Hindawi
Wireless Communications and Mobile Computing
Volume 2021, Article ID 1730655, 10 pages
https://doi.org/10.1155/2021/1730655

Review Article

Indoor Visible Light Applications for Communication, Positioning, and Security

Xiangyu Liu ,[1] Lei Guo,[2] and Xuetao Wei [1]

[1] *College of Engineering, Southern University of Science and Technology, Shenzhen 518055, China*
[2] *School of Communication and Information Engineering, Chongqing University of Posts and Telecommunications, Chongqing 400065, China*

Correspondence should be addressed to Xuetao Wei; weixt@sustech.edu.cn

Received 2 June 2021; Accepted 30 July 2021; Published 10 August 2021

Academic Editor: Petros Nicopolitidis

With the rapid development of smart cities, white light-emitting diodes (LEDs) are widely used in indoor lighting due to their characteristics of energy-saving, long lifetimes, and low cost. At the same time, the high-frequency modulated LEDs allow visible light to be used for indoor communications, positioning, and security. Visible light applications have many advantages, such as avoiding electromagnetic interference, high communication speed, great privacy, and high-precise positioning. In this paper, we will survey the application prospects and research results of visible light from scenarios such as high-speed communication, privacy security, and navigation localization and focus on analyzing and discussing the challenges and development trends encountered in visible light positioning.

1. Introduction

The rapid development of light-emitting diodes (LEDs) has laid an excellent hardware foundation for wireless optical communication [1, 2]. Visible light communication (VLC) technology based on light-emitting diodes not only meets daily lighting needs but also enables high-speed communication applications [3, 4]. Visible light communication has the advantages of anti-interference, good confidentiality, and abundant frequency band resources. This provides strong support for the realization of indoor visible light positioning (VLP) [5, 6] and visible light security (VLS) [7, 8]. Compared with other indoor wireless technologies, visible light applications have the following advantages:

(1) "Green" technology: when the LED transmits the data, the energy consumption of the LED is about 100 mW. The energy efficiency is high.

(2) Anti-interference: the LED does not cause electromagnetic or radio interference.

(3) Long life: LED can maintain reliable lighting for up to 10 years.

(4) High cost-effectiveness: for visible light application systems, the cost of LEDs and photodetectors is less than $1. The system cost is low.

(5) Security: visible light cannot penetrate the building wall, and the signals in adjacent units will not interfere with each other, and the confidentiality is good.

With the development of science and technology, people's demand for location information is increasing. Currently, a lot of effort is being made to commercialize the research effort conducted for visible light applications over the past decade [9]. Positioning technology is an important branch of visible light applications.

Positioning technology can be traced back to early ocean navigation. For example, the maritime compass has been used for long-distance navigation for thousands of years. Modern positioning technology almost uses electronic signals from satellites or base stations to determine the object's location information [10]. In recent decades, location-based service (LBS) technology has become a part of people's lives. Location applications can provide users with their current location information and intelligent navigation services, which are greatly significant in real-life scenarios [11]. The global positioning system (GPS) is the world's most crucial positioning technology. However, the GPS works poorly or inaccurately in indoor spaces [12]. The building's wall and ceiling block the GPS signal transmission.

Therefore, many scholars have proposed a variety of indoor positioning technologies, such as WiFi [13], radio frequency identification (RFID) [14], ZigBee [15], Bluetooth [16], ultra-wideband (UWB) [17], ultrasound [18], infrared [19], and various technologies [20, 21]. Those technologies can achieve indoor positioning at the centimeter to meter level. However, they face the following problems:

(1) Wireless positioning technology is susceptible to electromagnetic interference. The indoor complex wireless environment may cause the frequency band to overlap, and technologies such as WiFi, RFID, and UWB are prone to mutual interference

(2) There is a balance problem between positioning accuracy and positioning cost. When infrared and ultrasonic technologies are used for positioning, the positioning system can achieve centimeter-level accuracy. However, a large number of professional transmitters and receivers require high deployment costs

These problems limit the broad application of the aforementioned indoor positioning technology. More and more researchers are exploring better indoor positioning technology.

It is foreseeable that the novel visible light positioning technology has great potential in the field of positioning, which will encourage academia and industry to conduct in-depth research [22, 23]. Table 1 compares various indoor positioning technologies. From Table 1, we can see that visible light positioning technology and radio frequency positioning technology are almost the same in terms of cost and power consumption, but the positioning accuracy is 2-20 times that of radio frequency technology. Similarly, the visible light positioning technology is almost the same as the ultrasonic and ultra-wideband technology in terms of positioning accuracy, but the cost of the visible light positioning technology is lower. In summary, the visible light positioning technology has the advantages of high accuracy, low deployment cost, and extensive application scenarios. The LED-based visible light positioning technology can satisfy the system's balance between positioning accuracy and deployment cost.

In this paper, we first introduce visible light communication in Section 2. Then, we illustrate visible light positioning and visible light security in Sections 3 and 4. In Section 5, we give classic visible light applications. We look forward to and conclude the indoor visible light applications for communications, positioning, and security in Sections 5 and 6.

Table 1: Indoor positioning technology comparison.

System	Accuracy (m)	Deployment	Cost	Power consumption
WiFi	1-5	Medium	Medium	High
ZigBee	1-10	Low	Medium	Low
Bluetooth	1-5	High	Low	Low
Ultrasound	0.01-1	Low	Medium	Low
Infra-red	0.1-2	Low	Medium	Low
UWB	0.01-1	Low	Medium	Low
RFID	1-2	Medium	Low	Low
Visible	0.05-1	Low	Low	Low

2. Visible Light Communication

With the booming development of LEDs in the lighting field, LEDs have aroused extensive research interest among scholars in smart indoor lighting, communication, and positioning aspects, due to the characteristic of low energy consumption, green protection, rich spectrum resources, and ubiquity. Visible light communication is a disruptive technology based on LEDs that offers a free spectrum and high data rate, which can potentially serve as a complementary technology to the current radio frequency standards. Researchers from many countries have conducted detailed research on visible light communication technology.

