in the spectrum where plants show different optical characteristics in terms of reflected intensity allows more precise plant discrimination [6].

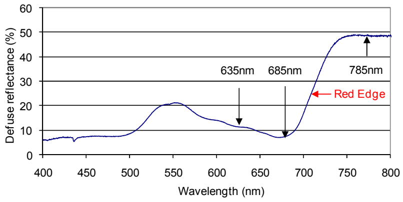


Fig. 1. Typical measured diffuse reflectance spectrum in visible region of leaves of Guinea Grass. In general the variations in the reflectance between 500nm and 800nm can be used to discriminate between different plants.

As previously described [4, 5], the output laser beam from the laser combination module passes through the custom fabricated multi-spot beam generator used for sample illumination in the plant detection system, as shown in Fig. 2. This beam generator is made of BK-7 rod. The rear side of the glass rod is coated with a highly reflective coating (R=99.5%) and the front side with a partially transmissive (T=8%) thin film coating. Uncoated 10mm entrance and exit windows are used at both ends of the rear side of the glass medium. The collimated input optical beam undergoes multiple reflections within the multi-spot beam generator and every time it hits the front surface a small fraction (8%) of its optical power is transmitted, thus projecting a laser spot array onto a sample object. The number of outgoing beams and hence the spatial resolution depends on the incident angle of the input beam.

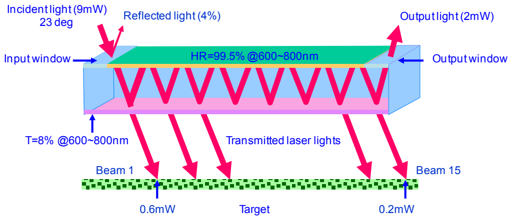


Fig. 2. Concept of the multi-spot beam generator. The front and rear surfaces are coated with semitransparent and highly reflective thin films, respectively.

The measured output optical power distribution for 635nm, 685nm and 785nm laser diodes is presented in Fig. 3. The intensity of the transmitted beams decreases further from the entrance beam. This optical power distribution causes a reduction in signal-to-noise ratio as shown in Fig. 4 (a). The reflected optical power recorded from a plant leaf (Figure 4b) is very small for the beams between 8 and 15 and all three wavelengths for two reasons: (1) high absorption by leaf structure at 635nm and 685nm wavelengths (Fig. 1), and (2) low optical power for the 785nm wavelength that should be maintained to prevent saturation of the image sensor due to high reflection at this wavelength from a leaf structure.

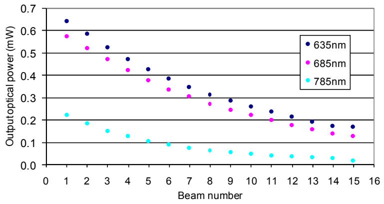
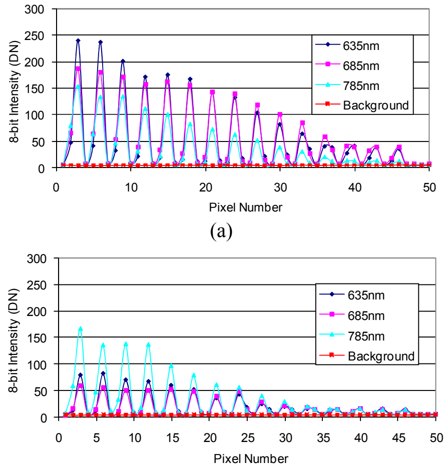


Fig. 3. Measured output optical power of the multi-spot beam generator at 635nm, 685nm and 785nm. Standard deviation was less than ±5µW. Front surface transmittance of the beam generator was 8% for all three wavelengths.



(a)

(b)

Fig. 4. Optical signal recorded by a line scan imager obtained when 15 beams illuminate: (a) a screen with constant diffuse reflectance in the wavelength region from 600nm to 800nm and (b) green leaves. The exposure time for the image sensor was adjusted to be 180µs. The experimental screen and plant leaf were illuminated in sequence by 635nm, 685nm and 785nm laser beams and data are presented on the same graph.

