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Kavitha Venkatarayan
Edith Cowan University

Sreten Askraba
Edith Cowan University

Kamal E. Alameh
Edith Cowan University

Clifton L. Smith
Edith Cowan University

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Multi-wavelength laser sensor for intruder detection and discrimination

Kavitha Venkatarayan^{1*}, Sreten Askraba¹, Kamal E. Alameh¹ and Clifton L. Smith¹

¹ Electron Science Research Institute, Edith Cowan University, 270 Joondalup Drive, Joondalup 6027, Western Australia. E-Mails: kvenkata@our.ecu.edu.au (K.V); s.askraba@ecu.edu.au (S.A); k.alameh@ecu.edu.au (K.E.A); Clifton.smith@ecu.edu.au (C.S).

* Author to whom correspondence should be addressed; E-Mail; kvenkata@our.ecu.edu.au ; Tel.: +61 8 6304 5836, Fax: +61 8 6304 5302.

Abstract: An intruder detection and discrimination sensor with improved optical design is developed using lasers of different wavelength to demonstrate the concept of discrimination over a distance of 6m. A distinctive feature of optics is used to provide additional transverse laser beam scanning. The sample objects used to demonstrate the concept of discrimination over a distance of 6m are leaf, bark, black fabric, PVC, wood and camouflage material. A camouflage material is chosen to illustrate the discrimination capability of the sensor. The sensor utilizes a five-wavelength laser combination module, which sequentially emits identically-polarized laser light beams along one optical path. A cylindrical quasi-optical cavity with improved optical design generates multiple laser light beams for each laser. The intensities of the reflected light beams from the different spots are detected using a high speed area scan image sensor. Object discrimination and detection is based on analyzing the Gaussian profile of reflected light at the different wavelengths. The discrimination between selected objects is accomplished by calculating four different slopes from the objects' reflectance spectra at the wavelengths 473nm, 532nm, 635nm, 670nm and 785nm. Furthermore, the camouflage material, which has complex patterns within a single sample, is also detected and discriminated over a 6m range by scanning the laser beam spots along the transverse direction.

Keywords: Laser spectroscopy; Remote sensing; Object identification; Optical data processing.

1. Introduction

One of the major challenges facing military is to accurately identify and locate targets within a secured area. Since 1980's, substantial efforts have been made to overcome this problem, and laser scanning technology has been considered as the best approach for identifying and locating targets in military applications [1].

The laser scanning system provides geometric results in terms of distance, position, attitude and co-ordinates. To obtain information from more than one point of an object, a scanning mechanism must be used to deflect the laser beam from the laser source, to the desired object surface. This deflection is usually in two or three dimensions opto-mechanically in conventional laser scanning. This type of laser scanners can be used for various types of applications such as airborne

topographic mapping, surveying of buildings and plants, model generation for animation purposes [2]. Laser scanning has also been employed for satellite and missile tracking, target discrimination, surveillance and numerous other applications. Fault-tolerance and reliability have been the key factors that assess the performance of a solid intrusion detection system [3]. Tests conducted to determine the feasibility of using laser scanning for intrusion detection, have confirmed the capability of detecting humans at 25m range and vehicles at 80m range [4], respectively. These tests demonstrated large area coverage, the ability to determine the size of the intruder and a low false alarm rate [4].

Multiwavelength laser scanning is an improvement from object detection to object identification and discrimination, where the objects and materials are discriminated by measuring their reflectance characteristics at specific wavelengths and matching them with their spectral reflectance curves. Multiwavelength imaging method has been used to detect foreign material in cotton and the spectral region used was from 405nm to 940nm [5]. Multiwavelength lasers were also used for micromachine-based cell counting and sorting system, which had the capability to detect different fluorescent dyes cells individually using lasers with different wavelengths [6].

Multiwavelength laser scanning is necessary to discriminate materials such as camouflage material which has numerous patterns embedded into its fabric. Holographic gratings cannot be implemented for multiple-wavelength laser scanning because different wavelengths will be diffracted along different angles. This makes the overlapping of collimated beams of different wavelengths difficult, and hence, object discrimination becomes impractical. With the recent advances in the development of high-speed sensors and high-speed data processors, the implementation of multi-wavelength laser scanners identification and discrimination for complex materials like camouflage material has now become feasible.

