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Review Article

A Survey on Visible Light Positioning from Software Algorithms to Hardware

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The prevalence of illumination equipment and the inherent advantages of the Visible Light Communication (VLC) technique have resulted in a growing interest in Visible Light Positioning (VLP). There exist many excellent VLP techniques over the past several years. However, one limitation of most VLP survey works is that they mainly focus on the analysis from the perspective of techniques but ignore the equally important hardware aspect, since the hardware part directly affects the performance and cost of VLP systems and also determines whether it can be put into practical use. Different from most surveys concentrating on a single perspective, we provide an intensive overview of VLP systems from software algorithms to hardware devices. A novel-innovative classification method is used in the software algorithms, while the hardware aspect is introduced in terms of transmitters, modems, and receivers, making up for the deficiencies of the previous works. Massive papers including pioneering papers and the state-of-the-art ones in related areas are gathered and categorized. These solutions have also been evaluated in terms of accuracy, cost, range, and complexity. Furthermore, current open issues and tendencies regarding VLP are also illustrated in this paper.

1. Introduction

With the rapid development of the Internet of Things (IoT) technology, positioning technology has emerged and has been applied in various fields. Global Positioning System (GPS) [1] is the first technology that comes to mind in many positioning technologies. Nevertheless, the poor performance of GPS in indoor positioning makes it not a flawless positioning technology [2]. Therefore, several approaches have been developed to be the supplement of GPS, such as Ultra-Wideband (UWB) [3], WiFi [4], Radio-Frequency Identification (RFID) [5, 6], and fingerprint [7]. They may be able to obtain higher positioning accuracy than GPS even in outdoor environments, but this also means that the cost is relatively high. In addition to the abovementioned positioning technologies, positioning based on Visible Light Communication (VLC) as a novel positioning technology is attracting the attention and research of many scholars in recent years.

Just as its name implies, the Visible Light Positioning (VLP) system obtains the position of moving objects by utilizing visible light signals. It has several advantages in comparison to Radio Frequency- (RF-) based localization. First of all, the existing luminaire infrastructure composed of white Light-Emitting Diode (LED) can help us reduce the cost of deploying VLP systems. Secondly, since the wavelength of visible light is shorter than that of other RF waves, visible light has a better immunity against multipath effects and has higher predictability in light propagation compared to other RF signals [8, 9]. For the foregoing reason, higher localization accuracy can be gained with VLP. Thirdly, since the main function of LED lights is still lighting, the VLP system can be used for positioning services while retaining the lighting function. Last but not least, for the immunity of VLC to the interference from other electromagnetic waves and no EM interference production, the application scenarios of VLP can be numerous environments that are inapplicable to RF [10].

In addition to the above advantages, the other reason why VLP research is so popular is the ubiquitous lighting equipment and the excellent development prospects of LED devices. Benefiting from the characteristics including long service life, powerful controllability, cost-effectiveness, and environmental friendliness, LEDs are considered the lighting device of the 21st century. At the same time, thanks to the continuous improvement of LED equipment, VLC technology based on LED lights has also gradually developed into one of the hottest directions for future wireless technology research. Once LED-based lighting equipment is widely deployed and even becomes ubiquitous, VLP can provide us with lower cost, wider coverage, and more localized location services than other current positioning techniques.

In the past few years, many scholars have conducted research on the field of VLP and published a large number of papers related to this field. Nevertheless, few review articles which work on VLP are presented, and most of these papers do not make a comprehensive summary of the hardware aspects. In [11], a number of VLP techniques were categorized and compared. However, only very little detail of each technique was introduced, and the localization technique based on vision was not included in this article. The authors of [12] introduced and compared four VLP approaches and also presented restrictions of these approaches. However, this paper does not make reference to the three most popular technologies in the VLP field: Angle of Arrival (AOA), Time of Arrival (TOA), and Time Difference of Arrival (TDOA).

A survey of the research status of indoor positioning systems on the basis of VLC was presented in [13]. Though several additional papers were collected, this paper mentioned very little detail on the localization mechanisms. The authors of [14] gave us a detailed overview of the VLP algorithms. But disappointingly, this article pays great attention to the comparison of AOA and vision analysis methods, which leads to a lack of in-depth introduction to other VLC-based positioning technologies. An intensive survey on VLP algorithms was presented in [15]. Nevertheless, several common VLP algorithms, including TOA and proximity, are ignored. Similarly, the authors of [16] proposed an in-depth overview of the VLP system from the perspective of positioning algorithms. However, this paper ignores the hardware aspects of VLP systems that are as important as software algorithms, which is one of the key studies of our work. Eventually, an in-depth overview of VLP systems was proposed in [17] with the perspective of positioning algorithms. However, this paper does not involve any aspect of related hardware, which is one of the classification bases of our article.

From the above analysis, we can conclude that most of the abovementioned existing work does not comprehensively summarize the VLP system. References [11–13] and [16] summarize the software algorithms of the VLP system incompletely, and several common positioning algorithms are ignored. Reference [14] only compares the two positioning methods (i.e., vision analysis and AOA techniques) so that it lacks the in-depth introduction of other VLP algorithms. And the most important point is that the abovementioned work including reference [17] ignores the extremely important VLP hardware part. On the other hand, the choice of visible light hardware directly affects the performance and cost of the VLP system. At the same time, for different application scenarios, the hardware selection of the VLP system is also different, which determines whether the VLP system can be put into practical use. Therefore, based on the above shortcomings, this paper not only summarizes more comprehensive VLP algorithms but also classifies and divides the visible light hardware used in the existing work.

This paper makes the following three main contributions:

(i) This paper makes a detailed overview of the VLP system. We not only analyze the software algorithms of the VLP system but also make a detailed analysis of the hardware, which makes up for the shortcomings of the previous work. It also provides a reference for researchers in the selection of visible light algorithms and hardware of the VLP systems

(ii) We propose two novel classification methods for software algorithms and hardware. The software algorithms are divided into two parts according to whether the sending device is modulated. According to the hardware part, we introduce it from three parts (i.e., transmitter, receiver, and modem) based on the hardware structure of the VLP systems

(iii) Massive papers are gathered, including the excellent literature and the pioneering papers, and we also evaluate the accuracy, cost, scope, and complexity of these papers. At the same time, open issues and future direction are also discussed

The organization of the remainder is as follows. Section 2 presents the taxonomy of VLP systems in terms of both software algorithms and hardware. Sections 3 and 4 introduce the software algorithms and hardware of VLP systems, respectively. Section 5 discusses the open issues that VLP faces, and Section 6 gives the conclusion of this article.

2. Taxonomy of VLP Systems

A complete VLP system generally consists of two parts: software algorithms and hardware. Therefore, an excellent VLP system will take into account both software algorithms and hardware to achieve the best positioning effect. Figure 1 illustrates the classification method and classification results of the VLP system. Among them, software algorithms and hardware are further divided into multiple small parts according to different classification principles. In this section, we will introduce software algorithm taxonomy and hardware taxonomy, respectively.

2.1. Taxonomy of Software Algorithms. Based on our previous work [18], we classify the existing VLP algorithms into two categories according to whether the transmitter is modified or not: customized light hardware-based VLP systems and unmodified light hardware-based VLP systems. Next, we will introduce these two parts separately.

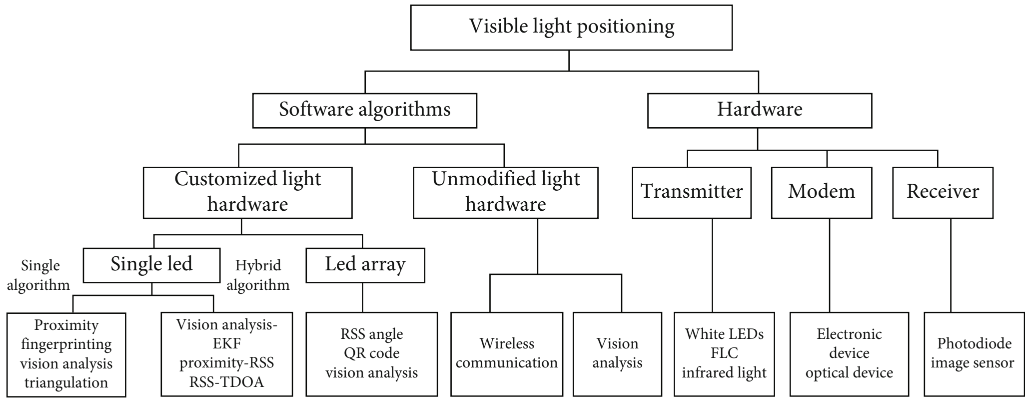

Figure 1: Taxonomy of VLP systems.

2.1.1. Customized Light Hardware. Generally speaking, the LED-based localization techniques requiring customized beaconing circuits to be added to the LED driver pertain to the customized light hardware-based category. According to the number of LED lights, we can further divide the customized light hardware into two parts: single LED and LED array. Depending on the number of LED lights used, the corresponding algorithms are also different.

