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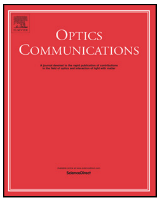

Theoretical analysis and experimental study of constraint boundary conditions for acquiring the beacon in satellite–ground laser communications

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ABSTRACT

Acquisition and recognition for the beacon is the core technology of establishing the satellite optical link. In order to acquire the beacon correctly, the beacon image should be recognized firstly, excluding the influence of the background light. In this processing, many factors will influence the recognition precision of the beacon. This paper studies the constraint boundary conditions for acquiring the beacon from the perspective of theory and experiment, and as satellite–ground laser communications, an approach for obtaining the adaptive segmentation method is also proposed. Finally, the long distance laser communication experiment (11.16 km) verifies the validity of this method and the tracking error with the method is the least compared with the traditional approaches. The method helps to greatly improve the tracking precision in the satellite–ground laser communications.

1. Introduction

Satellite optical communications are divided to inter-satellite optical communication and satellite–ground optical communication. In recent years, there has been a great interest in satellite optical communications research all over the world [1–4], such as STRV-2 satellite optical communication terminal [5–7] and ETS-VI satellite optical communication terminal (Japan) [8]. In satellite–ground laser communication, how to acquire the beacon is an important key technology, so we need to consider some factors, such as background light and atmospheric turbulence. The background light can cause spot noise on the CCD [9], and the atmospheric turbulence can cause the fluctuation of optical power.

In this paper, the constraint boundary conditions for acquiring the beacon are discussed. In the processing of the beacon image, how to obtain a proper segmentation threshold is very important, and it is very useful for suppressing the noise of CCD. At present, some methods for getting the segmentation threshold, such as Fixed global threshold method and Multi-Local threshold method [10] exist. They are suitable for the static image processing, however, the dilemma of traditional threshold methods for dynamic tracking is how to adapt to changes in the environment quickly. So we introduce a new threshold for solving this problem.

This paper studies the influence of the background light and the atmospheric turbulence on the acquisition for the beacon. The background light and atmospheric turbulence can induce the positioning error when the beacon is acquired. The laser link can be interrupted without the particular processing for these influencing factors. This paper presents a method for obtaining an optimum segmentation threshold considering the influence of background light and atmospheric turbulence when the beacon image is processed. The theory approach and the real experimental verification can verify the effectiveness of this method. The influence of vertical link atmospheric channel for the laser transmission is less than that of 10 km horizontal link atmospheric channel [11], so the horizontal laser communication link is used to verify the validation of the new method described in this paper, which can guarantee the feasibility of the algorithm for the satellite–ground laser communications.

The structure of this paper is arranged as follows. In Section 2, the theory of adaptive segmentation threshold is proposed. Flow of the algorithm is performed in Section 3. A long distance (11.16 km) laser communication experiment is conducted in order to verify the validity of the approach in Section 4. Section 5 summarizes our conclusions.

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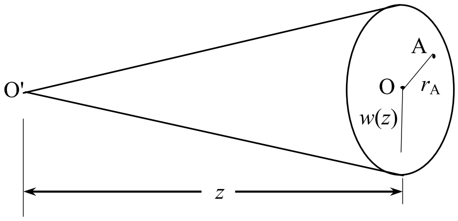

Fig. 1. Sketch map of the laser communication link.

2. Theory

In the spatial optical communication system, the laser is used as the information carrier, and the transmitting laser is Gaussian beam. The distance from the transmitting antenna (O') to the receiving antenna (O) is z, $w(z)$ is the radius of the $1/e^2$ contour after the wave has propagated a distance z, the light intensity of the centre of the receiving plane is I_0, I_A is the light intensity of A in the receiving plane, and r_A is the distance from A to O as shown in Fig. 1.

When a laser beam propagates though the atmosphere, there are many effects can induce the effect of angle of arrival (AOA) fluctuations [12–14]. So in this paper we actually discuss full operational tracking system correcting all AOA deviations not particularly scintillation effect.

In the beginning, the centre of the receiving plane is O. When the atmospheric fluctuation occurs, the centre of the transmitting beam shifts from O to A (A is the centre of the transmitting beam induced by atmospheric fluctuation), and moving angle of the centre of the transmitting beam is $\Delta\theta$, so

$$\Delta\theta = \frac{r_A}{z} = \alpha \tag{1}$$

where α is variation angle which is induced by the atmosphere turbulence.

