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METHODS FOR MEASURING THE EFFICIENCY OF UAVS IN THE AIR NAVIGATION SYSTEM

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Abstract—*The article discusses the concept of efficiency in the context of assessment system solutions and the methods used to measure it. Efficiency is defined as the ability to produce effects and achieve results, while effectiveness is understood as the outcome of certain actions. Efficiency theory is based on operations research and decision-making methods using mathematical models such as probability theory and machine learning techniques. The results of performance measurements can be used to solve a variety of practical problems related to unmanned aerial vehicles, including comparing similar systems, conducting operational assessments, and optimizing requirements. The paper also discusses the modification of flight control and planning models, where stochastic parameters that affect mission quality need to be considered. Societal effects, such as flight normality and safety, can be measured by direct assessment methods and statistical metrics. More generalized metrics can be used to assess flight safety by comparing the number of accidents and workload. Suggested methods include the use of mathematical models and integration techniques to assess flight safety.*

Index Terms—Unmanned aerial vehicles efficiency; flight safety; statistical indicators; economic effect; air navigation system; performance measurement; control and planning; multicriteria optimization.

I. INTRODUCTION

The measurement of inputs and outputs is based on the general principles of evaluating system solutions, as well as on the specific methods for determining the efficiency of various complex systems discussed in the previous section. The category of efficiency is of great theoretical and applied importance.

The concept of efficiency for the implementation of the method of its measurement can be formulated as follows.

The above definition of efficiency implies the following properties:

1) efficiency has a quantitative measure and is represented by functionality;

2) the efficiency metric is external to the system, i.e., the description of the system does not provide a basis for introducing such a measure;

3) efficiency is characteristic of purposeful systems;

4) efficiency assessment takes into account certain properties and interconnection of the supersystem with the system under evaluation;

5) system efficiency management is associated with the variation of its resources in order to change the result of the subsystem's influence and actions.

The concepts of effect and efficiency are usually distinguished. Effect is generally understood as the result of certain actions, and efficiency is the ability to create an effect and obtain a result.

The basics of efficiency theory are based on the methodology of operations research and decision-making. They include a wide range of mathematical models built using the methods of probability theory, mathematical statistics, game theory, information theory, schedules, fuzzy sets, machine learning technologies, etc.

The results of the performance measurement allow us to solve the following practical problems of unmanned aerial vehicles (UAVs) in general and cargo drones in particular:

1) comparison of similar systems;

2) selection of similar systems from a group of systems;

3) operational assessment of the systems;

4) verification of the system's compliance with its purpose;

5) identifying the presence or absence of targeting;

6) determination of the level of compliance of the system with the purposefulness;

7) determining the technical level, prospects and feasibility of new system developments;

8) optimization of tactical and technical requirements;

9) establishing the conditions for acceptable and most effective use of systems;

10) determining the feasibility of replacing systems in operation with more promising ones.

II. PROBLEM STATEMENT

Let's consider a modified model of flight control and planning, when both the air traffic controller and the remote pilot, who control a set of aircraft taking off or landing, must take into account the random nature of a number of parameters that determine the quality of the task. These include, in particular, the moment when the aircraft appears at the calculated point and the errors in the execution of commands by individual aircraft, which are also affected by external disturbances.

To solve this kind of problem, a conceptual approach based on different types of effect is required. Technical and economic assessments can be obtained by linking functional and economic assessments. These types of effects are in a certain relationship, which leads to their mutual influence.

The social effect is manifested primarily in ensuring the safety and regularity of aircraft flights. To measure the social effect, methods based on its direct assessment are used. For example, the regularity of flights can be assessed by the average duration of flight delays, the accuracy of flight schedules, economic losses, etc.

Flight safety is characterized by the level of flight security and is a characteristic of the aviation transport system, which is determined by the probability that a catastrophic situation will not occur during the flight. To quantify flight safety, statistical and probabilistic indicators are used, which can be general and specific, absolute and relative. General indicators characterize flight safety in general for all causes, and specific indicators for individual causes or their groups.

General absolute statistical indicators of flight safety include: the number of air accidents, the number of deaths in air accidents over a certain period of time. Individual absolute indicators include the number of accidents caused by any i-cause, the number of accidents at the j-th stage of the flight, etc. Absolute statistical indicators allow to identify a general trend in the state of flight safety for a certain period, but they do not reflect the level of flight safety.