Single LED. Nowadays, most VLP systems use a single lamp and then combine different positioning algorithms to achieve their functions. According to the use of different positioning algorithms, the algorithms of the single LED can be further divided into two parts, i.e., single algorithm (e.g., proximity, fingerprinting, vision analysis, and triangulation) and hybrid algorithm (e.g., vision analysis-EKF, proximity-RSS, and RSS-TDOA).

LED array. LED array means that at least two LED lights are combined into a specific pattern to cooperate with each other for positioning. This method is not common compared to the single lamp. We have summarized a lot of literature about the LED array and mainly introduced the following algorithms, including RSSR angle, OR code, and vision analysis.

2.1.2. Unmodified Light Hardware. The unmodified lighting hardware only uses the original LEDs for positioning by digging out the potential feature information in the original LED lights. Obviously, since the inherent characteristics of LED lamps are very difficult to extract and analyze, positioning technology using unmodified LED lights is more difficult than modulated LED lights. However, unmodified lighting hardware does not need to consider the cost of modifying the original lighting circuit and the original lighting equipment and also does not need to consider the issue of large-scale deployment in a special environment. Therefore, compared with modified LED hardware, unmodified lighting hardware has better versatility and lower cost because it does not make any modifications to the original LED lights. Without considering the number of LED lights, we further divide them into two types: wireless communication and visual analysis.

2.2. Taxonomy of Hardware Structure. Utilizing the right hardware can not only simplify the positioning process but also greatly improve the robustness of the VLP system and be cost-effective. Figure 2 illustrates the hardware structure of a typical VLP system. The transmitting end composed of the modulator and transmitter first emits optical signals to the free space channel, and then the receiving end composed of the demodulator and receiver perceives the emitted optical signals. Finally, the location information is obtained by executing the corresponding VLP algorithms. In general, many VLP systems use the modulator before the transmitter to modulate the circuit and next drive the transmitter to broadcast the specific light signals, and then the demodulator performs demodulation operation on the light signals perceived by the receiver. However, there are also some articles on VLP technology that place the modulator behind the transmitter and utilize the optical characteristics to modulate the light emitted by the transmitter; no special modulation of the circuit is required. Therefore, considering the uncertainty of the positions of the modulator and demodulator in the VLP system, we classify the hardware structure of the VLP system into three parts: transmitter, modem, and receiver.

3. Software Algorithms of VLP Systems

In this section, we give a detailed introduction to the two categories of customized light hardware and unmodulated light hardware, which are mentioned in Section 2. To begin with, a customized light hardware- or an unmodified light hardware-based positioning system requires complying with the core requirements below to a variable extent:

Accuracy. Pinpoint positioning accuracy is all the time the paramount concern for virtually all localization systems; VLP systems are no exception [19, 20]. One example is navigation, which assists users in finding their way from one place to another utilizing LED's feature [21]. The accurate position information of entities is of crucial importance in overwhelming applications and services. Pay attention to disparate application scenarios that have diverse localization accuracy demands. For instance, lower accuracy is sufficient for advertisements based on the position like shopping, restaurant, and hotel recommendations. Room-level precision is adequate for seeking out a specific store in a large-scale shopping center.

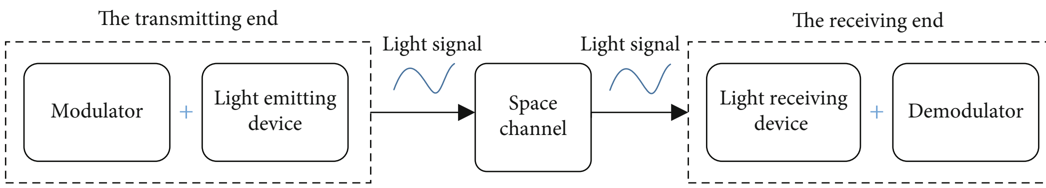

Figure 2: Hardware structure of a VLP system.

Immediacy. To make location predictions of injured or missing persons as soon as possible plays a crucial role for a time-critical service [22], such as underground rescue [23, 24] and elderly fall detection. When coping with an emergency, the users are eager to reveal their position information most of the time. In such a way, the rescue teams such as ambulance staff can make a rapid movement to approach the sufferer position to carry out the rescue operation as quickly and accurately as possible. In healthcare assistance, action with immediacy is also required to prevent medical accidents from locating patients behind time.

Expense. For the VLP system, expense plays an essential role in measuring business success [25]. There exist four main ingredients:

(1) Hardware Expense. This part covers terminals like light-emitting diodes and optical sensors, which stand for the transmitting terminal and receiving terminal, respectively.

(2) Infrastructure Expense. A few positioning systems depend on standalone devices to maintain normal work, yet the majority of localization systems still demand to construct a network with the support of additional equipment. For instance, for VLP systems, specific devices are required to receive or transmit signals in order to gain the measured value for location prediction.

(3) Installation Expense. Installation and configuration are demanded by most of the positioning systems before putting into use. For customized light hardware-based VLP systems, the installation of light hardware requires to be in a particular way, and these certain hardware components also need to be mounted on the light-emitting diode.

(4) Maintenance Expense. For a VLP system that makes use of many devices (e.g., light-emitting diodes, photodiodes), the longstanding maintenance work (such as the replacement of batteries) can be costly as well as complicated. All the above expenses should be taken into account so that developing a VLP system will not be too exorbitant.

Energy efficiency. It is especially important for the development of positioning approaches to mitigate energy concerns. For receivers (such as a photodiode or CMOS camera), power consumption is a nonnegligible suppression factor [26]. It is because the proper functioning of the localization systems is restrained by the capacity of the receiver battery. Since the supply of power resources may be difficult or even impossible in some situations, it will be of the essence for these VLC-based methods to take an energy-efficient strategy [27].

Expandability. Expandability is another principal element for a localization system, especially for commercial purposes. As the density of users increases, the positioning system can be overloaded. When encountering message switching between the server and the devices, the competition will generate between devices for priority transmission on account of limited amounts of wireless channels. Besides, since the transmission range of signals is restricted, the wider the region of interest is, the more equipment is demanded [28]. As a consequence, the localization system should be capable of coping with other extra devices and can cover a wide range of regions, which is of interest with service maintenance.

3.1. Customized Light Hardware. VLC has the advantage of high security, green energy saving, high response sensitivity, and good modulation performance. First, we should make the definition of customized light hardware clear. In this paper, being defined as customized lighting hardware means that additional functional modules are added to the original lighting circuit of the transmitter, such as synchronization equipment, code modulation, and Microprogram Control Unit (MCU). Next, the customized lighting hardware can be further divided into two categories, that is, single LED-based and LED array-based. The single LED means that each LED represents a positioning unit, while the LED array means that each positioning unit is composed of multiple LEDs.

3.1.1. Customized Single LED. In this subsection, we introduce the customized single LED-based approaches according to different positioning principles, such as proximity, fingerprinting, vision analysis, triangulation, and the combination of different algorithms.

(1) Proximity. Proximity is the simplest position sensing solution, which can only provide proximity position information instead of absolute or relative locations. This technique uses the optical signal transmitted by a single LED light to determine the proximity position of a moving object. The mobile device will receive the unique Identification (ID) information sent by each LED light. A mapping relationship will be established between each ID and the specified position of the LED light, and the mapping information will be stored in the database. After receiving the optical signal from the LED light with a specific ID, the moving device will obtain the location information corresponding to this specific ID in the established database.

As an attractive research direction, proximity has been proposed and improved by numerous scholars. In [29], a VLP navigation system utilizing LED lights and a geomagnetic sensor integrated into a ubiquitous smartphone was presented. The route information can be obtained by using the geomagnetic sensor. The purpose of designing the navigation system is to support travel for visually impaired people and provide precise guidance for the location information as well as moving direction. Voice navigation can also be provided by this system, and its accuracy is approximately 1 m to 2 m. A physical simulation model for VLP systems assisted by the 6-axis sensor was proposed in [30]. The accurate Field of View (FOV) limit can be calculated by the use of Support Vector Machines (SVMs) and a 3D rotation matrix with cone function. The FOV limit indicates the maximum region in which the VLC receiver can receive signals concerning its FOV configuration, and SVMs are supervised learning approaches that build a model that predicts which category a new input should fall into by utilizing the training algorithm. The mathematical definitions of possible azimuth and tilt angulations are made on the basis of sensitivity and FOV limits. The paper has proved that the proposed model is capable of reducing the computation by at least 80% during Geometric Optics (GO) calculation.

Yong and Kavehrad [31] presented a VLP system utilizing ad hoc wireless network infrastructure, which contains two design techniques and can provide a more convenient and more precise location service. One of the abovementioned design techniques is the noncarrier VLC-based transceiver scheme, which has been proved to be more suitable for the low data rate and long-range localization on account of its lack of a carrier and simple circuits. However, a narrow-range of VLC reception and low-frequency noise are its shortcomings. The other one of the design techniques is the 4 MHz carrier VLC-based transceiver scheme. Contrary to the previous one, this scheme is applicable to the high optical data rate and mid- or short-range localization by reason of its wide-range VLC reception and robustness against noise. This system is designed for solving the problems of high cost, low estimation accuracy, and limited service range of the traditional localization methods.

