VISIBLE LIGHT COMMUNICATION LOCALIZATIONIN UNDERGROUND MININGRESCUE

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Abstract - In the traditional mine rescue, relying on manual mining to rescue the trapped miners is not only inefficient but also increases the risk factor of the rescuers. However, the obstacles distribute in mining, and it is difficult to determine the real-time position of the trapped miners. Unmanned aerial vehicle (UAV) is considered as the primary selection; it can enhance the efficiency in the mining rescue. This paper presents a visible light communication (VLC) localization rescue system based on multi-UAVs. The location of UAVs can be transmitted to the cloud server. Analysis of multi-UAV's positions and online trajectory predictions are also carried out in the cloud. Experimental data verified the accuracy of the selected localization algorithm. Results demonstrate that multi-UAVs can be located by visible light communication, and their trajectory optimization can be realized in the cloud so that the accuracy of position is improved and the localization information can be stored in the cloud. This study provides references in the fields of system modeling, minimizing the localization estimation error, and information exchange for solving the contradiction between the low efficiency of positioning and the randomness of trajectory acquisition, subsequently realizing the application of visible light communication based on multi-UAVs in underground mining rescue.

Keywords - Visible Light Communication, UAV, Underground Mining Rescue, Cloud Storage.

I. INTRODUCTION

In recent years, with the rapid development of the mining industry, the sudden gas explosion and collapse under the mine will result in accidents to miners. Once the accident has happened, monitoring the disaster environment and locating the trapped people become difficult in underground mining. Among many positioning methods, Global Navigation Satellite System (GNSS) and Global Positioning System (GPS) tend to be mature.

However, in relatively closed space such as mining, the radio signal is almost completely blocked, and the received positioning signal is also weak, resulting in inaccurate positioning, so GPS and other satellite positioning technologies are difficult to be applied to mining rescue [1]. At present, the visible light communication (VLC) has been developed rapidly. The LEDs are consideredas the lighting conditions in the VLC system.VLC positioning does not need to arrange unique emission points. Therefore, with the advantages of low power consumption, high positioning accuracy, low cost, wide application occasions, and no electromagnetic interference, visible light communicationlocalizationsystem can be used in underground mining.

Every fifteen seconds, a worker suffers a disaster or disease in the miningwhere it is inherently more dangerous than others working environment and working in the mining also meetsthe risk and threatening situations [1].There are some uncertain factors in the environment, such as obstacles and the random selection of UAV's trajectory. These factors can affect the accuracy of the drone's positioning and the stability of the attitude in underground mining. Therefore, we propose a real-time three-dimensional positioning system based on the UAV, visible light communication, and cloud server technology. In the system, the UAV will apply VLC to locate its position and transmits the positioning information to the cloud in real-time in order to perform trajectory prediction and location storage in the cloud, which can improve the rescue efficiency in mine rescue.

The remainder of this paper is organized as follows. The second section introduces the related work on positioning solutions and UAV attitude control. The third section mainly constructs three-dimensional VLC positioning systems, multi-UAV online trajectory prediction in the cloud in order to achieve trajectory predictionduring dynamic flight. The fourth section focuses on experimental measurements and results analysis. Finally, this paper summarizes the relevant conclusions.

II. RELATED WORK

Scholars have studied how to use visible light communication and UAVs to locate the position of the trapped people. In the literature, there are some publications related to positioning theory and the application of UAV in positioning [2]-[16].

Regarding different positioning methods, Global Positioning System (GPS), Radio Frequency Identification (RFID), Wireless Fidelity (Wi-Fi), and

ZigBee have been preferred to provide positioning [2]-[9]. In [2]-[7], GPS was ineffective in the underground mining environment, which was due to building materials that tend to block signals, and mobile terminals were unable to process beacons sent from satellites. In [13], a method was proposed to locate the vehicle equipped with an RFID reader in the underground environment by using particle filter and passive RFID tag, to solve the problem of node location and estimate the distance of error position estimation is about 5m. In the underground mining tunnel, the work proposed in [8] utilized the location of mobile nodes with the Wi-Fi network. Owlps (OWL positioning system)is used to track miners who encounter accidents, but the transmission of radio signals is a problem. In [9], a kind of underground positioning system based on ZigBee technology, ZigBee equipment determined the position of the miners through the real-time algorithm based on the received signal strength indicator (RSSI). However, the average position estimation error is quantized to about 2.5m.

