DOI: 10.54254/2755-2721/42/20230782

Research on the 3D indoor positioning technology based on feature light source

Yiqi Xu

Oaks Christian High School, Westlake, California, 91362, US

yxu@student.oakschristian.org

Abstract. Nowadays, positioning technologies mainly consist of three methods: positioning based on satellites, positioning based on RF and positioning based on self-contained sensors. However, due to the complex propagation characteristics of wireless signals in indoor environments, the existing positioning technologies widely used in outdoor environments cannot meet the requirements of indoor applications. Compared to outdoor environments, indoor environments are more complex, and wireless signals are affected by various factors, making it difficult for existing indoor positioning systems to meet the requirements of high accuracy and low cost. Thus, a three-dimensional indoor positioning technology based on a characteristic light source and a spherical lighting device is proposed in this paper to solve the problems. The technology measures the angle of the optical signal through a spherical lighting device, which can receive light in all directions and obtain height information compared with flat mode. Pseudo-source interference caused by the wave nature of light will not be introduced with the use of the particle nature of light. Array layout and optimization algorithms can further improve positioning accuracy. A simulation experiment in Matlab is conducted. The experimental results and the analysis of accuracy confirmed that the positioning accuracy can be controlled within a small error. Three-dimensional indoor positioning technology can achieve high accuracy at a low cost.

Keywords: Three-dimensional Indoor Positioning, Feature Light Source, Spherical Lighting Device.

1. Introduction

As science and engineering develop, there's a growing need for real-time, accurate positioning information, making positioning technologies more and more important. Nowadays, positioning technologies based on satellites are rather mature in outdoor situations. However, indoor circumstances, in which people have most activities, face a slower development because indoor positioning technology, as an end of positioning technology, has developed relatively slowly. Currently, positioning technologies mainly consist of three methods: positioning based on satellites, positioning based on RF and positioning based on self-contained sensors. The first method, for example, positioning using Global Positioning System,or GPS, has been successfully applied to outdoor localization. However these technical means are difficult to extend to the field of indoor positioning. The indoor environment is often more complex in terms of building layout, structure, decoration, etc., which also poses more technical challenges for indoor positioning compared to outdoor positioning. In recent years, many scholars at home and abroad have conducted research on indoor positioning and achieved certain results. However, current indoor positioning technologies have several problems such as low accuracy, large limitations, lack of three-dimensional information, and poor anti-interference ability.

On the basis of introducing existing indoor positioning technologies, this study proposes a three-dimensional indoor positioning system based on feature light sources, elaborates on the principle of the system and the specific implementation method of three-dimensional indoor positioning based on the system, and conducts error analysis through Matlab simulation. The feasibility and research prospects of the three-dimensional indoor positioning system are demonstrated.

2. Summary of positioning principles

A positioning system usually consists of two parts: the mobile unit and the stationary one. The position of the stationary unit is already known, as is the position of the base station in mobile communications, while the mobile one is normally carried by pedestrians who need to be located or placed on desired objects. The mobile unit communicates with the stationary unit to acquire its related position parameters, like distance, angles, etc., and finally obtain its actual position coordinates.

2.1. Position Variables

No matter what kind of positioning system is adopted, before obtaining position information, relevant position variables must be obtained in the first place, subsequently establishing corresponding mathematical and physical models to realize the calculation of specific position coordinates. In the field of indoor positioning, there are currently four position variables in use.

First, time of flight, or ToF. ToF is the time it takes for a signal to be transmitted and received. Combined with the speed of propagation of a signal in a certain medium, the distance between stationary and mobile units can be determined.

Second, received signal strength, or RSS. RSS is the strength of the received wireless signal, which usually decays with the increase in propagation distance. A mathematical model has been established between the strength of the wireless signal and the propagation distance based on a large amount of experimental data. Therefore, the distance from a mobile unit to a stationary unit can be accurately calculated within a certain range based on the strength of the wireless signal [1].

Third, time difference of arrival, or TDoA. In a system with a single signal receiver, multiple time-synchronized transmitters, and multiple synchronous signal transmitters, the time recorded by the signal receiver for consecutive signals differs. Based on the TDoA, the relative spatial location of each signal transmitter at the signal receiver can be calculated, thereby further determining the coordinates of the mobile terminal.