In [32], an indoor hybrid positioning system utilizing VLC and a five-hop ZigBee wireless network was developed, which can realize long-range positioning. This system has its advantages of low power as well as high security and can improve localization accuracy. To optimize implementation complexity and cost, an indoor VLP system that adopts LED lamps as beacons was presented in [33] in order to optimize implementation cost and complexity. This system was composed of LED lamps and a mobile device, where the lamp acted as a beacon by sending ID or coordinates repeatedly, and then the mobile device would receive these location data and therefore obtain a determined location. Moreover, two disparate kinds of beacons were also presented: passive beacon and active beacon. The experimental results verified that the error-free range of communication reaches 4.5 m, and when the power of the lamps used is higher, the system is suitable for a larger range.

(2) Fingerprinting. Fingerprint positioning refers to the estimation of the relevant position by mapping the measurement data obtained with the position-related data measured online, so fingerprinting is also called scene analysis. Due to the irregularity of the base station distribution, the uncertainty of obstacles, and the inherent diversity of base stations, the fingerprints corresponding to the measurement data may vary with changes in location. For instance, by reason of heterogeneous distribution of LED lamps, the scatter as well as reflections of light resulting from the influence of appliances and the wall, and even on account of the diversification of every LED's transmitted power, the power received changes in diverse locations. The fingerprinting technique leans upon these differences to correspond to a certain position and realize the estimation of location.

Existing fingerprinting techniques can be classified into two types, which are radio-map-based fingerprinting positioning and map-free fingerprinting positioning. Map-based fingerprinting positioning consists of two stages: offline stage and online stage. In the offline stage, the relevant position data of every position in a circumstance is gathered and then the radio-map can be generated. In the online stage, the localization technique matches the currently measured data with the radio-map to obtain the relative location of the target. The map-free fingerprinting approach as another fingerprinting is capable of reducing the complexity of mapping maintenance. A few articles which employ the fingerprinting algorithm to achieve localization are presented next.

In [34], an indoor positioning system utilizing the fingerprinting of intensity-modulated visible lights emitted from LEDs was introduced. The receiver and transmitters were designed to make use of visible lights as the signals for positioning. At the transmitter side, the input current/voltage was modulated with continuous waves before being sent to LEDs, where different frequencies are assigned to each transmitter. At the receiver side, the power spectral density of the received signal was computed and the estimated position was considered to be one of the fingerprint positions utilizing a novel but simple algorithm. It has been proved that the system has the potential to achieve the position estimation in the centimeter level when in a controlled environment.

Vegni and Biagi [35] presented a novel and simple approach for Indoor Positioning Service relying on infrared LED devices. The designed method provided an Indoor Positioning Service (IPS) by means of a fingerprinting technique, i.e., use of the impulse response knowledge, and comparison to power samples and time measurement map of the environment. Opportunely sampling the environment and deploying LED transmitters can effectively avoid ambiguity cases. Results of the simulation proved the efficacy of the presented method in terms of the localization error and the number of detected receivers.

Multiple tilted photodiodes with different angles forming an array aimed at obtaining light signals transmitted by a fixed single LED lamp were exploited in [36, 37]. The received power of different optical receivers varies as the light would impinge at diverse incidence angles. Besides, the distance from the optical transmitter to the multiple optical receivers varies at different locations in the room, and the angle of incidence for each receiver will also vary. As a consequence, the measurement of the received power gain which resulted from the angle can be realized, so the fingerprinting for positioning has been prepared. The results of the simulation reported an average error of 4 cm and the maximum error of 13 cm.

An Optical Wireless Location sensing system utilizing LEDs was introduced in [38], which assigns a unique address to each LED lamp. Some LED properties, such as switching and lighting, were efficiently utilized. The addresses assigned to LEDs were transmitted, and the LED ceiling lights were used for illumination. Then, the position of the target that can be obtained relied on the correlation between the received data and the predetermined address. Experimental results reported a maximum distance error of 12.46 cm and an average distance error of 4.38 cm. In [39, 40], the alleged extinction ratio was selected as the fingerprint for positioning, which represents the specific value between received powers of transmitting bits 1 and 0. The simulation results showed that the average error of a triangular battery with a side length of 60 cm is 1.58 cm.

(3) Vision Analysis. The vision analysis involves the geometric relationship between the two-dimensional position of an object projected by the image sensor and its three-dimensional position in the real world. All geometric relationships in the visual analysis are derived from the pinhole camera model. The pinhole camera model is the basis of all geometric relationships in vision analysis. Figure 3 shows a typical pinhole camera model, which is very simple and widely used in vision analysis. Three coordinate frames are illustrated, which are the two-dimensional image coordinate frame (origin is O_i), the three-dimensional camera coordinate frame (origin is O_C), and the three-dimensional world coordinate frame (origin is O_W). The three-dimensional world coordinate frame is used to describe the position of the camera and the object in the real world, the three-dimensional camera coordinate frame is used to describe the position of the image in the camera, and the two-dimensional image coordinate frame is used to describe the position of the pixel in the image. Suppose the position of an object M in the world coordinate frame is $M(X_\mathrm{W}, Y_\mathrm{W}, Z_\mathrm{W})$; then, its projection on the image plane (i.e., the coordinates in the two-dimensional image coordinate frame) is $M_\mathrm{i}(X_\mathrm{i}, Y_\mathrm{i})$, and the position of the object M in the three-dimensional camera coordinate frame is $M_\mathrm{C}(X_\mathrm{C}, Y_\mathrm{C}, Z_\mathrm{C})$. The conversion relationship between the two-dimensional image coordinate frame and the three-dimensional camera coordinate frame is

$$Z_\mathrm{C}[X_\mathrm{i}\ Y_\mathrm{i}\ 1]^T = R[X_\mathrm{C}\quad Y_\mathrm{C}\quad Z_\mathrm{C}\quad 1]^T,\quad R = \begin{bmatrix} f & 0 & 0 & 0 \\ 0 & f & 0 & 0 \\ 0 & 0 & 1 & 0 \end{bmatrix}, \tag{1}$$

where R is the camera correction matrix and f is the distance from point O_C to the image plane. And the conversion relationship between the two-dimensional image coordinate frame and the three-dimensional world coordinate frame is

$$[X_\mathrm{C}\quad Y_\mathrm{C}\quad Z_\mathrm{C}\quad 1]^T = \begin{bmatrix} N & t \\ 0 & 1 \end{bmatrix}[X_\mathrm{W}\quad Y_\mathrm{W}\quad Z_\mathrm{W}\quad 1]^T, \tag{2}$$

where t is a 3×1 three-dimensional translation vector and N is a 3×3 orthogonal rotation matrix [41].

A VLP approach for indoor self-positioning utilizing a single high-speed fish-eye lens-equipped camera was proposed in [42]. The data transmission speed of the LED light was 9.6 kbps, and the sampling rate of the receiving signal was 48 kHz. The order of data in buffer memory was swapped in order to reconstruct the original ID frames. Furthermore, a self-positioning estimation program utilizing the Levenberg-Marquardt algorithm has been implemented. A localization experiment has also been conducted utilizing LEDs and a fixed fish-eye camera. The performance of the presented system has been proved by the maximum horizontal error being no more than 10 cm.

Successful implementation of indoor localization through the use of dual PC cameras and four single LEDs was presented in [43]. The location information corresponding to each LED was identified according to different colors. Then, the demanded unknown location of the target is estimated utilizing the location information of LEDs and the geometrical relation of projections on the two image sensors. A set of four quadratic equations was solved by using a vector estimation algorithm. For removing a fluctuating behavior caused by the quantization error of the pixel, the center of an image in terms of the decimal point pixel was adopted, which improved the positioning accuracy.

In [44], Kuo et al. proposed a high-precision indoor positioning method based on slightly modified LED lights and unmodified smartphones. The LEDs were modified to send optical pulses that carry information that uniquely identifies its location, which is invisible to the human eye. At the same time, a smartphone equipped with a camera is used to capture the image frame, which can sense the presence of the light source in the image, decode the identifiers and positions, and estimate the position and direction of the smartphone relative to the LED lamp. The experimental results proved that it is possible to use a smartphone to achieve localization errors in the decimeter level and 3° orientation error at the same time when you are walking under the overhead LED lights.

