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Stochastic Model of Functional Behavior of Radio Electronic Complex System for Detection of Low-Flying Unmanned Aerial Vehicles

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ABSTRACT A radio electronic complex system for detecting low-flying unmanned aerial vehicles is considered. It includes two acoustic systems, a repeater, an optoelectronic system, and an information control system. To determine the efficiency of the radio-electronic complex system, a discrete-continuous stochastic model of its operational functional behavior is developed. The degree of adequacy of the proposed discrete-continuous stochastic model of the operational functional behavior of the radio-electronic complex system is determined by the list of functionality indicators considered for the systems comprising it. A verbal model of operational functional behavior is built based on its functional algorithm. Functional indicators for each system in the stochastic model use "the probability of detecting unmanned aerial vehicles when they are in the corresponding controlled zone" and "the average values of the time intervals from the moment of appearance of unmanned aerial vehicles in the controlled zone to the moment of their detection by the corresponding system". The stochastic model makes it possible to calculate the values of the functionality indicators of its systems for a given value of the radio-electronic complex system's efficiency indicator. The results of validation experiments conducted on the developed stochastic model of the functional behavior of the radio-electronic complex system for detecting low-flying unmanned aerial vehicles are provided.

KEYWORDS radio electronic UAV detection complex system; acoustic UAV detection system; optoelectronic UAV detection system; operational functional behavior of the complex system; mathematical modeling, discrete-continuous stochastic model.

I. INTRODUCTION

Detecting and destroying enemy unmanned aerial vehicles (UAVs) requires the effective execution of the following tasks:

1) detecting unmanned aerial vehicles;

2) tracking their flight path (one party to the conflict tracks the flight path of the unmanned aerial vehicle (UAV) with the aim of destroying it. The other party to the conflict controls the UAV's flight, specifically maneuvering and changing its flight path to prevent its destruction);

3) identifying the type of aerial object (enemy UAV, friendly UAV, bird);

4) making a decision of regarding a "hostile UAV" and providing high-precision targeting guidance to the weapon system.

It should be noted that this article presents the development of a discrete-continuous stochastic model for studying the effectiveness of an electronic warfare system for detecting unmanned aerial vehicles. The considered electronic detection system (EDS) is designed to detect low-flying unmanned aerial vehicles whose flight is accompanied by acoustic noise. This refers to the level of acoustic noise that can be detected by an acoustic sensor.

A distinctive feature of the electronic warfare system under consideration is that it does not include a radar system whose operation would reveal the presence of a weapon system in the UAV's path. However, the radar system performs a function that is crucial for the electronic warfare system: the "early" detection of UAVs and the transmission of target designation to the weapon system. Therefore, in the radio electronic complex system (RECS) the "early" detection function is performed by the acoustic sensors of the first acoustic system, installed at the forward edge of the far-range controlled zone. Signals from the acoustic sensors are transmitted to the weapon via a repeater and the information control system.

In the RECS the function of identifying the type of aircraft is assigned to acoustic systems and is performed based on the analysis of acoustic signals. The solution to this problem is

presented in the review subsection "II.A." based on the analysis of the articles [2–5].

The function of identifying the type of UAV can also be performed by an optoelectronic system. Since the RECS for detecting unmanned aerial vehicles operates both day and night, the optoelectronic system must ensure that the identification function is performed based on optical image signals and thermal field signals. The solution to this problem is presented in the review subsection "II.B." based on the analysis of the articles [6–9].

An important component of the process of countering enemy unmanned aerial vehicles is their detection. One of the ways to increase the effectiveness of low-flying UAV detection systems is to combine several detection systems of different types into a radio-electronic complex system [1].

Reference [1] described the ways of combining multiple detection systems into single RECS. However, this work does not include values of performance indicators for separate systems and combined radio electronic systems. The availability of the values of the performance indicators of the developed RECS for the detection of unmanned aircraft will ensure their correct selection for practical use.

It is common to use the "probability of detection of unmanned aircraft" as an efficiency indicator. There are two known approaches to obtain the values of the efficiency indicator of the unmanned aircraft detection system. One approach is to operate the RECS and collect data on its effectiveness in detecting unmanned aircraft. Based on this data, the value of the "probability of detecting unmanned aircraft" indicator is determined. It should be noted that using the first approach to determine the performance indicator requires the creation of the RECS and time for its test operation. And if the result is negative, using the RECS becomes impractical. The second approach to determining the RECS performance indicator is used during the system-engineering design phase of RECS.

The paper presents the solution to the problem of developing a discrete-continuous stochastic model of the operational functional behavior of RECS, which includes: two acoustic systems whose acoustic sensors are installed at the boundaries of the far and near controlled zones; a repeater installed in the far controlled zone; an information control system (ICS); and an optoelectronic system (OES). It should be noted that the ICS and OES are installed on a multipurpose robotic platform, and this configuration of the system ensures its operational stealth against enemy electronic intelligence. Based on its operational algorithm and the corresponding deployment of its systems on the ground, the electronic complex detects unmanned aircraft in three zones:

a) in the far controlled zone, acoustic sensors of the first acoustic system detect unmanned aerial vehicles;

b) in the middle-controlled zone, the day-night vision optoelectronic system detects unmanned aerial vehicles;

c) in the near controlled detection zone, the detection of unmanned aerial vehicles is provided by acoustic sensors of the second acoustic system and OES (equipped with day and night vision) basing on target designation from the second acoustic system.

Improving the adequacy of the stochastic model of the operational functional behavior of RECS is an important contribution to designing technology of countermeasure developments against UAVs.

II. KNOWN RESULTS OF RESEARCH ON SYSTEMS FOR DETECTING LOW-FLYING UNMANNED AERIAL VEHICLES

It should be noted that no publications directly related to the development of a stochastic model of the operational functional behavior of RECS in the above-described composition were found. Therefore, we analyzed publications on the use of radio-electronic systems for detecting low-flying unmanned aerial vehicles, which contain information on the results and recommendations useful for building a verbal model of the operational behavior of the studied RECS. We focus on the use of acoustic, optoelectronic, thermal imaging, and radar systems.

A. ARTICLES ON IMPROVING ACOUSTIC SYSTEMS DESIGN TO DETECT UAVs

The purpose of research [2] was to create a database of raw acoustic signals from as many UAVs as possible while operating in different terrains and conditions. The authors pointed out the expediency of installing acoustic sensors on the perimeter of a strategic object to receive notifications of the approach of low-flying unmanned aircraft.

The authors of article [3] used two methods to determine the flight parameters: the least squares method and the autocorrelation method. The authors recommended applying these methods to real acoustic signals from sensors, assuming that the aircraft flies at constant speed and the flight path is straight line.

In paper [4], the system configuration for automatic detection and localization of unmanned aerial vehicles by acoustic signal was proposed.

The authors of [5] improved the method of UAV detection based on the results of spectral analysis of acoustic signals generated by their operation. The criterion for reliable UAV detection is the presence of at least three characteristic harmonics in the received acoustic signal.

No articles were found on research into the efficiency of using acoustic systems in combination with other systems.

