2011

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10.1109/JLT.2011.2158571
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Optical cavity based multi-wavelength sensor for spectral discrimination and object position detection

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Abstract—An optical-cavity-based multi-wavelength sensor is developed for object discrimination and position finding. The working principle of this device employs the multiple laser beam triangulation method to determine object position in addition to its ability to recognize them. The multi-wavelength sensor employs five different identically-polarized and overlapped laser light beams that are sequentially pulsed and launched through a custom-made curved optical cavity to generate multiple laser spots for each laser. The intensities of the reflected light beams from the different spots are detected by a high-speed area scan image sensor. The discrimination between five different objects, namely, brick, cement sheet, roof tile, cotton and leather is accomplished by calculating the slopes of the objects’ reflectance spectra at the employed wavelengths. The object position (coordinates) are determined using the triangulation method, which is based on the projection of laser spots along determined angles on the objects and the measurements of the objects’ reflectance spectra using an image sensor. Experimental results demonstrate the ability of the multi-wavelength spectral reflectance sensor to simultaneously discriminate between different objects and predict their positions over a 6m range with an accuracy exceeding 92%.

Index Terms—Laser spectroscopy; Object identification; Laser triangulation sensor; Optical data processing.

I. INTRODUCTION

LASER scanning has become an essential tool in many industries requiring digital three-dimensional reconstruction of an object or a scene. In military applications, laser scanning technology has also been employed for projectile guidance, satellite and missile tracking, gun fire range measurements, surveillance, target discrimination and recognition.

In the last decade, laser scanning has found new uses as an active optical sensor for perimeter security. Its key features are the ability to determine the intrusion size, speed and precise location [1]. Holographic gratings can be used for single-wavelength laser spots. However they cannot be implemented for multi-wavelength laser scanning as different wavelengths are diffracted along different angles, and hence overlapping of multi-wavelength spots cannot be maintained [2]. A multi-wavelength photonic based sensor for object discrimination has been reported [2]. However, this sensor is limited to an object range of 2m.

This paper describes and demonstrates an optical-cavity-based multi-wavelength sensor for spectral discrimination and position finding through laser triangulation. The schematic representation of the sensor is shown in Figure 1.

![Figure 1. Schematic diagram of the optical-cavity-based multi-wavelength sensor comprising a laser combination module with five different lasers, a custom fabricated curved optical cavity that generates multiple beams and a custom-designed image sensor.](image)

This optical cavity based sensor employs an improved optical design and an optimized discrimination algorithm to extend the range for object position detection to 6 meters. Object samples including brick, cement sheet, roof tile, cotton and leather are placed at up to 6m from the sensor and are analyzed using a statistical error analysis. Experimental results demonstrate the discrimination and position finding capabilities of the sensor.

II. METHODOLOGY

The reflectance spectrum of each object is unique and can be measured using visible and infrared spectrometers. For example, the reflectance spectrum of cotton and the key wavelengths that can be used to discriminate cotton from other objects are shown in Figure 2. Generally, variations in the reflectance spectra of the different objects between 450nm to
800nm can easily be monitored and used to calculate the slopes of the reflectance spectra for discrimination between various objects.

To determine the positions of various objects along a secured perimeter, only a single laser wavelength is needed (e.g., 635nm). This is achieved by launching an optical beam into the custom fabricated curved optical cavity, thereby generating multiple laser beams through partial internal beam reflections within the cavity, as illustrated in Figure 3. Each transmitted laser beam has a unique outgoing angle, \( \theta_i \), and is at a determined baseline distance, \( b_i \), from the axis of the imager’s lens. The object position, \( P \) is determined by calculating its coordinates \((X, Z)\). This is achieved using the laser triangulation method [3], which only requires \( b_i \), \( \theta_i \), the pixel at which the object is imaged and the imager focal length to be known, as described in Section B.

A. Spectral object discrimination method using multi-wavelength

The method for discriminating between various objects is based on the analysis of slopes of the reflectance spectra at the five laser wavelengths used in the sensor [2, 4–6]. Four slope values, \( S_1 \), \( S_2 \), \( S_3 \) and \( S_4 \) are defined as follows:

\[
S_1 = \frac{R_{\lambda_1} - R_{\lambda_2}}{\lambda_1 - \lambda_2}, \quad S_2 = \frac{R_{\lambda_2} - R_{\lambda_3}}{\lambda_2 - \lambda_3}, \quad S_3 = \frac{R_{\lambda_3} - R_{\lambda_4}}{\lambda_3 - \lambda_4}, \quad S_4 = \frac{R_{\lambda_4} - R_{\lambda_5}}{\lambda_4 - \lambda_5}
\]

where \( \lambda_n \) is the wavelength of the \( n \)th laser diode in nanometers, \( R_{\lambda_n} = \frac{P_n}{I_n} \) is the calculated reflectance, \( I_n \) is the peak recorded intensity in arbitrary units represented by 12-bit digital numbers and \( P_n \) is the measured optical power for each spot transmitted through the optical cavity in watts. The values for \( I_n \) are obtained by applying a Gaussian curve fitted to the recorded intensity profile of the laser spot image to calculate its peak intensity.