In [45], a new localization approach making use of visible light LEDs and an image sensor was introduced. The color LEDs were employed to estimate the location of the target. The localization accuracy of less than 5 cm based on the proposed technique was realized. The introduced method was also applied to a robot, and the precise location control of a robot being feasible is demonstrated. The system design of PIXEL was proposed in [46], which can offer a lightweight VLP method for resource-constrained moving devices. Polarization-based VLC without the problem of light

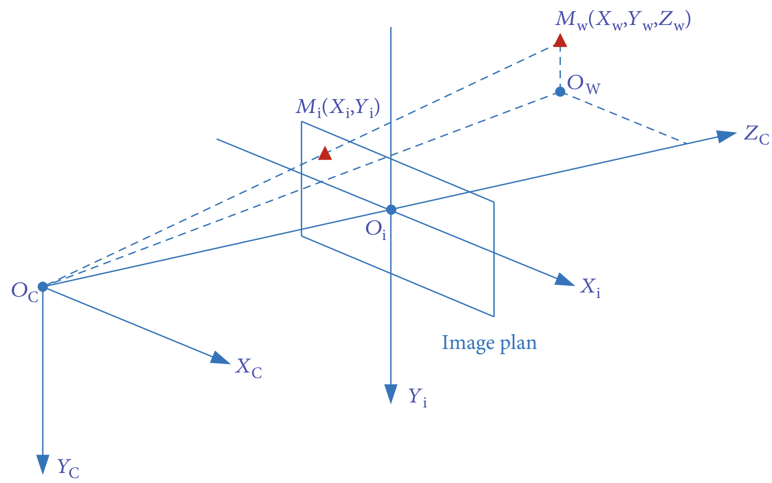

Figure 3: Pinhole camera model.

flickering was utilized as intensity-based VLC. As a result, the heavy burden on receiving equipment which resulted from a high pulse rate is eliminated successfully. PIXEL also incorporated an adaptive downsampling algorithm, a novel modulation scheme based on color and computational optimization approaches to solve the problems of uneven camera sampling, user mobility, and limited computational resource. The experiment results showed that PIXEL is able to offer precise real-time VLP for wearable devices and smartphones with CPU frequency as low as 300 MHz and camera resolution as coarse as 60 pixels × 80 pixels.

(4) Triangulation. Triangulation utilizes the geometric characteristics of the triangle to determine the absolute position of the target. Angulation and lateration techniques are derived from triangulation. Angulation measurement techniques (e.g., AOA) determine the position of the mobile device based on the measured angles corresponding to multiple LED base stations. However, lateration techniques, including Received Signal Strength (RSS), TOA, and TDOA, depending on the measured distances from multiple LED base stations to mobile devices to estimate location.

AOA. The estimated Angle of Arrival of signals transmitted by multiple LED lights is used to estimate the position of the moving target in the AOA positioning technique. Figure 4 illustrates the AOA mechanism. The crossing point of the bearings is estimated as the location of the moving target. Comparing with other algorithms for Visible Light Positioning, AOA takes advantage in terms of being capable of estimating the moving target location with two measurement values for two-dimensional localization or three measurement values for three-dimensional localization. Another advantage of AOA is that it does not need the synchronization between LEDs.

In general, a PD array can be utilized to gain the Angle of Arrival. The received power will change with the variation of the Angle of Arrival due to the Lambert cosine law, which the lights emitted from LEDs all follow. Hence, the difference between the received powers of a known angle and the current angle can be used to estimate the light angle. The authors of [47] proposed an Optical Wireless Location (OWL) system with optical AOA localization. The OWL system utilized a moving optical receiver, which promoted triangulation by measuring the Angle of Arrival bearings from LEDs. The receiver settled in a corner cube contains three photodiodes to promote differential photoelectric currents of the incident light AOA. Compared to known optical RSS localization, optical AOA localization has been proved to possess a basic advantage of lacking sensitivity to power and alignment disbalances of the optical beacon grid. Experimental results showed that this method achieves an average 3D positioning error of 5 cm through optical AOA positioning.

Lee and Jung [48] presented the AOA estimation technique under VLC circumstance for the sake of obtaining the position of a light source (LED) utilizing a circular PD array. A truncated weighting approach that is aimed at reducing the error of estimated AOA was also introduced. Simulations showed that the number of photodiodes in a circular PD array has an influence on the accuracy of AOA estimation. Furthermore, the presented truncated weighting scheme has a better position awareness performance of AOA estimation than those of simple mean and max schemes.

By utilizing an accelerometer, [49, 50] can obtain the determination of AOA based on only one photodiode. The rotation of PD is made with different directions, and measurements of received power that corresponded to these directions are acquired. Through making use of an accelerometer, the direction of the photodiode is always known. Two orientations of the PD were measured for each LED base station. The irradiance of the light can be gained on the basis of the measurements of received powers in two directions. The VLC signal contained the position information of multiple base stations, and TDM was utilized to distinguish signals radiated from LEDs. The determination of the mobile device location can be made after acquiring the irradiance angles corresponding to three LEDs. The results of the simulation reported that the mean location error is less than 25 cm with a static receiver.

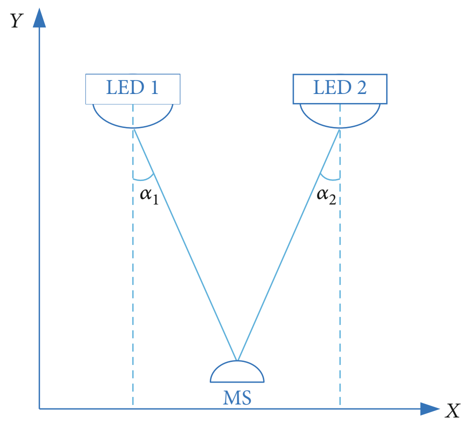

Figure 4: Localization based on AOA.

The work of [49, 50] was improved by a succeeding paper [51], which exploited multiple inclined PDs in combination with an accelerometer to determine the estimation of AOA without the rotation of the moving device. The estimation of AOA can be determined more quickly, and the proposed system supports the mobility of users. For mitigating the error that resulted from nonzero distances between the PDs, this system presented a power calibration method. The results of experiments reported an average location error of less than 6 cm even for the circumstance of the mean speed of receiver movement being 1.3 m/s.

RSS. The distance between the LED base station and the mobile device is calculated by RSS based on the Received Signal Strength. Many researchers try to use the method of establishing signal attenuation models to calculate the signal path loss during signal propagation. Nonetheless, the severe multipath fading may fail the path loss models. In [52], multiple signals were distinguished by the use of the Optical Orthogonal Code (OOC). RSS was used to calculate the distances to different LEDs, and the estimation of location was determined by utilizing trilateration. The results of the simulation reported a mean error of 8 cm with a region of 12 m × 35 m.

Luo et al. [53] took advantage of the Dual-Tone Multifrequency (DTMF) technique to develop a VLP system. The DTMF technique can be applied to the electronic banking system, voice mail, and telephone dialing. By using the DTMF technique, light signals emitted by different base stations can be separated. In addition, another proposed algorithm utilized RSS related to different frequencies to compute the path loss. It is assumed that the mobile device was aware of the positions of LED base stations. The results of the simulation demonstrated that the mean localization error distance is 18 mm in a region of 2 m × 2 m.

In [54], a signal containing positional information of each base station was transmitted from a beacon light which was modulated in Binary Frequency Shift Keying (BFSK) to the mobile device. For the precaution of flickering, the duty cycle of different frequencies remained the same. The persistent collision between light sources can be avoided by the use of random channel hopping. A simple model was utilized to convert the RSS into the distance with an assumption of the orientation of the receiver being squarely upward toward the overhead and all LEDs facing downward. Then, the estimation of location was determined by the use of the Least Mean Square (LMS) approach. The accuracy reported in an experiment was 0.3 m and 0.7 m for the meeting room of 5 m × 8 m and the cubicle of 3.5 m × 6.5 m, respectively. [55] extended the work of [54] by means of addressing more practical challenges containing enabling robust positioning and reliable communication in the event that imperfect orientation or insufficient light sources occurred. The results of the simulation demonstrated that the accuracy of 0.4 m in a space of 20 m × 20 m × 3 m had been realized.

RSS and RSSD. Different from the RSS technique, the Received Signal Strength Ratio (RSSR) method estimates the location by using the ratio of distance which was converted from the ratio of the received power from LED base stations. Compared to RSS, RSSR has the advantage that errors that resulted from the nonzero irradiance angle of light can be canceled by utilizing the ratio of received power. Thereby, the ratio of distance converted from the ratio of received power can achieve higher precision than the distance converted from received power directly. One main restriction of the RSSR method is that the receiver surface needs to be parallel to the LED lamp, and for some applications, it might be unrealistic.

RSSR indoor VLP systems were presented in [56–58]. In these introduced systems, it is assumed that the receiver was parallel to the LED lamp, and as a consequence, the angle of irradiance and the angle of incidence are equal. Besides, an assumption was also made that the FOV was larger than the incidence angle at all measurement points. In the aforesaid systems, signals transmitted from different LEDs were distinguished by using time division multiplexing. The experimental environment was a region of 1 m × 1 m, and the error of distance ranged from 3.89 cm to 1.68 cm.

The Received Signal Strength Difference (RSSD) method is another derivation of RSS, which was provided in [59, 60]. The distance was derived from the difference of received powers between logical 0 s and 1 s rather than obtaining the distance from received power directly. The visible LED light which was modulated in the On-Off Keying (OOK) format was utilized to transmit base station IDs to receivers. For lessening the requirement of perfect synchronization between base stations, the LED base stations made use of the Framed Slotted ALOHA (FSA) protocol to realize the transmission of their IDs with no collision. A proposed model was utilized to compute and translate the difference of received power between logical 0 and 1 to the distance. Then, trilateration equations can be solved by utilizing the linear least square approach, and the position was thereby gained. Simulation results reported that the position errors were 17 cm with an assumption of direct sunlight exposure and 11 cm with an assumption of no direct sunlight exposure in a region of 6 m × 6 m.