III. PROPOSED METHOD

More generalized indicators are those in which the number of aircraft accidents is compared to the amount of work performed or work in progress. These indicators allow us to assess the level of flight safety, take into account all factors and causes of aviation events.

Since the system operates under the influence of random variables, the mathematical expectation of the criterion functional *Q*, which has the form

$$Q = \int_0^T G[x(t),\ u(t)]dt + \varphi_1\left[x(T)\right], \qquad (1)$$

where $x(t)$ are coordinates of the control object; $u(t)$ is a certain sequence of controls minimizing the value of *Q*; *T* is a fixed time; $\varphi_1\left[x(T)\right]$ is a function that characterizes the movement of the object.

The main advantage of statistical indicators is their objectivity, as they characterize the events that have occurred. At the same time, such indicators also have a number of disadvantages: they cannot be used in long-term planning of the level of flight safety, since they do not take into account the features of new equipment, changes in its operating conditions; they do not allow determining the degree of danger of adverse factors and their impact on flight safety, and, as a result, cannot be used in finding effective ways to prevent aviation accidents before their practical implementation.

The probability of completing a flight without an accident, the probability of a precondition for an accident, and a number of others can serve as an analytical indicator that determines the safety of UAVs. In the general form of probabilities, the flight safety indicator can be represented as follows.

Let the state of the system be represented by a vector:

$$\vec{Z}(t) = \{Z_1(t), \ldots, Z_n(t)\} \in R^n, \qquad (2)$$

where *t* is time; R^n is the state space. In the space R^n, a region Ω is selected such that $Z(t) \in \Omega$ at $t \in I_t = [t_1, t_1 + \tau]$ are acceptable, satisfying the functional purpose of the system. On the contrary, $Z(t) \notin \Omega$ corresponds to a deviation from normal operation, for example, an aviation event or its precondition. It depends on the level of consideration of the formulated problem. Thus, the requirement for flight safety is to keep the phase point of the system, which is represented by the vector $\vec{Z}(t)$, within the domain Ω. Note that the region Ω depends in general on time *t*, and the boundary of the region Γ_Ω is the surface in the space of *n* + 1 measurements of the variables $\{Z_1, Z_2, ..., Z_n, t\}$.

If the probability distribution of the components of the state vector $F\{Z_1, Z_2, ..., Z_n, \tau\}$ is known, provided that the boundary has never been violated until $t+\tau$. The density of this probability is usually defined as the solution of the second Kolmogorov equation. Let us denote by Q some safety criterion. Then Q can be represented as follows:

$$Q=\int_{\Omega(\tau)} f\left(\vec{Z}\right) dF\left(\vec{Z},\tau\right). \tag{3}$$

Here, $f\left(\vec{Z}\right)$ is a weighting function that determines the content of the criterion Q; $\Omega(\tau)$ is the domain of permissible values of the vector $\vec{Z}$. As can be seen from (3), in order to quantify the level of flight safety, it is necessary to know or be able to construct the domain $\Omega(\tau)$.

The set $M \subset Rn$ is called connected if any two of its points can be connected by a broken (or piecewise smooth) curve, all points belonging to this set.

If $M \subseteq Rn$ is an open connected set, then any two points in M can be connected by a curve completely located in M (Fig. 1).

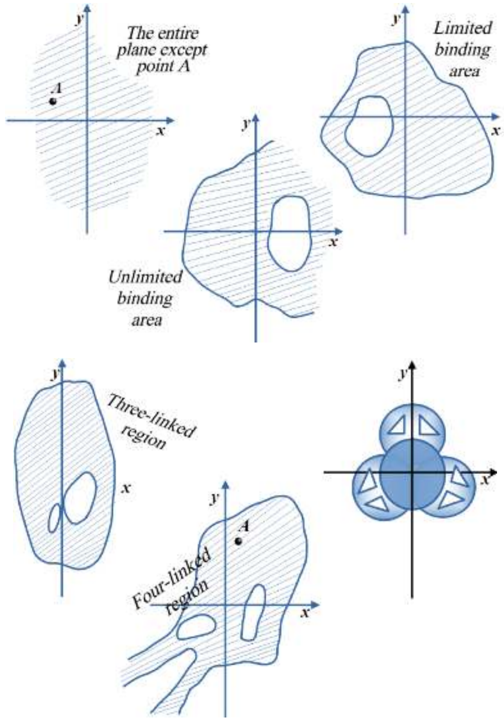

Fig. 1. Areas of connectivity of sets of parameters

Example. The ring Example. The ring $M=\{(x_1,x_2) \mid 0<a<x_1^2+x_2^2<b \subset \boldsymbol{R^2}$ is a connected set. An open connected point set is called a domain. A domain G is called one-connected if its boundary is a connected set. Otherwise, G is called a multi-connected domain. The union of a domain G and its boundary is called a closed domain. If a domain G is one-connected, then any closed curve without self-intersections lying in G can be contracted to a point by continuous deformation inside G. is a connected set.

