KAPITEL 2 / *CHAPTER 2* [2]

METHODICAL APPROACH TO TECHNICAL AND ECONOMIC ASSESSMENT OF WAYS TO COMBAT AGAINST UAVs

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Introduction.

UAVs (or drones) is a new type of weapon on the battlefield, they are used by the armed forces of the world's leading countries and the results of their effective use in recent military conflicts have already appeared.

The rapid development of UAVs has led to the emergence of many varieties that are very different in size. The strike UAVs are weapon carriers and "kamikaze" UAVs (or barrage ammunition) are particularly dangerous. Kamikaze UAVs are classified as a type of strike UAV, they destroy targets by attacking from above and exploding. During military conflicts, for example, the warring parties show spectacular video footage transmitted by reconnaissance drones, video from drone cameras or recordings of target detection and homing to targets transmitted by "kamikaze drones".

All the leading countries of the world are actively developing this new type of weapon, which has a very great potential for development and use in current and future wars. The United States, Israel, Turkey, China, Canada, France, Germany and other countries are mass-producing and actively using UAVs in recent military conflicts, gradually improving their technical characteristics and principles of application (Israel is considered to be a leader in technological developments in the field of UAVs. Israel is followed by the United States, China and Canada).

Due to the development of the principles of UAV use, the development of weapons capable of counteracting this new type of weapon is taking place. Traditionally, anti-aircraft systems of different types are involved in solving this problem, which by their characteristics are able to detect and hit UAVs. But usage of the most anti-aircraft systems is unacceptable on the basis of "efficiency-cost".

Given this state of affairs, there is a search for acceptable means of combating UAVs. Such work is aimed at the use of electronic and optoelectronic combat, and means of camouflage and models of equipment, and various obstacles in the air (balloons, nets, etc.), as well as the possible modernization of anti-aircraft systems, the

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characteristics of which can potentially be improved for effective combat with a UAV. Execution of the given directions of works provides carrying out of a preliminary estimation of their efficiency, both on separate decisions, and in set of decisions.

The task of substantiation and assessment of the account of such means of counteraction and struggle, which are deprived of shortcomings inherent either in modern antiaircraft systems, which are capable to detect and strike combat UAVs, to carry out tasks of struggle independently, or as a part of existing antiaircraft systems, directly as a part of military equipment becomes actual.

Analysis of recent research and publications. Analysis of publications in the field of counteracting UAVs shows that there are many scientific articles on this topic. The majority of work in this area is dominated by overly optimistic conclusions about the success of the destruction of all types of UAVs by existing Russian air defense and EW. The situation is reminiscent of the beginning of the development of aviation and ground means of counteracting their use - air defense. And it so happened that the development of aviation has always outpaced the development of ground-based air defense. It was the aviation that fought aviation well.

However, the sharp and diverse intrusion of UAVs into modern hostilities, their rapid technological development has revealed the problem of effective control, especially with small UAVs, which currently remains extremely complex, systemic, and still effectively unresolved. Only a few countries in the world have partially available and develop tools that can effectively counteract the use of modern UAVs.

The publications offer certain technical solutions for UAV control and theoretical approaches to assessing their effectiveness, which are usually optimistic [2-9, 12-17], with a superficial theoretical justification and the availability of appropriate practical results and are not quite suitable for synthesis means of counteracting UAVs in the conditions of modern intensive hostilities, in different conditions of the combat situation and climate.

In addition, these works usually do not discuss the military-technical aspect of the evaluation of technical solutions on the criterion of efficiency-cost.

The question arises in the objective comparison of the effectiveness of technical solutions to combat modern and promising UAVs with a justification of their cost.

