Optical-Wireless VN-CSK Communication-Based Indoor Positioning System

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Abstract

Indoor visible-light communications using lighting devices is attracting attention. Using a communication function, a lighting function and a positioning function simultaneously is expected to upgrade the previous optical wireless system. We previously proposed the variable N-parallel code shift keying (VN-CSK) system with a positioning function. Triangulation location scheme using pseudonoise (PN) codes was proposed for the VN-CSK system. In this paper, a VN-CSK communication-based optical fingerprint scheme is proposed. The most suitable placement pattern of LEDs in the optical fingerprint scheme differs from that in the triangulation location scheme in that the optical fingerprint uses the signals received from all LEDs. The positioning accuracy of the optical fingerprint scheme is the same as that of the triangulation location scheme.

1. Introduction

In optical wireless communications, indoor visible-light communications using lighting devices is attracting attention [1]-[4]. For indoor visible-light communications, it is desirable to provide a communication function, a lighting function and a positioning function simultaneously. To realize the communication function, a dimming-level-independent constant data transmission scheme and a suppression scheme for co-channel interference between neighboring lighting systems are required. To realize the lighting function, the realization of dimming control, safety for human eyes and flicker mitigation are required. To realize the positioning function, positioning regardless of dimming control and elimination of interference from neighboring lightings are required. We focused on the variable N-parallel code shift keying (VN-CSK) system as a way to realize the lighting function and the communication function [5]. Moreover, we have proposed a VN-CSK system with a positioning function [6]. The positioning function is actualized using the principle of a triangulation location scheme with the pseudonoise (PN) codes of the VN-CSK system. Regarding the positioning system, although there are some systems that use the time of arrival (TOA) of the code [7], it is difficult to use in our system because the VN-CSK system uses a cyclically shifted code as the PN code.

In this paper, we present a new positioning scheme for the VN-CSK system using the characteristics of transmission codes: an optical fingerprint scheme. The optical fingerprint scheme estimates the positional information using the relationship between the received optical power and the information on the stored reference optical intensity distribution. In this paper, we evaluate the positioning accuracy of the optical fingerprint scheme under the indoor propagation model. Moreover, we compare the optical fingerprint scheme with the triangulation location scheme.

2. VN-CSK System with MPSC

2.1 Modified prime sequence codes

In this system, modified prime sequence codes (MPSC) [8], [9] are used as the PN codes. MPSC are constructed on a Galois field $GF(M)$, where $M$ is a prime number. MPSC have $M$ groups and each group has $M$ codewords. The length of each codeword is $M^2$.

MPSC have some special characteristics. The autocorrelation value of a codeword is $M$. The cross-correlation value between any two codewords belonging to the same MPSC group becomes 0, which means that they are orthogonal to each other. The cross-correlation value between different MPSC group codewords becomes always 1.

2.2 System structure

Figure 1 shows the structure of the VN-CSK system. At the transmitter, the transmission codes are selected on the basis of the source data and the dimming control data. The number of transmission codes ($N$) depends on the dimming control data. In this system, MPSC are used as the transmission code set. $N$ codes are selected from $M$ codes of the MPSC, and they are combined. When $M$ is 5, $N$ codes are selected from four of these codes. For example, when $N$ is 2, two codes are selected from the same MPSC group. There are six patterns for selecting two codes to be used from four codes. At this time, one code of the MPSC group is not selected as a
code for transmission because it can be used to eliminate the interference. Finally, the electric signal is converted into the optical signal and transmitted.

At the receiver, the received optical signal is converted into the electric signal. Then, the signal is correlated with the reference signal. There are $M$ correlators. The transmitted data is estimated by maximum likelihood estimation. Figure 2 shows the phase of the correlator. Moreover, the correlator output values are used for positioning. By subtracting the minimum value from the maximum output value, the signal from the target LED can be received. The minimum value used here is a correlation value with a code not used in transmission. From the interference elimination, some data for positioning can be estimated. Then the receiver position is estimated using the positioning data.

3. Positioning Schemes

There are a variety of schemes to realize positioning. In this section, we explain the triangulation location scheme and the optical fingerprint scheme.

3.1 Propagation model

Figure 3 shows the propagation model. In this model, LEDs are installed as transmitters on the ceiling of a room. For each LED, an MPSC group corresponding to the LED number is assigned. For example, MPSC group 1 is assigned to LED #1, MPSC group 2 is assigned to LED #2.

