

System Analysis of the Use of a Group of Unmanned Aerial Vehicles for Remote Sensing

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Abstract

The paper is devoted to optimization of formation flight of UAV carrying out remote sensing of earth surface being positioned at different heights taking into account the differences of atmospheric transmittance at these heights. The task of optimization of remote sensing of the earth's surface by a group of UAVs carrying out formation flight at various altitudes and at various locations away from a mobile center, which receives information from the UAV upon reaching the same altitude, has been formulated and solved. The optimal type of function for the relationship between the UAV position altitude and the distance between them and the mobile information reception center has been determined under criterion to reach maximum of the total value of atmospheric transmission.

Keywords

UAV, Formation Flight, Atmospheric Transmittance, Mobile Information Reception Center, Position Altitude

1. Introduction

As noted in [1], approximately 75% - 90% of all information contains coordinates or spatial locations of objects. Analysis of this type of information allows us to obtain qualitatively new geographic information and discover previously unknown patterns. Modern methods of collecting information, such as ground-based, cartographic and remote methods, are widely used in practice. Remote data collection methods can be implemented using spacecraft, manned and unmanned aerial vehicles. Effective planning of the operation of unmanned aerial vehicles (UAVs) allows us to obtain high-resolution remote information in a short period of time. The use of UAVs to obtain remote information helps to avoid some problems and dangers. previously encountered when obtaining information about cer-

tain objects or processes [2] [3].

As noted in the work [4], at present, UAVs equipped with appropriate equipment are widely used to study the condition of forests and agricultural areas, to control various emergency situations, to monitor various pipelines, and for other purposes that require obtaining accurate and timely information for making operational decisions.

According to [5], UAVs can be successfully used to validate remote sensing data obtained from satellites, including data obtained from small satellites flying in formation. Formation flight technologies are also being applied to UAVs [6]. Formation flights of UAVs allow one to avoid limitations inherent to unmanned aerial vehicles, such as short flight times, small payloads, and small volumes of received data. It is obvious that the use of a group of UAVs to obtain reliable and accurate data on certain processes or objects requires their optimal placement at different flight altitudes and distances till data receive center in real atmospheric conditions, which are often characterized by high pollution, turbulence, and thermal heterogeneity. In general, unfavorable atmospheric conditions may create some problems for the successful implementation of a planned mission of a formation flight of several UAVs. As it was well-known [1]-[4] UAV formation flight can be classified into three categories: position based; displacement placed and distance placed interaction topology. Major factor negatively affected on volume of information obtained by a group of UAVs, is the atmospheric attenuation of electromagnetic signals transmitted from the UAV to the information receiving unit from different altitudes. But the task on optimization of said tiopological factors concerning the interrelation of them linked with information losses was not researched.

Further in this article, we analyze the condition for avoiding extreme information losses that occur during group flights of UAVs at different altitudes transmitting information to a common mobile information receiving node.

2. Materials and Methods

A graphical illustration of the operation of several UAVs performing a group flight for remote sensing purposes is shown in **Figure 1**.

As shown in the work [7], the Beer-Lambert law can be taken as a basic model for the passage of electromagnetic radiation through the atmosphere, as applied to the case when the flight is carried out at a height h and the information is transmitted over a distance d till the data receiving center. According to this law

$$\eta_{\text{atm}}(h) = \exp[-\gamma(h) \cdot d] \quad (1)$$

where $\eta_{\text{atm}}(h)$ is the atmospheric transmittance.

According to the work [8], the function $\gamma(h)$ is defined as follows:

$$\gamma(n) = \alpha_0 \exp\left(-\frac{h}{h_0}\right) \quad (2)$$

where $\alpha_0 = 5 \times 10^{-6} \text{ m}^{-1}$; $h_0 = 6000 \text{ m}$.

