# UNMANNED AERIAL VEHICLE RECONNAISSANCE FLIGHT IN THE ENERGY SAVING MODE

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*The targets and vehicle objects tracking on the ground and control by use of UAV are two well-studied problems. However, most of the papers focused on the quality of detection of moving targets from one or more UAVs and did not mention energy efficiency. This article discusses the problem of minimizing the energy consumption of a UAV performing a reconnaissance mission, with the maximum number of observed objects on the ground. The mathematical formalization of the problem is considered. The condition for minimizing the UAV energy consumption is formulated. An objective function is obtained, which must be minimized to solve energy saving problem. The energy-informational efficient mode of operation of the UAV is considered. Criteria for minimizing UAV power consumption have been developed and considered.*

***Key words:*** *unmanned aerial vehicle, minimization of energy consumption, reconnaissance flight, monitoring, ground facilities.*

## 1. INTRODUCTION

In recent years, there has been a widespread use of unmanned aerial vehicles (UAVs) in various fields, including the military. The invention of lightweight materials, low-power machines, and high-performance processors has led to the creation of flexible flying robots - UAVs. They can be used in various applications such as vehicle tracking, traffic control, and fire detection [1]. UAVs can fly autonomously at different altitudes and are usually equipped with sensors for monitoring the environment and communication devices for communicating with other UAVs or central stations.

The problem of ground target tracking and vehicle control has been well studied. However, most of the works focused on the quality of detection of moving ground targets from one or more UAVs and did not mention the energy efficiency of the flight, minimizing energy consumption. The authors propose in more detail methods for constructing a control strategy, thanks to which good visibility of targets on the ground is maintained.

When carrying out reconnaissance operations for monitoring moving and stationary objects on the ground with the help of UAVs, one of the important tasks is the choice of an energy-saving UAV flight mode [2,3,4]. This is achieved by various methods and means. In this case, we will consider monitoring the movement of vehicles (objects) or stationary targets using a UAV using broadside (wide-angle) lenses. This provides simultaneous monitoring of several mobile or stationary objects along the path of movement.

It is assumed that the UAV has a maximum viewing angle and a maximum range beyond which the UAV cannot detect an object on the ground. The UAV flies as high as possible to control a larger area and detect more objects. However, the higher the UAV flies, the more energy it consumes. But at the same time, the UAV completes the monitoring of all mobile and stationary objects faster. In order to optimize energy consumption and task completion time, the UAV itself regulates the flight altitude.

Thus, it is required to optimize the energy consumption, the UAV flight altitude and the UAV task execution time. This paper gives a mathematical formulation of the problem of minimum energy consumption under the condition of observing the maximum number of objects and the optimal UAV flight altitude.

## 2. FORMULATION OF THE PROBLEM

Let assume that the system is represented as a 2-dimensional terrain with $X$ and $Y$ axes. A set of objects

$$M=\{M_1,M_2,\ldots,M_n\}$$

can move by randomly with a speed of

$v_i, \forall\, i \in [1, n]$ along $X$ and $Y$ axes; here $n$ is a number of the objects $M$ on the ground which monitored by UAV.

The length of the path of movement of objects is equal to $S_0$, the area of view of the UAV camera on the ground is equal to $S_j$ at the height of the UAV flight $h_j$.

Each UAV is equipped with a camera aimed at the ground. The camera has a maximum viewing angle $\theta$. The field of view is a cone with height $h$ and angle $\theta$. The flat surface of the cone represents the observation area, and every target $M_i$ located in this area can be observed by the UAV. The UAV can move up or down to increase or decrease the size of the surveillance area.

The height of the UAV can be controlled by controlling the power level of the engines. Accordingly, the larger $h$, the greater the energy consumption. The energy consumption of the UAV at any time $\tau$ is equal to $E_\tau = m \cdot g \cdot h_\tau$ (1) Here, $m$ is an UAV's mass, $g$ is the acceleration of gravity, and $h_\tau$ is UAV height at time τ. The initial amount of energy is equal to $E_0$. The flight of the UAV is limited by the minimum height $h_{min}$ and the maximum height $h_{max}$, that is, $h_{min} < h < h_{max}$.