TOA. TOA measures the distance between the transmitter and the measured object by calculating the time difference between the transmitted signal and the received signal. Then, the distance between the transmitter and the moving object can be calculated by multiplying the speed of light by the propagation delay of the signal (i.e., the time difference). In order to determine the 2D position, it needs to be no less than three LED base stations.

Neild et al. [61] analyzed the localization precision of an indoor VLP system that made use of TOA. The estimation of TOA-based distance was obtained on the basis of modulated signals transmitted from the LEDs. Light signals emitted from different LED base stations were separated by employing the Orthogonal Frequency Division Multiplexing (OFDM). It was assumed that there exists perfect synchronization between PDs and LEDs. The estimation accuracy is calculated by utilizing the Cramer-Rao bound, and the experimental results showed that the error range is from 2 cm to 6 cm.

TDOA. The light signals are transmitted from all LED base stations to the mobile device at the same time. The arrival times of signals will be different on account of the difference in the distance from the LEDs to the mobile device. The TDOA technique estimates the location of the moving device on the basis of the Time Difference of Arrival of the light signals transmitted by multiple LED lamps. For every TDOA concerning two LED base stations, the difference of distances from the moving device to the two base stations is computed by multiplying the speed of light by the time difference. Hence, for the measurements of each TDOA, a hyperbola of possible locations that has a constant difference in the distances to the two LED base stations can be determined. For 2D localization, the measurement of TDOA with reference to at least three base stations needs to be gained.

An indoor VLP system designed for position-based service applications was developed in [62, 63]. The proposed system employed BPSK to modulate the visible light emitted from four LED panels. After obtaining the TDOA information, the nonlinear least square algorithm is used to obtain the estimated position. The simulation results showed that the average error of this method is 0.14 m.

Do et al. proposed an indoor VLP system utilizing TDOA in [64, 65]. The system contains a PD that can receive the signals transmitted by multiple LED base stations with known locations. Signals transmitted by different LEDs were distinguished by using time division multiplexing. A pilot signal without conveying any information was transmitted from each LED to the PD. Hence, the ID of the received signal was unknown for the PD. To solve the problem of anonymous pilot signals, the proposed system utilized a peculiar guessing mechanism to identify the ID of each signal, and then the location of the moving device can be estimated. The results of the simulation demonstrated a mean error of 3 cm.

In [66], a method similar to the work of [64, 65] was introduced, which employed a sinusoidal pilot signal rather than a square pulse. The rising and falling times of the LED were taken into consideration by the conducted simulation. The simulation result reported a mean error distance of 68.2 cm.

(5) Hybrid Algorithm. The author in [67] utilized the two stages of RSS and AOA to calculate the position of the moving device in the indoor environment. In the first stage, the maximum possible RSS value is used to determine the coarse location of the moving device. In the second stage, when the actual position of the PD is below the LED, the ratio of the actual received power that the PD should receive to the theoretical power is used to estimate the angle between the transmitter and the receiver. The basis for calculating the above theoretical received power is established through the known parameters of PD and LED. Then, the fine location can be determined by quadratic programming using the distance from the LED to the PD obtained based on the estimated AOA. Simulation results showed that this method can achieve a positioning accuracy of 14 cm.

Nishikata et al. [68] proposed a tracking system utilizing dead reckoning and VLC, which was applied in the indoor environment. First, the location of the moving device was estimated by the use of VLC. Subsequently, a Kalman filter as well as the geomagnetic and gyrosensor output was used to perform the process of dead reckoning. A small robot with a movement speed of 0.6 m/s was employed in the implemented experiment, and the result reported that the localization and angular errors were 10.5 cm and 6°, respectively.

With a view of handling the indoor positioning problem of mobile robots on the basis of VLC, an integrated AOA-RSS positioning approach utilizing a PD array was proposed in [69]. It has been proved that the number of PDs installed on a moving robot made a difference to the performance of the presented integrated positioning approach. Aimed at achieving higher precision of the mobile robot's location, a combination of the abovementioned AOA-RSS positioning approach and Extended Kalman Filter (EKF) technique was proposed. Results of simulation demonstrated that the localization error would get smaller with the number of PDs increasing, and adding the EKF can remove accumulated errors and reduce the mean error.

In [70, 71], signals from the LED traffic light were received by using a linear PD array, which was mounted on a vehicle horizontally. For separating different LEDs spatially, the front of the PD array was equipped with a convex cylindrical lens. The location of the vehicle was estimated by using an extrinsic parameter calibration. As the linear PD array was capable of sensing LED spatial information with one dimension, there must be no less than four LEDs in the sight of the PD array for enabling localization. Ultimately, the location of the vehicle was tracked by putting the Extended Kalman Filter into use. The result of the experiments reported that the maximum error of distance was less than 0.2 m.

3.1.2. Customized LED Array. An indoor location detection method was proposed in [72], in which smart terminals and LED QR codes were utilized. The location detection method using smart terminals and LED QR codes is used as the research object as scores of people have increased the use of smart terminals and QR codes. A QR code was controlled utilizing LED by a control server in PC, which can periodically provide and update the position information of the LED QR board. Afterwards, the coordinates of the LED

Table 1: Evaluation criteria in terms of accuracy, cost, range, and complexity.

	1 (worst)	2	3	4	5 (best)
Accuracy (cm)	>100	100-50	50-25	10-25	<10
Cost	Very high	High	Medium	Low	Very low
Range (m)	<1	1-2	2-4	4-6	>6
Complexity	Very high	High	Medium	Low	Very low

QR are sent to the smart terminal to indicate indoor positioning information.

In [73, 74], two image sensors mounted in the mobile device were exploited to acquire the estimation of the distance from four LEDs, which form an array to the mobile device. On the basis of the four estimated distances, the moving device's position can be obtained utilizing the method of trilateration. The simulation results reported that the localization error can be minimized to a few centimeters by this system.

The authors of [75] utilized partially collimated light transmitted from multiple LEDs inside a luminary for indoor positioning. A simple optical element was utilized to offer angular diversity from multiple LEDs and create multiple regions separated spatially of overlapping light that can be addressed by a single detector receiver. The advantage of this system is that position information can be obtained even without relying on signal strength measurement. Low complexity and high positioning accuracy were achieved through a large number of unique detectable areas generated by multiple LEDs in each luminary. The experimental results showed that in an area of $5\,\mathrm{m} \times 5\,\mathrm{m} \times 3\,\mathrm{m}$, the average positioning error of using 4 LED lamps is 26 cm, and the average positioning error of using 9 LED lamps is 12.9 cm.

In [76], Wang et al. proposed an RSSR-based positioning technology that uses a Multidirectional LED Array (MDLA) to reduce the orientation influence of the PD. In addition, the Average Angle Acceptance Ratio (AAAR) and the Coverage Ratio (CR) are used to evaluate the orientation acceptance and location coverage of the positioning scheme. The simulation results showed that in the 3D and 2D positioning of the proposed positioning scheme, when the LED tilt angle is 15°, the Root Mean Square Error (RMSE) is 0.06 m and 0.04 m, respectively.

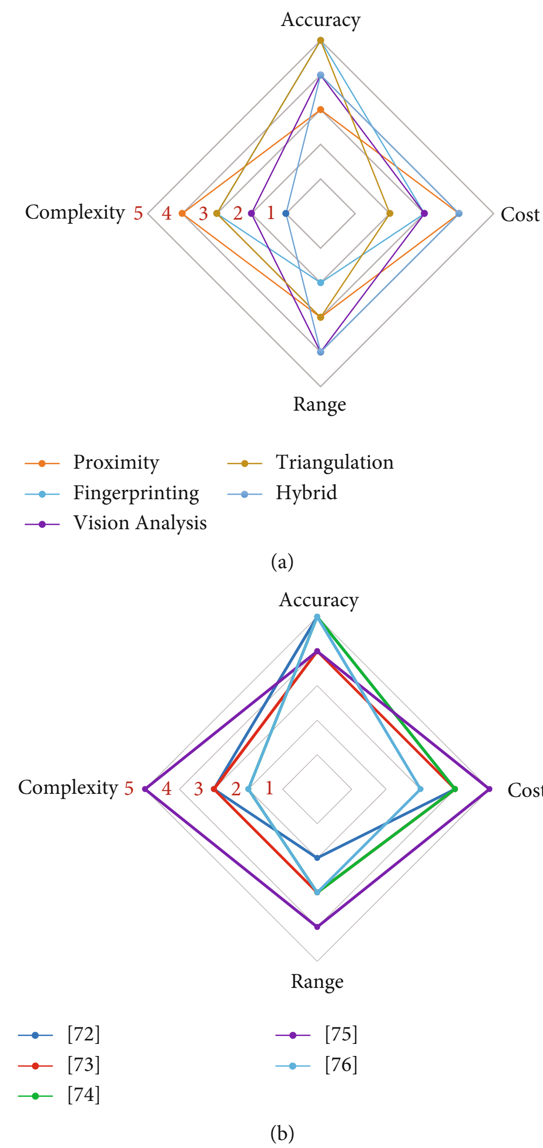

Figure 5: Performance comparison of customized methods. (a) Performance comparison of customized single LED methods. (b) Performance comparison of customized LED array methods.