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The simplest case of flight safety analysis is to maintain a binary criterion that takes on only two values $\{0,1\}$.

The economic effect has a multifaceted expression due to the large number of different indicators. The economic effect of using a UAS system can be represented, on the one hand, in terms of resource costs associated with development, production, and operation, and, on the other hand, in terms of the additional effect obtained by improving air traffic performance.

Along with the generalized ones, individual performance indicators can be used. They are used to assess certain important aspects of production efficiency, analyze the factors that generate economic effect, and verify the initial assumptions to form a set of acceptable options for implementing the measure.

Despite the difference between the forms of expression of the economic effect, the methods of their calculation are identical. The national economic and self-supporting forms of the effect are defined in the same way – as the difference between the results and the costs of achieving them. In other words, the economic effect is a difference indicator. This indicator can be presented in one of the following forms:

$$\begin{aligned}
&\max_j \varepsilon^j,\\
&\max_j (P_T^j-\varepsilon_T^j),\\
&\max_j \left(\sum\nolimits_{t=t_n}^{t_k} P_t^j\cdot\alpha_t \sum\nolimits_{t=t_n}^{t_k}\varepsilon_t^j\cdot\alpha_t\right),\\
&\max_j \sum\nolimits_{t=t_n}^{t=t_k}\left(P_t^j-\varepsilon_t^j\right)\cdot\left(1+E_H\right)^{t_p-t},
\end{aligned} \tag{4}$$

where $P_T^j, P_t^j, \varepsilon_T^j, \varepsilon_t^j$ are, respectively, the total results and costs for the entire period of the measure implementation in the *t*th year; $\alpha_t=(1+E_H)^{(t_p-t)}$ is the coefficient of bringing the results and costs of the *t*th year to one point in time (the calculation year t_p); $E_H=0.1$ is the standard capital investment efficiency ratio; t_H, t_k are, respectively, the initial year (the year of the start of financing of works related to the measure) and the final year of the calculation period; *j* is the index of the option under consideration.

One case of implementing a measure is when the choice must be made among options that differ only in the dynamics and magnitude of the cost components (one-time and recurrent). In this case, the economic criterion of maximum effect (4) is transformed into another, simpler one – minimum total costs:

$$\max_{j} \sum\nolimits_{t=t_n}^{t_k} \varepsilon_T^j \cdot \left(1+E_H\right)^{t_p-t} \cdot \max_{j} \varepsilon_T^j, \tag{5}$$

However, the absence of a change in the results does not eliminate the need to evaluate these results in cost terms. This is because the reduction in costs in the production of final products using the new technique compared to the use of the basic technique is not a reason to use the new technique if the products are ultimately unprofitable.

In this regard, and for measures of the type under consideration, the economic effect is calculated using the formula:

$$\varepsilon_T = \sum\nolimits_{t=t_n}^{t_k} \left(P_t - \varepsilon_t\right) \cdot \left(1+E_H\right)^{t_p-t}. \tag{6}$$

The fundamental point of this methodology is the need to value the production, social, economic and other results achieved, even if they are identical in the compared options.

The complexity of assessing the economic effect of the UAS system lies in the lack of methods for calculating components (3) – (6) and the need to take into account component (3).

It is obvious that, when calculating ε_T, it is necessary to take into account the savings due to the reduction of non-productive costs associated with aircraft waste to the alternate airfield, erroneous change of echelons, unnecessary waste to the second circle; to take into account the savings to reduce the consumption of fuels and lubricants as a result of streamlining the flow of aircraft and optimizing flight paths, reducing non-productive maneuvers of aircraft, etc.

To solve problems (3) – (6), a formalized linkage of air navigation system parameters with cost indicators is required. Until recently, this problem has not been solved and requires an assessment of the functional effect.

The functional effect is manifested in the influence of the characteristics of the means of a complex system on the indicators of its functioning.

