The Research of Indoor Positioning Based on Visible Light Communication

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Abstract: The key techniques in indoor positioning based on visible light communication and the state of the art of this research were surveyed. First, the significance of indoor positioning based on visible light communication from two aspects of the limitations of current indoor positioning technology and the advantages of visible light communication was discussed; And then, the main four technology of indoor positioning based on visible light communication were summarized and the triangulation of RSS method and the principle of image positioning were introduced in detail; Next, the performance characteristics of various typical algorithms were compared and analyzed; In the end, several suggestions on future research of indoor positioning based on visible light communication were given.

Keywords: visible light communication; indoor positioning ; imaging positioning RSS

I. INTRODUCTION

Positioning technique refers to realize objection positioning by using a variety of techniques such as wireless communication, base station location, navigation positioning, etc. With the development of the technology and social economy, the demand for positioning is no longer limited to the outside, the demand for indoor positioning is growing. In the large place such as hypermarket, exhibition hall, hospital, airport, etc, user can find out the target quickly by indoor positioning, and realize indoor navigation. Accurate indoor positioning can help to find out the people quickly who need to be rescued in the case of emergency. The blind man can apply position indicator for the convenience of indoor activities by transmitting the location to the ear. Indoor positioning has great application value, it is estimated that the indoor positioning market value will be $5 billion in 2018 [1].

The common positioning technology is the Global Position System (GPS) technology so far. However, in the indoor environment such as superstore, underground parking, etc, due to the multipath fading and disturbances from other radio sources lead to large positioning error in traditional radio positioning like GPS. Now, the main technology of indoor positioning are Ultra-Wide Band (UWB), Radio Frequency Identification (RFID), Cellular, Bluetooth, ultrasonic, etc. These methods deliver positioning accuracy from

tens of centimeters to several meters [2], which can satisfy the requirement of positioning in some degree. However, these methods have the problem of difficult deployment and high equipment cost. What's worse, these methods are easy to be disturbed, some positioning technology based on RF can not use in the electromagnetic sensitive environment.

VLC (Visible light communication) with the light source of white LED (light emitting diode) as a green communication way, become a new research area of concern due to LED has the advantage of high efficiency, low price and long life. Compared with the traditional way of indoor positioning, indoor positioning technology based on VLC has the advantages as follow:

1) Visible light positioning with low price and simple hardware implementation, transmits positioning ID by the ready-made LED without extra device [3]. The receiver gets the signal from LED and implements the positioning algorithm to realize indoor positioning just with photoelectric receiver and processing segment .

2) Visible light communication can be used in RF sensitive area like hospital and air crafts, due to no electromagnetic and RF interference.

3) VLC has little influence of multipath interference that caused by non-line of sight, because the main energy of indoor visible light concentrate in the line of sight link.

4) Visible light positioning can provide higher precision than traditional positioning that based on electromagnetic wave.

5) LED had been widely used, so visible light positioning based on LED can be easy to extend.

Many indoor positioning technologies based on VLC have been proposed. Visible Light Communication Consortium (VLCC) of Japan realized positioning experiment in supermarket using visible light positioning [5]. National semiconductor lighting innovation laboratory and Huace optical communication science and technology company of China jointly developed U-beacon indoor positioning based on LED with independent property rights. The accuracy of the positioning is 1meter, and realized commercial operation in Changzhou city of Jiangsu province in 2014 [6].

The key techniques in indoor positioning based on visible light communication and the state of the art of this research were surveyed.

II. Typical Positioning Method

The indoor positioning methods based on visible light communication are mainly as follow: triangulation, scene analysis, proximity and image positioning method so far. Each of them which has its advantages and disadvantages, should be selected according to the needs of positioning methods in different scenarios. The scene analysis method and proximity method are briefly summarized, the triangulation of RSS method and the principle of image positioning are focused on in this part.

2.1 Scene analysis and proximity method

Scene analysis method, also known as fingerprints analysis, refers to finding out target's location by matching real-time measurements with the fingerprints that collection in information base [7]. Scene analysis is divided into two phases, building information base and matching fingerprints. Building information base means collecting fingerprints associated with every position in a scene. The fingerprints can be the time of arrival (TOA), time difference of arrival (TDOA), received signal strength (RSS), etc. Matching fingerprints refer to matching real-time measurements with the fingerprints that collection in information base. The main advantage of the scene analysis method is finding out target's location just only by matching real-time measurements with the fingerprints, without depending on any theoretical model and hardware which omitting a large amount of calculation. The disadvantage is that it need an advance information base, what's worse, it will bring incorrect positioning when the environment changes and the information of base is not

updated timely.