Japan is the pioneer in the field of visible light communication technology. In 2002, scholars from Keio University proposed the idea of using indoor white LEDs for communication and building an access network [24]. Then, Keio University established the Visible Light Communication Consortium (VLCC) with NEC, Matsushita Electric, Toshiba, Casio, Sony, and South Korea's Samsung Group and other well-known electronics companies [25].

In the visible light communication system, the LED at the transmitter can be switched between the "on" and "off" state at the high frequency through the microcontroller. The "on" and "off" switch state encodes transmitted data into visible light, and high-frequency switches make the human eye unable to perceive the change in brightness. The application of visible light communication realizes not only high-speed communication but also meets normal indoor lighting [26, 27].

At present, visible light communication has the Gbps-level data transmission capability in experimental tests, and the 96 Mbps transmission standard is defined in the IEEE 802.15.7 standard [28, 29]. Visible light communication can be widely used in indoor high-speed internet access, military security communication, underwater communication, and other scenarios [30, 31].

In this paper, we focus on visible light positioning technology, which is the important application branch of visible light communication.

3. Visible Light Positioning

In this section, we introduce the visible light positioning principle and application.

3.1. Visible Light Positioning Architecture. Visible light positioning is a promising solution for its reuse of lighting system and decimeter accuracy. In environments such as indoor offices, supermarkets, and corridors, the visible light positioning system model is a cube-shaped space, as shown in Figure 1. In the model, several LEDs (transmitter) are deployed on the ceiling as basic lighting facilities; photodiodes or cameras (light-sensing devices) are placed at a height h above the ground as the receiver.

The transmitter uses the Cartesian coordinate system to establish world coordinates in the room. Each LED has a uniquely identified world coordinate. Similarly, each LED transmits uniquely identified landmark information (modulated signals or LED light characteristics) in the free space optical channel.

The receiver uses the light-sensing device (camera or photodiode) to receive the landmark information transmitted by each LED. The system demodulates and decodes the LED and finds the world coordinate for each LED. Then, the receiver achieves the location information service by adopting a suitable positioning algorithm.

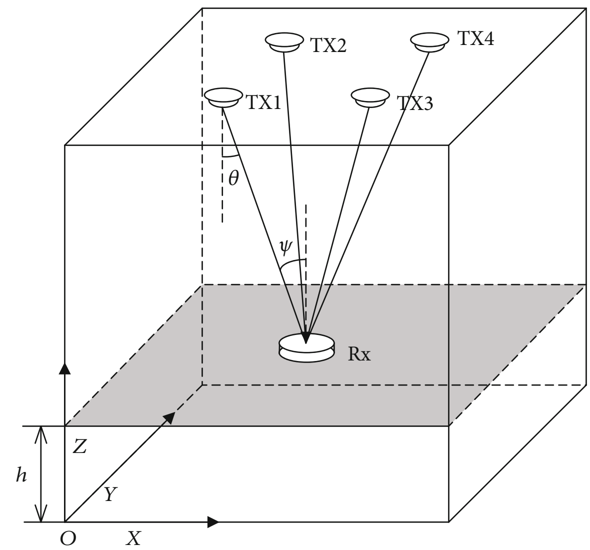

Figure 1: Visible light positioning system model.

3.2. Visible Light Positioning Implementation. We give the specific implementation principle of the visible light positioning system, as shown in Figure 2.

Step 1. When we build the visible light positioning system, the LED on the ceiling needs to transmit the landmark information. The landmark is the binary sequence transmitted by the microcontroller. The landmark forms the high-level and low-level voltage through the LED drive circuit and then transmits a light intensity signal through the fast on-off switch. Usually, the landmark information has more than 30 bits, which includes the following parts: (1) preamble—it is convenient for the receiver to receive the header of the data packet; (2) the transmitting sequence—it represents the world coordinate of the LED at the transmitter; (3) error correction code—it is used for information verification; and (4) the end of the packet. Many indoor positioning systems involve two or more LEDs in a room, which means that the receiver needs to receive the landmark information from multiple transmitters at the same time. When the positioning system uses the photodiode as the receiver, it needs to use multiplexing protocols, for example, frequency division multiplexing (FDM) [32], time division multiplexing (TDM) [33], and other protocols to avoid conflicts between different landmark signals.

Step 2. In the positioning process, in order to ensure the effective transmission of the landmark, the visible light channel is supposed to include a line of sight (LOS) path from the LED to the receiver. The LOS signal received by the receiver is stable, and the landmark recognition rate is high. For transmission over a non-line-of-sight (NLOS) path, the quality of the received landmark signal can seriously affect system performance. Gu et al. [23] placed some obstacles on the test bench to block the line-of-sight propagation path. The results show that the system positioning error is 14.8 cm under LOS propagation and 22 cm under NOS propagation. It illustrates that the NLOS path will affect the system positioning accuracy.

Step 3. The positioning system is to estimate the receiver location by positioning algorithms. When the receiver detects the landmark signal, the system measures the light characteristics, for example, received signal strength (RSS) [34], time of arrival (TOA) [35], or angle of arrival (AOA) [36]. Then, the positioning system inputs certain characteristics into the positioning module. Similar to other indoor positioning technologies, the receiver calculates the position of the object by combining the light characteristics with fingerprint library comparison, triangulation/trilateral measurement, or image processing algorithms [37, 38]. In addition, when the positioning system receives the landmark signal, the transmission channel has the light noise, the positioning system needs to take some filtering measures to decrease the impact of noise on the positioning accuracy, and the filtering methods include Kalman filtering and Particle filtering. The light characteristic and the positioning algorithm often used in the visible light positioning system are shown in Figure 3.

3.3. Visible Light Positioning Security

3.3.1. Navigation. Visible light positioning technology supports indoor navigation, for example, in large shopping malls, museums, underground parking garages, and other places. The applications (APPs) provided by smartphones can guide users to their destinations. In addition, visible light positioning systems can also be used in airports and railway stations, because these scenes are usually very crowded. With the help of the visible light positioning system, passengers can quickly make the correct route to the entrances and exits of the train/bus station, toilets, and shops [39, 40].