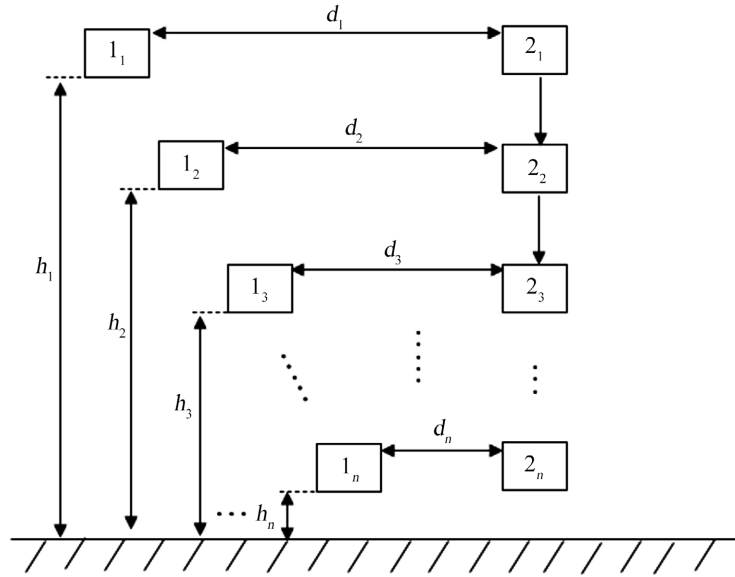


Figure 1. Graphical interpretation of group flights of UAVs in quantity n at different altitudes, performing remote sensing of the earth, transmitting data to the receiving center occupying positions at different altitudes. The numbers show: 1_i ($i = \overline{1, n}$) - UAV at altitude h_i , transmitting data to the center located at a distance d_i ; 2_i - positions of the UAV data reception center.

Taking into account (1) and (2) we obtain

$$\eta_{atm}(h) = \exp \left[- \left[\alpha_0 \exp \left(- \frac{h}{h_0} \right) \right] d \right] \quad (3)$$

Taking into account the monotonic nature of the exponential function, we will investigate the expression found in the exponent of the first exponent, *i.e.* the function $f(\alpha_0, h, h_0, d)$ in the form

$$f(\alpha_0, h, h_0, d) = -d\alpha_0 \exp \left(- \frac{h}{h_0} \right) \quad (4)$$

Obviously, to achieve maximum transmission, we must have the maximum value of $f(\alpha_0, h, h_0, d)$, *i.e.*, the maximum $-d\alpha_0 \exp \left(- \frac{h}{h_0} \right)$. To solve this problem, we will generalize it to the case of and the number of UAVs performing remote sensing at altitudes $h_i, i = \overline{1, n}$ and transmitting information over a distance $d_j, j = \overline{1, n}$.

Let us consider the total value β of functions $f(\alpha_0, h, h_0, d)$ in the form

$$\beta = -d\alpha_0 \exp \left(- \frac{h}{h_0} \right) \quad (5)$$

To study β the group flight of UAVs, we introduce for consideration the optimized function

$$h_i = \psi(d_j) \quad (6)$$

Further, in relation to group flights of UAVs, we can consider the problem of calculating the total value β in the form

$$\beta_{cp} = -\sum_{i,j}^n d\alpha_0 \exp\left(-\frac{h_i}{h_0}\right) \quad (7)$$

Taking into account (6) and (7), moving to a continuous model of the process under consideration, we can formulate the following objective functional F_1 in the form

$$F_1 = -\int_{d_{\min}}^{d_{\max}} d\alpha_0 \exp\left[-\frac{\psi(d)}{h_0}\right] d(d) \quad (8)$$

Continuous model (8) upon growth of n can be calculated using well-known Simpson formulae used for numerical calculation of integrals. Concerning the considered case this formulae comprise Formulae (7) multiplied to determined constant linked with increment of d . So that the inverse procedure *i.e.* transition from discrete model (7) to continuous model (8) is may be considered as correct. To determine the optimal form of the function, in which F_1 the extreme value would be reached, we impose the following restrictive condition on the function $\psi(d)$.

$$\int_{d_{\min}}^{d_{\max}} \psi(d) d(d) = C; C = const \quad (9)$$

The condition (9) means that the sum of UAVs positions altitude should be limited. If not the energy consumption during formation flight may be extremely high. From another side the flight altitude is related with noisy images taken by them and big losses upon transfer of them to data receiving center. Taking into account expressions (8) and (9), we will compose the following target functional F_0 of variational optimization

$$F_0 = -\int_{d_{\min}}^{d_{\max}} d\alpha_0 \exp\left[-\frac{\psi(d)}{h_0}\right] d(d) - \lambda \left[\int_{d_{\min}}^{d_{\max}} \psi(d) d(d) - C \right] \quad (10)$$

where is λ the Lagrange multiplier; $\lambda = const$.