B. Object position detection through triangulation

The schematic diagram illustrating the principle of active laser triangulation is shown in Figure 3. The target object point \( P \), the lens centre positioned in line with \( Z \)-axis and the outgoing laser beam from the cavity determine the triangle required to measure the coordinates of \( P \) [3]. The \( X \)-axis is positioned in the centre of the lens \( L \), \( b \) is the baseline distance between the outgoing laser beam and the lens axis, \( f \) is the focal length of the lens used to image the laser spots and \( \theta \) is the tilting angle of the laser source with respect to the lens axis. Different beams have different baseline distances \( b \) and outgoing angles \( \theta \).

The basic equation for deriving \( X \) and \( Z \) from image formation [3] and hence locating the object in the \((X, Z)\) plane is given by:

\[
X = \frac{xZ}{f} - x \quad \text{and} \quad Z = \frac{X + b}{\tan(\theta)}
\]

\[
Xf \tan(\theta) - xX = xb - xf \tan(\theta)
\]

\[
X(x - f \tan(\theta)) = x(f \tan(\theta) - b)
\]
\[ X = x \left( \frac{f \tan(\theta) - b}{x - f \tan(\theta)} \right) \]  

(3)

Similarly,

\[ Z \tan(\theta) - b = \frac{xZ}{f} - x \]  

(4)

\[ fZ \tan(\theta) = xZ + fb - xf \]

\[ Z(x - f \tan(\theta)) = f(x - b) \]

\[ Z = f \left( \frac{x - b}{x - f \tan(\theta)} \right) \]  

(5)

where \( f \) is the focal length of the lens, \( x \) is the image point in the camera pixel array, \( b \) is the baseline distance from the laser beam to the lens centre and \( \theta \) is the outgoing angle of the laser beam.

III. EXPERIMENTAL SETUP

A. Experimental setup for the spectral object discrimination

The experimental setup for spectral material discrimination comprises a laser combination module with five lasers of different wavelengths, four optical combiners for combining the laser beams, a custom fabricated curved optical cavity which acts as a multi-spot beam generator, and a CCD imager that images the reflected laser beams from the target object, as shown in Figure 1.

Five lasers of wavelengths 473nm, 532nm, 635nm, 670nm and 785nm were selected because the spectral reflectance signatures of the objects under investigation (obtained using commercially available visible and infrared spectrometers) are significantly different at these wavelengths, thereby resulting in the best discrimination between these objects. The laser combination module was arranged in such a way that the outgoing laser beams from the five lasers were collimated at 4 mm diameter, spatially overlapped over 6m and were pulsed sequentially. The output optical powers for the 473nm and 532nm lasers were set to 8mW and 7mW, respectively. The other three lasers had equal power level of 6mW each. The curved optical cavity was used to generate multiple laser spots from each laser source through partial internal beam reflections as illustrated in Figure 1. The curved optical cavity was made of BK-7 glass. Thin film coatings were deposited on both sides of the cavity, leading to a highly reflectivity (\( R \geq 99.5\% \)) for the rear side and partial transmission of \( T \sim 13\% \) for the front side.

Thus 13% of the input power of each laser was launched the sample objects. It is important to note that, since the maximum detection range was limited to 6 meters, the chromatic dispersion was negligible and beams of different wavelengths were adequately overlapped within the 6-m range. The laser diode sequencing, as well as the optical power of each laser was controlled by an in-house developed laser driver. The intensities of the light beams reflected from the sample (illuminated by the multi-spot beam generator) were recorded by a 0.5-inch-aperture CCD imager having 768(H) × 494(V) pixels, each of size 8.4 × 9.8\( \mu \)m. A C-mount TV lens of focal length \( f = 12.5\)mm collected the reflected laser light and the lens iris was adjusted appropriately to avoid saturation of the imaged spot. The images from the camera were digitized in 12-bit form using a Spiricon frame grabber circuit board. This particular imager exhibited high sensitivity over the wavelength range (470nm – 850nm). The estimated CCD acquisition time was 200\( \mu \)sec and the overall acquisition time was 2msec.

