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Indoor high precision three-dimensional positioning system based on visible light communication using modified genetic algorithm

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A B S T R A C T

To improve the precision of indoor positioning and actualize three-dimensional positioning, a reversed indoor positioning system based on visible light communication (VLC) using genetic algorithm (GA) is proposed. In order to solve the problem of interference between signal sources, CDMA modulation is used. Each light-emitting diode (LED) in the system broadcasts a unique identity (ID) code using CDMA modulation. Receiver receives mixed signal from every LED reference point, by the orthogonality of spreading code in CDMA modulation, ID information and intensity attenuation information from every LED can be obtained. According to positioning principle of received signal strength (RSS), the coordinate of the receiver can be determined. Due to system noise and imperfection of device utilized in the system, distance between receiver and transmitters will deviate from the real value resulting in positioning error. By introducing error correction factors to global parallel search of genetic algorithm, coordinates of the receiver in three-dimensional space can be determined precisely. Both simulation results and experimental results show that in practical application scenarios, the proposed positioning system can realize high precision positioning service.

1. Introduction

Nowadays, with the rapid development of wireless sensor network (WSN) and physical networking technology, demands for location-based services gradually present a significant growth trend [1–3]. In the field of positioning, global positioning system (GPS) is well-known for its wide coverage and low cost of application. GPS has found an increasingly wide utilization in many situations, such as vehicle navigation, map service and so on. For outdoor environment, GPS has provided satisfactory services, however, it has low accuracy in indoor positioning [4]. GPS is still far from a perfect system in the field of positioning when it comes to a situation that indoor environment for radio signals from a satellite will be blocked by tall buildings causing big positioning error. To meet the increasing need of indoor positioning service, Wi-Fi, Bluetooth, radio frequency identification (RFID) and camera-based positioning system have been developed to complement GPS. All positioning system mentioned above can provide a position precision from tens of centimeters to several meters and some of them have already been used in indoor environment. However, due to the disadvantages of high cost, low positioning accuracy, electromagnetic interference and other factors, the schemes above are not ideal candidates [5]. Those solutions of indoor positioning have the following disadvantages: (1) To install these systems, extra device should be added to an indoor environment, which increases the cost and complexity of operation and control. (2) In some RF-inappropriate environments like an underground mine, radio-based indoor positioning systems are unable to work. (3) The uneven spatial distribution of wireless signal leads to an intense volatility at a same location which results in a reduction of positioning accuracy. (4) These radio-based positioning systems will produce Electromagnetic Interference to the indoor electronic device like a MRI scanner in a hospital. (5) The confidentiality of radio-based communication system is usually not high, which may lead to a location information leakage.

Visible light communication (VLC) based positioning system is a new solution of indoor positioning which has the advantages of high positioning accuracy, no electromagnetic interference, fewer extra modules, good communication confidentiality and integration of lighting and communication. Positioning systems based on VLC can be divided into two formats: (1) photodiode-based (PD-based). (2) Image sensor-based [6,7]. As an image sensor-based positioning system usually need

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to use image processing techniques which sets a great demand on system performance, the simplicity, reliability and low cost of PD-based positioning system show wide application in indoor positioning field. In PD-based systems, the receiver collects optical signal from signal sources to estimate distances between itself and t signal sources using a series of methods such as received signal strength (RSS) [8,9], angle of arrival (AOA) [10], time of arrival (TOA) [11], time difference of arrival (TDOA) [12] and so on [13]. Among these methods introduced, time of arrival (TOA) and time difference of arrival (TDOA) are immune to noise, and the angle of arrival (AOA) measures the distance between by the angle of received signal while this is difficult to achieve in reality for the layout of transmitters and receiving range of a PD brings a dramatic effect on the angle of arrival measured which results in a big error in positioning accuracy. Instead, the received signal strength (RSS) detects the distance only according to the received signal strength which reduces circuit complexity of transmitters while ensuring the localization accuracy of the premise. At the same time, for a receiver it is easy to measure the signal strength by using an AD converter. Hence RSS is studied deeply. For example, Yang et al. proposed an indoor positioning system using single transmitter and multiple receivers, the device can find its location using RSS and the relative position of optical receivers, the average positioning error was reported to be 0.65 cm [14]. Jung et al. defined received signal strength ratio (RSSR) between received signals, three equations could be obtained using the distance ratios which is a function of RSSR, the target can be located by solving the equations [15]. The methods above both achieve satisfied precision, however, they fail to give the height information. In [16], Xu Wei et al. focus on a unique scenario where a single target terminal with multiple PDs given their relative positions known which can give 3D coordinates of target. Trilateration algorithm can also be applied for estimating 3D positions within the projection area surrounded by LEDs. However, when the target located outside the projection region, the algorithm is no more applicable [17].

In order to actualize indoor positioning using visible light based on the method of RSS, the problem that should be solved first is the interference of optical communication. The introduction of a multiple access technique is necessary. In consideration of possibility that many LEDs' existing in an indoor environment at the same time, frequency bands will be divided too detailed when using the frequency division multiple access (FDMA) resulting in difficulty of filter design. As for the time division multiple access (TDMA), it will be difficult to control the transmitters for the communication time slot will be short when there are too many LEDs. The code division multiple access (CDMA) modulation can separate the signal overlapping both in time domain and frequency domain, and the spread spectrum technology in CDMA can also reduce the inter symbol interference caused by the presence of multipath effect indoor which improves communication quality and increase system stability [18–20].