B. ARTICLES ON IMPROVING OPTICAL-ELECTRONIC SYSTEMS DESIGNED TO DETECT UAVs

In article [6], the authors drew attention to the possibility of developing algorithms for tracking small unmanned aerial vehicles based on video surveillance data. The Kalman-type correlation algorithm was proposed for tracking a small unmanned aerial vehicle in the presence of spatially uncorrelated interference, which is most encountered in practice.

The author of work [7] concluded that an appropriate option for solving the problem of combating UAVs is the development of a multifunctional integrated complex system for UAV detection and identification. It is based on the combination of a radar system for detecting low-moving, low-flying and an optoelectronic system. The structure of this complex system was proposed.

The author of dissertation [8] considered the use of a computer vision system both for detecting unmanned aerial vehicles and for estimating their position.

In article [10], the authors proposed a solution to the problem of distinguishing between low-flying UAVs and birds using an optoelectronic day vision system.

No articles were found on research into the efficiency of using an optoelectronic system in combination with an acoustic

system.

C. ARTICLES ON IMPROVING RADAR SYSTEMS DESIGNED TO DETECT UAVs

In [10], the authors noted that the main problem with traditional means of countering enemy UAVs is the short range of detection and neutralization. The authors proposed the concept of an airborne platform to counter enemy UAVs. The experimental results showed that the created platform fulfills the task of detecting an enemy UAV, determining its coordinates and neutralizing it with the help of a "UAV-hunter".

In article [11], to justify the feasibility of using a radar system, authors described the advantages and disadvantages of technologies for detection of small UAVs with the autonomous use of passive and active radar systems, optoelectronic systems and acoustic systems.

The results presented in article [12] are a continuation of the authors' research presented in article [10]. The article compared the results of detecting four types of aircraft using two naval radar systems of different operations.

In article [13], the author stated that radar systems, compared to optoelectronic and acoustic systems, can detect UAVs in all weather and light conditions and at greater distances. At the same time, they can determine the range, speed and coordinates of the UAV. Based on the analysis of the publications of the last years (85 publications in the reference list), the author noted that the radar method of detection and recognition of classes and types of UAVs is being actively developed in scientific research.

The authors of article [14] noted that the main problem in radar detection of operational-tactical and tactical UAVs is their low radar visibility. Therefore, radar equipment with high energy potential is required to detect such aircraft. The use of such radars is advisable for detecting UAVs at line-of-sight ranges of 10-20 km. However, it should be noted that the radar does not provide stealth for its operation.

D. ARTICLES ON THE USE OF NEW METHODS FOR DETECTING UAVs

Article [15] is a review with generalization and systematization of the methods available in the publications for receiving and processing of radar, acoustic, optical and infrared signals for detection-recognition, measurement of coordinates and parameters of UAV movement. The authors pointed out that the known methods of energy detection of UAV signals are not effective enough, since the operation is performed, as a rule, in the presence of interference, which has a certain structural similarity with the signal from the UAV. The main attention was paid to methods of interpretation of the obtained data using trained neural networks.

The authors of article [16] noted that modern technologies for detection of unmanned aerial vehicles are mainly based on radar systems, optoelectronic systems, acoustic systems and electronic intelligence. However, the authors consider that the most common method for detecting low-altitude UAVs is their detection using computer vision. Traditional computer vision detection methods typically use the sliding window method to count possible frames in an image and extract important information about features before classifying and identifying the UAV. The authors presented an improved DRBD-YOLOv8 UAV detection technology that provides high computational speed, increased accuracy, reduced computational requirements, and low memory requirements. This technology, according to the authors of the article, provides real-time detection of UAVs.

In article [17], the authors presented an overview of publications on the use of UAVs for collecting video information for various purposes. The reference list contains 125 publications. The authors noted that these works were considered to determine the requirements for the application of computer vision.

Work [18] provided a list of questions that need to be answered when assessing the quality of means of detection and countermeasures of UAVs. The list contains 17 general questions, 10 questions for active radar system, 17 questions for passive radar system, 6 questions for electro-optical system, 7 questions for acoustic system. It should be noted that the list of questions includes a question about the efficiency indicator of each system: "What is the relationship between the probability of detection and the distance between the system and the UAV?"

E. ARTICLES JUSTIFYING THE FEASIBILITY (WITH RECOMMENDATIONS) FOR COMBINING RADAR, ACOUSTIC, AND OPTICAL-ELECTRONIC SYSTEMS INTO SINGLE RADIO-ELECTRONIC COMPLEX SYSYTEM FOR DETECTING UAVs

In article [19], authors pointed out that the low efficiency of the autonomous use of radar and AS for the detection of UAVs relates to their low visibility both in the electromagnetic and in the acoustic wavelength range. A promising direction for increasing the use of radar and AS is their combination in a single complex system.

In article [20], the authors justified the feasibility of including a thermal imaging system into the composition of a radio-electronic complex, which already has an optoelectronic and acoustic system. The results of a study of the dependence of the efficiency of the RECS on the distance to the target are presented. At the same time, the authors of the article noted that the combination of three systems provides higher reliability of UAVs detection than the RECS with two systems. For the RECS, this means a reduction in the number of false alarms and the number of undetected UAVs.

In article [21], the authors show the principle of building a RECS for detecting unmanned aircraft using low-power radar systems, acoustic sensors, an optoelectronic system, and an information and control system. Low power radars and acoustic sensors are placed at the front line of the controlled area. The number of radars and acoustic sensors depends on the length of the front line. The optoelectronic system includes an infrared detector sensitive to the 8-12 μm wavelength range, which ensures its operation day and night. To improve the resolution during the day, a television camera is used in the optoelectronic system. The optoelectronic system detects UAVs in the controlled area upon a message from the corresponding radar system and/or the corresponding acoustic sensor.

The authors of article [21] presented methods for solving problems of assessing the effectiveness of tactical UAV detection by acoustic, optoelectronic, thermal imaging, and active and passive radar surveillance systems. Factors influencing detection efficiency are analyzed.

The probability of detection of a target in the operation area of each surveillance system depends on its ability to find the target in the given physical conditions of the controlled area, the characteristics of the UAV flight through the controlled area, and the method of using the surveillance system when

detecting the target. Then, in each specific case, the probability of target detection can be estimated correctly only considering the degree of influence of each of these factors.

Article [27] proposed a solution to the problem of UAV flight control. It concerns a UAV designed to operate in environments where radio wave propagation is obstructed. This article has no direct relevance to the problem of detecting and destroying enemy low-flying unmanned aerial vehicles with a certain level of acoustic noise.

However, by referring to this article, we draw the reader's attention to the fact that a UAV may have the ability to maneuver to overcome obstacles, either autonomously or at the operator's command. For example, when an operator receives a message from an electronic intelligence unit that their UAV has been detected, maneuvering provides a chance to save it from destruction.

F. ARTICLES ON THE DEVELOPMENT AND APPLICATION OF MEANS OF COUNTERACTING UNMANNED AERIAL VEHICLES

In [23], the authors presented a testing and performance evaluation methodology for the development of counter-UAV technologies.