The optical power received from LED, $P_{\text{rec}}$, is given by

$$P_{\text{rec}} = P_{\text{trans}} \cdot \frac{m + 1}{2^{m+2}} \cdot S \cdot \left(\frac{h}{r}\right)^{m+1}$$  (1)

where $P_{\text{trans}}$ is the average transmitted power per LED, $m$ is the index of the Lambertian emission law, $r$ is the communication distance, $S$ is the physical area of the receiver and $h$ is the vertical distance between the LED and the receiver [4]. The index of the Lambertian emission law, $m$, is given by

$$m = \frac{1}{\log_2(\cos \Phi_{1/2})}$$  (2)

where $\Phi_{1/2}$ is the half-power semiangle. At this time, the interference from neighboring LEDs is eliminated at the receiver by using the characteristics of the MPSC group. Therefore, only optical power from the target LED can be received.

3.2 Triangulation location scheme

Triangulation location is the most popular positioning scheme. This is the same as the code positioning scheme of the Global Positioning System (GPS).
As previously mentioned, the receiver can obtain $P_{rec}$ from each LED. Therefore, the communication distance for each LED can be estimated. In this paper, the triangulation location is performed using the three LEDs with the three shortest communication distances. From Eq. (1), the communication distance is calculated using the received signal power with the interference $P_{rec}$ removed.

$$r = \sqrt{\frac{P_{trans} \cdot (m + 1) \cdot S \cdot h^{m+1}}{2\pi \cdot P_{rec}}}$$

The formula of the triangulation location is given by

$$\begin{align*}
(X - x_1)^2 + (Y - y_1)^2 + (Z - z_1)^2 &= r_1^2 \\
(X - x_2)^2 + (Y - y_2)^2 + (Z - z_2)^2 &= r_2^2 \\
(X - x_3)^2 + (Y - y_3)^2 + (Z - z_3)^2 &= r_3^2 \\
(X - x_M)^2 + (Y - y_M)^2 + (Z - z_M)^2 &= r_M^2
\end{align*}$$

where $(X, Y, Z)$ is the coordinates of the receiver, $(x_i, y_i, z_i)$ is the coordinates of LED $\#i$ and $r_i$ is the communication distance between LED $\#i$ and the receiver ($i = 1, 2, \ldots, M$). At this time, the receiver knows the coordinates of each LED. From Eq. (4), the receiver position is estimated.

### 3.3 Optical fingerprint scheme

The optical fingerprint scheme is one of the schemes of positioning [10]. This scheme uses the distribution of the received optical power. The received optical power depends on the receiver position. In this scheme, the receiver position is estimated by correlating the stored reference optical power with the measured optical power.

![Received optical power distribution from LED #1](image)

In this study, positioning is performed using the ratio of the received optical power from each LED. Figure 4 shows the stored reference optical power distribution from LED #1. First, we normalize $P_{rec}$ for each LED. This normalization is performed by dividing $P_{rec}$ from each LED by the total received optical power.

$$Ref_{\#i(x,y,z)} = \frac{P_{rec\#i}}{P_{rec\#1} + P_{rec\#2} + P_{rec\#3} + P_{rec\#4}}$$

$$Ref(x,y,z) = [Ref_{\#1(x,y,z)}, Ref_{\#2(x,y,z)},$$

$$Ref_{\#3(x,y,z)}, Ref_{\#4(x,y,z)}]$$

where $Ref_{\#i(x,y,z)}$ is the normalized value from LED $\#i$ at the receiver position coordinates $(x, y, z)$ and $P_{rec\#i}$ is the received optical power from LED $\#i$ when there is no noise. From this normalization, the ratio of the received optical power at a certain receiver position is obtained. Then, the received optical power with noise is correlated with the normalized value, $Ref$. When the receiver position is $(X, Y, Z)$, the received optical power with noise, $rec(X,Y,Z)$, is expressed as

$$rec(X,Y,Z) = [rec_{\#1(X,Y,Z)}, rec_{\#2(X,Y,Z)},$$

$$rec_{\#3(X,Y,Z)}, rec_{\#4(X,Y,Z)}]$$

where $rec_{\#i(X,Y,Z)} (i = 1, 2, 3, 4)$ is the practical optical power from LED $\#i$.