The sample objects were illuminated with an array of laser beams which were emitted through the optical cavity, and then the reflectance properties of each object were collected by the image sensor to calculate the slope values to be used for object discrimination. The chosen sample objects, which are commonly found indoor and outdoor, were brick, cement sheet, leather, roof tile and cotton.

B. Experimental setup for object position detection through triangulation

The object position detection experimental setup is illustrated in Figure 4. The 635nm laser, with output optical power of 6mW from the laser module described in Section A, was selected to obtain the coordinates of the sample objects using the triangulation method.

![Figure 4. Experimental setup for object position detection using triangulation method.](image-url)
The optical cavity and the imager were mounted on the same stage with a separation distance of 17.7cm, which defined the baseline distance $b$ (see Figure 3). The number of laser beam spots that can be generated depends upon the incidence angle of the input laser beam. For example, for an incidence angle of 40°, 20 laser spots can be generated leading to a resolution of $6\times\tan(4.5°) = 0.47$ meters. The experiment was carried out using a laser tilting angle of 40˚ which resulted in 20 laser spots after the laser generated multiple reflections within the curved optical cavity.

The objects were placed within the imager’s field of view at a particular distance from the optical cavity and the triangulation method was used to calculate the position of objects which are illuminated by different laser beams. The collected data was then processed via projecting the measured values of $\theta$ and $b$ into the actual $(X, Z)$ plane and hence determine the object coordinates as shown in Figure 3. In general, more than one beam can get reflected from the object where each beam has corresponding values for $\theta$ and $b$. These measured values do not just tell the location of the object but also present a possibility to determine its shape by simply measuring the differences $\Delta\theta_{i(i+1)} = \theta_i - \theta_{i+1}$ and $\Delta b_{i(i+1)} = b_i - b_{i+1}$, where $i$ is the reflected beam index. A threshold value, i.e. the calibration values of $\theta$ and $b$, will determine if the differences $\Delta\theta$ and $\Delta b$ are negligible and hence to determine the degree of uniformity of the object’s surface.

Alignment errors were experienced, which can be attributed to (i) the inaccuracy in the measurement of the baseline distances, $b_i$, from the image sensor’s lens centre to the laser beam spot and or (ii) the slight misalignment of the optical axis and the centre of the lens. Accurate measurements of the position of the object’s image on the image sensor (see Figure 3) significantly reduced the errors in calculating the object’s position.

IV. EXPERIMENTAL RESULTS AND DISCUSSION

A. Spectral object discrimination results

Five different objects namely brick, cement sheet, roof tile, cotton and leather were used to demonstrate the concept of spectral object discrimination in the laboratory. The reflectance spectra of the objects are shown in Figure 5.

Sample objects were placed at 6m from the multi-wavelength sensor. The detection range was limited to 6 meters mainly because of the chromatic dispersion of the optical system and the divergence of Gaussian beams. The reflected beam intensities for the five wavelengths were measured at different times, and Equation (1) was used to calculate the average slopes $S_1$, $S_2$, $S_3$ and $S_4$ for each object and their standard deviations. The spectral reflectance slopes of the five objects for 6m range are shown in Figure 6. Clearly, there was no simultaneous overlapping between the slope values of the different objects. For example, while the slopes $S_2$ and $S_3$ of leather and cement overlap, their $S_1$ and $S_4$ slopes did not overlap. Also, while the slopes $S_4$ of the roof tile, leather and brick overlap, they can be discriminated through the measurements of their non-overlapping slopes $S_2$ and $S_3$ at a 6m range. The increase in slope variance with an increase in the detection range is attributed to the lower detected signal for a higher range, which results in a lower signal-to-noise ratio.

![Figure 5. Measured spectral response of the different sample objects.](image1)

![Figure 6. Average values with standard deviations for slopes $S_1$, $S_2$, $S_3$ and $S_4$ for five different objects placed at 6m from the optical cavity.](image2)
ratio. These experimental results validate the capability of the multi-wavelength spectral reflectance sensor to discriminate between the target objects. Note, by using more wavelengths (of appropriate values that ensure at least two non-overlapping slopes for all objects), more number of objects can be discriminated.

B. Error Analysis

The measured errors which occurred while recording the experimental data were analyzed using a statistical algorithm [7], to calculate the percentage of error for results produced at the 6m distance shown in Figures 6.