Among most existing studies on the VLC positioning system based on RSS, the work focus is on how to realize the positioning [14–17], problem of positioning error is not discussed deeply. In order to actualize high-precision positioning based on VLC, reasons causing positioning error should be discussed first. Usually, in practical application, noise and imperfection of the device cause the deviation from the theory. And certain parameters can be introduced to fix the positioning error based on the principle of RSS. According to the assumption, the high precision positioning problem can be treated as a multi-parameter optimization problem. In order to solve the problem, the global parallel search of GA is obviously an ideal solution. By optimizing the attenuation factor in RSS, high precision positioning can be realized. And rate of convergence of GA is discussed further to improve system availability.

This paper is organized as follows. The model of indoor positioning, including indoor optical wireless channel model, model of communication system and method of positioning is described in Section 2. Simulations, analysis and experiment are described in Section 3. The conclusion of this paper is given in Section 4.

2. System principle and positioning algorithm

2.1. The channel model of indoor optical communication

In the indoor positioning system based on visible light communication, light sources (LEDs) are regarded as reference points, and terminal is the optical signal receiver. As Fig. 1 shows, the positioning system is consisted of two parts: (1) LEDs installed on the ceiling of the room model. (2) The receiver. In order to describe the indoor optical communication process, several parameters are introduced. The distance between LEDs and the receiver is defined as d, the angle of irradiance with respect to the perpendicular axis of the transmitter is defined as θ, the incidence angle with respect to the receiver's normal is defined as ϕ and the orientation angle between the receiver's normal and the vertical is defined as φ.

LEDs can be treated as Lambertian sources for their large beam divergence when discussed in the indoor positioning. The channel gain of a line-of-sight (LOS) wireless channel can be described as the following formula [19]:

$$\mathrm{H}(0)=\begin{cases}\dfrac{\mathrm{m_t}+1}{2\pi \mathrm{d}^2}\mathrm{AT_S}(\phi)\,\mathrm{G}(\phi)\cos^{\mathrm{m_t}}(\theta)\cos^{\mathrm{m_r}}(\phi), & 0\le\phi\le\psi_c\\ 0, \quad \phi\ge\psi_c\end{cases} \tag{1}$$

where the effective area of PD is given by the constant A, the filter gain and concentrator gain are given by $\mathrm{T_S}(\phi)$ and $\mathrm{G}(\phi)$, and the FOV of PD is defined as ψ_c. The Lambertian parameters can be represented as following:

$$\begin{cases}\mathbf{m_t}=-\dfrac{\mathbf{ln2}}{\mathbf{ln}\left(\mathbf{cos}\theta_{1/2}\right)}\\ \mathbf{m_r}=-\dfrac{\mathbf{ln2}}{\mathbf{ln}\left(\mathbf{cos}\phi_{1/2}\right)}\end{cases} \tag{2}$$

where $\theta_{1/2}$ and $\phi_{1/2}$ are the half-power angles of the transmitter (LED) and the receiver (PD) respectively. $\theta_{1/2}$ refers to the angle at which luminous intensity is half of the axial (normal) luminous intensity and $\phi_{1/2}$ refers to the angle at which received signal strength (photocurrent response) is half of the value in the normal direction. Received optical power P_r can be represented as:

$$P_r=P_tH(0)+P_{background} \tag{3}$$

where P_t is the average transmitted optical power, and $P_{background}$ is the incident optical power caused by other optical resources existing in the background environment. Go a step further, we may use the means of average electric current μI_r to measure the incident optical power produced by the PD:

$$\mu I_r=\frac{R_pP_r}{A} \tag{4}$$

where R_p is the responsivity of the PD, it is a constant to the optical signal with the same wavelength. [18] The average PD current is affected by two noise processes: (1) shot noise which is caused by incident optical power including the desired signal and lighting environment. (2) thermal noise which is caused by the stochastic behavior of electrons. The total noise σ^2_{noise} can be seemed as a Gauss process which is the sum of shot noise σ^2_{shot} and thermal noise $\sigma^2_{thermal}$, represented as [21]:

$$\sigma^2_{noise}=\sigma^2_{shot}+\sigma^2_{thermal} \tag{5}$$

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

$$\sigma^2_{thermal}=\frac{8\pi kT_k}{G_0}\eta AI_2B^2+\frac{16\pi^2k\Gamma T_k}{g_m}\eta^2A^2I_3B^2 \tag{7}$$

In these formulas, $q, B, k, I_{bg}, T_k, G_0, \Gamma, \eta, g_m$ is the elementary charge, equivalent noise bandwidth, the Boltzmann constant, background current, absolute temperature, the open loop voltage gain, the channel noise factor, the fixed capacitance of photo-detector (PD), and the trans-conductance, respectively. I_2 and I_3 are the noise bandwidth factors.