The solution of problem (10) according to Euler's method satisfies the following condition:

$$\frac{d \left\{ d\alpha_0 \exp\left[-\frac{\psi(d)}{h_0}\right] - \lambda \psi(d) \right\}}{d(\psi(d))} = 0 \quad (11)$$

From condition (11) we obtain

$$\frac{d\alpha_0}{h_0} \exp\left[-\frac{\psi(d)}{h_0}\right] - \lambda = 0 \quad (12)$$

From expression (12) we find

$$\exp\left[-\frac{\psi(d)}{h_0}\right] = \frac{\lambda \cdot h_0}{d\alpha_0} \quad (13)$$

Taking the logarithm of expression (15) we obtain

$$\psi(d) = h_0 \cdot \ln \frac{d\alpha_0}{\lambda \cdot h_0} \quad (14)$$

Thus, when solving (14), the objective functional (10) reaches an extreme value. Applying the Lagrange criterion, it is easy to determine that this extremum is a maxima, since the derivative of expression (12) with respect to the function $\psi(d)$ turns out to be a negative value, which swings the factor λ , t_0 , and the value can be determined using expressions (9) and (14). Taking into account expressions (8) and (14), we obtain

$$\begin{aligned} F_1 &= -\int_{d_{\min}}^{d_{\max}} \lambda \cdot h_0 \cdot d(d) = -\frac{\lambda \cdot h_0 d^2}{2} \Big|_{d_{\min}}^{d_{\max}} \\ &= -\frac{h_0 \cdot \lambda (d_{\max}^2 - d_{\min}^2)}{2} = -C_1 \cdot (d_{\max}^2 - d_{\min}^2) \end{aligned} \quad (15)$$

where

$$C_1 = \frac{\lambda \cdot h_0}{2} \quad (16)$$

Thus, the average value of atmospheric transmission according to expressions (3) and (15) reaches its maximum value when solving (3)

$$\eta_{atm.max} = \exp \left[-C_1 (d_{\max}^2 - d_{\min}^2) \right] \quad (17)$$

To determine the reliability of the obtained results, we will conduct a model study.

3. Model Study

In the obtained solution (14), to simplify the model study we will adopt the following relationships for simplicity and clarity.

$$\frac{\alpha_0}{\lambda h_0} = 1; h_0 = 1 \quad (18)$$

In this case, expression (14) takes the following form

$$\psi(d) = \ln d \quad (19)$$

The functional (8) takes the following form

$$F_1 = -\int_{d_{\min}}^{d_{\max}} \alpha_0 d(d) = -\alpha_0 (d_{\max}^2 - d_{\min}^2) \quad (20)$$

The graph of the function $\psi(d)$ defined by expression (19) is shown in **Figure 2**.

In the interval $d_{\min} = (5.7 - 15.4)$, curves 2.3 satisfying condition (11) were constructed graphically. The values were calculated F_1 using Formula (22), which are given in **Table 1**.

As can be seen from the data given in the table with solution (21), the greatest value is observed F_1 , i.e. the maximum total transmission of the atmosphere can be achieved at all heights occupied by free-riders [8].

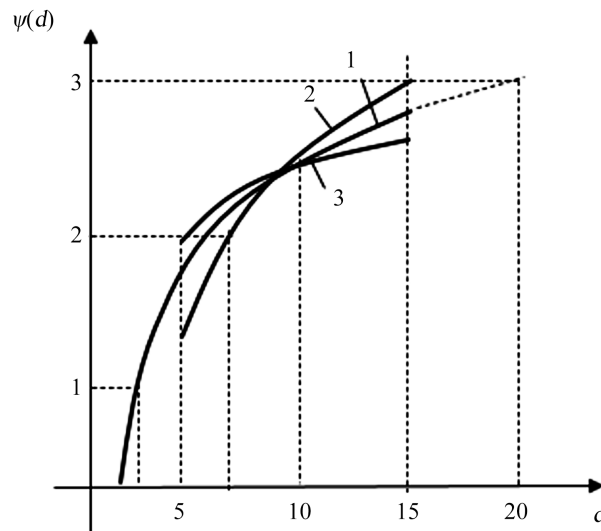


Figure 2. Graphs of the function $\psi(d)$ and alternative functions $f(d)$ satisfying $\varphi(d)$ condition (9). The numbers indicate: 1-graph of the function $\psi(d)$; 2-graph of the function $f(d)$; 3-graph of the function $\varphi(d)$.

Table 1. Magnitudes of the function F_l .

The magnitude of the function F_l according to Formula (20)		
Curved function $\psi(d)$ 1	Curved function $f(d)$ 2	Curved function $\varphi(d)$ 3
-25.6	-25.5	-25.3

4. Conclusions

1) The problem of optimizing the remote sensing of the earth's surface by a group of UAVs occupying positions at various altitudes and at various locations away from a mobile center for receiving information from them, which receives information from the UAV upon reaching the same altitude, has been formulated and developed.

2) The optimal type of function for the relationship between the position altitude and the distance between the UAV and the mobile information reception center has been determined, at which the total value of atmospheric transmission reaches a maximum.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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