This paper describes and demonstrates object discrimination through multiple wavelength laser sensor over a distance of 6 meters. The sensor architecture comprises a laser combination module, cylindrical quasi-optical cavity, collecting lens and the charged coupled device (CCD) imager. The most important feature about this particular sensor is the cylindrical quasi-optical cavity that generates multiple laser spots from a single laser source. The improved optical design of the sensor produces a 2D laser spot array in a concealed wide area, as illustrated in Figure 1.

The sample objects considered to demonstrate the proof-of-concept for detection are leaf, wood, bark, PVC material and black fabric. These objects can be easily discriminated by a single laser spot, but a single laser spot is not enough to discriminate the camouflage material from other objects, because it has numerous patterns embedded in a single sample. Hence, it is necessary to strike the camouflage material along the transverse direction with several beam spots (each spot sequentially illuminated with various wavelengths) in order to detect it. Through reflectance spectral measurements, a camouflage material exhibits slight change in spectral reflectance for some beams, whereas for a uniform object no change in spectral reflectance is measured for all beams. By projecting the laser spots along the transverse direction, the sensor was able to discriminate the camouflage material after processing the intensities of the reflected laser beams at different wavelengths. Experimental results demonstrate the ability of the sensor to discriminate the above-mentioned objects over a range of 6m.

2. Methods and Materials

2.1 Laser combination module

The laser combination module is made of five lasers of different wavelengths, appropriately aligned using four free-space beam combiners. The lasers used in the experiments are 473nm laser: model MBL 473, 532nm: model MPL 532, these lasers are made by CNI Laser. The 635nm laser: model LDM 635, 670nm: model LDM 670 and 785nm: model LDM 785; these lasers are made by UVH Industries. The beam combiners used in the experiments are made by Edmund.

The laser module produced five collimated and overlapped laser pulses of different wavelengths with similar polarization, which were turned on sequentially at any switching time using a custom-made electronic driver, which can be operated automatically or in a manual mode. The diameter of each collimated laser beam was 4mm. The 635nm, 670nm and 785nm lasers had 6mW output power each, while the output power of both 473nm and 532nm lasers was 12mW. The optical beams of lasers 635nm, 670nm and 785nm were combined using the beam combiner 1 and 2, respectively. The other two lasers of wavelength 473nm and 532nm were combined with a beam combiner 3. Finally, the outputs from combiners 2 and 3 were combined with a beam combiner 4.

The plane mirror 1 was placed at 45° with respect to the beam combiner 4, while the plane mirror 2 was shifted slightly in such a way that the laser beams stroked the entrance window of the cylindrical quasi optical cavity at different positions. The combined (five) laser pulses were sequentially launched into the entrance window of the optical cavity which produced multiple laser beam spots, and by slightly shifting mirror 2 vertically without changing the angle of the mirror, the laser spots generated at the camouflage material were shifted in the transverse direction, as illustrated in Figure 2.

2.2 Cylindrical quasi-optical cavity

A cylindrical quasi-optical cavity, fabricated using BK-7 glass medium [7], was devised to produce multiple laser spots, as shown in Figure 3.

The number of laser spots that the optical cavity can produce depends on the incident angle of the laser beam in the entrance window of the cavity. The rear side of the optical cavity was deposited with a high reflective coating ($R_2 \geq 99\%$) while the front side had a partial transmission ($T_1 \leq 13\%$, or $R_1 = 87\%$) coating.

Figure 4 shows the principle of multiple beam reflections within the optical cavity. An injected laser beam of intensity P , undergoes multiple internal partial reflections according to the coating applied to either side, where P' is the reflected power (approximately 4%) from the non-coated entrance window of the optical cavity.

Given P and either the transmittance or reflective coating values, the outgoing power of each laser beam $P_1 - P_n$ and values of L , L' , P' can be calculated through the iterative sequence of basic equations (1a-1d) as shown below.

$$P'_n = L_n T_2 \quad (1a)$$

$$L'_n = L_{(n-1)} R_1 \quad (1b)$$

$$P_n = L'_{(n-1)} T_1 \quad (1c)$$

$$L_n = L'_n R_2, n \geq 1 \quad (1d)$$

where P is the intensity of the injected laser beam, P' is the reflected power from the uncoated entrance window of the optical cavity (loss is approximately 4%), L is the laser power transmitted through the entrance window, L' is the laser power reflected off the transmittance coating back into the cavity and T is the coating transmittance value.

