Position Estimation Method Using Directional Amplitude Modulated Pulsed Light with Simulation Based on Real Environment Measurements

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Abstract. We propose a position estimation method using directional amplitude-modulated pulsed light based on real-world measurements and their simulation as a position estimation method that can be used in small drones. The proposed method enables highly accurate position estimation in a real environment using commercially available LEDs and photodetectors.
Keywords: Location Estimation System , Simulation System , Modulation signal measurement technology

1. Introduction

In recent years, unmanned aerial vehicles (UAVs) have been studied in various fields such as agriculture and logistics. In actual society, UAVs have also started to be used in various fields such as surveying and disaster investigation[1]. At present, the actual use of UAVs is generally based on the assumption that they will be operated by a single aircraft. In order to further expand the use of UAVs in the future, technology for cooperative flight of multiple aircraft is required. For example, in the field of agriculture, it is necessary to take images from various angles in order to obtain an accurate 3D model of each individual plant[2][3]. Rather than using a single UAV to capture images from multiple viewpoints, it is better to use multiple UAVs to capture images of a single object to reconstruct the 3D model because it eliminates the effects of wind and time. This is more suitable. In order to perform cooperative flight with multiple UAVs, self-position estimation of each UAV is necessary. This can be achieved by existing methods using optical motion sensors and GNSS[4] . However, there are drawbacks to these existing methods. Optical motion sensors can only be used in a limited, known indoor space because multiple cameras need to be installed and calibrated in advance. In addition, a high-performance computer is required to estimate the position in real time, and the cost is high. On the other hand, GPS is less costly, but it cannot be used indoors because its position estimation accuracy is basically degraded by various factors such as multipath. To solve these problems related to self-positioning, an inexpensive position estimation system that can be used both indoors and outdoors is needed. A position estimation method using amplitude-modulated pulsed light exists as a possible solution to the aforementioned problems[5]. However, the existing method assumes a point light source as the source of the light used for estimation, making it difficult to use easily. In this study, we apply the existing 3D position estimation method using amplitude-modulated pulsed light and propose a system that can be used in practice by integrating it with simulation using data measured in a real environment when a directional light source is used.

2. Related Research

2.1.1 Formation flight using GNSS

Device parts for use in position estimation using GNSS are attractive in that they can be installed at a relatively low cost. In addition, GPS in a format that does not use reference points is highly convenient in that it does not require any special preparation[6]. However, it is less accurate because estimation errors may be caused by multipaths such as satellite orbits, weather, and buildings. It is not accurate enough for controlling UAVs, especially in dense areas. The problem with RTK-GPS with high accuracy is the cost of preparation work by each location due to the preparation of reference points and the high financial cost of the device itself.

2.1.2 Formation flight using optical motion sensors

Optical motion sensors are characterized by their high sampling rate compared to other positioning systems. Previous research has developed cooperative flight of UAVs using optical motion sensors, such as the "Micro Quadrotors" developed by the GRASP Lab at the University of Pennsylvania and KMel Robotics, and presented formation flight using optical motion sensors[7]. Micro Quadrotors" can perform coordinated flight with an accuracy of a few centimeters using about 20 UAVs.

2.1.3 Other typical location estimation methods

Other typical position estimation methods that can be used for UAV formation flights include those using depth cameras, stereo cameras, and laser scanners. Existing research includes examples on UGV (Unmanned Grand Vehicle) using the aforementioned methods; in the UGV example, a laser scanner is used to perform autonomous control with position estimation on an agricultural vehicle[8]. Another example is a UGV that uses a 3D distance and image sensor, Kinect, to recognize the target position and control the vehicle to follow it. UAVs are more challenging than UGVs because the cooperative flight of UAVs requires measuring and recognizing the environment as a 3D space. To measure the 3D space, a 3D laser scanner is necessary. However, 3D laser scanner equipment is expensive and heavy. However, the 3D laser scanner equipment is expensive and heavy, and the computer used for the processing generally requires high performance, making it difficult to mount on a small UAV from the viewpoint of weight[9].

2.2.1 Indoor Location Estimation Method Using Visible Light LEDs with Multiple Light Receivers

There exists research on location estimation methods using received signal strength (RSS), which varies with transmission distance and angle[10]. In this study, in order to estimate the position, the position code of the transmitter is received by a receiver whose multiple positional relationships are known. This study shows that in a 2m x 2m x 2m room environment, a position error of less than 1.5cm can be obtained for a symmetric circular pattern and is feasible for an asymmetric circular pattern. However, this study assumes a specific plane in 3D space, and furthermore, it does not mention the receiver's orientation.