In article [24], the authors noted that in recent years, laser, microwave, and other energy directed weapon systems had become the primary means of countering unmanned aerial vehicles. Currently, the U.S. Navy's ship-based laser weapons are capable for destroying air and surface targets at close range (about 4 nautical miles / 7.4 km). In the future, they will be able to destroy targets up to 10 nautical miles away. In order to verify the effectiveness of laser devices for attacking miniature UAVs, flight tests of miniature UAVs were conducted. According to the test results, the laser devices were tested and evaluated according to two indicators: maximum jamming range and maximum interception range.

In paper [25], the authors presented a system to counter unauthorized UAVs, consisting of a ground control station and an UAV-hunter. The UAV-hunter is a six-rotor UAV equipped with a visual tracking system and an on-board cable device to intercept unauthorized UAVs at close range.

In paper [26], the authors considered two types of attacks: a jamming attack and a hijacking attack, and demonstrated the feasibility of performing jamming and hijacking attacks in both autonomous and non-autonomous flight modes for Crazyflie drones. This article presented the results of an experimental study of the consequences of attacks on the Crazyflie ecosystem.

Article [27] proposed a solution to the problem of UAV flight control. It concerns a UAV designed to operate in environments where radio wave propagation is obstructed. This article has no direct relevance to the problem of detecting and destroying enemy low-flying unmanned aerial vehicles with a certain level of acoustic noise.

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G. SUMMARY OF THE RESULTS OF THE PUBLICATIONS REVIEW

Several publications declared an increase in the efficiency of UAV detection with the proposed improvements. There are articles that describe experimental studies to evaluate the effectiveness of the proposed improvements. Most authors drew conclusions that to increase the efficiency of UAV detection it is advisable to combine several systems of different types in one radio-electronic complex system. It was not mentioned that in order to obtain the value of the efficiency indicator "probability of detection of unmanned aerial vehicles" it is necessary to develop discrete-continuous stochastic models of the operational behavior of RECS.

However, the authors of the article?? have experience in the development of discrete-continuous stochastic models of the operational functional behavior of RECS with different configurations and for other purposes.

In article [28], a stochastic model of the operational behavior of RECS including radio-electronic reconnaissance system, a radar, an optical-electronic system, a thermal imaging system and an acoustic system were offered.

In article [27], which is a continuation of article [26], the developed stochastic model was used and a comparison of efficiency of RECS with different combinations of such systems was presented.

A stochastic model of the operational behavior of RECS for detection of enemy ground objects hit by artillery was presented in article [28].

A stochastic model of security alarm complex considering all options for detection of moving objects while crossing two controlled zones with a seismic sensor arrangement scheme {3+3} was offered in article [29]. Two decision schemes based on the majority principle {2 out of 3} for each controlled zone and the scheme for determining the coincidence of messages from controlled zones were considered.

A security system as part of a security alarm complex system based on seismic sensors and an unmanned aircraft complex was presented in article [30].

Thus, a review of publications showing the solutions to the system engineering design tasks of the RECS for detecting unmanned aerial vehicles confirms the relevance of developing a discrete-continuous stochastic model of the operational behavior of the RECS consisting of two acoustic systems, whose acoustic sensors are installed at the front lines of the far and near controlled zones, a repeater installed in the far controlled zone, an information and control system, and an optoelectronic system.

III. VIRTUAL OPERATIONAL FUNCTIONAL BEHAVIOR OF THE RADIO ELECTRONIC COMPLEX SYSTEM

A. SCHEME FOR DEPLOYMENT OF THE RADIO ELECTRONIC COMPLEX SYSTEM ON SITE

For the deployment of the RECS, the terrain is conventionally divided into 3 controlled zones: far, middle and near. The scheme for the deployment of the RECS on site is shown in Fig. 1.

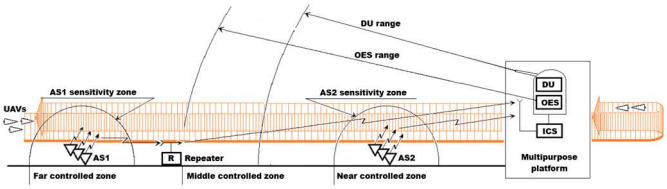

Figure 1. Scheme for deployment of the radio electronic complex system on site (AS1 – acoustic system 1, a combination of acoustic sensors installed at the border of the far controlled zone; AS2 – acoustic system 2, a combination of acoustic sensors installed at the border of the near controlled zone, DU – destruction unit, OES – optoelectronic system, ICS – information and control system).

Structurally, the RECS consists of the following components: a multi-purpose robotic platform on which an Information and Control System (ICS) and an Optoelectronic System (OES) are installed, a certain number of acoustic sensors installed on the front lines of the far (acoustic system AS1) and near (acoustic system AS2) control zones, and a repeater installed in the far controlled zone. A demolition device is installed on the robotic platform.

The number of acoustic sensors in the acoustic system AS1 for the far controlled zone determines the length of the line, the size of the sensitivity zone of each acoustic sensor, and the distance between adjacent acoustic sensors. The placement of the adjacent acoustic sensors on the far zone line should be positioned so that their sensitivity zones partially overlap. This provides functional redundancy of the acoustic sensors to detect an unmanned aircraft crossing the line of the far controlled zone.

Acoustic systems AS1 and AS2 are turned on in standby mode to receive an acoustic signal. Each acoustic sensor of the AS1 and AS2 acoustic systems must distinguish the acoustic signal coming from the UAV from other acoustic signals. Each acoustic sensor has its own radio transmitter, which provides transmission of UAV detection messages to the repeater. At the same time, this radio channel should provide a certain level of secrecy for the transmission of messages from the enemy's electronic intelligence. A repeater is situated at some distance from the boundary of the far controlled zone, i.e., from AS1.

The repeater should be robust to the electronic intelligence means and provide secure transmission of messages about the appearance of unmanned aircraft, received from acoustic sensors to the ICS. For the stochastic model of the operational behavior of the RECS, the condition is assumed that the probability of transmission of a radio signal with a message about a detected UAV from the corresponding acoustic sensor through the repeater to the ICS is equal to 1.

On command from the ICS in the middle-controlled zone, the OES and the means of destruction strike unmanned aircraft detected in the far controlled zone.

The placement of the sensors of the AS2 acoustic system at the front line of the near controlled zone is similar to the placement of the sensors of the AS1 acoustic system. The transmission of messages from the AS2 sensors to the ICS is directed without repeating.

At the command of the ICS in the near controlled zone, the OES and the means of destruction strike the UAV detected in the near controlled zone.

B. FUNCTIONAL ALGORITHM OF THE RADIO-ELECTRONIC COMPLEX SYSTEM

The functional algorithm for the operation of the radio-electronic complex system for the detection of unmanned aerial vehicles using two acoustic systems and one optoelectronic system is as follows.

Start: UAV crosses the front line of the far controlled zone.

Step 1: One of the sensors of the acoustic system AS1 installed in the far controlled zone must respond to the acoustic signal from the UAV and its radio transmitter must transmit a message about the detection of the UAV to the information and control system through a repeater.