Huang and Savkin [10] assumed that the user's location is unknown, use the automatic UAV to measure the received signal strength, determine its location, and share information with other UAVs nearby. In [11], Huang and Savkin proposed a distributed algorithm to detect the optimal local coverage of UAV. In [12], Huang and Savkin designed motion decision-makers, and they proposed a decentralized navigation algorithm to locate the new location of UAV in three-dimensional space.

III. VISIBLE LIGHT COMMUNICATION VIA MULTI-UAV LOCALIZATION

Visible light communication is based on the LED optimal wireless communication (OWC) system [15-19]. With the development of laser diode (LD), LED devices have developed rapidly with high efficiency and brightness. As the primary transmission source in the conventional VLC system, LED devices with such characteristics have their transmission speed increased to the Mbps level [14]. With the dual function of lighting and communication, the visible light communication system can be widely used in the underground mining rescue to realize the fast location of trapped miners and reduce the rescue time.

The three-dimensional positioning system based on the VLC consists of an LED transmitter installed on the ceiling of mine channel and receiver installed at the top of the UAV. In the receiver, it contains a photodiode (PD) primary trans-impedance amplifier circuit and an I/V conversion amplifier circuit. Sincethe length of the LED is smaller than the transmission distance of the actual optical signal, it is often analyzed as a Lambert body, as shown in Figure 1.

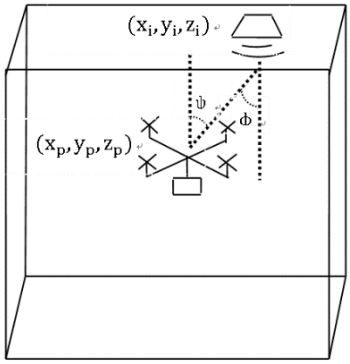


Figure 1: Visible light communication (VLC) channel model

If the Lambertian radiation modelis considered in the VLC system, the model of impulse response can be describedwith same type with the Lambertian radiation model. The optical signal transmission characteristics between the transmitter and the receiver, and its transfer function can be calculated. LED acts as the illumination signal source, and the line of sight (LOS) link is also used. However, the visible light communication system is not an ideal direct link channel. Objects with reflective properties such as walls, coal, and black obstacles can have diffuse reflection and multi-path effects on optical signals, so the transfer function of diffuse reflection channels can be calculated as (1).

$$H_{LOS}(0)_{ref} = \begin{cases} \frac{A_r \rho (m_t + 1)}{2\pi d^2} (\cos\alpha \cos\beta \, dS_f) \cos^{m_t}(\varphi) T_s(\psi) g(\psi) \cos^{m_r}(\psi), \\ \qquad if \quad 0 \le \psi \le \psi_C \\ 0, \\ \qquad if \quad \psi > \psi_C \end{cases} \tag{1}$$

where ρ is the coefficient related to the reflective material of the UAV, dS_f is the area micro-element of thereflector.α and $\beta$are the incident angle and the outgoing angle of the reflected light signal, respectively. A_r is the effective sensitive receiving area of photo-diode (PD), d is the distance between LED and the photo-detector (on the surface of UAV), ψ_C is the optical receiver viewing angle, m_r and $m_t$are the Lambertian radiation pattern number, φ the illumination angle or radiation angle, $\varphi_{1/2}$ is the half power angle of the transmitter, ψ is the incident angle or receiving angle of LED, $T_s(\psi)$ is the receiver filter gain, $g(\psi)$ is the condenser lens gain, and n is the refractive index.