Proximity method is a very simple method of positioning. Indoor positioning system based on proximity method was demonstrated by Lee and other's experiments [8]. It dependent on a dense grid of reference points which have a well-known position. It is considered to be co-located with the reference points when a mobile target collects signal from it. Proximity method is very simple but provide accuracy no more than the resolution of the grid itself.

2.2 A triangulation method based on RSS

The triangulation method is based on the geometric properties of the triangle to estimate the target's position. It has two sub-branches: the method of lateration and angulation. Using the method of lateration, the target's position is found out by measuring the distance from the multiple reference points. The distance can not be measured directly, but measured indirectly by TOA, TDOA, RSS. Using the method of angulation, the target location is estimated by measuring the angle relative to several reference points. We focus on the triangulation based on RSS in this section.

2.2.1 System Model

The model of indoor positioning system that based on visible light is shown in figure 1. Each LED transmits its own coding, and the receiver can calculate distances d_1、d_2、d_3、d_4 by measuring the RSS of light from the LED of *A, B, C, D*,Then, it can estimate the target's position from the geometric properties composed by distances. It shown in figure 2, d_A, d_B, d_C are horizontal projection of d_1, d_2, d_3 respectively. The intersection of the three circle is the target's position.

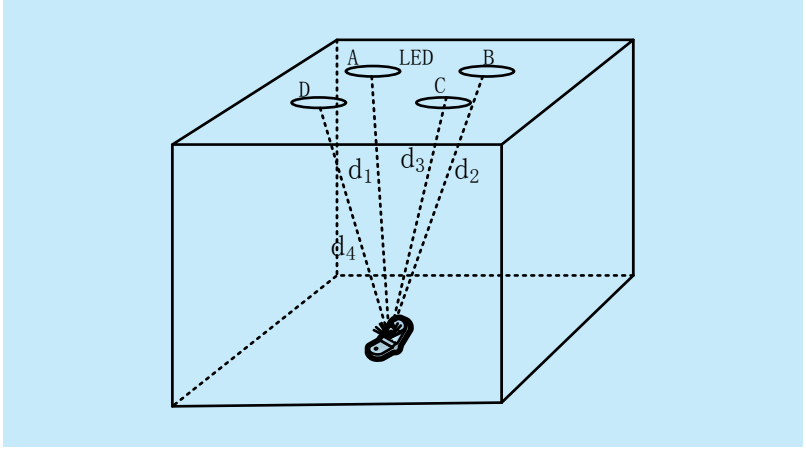

Fig.1 *Indoor VLC positioning system*

2.2.2 Indoor Channel of Optical Wireless

In indoor visible light communication system ,the light include directed light and reflected light. The rate of directed light is about 95.16%, the first reflected light is 3.57%, and the second reflected light is 1.27% [9]. It is demonstrated that the influence of the directed light is large in visible light communication, so we only consider the directed light for the convenience of analysis. The line-of-sight transmission model diagram in VLC is shown in the figure 3.

The channel DC gain is given [9] as:

$$H(0)=\begin{cases}\dfrac{m+1}{2\pi d^2}A\cos^m(\phi)T_s(\varphi)g(\varphi)\cos(\varphi), & 0\le\varphi\le\varphi_C\\ 0, & \varphi>\varphi_C\end{cases} \tag{1}$$

Where, m is the order of Lambertian emission, and is given by the semi-angle at half illuminance $\Phi_{1/2}$ of an LED, m=ln(1/2)/ ln(cos($\Phi_{1/2}$)), A is the physical area of the detector in a PD, d is the distance between a transmitter and a receiver, ϕ is the angle of irradiance, φ is the angle of incidence, $T_s(\varphi)$ is the gain of an optical filter, $g(\varphi)$ is the gain of an optical concentrator, φ_c is the field of vision at a receiver. $g(\varphi)$ is the optical concentrator as[10]:

$$g(\varphi)=\begin{cases}\dfrac{n^2}{\sin^2\varphi_c}, & 0\le\varphi\le\varphi_c\\ 0 & \varphi>\varphi_c\end{cases} \tag{2}$$

n is refractive index.