If one of the AS1 sensors has detected the UAV, we go to step 2.

If none of the AS1 sensors have detected the UAV, the system proceeds to step 3.

Step 2: The information and control system, based on the message received from AS1 of the far controlled zone, gives the command to the optoelectronic system to start working in the middle-controlled zone. When the OES work, the information and control system sets for the OES the maximum duration of its operation in the middle-controlled zone. This duration depends on the flight speed of the UAV.

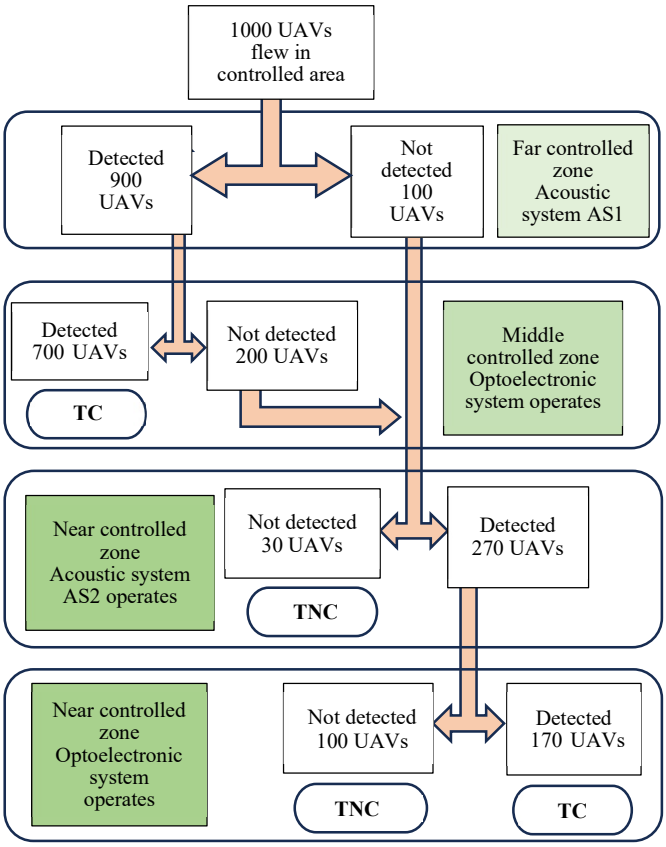

Figure 2. Results of virtual observation of unmanned aerial vehicles flights through three zones controlled by the radio electronic complex system: TC – RECS task is completed; TNC – RECS task is not completed

If the OES detects the UAV within the specified duration of its operation, it transmits the target designation to the means of destruction. The RECS task is completed. For stochastic model development, we assume that after the detection of the unmanned aircraft by the optoelectronic system, it is neutralized by the destruction unit.

If the OES does not detect the UAV within the specified time of its operation in the middle-controlled zone, then go to step 3. Note that the OES will not shut down in this situation.

Step 3: One of the acoustic sensors AS2 of the near controlled zone must respond to the acoustic signal generated by the UAV and transmit a detection message to the information and control system.

If one of the AS2 sensors has detected a UAV, go to step 4.

If none of the AS2 sensors have detected a UAV, the RECS task is not completed.

Step 4: The information and control system, based on the message received from the corresponding acoustic sensor AS2, gives the command to the optoelectronic system to start working in the vicinity of the controlled zone. At the same time as the OES is put into operation, the information and control system sets for the OES the maximum duration of its operation

in the near-controlled zone. This duration depends on the flight speed of the UAV.

If the OES detects a UAV within the specified duration of its operation, it transmits the target designation to the means of destruction. The RECS task is completed.

If the OES does not detect UAV, the RECS task is not completed.

C. VERBAL MODEL OF VIRTUAL OPERATIONAL FUNCTIONAL BEHAVIOR OF A RADIOELECTRONIC COMPLEX SYSTEM DURING LONG-TERM OBSERVATION OF ITS WORK ON DETECTION OF UNMANNED AIRCRAFT

The verbal model of the virtual operational behavior of the RECS for the detection of unmanned aircraft shows all (from the point of view of the developer of the stochastic model) events and situations that occur during their flights through the zones controlled by the systems included into RECS.

The diagram showing an example of the developer's vision of the virtual operational behavior of the RECS is shown in Figure 2. It shows the distribution of statistical but imaginary observation of RECS operation for one month. It is assumed that during this period 1000 unmanned aircraft flew into the area where the RECS is deployed. The acoustic system AS1, whose acoustic sensors are located at the front line in the far controlled zone, detected 900 unmanned aircraft.

For various reasons, 100 unmanned aircraft were not detected. The other proportions of detected and undetected UAVs in the far controlled zone are described below.

The beginning of the observations of the operation of the RECS: the acoustic system AS1, the acoustic sensors of which are installed at the front line of the far controlled zone, continuously waits for the appearance of the next UAV.

First expected pair of events: event 1.1 "the next UAV flies into the far controlled zone" and event 1.2 "one of the sensors of the AS1, installed at the front line of the far controlled zone, detects the appearance of the next UAV".

For the expected event 1.2, two alternative options are possible, when "one of the sensors of the AS1, installed at the front line of the far controlled zone, detects the appearance of the next UAV".

In the first option of the expected event 1.2, we can see that some of the unmanned aircraft, from among those that flew into the far controlled zone through different sections of the line, are detected by the corresponding sensor of the AS1.

Note that the indicator of the functionality of the acoustic system AS1 operating in the far controlled zone is the "probability of detection of unmanned aircraft in the far controlled zone by the acoustic system AS1 P_{AS1}.

In the continuation of the observations of the part of the unmanned aircraft for which the first variant of event 1.2 occurred, the second expected pair of events will be relevant: event 2.1 "transmission of messages about detected unmanned aircraft from the sensors of the acoustic system AS1 to the repeater" and event 2.2 "receiving of messages from the sensors of the acoustic system AS1 by the repeater".

In the second variant of the expected event 1.2, we "observe" that the second part of the unmanned aerial vehicles, from among those that flew into the far controlled zone through various sections of the border, was not detected by the sensors of the acoustic system AS1.

Note that the probability of the UAV non-detecting in the far controlled zone by the AS1 is defined as $(1 - P_{AS1})$.

Continuing the "observation" of some of the unmanned aerial vehicles for which the second variant of event 1.2 occurred, ***sixth expected pair of events*** is relevant.

Second expected pair of events: event 2.1 "Transmission of messages about detected unmanned aerial vehicles from the sensors of the AS1 to the repeater" – event 2.2 "Receiving of messages from the sensors of the acoustic system AS1 by the repeater". We are talking about the sensors of the AS1 installed at the edge of the far controlled zone.

Note that in the stochastic model the indicator "Probability of successful completion of the procedure of transmission of messages from the sensors of the acoustic system AS1 to the repeater" is taken as 1. Therefore, we do not consider alternative endings for event 2.2 in the stochastic model.

We continue to observe unmanned aircraft for which the expected event 2.2 has occurred. For these unmanned aircraft, ***third expected pair of events*** is relevant.

