Application of Small Mobile Ground Station in UAV Location

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Abstract. Aiming at the problem that UAV can't locate accurately in the areas where the satellite navigation signal is poor or even lost, this paper proposes to establish a mobile ground station positioning system to realize the precise positioning of UAV in such areas. Mobile ground station positioning system is a new positioning concept, as a supplement to satellite navigation and positioning system, and a breakthrough to the existing ground-based reinforcement system fixed ground station, has greatly expanded the area and type of UAV mission execution, and further promoted the application of UAV in mission execution.

1. Introduction

Unmanned aerial vehicle (UAV) has the characteristics of strong mobility and flexible application. It can perform aerial reconnaissance, target search and precision strike in various weather conditions and harsh environments. Therefore, UAV has been widely used in both military and civilian fields.

UAVs perform their tasks on the basis of their precise position known. At present, most UAVs use satellite navigation and positioning. Satellite navigation signal has the advantages of long transmission distance and wide coverage, but as far as the current situation is concerned, there are still areas that can not be covered by satellite navigation signal. In addition, satellite navigation signals are vulnerable to interference and occlusion, which leads to more positioning errors in buildings, urban canyons, underground and jungle, and even unable to provide positioning services.

To reduce the coverage area of satellite-free signal and realize high-precision positioning of UAV in harsh signal receiving environment, many countries have carried out research on ground-based reinforcement system. Ground reinforcement system establishes a fixed ground station at a specific and appropriate location to assist satellite positioning or independent positioning. Although the ground reinforcement system can achieve the positioning of UAV and improve the positioning accuracy of UAV to a certain extent, but it is impossible to build the ground reinforcement station in the complex mountain areas and the harsh desert plateau areas because of the stringent requirements of the ground station location of the ground reinforcement system and the high requirements of the topography, geology and surrounding environment. Moreover, the enhancement effect of the ground reinforcement system will decrease with the increase of the distance between the UAV and the ground station.

In this regard, aiming at the location problem of UAV in areas without satellite navigation signal coverage and support from ground-based augmentation system, a maneuvering ground station positioning system for UAV is proposed to realize precise positioning of UAV in such mission areas.
2. Positioning Principle of Mobile Ground Station System

To establish the mobile ground station system, the location of the mobile ground station must be determined in the mission flight areas. Signal receiving equipment and maneuvering mode must be proper. Temporary ground station positioning system must be established in time. On the basis of multiple mobile ground stations, according to the different time of UAV signal arriving at each mobile ground station, use multi-point positioning technology\(^{[2-3]}\) to achieve precise positioning of UAV. Specifically, to achieve the three-dimensional positioning of UAV, at least four mobile ground stations should be installed, as shown in Figure 1. Assuming that the coordinates of UAV are \((x, y, z)\), the position coordinates of the four mobile ground stations are \((x_0, y_0, z_0)\), \((x_1, y_1, z_1)\), \((x_2, y_2, z_2)\) and \((x_3, y_3, z_3)\), the difference of the time when UAV signals reach different mobile ground stations and the coordinates of ground stations can be obtained as follows: hyperbolic equations can be obtained by solving the equations, and the three-dimensional position coordinates \((x, y, z)\) of UAV can be obtained.

\[
\begin{align*}
\Delta t_{10} \cdot c &= \sqrt{(x_0-x)^2 + (y_0-y)^2 + (z_0-z)^2} - \sqrt{(x_1-x)^2 + (y_1-y)^2 + (z_1-z)^2} \\
\Delta t_{20} \cdot c &= \sqrt{(x_0-x)^2 + (y_0-y)^2 + (z_0-z)^2} - \sqrt{(x_2-x)^2 + (y_2-y)^2 + (z_2-z)^2} \\
\Delta t_{30} \cdot c &= \sqrt{(x_0-x)^2 + (y_0-y)^2 + (z_0-z)^2} - \sqrt{(x_3-x)^2 + (y_3-y)^2 + (z_3-z)^2}
\end{align*}
\]

(1)

Here, \(c\) is the speed of light. Each equation determines a hyperboloid in three-dimensional space. The intersection of the hyperboloid is the position of the UAV, as shown in Figure 2.