3.1.3. Performance Comparison. In conclusion, although the methods which are mentioned previously share some common traits, there still exist certain differences in some ways, such as accuracy, as well as other details (e.g., cost, range, and complexity). Table 1 gives the corresponding evaluation criterion, which is segmented into five levels. As illustrated in Figures 5(a) and 5(b), the star chart contains four directional axes indicating the four classification criteria. And for each criterion, there exist five diverse circular tiers, such as Levels 1-5 in Table 1. The highest value of the outermost layer is 5, and the lowest value of the innermost layer is 1. A higher value means better performance and vice versa.

Accuracy is the paramount factor in evaluating the performance of a positioning system, which can reflect the closeness degree between the estimation from a localization method and the physical location of the target. The average distance error is usually utilized to determine the positional accuracy. The development and improvement of positioning systems have continued for decades. The localization accuracy has been dramatically improved, which can be confirmed by the measurement unit for positional accuracy changing from kilometers to meters. Besides, even a few centimeters of the distance error can also be achieved by the latest and finest localization systems. As a consequence, the best localization precision is set to less than 10 cm and the worst is set to more than 100 cm in this paper.

The evaluation of cost-effectiveness is made based on four costs of expenses mentioned before like infrastructure, hardware, maintenance, and installation expenses. The figures can be divided into five levels, as shown in Table 1. For those customized light hardware-based positioning methods, the specialized hardware is the essential concern while assessing cost.

The range represents the distance between the receiver and the transmitter, which determines how far a receiver can be from a transmitter. We make an analysis of the possible cover range of different localization techniques. The deviation of measuring distances can be mainly from less than 1 m to larger than 6 m due to the restriction of infrastructure or signals.

Complexity is measured by how many resources and how much time are required to fulfill the positioning for a localization approach. We evaluate the complexity of each localization technique relying on the approximate time consumption and resource consumption. A positioning system with excellent performance might have very low complexity. The criteria of complexity can be divided into five levels, as demonstrated in Table 1.

3.2. Unmodified Light Hardware. Contrary to the characteristics of customized light hardware-based localization mentioned in Section 3.1, the biggest feature of unmodified light hardware-based localization is that the inherent properties of the LED are used for VLP systems without modifying the original lighting equipment or lighting circuit. This means that the unmodified light hardware does not need to consider the deployment cost and the cost of modifying the lighting circuit. At the same time, the customized light hardware also involves the issue of universality; that is, it may not be deployed on a large scale in a special environment. However, the unmodified light hardware can ignore the above problem, which is also one of its main advantages compared to the customized light hardware. Similarly, the shortcomings of unmodified light hardware are also very obvious; that is, since the inherent characteristics of LED lamps are very difficult to extract and analyze, the difficulty of utilizing the unmodified light hardware for positioning has increased sharply. Therefore, only a few methods for positioning using unmodified light hardware have been proposed and introduced in this section.

3.2.1. Triangulation. We introduce the VLP system based on the unmodified LED hardware utilizing the triangulation algorithm in this subsection. It should be noted that since we have introduced the principle of using the triangulation algorithm for indoor VLP in detail before, we will omit unnecessary details about the triangulation algorithm here. Instead, we directly introduce some VLP systems that use triangulation algorithms based on unmodified light hardware. The authors of [77] proposed an algorithm that can achieve high-precision VLP using only LEDs, without relying on any additional infrastructure. The main idea is to assign a unique frequency address for the light emitted by each LED lamp, and then the TDOA algorithm based on the phase difference is used. The experimental results showed that this method can achieve a positioning error of 1 cm when the indoor space is 5 m × 5 m × 3 m.

In [78], Zhang and Zhang proposed to identify multiple LED lights by using PDs embedded in mobile devices by using the inherent light radiation characteristics of LED lights, which is named Pulsar. At the same time, a novel sparse photogrammetry mechanism is designed to make up for the lack of spatial resolution of PDs. This method can triangulate the 3D position of the moving device and even the direction of the moving device and resolve the Angle of Arrival of the light source. Considering the widespread deployment of LED lights, this paper also proposed a light registration mechanism to automatically register the location of LED lights as landmarks. The experimental results showed that this system can simultaneously achieve decimeter-level positioning accuracy and controlled circumstance for large buildings.

3.2.2. Vision Analysis. Vision analysis based on unmodified light hardware is also used for VLP in some papers. The authors of [79] designed a positioning system called LiTell. It uses unmodified fluorescent lamps as positioning landmarks and then uses the camera of the smartphone as the photoelectric sensor for personnel positioning. The principle of LiTell is that each fluorescent lamp has its own characteristic frequency, which is also the intrinsic property of fluorescent lamps. By combining signal amplification, a cluster of sampling and camera optimization mechanisms enables smartphones to capture extremely weak- and high-frequency characteristics. The experimental results reported that LiTell can achieve submeter positioning accuracy in the indoor environment.

The authors of [80] proposed a system for high-precision and dependable positioning by tapping the potential visual features of ordinary LED lights and fluorescent lights, called iLAMP. The main idea of iLAMP is that the front camera of the smartphone can capture some of the inherent features of the LED lights that are invisible to the human eye and extract these potential features by processing the captured image frames. In addition, the authors also designed a model for determining the 3D position of the smartphone (i.e., the camera of the smartphone) and estimating the direction of the user's next moment, which is realized by combining the image taken by the camera with the output of the accelerometer. The authors have conducted intensive experiments, and the experimental results showed that the average accuracy of the system is 3.5 cm (2.8°) and 3 cm (2.6°) in the 90th percentile of the cases.

3.2.3. Performance Comparison. In this section, we compare and analyze the performance of the abovementioned different positioning methods based on unmodified light hardware. Figure 6 shows a quick and concise view of the performance of each localization method for the reader to

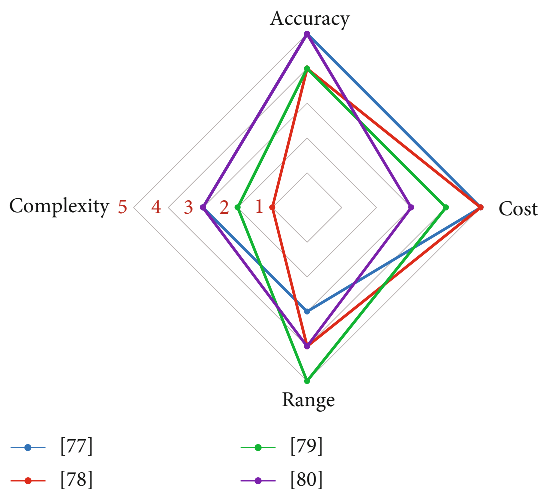

Figure 6: Performance comparison of unmodified hardware methods.

better understand. As shown in Figure 6, a simple and easy-to-understand diagram is drawn to visually display the performance of each positioning method. The criteria applied remain unchanged as the ones for the comparison of customized light hardware-based localization techniques, in conformity to accuracy, cost, range, and complexity. In general, each positioning method based on unmodified light hardware has its own application scenarios and scope; hence, they have their own strengths in different execution performances. We cannot simply evaluate which positioning method is good or bad, but we can choose the most suitable positioning mechanism based on the characteristics of different methods.

3.3. Summary of Research Studies in Software Algorithms. The localization algorithms reviewed in this paper are summarized as shown in Table 2. Regarding the accuracy of positioning, some researchers have not verified the accuracy of their work, but some researchers have demonstrated the accuracy of their work through experiments or simulations. Simulation experiments are mostly carried out by setting various parameters or environment simulations according to the experimental requirements. For actual research, the experimental results obtained by different test environments may also be different. For instance, testing environments of some experiments may be large regions of hundreds of m^2 while others may be small boxes measuring less than 1 m^3. Hence, the performance of the abovementioned algorithms demonstrated in Figure 6 should not be compared based solely on the reported accuracy.

4. Hardware Structure of VLP Systems

In this section, we introduce the hardware of the VLP system in the order of transmitter, modem, and receiver. Since the hardware of most VLP systems includes the above three parts, the same article may be mentioned in different subsections, but their emphasis is different.

4.1. Transmitter. Different transmitters can be selected according to the special designs of VLP systems. Since illumination is still the main role in real life, most of the VLP articles utilize white LEDs as the transmitter, which are not only cheap and energy saving but also have a good modulation performance. In addition to white LEDs, there are also some articles that utilize special transmitters for positioning, and the details are as follows.

Fluorescent Light Communication (FLC) is widely used in indoor guidance systems, which utilizes fluorescent lamps instead of LEDs as the transmitter. In [81], an indoor self-localization system was proposed using FLC. It uses fluorescent lights instead of LEDs as the transmitter to send the light signals with position information and a photosensor on the user's shoulder as the receiver to obtain the emitted light signals; then, the system broadcasts the information to the user through the PDA for the blind. Similarly, the fluorescent lamps were also used in [82–84] to achieve the indoor guidance systems by different positioning algorithms.