Third expected pair of events: Event 3.1 "Transmission of messages about detected UAV from the repeater to the ICS" – event 3.2 "Receiving of messages from the repeater in the information and control system". We recognize that we are talking about the unmanned aircraft previously detected by the sensors of the AS1 in the far controlled zone.

Note that in the stochastic model the value of the indicator "Probability of successful completion of the procedure for transmission of messages from the repeater to the information and control system" is taken as 1. Therefore, we do not consider alternative endings for event 3.2 in the stochastic model.

We continue to observe the part of the unmanned aircraft for which event 3.2 occurred. For them, ***fourth expected pair of events*** is relevant.

Fourth expected pair of events: event 4.1 "Beginning of the procedure for switching to the OES in the middle-controlled zone" – event 4.2 "Completion of the procedure for switching to the OES in the middle-controlled zone".

Note that the procedure for switching to OES is performed on command from the ICS according to the target designation from AS1.

Note that the indicator "Probability of successful completion of the procedure for switching to the OES" in the stochastic model is taken as 1. Therefore, we do not consider alternative endings for event 4.2 in the stochastic model.

We continue to observe the part of the unmanned aircraft for which event 4.2 occurred. ***Fifth expected pair of events*** is relevant to it.

Fifth expected pair of events: event 5.1 "The OES system starts searching UAVs in the middle-controlled zone" – event 5.2 "The OES system detects an unmanned aircraft in the middle-controlled zone". We are talking about the unmanned aircraft previously detected by the AS1 sensors in the far controlled zone.

For the expected event 5.2, two options can be considered, when "the optoelectronic system should detect an unmanned aircraft in the middle-controlled zone and transmit a message to the information and control system, which in turn transmits the target designation to the destruction unit".

In the first option of the expected event 5.2, we observe that a part of the unmanned aerial vehicle of the number detected by the corresponding sensor of the acoustic system AS1 in the far controlled area is detected by the optoelectronic system in the middle-controlled area and its tracking to the means of destruction is carried out. An indicator of the functionality of the optoelectronic system during operation in the middle-

controlled area is the probability of detection of unmanned aircraft P_{OES1} (probability of detection of unmanned aircraft flying through the middle-controlled area).

In the stochastic model, the continuation of the observation of the part of the unmanned aircraft for which the first variant of the expected event 5.2 has occurred is stopped – the execution of the RECS task is reached.

In the second variant of the expected event 5.2 we observe that a part of the unmanned aircraft from among those detected by the corresponding sensor of the acoustic system AS1 in the far controlled area is not detected by the optoelectronic system in the middle control area (for example, due to weather conditions). Accordingly, the probability of not detecting an unmanned aircraft flying through the middle-controlled area by the optoelectronic system is defined as $(1 - P_{OES1})$.

We continue to observe the part of unmanned aircraft for which the second variant of the expected event 5.2 occurred. For them, ***sixth expected pair of events*** is relevant.

Sixth expected pair of events: event 6.1 "the next UAV enters the near controlled zone" and event 6.2 "one of the sensors of the AS2, installed at the boundary of the near controlled zone, detects the appearance of the next UAV".

Note that the sensors of the acoustic system AS2, installed at the front line of the near controlled zone, are continuously monitoring the appearance of the UAV.

Note that we are talking about those UAVs that have not been detected by the sensors of the acoustic system AS1 in the far controlled zone as well as those unmanned aircraft that have been detected by the sensors of the AS1 but have not been detected by the OES in the middle-controlled zone. There are UAVs about which the targeting data was not transferred to the destruction unit when they were in the middle-controlled zone.

For the expected event 6.2, two possibilities can be considered, when one of the sensors of the acoustic system AS2, installed at the front line of the near controlled zone detects the appearance of an unmanned aircraft" and sends a message to the ICS.

Note that the functionality indicator for the acoustic system AS2 is the probability of detection of unmanned aircraft P_{AS2} (the probability that unmanned aircraft flying into the near-controlled zone will be detected by the acoustic system AS2).

We continue to observe the part of the unmanned aircraft for which the first variant of the expected event 6.2 occurred. ***Seventh expected event pair*** is relevant for it.

In the second variant of the expected event 6.2, we observe that some of the UAVs among those that enter the near controlled zone are not detected by the acoustic system AS2.

Note that the probability of unmanned aircraft entering the near controlled zone not being detected by the AS2 acoustic system is defined as $(1 - P_{AS})$.

The continuation of "observations" of some of the unmanned aircraft for which the second variant of the expected event 6.2 occurred is terminated in the stochastic model – we obtain the failure to complete the RECS task (*the RECS task has not been completed).*

Seventh expected pair of events: event 7.1 "Beginning of the procedure for switching to the OES in the near controlled zone" – event 7.2 "Completion of the procedure for switching to the OES in the near controlled zone".

Note that the procedure for switching to the OES is performed on command from the ICS.

The value 1 will be taken for the indicator "probability of switching on the optoelectronic system" in the stochastic model. Therefore, we do not consider alternative endings for event 7.2.

We continue to observe the part of unmanned aircraft for which event 7.2 occurred**.** ***Eighth expected pair of events*** is relevant for them.

Eighth expected pair of events: event 8.1 "Start of the UAV searching in the near controlled zone by the OES" – event 8.2 "The OES detects an UAV in the near controlled zone".

Note that the OES transmits a message to the information-control system, which in turn transmits target designation to the means of destruction.

The search by the OES of the UAV in the near controlled zone is performed on command from the information-control system, which received a message from one of the sensors of the acoustic system AS2.

We are talking about those unmanned aircraft that were not detected by the sensors of the acoustic system AS1 in the far controlled zone. And, about those unmanned aircraft that were detected by the sensors of the AS1 acoustic system but were not detected by the OES in the middle-controlled zone.

For the expected event 8.2, two options are possible when the optoelectronic system should detect an unmanned aircraft in the "near controlled zone" and transmit a message to the information and control system. The information and control system, in turn, transmits the target designation to the means of destruction.

In the first option of the expected event 8.2, we observe that some of the unmanned aircraft, among those detected by the corresponding sensor of the acoustic system AS2, are detected by the optoelectronic system in the near controlled zone and are tracked by the means of destruction. An indicator of the functionality of the optoelectronic system during operation in the near controlled zone is the probability of detection of unmanned aircraft P_{OES2} (probability of detection of unmanned aircraft flying through the near controlled zone). It should be noted that as the distance between the optoelectronic system and the UAV decreases, the conditions for detecting the UAV improve. Therefore, we believe that the probability of detection of an unmanned aircraft in the near controlled zone by the optoelectronic system P_{OES2} is greater than the probability value of detection of an unmanned aircraft in the middle-controlled zone by the optoelectronic system P_{OES1}.

Continuation of "observations" of a part of an unmanned aircraft for which the first variant of the expected event 8.2 occurred is terminated in the stochastic model – we obtain execution of the RECS task. *(the RECS task has been executed).*

In the second variant of the expected event 8.2, we "observe" that a part of the unmanned aerial vehicle from among those detected by the corresponding sensor of the acoustic system AS2 in the near controlled zone is not detected by the optoelectronic system (for example, due to weather conditions). Accordingly, the probability that the optoelectronic system will not detect an unmanned aircraft flying through the near controlled zone is defined as follows $(1 - P_{OES2})$.