2.2.2 Position Estimation Method Using Amplitude Modulated Pulsed Light

A study of an existing method for position estimation using amplitude modulated pulsed light is presented[5]. The method uses an infrared signal with a waveform of amplitude modulation whose energy decays with time and pulse modulation of 38 kHz to reduce interference for 3D position estimation. The self-position transmitter for this method consists of an infrared LED, a small battery power supply, and a simple signal generation circuit. The device on the receiving end of the signals for position estimation consists of an infrared receiving sensor equipped with a filter circuit and a signal receiving circuit including a microcontroller. Both of these methods are smaller and cheaper than any of the methods described above. However, it is assumed that the self-positioning LED is always at a certain relative angle to the point source or receiver. Therefore, it is difficult to actually perform 3D position estimation regarding relative position and angle. Therefore, in this research, we propose a solution to this problem. For this purpose, existing methods will be explained in more detail.

When an amplitude modulation signal is output from a transmitter, the time of the signal that can be received by the receiver changes according to the distance. When the distance between the transmitter and receiver is changed, the light-receiving time of the signal becomes shorter with distance due to the characteristics of amplitude modulation. In addition, the energy per unit area of light received changes according to the angle the light receiving element surface is facing, so the time of the signal that the light receiving element can receive changes according to the angle.

When the sensor has a certain light-receiving time, the source can be estimated to be at a position on a quadratic curve whose variables are distance and angle (α and β are dependent and one-dimensional). figure.1 shows that the position of the transmitter can be estimated when sensor A is 3ms and sensor B is 1ms.

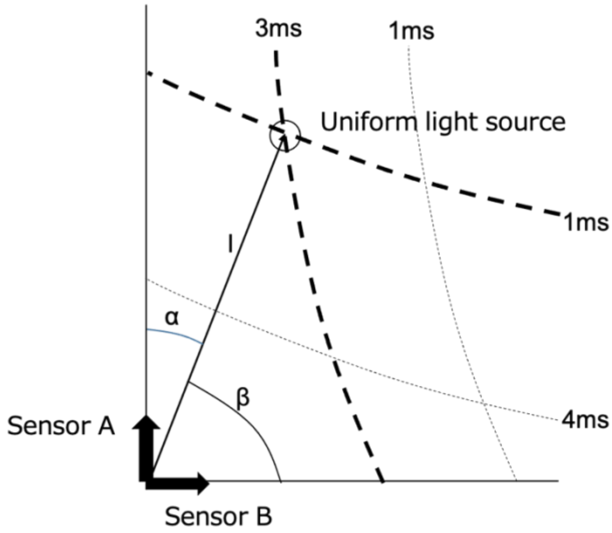


Figure1. Image of a point light source position estimation

When considering a point light source, if the distribution of output energy is not uniform with respect to the angle, there will be a decrease in accuracy. Keeping a constant relative angle at all times will limit the use of the system.

In order to solve the above problems of existing methods, the proposed method assumes that a general directional LED is used as the transmitter, and it can be used realistically by using measurements and simulations in real environments.

3. PROPOSED METHOD

The proposed method is an application of the position estimation theory using amplitude-modulated pulsed light, which assumes a point light source with a uniform light energy output with respect to the angle of the existing method, and uses a transmitter with a common LED with different output energy with respect to the angle. Furthermore, this method is one whose availability is reinforced by real-world measurements and simulations.

In section 3.1, we explain the theory of the proposed method assuming a two-dimensional space for simplicity, and in section 3.2, we explain the extension to three dimensions, which is assumed in actual use.

The proposed method consists of two types of devices: a transmitter (LEDs and a control unit) and a receiver (a light receiving sensor and peripheral circuits including a microcomputer). The transmitter consists of a control unit for generating amplitude-modulated pulse signals and one or more LEDs. As the number of LEDs increases, the distribution of light energy intensity with respect to distance and angle in space becomes more complex. However, multiple LEDs can be used to output energy over a wide area, thus increasing the range of position estimation. However, since LEDs are not point light sources with uniform output energy with respect to angle, the value of the LED output energy measured by the receiver varies depending on the two parameters of distance and angle. The receiver consists of sensor modules and peripheral circuits that receive and demodulate amplitude modulated pulse signals, and the more sensors are used, the more accurate the position estimation becomes.

The basic principle is the same as the method of position estimation using amplitude-modulated pulsed light described in the related research, where the LED outputs amplitude-modulated pulsed light and the light-receiving time of the signal received by the sensor shortens with angle and distance.