If a system *G* performs *N* functions Φ_1, Φ_2, …, Φ_g, …, Φ_N, which depend on *n* processes or quality indicators $F_1^{(1)}, F_2^{(1)}, ..., F_i^{(1)}, ..., F_N^{(1)}$, the efficiency of the gth function is equal:

$$\varepsilon_\Phi = \varepsilon_\Phi\left(F_1^{(g)}, F_2^{(g)}, ..., F_n^{(g)}\right) = \varepsilon_\Phi\left(\left\{F_i^{(g)}\right\}\right), \quad i=\overline{1,n}, \; g=\overline{1,N}. \tag{7}$$

Estimating this effect is one of the problems of air navigation operator that needs to be addressed. Its complexity lies in the fact that:

a) it is necessary to take into account a large number of quality indicators (endogenous variables);

b) there is uncertainty in the conditions of functioning and use of UAS at the stage of operation.

The overall effectiveness of the system, which includes the considered types of effect, is, as will be shown below, a vector-function.

It is quite obvious that the assessment of obviousness will be more accurate the more indicators that affect it are taken into account. In this case, we have to overcome the problem of solving multi-criteria problems and use one of the following two approaches.

The first approach is associated with the formation of a resulting (complex) quality indicator, which simplifies the solution of the efficiency measurement problem and has the form $E_K = \sum_{i=1}^{n} b_i E_i$. We call this problem a convolution problem or a problem of the first type.

The second approach is associated with the explicit expression of the determining factors and represents one of the central problematic tasks. The solution of such problems is necessary to manage the efficiency of a complex system of the type

$$\beta = \int_0^T \int\int\int'_{B_n} p\left(a_1, a_2, ..., a_n, t\right) da_1 da_2 \, ... \, da_n dt.$$

The essence of this problem is the multidimensionality and multiconnectivity of a weakly structured system.

IV. CONCLUSIONS

A rational way to formalize such a system is to use a multi-level hierarchy of descriptions, in which the formalization of a higher level will depend on the generalized and factorized variables of a lower level. The hierarchy is created by multilevel factorization of processes $\{F_i\}$ using generalized parameters $\{\lambda_i\}$, which are functionalities of $\{F_i\}$.

This approach allows us to link the properties of the elements interacting with the environment (lower-level subsystems) with the system efficiency. This is the second type of problem.

It should also be noted that depending on the degree of uncertainty in the conditions of UAS application, which is caused in many cases by unpredictable or poorly predictable situations of the operation process, a certain efficiency model should be applied. The complexity of such a model is due to the presence of explicit (allowed in the analytical form) or implicit (informal) relationships between the parameters of hierarchically related systems. Explicit relationships are taken into account at the macro- or microsystem levels. The microsystem level of description refers to the stage of measuring the functional effect. Different types of effects are determined by the functioning of the entire UAS system, the characteristics of the controlling and controlled subsystems, and the control and management circuits. It is clear that under such conditions, efficiency measurement can be carried out only if the problem of formalizing the problem of UAS system efficiency and building appropriate models is solved.

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Хаоян Лі, В. П. Харченко. Методи вимірювання ефективності безпілотних літальних апаратів в аеронавігаційній системі

У статті розглянуто поняття ефективності в контексті рішень системи оцінювання та методи, які використовуються для її вимірювання. Ефективність визначається як здатність виробляти ефекти і досягати результатів, тоді як результативність розуміється як результат певних дій. Теорія ефективності базується на дослідженнях операцій та методах прийняття рішень з використанням математичних моделей, таких як теорія ймовірності та методи машинного навчання. Результати вимірювань ефективності можуть бути використані для вирішення різноманітних практичних завдань, пов'язаних з безпілотними літальними апаратами, включаючи порівняння подібних систем, проведення експлуатаційних оцінок та оптимізацію вимог. Також розглянуто модифікацію моделей керування і планування польотів, де необхідно враховувати стохастичні параметри, що впливають на якість місії. Соціальні ефекти, такі як нормальність і безпека польотів, можуть бути виміряні за допомогою прямих методів оцінки і статистичних показників. Більш узагальнені показники можна використовувати для оцінки безпеки польотів шляхом порівняння кількості аварій і робочого навантаження. Запропоновані методи включають використання математичних моделей і методів інтеграції для оцінки безпеки польотів.

Ключові слова: ефективність безпілотних літальних апаратів; безпека польотів; статистичні показники; економічний ефект; аеронавігаційна система; вимірювання ефективності; управління та планування; багатокритеріальна оптимізація.

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