The continuation of observations of the part of the unmanned aircraft, at which the second variant of the expected event 8.2 occurred, is terminated in the stochastic model – we got the failure of the RECS to perform the task. (*the RECS has failed the execution of the task).*

Based on the formed verbal model of the virtual operational behavior of the RECS, according to the stochastic modeling technology, a probabilistic graph of the operational behavior of the

RECS is developed.

D. THE FORMULA FOR THE DETERMINATION OF THE EFFICIENCY INDICATORS OF THE RADIO-ELECTRONIC COMPLEX SYSTEM

The RECS performance indicator "Probability of detection of unmanned aircraft" P_D characterizes the percentage of UAVs overflights when detection of unmanned aircraft by the optoelectronic system was performed in the middle or near controlled zones. That is, the formula for determining the indicator has two components and should be composed as the sum of two conditional a priori probabilities of detection of unmanned aircraft by an optoelectronic system in the middle and near controlled zones.

The first component of the formula for the RECS efficiency indicator "probability of detection of unmanned aircraft" P_{D1} is formed as a conditional a priori probability of detection of UAVs using OES in the middle-controlled area, provided that:

1) the UAV is detected by the acoustic system AS1 in the far controlled zone;

2) the message about the detected UAV is successfully transmitted from the acoustic system AS1 through the repeater to the information and control system;

3) the command to start the operation is sent from the information and control system to the UES.

Thus, the first component of the formula is as follows:

$$P_{D1} = P(O_1|A_1, R, I), \quad (1)$$

where O_1 is the event "detection of a UAV by the optoelectronic system in the middle-controlled area"; A_1 is the event "detection of a UAV by the acoustic system AS1 in the far controlled area"; R is the event "successful transmission of a message about the detected UAV from the sensor of the acoustic system AS1 through the repeater to the ICS"; I is the event "of successful acceptance by the OES of the command from the ICS to start operation".

The second component of the formula for the RECS performance indicator "Probability of detection of unmanned aerial vehicles" P_{D2} is formed:

a) for those unmanned aerial vehicles that were not detected by the acoustic system AS1 in the distant controlled area;

b) for those unmanned aerial vehicles that were detected by the acoustic system AS1, but the message about the detected UAV was not transmitted from the acoustic system AS1 through the repeater to the ICS or was not received;

c) for those UAVs that were detected by the AS1, the message about the detected UAV was successfully transmitted from the AS1 acoustic system through the repeater to the information and control system, but the UAV was not detected by the UAS in the middle control zone.

The second component of the formula for the RECS performance indicator "probability of detection of unmanned aircraft" P_{D2} is formed as a conditional a priori probability of detection of a UAV using the UES in the near controlled area under the following conditions

1) the UAV is not detected in the far and middle-controlled zones, but is detected by the acoustic system AS2 in the near controlled zone;

2) the message about the detected UAV is successfully transmitted from the acoustic system AS2 to the ICS;

3) the command to start operation in the near controlled zone was sent from the information and control system to the optoelectronic system.

Thus, the second component of the formula is as follows:

$$P_{D2} = P(O_2|A_2, I), \quad (2)$$

where O_2 is the event "detection of a UAV by the optoelectronic system in the near controlled area"; A_2 is the event "detection of a UAV by the acoustic system AS2 in the near controlled area"; I is the event "successful acceptance by the OES of the command from the ICS to start operation in the near controlled area".

The compiled formula for determining the RECS performance indicator "probability of detection of unmanned aircraft" is as follows:

$$P_D = P_{D1} + P_{D2} = P(O_S|A_S, R, I) + P(O_B|A_B, I). \quad (3)$$

The final form of the formula for determining the RECS efficiency indicator "probability of detecting unmanned aircraft" is formed after the development of a probabilistic graph of the operational functional behavior of RECS.

The discrete-continuous stochastic model of operational behavior formed according to the probability graph in the form of a system of differential equations allows us to determine the value of the RECS efficiency indicator for detection of UAVs according to formula (3).

IV. PROBABILISTIC GRAPH BASED ON A VERBAL MODEL OF THE OPERATIONAL FUNCTIONAL BEHAVIOR OF THE RADIO-ELECTRONIC COMPLEX SYSTEM

A. ASSUMPTIONS AND CONDITIONS TAKEN INTO ACCOUNT IN THE STOCHASTIC MODEL

1) In the stochastic model it is assumed that the UAV crosses the far, middle and near controlled zones in this order during each flight.

2) The time intervals from the moment when the UAV appears in the far controlled area until it is detected by the acoustic system AS1 sensor are a continuous random variable and are represented in the stochastic model by an exponential distribution law. Such a distribution law for these time intervals corresponds to the condition that in most flights of unmanned aircraft through the far controlled area, acoustic sensors detect unmanned aircraft at the beginning of its section and rarely at its end. By similar reasoning, the exponential distribution law is adopted for time intervals from the moment of appearance of unmanned aircraft in the near controlled area to the moment of their detection by the acoustic system AS2 sensor.

3) The time intervals from the estimated moment of appearance of unmanned aircraft in the middle-controlled area (at the command of the information and control system) to the moment of their detection by the optoelectronic system are also represented by an exponential distribution law.

4) The repeater of messages from the sensors of the acoustic system AS1 to the information and control system and the information and control system are always in good condition and perform their functions successfully with probability 1.

5) For the optoelectronic system, we assume that the completion of the procedure for switching on the command from the ICS is completed successfully with probability 1.

B DETERMINING THE BASIC EVENTS OF THE OPERATIONAL FUNCTIONAL BEHAVIOR OF THE RADIO ELECTRONIC COMPLEX SYSTEM

All homogeneous events of the operational functional behavior of the radio-electronic complex system, which are considered in its stochastic model, are presented in pairs in Table 1. We call homogeneous events a pair of events that belong to the same procedure of the RECS functioning algorithm. In each pair of homogeneous events, we distinguish current and subsequent events. We call current and subsequent events the events that represent the beginning and end of the RECS functioning algorithm procedure. We use subsequent events of operational functional behavior as basic events (BE) for developing a probability graph [32]. Note that the values of time intervals between homogeneous events, i.e., the duration of procedures, are random variables with corresponding mean values. It is considered that there is a large difference between the mean values of the durations of different procedures. Accordingly, for the model, very small mean values are taken to be zero. Therefore, some of the basic events became combined basic events (CBE).