Set transmit power is P_t the received power can be expressed as:

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

2.2.3 Positioning method

If the transmitter power difference between 0 and 1 is P_{diff}, the receiving power P_{diff_r} can be

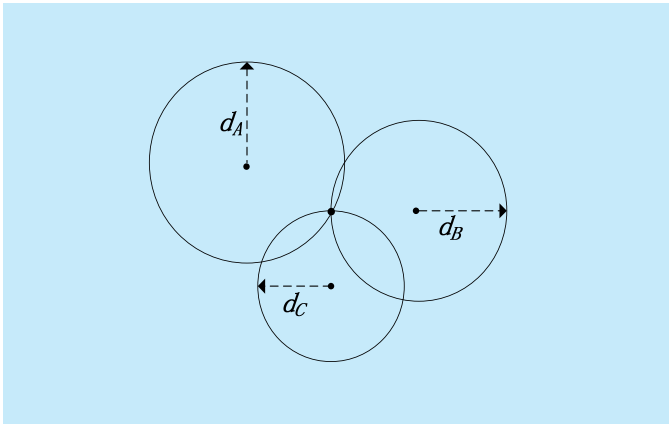

Fig.2 *Positioning based on RSS measurements*

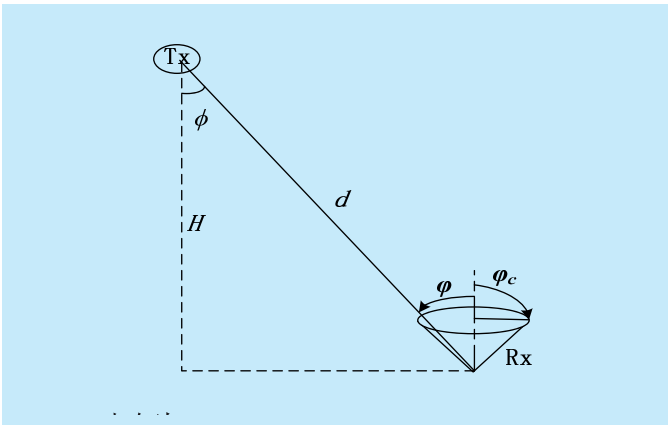

Fig.3 *VLC transmission model*

given as[11]

$$P_{diff\_r} = H(0)P_{diff} = \frac{m+1}{2\pi d^2} A\cos^m(\varphi)T_s(\phi)g(\phi)\cos(\phi)P_{diff} \quad (4)$$

By measuring the receiving power difference P_{diff_r}, the distance can be estimated, as:

$$d_{est} = \sqrt{\frac{(m+1)A\cos^m(\varphi)T_s(\phi)g(\phi)\cos(\phi)P_{diff}}{2\pi P_{diff\_r}}} \quad (5)$$

Assume that receiver axis and transmitter axis are perpendicular to the ceiling. So the distance can be expressed as:

$$d_{est} = \sqrt{d_{est-xy}^2 + H^2} \quad (6)$$

$$\cos(\varphi) = \cos(\phi) = H / d_{est} \quad (7)$$

Where, $d_{est\text{-}xy}$ is the estimated horizontal distance between transmitter and receiver, H is the vertical distance between transmitter and receiver. Assume all the LEDs are first-order Lambertian light sources, so m=1.

$d_{est\text{-}xy}$ can be calculated by (4)-(7):

$$d_{est-xy} = \sqrt{\sqrt{\left(\frac{AT_s(\phi)g(\phi)P_{diff}H^2}{\pi P_{diff\_r}}\right)} - H^2} \quad (8)$$

The receiver gets the transmitter signal from each LED, and then calculates the power of at least three LED signal, the target's location by the method of triangulation is calculated at last.

After estimating the horizontal distance between the transmitter and three LEDs, can get[12]:

$$(x-x_A)^2 + (y-y_A)^2 = d_A^2 \quad (9)$$

$$(x-x_B)^2 + (y-y_B)^2 = d_B^2 \quad (10)$$

$$(x-x_C)^2 + (y-y_C)^2 = d_C^2 \quad (11)$$

Where, $[x_A, x_B, x_C]$ and $[y_A, y_B, y_C]$ are the LED's coordinate of x-axis and y-axis respectively. $[d_A, d_B, d_C]$ is the horizontal distance between LED transmitter and receiver, (x, y) is the position of receiver. From (9)-(11), we can get:

$$\begin{cases} 2x(x_A-x_C) + x_C^2 - x_A^2 + 2y(y_A-y_C) + y_C^2 - y_A^2 \\ \qquad = d_C^2 - d_A^2 \\ 2x(x_B-x_C) + x_C^2 - x_B^2 + 2y(y_B-y_C) + y_C^2 - y_B^2 \\ \qquad = d_C^2 - d_B^2 \end{cases} \quad (12)$$

The target's position (x, y) can be estimated by solving the formula(12).

The triangulation method is used most frequently, but the disadvantage of the triangulation positioning method based on RSS is the slowdowns in performance when the users near the corner for the SNR decrease.