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{Figure1.png}
\caption{System schematic}
\end{figure}

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{Figure2.png}
\caption{Positioning schematic}
\end{figure}
The mobile ground station system can solve the problem of UAV positioning without good satellite navigation signal and enhanced signal coverage area, and has the following advantages:

1) Good environmental adaptability. Because the mobile ground station system is temporarily erected for short-term and specific tasks of UAV, there are no strict geological and environmental constraints compared with the ground station used in the ground enhancement system, and the station can be built in time according to needs.

2) Good compatibility. As long as the layout of the ground stations can meet the positioning requirements, all the systems in the area can be positioned.

3) Reused with low erection cost. When the UAV mission is completed, the existing ground station is dismantled and recycled, and a set of equipment can be used many times, which greatly saves the cost of building the station.

4) High positioning accuracy. By optimizing the layout of the existing ground stations and improving the ranging accuracy, the positioning accuracy in the positioning area is less than 10m.

However, the mobile ground station system also has regional limitation. Because the limited distance of signal transmission, both ground station system and satellite navigation system are effective in a certain area, which is not wider than that satellite navigation system.

3. Derivation and Calculation
Let \( \Delta r_i = \Delta r_{i0} \cdot c \) (i=2,3,4), the formula (1) can be simplified as follows:

\[
\Delta r_i = \sqrt{(x_0-x)^2 + (y_0-y)^2 + (z_0-z)^2} - \sqrt{(x_i-x)^2 + (y_i-y)^2 + (z_i-z)^2}
\]

Differentiation on both sides of equation (2) is obtained:

\[
d\Delta r_i = \left( \frac{x-x_0}{r_0} - \frac{x-x_i}{r_i} \right) dx + \left( \frac{y-y_0}{r_0} - \frac{y-y_i}{r_i} \right) dy + \left( \frac{z-z_0}{r_0} - \frac{z-z_i}{r_i} \right) dz \quad (i=1,2,3)
\]

Formula (3) is written in matrix form as follows:

\[
R = H \cdot X
\]

here,

\[
H = \begin{bmatrix}
x-x_0 & x-x_1 & y-y_0 & y-y_1 & z-z_0 & z-z_1 \\
\frac{1}{r_0} & \frac{1}{r_1} & \frac{1}{r_0} & \frac{1}{r_1} & \frac{1}{r_0} & \frac{1}{r_1} \\
x-x_0 & x-x_2 & y-y_0 & y-y_2 & z-z_0 & z-z_2 \\
\frac{1}{r_0} & \frac{1}{r_2} & \frac{1}{r_0} & \frac{1}{r_2} & \frac{1}{r_0} & \frac{1}{r_2} \\
x-x_0 & x-x_3 & y-y_0 & y-y_3 & z-z_0 & z-z_3 \\
\frac{1}{r_0} & \frac{1}{r_3} & \frac{1}{r_0} & \frac{1}{r_3} & \frac{1}{r_0} & \frac{1}{r_3}
\end{bmatrix}
\]

\[
X = \begin{bmatrix}
dx \\
dy \\
dz
\end{bmatrix}
\]

\[
R = \begin{bmatrix}
d\Delta r_1 \\
d\Delta r_2 \\
d\Delta r_3
\end{bmatrix}
\]

Left multiplied the Transfer Matrix of H on both sides of formula (4), we can obtain:
\[
X = (H^T H)^{-1} H^T R
\]

Let
\[
(H^T H)^{-1} = B = \left[ b_{ij} \right]_{3 \times n}
\]

The covariance of positioning error is:
\[
P_X = E \left[ X, X^T \right] = B \left[ E \left[ d \Delta r, d \Delta r^T \right] \right] B^T
\]

The covariance of measurement error is as follows:
\[
P_r = E \left[ d \Delta r, d \Delta r^T \right]
\]
\[
= \begin{bmatrix}
\sigma_{\Delta r_i}^2 & \eta_{12} \sigma_{\Delta r_i} \sigma_{\Delta r_j} & \cdots & \eta_{1n} \sigma_{\Delta r_i} \sigma_{\Delta r_n} \\
\eta_{12} \sigma_{\Delta r_i} \sigma_{\Delta r_j} & \sigma_{\Delta r_j}^2 & \cdots & \eta_{2n} \sigma_{\Delta r_j} \sigma_{\Delta r_n} \\
\vdots & \vdots & \ddots & \vdots \\
\eta_{1n} \sigma_{\Delta r_i} \sigma_{\Delta r_n} & \eta_{2n} \sigma_{\Delta r_j} \sigma_{\Delta r_n} & \cdots & \sigma_{\Delta r_n}^2
\end{bmatrix}
\]