$$g(\psi) = \begin{cases} \frac{n^2}{\sin^2 \psi_C}, & \text{if } 0 \le \psi \le \psi_C \\ 0, & \text{if } \psi > \psi_C \end{cases} \tag{2}$$

The three-dimensional localizationis described in Figure 1, Figure 1shows that the expression of LED radiation angle in (3).

$$\cos\varphi = \frac{z_i - z_p}{\sqrt{(x_i - x_p)^2 + (y_i - y_p)^2 + (z_i - z_p)^2}} \tag{3}$$

where $(x_i, y_i, z_i)(i = 1,2,3)$ and (x_p, y_p, z_p) are the coordinates of LED1', LED2', LED3'and the UAV respectively.The IV conversion module is located at the center of the UAV. The purpose is to maintain the attitude balance of the aircraft by using the UAV's inertial measurement unit (IMU). On the other hand, the IV conversion PD is always parallel to the roof of the mine, so that $\cos\varphi = \cos\psi$ can be satisfied. Therefore, the impulse response of the system can becalculated in using (4).

$$H_{LOS}(0) = \frac{A_r(m+1)T_s(\psi)g(\psi)(z_i - z_p)^{m+1}}{2\pi[(x_i - x_p)^2 + (y_i - y_p)^2 + (z_i - z_p)^2]^{\frac{m+3}{2}}} (4)$$

Based on the above analysis, a distance measurement model based on received signal strength indication (RSSI) is constructed. RSSI indicates the signal strength at the receiving end of the illumination intensity. The distance between the nodes can be estimated by the received signal power and signal strength. In (5), it can be shown that the relationship between the light intensity (RSSI) and d, and further positioning analysis is performed based on the obtained results [19].

$$RSSI = P_r = -[P_t(d) + 10nlgd] (5)$$

The actual value of the distance d between the LED and the photodetector (PD) (on the surface of UAV) can be calculated in (6).

$$d = \left[\left[\frac{P_t A_r(m+1)T_s(\psi)g(\psi)(z_i - z_p)^{m+1}}{2\pi P_r}\right]^{\frac{1}{m}+3}\right] (6)$$

Under practical conditions, this distance is estimated based on the received and transmitted power and specific channel parameters; therefore, channel estimation is required. An experimental method of estimating channel parameters is based on placing one PD at different locations and measuring the received power. In order to calculate the position, the VLC mobile device uses a digital processor to perform trilateration. This goal is to locate the position of the UAV in equal spacing, and the UAV's position (the calculated position) is send to the dispatching center in real-time via the access point coordinated with the visible light communication system.

Multiple rescue UAVs can be in any position of the mine by using the three-dimensional trilateration positioning scheme based on visible light communication. To illustrate the principle of positioning, Figure 2 depicts a positioning system consisting of three LEDs and rescue UAVs. In the underground mining area, such system units can be installed. Each unit needs at least three LEDs to realize the three-dimensional positioning of multi-UAV.

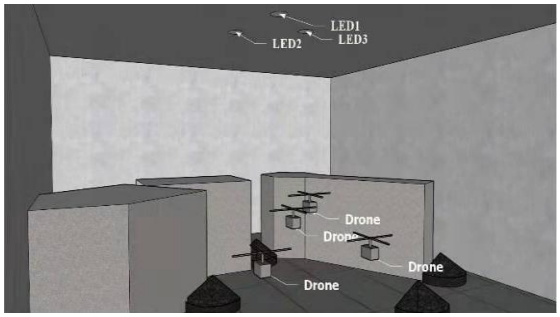


Figure 2: Schematic diagram of positioning system

For the three-dimensional positioning algorithm, the ternary method is used in the system, and at least three LED light source signals are required to calculate the position of UAVs [20]. In order to avoid mutual interference between LEDs, the time-division multiplexing method is adopted in the system to cycle the LED and collect the light intensity of the three LEDs acting on the UAVs separately. The geometric relationship between the LED and the UAVs is shown in Figure 3. The linear distance d between the UAV and the LED can be calculated from the light intensity. If the height of the LED is a specific value H, the distance r between the projection LED' on the illuminated object surface and the UAVs conforms to the Pythagorean law in (7).