For real time applications in sunny conditions, the optical signal recorded by the linear image sensor is strongly affected by the intensity of solar radiation – increasing background noise up to saturation level. The spectrum of solar irradiation is shown in Fig. 5, along with the energy density that strikes the surface of the Earth with maximum in the region between 400nm and 900nm. The absorption spectrum of chlorophyll *a* (curve C in Fig. 5) indicates approximately the portion of the solar output that is utilized by plant leaves [7].

In this paper, the performance of a multi-spot beam generator which has uniform distribution of output optical power across all beams using a two-band-pass optical filter used to minimize the effect of solar radiation on the signal received by the image sensor is experimental investigated.

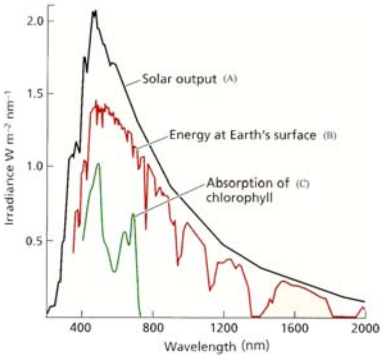
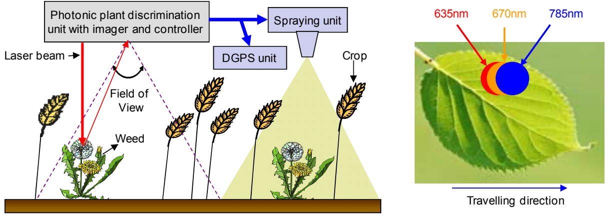


Fig. 5. Solar irradiation spectra above the atmosphere (curve A), at sea-level (curve B). Curve C is absorption spectrum of chlorophyll ***a*** present in plants, which absorb strongly in the 430nm and 680nm regions of spectrum [7].

II. SYSTEM DESCRIPTION

The photonic based plant discrimination sensor is comprised of a laser combination module, a multi-spot beam generator, a line scan image sensor and control unit. Fig. 6 shows a schematic representation of the sensor architecture where a leaf, stem or soil spot is sequentially illuminated by laser beams of three different wavelengths.



(a)

(b)

Fig. 6. (a) Schematic diagram of photonic based real-time plant discrimination sensor. (b) Plants are sequentially illuminated with laser beams at varying wavelengths along one optical path, striking approximately the same spot on the leaf. Plant identification is determined by processing the recorded reflected light signal for each wavelength.

Discrimination is achieved by recording and processing plant reflectance data for each wavelength. Sample illumination and image sensing are synchronized by software developed to control the operation of lasers, image sensor and perform data acquisition and 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 Deferential Global Positioning System (GPS), thus enabling the application of herbicide only to the area infested by weeds.

Laser combination module

The laser combination module contains two free-space beam combiners and 635nm, 685nm and 785nm laser diodes appropriately aligned as shown in Fig. 7. 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 projected on a leaf is 4mm. The output optical power of each laser diode was controlled by constant current laser driver and it should be optimized by considering the following factors: (a) the total power of 15 beams including the power loss along the beam propagation path should not exceed approximately 80% of the maximum power of the laser diode; (b) the detected reflected light from the vegetation should not exceed the saturation level for the image senor used with constant exposure time for all three wavelengths, and (c) the intensity of each beam should not damage the plant leaf anatomy and internal molecular structure.

Multi-spot beam generator

The output from the laser combination module passes through a multi-spot beam generator for sample illumination. The front surface of this device has graded transmittance and generates a uniformly distributed optical power across 15 beams with spatial resolution of 15mm and 4mm in diameter. This beam resolution allows detection of plants which are narrow leaved. The multi-spot beam array projected onto a leaf over background soil is shown schematically in Fig. 7.

