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Abstract: A Photonic-based multi-wavelength sensor capable of discriminating objects is proposed and demonstrated for intruder detection and identification. The sensor uses a laser combination module for input wavelength signal multiplexing and beam overlapping, a custom-made curved optical cavity for multi-beam spot generation through internal beam reflection and transmission and a high-speed imager for scattered reflectance spectral measurements. Experimental results show that five different wavelengths, namely 473nm, 532nm, 635nm, 670nm and 785nm, are necessary for discriminating various intruding objects of interest through spectral reflectance and slope measurements. Objects selected for experiments were brick, cement sheet, cotton, leather and roof tile.

OCIS codes: (300.6360) Spectroscopy, laser; (120.0280) Remote sensing; (280.3420) Laser sensors; (200.4560) Optical data processing.

References and links


1. Introduction

Prevention of unauthorized entry into buildings containing assets is a significant measure in reduction of crime and terrorism. Defence and Security organisations have recently adopted laser scanning technologies for projectile guidance, surveillance, satellite and missile tracking and target discrimination and recognition. Over the last decade, terrestrial laser scanning (TLS) has increasingly played an advanced role in exterior and interior intrusion sensing as a part of Critical Infrastructure Protection (CIP), specifically Perimeter Intruder Detection Systems (PIDS). Laser scanning technique has been tested in British Home Office – Police Scientific Development Branch (PSDB) in 2004. It was found that laser scanning has the capability to detect humans in 30m range and vehicles in 80m range with low false alarm rates [1].

Multiwavelength laser scanning is a natural progression from object detection to object identification and classification, where specific features of objects and materials are discriminated by measuring their reflectance characteristics at specific wavelengths and
matching them with their spectral reflectance curves. With the recent advances in the development of high-speed sensors and high-speed data processors, the implementation of multi-wavelength laser scanners for object identification has now become feasible.

While holographic gratings can be used to generate multiple single-wavelength laser spots for intruder detection, the same cannot be implemented for multi-wavelength laser scanning. The reason being laser beams of different wavelengths will be diffracted from a holographic grating at different angles, hence making this technique impractical for maintaining a high-degree of overlapping between beams of different wavelengths projected at a particular spot [2]. A two-wavelength photonic-based sensor for object discrimination has recently been reported [2], where an optical cavity is used for generating a laser spot array and maintaining adequate overlapping between tapped collimated laser beams of different wavelengths over a long optical path [2,3]. However, the main drawback of this approach is the limitations in the number of objects that can be discriminated [2].

By increasing the number of wavelengths at which objects exhibit different optical characteristics, the number of objects and materials that can be identified and discriminated increases significantly. Figure 1 shows a typical reflectance spectra obtained by using two different spectrometers, visible (from 400 to 850nm) and infrared (from 850 to 2100nm) spectrometers for cotton, soil, vegetation and clear water. The reflectance spectrum of a material can be used as a unique signature that identifies this material from other materials. This is the basis for the multiwavelength remote sensing for object identification.

![Fig. 1. Typical measured reflectance spectrum of cotton soil, vegetation and clear water. The reflectance spectrum of a material is a unique signature that can be used for material identification.](image)

In this paper, novel multiwavelength photonic-based sensor architecture for object discrimination and identification is proposed and demonstrated. The sensor architecture is based on the projection of pulsed laser beams of different wavelengths and the processing of the recorded reflected intensity data to achieve identification and discrimination of five objects commonly encountered in intruder-detection scenarios, namely, brick, cement, cotton, leather and roof tile. Through the use of a novel combination of the normalized difference vegetation index (NDVI) and slopes of the reflectance spectrum we develop a demonstrator that can identify objects on a limited basis. Results clearly show that by optimizing the wavelength values, different objects do differ in at least one region of the reflectance spectrum and that a multiple laser array can detect differences between objects.
2. Multiwavelength MicroPhotonic Sensor Architecture

The schematic diagram for the proposed photonics-based multiwavelength sensor architecture for object identification is shown in Fig. 2. It is comprised of a laser combination module, a multi-spot beam generator, an area image sensor and collecting lens. The laser beams are modulated using custom-made electronic drivers integrated on a printed circuit board. This result in laser pulses of different wavelengths illuminating the objects under investigation sequentially. Object discrimination and identification is achieved by recording and processing the intensities of the different laser beams reflected off the various spots illuminating the object, for each illuminating wavelength. The bench top set up in the laboratory used to conduct the experiment is shown in Fig. 3.