Near-Infrared light is an electromagnetic wave with a wavelength between visible light and mid-infrared light, which is invisible and does not cause harm to humans. The authors of [85] designed a wearable eye tracker glasses and proposed a two-dimensional pupil positioning method based on the effect of the pupil's light absorption. This kind of glasses utilizes a few Near-Infrared (NIR) lights as the transmitting end and some photodiodes around the eye as the receiving end. When the fixed NIR light hits the eyeball, the light reflected by the eyeball is sensed by the photodiodes around the eye, and the movement of the pupil will cause changes in the reflected light. Experiments showed that the positioning accuracy of this method can reach the submillimeter level; the accuracy achieved was an average distance error of 0.8 mm in tracking the pupil's 2D position.

In [86], an indoor positioning system called SpinLight was presented. A hemisphere-shaped model was divided into N rings, and each ring was further divided into M cells; each cell was used as a point light source. The "light on" represents 1, and the "light off" represents 0. When the hemisphere-shaped model rotates, the light sensors will get a specific sequence consisting of the on and off information of the cells, then infer the location information. To avoid the visual disturbance to human eyes caused by the rotation of the hemisphere-shaped model, SpinLight also chose infrared light as the transmitter.

However, some VLP systems do not need a specific transmitter and even natural light can meet the positioning requirements. The authors of [87] introduced an indoor positioning system that utilizes the polarizers and birefringent materials to generate specific interference and spectrum in different directions for positioning. Because it does not actively modulate the light, this method does not require a specific emitter.

4.2. Modem. The modem is the general term for the modulator and demodulator. In a VLP system, the function of the modulator is to encode position information in the light, and the demodulator demodulates the received optical signals to obtain the position information. Considering that

Table 2: Summary of different localization algorithms.

Transmitter		Algorithm	Reference	Receiver	Accuracy	Application environment
Customized light hardware	Customized single LED	Proximity	[29]	PD	1-2 m	2D
			[30]	PD+6-axis sensor	30-60 cm	2D
			[31, 32]	PD		2D
		Fingerprinting	[33]	PD	4.5 m	2D
			[34]	PD	15-20 cm	2D
			[35]	PD	20-80 cm	2D
			[36, 37]	PD array	4-13 cm	2D
			[38]	PD	4.4-12.5 cm	2D
			[39, 40]	PD	1.58 cm	2D
		Vision	[42]	Camera	10 cm	2D
			[43]	2 cameras	85 cm	3D
			[44]	Camera	10 cm	3D
			[45]	Camera+accelerometer	5 cm	3D
			[46]	Camera	30 cm	2D
		Triangulation	[47]	PD array	5 cm	3D
			[48]	PD array	5-30 cm	2D
			[49, 50]	PD+accelerometer	25 cm	3D
			[51]	PD array+accelerometer	6 cm	3D
			[52]	PD	8cm	3D
			[53]	PD	1.5 cm	2D
			[54]	PD	0.3-0.7 m	2D
			[55]	PD	0.4 m	2D
			[56–58]	PD	1.7-3.9 cm	2D, 3D, 2D
			[59, 60]	PD	11-17 cm	2D
			[61]	PD	2-6 cm	2D
			[62, 63]	PD	14 cm	2D
			[64, 65]	PD	3 cm	2D
		Hybrid	[66]	PD	68.2 cm	2D
			[67]	PD	14 cm	3D
			[68]		10.5 cm	2D
			[69]	PD array	20 cm	2D
			[70, 71]	Camera	0.2 m	3D
	Customized LED array	LED QR code	[72]	Camera		2D
		Vision	[73, 74]	2 cameras	1.5 m	3D
		Proximity	[75]	PD	12.9 cm	2D
		Triangulation	[76]	PD	4-6 cm	2D & 3D
Unmodified light hardware		Triangulation	[77]	PD	1 cm	3D
			[78]	PD array	Decimeter level	3D
		Vision	[79]	Camera		2D
			[80]	Camera+accelerometer	3-3.5 cm	3D

the modulation methods in the existing technology are quite different, for the sake of clarity, we divide the modulation methods of these VLP systems into two categories: active modulation and passive modulation. Active modulation refers to the use of electronic devices to modulate the circuit so that the transmitter actively sends modulated light with specific position information, modulation mainly by changing the transmitter's emission mechanism. Passive modulation refers to the modulation of the light emitted by the transmitter based on some optical properties such as refraction and reflection of light. These systems usually need special optical devices and use optical characteristics to obtain position information. Therefore, we further classify the modem into electronic devices and optical devices according to the modulation types.

4.2.1. Electronic Device. Many VLP systems use electronic devices with modulation functions to modulate the circuit with different modulation schemes, such as OOK, Pulse Position Modulation (PPM), and OFDM. Then, the transmitter is driven to broadcast the optical signals carrying the position information through the free space channel. The electronic devices of VLP systems mainly refer to the embedded development electronic devices such as the Digital Signal Processor (DSP) and Field Programmable Gate Array (FPGA). Since these electronic devices are widely used in VLP systems, so we just make an introduction about their advantages and disadvantages briefly.

DSP is a specialized microprocessor aimed at processing large amounts of information with digital signals. It can be used to quickly implement various digital signal processing algorithms such as digital filtering and signal extraction.

FPGA is a special integrated programmable circuit including a large number of logic gates and triggers. It has lots of advantages, including large scale, high integration, fast processing speed, and high execution efficiency. It can complete complex sequential logic design and programming. When the sampling rate or data transmission rate is particularly high, the performance of FPGA is higher than DSP. FPGA can execute concurrently between different logic functions and has strong scalability.

4.2.2. Optical Device. In addition to the electronic devices, there are also some articles that make clever use of optical characteristics to locate corresponding optical devices. Although some articles may not point out the specific optical devices, they all utilize optical characteristics such as reflection and refraction that can be achieved with common materials, even the floor. Therefore, we also regard the optical devices in these articles as modems.

As showed by the authors of [88], the convex lens was cleverly used as the modulator to change the propagation path of lights emitted by a single LED lamp according to the light splitting properties of a convex lens. The light emitted by each LED is identified by its own frequency; then, a one-to-one mapping between the position of each photodiode and a series of light signals received at each position was created. Each photodiode can perceive mixed light signals in different circular areas in the LED lamp and determine its position by the one-to-one mapping created before. Finally, the experiments proved that the positioning is achieved with an average accuracy of 10 cm and a 90-percentile error within 50 cm, which indicates that this method has high positioning accuracy.

Similarly, the authors of [75] also proposed a method of using the lens for positioning by placing a convex lens behind a group of LEDs with a specific frequency for each LED and using a photodiode as the receiver for positioning. Different from [88], this method exploits the different intersecting illumination areas behind the converging lens while SmartLight in [88] uses the circular area composed of different LEDs in front of the lens. The mixed light signals received by the photodiode is used to determine the different circular areas according to which frequencies are perceived. The experiments showed that the average error using 9 LED lights is 26 cm lower than SmartLight.

Li et al. [87] presented a simple and innovative approach for indoor positioning that exploits the birefringence and interference properties of light, using two polarizers with the same polarization direction and a birefringence material such as plastic to form an anchor as the modulator. When light passes through the anchor, the specific interference and light spectrum will occur in different directions. The positioning accuracy of this method is higher; the error in the 2D case is between 2 and 3 cm, and the error in the 3D case is 9.6 cm in the daytime and 20.5 cm when the light is on at night.

In [89], a VLP system named STARLIT was proposed utilizing the light reflection property. The floor is utilized as the reflective surface, and the light signal with the ID tag emitted by the LEDs on the ceiling is reflected to the smartphone and then through the rolling shutter mechanism in the smartphone cameras for location via RSS. The experimental measurements reported that it can achieve an average error of 23 cm and an 80-percentile error within 55 cm.

The authors of [90] proposed an indoor positioning system based on multipath reflections. This technology exploits the diffuse reflection phenomenon generated when light hits some special materials by calculating the impulse response time of different diffuse reflection components to the receiver of the uplink channel for positioning. We think of all the indoor objects that can produce diffuse reflections as modems. The positioning accuracy of this technology is 25 cm when there is one photodiode, and the positioning accuracy can be improved to 5 cm in the case of four photodiodes.

4.3. Receiver. A receiver in a VLP system refers to the photodetector that can convert light signals into electrical signals. The currently popular receivers of VLP systems mainly include two types: photodiodes and image sensors. Figure 7 illustrates the principle of the photodetector. When the light hits the depletion layer of the photodetector, the low-energy state electrons jump to the high-energy state after absorbing the light energy, thus forming the photogenic electron-hole pairs. Under the action of the internal electric field, the electrons flow to the N region and the holes flow to the P region, thereby realizing the conversion of light signals to electrical signals. Generally speaking, the VLP system using the photodiode as the receiver is the passive positioning. It can obtain the position information carried in the light signals only when the photodiode senses light to determine if the user has reached a certain location. However, the VLP system using the image sensor as the receiver is mostly active positioning. The image sensor actively distinguishes where the user has come through a series of images. In Figure 6, we have already classified articles by using the photodiode or image sensor as the receiver. Next, we will introduce the photodiode and image sensor, respectively.