Thus, in [5-7] only an analytical review of the features of UAV counteraction methods was performed without comparing them with each other. In [3] the algorithm of estimation of efficiency of complex counteraction measures, some tactical and technical characteristics of the UAV is resulted but it does not consider possible conditions of a combat situation and climatic circumstances. In [4],

a qualitative assessment of UAV counteraction methods without quantitative assessments is proposed. [17] proposed a system of criteria for assessing the effectiveness of methods of counteracting UAVs with their quantification, but the systematization of methods of counteraction is very subjective, without taking into account the characteristics of objects of cover, cost indicators and features of protection systems.

The emergence of a new type of weapon - UAVs and their use in recent military conflicts have revealed significant shortcomings of anti-aircraft systems, which are in service in different countries. It so happened that independent Ukraine inherited from the Soviet Union, along with anti-aircraft weapons, all their technical shortcomings in the ability to conduct effective combat against modern UAVs, especially small ones. Insufficient work has been done to modernize these complexes and address these shortcomings. Analysis of the characteristics of anti-aircraft air defense systems of the world's leading countries shows that many of the various claimed air defense systems are said to be able to hit both UAVs and air-to-ground missiles, aircraft and helicopters. However, it should be borne in mind that the fight against UAVs of different classes differs significantly. The large and medium-sized UAVs. indeed, (such as Predator and Reaper from General Atomics) are detected, monitored and affected with a fairly high efficiency, and small UAVs have significant problems.

Conceptual approaches to solving the problem of UAV control, which are found in most publications, can be summarized as follows:

a multi-tiered group of different types of anti-aircraft systems, such as anti-aircraft missile system, anti-aircraft artillery complex, anti-aircraft missile and cannon complex, portable anti-aircraft missile system, which have a fairly high reconnaissance and fire capabilities for the detection and fire damage of small UAVs formation;

development and application of existing channels of detection and support of targets as a part of the existing anti-aircraft missile system, anti-aircraft artillery complex, anti-aircraft missile and cannon complex for the purpose of conducting effective fight against small UAVs;

development of perspective samples of anti-aircraft missile system, anti-aircraft artillery complex, anti-aircraft missile and cannon complex capable of combating a wide range of targets, both aircraft (conventional and stealth technology) and small UAVs;

development of specialized automated means of protection of combat equipment of the Land Forces against combat UAVs of the "kamikaze" type;

application of a set of means for electronic suppression of control channels, reconnaissance, and combat use of UAVs;

development of specialized means and systems for combating small UAVs, which apply non-traditional principles of combat.

In [2] it is noted that to detect small UAVs it is necessary to identify specialized intelligence tools that have the best intelligence capabilities to detect and support small UAVs, to create specialized channels of primary transmission and exchange of intelligence information on the activities of small UAVs. To achieve high efficiency of the air target reconnaissance system, it is considered important to implement a set of organizational and tactical measures, namely: more frequent change of radars station' positions and communications; deployment of a system of erroneous positions with simulation of electronic means; carrying out high-quality engineering equipment of reconnaissance radar positions and anti-aircraft complexes, intensive use of passive reflectors-traps, simulators of thermal radiation; deployment near the positions of the radar station reconnaissance air defense means; organization of protection of intelligence means from actions of sabotage groups and others. As the results of recent fighting in Nagorno-Karabakh have shown, these measures remain ineffective. Finding a small UAV in a dead funnel of anti-aircraft weapons, directly above ground targets leads to impunity for UAVs to hit these targets.

It should be noted that effective combat with small UAVs (with an EPR of at least 0,01 m^2) of existing anti-aircraft systems is possible only with great restrictions on their timely detection and firing. Effective control of UAVs with EPR less than 0.01 m^2 by modern anti-aircraft systems is almost impossible.

The purpose of the study is to develop a methodological apparatus of technical and economic analysis of the proposed technical solutions to combat UAVs on the criterion of efficiency-cost.

Main text. Each technical system (complex) of UAV control as a complex system must have a number of technical components (subsystems) combined into a single whole. Subsystems have their intended purpose. Conventionally, as part of complex technical systems are allocated for the purpose of information, control, executive subsystem and subsystem support. Their joint work should ensure the effective operation of the entire UAV control system.