It is necessary to build a model for optimizing the UAV flight mode in such a way as to control all $n$ objects along the path $S_0$ with a minimum energy consumption $E_\tau$.

Let assumed that each object on on the ground ($h$ = 0) $M_i \in M$ is characterized by its coordinates $(X_{Mi}, Y_{Mi})$. At every moment of time τ the UAV is localized in ($x$, $y$, $h$), when the distance between UAV and object on the ground $M_i$ ($h$=0) which is observed, is equal

$$D_{Mi}^{xy} = \sqrt{(X_{Mi} - x)^2 + (Y_{Mi} - y)^2}$$

Let's set the variables that determine the conditions for observing the object $M_i$ on the ground.

Each UAV has an overview, which is a circle on a plane with a radius $r_h$. The higher $h$, the longer the radius $r_h$. Then the conditions for observing the object will be

$$\delta_{xyh} = \begin{cases} 1, if\ UAV \in (x,y,h) \\ 0, if\ UAV \notin (x,y,h) \end{cases} \quad (2)$$

$$\sigma_{Mi} = \begin{cases} 1, if\ M_i \in \{M_{UAV}\} \\ 0, if\ M_i \notin \{M_{UAV}\} \end{cases} \quad (3)$$

determined as follows:

That is, if the UAV is $(x, y, h)$, a point with coordinates,

then $\delta_{xyh} = 1$, if is not located, then $\delta_{xyh} = 0$. If the object $M_i$ is observed by UAV, then $\sigma_{Mi}$=1, if is not observed, then $\sigma_{Mi}$=0.

The value $h$ belongs to the interval of ($h_{min}$, $h_{max}$) and the projection of the flight area is a rectangle with length $x_{max}$ and width $y_{max}$. The time range $[\tau_{min}^{Mi}, \tau_{max}]$ is connected with each object $M_i \in M$. This means that the object $M_i$ is located at the beginning at the point with coordinates ($X_{Mi}$, $Y_{Mi}$), and it must be observed in the time domain specified in the corresponding time range.

The mathematical formulation of the problem of the minimum energy consumption under the condition of observing the maximum number of objects is presented below. Let Δτ is the time interval at which the mobile object $M_i$ reaches a new position. Then, using (1,2,3), we write the condition for minimizing energy consumption in the following form:

$$min\left[\frac{\tau_e-\tau_s}{\Delta\tau}\left(mg\sum_{(x,y,h)}h\delta_{xyh}\sum_{k}\sigma_{Mk}\right)\right] \quad (4)$$

here, $M_k$ – is a number of objects are observed by UAV in given moment of the moment of photography.

The objective function (4) to be minimized is the total energy consumption. It is assumed that, moving along the monitoring trajectory, only in one position the UAV photographs the number of objects $M_k$. Using the functional (4) for a specific case of UAV reconnaissance flight, it is possible to optimize monitoring conditions, flight altitude and UAV power consumption.

It should be noted that when minimizing function (4), the following restrictions must be used:

- the UAV is in no more than one position at the time of photographing;
- if the viewing radius of the target on the ground is less than the distance between the targets, then it is assumed that one target is observed;
- each target on the ground is observed by one UAV;
- when calculating, the initial and final time of UAV observation are taken into account.

The considered mathematical model assumes that the number of UAVs can be infinite. When the UAV moves to another position, it is replaced by another one. This hypothesis simplifies the model and does not affect the solution, since the goal is to minimize the overall energy consumption.

It should be noted that the problem of the optimal location of flying UAVs is formulated as a binary optimization model characterized by a large number of variables and constraints. Therefore, it is not possible to determine the optimal solution of model (4), in a limited time. Since the solution process takes a very long time even for a small amount, it is mandatory to use a heuristic approach to determine a feasible solution.