The expression for the slope values, defined in Equation (1), can be generalized as:

\[ S_i = \frac{R_{i\lambda_j} - R_{i\lambda_k}}{\lambda_j - \lambda_k} \]  

Using Equation (8) and (1b), and after some algebra, the error in slope value is given by

\[ \Delta S = \Delta I + \frac{I_j}{P_j(\lambda_j - \lambda_k)} \Delta P_j + \frac{I_i}{P_i(\lambda_i - \lambda_k)} \Delta P_i + \frac{I_k}{P_k(\lambda_k - \lambda_j)} \Delta P_k \]  

For example, the error in slope \( S_3 \) is given by

\[ \Delta S_3 = \frac{1}{P_{3\lambda_6} - A_{3\lambda_6}} \Delta I_{3\lambda_6} + \frac{I_{3\lambda_6}}{P_{3\lambda_6} - A_{3\lambda_6}} \Delta P_{3\lambda_6} + \frac{I_{3\lambda_6}}{P_{3\lambda_6} - A_{3\lambda_6}} \Delta A_{3\lambda_6} \]

\[ + \frac{1}{P_{3\lambda_7} - A_{3\lambda_7}} \Delta I_{3\lambda_7} + \frac{I_{3\lambda_7}}{P_{3\lambda_7} - A_{3\lambda_7}} \Delta P_{3\lambda_7} + \frac{I_{3\lambda_7}}{P_{3\lambda_7} - A_{3\lambda_7}} \Delta A_{3\lambda_7} \]  

where \( R_{635} = I_{635} / P_{635} \) and \( R_{670} = I_{670} / P_{670} \). To calculate the slope error, \( \Delta S_3 \) for brick, the 635nm and 670nm lasers were turned on and the transmitted intensities \( P_{635} \) and \( P_{670} \), as well as the intensities reflected \( I_{635} \) and \( I_{670} \) of the imaged object were measured over a long time interval, which enabled \( \Delta I_{635} \), \( \Delta I_{670} \), \( \Delta P_{635} \) and \( \Delta P_{670} \) to be calculated. Note that \( \Delta I_{635} \) and \( \Delta I_{670} \) were assumed negligible, since lasers were provided with heatsink housing. It was found that the fluctuations in transmitted laser optical power are proportional to the fluctuations in the reflected optical power, which were the major source of error in S3 calculation. The fluctuations in the imaged optical intensities (b) 635nm and 670nm over a 120-minute period are shown in Figure 7 for brick exhibiting a maximum error in the slope \( S_3 \) of 13% at a 6 m range.

C. Object positioning results

In order to demonstrate the capability of the triangulation method to determine the position of the object, a sample object was placed within the field of view of the imager. The optical cavity produced 20 laser spots for an input laser beam launched at an incidence angle of 40°. From these 20 spots, only three (different) laser spots, namely 2, 3 and 4, were investigated in the experiments, which are sufficient to validate the triangulation method for finding objects at different positions. The coordinates of the sample objects illuminated by spots 2, 3, and 4 were measured using the triangulation method described in Section II.B. Spots 2, 3, and 4 had baseline distances \( b_3 = 19 cm \), \( b_4 = 20.3 cm \) and \( b_4 = 21.6 cm \), respectively and their outgoing angles were \( \theta_3 = 41° \), \( \theta_2 = 42° \) and \( \theta_2 = 43° \) respectively. The measured and simulated values for the X and Z coordinates versus the pixel number x, are shown for the three spots in Figure 8(a-b), Figure 9(a-b) and Figure 10(a-b), demonstrates excellent agreements between the simulation and experimental results. The maximum object position finding error in the X and Z directions was 8% when all measurements were carried out in the laboratory with ambient fluorescent light.
V. CONCLUSION

A novel five-wavelength spectral reflectance sensor has been developed and used in conjunction with the laser triangulation method to identify and locate the position of various objects. Sample objects namely brick, cement sheet, roof tile, cotton and leather have been used to validate the discrimination capability of the sensor. Spectral analyses have shown that the laser wavelengths 473nm, 532nm, 635nm, 670nm and 785nm are the most appropriate for object discrimination.

Object discrimination has successfully been demonstrated over a 6m range by determining four spectral reflectance slopes at the employed wavelengths. Statistical investigations and calculated standard deviations have confirmed no simultaneous overlapping between the slope values of the sample objects, making the identification of the selected objects accurate.

In addition to object discrimination, the capability of the sensor to accurately predict the coordinates of objects has been demonstrated over a 6m range and has resulted in an accuracy exceeding 92% using the triangulation method.

In addition to Security, the discrimination method reported in this paper can find application in other sectors, such as Food, Agriculture, Textile and Transport.

Future research and development will focus on improving the discrimination precision of the sensor, by introducing additional lasers of different wavelengths and by improving the optical and electronic design of the sensors imager to extend the sensor’s range beyond 10m.

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