Consider the main functions that should solve the subsystems of the UAV control system.

The function of the information subsystem is to search, detect and recognize UAVs located in the upper (especially dangerous) hemisphere.

As an information subsystem can be used radar, optical, infrared and other types of sensors (sensors) with appropriate equipment for information processing and decision-making on the detection and destruction of UAVs. The operating distances of these sensors are different, depending on external conditions and interference. Therefore, the efficiency of the information subsystem with one of these sensors in addition to their technical characteristics will depend on the degree of influence of external conditions and interference.

As an information subsystem can be used radar, optical, infrared and other types of controllers (sensors) with appropriate equipment for information processing and decision-making on the detection and destruction of UAVs. The operating distances of these sensors are different, depending on external conditions and interference. Therefore, the efficiency of the information subsystem with one of these sensors in addition to their technical characteristics will depend on the degree of influence of external conditions and interference.

The functions of the control subsystem are to control the operation of all subsystems of the counteraction system based on the recognition and classification of UAVs.

The function of the executive subsystem is the direct defeat or counteraction of the UAV.

The function of the support subsystem is to provide all subsystems with power supply, control of operation, maintenance and repair.

In various versions of the UAV control system, the functions of these subsystems may be limited or partially missing.

It is clear that each of these subsystems must work properly, with appropriate efficiency. Their development and manufacture require some funding and determine the final cost of the entire system. Thus, there is a need to assess the effectiveness of the UAV control system by assessing the effectiveness of the components of the subsystems with an assessment of their cost indicators.

Table 1 proposes criteria for assessing the effectiveness of these subsystems in the UAV control system (option).

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Table 1 - Target criteria for assessing the effectiveness of these subsystems in the UAV control system

Information subsystem	
Evaluation criteria	Level of assessment
1. Spatio-temporal characteristics:	
1.1. Effective detection range. 1.2. Detection time. 1.3. Viewing angle at the coordinate X. 1.4. Viewing angle at the coordinate Y. 1.5. Review time at coordinate X. 1.6. Review time at coordinate Y.	1.1: 0 – range less than 100 m; 1 – дальність more than 100 m. 1.2: 0 – time more than 3 sec; 1 – time less than 3 sec. 1.3: 0 – the angle is smaller 90^0; 1 – the angle is larger 90^0. 1.4: 0 – the angle is smaller 90^0; 1 – the angle is larger 90^0. 1.5: 0 – inspection time more than 1 sec; 1 – inspection time less than 1 sec. 1.6: 0 – inspection time more than 1 sec; 1 – inspection time less than 1 sec.
2. Electromagnetic compatibility (EMC)	
–	0 –incompatibility in the combat zone; 0,5 - incompatibility in the area up to 50 m; 1,0 – full compatibility.
3. Versatility of use:	
3.1. The range of external influencing factors, that ensure sustainable operation: 3.1.1. wind 3.1.2. temperature 3.1.3. humidity 3.1.4. Difficult background and target situation	3.1: 3.1.1 - 3.1.3: 0 - minimum value; 1,0 - maximum value. 3.1.4: 0 - lack of selection on a complex background; 0,9 - the ability to distinguish combat UAVs on a complex background; 1,0 - the ability to distinguish kamikaze UAVs on a complex background.
3.2. Possibility of use of other type of base (land, sea) for counteraction of the UAV.	3.2: 0 - impossible; 0,5 -with the average technical complexity and cost of completion; 1,0 - possibly without refinement.