3.3.2. Tracking. Visible light positioning technology can be used to track objects such as people, devices, robots, and gestures in indoor environments. Visible light positioning

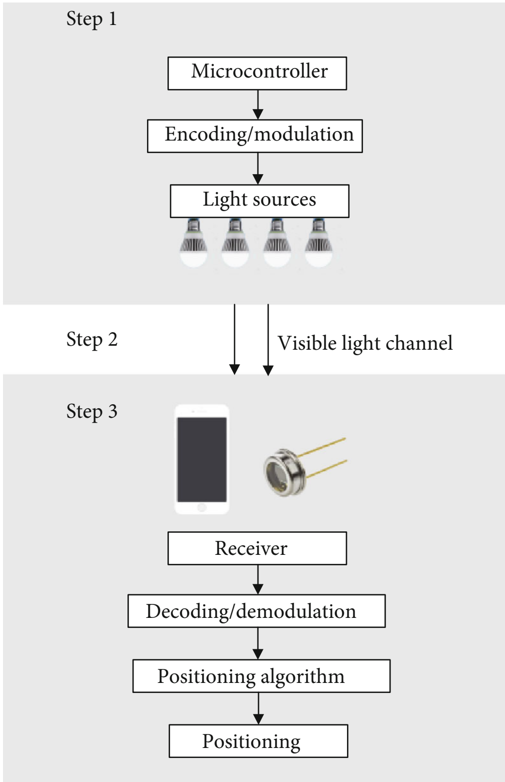

Figure 2: The implementation principle of the visible light positioning system.

systems can track luggage in real-time at airports and patients, medical wheelchairs, or any other medical device in healthcare institutions. In addition, the visible light positioning system can also be used for interactive human-computer interfaces, such as finger tracking through the virtual keyboard on the desktop or gesture recognition in the room [41, 42].

3.3.3. Security. Visible light positioning technology can provide passive indoor positioning services. This technology can be used to detect and track intruders in the indoor environment and provide security services. In traditional security systems, motion detection or video surveillance technology can passively track objects without any equipment, but it requires deployment costs and labor costs. Visible light positioning technology overcomes the above shortcomings and can provide free services with lower deployment costs and better privacy protection [43, 44].

4. Visible Light Applications for Positioning

As mentioned in recent surveys, there are different solutions for indoor visible light positioning technology. In this section, we provide the latest developments in visible light positioning systems. The visible light positioning system is usually divided into image processing (camera-based) positioning systems and signal processing (photodiode-based) positioning systems.

However, more and more scholars use unmodified light sources in positioning systems. Therefore, we adopt a new classification method to summarize the visible light positioning system, as shown in Table 2. The visible light positioning system is divided into modified LEDs, unmodified LEDs, and sensing and security.

4.1. Modified LEDs. Kuo et al. [45] proposed the Luxapose visible light positioning system, which used modified LEDs on the ceiling and smartphone to achieve the positioning. Each LED transmitted the unique on-off keying (OOK) signal as the landmark and communication information. At the receiver, the smartphone adjusted its exposure rate and sensitivity to remove the background interference of captured images and uploaded captured images to the cloud server. The cloud server performed image processing, including image binarization, edge extraction, and subimage segmentation to achieve landmark decoding. Finally, the Luxapose positioning system used the angle of arrival (AoA) and scale factor algorithm to achieve high-precision positioning.

Li et al. [46] proposed the Epsilon visible light positioning system, which used LEDs as anchor points and used the trilateration algorithm to locate light-sensing devices. The Epsilon positioning system adopted binary frequency shift keying (BFSK) and channel frequency hopping mechanisms to enable multiple uncoordinated light sources for reliable landmark transmission. When light sources captured by the receiver were insufficient, the system used the user participation information to solve the stability and accuracy problems. Experimental results showed that the Epsilon positioning system could achieve 1.1 m positioning accuracy under the single light source and 0.4 m~0.8 m positioning accuracy under multiple light sources.

Wang et al. [47] proposed the lightweight ALS-P visible light positioning system, which used the ambient light sensor (ALS) in the smartphone to detect the specific high-frequency signal transmitted by the LED at the transmitter. In the ALS-P positioning system, the sampling rate of the ambient light sensor was low, and the receiver applied the undersampling principle to mitigate the frequency aliasing effect. The smartphone sampled the input signal at two different sampling frequencies to distinguish more frequency information. Meanwhile, the transmitter needed to use the specific frequency to decrease the harmonic interference effect. In the decoding process, the ALS-P positioning system took two decoded frequencies as candidate frequencies and then checked the distance of the LEDs corresponding to the candidate frequencies under the world coordinate system. If the distance between two LEDs was less than the predefined threshold, the candidate frequencies were selected correctly. Next, the ALS-P positioning system used the trilateral positioning algorithm to achieve the positioning.

Liu et al. [48] proposed the DIMLOC visible light positioning system under smart LEDs. The system transmitter was composed of smart LEDs, which can emit dimmable light. During the positioning process, the captured images occurred the blurring effect due to the brightness change of the smart LEDs, which caused the receiver decoding failure.

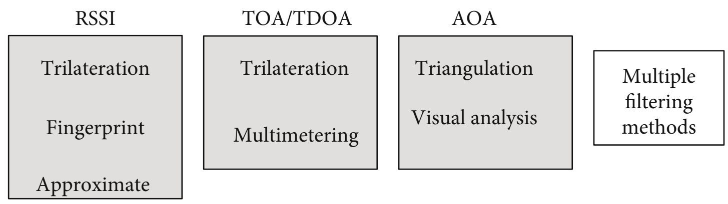

Figure 3: Positioning algorithms in visible light positioning systems.

Table 2: Classic visible light positioning systems comparison.