## 3. ENERGY-EFFICIENT UAV COMMUNICATION AND TRAJECTORY OPTIMIZATION

In [5], another method of energy-efficient UAV flight is considered. The UAV is assumed to be flying horizontally at a fixed height, and an energy-efficient communication between the UAV and the ground terminal is studied by UAV trajectory optimization, which takes into account both the communication capacity and the UAV power consumption. To this end, the fixed-wing UAV energy consumption model is first considered as a function of UAV speed, direction and acceleration.

Further, without taking into account the consumption of radiation energy and signal processing, the energy efficiency of UAV communication is determined as the total number of transmitted bits of information, normalized to the energy of UAV movement. The UAV flight path in a circle is considered, in which the flight radius and UAV speed are jointly optimized to maximize energy efficiency. In addition, an efficient design is proposed to maximize the energy efficiency of the UAV. The proposed designs provide a significantly higher energy efficiency of communication with the UAV.

Thus, for the optimal distribution of the UAV energy balance, it is necessary to optimally choose the flight path and the order of communication. It should be noted that the end product of reconnaissance UAVs is the amount of information collected during the flight. That is, as noted in [6], the UAV must operate in an energy-informational efficient mode of operation. In this work, a methodology has been developed for calculating the optimal regime parameters that provide an energy-information-efficient UAV operation mode.

The proposed method is based on the representation of the UAV as a cybernetic system powered by an electric battery and provides for a two-stage optimization of the UAV operation mode:

1. Carrying out optimization in order to determine the mode of energy-efficient functioning. The UAV is presented as a system consisting of cybernetic, physical and energy subsystems. Indicators of the energy-efficient mode of subsystems are introduced: $x_1$ - cybernetic; $x_2$ - physical; $x_3$ - energy; criterion of the energy-efficient mode $\Psi_{extr}$; criterion of energy-information-efficient UAV operation mode $\varphi_{extr}$. The following operations are carried out here:

1) Calculation of quantities of $x_1$, $x_2$, $x_3$;

2) Calculation of the criterion of $\Psi_{extr}$ by the given expression

$$\Psi_{extr} = \Psi(x_1, x_2, x_3)$$

2. Determining the conditions for the energy-information-efficient mode of operation. Here the criterion $\varphi_{extr}$ is determined by the given expression

$$\varphi_{extr} = \varphi(\Psi_{extr})$$

For the analysis, the well-known result is used that the energy consumption of the physical part of the UAV has a minimum of the flight speed. The well-known expression for the discharge of the battery capacity from the load current is also used. As a result of the research, a quadratic equation was obtained, the solution of which made it possible to determine the optimal value of the load current on the battery.

## 4. THE CRITERIA FOR MINIMIZATION OF UAV ENERGY CONSUMPTION

There have been considered and offered many options for saving energy consumption. In order to achieve a solution to this problem, various criteria for an energy-saving UAV flight are considered. These criteria are discussed below. As a result of the research and review of existing literature (see, for example [2,3,4]), the following criteria for minimizing energy consumption during UAV flight have been developed and are proposed:

1) UAV flight should be as low as possible, the higher the flight of the drone, the lower the air density, and the lower the lift, in order to compensate for this, it is necessary to increase the thrust, and this leads to an increase in energy consumption;

2) Most tactical UAVs fly at altitudes up to 1500 m. Considering that the air density changes by only 0.09% up to a height of 1000-1500 m, it is possible to quickly reach cruising speed when climbing, while energy consumption will be optimal;

3) After completing the task, when the UAV returns to the base, if possible, the gentlest descent from a given height at a minimum speed should be made;

4) One of the important criteria is the optimal flight during barrage (reconnaissance flight) with the choice of the shortest trajectories between given objects on the ground that are to be investigated;

5) When developing a flight task, choose such modes, in which the flight occurs, if possible, with uniform rectilinear motion, with the least curvature of the trajectory, with fewer turns;

6) When performing a reconnaissance flight, in which the task is to examine (photograph) some objects on the ground, it is recommended to use a wide-angle lens. This achieves the possibility of covering more objects in the frame with one shooting (see figure 1).