4. The presence of a UAV type recognition function:	
4.1. Selection on a background of birds. 4.2. The effective scattering area of the UAV, which is detected in automatic or automated mode. 4.3. UAV type recognition (heavy, medium, light, mini, micro, or on another basis).	4.1: 0 – lack of selection; 1,0 selection is. 4,2., 4,3: 0 – more than 1,0 м^2 0,1 – more than 0,1 м^2 0,3 – more than 0,01 м^2 0,5 – more than 0,005 м^2 1,0 – more than 0,001 м^2
Control subsystem	
5. Degree of work automation:	
5.1. The required number of operators to counter the UAV (from 0 to 1). 5.2. Availability of recognition and classification of targets (from 0 to 1).	5.1: 0 - operator required; 0,2 - automation of work in one of the modes; 0,4 - automation in the mode of detection and maintenance; 0,6 - automation in the mode of detection and tracking; 0,8 - automation in the modes of detection, maintenance and defeat under the control of operators; 1,0 – fully automatic operation. 5.2: 0,8 - deep automation of recognition and classification in the whole detection zone; 1,0 - automatic recognition and classification throughout the detection area.
Executive subsystem	
6. Decrease in efficiency of performance of the target task of the UAV from means of defeat and counteraction:	
6.1. Artillery canal. 6.2 Rocket channel. 6.3 Special UAV. 6.4 Optical traps. 6.5 Electronic warfare, and optoelectronic interference control. 6.6 Cover object layouts. 6.7 Masking tools. 6.8 Interception of control.	0 - guaranteed fulfillment of the target task; 1,0 - the method of self-defense is ineffective.

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Support subsystem	
Availability of autonomous power supply. The presence of self-diagnosis (functional control). The presence of a repair kit. Availability of maintenance.	0 – not available; 1,0 – is available.

Each target criterion given in the table is normalized and is in the range from 0 to 1. The effectiveness of each of these j-s (in this case j-1,4) subsystems $E_j(i)$ can be estimated by convolution of all their target (partial) i -th criteria:

$$E_j(i) = \prod_{i=1}^{M} k_i^{c_i} = k_1^{c_1} \times k_2^{c_2} \times \ldots \times k_M^{c_M}, \quad (1)$$

where:

$k_1, \ldots, k_M$- partial criteria of efficiency of performance of the functions by component subsystems; $C_1, \ldots, C_M$- weights of partial efficiency indicators,

$\sum_{i=1}^{M} C_i = 1$; M - the number of partial performance indicators.The sequence (stages) of selecting the convolution function is as follows:

1. Rationale for the admissibility of the convolution - the criteria to be convoluted must be homogeneous.

2. Normalization of criteria - the criteria that are collapsing must be normalized. In problems where local criteria have different units of measurement, it is necessary to reduce the criteria to a single, preferably dimensionless, scale of measurement.

3. Taking into account the priorities of the criteria - the formation of weights that reflect the importance of the criterion.

4. Construction of the convolution function.

The following functions are used to collapse the criteria:

additive convolution;

multiplicative convolution;

aggregation and others

The weight coefficients C_i of partial efficiency indicators are usually determined by the method of expert evaluations (and only when it is impossible to conduct an expert survey, the weights of all partial indicators are taken as equilibrium $C_i = 1/M$).

Let's define the efficiency-cost evaluation criterion of the whole UAV control system.

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We will assume that the effectiveness of the technical system (TS) to combat UAVs $\mathrm{E}_{\mathrm{TS}}^{protection}$ should be no worse than acceptable $\mathrm{E}_{\mathrm{TS}\,valid\,value.}^{protection}$, the value of which ensures the preservation of the combat capability of the object of protection, with a minimum of resource costs:

$$\mathrm{E}_{\mathrm{TS}}^{protection} \geq \mathrm{E}_{\mathrm{TS}\,valid\,value}^{protection},\ at\ P_{\mathrm{TS}}^{protection} \rightarrow P_{\mathrm{TS\,min}}^{protection}, \quad (2)$$

where:

$P_{\mathrm{TS}}^{protection}$ – the price of the technical solution of protection;

$P_{\mathrm{TS\,min}}^{protection}$- the possible price of the technical decision of protection.