Finally, angle of arrival, or AoA. When a wireless signal from a fixed unit arrives at a moving unit, its trajectory is relative to a predetermined angle in a certain direction. Based on this, combined with geometric knowledge, the calculation of the position of the moving unit can be achieved.

2.2. Positioning Technologies

Different indoor positioning systems use various wireless signals to measure the position variables mentioned above. The type of signal is normally determined by the positioning accuracy, safety, equipment cost, etc. required by the system. Currently, common positioning technologies are shown as follows.

Infrared, or IR signals, as an electromagnetic wave within a specific wavelength range, have long been adopted as a tool in indoor positioning. However, it has rather low accuracy and can be easily obstructed by objects, which results in its low practicality.

Ultrasonic positioning mostly uses reflective raging methods, with an accuracy of up to cm. However, it suffers from a high cost and significant attenuation, affecting its positioning range.

Radio frequency, or RF identification technology utilizes the coupling characteristics of inductance and electromagnetism to achieve automatic identification of identified objects. It is widely used in the field of automatic control due to its simple deployment, low cost, certain accuracy and anti-interference.

Indoor positioning systems based on radio frequency identification are usually composed of electronic tags, radio frequency readers and writers, middleware, and computer databases.

3. Research on indoor positioning

Optical signals, as a commonly used communication medium, has been introduced into indoor positioning research in recent years. Yoshino et al. used an 1000×1000 pixels sized image sensor as the optical receiver and the error was approximately 1.5m [2]; Rahman et al. designed a VLC localization method based on dual image sensor which receives light from at least three LEDs through two 6 megapixel image sensors and calculates the three-dimensional coordinates of the target point within a 1.8m×1.8m×3.5m experimental space, the error can be controlled within 0.15m [3, 4, 5].

This study proposes a three-dimensional indoor positioning system based on characteristic light sources, with the light sources as fixed units and spherical lighting devices as mobile units. By measuring the AoA of the light signal, three-dimensional indoor positioning is achieved. Compared to existing research results, the positioning system proposed in this article has the following advantages:

1) By adopting an array based curved lighting mode, it breaks through the limitations of flat lighting panels on the position of light sources and can obtain the height information of the target.

2) Simultaneously identifying the frequency and encoding of light, rather than a single color detection, improves measurement accuracy.

3) Position calculation based on the incident angle of light, rather than image sensors, simplifies the calculation model while reducing costs.

3.1. System Construction

The system is shown in Figure 1.

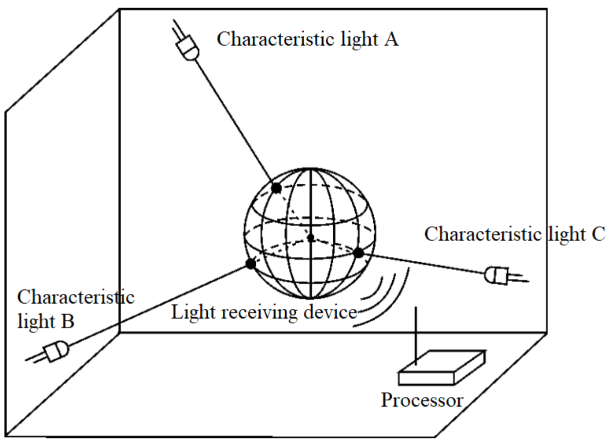

Figure 1. Schematic diagram of system structure.

It consists of three modules: a characteristic light source, a spherical light receiving device, and a processor. Among them, the characteristic light source serves as a fixed unit to emit characteristic light. The spherical light receiving device is placed as a mobile unit at the desired positioning position or carried by the desired positioning person, receiving the light emitted by the characteristic light source. And the processor analyzes and processes the light data collected by the spherical light receiving device to determine its position. The following is a detailed description of the three components of the system.

The characteristic of light lies in its frequency and/or encoding. The meaning of using frequency as a feature is that the frequency of light emitted by feature light sources is different from each other, such as the different colors of visible light. The meaning of using encoding as a feature is that the encoding of the light emitted by the characteristic light source is different from each other. For example, light flickers with a different period of time in between, but all at high frequencies, making it unrecognizable

DOI: 10.54254/2755-2721/42/20230782

to the naked eye, but capable of photoelectric signal conversion and counting by the processor. In order to ensure subsequent calculations, the system needs to have at least three light sources with different features.