System name[1]	Modified lights	Using smartphone	Using photodiode	Passive system[2]	Characteristic method	Accuracy	Deployment[3]	Goal
Luxapose	Yes	Yes	No	No	Scale factor/AoA	40 cm	M	Positioning
Epsilon	No	Yes	No	Yes	RSS/trilateral	80 cm	L	Positioning
Okuli	Yes	No	Yes	No	Fingerprint/classification	7 cm	H	Tracking
LiSense	No	No	Yes	Yes	Reasoning algorithm	—	H	Sensing
PIXEL	No	Yes	No	Yes	AoA/LM algorithm	30 cm	H	Positioning
LiTell	No	Yes	No	Yes	Fingerprint/scale factor	25 cm	L	Positioning
CeilingSee	No	No	No	Yes	Fingerprint/machine learning	—	L	Occupancy
Pulsar	No	Yes	Yes	Yes	Sparse measurement	31 cm	M	Positioning
NaviLight	No	Yes	No	Yes	RSS/KNN	35 cm	L	Positioning
iLAMP	No	Yes	No	No	Sensor/scale factor	40 cm	M	Positioning
EyeLight	Yes	No	Yes	No	Fingerprint/difference algorithm	—	M	Occupancy
RETRO	No	No	Yes	No	RSS/trilateral	2 cm	H	Positioning
RainbowLight	No	Yes	No	Yes	Polarization/direction intersection	9.6 cm	L	Positioning
DIMLOC	Yes	Yes	No	No	Scale factor/AoA	8 cm	M	Positioning
FieldLight	No	No	Yes	Yes	Recursive algorithm	84 cm	H	Positioning
ALS-P	Yes	Yes	No	No	Undersampling/LM algorithm	25 cm	M	Positioning
PassiveVLP	No	No	Yes	Yes	Iterative derivation	5.3 cm	H	Positioning
LiTag	No	Yes	No	Yes	Color pattern/geometric	12 cm	L	Positioning

[1]The system is arranged in a chronological order. [2]Passive system means that the object does not carry any devices, including tags. [3]High, medium, and low are represented by H, M, and L, respectively.

To deal with the blurring effect, the DIMLOC positioning system performed the image processing, including second-order polynomial fitting, histogram equalization, and Sobel filtering on captured images, and decoded the landmark information by setting a reasonable threshold. Finally, the DIMLOC positioning system used scale factors and visual analysis principles to achieve indoor high-precision visible light positioning.

4.2. Unmodified LEDs. Yang et al. [49] proposed the PIXEL visible light positioning system, which did not make any modification to the ceiling LED. The transmitter modulated the landmark signal by placing liquid crystal, polarizer, and disperser in the front of the LED. The PIXEL positioning system changed the input voltage of the liquid crystal to control the light intensity passing through the polarizer and used a disperser to make each direction have a different dispersion value, so as to achieve each LED landmark coding. The wearable smart devices with the disperser were used to the system receiver. When the receiver is moving, the receiver received the polarized light signal with different colors and light intensities and decoded each LED landmark information. Finally, the PIXEL positioning system used the angle of arrival positioning algorithm to achieve the positioning.

C. Zhang and X. Zhang [50] proposed the LiTell visible light positioning system. The system found that each fluorescent lamp at the transmitter had a unique characteristic frequency, which could be used as the unique landmark for the positioning system. The basic frequency of fluorescent lamps was usually in 40 kHz-60 kHz, and different resonance frequencies caused each fluorescent lamp to emit the unique characteristic frequency, which made it possible to achieve the landmark differentiation. In the positioning process, the smartphone captured images with the fluorescent lamp, and then took sampling and amplification mechanism to find the characteristic frequency of the fluorescent lamp. Finally, the LiTell positioning system matched the captured characteristic frequency with the characteristic frequency in the database to achieve the smartphone positioning.

Later, C. Zhang and X. Zhang [51] proposed the Pulsar visible light positioning system. The system found that the potential characteristic frequency of ceiling LEDs achieved the landmark differentiation. The receiver used the smartphone with the designed dual-photodiode module rather than the embedded camera to receive the light signal. The compacted dual-photodiode module could effectively remove the interference caused by the received signal strength, while reducing the energy consumption of the smartphone. The dual-photodiode module had a higher dynamic range and could capture the characteristic frequency of the LED within a distance of 9 m. The Pulsar positioning system used the sparse photogrammetry mechanism to analyze the incident angle and triangulated the position and orientation of the smartphone according to the number of LEDs. When the landmarks were successfully matching, the positioning system could achieve high-precision indoor visible light positioning.

Zhu and Zhang [52] proposed the iLAMP visible light positioning system. The system used LEDs or fluorescent lamps as the light source, which did not require any modification. The iLAMP positioning system used the different visual characteristics emitted by each light source to distinguish landmarks. In the positioning process, the system first needed to capture benchmark images of all light sources. Then, the positioning system extracted visual characteristics from images and registered them in the server database. At the same time, the positioning system also captured two auxiliary parameters: color pattern value and visible light intensity ratio. The iLAMP positioning system transmitted three characteristic vectors to the server for decoding the landmark. Finally, the iLAMP positioning system used photogrammetry, image information, and gravity sensor parameter to calculate the three-dimensional (3D) position of the object.

Zhao et al. [53] proposed the NaviLight visible light positioning system. The system used light intensity information as the fingerprint database at the transmitter. Since light intensity information was used as the fingerprint, the positioning system did not need to modify the light source, which decreased the complexity of the system design. However, compared with the wireless received signal strength indicator (RSSI), the light intensity information is inferior in terms of accuracy. The light intensity information was more susceptible to light interference in the ambient environment and may include the non-line-of-sight signal transmission. Therefore, the NaviLight positioning system combined the light intensity information with the user's walking parameters (inertial navigation data) to form a two-dimensional vector, which matched the database to obtain accurate positioning.

Shao et al. [54] proposed the visible light positioning system based on the retroreflector. The system designed a reverse light link channel from the receiver to the light source at the transmitter and located passive devices through the retroreflector. In the positioning system, the object changed the incident light into the reflected light parallel to the incident light through the retroreflector, and then the reflected light was received by the photodetector on the ceiling. In order to distinguish multiple objects, the positioning system used the liquid crystal display (LCD) to modulate the reflected light on the front of the retroreflector. When the object changed the position, the photodetector would receive different light powers. The positioning system used different light powers and the trilateral positioning algorithm to position the object and provide the real-time tracking solution.