![Fig. 2. Schematic diagram for the experimental set up.](image)

![Fig. 3. Experimental set up for object discrimination. Objects are illuminated with laser beams at varying wavelengths along one optical path, striking the same spot on the object. By measuring and processing the reflected light intensities for each wavelength, a large variety of objects can be identified.](image)

2.1 Laser combination module

The laser combination module has two sections, as shown in Fig. 4. Section 1 is a laser combination module which includes three laser diodes of wavelengths 635nm, 670nm and 785nm, respectively, two free space beam combiners and a constant-current laser driver. Section 2 is another laser combination module that combines two lasers of wavelengths 473nm and 532nm driven by a constant-power laser driver. This arrangement of laser sources and optical combiners enables the generation, overlapping and polarization alignment of five...
collimated laser beams of different wavelengths. Polarization alignment for all laser beams is necessary in order to minimize the impact of the polarization-dependent scattering loss of the object under investigation. All combined laser beams are collimated at a diameter of 4mm.

Fig. 4. Laser beam combination module with five wavelengths and four beam combiners. This arrangement generates five collimated and overlapped laser beams with the same polarization orientation.

The laser diodes are switched sequentially using laser drivers that are switched via a custom-made electronic printed circuit board. The optical output power of each laser diode is adjusted via trim-pots integrated on the laser driver circuits. The output optical power levels for the 473nm and 532nm lasers were set to 8mW and 7mW, respectively, while the other three lasers had equal output power levels of 6mW. The divergence for all output collimated laser beams was less than 1.5 mrad. The output power of each laser beam from the cavity was measured using a free-space optical power meter. The active area of the detector has a diameter of 5mm. This power meter was mounted onto a linear optical stage, which enables precise alignment of the laser beams to the centre of the detector’s active area and accurate measurements of the laser beam intensities which are displayed in Fig. 5.
Fig. 5. Measured output optical power for each laser beam after passing through the optical cavity.

2.2 Multi-spot beam generator

The output laser beam from the laser combination module passes through the custom fabricated multi-spot beam generator for object illumination. This beam generator is made of BK-7 glass with inner and outer interface radii of $R_1$ and $R_2$, respectively. $\theta$ is the angle of curvature of the multi-spot beam generator (Fig. 6(a)). The rear side of the glass is coated with a highly reflective ($R \geq 99.5\%$) and the front side with a partial transmission ($T \geq 13\%$) thin film.

An uncoated 10mm entrance and exit windows are used at both ends of the rear side of the glass medium. Hence, an input collimated optical beam undergoes multiple reflections within the optical cavity, and every time it hits the front surface a small fraction (around 13\%) of its optical power is transmitted, thus projecting a laser spot array onto an object sample. This multi-spot beam generator has a $45^\circ$ curvature and generates 20 spots when an
incident beam is injected through the entrance window. The number of outgoing beams depends on the incident angle of laser beam.

2.3 Image sensor

The intensities of the laser beams reflected off the spots illuminated by the beam generator are captured by an area image sensor that images the reflected laser beams sequentially. Figure 7 shows the spectral response of the image sensor used in the experiments. This particular imager exhibits high sensitivity over the wavelength range (470 – 785nm). An imaging lens is usually used in conjunction with the imager sensor in order to map the intensities of the beams scattered from the different laser spot into the imaging plane. For the imager used in the experiments, a 0.5-inch interline transfer CCD imager was employed having 768(H) × 494(V) pixels of size 8.4µm × 9.8µm. A C-mount TV lens of focal length f = 12.5mm was used to collect the light scattered from the illuminated laser spots. The estimated CCD acquisition time is 200µsec and the estimated overall acquisition time is 2msec. The lens iris was adjusted appropriately to avoid saturation of the imaged laser spot array. The images from the camera are digitized in 12-bit form using a Spiricon frame grabber circuit board.

![Fig. 7. Spectral response of the image sensor used for the experiments (as per manufacturers specifications).](image)

2.4 Object discrimination method

The object discrimination method is based on determining the slope in the reflectance at the five wavelengths [2,4–6]. The four slope values, , are defined as:

\[
S_1 = \frac{R_{\lambda_{570}} - R_{\lambda_{532}}}{\lambda_{532} - \lambda_{570}}, \quad S_2 = \frac{R_{\lambda_{635}} - R_{\lambda_{532}}}{\lambda_{635} - \lambda_{532}},
\]

\[
S_3 = \frac{R_{\lambda_{670}} - R_{\lambda_{635}}}{\lambda_{635} - \lambda_{670}} \quad \text{and} \quad S_4 = \frac{R_{\lambda_{785}} - R_{\lambda_{670}}}{\lambda_{785} - \lambda_{670}}
\]

(1)

where \(\lambda_n\) is the wavelength of the laser diode in nanometers, \(R_n = I_n/P_n\) is the calculated reflectance, \(I_n\) is the peak intensity of a beam spot imaged by the image sensor (usually represented by a 12-bit digital number (DN)) and \(P_n\) is the measured optical power for each
spot generated by the optical structure in watts. The peak intensity values, $I_\lambda$, were obtained 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 middle of the laser spot, along the x-axis. The Gaussian curve is fitted to the intensity profile of the laser spot to obtain the peak intensity of laser spot using the Matlab add-on toolbox. An example of such fitted Gaussian curve is shown in Fig. 8.