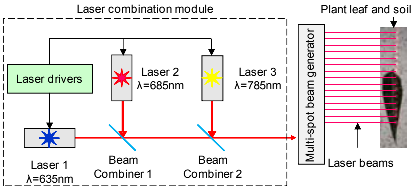


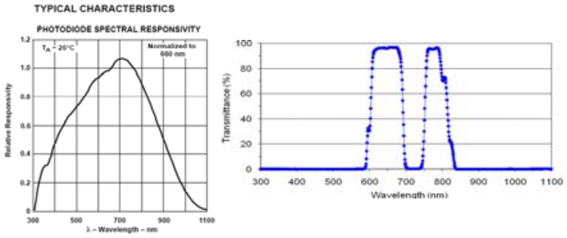
Fig. 7. Schematic concept of a laser combination module with three wavelengths and optical structure projecting 15 laser beams onto a leaf over background soil.

There are two advantages of using this device for plant illumination: a) multiple beams can be generated from one laser source; and b) the stable alignment of the generated beams regardless of the movement of the whole sensor housing mounted on a moving farming vehicle. This stable alignment is especially important when scanning along rugged terrain where the vertical sensor-plant distance may vary rapidly.

Image Sensors with two-band-pass optical filter

The intensity of the reflected light from a sample illuminated by laser beams emitted by the multi-spot beam generator is recorded by a linear image sensor placed behind an appropriate C-mount lens assembly. The image sensor has a linear array of 102 pixels of size 77×85μm and line rate of 10kHz. The output signal from the image sensor is in 8-bit serial format. The image sensor with larger pixel size is less sensitive to misalignment with 15 laser beams emitted by the multi-spot beam generator. The line rate of the linear sensor array is sufficient for detection when the plant discrimination system is mounted on a farming vehicle traveling at a typical speed of 20km/h.

A C-mount lens of focal length of 12.5mm was used to collect reflected laser light. To reduce background noise caused by daylight, a two-band-pass optical filter was designed and assembled on the imager’s lens. The spectral response of the image sensor and measured optical transmittance of the two-band-pass optical filter are shown in Fig. 8.



(a) (b)

Fig. 8. (a) Spectral response of the image sensor used to record reflected light from a plant leaf. (b) Measured optical transmittance for the filter used to minimize the effect of sun radiation on signal received by image sensor.

Acquisition process

The operation of the photonic based plant discrimination sensor is controlled by a microcontroller. The plant discrimination sensor can operate as a standalone unit or up to 100 sensors can be integrated in one system by using the Controller Area Network (CAN) bus protocol. The data acquisition and data processing is synchronized by operating lasers in sequence. The calculated peak intensities, stored in arrays A1, A2 and A3 for all three laser diodes are used to determine the spectral characteristics of the illuminated target. If the calculated optical signature matches a value stored in the Discrimination Lookup Table a signal that activates the spraying unit is generated.

Discrimination method

Plant discrimination is based on determining the slope in the reflectance at the three wavelengths used. The two slope values, S1 and S2, are defined as:

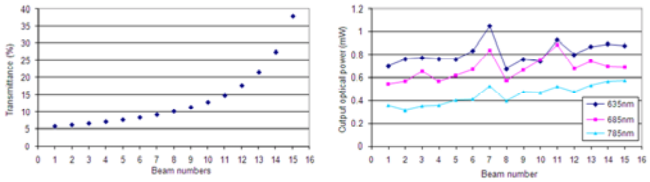
$$S_1 = \frac{R_{635} - R_{670}}{\lambda_{670} - \lambda_{635}} \quad \text{and} \quad S_2 = \frac{R_{785} - R_{670}}{\lambda_{785} - \lambda_{635}}, \qquad (1)$$

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. The Normalized Difference Vegetation Index (NDVI) defined by Eq. (2) can be used to discriminate soils and green leaves.