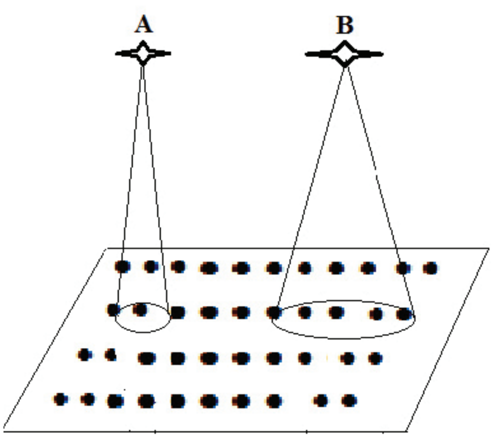


Fig. 1. The possibility of covering more objects in the frame with one shooting

In option **A**, when one object is surveyed, the number of surveys is equal to the number of objects on the ground. In this case, the UAV must fly around all objects and take pictures every time. With option **B**, when several objects are being surveyed at the same time, the number of surveys is less than with option **A**. In this case, the UAV flies along the optimal trajectory with a cone-shaped view of all the intended objects on the ground, avoiding repeated coverage of targets. Therefore, in mode **B**, energy consumption is less. Drone flight according to option B is more energy-saving. Photographing each object individually on the ground takes more time than photographing a group of objects at the same time. Therefore, the flight lasts longer.

7) It is proposed to optimize the power of the radio transmitter, designed for data transmission. The more powerful the radio transmitter, the greater the power consumption.

8) Energy efficient planning by a system of several UAVs that track events and objects on the surface of the earth. UAVs themselves adjust their height so that each time they cover more or less objects. This self-control is achieved by radio communication between the UAVs and results in energy savings of up to 150% compared to the case when the UAVs are placed statically.

9) Joint optimization of both energy efficient (capacity) radio communication and UAV flight path.

10) Optimization of the operation of a reconnaissance remote sensing UAV flying in an energy-information-efficient mode, when information is transmitted using special filters.

11) The use of faster processors will allow the UAV to complete missions quickly and therefore save energy. This is because most of the UAV's energy is consumed by the motor, hence faster calculations can reduce mission time and energy accordingly. Improvement is achieved up to 5 times.

12) Planning the UAV monitoring path in such a way as to minimize the UAV power consumption. The bottom line is to minimize the amount of course change and maximize the amount of straight flight range, this will reduce the power consumption of the UAV.

13) To reduce the power consumption of the UAV, limit the number of UAV flight adjustments while still keeping the target in the camera's field of view.

14) Application of energy-efficient brushless DC motors for UAVs with electric motors. The use of these drives leads to a decrease in the dimensions and weight of the UAV and to a decrease in power consumption.

Thus, the paper notes the importance of choosing an energy-saving UAV flight mode. In order to minimize energy consumption, 14 criteria for UAV flight modes were considered and proposed to save energy consumption. Experiments have shown that savings of up to 500% can be achieved in some cases.

## 5. CONCLUSIONS

Thus, the paper considers the problem of minimizing the energy consumption of a UAV performing a reconnaissance mission. The condition for the minimum energy consumption with the maximum view of objects on the ground is set. The mathematical formalization of the problem is considered and the functional is obtained, which must be minimized to determine the optimal monitoring conditions, flight altitude and UAV power consumption. This approach can be applied to a wide range of problems. The energy-informational efficient mode of operation of the UAV is considered. Criteria for minimizing UAV power consumption have been developed and considered.

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