(7)

Among them, \( \sigma_{\Delta r_i} \) is the Standard deviation of distance measurement error between the i station and the reference station. \( \eta_{ij} \) is the coefficient of correlation between \( \Delta r_i \) and \( \Delta r_j \).

\[
\eta_{ij} = \frac{\text{cov}(\Delta r_i, \Delta r_j)}{\sigma_{\Delta r_i} \sigma_{\Delta r_j}}
\]

Here, let
\[
P_r = \left[ \sigma_{ij} \right]_{n \times n}, \quad P_X = \left[ m_{ih} \right]_{3 \times 3}
\]

(8)

and
\[
\sigma_{ij} = \begin{cases}
\sigma_{\Delta r_i}^2 & i=j \\
\eta_{ij} \sigma_{\Delta r_i} \sigma_{\Delta r_j} & i \neq j
\end{cases}
\]
\[
m_{ih} = \sum_{i=1}^{n} \sum_{j=1}^{n} b_i b_j \sigma_{ij} \quad (l,h=1,2,3)
\]

Therefore, the variances of positioning errors in x, y and z directions are respectively:
Then GDOP\[^4,5\] can be expressed as:

\[
GDOP = \sqrt{\sigma_x^2 + \sigma_y^2 + \sigma_z^2}
\]

\[
= \sqrt{\sum_{i=1}^{n} \sum_{j=1}^{n} (b_i b_{ij} + b_i b_{ij} + b_i b_{ij}) \sigma_{ij}}
\]

From the above deduction, it can be concluded that the value of GDOP is related to the geometric layout of each station, and the smaller the value of GDOP, the higher the positioning accuracy of UAV.

4. Simulation Verification
In the layout of multi-point positioning ground stations, the typical layout methods are star, inverted triangle and diamond, as shown in Figure 3 (a), (b), (c). Because the first three kinds of station layout have stations in the direction of UAV flight (Y axis), it is possible that the landing site of the aircraft is exactly the site location. Therefore, a parallelogram layout scheme is proposed, as shown in Figure (d), in order to avoid the UAV landing position.

![Station modes](image)

**Figure 3.** Station mode
Next, we simulate and analyze the four methods of station distribution by MATLAB, as shown in Figure 4 (a), (b), (c), (d). In the simulation process, in order to complete and intuitive reflection of GDOP distribution map, the selection of coordinate axis range was adjusted appropriately.

![Star station](image1)
![Diamond cloth station](image2)
![Inverted triangle cloth station](image3)
![Parallelogram station](image4)

**Figure 4. GDOP distribution**

As shown in the above simulation results, we can draw the following conclusions:

1) The positioning of UAV can be achieved by using mobile ground station system, and the requirement of high precision positioning can be satisfied by reasonable deployment of mobile ground station.

2) Inverted triangle and diamond stations, GDOP distribution has strong directionality, when UAV flight direction is determined, these two stations can be considered.

3) Parallel quadrilateral station layout has the highest positioning accuracy among the four methods, and it can avoid the situation that the landing point of UAV is just out of the station. Therefore, parallelogram station layout can be preferred in the process of station layout.

5. Concluding Remarks

Aiming at the shortcomings of satellite navigation signal being susceptible to interference, occlusion and the strict limitation of station layout and distance of signal enhancement in ground-based enhancement system, this paper puts forward that the location of UAV can be realized by setting up a small mobile, removable and reusable ground station system on the spot, which can be used as a supplement to the existing UAV location methods. In addition, by deploying the geometric layout of mobile ground station scientifically and reasonably, the positioning accuracy of UAV can be improved,
and the mission of UAV can be carried out smoothly in areas where the reception of satellite navigation signals is not good, which has a strong use value.

6. References

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