Li et al. [55] proposed the RainbowLight visible light positioning system. The system could achieve three-dimensional positioning by using ambient light, and it was beneficial for positioning device deployment in today's buildings. The RainbowLight positioning system used polarizers and birefringent materials to design landmark chips. When ambient light shined on landmark chips, each landmark chip produced different colors from different directions. The phenomenon was caused by light interference. Furthermore, the RainbowLight positioning system derived a relationship model between direction, light interference, and spectrum. The positioning system calculated the relative direction between captured image location and the chip by using the relationship model. Finally, the RainbowLight positioning system used the direction intersection positioning algorithm to calculate the smartphone positioning.

Konings et al. [56] proposed the FieldLight visible positioning system. The system did not need to be equipped with a light-sensing device on the object to achieve passive positioning. The FieldLight positioning system used the phenomenon of ambient light changes caused by the object movement to achieve object detection and used a large number of photodiodes and artificial potential field algorithm to achieve the object positioning. The system did not need to modify the existing lighting infrastructure, which decreased the complexity of the positioning system.

Wang et al. [57] proposed the PassiveVLP positioning system. The system modified the outer surface of the object so that the reflected light could provide coded information with sufficient light intensity to the photodetector. In order to effectively locate the object in the moving state, the PassiveVLP positioning system embedded the barcode-like identification number on the surface of the object and proposed a new positioning system framework that decoded these identification numbers through passive reflection. Experimental results showed that the PassiveVLP positioning system could provide high-precision object tracking.

Xie et al. [58] proposed the LiTag passive visible light positioning system. The system designed the chipless and batteryless light tag. The tag could display different color patterns from different viewing directions. When the LiTag positioning system captured the tag, the receiver used color patterns and geometric relationships between the camera plane and the world plane to calculate the tag positioning. Different from the existing visible positioning systems, the light tag in the LiTag positioning system did not need to be calibrated, which greatly decreased the calibration overhead and deployment cost. The LiTag positioning system could use widely deployed monitoring equipment to achieve positioning.

4.3. Visible Light Security and Sensing. Zhang et al. [59] proposed the Okuli visible light interaction system. The system used near-infrared light emitting diode and two photodiodes to form a projection device. The projection device could be used for point tracking of small screens and virtual keyboard applications. In order to prevent ambient light interference, the Okuli interaction system designed the simple cancellation mechanism, which used direct current bias and binary keying modulation to distinguish between useful signal and noise. When the user's finger was placed within the sensing range of the projection device, the light from the near-infrared LED was reflected by the finger to two photodiodes as the receiver, and the receiver used different received signal strengths between two photodiodes and the predefined fingerprint database to achieve tracking and positioning.

Li et al. [60] proposed the LiSense visible light sensing system. In the sensing system, a large number of photodiodes were placed on the ground, and the ceiling used unmodified light sources. When the object appeared in the sensing range, the LiSense sensing system designed the algorithm to extract the shadow in the photodiode array and used the low-resolution shadow information to continuously reconstruct the three-dimensional human bone posture. The LiSense perception system could infer the 3D posture of the human body in real time at 60 fps. The average angle error in 3D bone reconstruction was only 10 degrees. The real-time LiSense sensing system was widely used in wireless networks, machine vision, and human-computer interaction fields.

Yang et al. [61] proposed the CeilingSee visible sensing system. The system did not require heavy infrastructure deployment and could perform the occupancy inference only through ceiling LEDs. Based on the current LEDs, the CeilingSee sensing system used the photoelectric effect of the LED to convert the LED as the transmitter to the LED as the receiver. The LED is the receiver to sense the reflected light signal caused by the object, which could achieve the occupancy inference without deploying a large number of photodiodes. In order to achieve accurate occupancy inference, the CeilingSee sensing system combined multiple LED sensing information with the machine learning algorithm for correction. Experiments showed that the CeilingSee sensing system had a high accuracy occupancy inference.

Nguyen et al. [62] proposed the EyeLight sensing system. The system used LEDs on the ceiling to sense the occupancy of indoor objects (occupancy inference). Most visible light sensing systems required lots of photodiodes to be placed on the ground/wall. The EyeLight sensing system integrated photodiodes and LED light sources in a compact circuit board and used reflected light from the floor to achieve object sensing. In the sensing process, the system designed the weak signal synchronous detection circuit to distinguish different LEDs. The sensor readings were classified by tracking algorithm and activity recognition classifiers. Experiments showed that occupancy inference and activity classification could reach 93.7% and 93.78% accuracy for the EyeLight sensing system, respectively.

5. Discussion

The above solutions provide a powerful reference for the commercial application of visible light positioning systems [63]. In this section, we discuss the potential problems and future research trends of visible light positioning technology.

5.1. Open Challenges

5.1.1. NLOS Transmission Problem. In the visible light positioning system, any object obstructing the line of sight between the transmitter and the receiver will stop the positioning system or significantly affect the accuracy of the positioning system. Although EyeLight [62] uses shadows or reflected light to solve the NLOS transmission problem, the positioning accuracy is not as good as under LOS transmission conditions. It is a challenge for visible light positioning systems to finding a way to solve the NLOS transmission problem.

5.1.2. Light Interference Problem. In the channel of the visible light positioning system, landmarks are transmitted by multiple different LEDs. When the indoor scene is too small, or multiple positioning systems exist in the same scene, there is a problem of light interference between landmarks. The visible light positioning system needs to study the problem of interlandmark interference in the system.

5.1.3. Tilt Angle Problem. In the visible light positioning system, when the receiver is an image sensor, the system needs to decode the image to calibrate the object position [64]. If the smartphone at the receiver is tilted at a large angle, the current positioning algorithms do not have an effective solution. The tilt angle may cause system distortion and decrease the positioning accuracy. Therefore, it is an important problem for the visible light positioning to study the tilt angle at the receiver.

