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A linearly attenuated lighting for visible light positioning system based on RSSI

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ABSTRACT

The accuracy of indoor visible light positioning based on received signal strength indicator (RSSI) method has been obviously enhanced in recent years. In the method, inhomogeneous distributed positioning error leads to the partial magnification of the location uncertainty. The uncertainty area is called positioning fade zone. Aiming at the problem, a type of linearly attenuated lighting model is proposed to solve this. The performance of the proposed model is tested by simulation. The result of simulation shows that: The positioning error can be reduced by half using the new lighting model compared with the general model; The positioning fade zone can be effectively eliminated by the new model. By using free-form surface lens design method, an optical lens is formed. With the help of the lens, a lighting source with this new linearly attenuated model is obtained.

1. Introduction

Global positioning system (GPS) is the earliest positioning technology which emerged in the end of 20th century. GPS has become an essential implement in human life. However, because of serious strength attenuation and multipath effect, it cannot work well in some kinds of places such as underground garage, transportation tunnel, mall and airport [1–4]. Therefore, the positioning technology for indoor environments is urgent need. Visible light communication (VLC) is a new kind of communication method emerged recent years [3,5,6]. A kind of indoor positioning technology based on visible light communication is proposed by researchers which called visible light positioning (VLP) [3,7]. It has the advantages of high positioning accuracy, low construction and power costs, anti-electromagnetic interference, and free from spectrum permission limit [6,8].

The positioning methods of VLP can be categorized into two categories which are imaging method and non-imaging method. Imaging method is based on image sensor and has a higher positioning accuracy [5,7]. However, its application is restricted by the demanding requirement of the hardware capability. Non-imaging method is based on photo detector (PD) which means that the system is simple and higher efficiency [8,9]. Received signal strength indicator (RSSI) is a typical non-imaging positioning method [3]. RSSI positioning method is based on geometrical measurement [8,9]. In the method, the location of device is estimated according to the intensity of received signal from multiple signal sources. Although RSSI has a relatively high accuracy compared to other non-imaging methods, it is not very stabilized in the case of powerful background light. As the expectation of high-accuracy positioning increases, many efforts have been devoted to solve the problem. Several researches achieved the positioning accuracy close to 1 cm in the past two years [3,8,9]. And our previous work [10] has improved the accuracy to 4 mm by using wavelet denoise and correlation method to process the received signal. Another serious problem decreasing the positioning accuracy of RSSI has been found in the work. The spatial distribution of the positioning error appears asymmetrically, which may cause positioning fade zones in some areas. But few researchers have been intended to solve this problem.

Aiming at solving the problem and improving positioning accuracy, the paper analyzes the illuminating property of the signal sources in RSSI based visible light positioning (RSSI-VLP) system. A type of linearly attenuated irradiation model is proposed for this problem. The performance of the proposed model is proved by simulation. A free-form optical lens is designed to realize the linearly attenuated lighting for the positioning system.

2. RSSI based visible light positioning theory

Fig. 1 shows a typical indoor VLP system. There are light sources T1–T4, which are the transmitters in VLC system. The modulated light signal is emitted from transmitter. Then the signal is transformed into electric signal by the receiver in device. Finally, the position of device is obtained by processing the signal.

As one of the non-imaging positioning methods, RSSI positioning method calculates the position according to the strength of signal received by device [8,9]. The brief procedure of positioning is shown in Fig. 2 [10].

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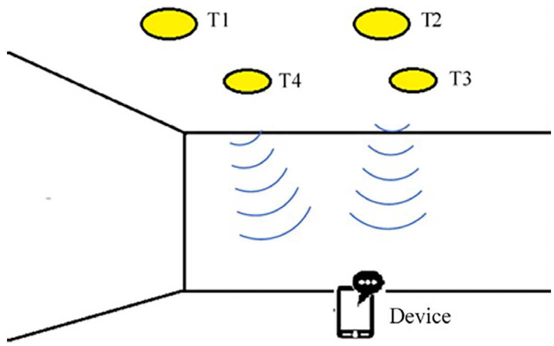

Fig. 1. Indoor visible light positioning.

The algorithm for RSSI-VLP method can be separated into two steps. The first step is ranging algorithm. In this step, horizontal distances between the device and transmitters is measured. the transmitter source in VLC system is light emitting diode (LED), and the irradiating property of LED obeys the Lambertian lighting model [11]:

$$I_\theta = I_0 \cos^m(\theta). \tag{1}$$

where, I_θ is the luminous intensity with directory angle θ, I_0 is the luminous intensity with directory angle 0 (the vertical direction to luminous surface), m is the order of LED which represents the light condensation of the Lambertian lamp. For lighting devices, beam angle is the solid angle between the directions with intensity $I_0/2$, denoted as $2\theta_{1/2}$, which means the effective viewing angle. The sketch of beam angle with the order $m = 1$ is given by Fig. 3. The relation between the order m and $\theta_{1/2}$ can be expressed as [11]