3.1 2D version of the theory

First, we explain how to use the proposed method to estimate the position in two dimensions. Figure 2 shows the geometric relationship between the transmitter and receiver.

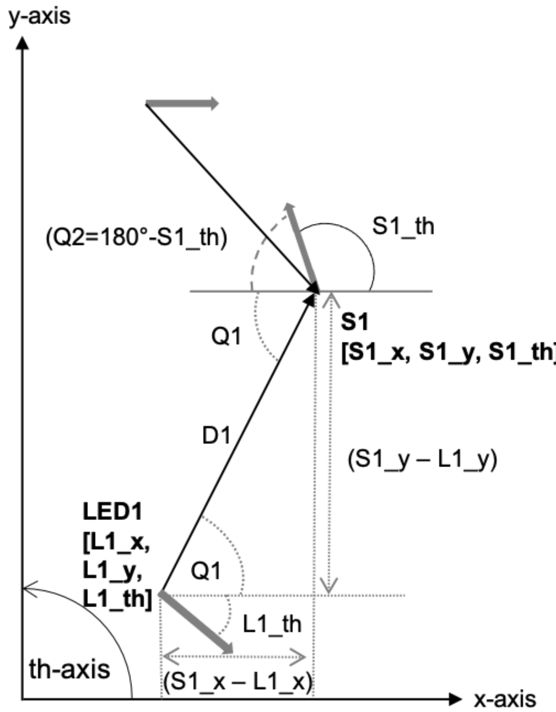


Figure2. Geometric relationship between transmitter and receiver

Let's discuss Figure 3.

The angle between the position of the LED and the optical axis in the plane coordinate system is expressed as follows (L1_x , L1_y , L1_th)

Similarly, the position of the receiver and the angle of the optical axis are expressed as follows (S1_x , S1_y , S1_th)

The light-receiving energy (number of light-receiving pulses ・ light-receiving time) of a single sensor is shown in Eq (1) below.

$$\mathrm{L1\_P} \times \mathrm{V} \times \frac{1}{D1^2} \times \mathrm{FL}(\mathrm{L1\_}th + \mathrm{Q1}) \times \mathrm{FS}(\mathrm{Q1} + \mathrm{Q2}) \quad \cdots (1)$$

・L1_P: Output time (number of pulses) of one wave tone output from LED

・V: Signal arrival rate coefficient considering light scattering, etc.

・D1: Distance between LED and sensor

・Function FL: (Output characteristic of energy against the angle of the LED)

・Function FS: (Input characteristic of energy against the angle of the sensor)

The light-receiving pulse of the sensor can be calculated by using the eq (1) . An image of the energy distribution of a directional LED, which is an important topic in this project, is shown in Figure 3.

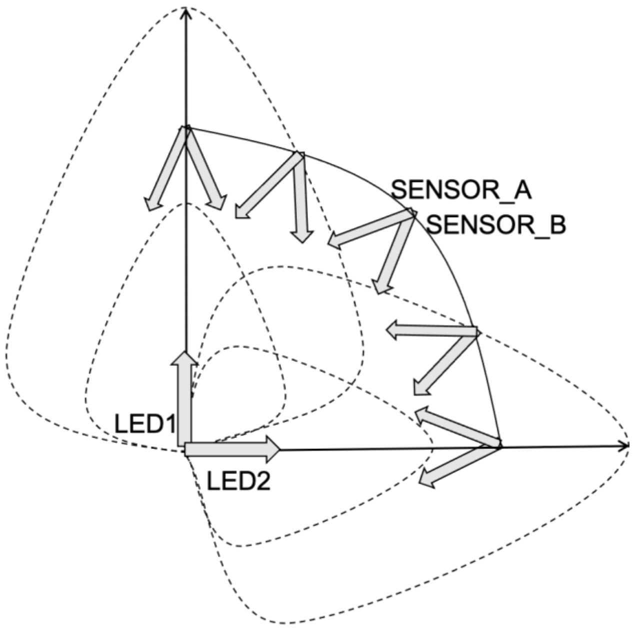


Figure. 3 Location estimation image of directional LEDs.

As shown in Figure. 3, the relative position and angle cannot be defined to a single point just by using the same two sensors due to the relationship between the transmitter and receiver. This is because there are not enough dimensions in two sensors to define the three dimensions: x-coordinate, y-coordinate, and angle. Here, by appropriately adding sensors in independent directions, the position can be defined to a single point.