2.3 Image positioning

Image positioning refers to using image sensor to positioning in visible light communication, its typical system is shown in figure 4 [13]. A、B、C、D are four LEDs which transmit location information. The two images sensor

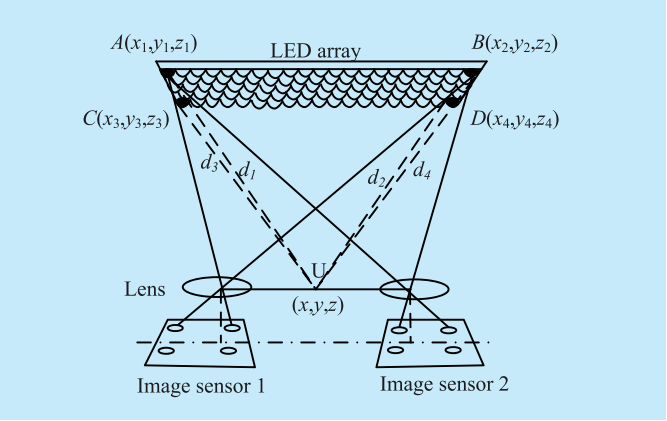

Fig.4 *Imaging positioning system*

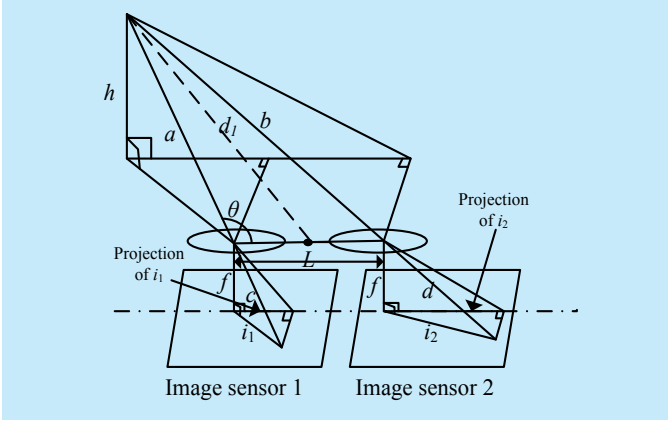

Fig.5 *The geometry of positioning algorithm*

receive the modulated signal from LEDs which distinguish from the position. It is the point U, the center point of the lens on the attachment that we measure.

The geometric structure of image positioning is shown in the figure 5, P_{i1}, P_{i2} is the projection of i_1, i_2. From the geometric structure of image and the similitude of the triangle that is similar, we can get formula (13) and (14), which can derive the distance of d_1 [14].

$$di = \left|Pi_2 - Pi_1\right|, h = \frac{f \times L}{di}, c = \sqrt{f^2 + i_1^2}$$
$$d = \sqrt{f^2 + i_2^2}, a = \frac{h \times c}{f}, b = \frac{h \times d}{f} \quad (13)$$

$$\theta = \cos^{-1}\left(\frac{a^2 + L^2 - b^2}{2aL}\right) \quad (14)$$

$$d_1 = \sqrt{a^2 + \left(\frac{L}{2}\right)^2 - 2a\frac{L}{2}\cos\theta} \quad (15)$$

In the same way, d_2, d_3, d_4 can be derived. So, we have four quadratic equations as:

$$(x - x_1)^2 + (y - y_1)^2 + (z - z_1)^2 = d_1^2 \quad (16)$$
$$(x - x_2)^2 + (y - y_2)^2 + (z - z_2)^2 = d_2^2 \quad (17)$$
$$(x - x_3)^2 + (y - y_3)^2 + (z - z_3)^2 = d_3^2 \quad (18)$$
$$(x - x_4)^2 + (y - y_4)^2 + (z - z_4)^2 = d_4^2 \quad (19)$$

Assume the d_i is correct, the position (x, y, z) can be estimated by solving any three equations in (16)-(19). In practice, the point in image is an aggregation by a lot of light points, so getting the center point need to quantization to find out the central value, the quantization error is caused, therefore, the d_i is an incorrect estimated value . In order to have an accurate value, we utilize four reference points to estimate. Equations (16)-(19) turn into an over-determined system of equations, termed as linear least square (LS) problem mathematically [13]. Unknown position of X can be calculated by solving equation (20).