The receiver position is estimated as

$$g(a,b,c) = \max_{x,y,z} \{ rec(x,y,z) \cdot Ref(x,y,z)^T \}$$

where $(a, b, c)$ is the coordinates when the right side of Eq. (8) becomes maximum. Finally, the position where the sum of the correlation coefficients is maximum is used as an estimate of the receiver position coordinates, $(X, Y, Z)$.

### 4. Performance Evaluation

Table 1 shows the simulation parameters.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Width of the room</td>
<td>5.0 [m]</td>
</tr>
<tr>
<td>Length of the room</td>
<td>5.0 [m]</td>
</tr>
<tr>
<td>Height of the room</td>
<td>3.0 [m]</td>
</tr>
<tr>
<td>Number of LEDs</td>
<td>4</td>
</tr>
<tr>
<td>Average transmitted power per LED ($P_{trans}$)</td>
<td>72 [W]</td>
</tr>
<tr>
<td>Half-power semisine ($\Phi_{1/2}$)</td>
<td>60 [deg.]</td>
</tr>
<tr>
<td>Height of receiver from the floor ($h$)</td>
<td>0.85 [m]</td>
</tr>
<tr>
<td>Prime number of MPSC ($M$)</td>
<td>5</td>
</tr>
<tr>
<td>Physical area of receiver ($S$)</td>
<td>1.0 [cm$^2$]</td>
</tr>
<tr>
<td>Field of view</td>
<td>80 [deg.]</td>
</tr>
<tr>
<td>APD noise</td>
<td>10.0 [µW]</td>
</tr>
</tbody>
</table>

The positioning accuracy is evaluated by simulation. Both the triangulation location and the optical fingerprint are used for positioning under the same conditions. In this simulation, it is assumed that the influences of background noise and reflection signals from a wall are nominal.
The receiver position is estimated at intervals of 20 [cm].

The number of observation points is 676 (26 × 26). The positioning accuracy is evaluated for four kinds of placement patterns of LEDs. In Pattern 1, four LEDs are installed in a general regular square shape. Pattern 2 is a shape obtained by rotating Pattern 1 by 45 degrees. In Pattern 3, four LEDs are arranged in an inverted Y shape. In Pattern 4, four LEDs are located along a straight line. Figure 5 shows the placements of LEDs and the average positioning errors of the triangulation location scheme and the optical fingerprint scheme. Figure 6 shows the positioning error distribution of Pattern 1 for the triangulation location scheme. Figure 7 shows the positioning error distribution of Pattern 3 for the optical fingerprint scheme.

In Fig. 5, it is seen that the positioning accuracy depends on the placement pattern of LEDs. In Pattern 4, since multiple estimated positions exist, the positioning decision is not provided. Regarding the average positioning error and root mean square error of the triangulation location scheme, Pattern 1 is better than the other three patterns. In the optical fingerprint scheme, Pattern 3 is the best among the four patterns. The most suitable placement pattern of LEDs for the optical fingerprint scheme differs from that for the triangulation location scheme in that the optical fingerprint uses the signals received from all LEDs. The positioning accuracy of the optical fingerprint scheme with Pattern 3 is the same as that of the triangulation location scheme with Pattern 1.

Moreover, in Fig. 6, the variance of the positioning error is small, but there are many points where the positioning error is large. On the other hand, in Fig. 7, the variance of the positioning error is large, but there are many points where the positioning error is small. From these results, it was found that the number of points with a small positioning error affects the positioning accuracy.

5. Conclusions

In this paper, we proposed a positioning system, that is, the VN-CSK communication-based optical fingerprint scheme. Moreover, we evaluated the positioning accuracy of the triangulation location scheme and the optical fingerprint scheme. As a result, it was found that optical fingerprint positioning using the VN-CSK system is possible. Moreover, it was found that the positioning accuracy of the optical fingerprint scheme is greater than that of the triangulation location scheme.

In future work, we will consider a fusion system of the optical fingerprint scheme and the triangulation location scheme. Moreover, we will investigate the positioning performance taking into account the effect of the reflected signal from the wall. Furthermore, we will also investigate a positioning scheme using the TOA to derive the communication distance.

### Acknowledgment

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References