5.2. Future Upcoming Technologies

5.2.1. Technology Diversification. The visible light positioning system that integrates different positioning technologies can improve the positioning accuracy and robustness of the positioning system, which is a new trend in future research. Epsilon [46] and NaviLight [53] used inertial sensors to enhance the positioning accuracy of visible light positioning systems under sparse light sources. Keskin et al. [65] improved the robustness of the visible light positioning system by using the temporary cooperation mechanism (using the information from the previous step in the current step) in the moving state.

5.2.2. Receiver Liberalization. At present, passive visible light positioning systems have been extensively studied [66]. Although the receiver without any light-sensing devices can achieve the positioning, it is either the system requires a large number of photodiodes to be placed in the environment (LiSense [60], FieldLight [56]) or the object needs to be labeled (PassiveVLP [57], LiTag [58]). The existing passive visible light positioning systems have not yet achieved receiver liberalization. In the future, it will be a meaningful research direction to construct the low-complexity, low-cost, passive visible light positioning system.

6. Conclusion

In this survey, we have provided a relatively understandable and comprehensive tutorial for indoor visible light applications, including communication, positioning, and security. We focus on the overview of visible light positioning system. At present, the visible light positioning systems use different light characteristics, such as spatial beams, polarized light, retroreflectors, light intensity fingerprints, and light shadows to achieve the landmark transmission and the positioning algorithm application. In the future, indoor visible light positioning will integrate different positioning technologies to achieve low-cost, high-precision, and robust indoor positioning and navigation services.

Disclosure

Any opinions, findings, and conclusions or recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of the funding parties.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

This material is based upon the work supported by the Natural Science Foundation of Guangdong Province under Grant No. 2021A1515011268 and Chongqing University Innovation Research Group (CQXT21019).

References

[1] J. Li, A. Liu, G. Shen, L. Li, C. Sun, and F. Zhao, "Retro-VLC: enabling battery-free duplex visible light communication for mobile and IoT applications," *2015 ACM 16th International Workshop on Mobile Computing Systems and Applications (HotMobile)*, pp. 21–26, 2015.

[2] S. Schmid, G. Corbellini, S. Mangold, and T. R. Gross, "LED-to-LED visible light communication networks," *2013 ACM 14th International Symposium on Mobile Ad hoc Networking and Computing (MobiHoc)*, pp. 1–10, 2013.

[3] A. Jovicic, J. Li, and T. Richardson, "Visible light communication: opportunities, challenges and the path to market," *IEEE Communications Magazine*, vol. 51, no. 12, pp. 26–32, 2013.

[4] P. H. Pathak, X. Feng, P. Hu, and P. Mohapatra, "Visible light communication, networking, and sensing: a survey, potential and challenges," *IEEE communications surveys & tutorials*, vol. 17, no. 4, pp. 2047–2077, 2015.

[5] A. Sevincer, A. Bhattarai, M. Bilgi, M. Yuksel, and N. Pala, "LIGHTNETs: smart lighting and mobile optical wireless NETworks — a survey," *IEEE Communications Surveys & Tutorials*, vol. 15, no. 4, pp. 1620–1641, 2013.

[6] T. Komine and M. Nakagawa, "Fundamental analysis for visible-light communication system using LED lights," *IEEE Transactions on Consumer Electronics*, vol. 50, no. 1, pp. 100–107, 2004.

[7] M. A. Arfaoui, M. D. Soltani, I. Tavakkolnia et al., "Physical layer security for visible light communication systems: a survey," *IEEE Communications Surveys & Tutorials*, vol. 22, no. 3, pp. 1887–1908, 2020.

[8] L. Yin and H. Haas, "Physical-layer security in multiuser visible light communication networks," *IEEE Journal on Selected Areas in Communications*, vol. 36, no. 1, pp. 162–174, 2017.

[9] Z. Ning, P. Dong, X. Wang et al., "Mobile edge computing enabled 5G health monitoring for internet of medical things: a decentralized game theoretic approach," *IEEE Journal on Selected Areas in Communications*, vol. 39, no. 2, pp. 463–478, 2021.

[10] Z. B. Tariq, D. M. Cheema, M. Z. Kamran, and I. H. Naqvi, "Non-GPS positioning systems," *ACM Computing Surveys*, vol. 50, no. 4, pp. 1–34, 2017.

[11] F. Zafari, A. Gkelias, and K. K. Leung, "A survey of indoor localization systems and technologies," *IEEE Communications Surveys & Tutorials*, vol. 21, no. 3, pp. 2568–2599, 2019.

[12] R. Xu, W. Chen, Y. Xu, and S. Ji, "A new indoor positioning system architecture using GPS signals," *Sensors*, vol. 15, no. 5, pp. 10074–10087, 2015.

[13] H. Zou, M. Jin, H. Jiang, L. Xie, and C. J. Spanos, "WinIPS: WiFi-based non-intrusive indoor positioning system with online radio map construction and adaptation," *IEEE Transactions on Wireless Communications*, vol. 16, no. 12, pp. 8118–8130, 2017.

[14] C. Y. Yao and W. C. Hsia, "An indoor positioning system based on the dual-channel passive RFID technology," *IEEE Sensors Journal*, vol. 18, no. 11, pp. 4654–4663, 2018.

[15] D. Konings, N. Faulkner, F. Alam, F. Noble, and E. M. Lai, "The effects of interference on the RSSI values of a ZigBee based indoor localization system," in *2017 IEEE 24th international conference on mechatronics and machine vision in practice (M2VIP)*, pp. 1–5, Auckland, New Zealand, 2017.

[16] B. Huang, J. Liu, W. Sun, and F. Yang, "A robust indoor positioning method based on Bluetooth low energy with separate channel information," *Sensors*, vol. 19, no. 16, p. 3487, 2019.

[17] J. Tiemann, F. Schweikowski, and C. Wietfeld, "Design of an UWB indoor-positioning system for UAV navigation in GNSS-denied environments," in *2015 IEEE international conference on indoor positioning and indoor navigation (IPIN)*, pp. 1–7, Banff, AB, Canada, 2015.