$$2\mathbf{M}^T\mathbf{MX}=\mathbf{M}^T\mathbf{D} \quad (20)$$

Where,

$$\mathbf{M} = \begin{bmatrix} x_4 - x_1 & y_4 - y_1 & z_4 - z_1 \\ x_4 - x_2 & y_4 - y_2 & z_4 - z_2 \\ x_4 - x_3 & y_4 - y_3 & z_4 - z_3 \end{bmatrix},$$

$$\mathbf{D} = \begin{bmatrix} (d_1^2 - d_4^2) - (x_1^2 - x_4^2) - (y_1^2 - y_4^2) - (z_1^2 - z_4^2) \\ (d_2^2 - d_4^2) - (x_2^2 - x_4^2) - (y_2^2 - y_4^2) - (z_2^2 - z_4^2) \\ (d_3^2 - d_4^2) - (x_3^2 - x_4^2) - (y_3^2 - y_4^2) - (z_3^2 - z_4^2) \end{bmatrix}$$

Solving equation (20), get:

$$\mathbf{X} = \frac{(\mathbf{M}^T\mathbf{M})^{-1}\mathbf{M}^T\mathbf{D}}{2} \quad (21)$$

Solving the equation (21) needs matrix **M** to have full rank. However, the reference LEDs are in the same plane, and it means all LEDs have the same z coordinate value, which make the matrix **M** dissatisfy the condition of full rank. While , this problem can be solved by adding a small value into the z axis value.

Image positioning has the limitation as follow:

1) The sensor must be in the same plane, and the two optical lens must have the same characteristic;

2) Positioning range must be within the work area of the system;

3) Positioning accuracy is influenced by quantization error.

III Performance Comparison

The four methods of indoor visible light positioning including the triangulation of RSS method, scene analysis, proximity and image positioning were stated in section 2, and their performances will be compared in this section which is shown in the table 1. The performances of the hardware complexity, algorithm complexity, accuracy, power, space dimension, synchronization will be compared.

The triangulation method is applied commonly with high accuracy, low complexity, but its performance was poor in the corner; the method of scene analysis has the low power consumption and low complexity, while it needs for advance information base; the method of proximity has low complexity and low power consumption, however its accuracy no more than the resolution of the grid itself. Image positioning has a high accuracy, power consumption and complexity. Each method has its advantages and disadvantages, we should select proper method according to the needs of positioning methods in different scenarios.

IV Summary and Future Research

We summarized the main four technologies of indoor positioning based on VLC; introduced the triangulation of RSS method and the principle of image positioning in detail; compared the performance characteristics of the four algorithms; made a conclusion of the disadvantages and advantages.

With the technology matures in visible light communication, indoor positioning based on visible light communication will gradually develop to the practical application. After summarizing the indoor positioning technology, these factors of future research will be considered:

1) Positioning technology should be considered condition of the rapid movement, rather than static or slow moving movement.

2) At present, the literature researched positioning in a very typically small indoor environment with less obstacle and weak diffuse. But in fact, the indoor environment is full with a lot of obstacle which the diffuse reflection is strong. So, we should pay attention to the positioning technology under the complex environment in the future.

3) VLC can illumination as well as communication, in order to have a large range of lighting, the LED's angle of emission should not be narrow , as a result , the LED beam received by receiver will increase at the same time. So, the positioning system need to solve the problem of the multiple access . The problem will become serious in the larger space.

4) In 2013, Intel corporation of the United States, South Korean conglomerate, etc, set up

Table I *Performance comparison of indoor positioning based on VLC*

Positioning technology	Triangulation based on RSS	scene analysis	proximity	Image positioning
complexity (hardware/ algorithm)	Low / moderation	moderation /Low	Low / Low	High / high
accuracy	0.5mm(simulation)	0.65cm(experiment)	dependent on a dense grid of reference points	several centimeters (simulation)
power	high	low	low	high
synchronization	no	no	no	no
space dimension	2D、3D	2D	2D	2D、3D

802.15 SG7a research team under the IEEE 802.15 organization, and proposed taking Optical Camera Communications (OCC) as a standard of 802.15.7 [15]. Which show the importance of imaging positioning technology, so, the future work should be focused on overcoming the disadvantage of the limitation in image positioning like quantization error.

5) To overcome the limitation of the typical algorithms, future positioning system should be hybrid system that combined with a variety of technology. Hybrid positioning system can take the advantages of the positioning technology, and make full use of advantages. For example, a hybrid system of VLC and Ad Hoc can overcome the disadvantage of high error in positioning, small positioning range and high cost. The hybrid system has a high accuracy with WiFi in up-link and VLC in down-link. The system gets over the VLC up-link transmission that causing discomfort to the human eyes as well as to the problem of high consumption of the terminal, and makes full use of the advantages that the majority of mobile devices like mobile phone has WiFi function.

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