Table 1. Events of operational functional behavior of the radio electronic complex system

Start event	End event	Average value of time intervals
Event 1.1 "The next UAV flies into the far controlled zone"	Event 1.2 "One of the sensors of the acoustic system AS1, installed at the front line of the distant controlled zone, should record (detect) the appearance of the next UAV" – **BE1**	T_{AS1}
Event 2.1 "Transmission of messages about detected unmanned aerial vehicles from the sensors of the acoustic system AS1 to the repeater"	Event 2.2 "Reception of messages from the sensors of the acoustic system AS1 by the repeater" – **CBE2**	$T_{AR} \approx 0$
Event 3.1 "Sending messages about detected unmanned aerial vehicles from the repeater to the information and control system"	Event 3.2 "Receiving messages from the repeater in the information and control system" – **CBE3**	$T_{RI} \approx 0$
Event 4.1 "Start of the procedure for switching on the optoelectronic system in the middle control zone"	Event 4.2 "Ending the procedure for switching on the optoelectronic system in the middle control zone" – **CBE4**	$T_{VO} \approx 0$
Event 5.1 "Start of the optoelectronic system search for an unmanned aircraft in the middle-controlled zone"	Event 5.2 "The optoelectronic system must detect an unmanned aircraft in the middle-controlled zone" – **BE5**	T_{OES1}
Event 6.1 "Another UAV enters the near controlled zone"	Event 6.2 "One of the sensors of the AS2 acoustic system installed at the front line of the near controlled zone must record (detect) the appearance of an UAV" – **BE6**	T_{AS2}
Event 7.1 "Start of the procedure for switching on the optoelectronic system in the near controlled zone"	Event 7.2 "Completion of the procedure for switching on the optoelectronic system in the near controlled zone" – **CBE7**	$T_{VO} \approx 0$
Event 8.1 "Start of the search by the optoelectronic system for UAVs in the near controlled zone"	Event 8.2 "The optoelectronic system should detect unmanned aircraft in the near controlled zone" – **BE8**	T_{OES2}

C. A VECTOR OF STATES FOR REPRESENTING A VERBAL MODEL OF THE OPERATIONAL FUNCTIONAL BEHAVIOR OF THE RADIO ELECTRONIC COMPLEX SYSTEM

The state vector of a probabilistic graph is a set of components that allow the operational functional behavior of the RECS to be represented with the necessary degree of adequacy. In our case, the state vector consists of five components.

1. The component of the state vector V1 determines the state of the acoustic system AS1 in the far controlled zone.
2. The component of the state vector V2 shows the state of the OES operating by command from the ICS in the middle-controlled zone.
3. Component of the state vector V3 determines the state of the acoustic system AS2 in the near controlled zone.
4. The component of the state vector V4 shows the state of the OES operating by command from the ICS in the near controlled zone.
5. Auxiliary component of the state vector V5 shows the correspondence of the final states of the graph with the efficiency indicators.

D. RADIO ELECTRONIC COMPLEX SYSTEM EFFICIENCY INDICATORS

1) P_{AS1} and P_{AS2} – probability of detection of unmanned aircraft by the acoustic system AS1 and acoustic system AS2 in the far and near controlled zones correspondingly;

2) T_{AS1} i T_{AS2} – average value of time intervals from the moment of UAV entry into the far and near controlled zones until its detection by the corresponding AS1 and AS2 sensor or until the end of UAV flight time through the far and near controlled zones;

3) P_{OES1} i P_{OES2} – probability of detection of unmanned aircraft with OES in the far and near controlled zones correspondingly;

4) T_{OES1} i T_{OES2} – average duration of OES operation in the far and near controlled zones correspondingly.

H. DEVELOPMENT OF PROBABILITY GRAPH OF THE OPERATIONAL FUNCTIONAL BEHAVIOR OF THE RADIO ELECTRONIC COMPLEX SYSTEM

According to modeling technology, the verbal model of the operational functional behavior of the RECS must be represented in the form of a probabilistic graph. To develop a probabilistic graph based on the verbal model of the operational functional behavior of the RECS, the methodology presented in article [32] was used. Table 2 shows the process of developing a probabilistic graph according to the verbal model of the operational functional behavior of the RECS. The columns of Table 2 have the following designations and names: 1 – number of steps; 2 – probability of alternative completion of the procedure (process); 3 – first component of the state vector V1; 4 – second component of the state vector V2; 5 – third component of the state vector V3; 6 – fourth component of the state vector V4; 7 – fifth component of the state vector V5; 8 – state number of the graph; 9 – transitions from state to state of the graph; 10 – formula for calculating the intensity of transitions between states of the graph.

Table 2. Development of a probabilistic graph of the operational functional behavior of the radio-electronic complex system

Step 1. The initial state of the graph is determined by the initial values of the components of the state vector.

5	**5**	**5**	**5**	**5**	**5**	**5**	**5**	**5**	**5**
0	0	0	0	0	0	0	0	0	0

Step 2. State vector 1 is considered. In this state, BE1 occurs "one of the sensors of the acoustic system AS1, installed at the front line of the far controlled zone, detects the appearance of UAV." As well as CBE2, CBE3, CBE4 are combined with it.

5	**5**	**5**	**5**	**5**	**5**	**5**	**5**	**5**	**5**
0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0

Comment to step 2.1: When a UAV is detected by the corresponding sensor of the acoustic system AS1 in the far controlled area, the value of component V1 changes from 0 to 1.
Comment to step 2.2: If none of AS1 sensors have detected UAV, the value of component V1 changes from 0 to 2.
The notations used are read as follows: state 2 of the graph shows that the AS1 has successfully performed its function; state 3 of the graph shows that the AS1 has not performed its function.
Note that here and further on, the formula for calculating the intensity of transitions between graph states is constructed as the product of the corresponding probability and the intensity of the basic event in the operational functional behavior of the RECS.

Step 3. State vector 2 is considered. In this state, BE5 occurs: "the OES detects an unmanned aircraft in the middle-controlled zone"

5	**5**	**5**	**5**	**5**	**5**	**5**	**5**	**5**	**5**
0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0

Comment on step 3.1: Upon successful completion of the OES operation in the middle-controlled zone, the value of component V2 changes from 0 to 1. We consider that the RECS task is completed. The state of the graph 4 is final (absorbing). The auxiliary component V5 is set to value 1, which indicates the completion of the RECS task.
Commentary to step 3.2: If the OES has not detected the UAV before the end of the UPS operation time set by the information and control system, the value of component V2 changes from 0 to 2. The value of component V5 = 2 indicates that the RECS has not completed the task in the middle-controlled zone. However, there is a probability of detecting this UAV in the near control zone.
The notations used should be read as follows: State 4 of the graph indicates that the UPS has successfully completed its function. This is also absorbing state of the probability graph.
State 5 of the graph indicates that the OES has failed to perform its function.

Step 4. State vector 3 is considered. In this state of the graph, the BE6 occurs "one of the sensors of the acoustic system AS2, installed at the front line of the near-controlled zone, detects the appearance of a UAV". And there is combined CBE7 event "completion of the procedure for switching on the optoelectronic system in the near-controlled zone".

5	**5**	**5**	**5**	**5**	**5**	**5**	**5**	**5**	**5**
1	1	1	1	1	1	1	1	1	1
2	2	2	2	2	2	2	2	2	2

Comment to step 4.1: When a UAV is detected by the corresponding sensor of the AS2 in the near controlled area, the value of component V3 changes from 0 to 1. If AS2 in the near controlled area has detected a UAV, then the auxiliary component V5 is set to 5.
Comment to step 4.2: If neither of AS1 sensors has detected a UAV flight, the value of component V3 changes from 0 to 2. If AS2 has not detected a UAV, then component V5 is set to the value 6.
State 7 is the absorbing state of the graph.