[18] M. Hazas and A. Hopper, "Broadband ultrasonic location systems for improved indoor positioning," *IEEE Transactions on Mobile Computing*, vol. 5, no. 5, pp. 536–547, 2006.

[19] H. Santo, T. Maekawa, and Y. Matsushita, "Device-free and privacy preserving indoor positioning using infrared retroreflection imaging," in *2017 IEEE international conference on pervasive computing and communications (PerCom)*, pp. 141–152, Kona, HI, USA, 2017.

[20] Z. Ning, S. Sun, X. Wang et al., "Blockchain-enabled intelligent transportation systems: a distributed crowdsensing framework," *IEEE Transactions on Mobile Computing*, p. 1, 2021.

[21] X. Wang, Z. Ning, S. Guo, M. Wen, and V. Poor, "Minimizing the age-of-critical-information: an imitation learning-based scheduling approach under partial observations," *IEEE Transactions on Mobile Computing*, p. 1, 2021.

[22] J. Luo, L. Fan, and H. Li, "Indoor positioning systems based on visible light communication: state of the art," *IEEE Communications Surveys & Tutorials*, vol. 19, no. 4, pp. 2871–2893, 2017.

[23] W. Gu, M. Aminikashani, P. Deng, and M. Kavehrad, "Impact of multipath reflections on the performance of indoor visible

light positioning systems," *IEEE Journal of Lightwave Technology*, vol. 34, no. 10, pp. 2578–2587, 2016.

[24] T. Komine and M. Nakagawa, "Integrated system of white LED visible-light communication and power-line communication," in *2002 IEEE 13th international symposium on personal, indoor and Mobile radio communications (PIMRC)*, vol. 4, pp. 1762–1766, Lisbon, Portugal, 2002.

[25] S. Kitano, S. Haruyama, and M. Nakagawa, "LED road illumination communications system," in *2003 IEEE 58th international conference on vehicular technology (VTC)*, vol. 5, pp. 3346–3350, Orlando, FL, USA, 2003.

[26] M. K. JJ, R. P. Green, A. E. Kelly et al., "High-speed visible light communications using individual pixels in a micro light-emitting diode array," *IEEE Photonics Technology Letters*, vol. 22, no. 18, pp. 1346–1348, 2010.

[27] I. Din and H. Kim, "Energy-efficient brightness control and data transmission for visible light communication," *IEEE Photonics Technology Letters*, vol. 26, no. 8, pp. 781–784, 2014.

[28] S. Rajagopal, R. D. Roberts, and S. K. Lim, "IEEE 802.15.7 visible light communication: modulation schemes and dimming support," *IEEE Communications Magazine*, vol. 50, no. 3, pp. 72–82, 2012.

[29] IEEE Standard Association, *IEEE Standard for Local and Metropolitan Area Networks-Part 15.7: Short-Range Wireless Optical Communication Using Visible Light*, pp. 1–309, 2011.

[30] X. Huang, F. Yang, and J. Song, "Hybrid LD and LED-based underwater optical communication: state-of-the-art, opportunities, challenges, and trends [invited]," *Chinese Optics Letters*, vol. 17, no. 10, p. 100002, 2019.

[31] J. Xu, M. Kong, A. Lin et al., "OFDM-based broadband underwater wireless optical communication system using a compact blue LED," *Optics Communications*, vol. 369, pp. 100–105, 2016.

[32] M. Afzalan and F. Jazizadeh, "Indoor positioning based on visible light communication," *ACM Computing Surveys*, vol. 52, no. 2, pp. 1–36, 2019.

[33] J. Beysens, Q. Wang, A. Galisteo, D. Giustiniano, and S. Pollin, "A cell-free networking system with visible light," *IEEE/ACM Transactions on Networking*, vol. 28, no. 2, pp. 461–476, 2020.

[34] S. H. Yang, H. S. Kim, Y. H. Son, and S. K. Han, "Three-dimensional visible light indoor localization using AOA and RSS with multiple optical receivers," *IEEE Journal of Lightwave Technology*, vol. 32, no. 14, pp. 2480–2485, 2014.

[35] M. F. Keskin and S. Gezici, "Comparative theoretical analysis of distance estimation in visible light positioning systems," *IEEE Journal of Lightwave Technology*, vol. 34, no. 3, pp. 854–865, 2016.

[36] H. Steendam, "A 3-D positioning algorithm for AOA-based VLP with an aperture-based receiver," *IEEE Journal on Selected Areas in Communications*, vol. 36, no. 1, pp. 23–33, 2017.

[37] F. Alam, M. T. Chew, T. Wenge, and G. S. Gupta, "An accurate visible light positioning system using regenerated fingerprint database based on calibrated propagation model," *IEEE Transactions on Instrumentation and Measurement*, vol. 68, no. 8, pp. 2714–2723, 2018.

[38] N. Wu, L. Feng, and A. Yang, "Localization accuracy improvement of a visible light positioning system based on the linear illumination of LED sources," *IEEE Photonics Journal*, vol. 9, no. 5, pp. 1–11, 2017.

[39] R. Zhang, W. D. Zhong, Q. Kemao, and S. Zhang, "A single LED positioning system based on circle projection," *IEEE Photonics Journal*, vol. 9, no. 4, pp. 1–9, 2017.

[40] J. Fang, Z. Yang, S. Long et al., "High-speed indoor navigation system based on visible light and mobile phone," *IEEE Photonics Journal*, vol. 9, no. 2, pp. 1–11, 2017.

[41] T. H. Do and M. Yoo, "An in-depth survey of visible light communication based positioning systems," *Sensors*, vol. 16, no. 5, p. 678, 2016.

[42] Z. Ning, P. Dong, X. Wang et al., "Partial computation offloading and adaptive task scheduling for 5G-enabled vehicular networks," *IEEE Transactions on Mobile Computing*, p. 1, 2020.

[43] C. An, T. Li, Z. Tian, A. T. Campbell, and X. Zhou, "Visible light knows who you are," *2015 ACM 2nd International Workshop on Visible Light Communications Systems (VLCS)*, pp. 39–44, 2015.