An example illustrating the output optical power distribution through iterative sequence of basic equations (1a-1d) is shown in Figure 5. The 635nm laser from the laser combination module, with 4mW of output optical power was launched at the entrance window of the optical cavity to generate multiple laser spots. Figure 5 also shows the measured output optical power distribution for 10 laser spots generated from a single laser source.

The multiple laser spot generation leads to reduction in laser spot power levels. However, the power levels of all beam spots are high enough to attain a sufficiently high SNR, and hence adequate object discrimination. The incident angle of the beam depends on the incident angle of the injected laser onto the entrance window of the cavity. However, it has no impact on object detection, because the laser beam striking a particular spot of the object scatters along all directions and only a part of the scattered beam (that falls within the field of view, or solid angle, of the imager's lens) is captured by the imager.

2.3 Capturing reflectance

A 0.5-inch interline transfer charged coupled device (CCD) imager was used to capture the intensity of reflected light from the sample illuminated by the cylindrical quasi optical cavity. The imager contains 768(H) \times 494(V) pixels of size $8.4\mu\text{m} \times 9.8\mu\text{m}$. A C-mount TV lens of focal length $f = 12.5\text{mm}$ was used to collect the light scattered from the illuminated laser spots. The lens aperture was adjusted appropriately to avoid saturation of the imaged laser spot array.

This particular imager exhibited high sensitivity over the wavelength range (470 – 785nm) as shown in Figure 6. Ten images were taken for each wavelength, and the images from the camera were digitized in 12-bit form using a Spiricon frame grabber circuit board. Then the images captured from the CCD were processed using MATLAB to find out the maximum peak intensity value. The estimated CCD acquisition time was 200 μsec and the estimated overall acquisition time was 2msec. The acquisition was synchronized by sequentially switching ON and OFF the lasers, and capturing the intensities reflected off the various spots for each wavelength.

2.4 Discrimination method

The first step for object discrimination was to transform the captured information from the imagers 12-bit form into digital numbers, $R(\lambda_n)$, where λ_n is the wavelength used to illuminate the object. This transformation was obtained by applying a Gaussian curve fitting and the function of the fitted curve is given in equation (2).

$$f(x) = a \cdot e^{-\frac{(x-b)^2}{2\sigma^2}} \quad (2)$$

where a , b and σ are the maximum value, maximum position and standard deviation respectively. Once Gaussian curve was fitting with the measured intensities at different wavelengths, the algorithm produced the a value (peak) of Eq. (2) expressed in digital numbers for all wavelengths.

The peak intensity values, a , were obtained for each beam by applying a non-normalized Gaussian curve fitted to the one-dimensional intensity profile of the imaged laser spot. The intensity profile is a row of pixels crossing the center of the laser spot, along the x-axis. The Gaussian curve was fitted to the intensity profile of the laser spot to obtain the peak intensity of the reflected laser beam, using the Matlab add-on toolbox named EzyFit.

The next step in object discrimination was the analysis of the slope values of the reflectance spectra at the five laser wavelengths used in the sensor [8, 9]. Four slope values S_1 , S_2 , S_3 and S_4 were defined as follows:

$$\begin{aligned} S_1 &= \frac{R_{473} - R_{532}}{\lambda_{532} - \lambda_{473}} \quad , \quad S_2 = \frac{R_{532} - R_{635}}{\lambda_{635} - \lambda_{532}} \\ S_3 &= \frac{R_{635} - R_{670}}{\lambda_{670} - \lambda_{635}} \quad \text{and} \quad S_4 = \frac{R_{670} - R_{785}}{\lambda_{785} - \lambda_{670}} \end{aligned} \quad (3)$$

where λ_n is the wavelength of laser expressed in nanometers. Using the above equation (3), four different slope values were identified and the difference in slope values enabled the discrimination between various objects.

Reflectance spectra for different materials were obtained by using USB 2000, visible spectrometer (400-850nm) made by Ocean Optics. The experimental setup for measuring the reflectance spectrum is shown in Figure. 7.

The reflectance spectrum of a material can be used as a unique signature that identifies materials from each other. This is the basis for the multiwavelength remote sensing for object identification and discrimination. Each material was first characterized with USB 2000 spectrometers.