As Gaussian beam [15],

$$\psi(r,z) = \frac{w_0}{w(z)} \exp\left[-\frac{r^2}{w^2(z)}\right] \exp\left\{-i\left[k_1\left(z+\frac{r^2}{2R(z)}\right) - arctg\frac{z}{f}\right]\right\} \tag{2}$$

$$w(z) = w_0\left[1+\left(\frac{\lambda z}{\pi w_0^2}\right)^2\right]^{\frac{1}{2}} \tag{3}$$

$$I(r,z) = |\psi(r,z)|^2 = \frac{w_0^2}{w^2(z)} \exp\left(-\frac{2r^2}{w^2(z)}\right) \tag{4}$$

where $\psi(r,z)$ represents the optical field distribution of the Base mode Gaussian beam (TEM_{00}), w_0 is the beam waist in the transmitter plane when $z=0$, f is the confocal parameter of the Gaussian beam, $R(z)$ is radius of curvature, λ is wavelength of the laser and $k_1 = 2\pi/\lambda$.

The receiving optical power can be obtained from double integral of Eq. (5), as follows:

$$P_r = \iint I(r,z)\, dr. \tag{5}$$

The approximate conditions of the far-field are shown as follows:

$$w(z) \approx z\theta_b/2 \tag{6}$$

$$\pi w^2(z) \gg A_r \tag{7}$$

where A_r is the area of the receiving antenna, θ_b is the beam divergence angle, z is the distance between two optical communication terminals.

Based on these formulae above, we calculate the received power and this is an approximate result, so we can get Eq. (8) as follows:

$$P_r \approx \frac{4w_0^2 A_r}{z^2\theta_b^2} \exp\left(-\frac{8\alpha^2}{\theta_b^2}\right). \tag{8}$$

The relationship between the optical power received by CCD and output grey value (255 as a maximum output 8 bit grey value) is shown as follows:

$$P_r = f(x). \tag{9}$$

In this model, approximately, $P_r = k_2 x$, k_2 is ratio coefficient, and x is output grey value.

Let us discuss α. The effect of angle of arrival fluctuation is investigated with the recorded data. For one experimental data trial, centroid coordinate (X_i, Y_i) of the ith frame is calculated by the grey centroid algorithm, that is [16]:

$$X_i = \frac{\sum_{x,y} x g_{xy}}{\sum_{x,y} g_{xy}} \qquad Y_i = \frac{\sum_{x,y} y g_{xy}}{\sum_{x,y} g_{xy}} \tag{10}$$

where gxy is grey-level value of the pixel with coordinate of (x,y).

Centroid coordinates of all frames in one data trial lead to two coordinate sequences of $X = (X_1, X_2, \ldots, X_n)$ and $Y = (Y_1, Y_2, \ldots, Y_n)$. The sequence $A = (\alpha_1, \alpha_2, \ldots, \alpha_n)$ for angle of arrival is obtained from the coordinate sequences by the following formula [17],

$$\alpha_i = \frac{d\sqrt{\left(X_i - \langle\bar{X}\rangle\right)^2 + \left(Y_i - \langle\bar{Y}\rangle\right)^2}}{M \times f_L} \tag{11}$$

where $\langle\cdot\rangle$ means ensemble average, α_i is the ith element in the sequence of A, d is pixel size of the CMOS, f_L is focal length of the receiving optical system and M is enlargement factor of the optical system.

For a Gaussian-beam wave, the variance of AOA can be expressed as [17],

$$\sigma_\alpha^2 = 1.093C_n^2 zD^{-1/3}\left[a + 0618\Lambda^{11/6}\left(\frac{kD^2}{z}\right)^{1/3}\right] \tag{12}$$

$$a = \frac{1-\Theta^{8/3}}{1-\Theta} \tag{13}$$

$$\Theta = 1 - \frac{z}{R_1} \tag{14}$$

$$\Lambda = \frac{2z}{k_1 w^2(z)} \tag{15}$$

where Θ and Λ are called the output plane (or receiver) beam parameters, R_1 is wavefront curvature radius.

For the long distance of laser transmission, the approximate conditions of the far-field are shown as follows [17]:

$$R_1 \approx z, \qquad a \approx 1 \quad \text{and} \quad \Lambda \approx 0. \tag{16}$$

For the long distance, C_n^2 is given by [17],

$$C_n^2 \approx \frac{\sigma_\alpha^2}{1.093\mathrm{zD}^{-1/3}} \tag{17}$$

where C_n^2 is the refractive-index structure parameter, D is the diameter of the receiving aperture and σ_α^2 is the variance of α_i.

With the influence of spatial background light and the noise of CCD, the false alarm probability of single frame and the leak judgment probability are inevitable. So we consider that the probability distribution of each pixel of the CCD obeys the normal distribution, and each pixel is independent mutually. Here we only consider the false alarm for background light.