The spherical lighting device consists of a spherical support, multiple optical fibers, and a data transmission module. Each of the multiple optical fibers has one end embedded into the spherical support at an angle perpendicular to the surface of the spherical support, with the intersection point being referred to as the lighting point, and the other end leading to the data transmission module. The light-collecting point has a limit on the angle of light incidence, which is used to collect the light signal emitted by the characteristic light source at a specific angle of incidence and transmit it to the data transmission module through optical fiber. The data transmission module transmits the characteristics of the collected light signal and the location of the light-collecting point that collected the light signal to the processor through wired or wireless means. The higher the number of optical fibers deployed at this location, the higher the positioning accuracy. Compared to existing planar light-sensitive devices, the designed spherical light-collecting device avoids blind spots and dead angles in light collection, and can sense light sources in all directions, achieving three-dimensional stereoscopic light sensing.

The processor records the features of each characteristic light source and its location in the room, and calculates the location of the spherical light receiving device based on the information mentioned above, thereby achieving three-dimensional indoor positioning. The processor can be embedded within the spherical lighting device, or separated from the spherical lighting device and able to communicate with the spherical lighting device via wired or wireless means for data transmission.

3.2. Positioning Process

The process for implementing 3D indoor positioning in this system is as follows. A spherical lighting device is arranged at the location that requires positioning, and then the characteristic light source is turned on to enable the spherical lighting device to capture light. Considering the restriction of the optical fiber on the angle of incident light, it can be considered that only light close to radial incidence can be collected by the corresponding optical fiber, which achieves AOA collection for specific light. After that, the processor analyzes the light signals received by each lighting point on the spherical lighting device and, based on the separation of the light characteristics of each characteristic light source, identifies which characteristic light sources have been received at the lighting point. Select the most important characteristic light sources for each lighting point and, based on this correspondence, select three different lighting points corresponding to three different characteristic light sources, as presented in Figure 2.

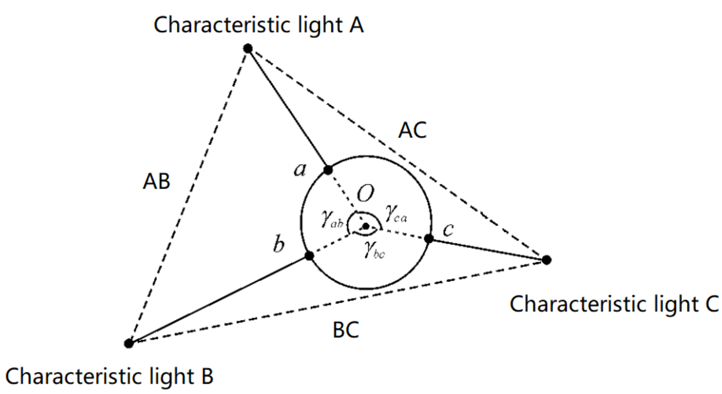

Figure 2. Schematic diagram of position calculation.

This study sets the position coordinates of three light source as $A(x_A, y_A, z_A), B(x_B, y_B, z_B), C(x_C, y_C, z_C)$,respectively. The spherical light receiving device measures the angle of the line connecting the light source and the center of the sphere, O, thus creating three light receiving point ,a, b, and c, subsequently, the angles namely $\gamma_{ab}, \gamma_{bc}, \gamma_{ac}$. Setting the position of three receiving point $a(r, \theta_a, \psi_a), b(r, \theta_b, \psi_b), c(r, \theta_c, \psi_c)$ and then the following can be obtained:

$$\gamma_{ab} = \arccos[\cos\theta_a \cos\theta_b \cos(\psi_b - \psi_a) + \sin\theta_a \sin\theta_b], (1)$$

$$\gamma_{bc} = \arccos[\cos\theta_b \cos\theta_c \cos(\psi_c - \psi_b) + \sin\theta_b \sin\theta_c], (2)$$

$$\gamma_{ac} = \arccos[\cos\theta_c \cos\theta_a \cos(\psi_a - \psi_c) + \sin\theta_c \sin\theta_a], (3)$$

The results of applying the cosine theorem to three triangles are as follows:

$$AO^2 + BO^2 - AB^2 = 2AO \cdot BO \cos\gamma_{ab}, (4)$$

$$BO^2 + CO^2 - BC^2 = 2BO \cdot CO \cos\gamma_{bc}, (5)$$

$$CO^2 + AO^2 - CA^2 = 2CO \cdot AO \cos\gamma_{ca}. (6)$$

In the equations, AB, BC, and CA can be calculated through distance formulas.