Then, the relative position of the transmitter, including the angle, can be identified using the three light-receiving times as in related research 2.2.2.

3.2 3D version of the theory

The proposed method for the 2-D version shown in 3.1 is extended to 3-D space. The formula is the same as in 2D, but the method of calculating the angle is different because it is 3D, but it is obvious due to the geometric derivation. The output signal strength of the LEDs decays with distance and angle. The input signal strength of the sensor has a specific characteristic for the angle. One of the characteristics of 3D position estimation is that the relative position must be estimated in three dimensions, defined by x, y, and z coordinates, and two dimensions of angle, for a total of five dimensions of information. Therefore, in order to determine a single point in the estimation space, it is basically necessary to use five appropriately placed sensors. However, if the estimation space is limited to a small area, or if the method uses time series data (time dimension), five sensors are not necessarily necessary.

4. EXPERIMENT

4.1 Simulation Implementation

The equipment used to run this simulation program is as follows:

・MacBook Air (13-inch, 2017)
・Processor 1.8 GHz dual-core Intel Core i5
・Memory 8 GB 1600 MHz DDR3
・The development and execution environment is as follows
・Xcode: Version 12.4 (12D4e)
・Language: C++

The theoretical equations shown in the proposed method are written as a program to be iterative process and executed on a computer field.

About consideration of computational complexity:

We now consider the computational complexity. The assumptions are a transmitter consisting of three LEDs and a receiver consisting of three photosensors.

Assuming that the estimated range space (x-coordinate 0-100cm,y-coordinate,0-100cm,z-coordinate,0-100cm,)*estimation accuracy 1cm, estimated angle (θ: 0-90deg, φ: 0-90deg), n LEDs × m sensors.

Assuming that the position of the LEDs is fixed at the origin. Relative position (x-y-z axis) 0cm-300cm in space, 1cm apart in a grid pattern

LED angle (θ,φ) is 0-180°. The angle of the sensor (θ, φ) is 0-180°.

Given that

$$n \times m \times 300^3 \times 180^4 \quad \cdot \cdot \cdot (2)$$

This is practically difficult because it requires calculations on the order of 10^{17}. Therefore, we will use the Monte Carlo method and set the parameters randomly by random numbers to obtain some accuracy in a realistic time.

4.2 Verification of measurements and simulations using real devices

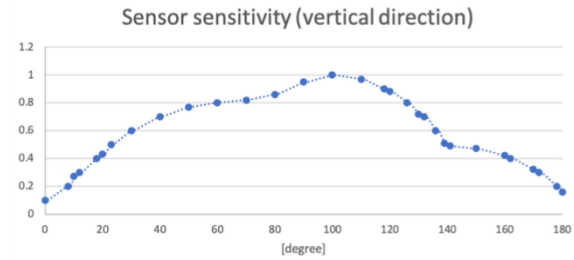
The following is a description of the main equipment used in the measurement experiments. In this experiment, we measured Vishay's TSSP58038 as a photodetector. Figure 4 shows the image of TSSP58038.

Figure4. The photodetector (TSSP58038) used in the experiment

Figure 5 shows the straight rail and digital protractor used to aid in the measurement.

Figure5. Straight rail and digital protractor

We examined the photosensitivity characteristics of the photosensor against the angle. Graph 1 shows the photosensitivity against angle (height direction).



Graph1. Sensor sensitivity(vertical direction)

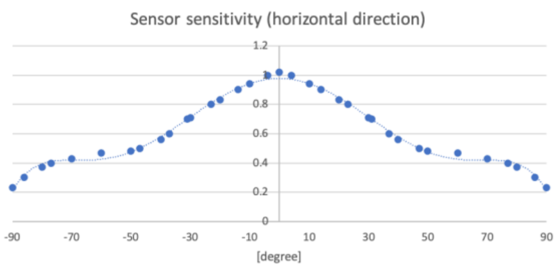
The approximate formula of photosensitivity against angle is shown in two parts from Graph 1.Approximate formula for photosensitivity to angle with respect to 0-100°.

$$y = -8 \times 10^{-12}x^6 + 10^{-9}x^5 - 7 \times 10^{-9}x^4 - 10^{-5}x^3 + 4 \times 10^{-4}x^2 + 1.27 \times 10^2 x + 0.0976 \cdots (3)$$

Approximate formula for photosensitivity to angle with respect to 100-180°.

$$y = 2 \times 10^{-10}x^6 - 2 \times 10^{-7}x^5 + 6 \times 10^{-5}x^4 - 1.11 \times 10^{-2}x^3 + 1.1471x^2 - 62.265x + 1393.3 \cdots (4)$$

Graph 2 shows the photosensitivity against angle (horizontal direction).