3. Experimental results and Discussion

3.1 Spectral object discrimination results

Six different objects namely leaf, bark, wood, PVC, black fabric and camouflage material were used to demonstrate the concept of spectral object discrimination in the laboratory. The reflectance spectra of leaf, bark, wood, PVC and black fabric are shown in Figure. 8.

The reflectance spectrum of the camouflage material is shown in Figure. 9. These reflectance spectra were obtained by using a visible spectrometer of spectral range 400-850nm. The sample objects were placed at 6m from the multiple wavelength sensor.

Equations (2) and (3) were used to calculate the average slopes S_1 , S_2 , S_3 and S_4 for the various objects, which are shown in Figure 10. The results in Figure 10 clearly demonstrate that each object differs from others in at least one slope value, making it distinguishable. It can be noted that small errors were encountered during the slope measurements, mainly because of the dark current of the image sensor and, predominantly, the optical power fluctuations of the laser sources.

The objects were placed at 6m from the optical cavity and illuminated with an array of laser beams emitted through the sensor. The reflected intensities from these objects were measured and processed. For each wavelength ten measurements were recorded with an interval of 30 seconds and the average slopes for all objects are shown in Figure 11.

Slope S_1 in Figure 11 shows that all the objects, except the black fabric, have negative non-identical slope values. It can be noted that, the main requirement for object discrimination is that there should be a difference in at least any two slope values, and this criterion was clearly satisfied with all other sample objects. When mirror (2) was slightly shifted the laser spots shifted in the transverse direction resulting in the measured slopes shown in Figure 12.

These experimental results shown in Fig. 11 and Fig. 12 validate the capability of the multiple wavelength sensor to discriminate between the various objects under investigation.

The camouflage material, however, has complex patterns in comparison with the other objects discriminated in Figures 11 and 12. These patterns are embedded in a single sample, and when the laser beams were projected onto that material, the intensities of reflected laser beams were dependent upon the pattern whereon the beam was projected. Scanning of the beam spots was required in order to identify that material. The multiple wavelength sensor (Figure 1) had five different wavelengths, however the improved optical design shown in Figure 2 had the capability to emit multiple sets of parallel laser beams and this was a key characteristic necessary to discriminate materials of complex patterns within a single sample.

Figure 13 shows the average slope values S_1 , S_2 , S_3 and S_4 for the camouflage material patterns measured from the reflectance spectra captured by a spectrometer.

Five different wavelengths were sequentially projected onto the camouflage material from the multiple-wavelength sensor. For a small shift in mirror 2 (shown in Figure 2), the projected laser spot array was shifted along the transverse direction, thus illuminating a different pattern. For every mirror shift, ten measurements were recorded for each wavelength to calculate the average reflectance of the camouflage material spots illuminated by the laser beams. Figure 14 shows the average slope values S_1 , S_2 , S_3 and S_4 for the camouflage material patterns measured by the multiple wavelength sensor at 6m in the laboratory. The measured slope values in Figure 14 were in good agreement with the slope values calculated from the measured reflectance spectra of the camouflage material patterns shown in the Figure 13. This clearly demonstrates that camouflage materials can be identified through transverse laser beam scanning.

4. Conclusion and Future Work

A novel five-wavelength laser scanner for intrusion detection and discrimination has been developed and demonstrated over a 6m range. Sample objects namely leaf, bark black fabric, PVC, wood and camouflage material placed at 6m from the sensor have successfully been identified and discriminated from one another by measuring four spectral reflectance slopes at the employed wavelengths.

Camouflage material of complex patterns have been identified by shifting the laser spots along the transverse direction thus enabling the various camouflage patterns to be individually identified. Spectral analyses have confirmed that the laser wavelengths 473nm, 532nm, 635nm, 670nm and 785nm are the most appropriate for object discrimination, and the calculated average slope values have confirmed that the selected sample object differs from others in at least one slope value, making them easily distinguishable.

The future goal of this research is to successfully develop and improve the discrimination precision of a multiple wavelength sensor for a range exceeding 10m. This can be achieved through (i) increasing the imager's resolution, (ii) extending the range of the imaging zoom lens, (iii) reducing the imager's noise floor, (iv) improving the Gaussian beam fitting method, (v) developing an improved object identification algorithm and (vi) using additional lasers of different wavelengths, which leads to higher-resolution optical signatures for the target objects.

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