By solving these equations, the values of AO, BO, and CO can be obtained. Since this is a system of ternary quadratic equations, 8 sets of solutions should be solved. Obviously complex and non-positive real number roots can be directly excluded. The remaining solutions may be the same, but they are not equal in most circumstances. To get the unique and only solution, the following method is recommended. It requires the spherical light receiving device to have a little displacement. Based on the same three characteristic light sources for calculation, complex and non-positive real roots are similarly excluded. When matched with the solution obtained in this calculation, combined with the displacement, a unique solution can be easily selected.

In practical applications, the above calculation process can be repeated by selecting three different characteristic light sources multiple times to cluster the calculation results and improve positioning accuracy.

4. Experimental demonstration and optimization analysis

This section will utilize Matlab to establish a model and simulate the proposed indoor positioning technology, conduct error discussion, and conduct optimization analysis based on experimental results.

4.1. Matlab Simulations

We use MATLAB 2023a for programming and simulation, and the procedure is as follows.

Initialization includes setting the position and size of the spherical lighting device, setting the density of spherical lighting points, and setting the number and position of characteristic light sources. For convenience in calculation, the center position of the spherical lighting device is set at the origin (0, 0, 0). The density of spherical lighting points is achieved by setting the minimum angle between each lighting point and the center line, which is a positive integer part of 2 π. The smaller the spherical lighting point, the higher the density. The number of light sources is ≥ 4, and the positions are randomly generated outside the spherical surface.

In the program, the method to obtain the optimal lighting point is as follows: after selecting three feature light sources, connect them to the center of the sphere, and generate three intersections between these three lines and the sphere. Then, select the lighting points closest to these three intersections as the lighting points for calculation. The relevant code is as follows:

```
a=[sym(atan((y(1)/x(1))))sym(atan((y(2)/x(2))))sym(atan((y(3)/x(3))))];
b=[sym(asin((y(1)/r(1))))sym(asin((y(2)/x(2))))sym(asin((y(3)/x(3))))];
%calculate optimal lighting point position
a(isnan(a))=0;
```

DOI: 10.54254/2755-2721/42/20230782

```
B(isnan(b))=0;
%avoid affects from points in z axis
a=round(a./p).*p;
b=round(b./p).*p;
%obtain actual lighting point position
```

In the code, p is the minimum angle between the lighting point and the center of the sphere. The calculation methods for various parameters and equations in the simulation program refer to the formula in Section 2.2, and will not be repeated here.

After fixing the light sources, we adjusted the value of p in the simulation experiment, and out came the impact of the distribution density of spherical lighting points on the positioning accuracy. Take the group of data shown in Figure 4 as an example.

The positions of three light sources are (8,0,6), (5,12,0), (4,6,8) respectively, and the center of the sphere is (0,0,0); the positioning result alters with p as in Table.1.

Table 1. Affect of lighting point density on positioning.

p	Positioning results
π/4	(-3.6269,2.2307,-1.9403)
π/6	(-0.5347,1.7000,1.4201)
π/12	(-0.3122,-0.2218,0.0041)
π/60	(0.0000,0.0000,0.0000)

The actual positioning effect is shown in Figure 3, where A, B, and C are the positions of three light sources, and O1O4 are four positioning results under different values of p.