$$m = \frac{-\ln 2}{\ln\left(\cos\theta_{1/2}\right)}. \tag{2}$$

In the system, the received power can be written as

$$P_r = P_t \times H(0), \tag{3}$$

where, P_r is the power received by the receiver, P_t is the aggregate power transmitted by LED, and $H(0)$ is the channel direct current gain, which is calculated by [11–14]

$$H(0) = \begin{cases} \dfrac{(m+1)}{2\pi}\cos^m\theta\cos\varphi T_s g\dfrac{A_r}{d^2}, & 0 \le \varphi \le \varphi_{fov} \\ 0, & \varphi > \varphi_{fov} \end{cases}, \tag{4}$$

where, θ and φ are the emission angle of transmitter and the incidence angle of receiver respectively, φ_{fov} is the field of view of the receiver, T_s and g are the gain of optical filter and the gain of optical concentrator respectively, A_r is the active area of photo detector, and d is the straight-line distance between the transmitter and the receiver. Thus, we can get the attenuation model of the received signal power in horizontal range (L) domain shown in Fig. 4. Through this approach, we can measure the horizontal distance by detecting the received signal strength.

The second step is locating algorithm, which is to estimate the location of device by the measured distances. The principle of locating algorithm is Trilateration [3]. As Fig. 5 shows, the estimation of location is equal to finding the junction point of three circles. S_1 to S_3 in the figure denote the signal sources in the system, and L_1 to L_3 respectively denote the horizontal distances from the location to these sources. Sources in the system are distinguished by loading the carriers with different frequencies. Each of the carrier carries the location information of its transmitting source. By obtaining the information from the sources and perceiving the received signal strength simultaneously, the location of device is estimated when more than 3 sources are detected by the device.

3. Linear attenuated model

3.1. Analysis of error inhomogeneity

Positioning accuracy is the key index of positioning method. The global positioning error is often used to evaluate the positioning accuracy. The error distribution should be another important indicator. It reflects whether the method is qualified in every corner of the range. There are several ways to improve the positioning accuracy. However, it is hard to improve the accuracy to an ideal degree for every place in the whole range of the space or time domain. Despite the Gaussian distribution as the noise obeyed, the positioning error does not distribute symmetrically around its mean value. In our recorded census, the range of error magnitude below the mean square error (MSE) always occupies more than 70 percent of the whole positioning range, as shown in Fig. 6. That means there are some small pieces of area should be of extremely higher error than the mean. The positioning function of the device in these areas may not operate well. These areas we call 'positioning fade zones'. $\bar{E}$ in the figure means the MSE, and E_L means the large error that may cause the positioning function disabled.

It is still found that these large errors are always recorded near the light sources. By the method of error analyzing, it can be theoretically explained. Cramer–Rao Bound (CRB) is an analyzing method that to estimate the least error of a measuring parameter [2,13–16]. Eq. (5) gives the CRB for measuring horizontal distance parameter $\hat{L}$ in an arbitrary link of VLP system [10,13,14].

$$\sqrt{D\left(\hat{L}\right)} \ge \frac{2\pi\left(L^2+h^2\right)^{\frac{m+5}{2}}\sigma}{(m+1)(m+3)A_r R\alpha h^{m+1}L}. \tag{5}$$

where, $\sqrt{D}$ is the standard deviation, h is the room height, R is the receiving response of PD, α denotes the peak-to-peak power emitted from the LED source, and σ^2 is the noise power which contents shot noise σ^2_{shot} and thermal noise σ^2_{ther} [17]:

$$\sigma^2_{\text{shot}} = 2qRP_r + 2qI_{\text{bg}}I_2B; \tag{6}$$

$$\sigma^2_{\text{ther}} = \frac{8\pi kT_k}{G_0}\eta A_r I_2 B^2 + \frac{16\pi^2 kT_k\Gamma}{g_m}\eta^2 {A_r}^2 I_3 B^2. \tag{7}$$

where, q is electronic charge, I_{bg} is background current, B is equivalent noise bandwidth, k is Boltzmann constant, T_k is absolute temperature, G_0 is open-loop voltage gain, η is the fixed capacitance per unit area of PD, Γ is the channel noise factor, g_m is transconductance, I_2 and I_3 denote noise bandwidth factor. The variation of CRB distributed in horizontal direction is shown in Fig. 7.

Distance measuring is an important step in positioning. From Fig. 7, the measuring of L remains a minor error in the mid-length distance range, while it increases rapidly when the device is either closer to or farther from the source. According to the principle of Trilateration, the areas near sources are more likely to be the fate zones, because that they are much closer to one of the sources and is also far enough from other two sources.

The measurement of distance is basing on the irradiance attenuation model of sources. To solve the problem, the illuminating property of the source should be taken into account. A certain noise intensity causes uncertainty of the received signal power (ΔP), then generates an uncertainty of the measured horizontal length (ΔL). ΔL is increased by the decreasing of power gradient $\partial P/\partial L$. As Fig. 8 shows, only in the mid-range of length, the uncertainty of L is small and cannot cause a large error in measurement.

3.2. Proposal of linearly attenuated model

Assuming that the measurement error with horizontal length L is denoted as $e(L)$, the variance of the measurement in whole range can be expressed as

$$D(L) = \int e(L)^2 \mathrm{d}L. \tag{8}$$