Determining the acceptable level of effectiveness of technical solutions to combat depends on the degree of preservation of the combat capability of the object of cover. It is clear that the possible damage to the object of cover should be minimal or absent. Hence, it is logical to strive for the absence of any damage to the object of cover and the acceptable level of efficiency of technical solutions near the unit. But it is clear that this option involves the implementation of a very expensive technical solution, the implementation of which is extremely difficult and impractical. Therefore, it is advisable as an acceptable level of efficiency of technical solutions to choose the level of the Fibonacci method or the golden ratio – 0,62. This level provides a survivable object of protection, the ability to further perform the tasks assigned to it and the reasonable cost of the protection system.

The efficiency of the technical system for combating UAVs $\mathrm{E}_{\mathrm{TS}}^{protection}$ is the result of the convolution of partial criteria for the **effectiveness** of their functions by the constituent subsystems.

All the above criteria of subsystems are interconnected, homogeneous, linear, normalized, positive, potentially have different priorities, and belong to the group of effective. Therefore, for the formation of the general criterion (super criterion) can be used by analogy multiplicative convolution in the form of a criterion of efficiency (1).

Based on this, the effectiveness of the technical system of UAV control (counteraction) can be assessed as the result (or level) of operation of all four subsystems, which tends to the maximum value, according to the formula:

$$\mathrm{E}_{\mathrm{TS}}^{protection} = E_j(i) = E_1^{B1} \times E_2^{B2} \times E_3^{B3} \times E_4^{B4} \rightarrow max, \quad (3)$$

where $E_1^{B1} \times E_2^{B2} \times E_3^{B3} \times E_4^{B4}$ - respectively, the efficiency of information, management, executive subsystems and subsystems of resource provision.

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$B_1,..,B_4$- weight coefficients of efficiency criteria of information, control, executive subsystems and subsystem of resource provision,

$$\sum_{j=1}^{4} B_j = 1..$$

The weight coefficients B_j of partial efficiency indicators of this subsystems are usually determined by the method of expert evaluations (and only when it is impossible to conduct an expert survey, the weights of all partial indicators are taken as equilibrium B_j=1/4).

Thus, each of the four subsystems that are part of the technical system to combat UAVs, contributes to the effectiveness of this system. As follows from the analysis of expression (3), the efficiency criteria of each of the subsystems must be quite high. Otherwise, the efficiency of the system will be low.

According to the results of the evaluation of the effectiveness of the methods of counteracting the UAV, it is expedient to further compare the methods according to the criterion "efficiency - cost".

The authors propose a five-point scale for assessing the effectiveness of the UAV control system, which is given in table 2.

Having established the permissible levels of efficiency of the UAV counteraction system, it is possible to determine the optimal decision-making criteria for the choice of UAV counteraction methods (3): the effectiveness of the UAV control system should be no worse than acceptable, with a minimum of resource costs.

Table 2 - Scale for assessing the effectiveness of the UAV control system

Level of efficiency	Indicator value
Very effective	$E_{TS}^{protection} \geq 0,8$
Effective	$0,8 > E_{TS}^{protection} \geq 0,6$
Not effective enough	$0,6 > E_{TS}^{protection} \geq 0,4$
Ineffective	$0,4 > E_{TS}^{protection} \geq 0,2$
Very inefficient	$E_{TS}^{protection} < 0,2$

The evaluation of the effectiveness of existing and prospective UAV control systems and its results are beyond the scope of this publication and will be presented in the next publication.

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Summary and conclusions.

1. Means of control and counteraction to UAVs should be considered from a systemic standpoint.

2. The proposed system of criteria allows:

to investigate in detail, the effectiveness of the main subsystems of the UAV control system;

to quantify the effectiveness of methods of combating and counteracting UAVs at the level of subsystems and the system as a whole;

perform comparisons between different implementations of one or more methods of UAV control;

identify the most effective ways to fight and counter in different environmental conditions and climatic conditions.

3. Evaluation of the use of several methods of counteraction is reduced to the formation of a single criterion by convolving the target criteria of each of the subsystems.

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