[44] G. Blinowski, "Security of visible light communication systems–a survey," *Physical Communication*, vol. 34, pp. 246–260, 2019.

[45] Y. S. Kuo, P. Pannuto, K. J. Hsiao, and P. Dutta, "Luxapose: indoor positioning with mobile phones and visible light," in *2014 ACM 20th Annual International Conference on Mobile Computing and Networking (MobiCom)*, pp. 447–458, Maui, Hawaii, USA, 2014.

[46] L. Li, P. Hu, C. Peng, G. Shen, and F. Zhao, "Epsilon: a visible light-based positioning system," in *2014 USENIX 11th international symposium on networked systems design and implementation (NSDI)*, pp. 331–343, Seattle, USA, 2014.

[47] Z. Wang, Z. Yang, Q. Huang, L. Yang, and Q. Zhang, "ALS-P: light weight visible light positioning via ambient light sensor," in *2019 IEEE international conference on computer communications (INFOCOM)*, pp. 1306–1314, Paris, France, 2019.

[48] X. Liu, X. Wei, and L. Guo, "DIMLOC: enabling high-precision visible light localization under dimmable LEDs in smart buildings," *IEEE Internet of Things Journal*, vol. 6, no. 2, pp. 3912–3924, 2019.

[49] Z. Yang, Z. Wang, J. Zhang, C. Huang, and Q. Zhang, "Wearables can afford: light-weight indoor positioning with visible light," in *2015 ACM 13th annual international conference on Mobile systems, applications, and services (MobiSys)*, pp. 317–330, Florence, Italy, 2015.

[50] C. Zhang and X. Zhang, "LiTell: robust indoor localization using unmodified light fixtures," in *2016 ACM 22nd annual international conference on Mobile computing and networking (MobiCom)*, pp. 230–242, New York City, New York, 2016.

[51] C. Zhang and X. Zhang, "Pulsar: towards ubiquitous visible light localization," in *2017 ACM 23rd annual international conference on Mobile computing and networking (MobiCom)*, pp. 208–221, Snowbird, Utah, USA, 2017.

[52] S. Zhu and X. Zhang, "Enabling high-precision visible light localization in today's buildings," in *2017 ACM 15th annual international conference on Mobile systems, applications, and services (MobiSys)*, pp. 96–108, New York, USA, 2017.

[53] Z. Zhao, J. Wang, X. Zhao, C. Peng, Q. Guo, and B. Wu, "NaviLight: indoor localization and navigation under arbitrary lights," in *2017 IEEE international conference on computer communications (INFOCOM)*, pp. 1–9, Atlanta, GA, USA, 2017.

[54] S. Shao, A. Khreishah, and I. Khalil, "RETRO: retroreflector based visible light indoor localization for real-time tracking of IoT devices," in *2018 IEEE international conference on*

computer communications (INFOCOM), pp. 1025–1033, Honolulu, HI, USA, 2018.

[55] L. Li, P. Xie, and J. Wang, "Rainbowlight: towards low-cost ambient light positioning with mobile phones," in *2018 ACM 24th annual international conference on Mobile computing and networking (MobiCom)*, pp. 445–457, New Delhi, India, 2018.

[56] D. Konings, N. Faulkner, F. Alam, E. M. Lai, and S. Demidenko, "FieldLight: device-free indoor human localization using passive visible light positioning and artificial potential fields," *IEEE Sensors Journal*, vol. 20, no. 2, pp. 1054–1066, 2020.

[57] W. Wang, Q. Wang, J. Zhang, and M. Zuniga, "PassiveVLP," *ACM Transactions on Internet of Things*, vol. 1, no. 1, pp. 1–24, 2020.

[58] P. Xie, L. Li, J. Wang, and Y. Liu, "LiTag: localization and posture estimation with passive visible light tags," in *2020 ACM 18th conference on embedded networked sensor systems (SenSys)*, pp. 123–135, Virtual Event online, Japan, 2020.

[59] C. Zhang, J. Tabor, J. Zhang, and X. Zhang, "Extending mobile interaction through near-field visible light sensing," in *2015 ACM 21st annual international conference on Mobile computing and networking (MobiCom)*, pp. 345–357, Paris, France, 2015.

[60] T. Li, C. An, Z. Tian, A. T. Campbell, and X. Zhou, "Human sensing using visible light communication," in *2015 ACM 21st annual international conference on Mobile computing and networking (MobiCom)*, pp. 331–344, Paris, France, 2015.

[61] Y. Yang, J. Hao, J. Luo, and S. J. Pan, "CeilingSee: device-free occupancy inference through lighting infrastructure-based LED sensing," in *2017 IEEE international conference on pervasive computing and communications (PerCom)*, pp. 247–256, Kona, HI, USA, 2017.

[62] V. Nguyen, M. Ibrahim, S. Rupavatharam, M. Jawahar, M. Gruteser, and R. Howard, "Eyelight: light-and-shadow-based occupancy estimation and room activity recognition," in *2018 IEEE international conference on computer communications (INFOCOM)*, pp. 351–359, Honolulu, HI, USA, 2018.

[63] X. Wang, Z. Ning, S. Guo, and L. Wang, "Imitation learning enabled task scheduling for online vehicular edge computing," *IEEE Transactions on Mobile Computing*, p. 1, 2020.

[64] Z. Ning, P. Dong, M. Wen et al., "5G-enabled UAV-to-community offloading: joint trajectory design and task scheduling," *IEEE Journal on Selected Areas in Communications*, p. 1, 2021.

[65] M. F. Keskin, A. D. Sezer, and S. Gezici, "Localization via visible light systems," *Proceedings of the IEEE*, vol. 106, no. 6, pp. 1063–1088, 2018.

[66] Z. Ning, S. Sun, X. Wang et al., "Intelligent resource allocation in mobile blockchain for privacy and security transactions: a deep reinforcement learning based approach," *Science China Information Sciences*, vol. 64, no. 6, pp. 1–16, 2021.