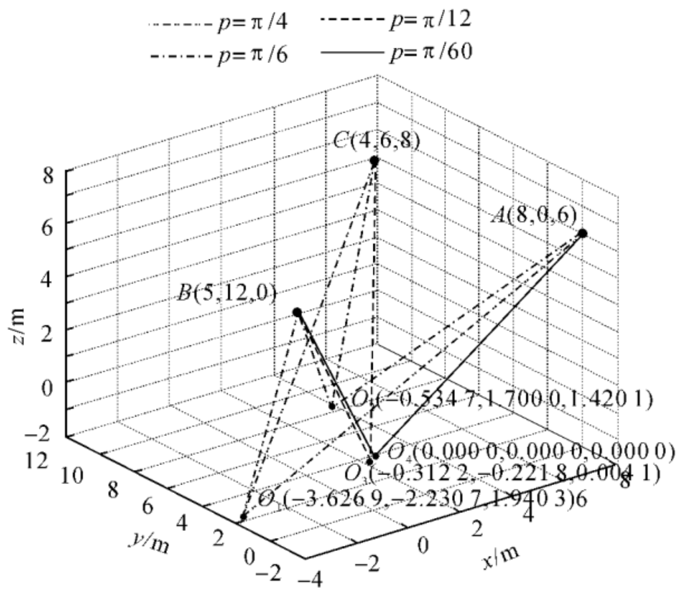

Figure 3. Schematic diagram of different lighting point density.

For example, when selecting a spherical lighting device with a diameter of 10cm, when p is taken as 15 °, the spacing between the lighting points on the spherical surface is about 2.62cm, which is not difficult to achieve in the manufacturing process. From the simulation results, it can be seen that such a device can achieve a positioning accuracy of 0.1m within a spatial range of 10m, and this positioning effect is excellent.

4.2. Error Discussion and Optimization Analysis

The number of optical fibers arranged on the surface of a spherical illuminator is limited. In theory, when the spherical lighting device moves, each set of incident angles can uniquely determine the position point of the spherical lighting device's center. As long as the fiber distribution of the spherical lighting device is sufficiently dense, slight movement will generate a new set of incident angles. From this, it can be inferred that the three-dimensional indoor positioning method can achieve arbitrary accuracy. In the production of spherical lighting devices, optical fibers should be arranged as densely as possible to improve positioning accuracy, as cost and the production process allow.

In simulation experiments, as p decreases, the accuracy of positioning can be greatly improved. In practical applications, due to cost and manufacturing process limitations, it is not practical to arrange too many high-precision optical fibers. In response to the system errors of the above two points, optimization can be considered in the algorithm to select the most suitable lighting points and feature light sources for positioning calculation. Compared with hardware improvements, although algorithmic optimization increases the computational load of the processor to a certain extent, it greatly reduces the cost of materials and production.

5. Conclusion

This study discussed various positioning technologies, both in outdoor and indoor circumstances. After discussing the disadvantages of applying outdoor positioning methods to indoor circumstances, the article introduced some indoor positioning technologies like infrared signal systems and ultrasonic signal systems. However, the current systems have flaws in some aspects, so this study introduced a new three-dimensional indoor positioning technology that has the advantages listed below:

(1) The spherical lighting mode breaks through the limitations of traditional flat lighting mode on the position of the light sources, allowing light sources to be placed at any position indoors, with low requirements for hardware deployment.

(2) The positioning method based on the optical signal AoA itself has the advantages of simplicity and accuracy. In addition, due to the use of the particle characteristics of light, it avoids the interference of pseudo light sources caused by the fluctuation characteristics of light.

(3) 3D spatial positioning can obtain the height information of the target, and the array layout and optimization algorithms based on this layout further improve the positioning accuracy, making the positioning results highly valuable.

However, this system still suffers from signal blocking. The positioning procedure needs at least three characteristic light sources simultaneously; if the position of the pedestrian happens to block one or two of the light sources, the positioning result may not be accurate. The solution to this problem is to either minimize the probability of the lighting sphere being blocked or add more characteristic light sources in various positions.

References

[1] Fang, Z., Zhao, Z., Guo, P., & Zhang, Y. G.. (2007). Analysis of distance measurement based on rssi. Chinese Journal of Sensors and Actuators.

[2] Yoshino, M., Haruyama, S., & Nakagawa, M.. (2008). High-accuracy positioning system using visible LED lights and image sensor. Radio and Wireless Symposium, 2008 IEEE. IEEE.

[3] Rahman, M. S., Haque, M., & Kim, K. D.. (2011). Indoor positioning by led visible light communication and image sensors. International Journal of Electrical & Computer Engineering, 1(2), 420-431.

[4] Rahman, M. S., Haque, M., & Kim, K. D.. (2011). Indoor positioning by led visible light communication and image sensors. International Journal of Electrical & Computer Engineering, 1(2), 420-431.

[5] Rui, S., Jian, Z., & University, I. E.. (2014). Indoor location method based on visible light communication. Journal of Information Engineering University.