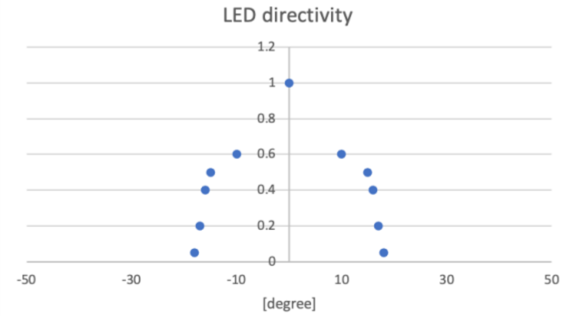
Graph.2 Sensor sensitivity (horizontal direction)

$$y = -5 \times 10^{-12}x^6 + 7 \times 10^{-20}x^5 + 8 \times 10^{-8}x^4 - 10^{-15}x^3 - 4 \times 10^{-4}x^2 + 8 \times 10^{-13}x + 0.9782 \cdots (5)$$

Figure 6 shows the 5 mm infrared LED with a half angle of 30 degrees used in the experiment.

Figure 6: Image of a 5 mm infrared LED with a half angle of 30 degrees.

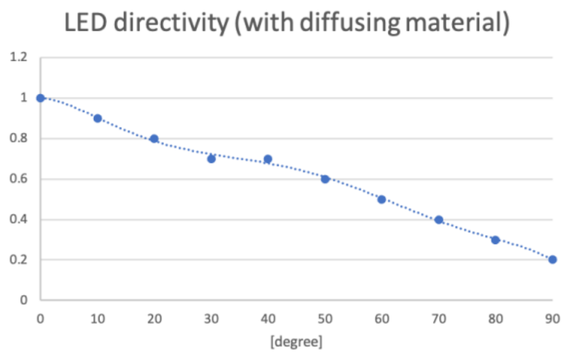
The luminescence energy characteristics of the LED against angle were investigated. Graph 3 shows the angular characteristics of the LEDs used in this experiment.



Graph.3 Emission angle characteristics of LED

From Graph 3, it was found that with the LED as it is, the light energy in the front is very strong and the sides cannot be used for estimation.

Therefore, we decided to use a light diffuser on the LED to disperse the light energy to the sides. The measured results of the energy against the angle of the LED are shown in Graph 4.



Graph.4 LED directivity(with diffusing material)

As a result of the measurements, we decided to use a model that calculates the output energy based on the angle from the optical axis for any direction, with the front surface being 0°. Therefore, the graph from 0° to 90° and the approximate formula to calculate the output factor from the angle are shown below.

$$y = -6 \times 10^{-11}x^6 + 10^{-8}x^5 - 10^{-6}x^4 + 6 \times 10^{-5}x^3 - 1 \times 10^{-3}x^2 + 1.63 \times 10^{-2}x + 0.1994 \quad \cdots(6)$$

It is expected that the approximate equation using the data obtained from the above experiments can be used to determine the appropriate placement of LEDs and sensors through simulation.

4.3 Device design using simulation

If the following items are known or can be measured by preliminary experiments, it is possible to simulate how the device will behave in the estimated range.

・The relationship between the position and angle of multiple LEDs

・Output characteristics of a single LED depending on its angle

・Relationship between the position and angle of multiple sensors

・Output characteristics of a single sensor depending on its angle

・Waveform of the amplitude modulation of the transmitter

・Range of the estimated space to be sought (coordinates and angle)

In order to estimate the position in the space to be defined using the simulation, it is possible to determine how many LEDs of the transmitter and how many sensors of the receiver should be installed at what position and angle, respectively. In addition, by using simulation, we can understand how accurately we can estimate the relative position and posture of the LEDs and sensors in the defined space, in relation to their positions and angles.

In the future, by inputting the range and accuracy of the space to be estimated, it will be possible to output the required number of LEDs and sensors and the optimal placement (angle).

5 Conclusion

We proposed a position estimation method using amplitude-modulated pulsed light with directionality based on measurements in a real environment and its simulation as a position estimation method that can be used in small drones. Since the emission and reception characteristics of actual LEDs and sensors vary from product to product, it is essential to measure and simulate each product independently in order to improve the accuracy of position estimation. In addition, there is still potential for further development in simulation, and further research will improve the accuracy and convenience.

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