The distance between UAV coordinates and three LED projection points LED1', LED2' and LED3' are R1, R2, and R3 respectively, it can be shown in Figure 3. In (8), it is the position relationship between the UAV and LED'. Where, $(x_i, y_i, z_i)(i = 1,2,3)$ and (x_p, y_p, z_p) are the coordinates of LED1', LED2', LED3'and the UAV respectively. The relationship between the distance d between the LED and the photo-detector (UAV), the height of the LED, and the projection LED' on the surface of the illuminated object is shown in (9).

$$R_i^2 + H^2 = d_i^2 (i = 1,2,3) (7)$$

$$R_i^2 = (x_i - x_P)^2 + (y_i - y_P)^2 (i = 1,2,3) (8)$$

$$(x_i - x_P)^2 + (y_i - y_P)^2 + H^2 = d_i^2 (i = 1,2,3) (9)$$

IV. ONLINE TRAJECTORT OPTIMATION

In underground mining, the visible light communication technology is used to locate UAV's position.In this case, multi-UAVs are utilized to find the trapped miners. Therefore, multi-UAVs trajectory navigation needs to be considered, and its goal is to avoid coincidence of search path by using multi-UAVs. Therefore, the method by using the average information gain and simulation landmark in the cloud is proposed, and it can be constructed a target function of UAV and adopted the extended Kalman filter-Simultaneous Localization and Mapping (EKF-SLAM) trajectory optimization combined optimal control algorithm to achieve the purpose of

approximate global optimization in [21].The selected objective function can be obtained by using (10).

$$J = \omega_1 \Delta I + \omega_2 S_n \quad (10)$$

where, ω_1 and ω_2 are the weight,the average relative information gain is calculated by using (11).

$$\Delta I = tr(\chi_k)/n_k - tr(\chi_{k+1})/n_{k+1} \quad (11)$$

where χ_k and χ_{k+1} are the state variance matrix of k and k+1 time. n_k and n_{k+1} representthe number of state variables in χ_k and χ_{k+1}.

The UAV observes the different number of landmarks at different times when the UAV finds the new landmarks, which makes the number of state variables change in real-time. In the system, the dimension of the variance matrix needs to be considered, the average information gain is added and it arts as the measurement of the uncertainty in positioning, so the uncertainty of the system can be accurately described, and the information gain can be more comparative at different times.

In the entire search area of underground mining S_n, There are m-th landmark which is distributed in the search area. We need to determine the average area $\bar{S} = S/m$ occupied by each landmark. The number of new landmarks observed by the UAV in underground mining is m_p, so the new exploration area can be obtained by using (12).

$$S_n = m_p \bar{S} = m_p (S/m) (12)$$

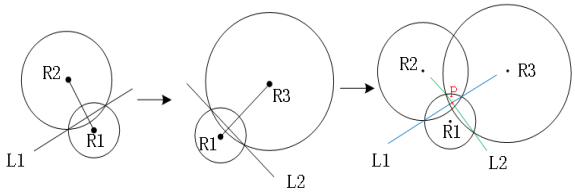


Figure 3: Distance relationship between actual position of UAV (P) and LED projection

Figure 3 shows that the position P is calculated by using (7), (8) and (9).However, the position of UAV(p) is a estimated position, there exits localization estimation error in the system. As for the localization estimation error, we propose anonline trajectory optimization in cloud and it can be shown in Figure 4, its goal is to minimize the localization estimation errorwhen the system is using the visible light communication to locate the position of UAV. In this method, the distance between LED and the UAV (intensity receiver) can be calculated, that is, the actual value $d_{act} = d.(x_i, y_i, z_i)(i = 1,2,3)$ is the coordinate of LED resource. The location estimation coordinate of the UAV (intensity receiver) is (x_p, y_p, z_p). However, in the actual system, it is impossible to minimize the positioning estimation error caused by additive Gaussian white noise (AGWN). Therefore, a location error correction method based on Newton-Raphson iterative algorithm is proposed. We assume the real estimated distance $d_{act(i)}$ in (13).