![Fitted Gaussian function for Leather@635nm](image)

Fig. 8. Fitted Gaussian function for Leather@635nm

3. Experimental results and discussion

Five different objects namely: brick, cement sheet, roof tile, cotton and leather were used to demonstrate the proof-of-concept of the photonic-based sensor in the laboratory. Each object was first characterized with two different commercially available (visible and near infrared) spectrometers. The experimental setup for measuring the reflectance spectrum is shown in Fig. 9.

![Experimental setup for measuring the reflectance spectra of the different sample objects](image)

Fig. 9. Experimental setup for measuring the reflectance spectra of the different sample objects.

The reflectance of a roof tile is generally low but has a peak around 600nm. For a brick, the reflectance spectrum is piecewise linear with a higher slope over the visible part of the
spectrum. The reflectance of cotton has a peak at 473nm and several deflection points within the visible and near infrared parts of the spectrum. On the other hand, the reflectance of leather is generally low for visible wavelengths and exhibits several peaks over the infrared part of the spectrum. For the cement sheet, the reflectance increases almost monotonically with increasing wavelength. The measured spectral reflectance curves for all objects are shown in Fig. 10. Note that these reflectance spectra were obtained by using two different spectrometers, namely a visible spectrometer of spectral range 400-850nm and an infrared spectrometer of spectral range 850-2100nm.

To identify the above mentioned objects, specific wavelengths, namely 473nm, 532nm, 635nm, 670nm and 785nm, were selected for two main reasons. Firstly, the spectral reflectance slopes at the different wavelengths are significant and do not overlap simultaneously and secondly, these wavelengths are synthesized using commercially available lasers.

The object samples were placed at 2m from the optical cavity and illuminated with an array of coplanar laser beams emitted through the multiwavelength photonic-based sensor and the reflected intensities from these objects were measured as illustrated in Fig. 2.

The average values of slopes $S_1$, $S_2$, $S_3$ and $S_4$ for the sample objects, calculated using Eq. (1) are shown in Fig. 11. Each object is distinguishable in at least one slope. The measured standard deviations of the slope values are shown in Fig. 12. Clearly, no simultaneous overlapping between slope values of different objects was present, demonstrating accurate discrimination of the various objects. For example if we look at the average slopes for a cement sheet, shown in Fig. 12, we do not see any overlapping with other objects in slopes $s_1$, $s_3$ and $s_4$, and hence the cement sheet can be discriminated from other objects. For cotton, there is no overlapping in slopes $s_1$, $s_2$ and $s_4$ with the other objects under investigation, while overlapping is seen in slope $s_3$ with roof tile. For brick, there is no overlapping in slopes $s_1$, $s_2$ and $s_3$, while overlapping is seen in slope $s_4$ with roof tile and leather. For roof tile, there is no overlapping in slopes $s_1$, while overlapping is seen in slopes $s_2$, $s_3$ and $s_4$ with other objects. For leather, there is no overlapping in slopes $s_1$ and $s_2$ with any other object. Note that the variances of the slopes are mainly due to fluctuations in the response of the image sensor and the optical intensities of the laser diodes. The non-overlapping slopes shown in Fig. 12 demonstrate the ability of the proposed novel multiwavelength photonic-based sensor to identify and discriminate objects frequently encountered in intruder-detection scenarios.
Fig. 11. Calculated average slope values for five different objects.

Fig. 12. Average values with standard deviation for slopes S1, S2, S3 and S4 for five different objects.

4. Conclusion and future work

A novel five-waveband laser scanner for intruder detection and object discrimination has been proposed and its principle has been demonstrated. The optical reflectance properties of various natural objects commonly encountered in the military perimeter such as brick, cement sheet, roof tile, cotton and leather have been measured, and the optimum wavelengths necessary for object identification and discrimination has been determined. Analyses of the spectral characteristics for the selected objects have shown that the lasers with 473nm, 532nm, 635nm, 670nm and 785nm wavelengths are the most appropriate for identification and discrimination of the selected objects.

Object samples have been illuminated with an array of collimated laser beams emitted through a multi-spot beam generator integrating lasers, free space beam combiners and an image sensor, and the reflectance properties of the objects under investigation have been measured. These measurements were carried out in the laboratory with ambient fluorescent light. Since our initial goal is a proof-of-concept demonstration, the experimental set up was
done in laboratory conditions. Note however, that the performance of the laser scanning system in the field will be reported elsewhere. Discrimination between objects has been demonstrated by determining four spectral slopes at the selected wavelengths. Spectral slope measurements have confirmed no simultaneous overlapping between slope values of the different objects, making the identification of the selected objects accurate even in the presence of laser power fluctuations.

It is important to notice that the addition of too many lasers increases the cost, bulkiness and slows the operating speed of the sensor. Future work will focus on determining the accuracy of the sensor for a broader range of objects. The end goal of this research project is to design a laser scanning system capable of identifying a wide range of objects in the field and attaining a detection range greater than 30m.