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

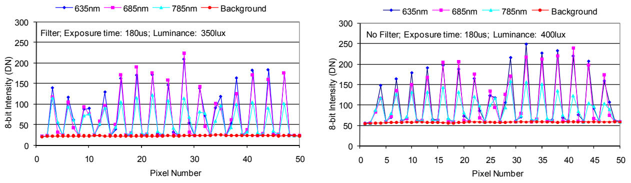
III. RESULTS AND DISCUSSION

In order to obtain a uniform distribution of the optical power across 15 beams (500µW per beam and input laser power of 9mW) the graded transmittance of the front surface of the multi-spot beam generator has been calculated (Fig. 9 (a)). Based on the calculated values for transmittance the multi-spot beam generator has been manufactured and the measured optical power distribution is shown in Fig. 9 (b). The input optical power to the multi-spot beam generator was 13mW, 11mW and 7mW for the 635nm, 685nm and 785nm lasers, respectively. Despite the uneven measured optical power distribution for some beams this design of the multi-spot beam generator improves the SNR performance in comparison with previously reported non-uniform multi-spot beam generators.

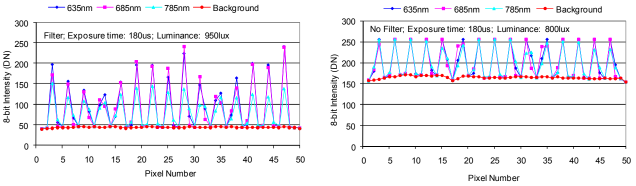


(a) (b)

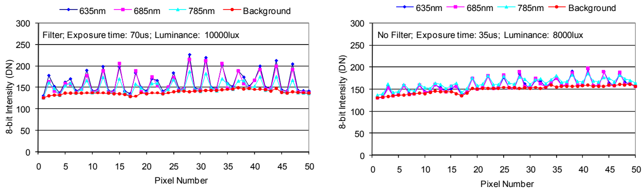
Fig. 9.(a) Graded transmittance for front surface of the laser multi-spot beam generator for producing uniform optical power distribution across 15 beams. (b) Measured output optical power distribution across 15 beams.



(a) Light conditions: Outdoor, shaded.



(b) Light conditions: Outdoor, clear sky, shaded.



(c) Light conditions: Outdoor, full sun, clear sky.

Fig. 10. Optical signal recorded by a line scan imager obtained when a screen with constant diffuse reflectance is illuminated by fifteen beams and three different level of luminance. The exposure time for the image sensor was adjusted to prevent saturation of the image sensor (c).

A two-band-pass optical filter with central wavelengths of 648±43nm and 783±29nm and transmittance above 95% in both bands has been designed and implemented. The effect of this filter on reduction of background noise caused by daylight has been examined. Fig. 10 shows the optical signal recorded by a line scan imager obtained when a screen placed outdoor on the ground is illuminated by fifteen beams produced by the multi-spot beam generator and three lasers. The daylight illumination was measured with LX1330B illuminance meter. The exposure time for the image sensor was adjusted to prevent saturation of the image sensor. Figure 10(b) shows that the background noise received by the imager is reduced by more than three times when the two-band-pass filter was applied.

IV. CONCLUSIONS

The optimisation of the optical signals in the photonic based spectral reflectance sensor for plant detection and weed discrimination has been presented. This optimisation has been achieved by using a multi-spot beam generator with graded transmittance of its front surface which produces 15 lasers beams with more uniform output power distribution and implementing a two-band-pass filter for reducing background noise caused by daylight illumination. The optical signal-to-noise ratio has been considerably improved, which will significantly improve plant discrimination rate for the selective herbicide spraying systems. Future development will include investigation of the polarisation filter on signal-to-noise ratio, implementation of a daylight sensor for automatic control of exposure time for the linear sensor array and integrating the data acquisition and data processing with an embedded control system which will operate the plant discrimination system.

ACKNOWLEDGEMENT

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