$$d_{act(i)} = d \pm \gamma_{(i)} (i = 1,2,3) (13)$$

where $\gamma_{(i)}$ is the white noise in the environment, and it is also a random variable and obeys continuous Gaussian distribution with zero-mean. The amplitude distribution of noise $\gamma_{(i)}$ is concentrated. The output offset of neural network is shifted to normal due to this noise in the environment, so the LED plane coordinate $(x_i, y_i, z_i)(i = 1,2,3)$ cannot be calculated in (13) at the same time. Based on the analysis of the geometric relationship in Figure 3, we assume that each LED is as the center, the circle formed by LED's projection may not intersect at a point. After analysis, the distance between LED and the UAV can be modified by Newton-Raphson iteration method.

In the system, the distance d trained by neural network method and the distance R between the projection LED' and multi-UAVs are given. The vertical distance H between the receiver and the LED can be calculated by using (14) and (15), and H is also the variation parameter. The actual heightz$_p$ of the UAV can be calculated in (15).

$$R_{act(i)} = \sqrt{\sum_{i=1}^{n} R_i^2} (14)$$

$$H_{act(i)} = \sqrt{d_{act(i)}^2 - R_{act(i)}^2} (i = 1,2,3) (15)$$

Based on the above analysis, after obtaining the estimated distance between the UAV and each LED, the location estimation coordinate of the UAV can be calculated by using (16) (this equation is a constraint equation), and the actual plane coordinate of the UAV can also be calculated.

$$(x_i - x_P)^2 + (y_i - y_P)^2 + H^2 = d_i^2 (i = 1,2,3) (16)$$

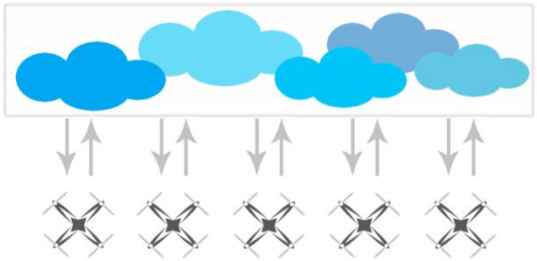


Figure 4: Location information exchange in the cloud

V. RESULT ANALYSIS AND DISCUSSION

Five random points are selected as the sampling points for location information acquisition. The

absolute position error of the UAV in x-axis and y-axis is shown in Table. 1.

Actual Coordinate		Measured Coordinate		Absolute Error	
X	Y	X	Y	X	Y
10.67	20.40	9.42	20.00	1.25	0.40
17.78	30.00	16.00	31.80	1.78	1.80
26.67	40.00	23.43	37.40	3.24	2.60
35.56	50.00	36.79	48.60	1.23	1.40
44.44	60.00	41.60	57.60	2.84	2.40

Table 1: Absolute error between actual position and measured position (unit: decimeter)

According to the proposed method, the experimental simulation is carried to locate the position of multi-UAVs in underground mining. Figure5 shows the proposed system and compares it with the other existing localization schemes in terms of the localization estimation error. The proposed system performances well compared with other three technologies (RFID, Wi-Fi and Zigbee). The average localization error for the visible light communication system is around 0.25m, and the accumulative approaches 100% within 1m. Therefore, the visible light communication system has a better performance for localization in underground mining.