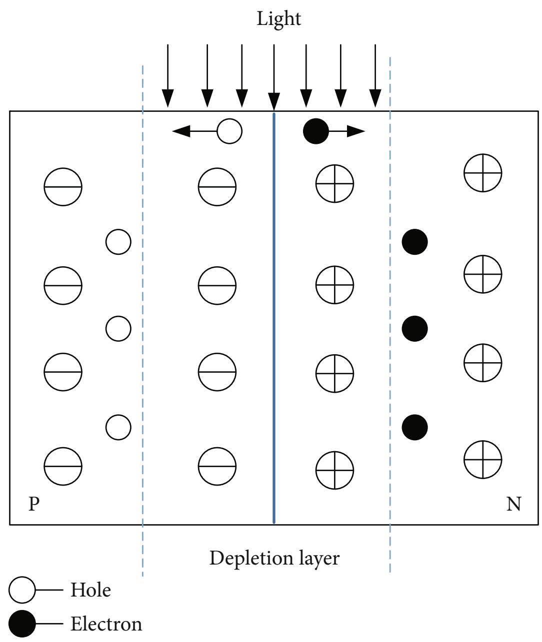

FIGURE 7: Photoelectric detection principle.

4.3.1. Photodiode. In the VLP system, there are always strong background noise and interference of the inherent noise of the circuit. Thus, the receiver with low noise is of great significance. As the typical photodetector, the photodiode has the advantages of low price, high accuracy, and low noise, as well as the characteristics of high reception bandwidth and smaller size. By converting light signals into electrical signals, the photodiode can not only detect light intensity and separate light signals of different frequencies but also determine the arrival time of optical signals due to its high response characteristics. Therefore, they are widely used in the current VLP systems, especially in the articles that use proximity, fingerprinting, or triangulation as positioning algorithms.

4.3.2. Image Sensor. The principle of positioning using the image sensor as the receiver is to analyze the presence or absence of the specific LEDs by analyzing a series of captured images. Compared with the photodiode, the image sensor can directly separate the light and it is less affected by external light. However, due to the limitation of the image acquisition rate, the sampling rate of the image sensor is much lower than the photodiode. Thereby, many articles exploit the rolling shutter effect in CMOS image sensors for positioning. It is widely used in the cameras of electronic devices such as smartphones; it can receive many bits of data encoded in the optical transmissions and only requires one frame capture.

4.4. Discussion of Different Hardware Components. Table 3 summarizes the different hardware components of the VLP system. We have classified and summarized all the references in this section and evaluated the cost and characteristics of different hardware components. Since the cost of different hardware is different and different models of the same hardware on the market are also very different, so we do not show the specific cost of the hardware. Instead, we used three evaluation levels for different hardware, namely, high, medium, and low, to indicate their cost. In terms of features, we highlight the reasons why the references choose different hardware, i.e., the characteristics of each hardware component. In terms of accuracy, since the accuracy of the VLP system is greatly affected by different algorithms, we cannot simply match the selected hardware to its accuracy.

5. Open Issues and Future Directions

In this section, we introduce the hot issues of the VLP system and the future direction needs to do on each issue. Five hot issues are given, and the future direction on each issue is given at the end of each subsection.

5.1. Outdoor Positioning Using VLP Technology. The use of VLP technology for outdoor positioning is a very attractive and very difficult problem, especially in the deployment of PDs in outdoor environments. First, it is very difficult to deploy PDs outdoors, and environmental factors have a greater impact on them. Second, a large number of PDs are often required for collaboration, which increases cost and operational complexity.

Future direction. In the future direction, it is likely for utilizing a camera to become a possible method in outdoor localization and to be a research focus in the short run. The development of ubiquitous surveillance camera equipment and smartphones has promoted the use of cameras for outdoor positioning. In addition, since high-power headlights and taillights are essential equipment for every vehicle, vehicle-to-vehicle positioning based on VLP and cameras is also worth studying.

5.2. Tracking and Navigation Using VLP Technology. Since the coverage range of each visible light base station is very limited, most VLP systems can only provide discrete position information and thus lack the ability to navigate and cannot provide real-time navigation or tracking for moving targets.

Future direction. Hence, in the future direction, adding the tracking capability to current localization systems is a fundamental open issue. Tracking capabilities can be applied to many scenarios, such as factory robot tracking and underground drone tracking. In addition to tracking, navigation is also one of the future directions that need to be focused on. In recent years, the development of the VLP system has also provided new ideas for blind navigation, indoor navigation of drones, cars, and robots.

5.3. Combination of Localization and Communication. A system that can provide both localization and communication functions would be requisite all the time. At the same time, ingenious designs of frame constructions might be demanded by such a system. For instance, the frame headers may be used for localization function in one way or another. Besides, another problem related to modulation also exists in such a system. Since the communication demands a high data rate, which might lead to the suffering of the visible light signal caused by intersymbol interference issue, the accuracy of localization would be influenced with great possibility.

Table 3: Summary of different hardware components.

Hardware components		Reference	Cost	Characteristics
Transmitter	White LED	[71]	Low	Cheap and widely used
	FLC	[71–74]	Medium	Cheap and green
	NIR	[75, 76]	High	Invisible to the human eye
	Natural light	[77]	No cost	No consumption and cost
Modem	Electronic device	[76]	High	Modulate the optical signal
	Convex lens	[78, 79]	Medium	Converging light
	Polarizer	[77]	Low	Generate polarized light
	Interference	[80]	—	Change the light path
	Reflection	[80, 81]	—	To reflect light
Receiver	Photodiodes	[75, 76, 78, 79]	Low	Low price and high efficiency
	Image sensor	[71–74, 77, 80, 81]	High	Widely deployed and easy to use

Future direction. So in the future direction, as the vast majority of existing localization systems were developed only for the purpose of localization, it would be necessary to realize the combination of localization and communication in a system.

5.4. Independence of the VLP System. Although high-precision localization methods are the most disquisitive aspect in many literary works, the proximity algorithm may be the one that possesses great potential in the thriving position-based service. The requirement of support from ZigBee, WiFi, or other Wireless Sensor Networks (WSNs) (e.g., [91–94]) for fulfilling the localization operation is the main restriction of current VLC-based proximity systems. For instance, after receiving the signal information, such as the ID of visible light, mobile devices require to transmit the ID to the external center for obtaining the location information.

Future direction. In the future direction, it will be satisfactory to develop a proximity system based on VLC which does not rely on RF wireless networks. The main reason lies in the following two aspects. For one thing, cost saving is one of the key factors to be considered in the future. For another, since light cannot pass through walls, safety is one of the main advantages of the VLP system, but the security of the VLP system cannot be guaranteed when relying on the RF wireless networks. Therefore, it is very meaningful to develop VLC-based proximity systems that do not rely on RF wireless networks in the future.

5.5. Application of Smartphones and Cameras. Nowadays, the camera function and processing capacity of smartphones have developed rapidly. Due to the tens of megapixels, the resolution of the current smartphone camera is definitely not a problem and is far enough to offer precision location. In addition, it seems that frame rates are also not a problem since most of the current smartphones can achieve a frame frequency of 240 fps. Nowadays, it is far more than enough for the processing capacity of smartphones to be qualified for the processing of any complex localization algorithm. Peculiarly, the image sensors and accurate inertial sensors are requisite equipment for each smartphone, which is favorable for offering accurate information of localization. Nevertheless, there exist few studies utilizing smartphones for localization based on VLC.

Future direction. The vast majority of image sensors containing those on smartphones as well as user cameras are CMOS sensors that employ the rolling shutter mechanism. While the data rate can be improved by using the rolling shutter mechanism, motion artifacts that may alter the location of LEDs in the image and therefore result in the degradation of localization accuracy are caused by the use of that mechanism in the meantime [95]. Existing VLP methods utilizing cameras all neglect this motion artifact. In the future direction, it would be another study aspect for VLC-based positioning utilizing the camera to seek mechanisms that can eliminate the adverse effect of CMOS sensors.

6. Conclusion

Due to the advantages of green environmental protection, energy saving, long lifetimes, high controllability, and ruggedness, LED lights are considered to be the illumination equipment of the 21st century. The advantages of LED light and visible light have promoted the development of VLC technology, which may make VLC the next generation of wireless communication technology. At the same time, the ubiquitous deployment of LED lights and the development of VLC technology also provide a great convenience for the popularization of VLP technology and demonstrate the great potential of VLP in the future IoT technology. In the future, the VLP system will provide wider coverage of localized services along with the continuous deployment of LED lights. And the research report shows that VLC-based positioning can achieve high-precision positioning. These prospects have attracted many researchers to develop new positioning systems based on VLC. An intensive overview of the VLP literature from both software algorithms and hardware perspectives is presented in this paper, in which a novel-innovative classification method is used in the software algorithms and the hardware is divided into three parts. This paper not only gathers and analyzes a large number of excellent papers using VLP methods for positioning but also evaluates the above articles based on different evaluation indicators we give. Finally, the current open issues and trends regarding VLP technology are also provided.

Data Availability

The data used to support this work are available from the corresponding author upon request.

Conflicts of Interest

We declare that we have no conflicts of interest.

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