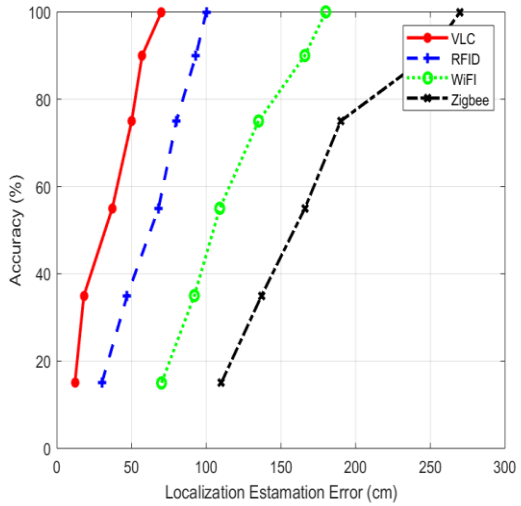


Figure 5: Performance comparison of VLC and other three technologies in termsof the localization estimation error (RFID, Wi-Fi and Zigbee)

The actual experiment is performed in simulated closed space. Assume that the obstacles with a height of two meters are randomly set in the actual testing site. The initial and end position is the same position[13,8,1.5]via [80,65,1.5] and [70,27,1.5] (unit: decimeter).

The multi-UAVs take off automatically and spontaneously searches the proper flight path. According to the intensity (RSSI) of the receiver, the position of the UAV can be in real-time to predict the next position to make sure that the UAV can select the optimal path from the starting point to the endpoint.

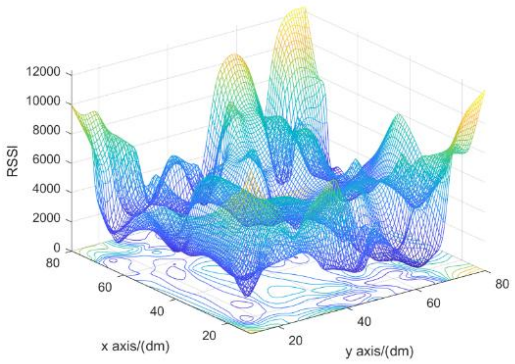


Figure 6: The light intensity distribution diagram

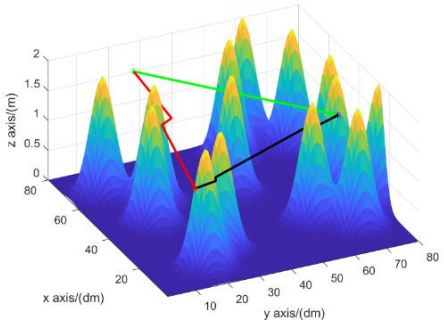


Figure 7: Online trajectory optimization (option 1)

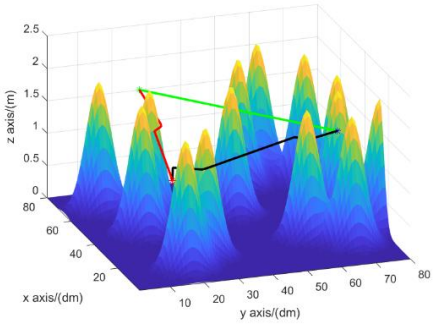


Figure 8: Online trajectory optimization (option 2)

Figure6, Figure7 and Figure8 show that the UAV will select the proper path by detecting the value of RSSI and the flight angel in the cloud. When the UAV meets the obstacle, the value of RSSI will increase, and the actual flight angel also increases. When RSSI decreases to the set-point, the UAV moves to accelerate in a clockwise or counterclockwise direction. When RSSI remains, the UAV remains in a clockwise or counterclockwise continually. Otherwise, when RSSI increases, and the actual flight angel is below the reference value, the UAV turns towards the target direction.

VI. CONCLUSION

Aiming at the problem that the UAV is difficult to achieve accurate positioning in underground mining,

this paper proposes a new type of positioning based on visible light communication technology, online trajectory optimization and cloud stage. The study and analysis of visible light communication positioning technology, the motion attitude analysis of the UAV, and actual path planning are carried out. However, we need to improve the information transmission speed in the actual experiment due to the limitation of environment and the actual altitude of the UAV also has limitations in the future study.

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