Step 5. State vector 5 is considered. In this state of the graph, the basic event BE6 occurs "one of the sensors of the acoustic system AS2, installed at the front line of the near-controlled zone, should detect the appearance of a UAV". And there is combined CBE7 event "completion of the procedure for switching on the optoelectronic system in the near-controlled zone".

5	**5**	**5**	**5**	**5**	**5**	**5**	**5**	**5**	**5**
1	1	1	1	1	1	1	1	1	1
2	2	2	2	2	2	2	2	2	2

Comment to step 5.1: Upon successful completion of the operation of AS2 in the near-controlled zone, the value of component V3 changes from 0 to 1. The auxiliary component V5 is set to the value 5, which indicates the detection of a UAV in the near-controlled zone.
Comment on step 5.2: Upon unsuccessful completion of the operation of AS2, the value of component V3 changes from 0 to 2. The value of component V5 = 6 indicates that no UAV was detected in the near-controlled zone.

Step 6. State vector 6 is considered. In this state of the graph, the BE8 occurs "the OES detects a UAV in the near controlled zone"

5	**5**	**5**	**5**	**5**	**5**	**5**	**5**	**5**	**5**
1	1	1	1	1	1	1	1	1	1
1	1	1	1	1	1	1	1	1	1

Comment on step 6.1: Upon successful completion of the OES operation, the value in component V4 changes from 0 to 1. Since the RECS task with the UAV is completed, state 10 is the absorbing state of the graph. Considering the values of the state vector components V1, V2, V3, V4, component V5 is set to 3.
Comment to step 6.2: Upon unsuccessful completion of the OES operation, the value in component V4 changes from 0 to 2. Accordingly, state 11 is also the absorbing state of the graph. Considering the values of the state vector components V1, V2, V3, V4, component V5 is set to 4. Note that state 10 of the graph shows that the OES has successfully performed its function; this state is the absorbing state of the graph.

Step 7. State vector 8 is considered. In this state of the graph, the basic event BE8 occurs "the optoelectronic system should detect a UAV in the near controlled zone"

5	**5**	**5**	**5**	**5**	**5**	**5**	**5**	**5**	**5**
1	1	1	1	1	1	1	1	1	1
1	1	1	1	1	1	1	1	1	1

Step 1. The initial state of the graph is determined by the initial values of the components of the state vector.

The probabilistic graph shown in Table 3 is developed accordingly to the verbal model of the operational functional behavior of the radio-electronic complex. It has 13 states and 12 transitions.

V. DISCRETE-CONTINUOUS STOCHASTIC MODEL OF VIRTUAL OPERATIONAL FUNCTIONAL BEHAVIOR OF THE RADIOELECTRONIC COMPLEX SYSTEM

The system of differential equations is based on a probability graph and has the following form (4).

The results of solving the system of differential equations (4), namely the values of the probabilities of transition to the final (absorbing) states of the graph, are intended for the

formula for determining the efficiency index of the RECS for detecting unmanned aircraft.

The formula for determining the efficiency index of the RECS is compiled in paragraph III.D.

VI. DISCUSSION

The subject of discussion is the reliability of the values of the RECS efficiency indicator obtained by the developer using a discrete-continuous stochastic model of the operational functional behavior of the RECS during the performance of system engineering design tasks. The reliability of the values of the RECS efficiency indicator is verified by validating the developed stochastic model.

To validate the developed stochastic model of the operational functional behavior of the RECS, we conduct "experimental" studies of selected dependencies, the nature of changes in which can be predicted [32]. Such dependencies are the dependencies of the RECS efficiency indicator on changes in the values of the functionality indicators of its components.

$$\begin{cases} \frac{dP_1(t_r)}{dt_r} = -\left[P_{AS1}\frac{1}{T_{AS1}} + (1-P_{AS1})\frac{1}{T_{AS1}}\right]P_1(t_r) \\ \frac{dP_2(t_r)}{dt_e} = P_{AS1}\frac{1}{T_{AS1}}P_1(t_r) - \left[P_{OES1}\frac{1}{T_{OES}} + (1-P_{OES1})\frac{1}{T_{OES}}\right]P_2(t_r) \\ \frac{dP_3(t_r)}{dt_r} = (1-P_{AS1})\frac{1}{T_{AS1}}P_1(t_r) - \left[P_{AS2}\frac{1}{T_{AS2}} + (1-P_{AS2})\frac{1}{T_{AS2}}\right]P_3(t_r) \\ \frac{dP_4(t_r)}{dt_r} = P_{OES1}\frac{1}{T_{OES1}}P_2(t_r) \\ \frac{dP_5(t_r)}{dt_r} = (1-P_{OES1})\frac{1}{T_{OES1}}P_2(t_r) - \left[P_{AS2}\frac{1}{T_{AS2}} + (1-P_{AS2})\frac{1}{T_{AS2}}\right]P_5(t_r) \\ \frac{dP_6(t_r)}{dt_r} = P_{AS2}\frac{1}{T_{AS2}}P_3(t_r) - \left[P_{OES2}\frac{1}{T_{OES2}} + (1-P_{OES2})\frac{1}{T_{OES2}}\right]P_6(t_r) \\ \frac{dP_7(t_r)}{dt_r} = (1-P_{AS2})\frac{1}{T_{AS2}}P_3(t_r) \\ \frac{dP_8(t_r)}{dt_r} = P_{AS2}\frac{1}{T_{AS2}}P_5(t_r) - \left[P_{OES2}\frac{1}{T_{OES2}} + (1-P_{OES2})\frac{1}{T_{OES2}}\right]P_8(t_r) \\ \frac{dP_9(t_r)}{dt_r} = (1-P_{AS2})\frac{1}{T_{AS2}}P_5(t_r) \\ \frac{dP_{10}(t_r)}{dt_r} = P_{OES2}\frac{1}{T_{OES2}}P_6(t_r) \\ \frac{dP_{11}(t_r)}{dt_r} = (1-P_{OES2})\frac{1}{T_{OES2}}P_6(t_r) \\ \frac{dP_{12}(t_r)}{dt_r} = P_{OES2}\frac{1}{T_{OES2}}P_8(t_r) \\ \frac{dP_{13}(t_r)}{dt_r} = (1-P_{OES2})\frac{1}{T_{OES2}}P_8(t_r) \end{cases} \quad (4)$$

Therefore, the task of model validation will be to study the trend of change in the values of the probability of completing the RECS task with an increase and decrease in the values of the functionality indicators of its components relative to the initial value:

a) by 0.05 the values of the probabilities of completion of the task by the acoustic systems in the far and near controlled zones;

b) average values of the time intervals from the moments of appearance of the unmanned aircraft in the far, middle and near controlled zones to the moments of their detection by the corresponding system;

c) by 0.05 the values of the probabilities of completion of the OES task in the middle and near controlled zones.

The formula for calculating the values of the RECS efficiency indicator (3) "receives" the values of conditional probabilities after solving the system of differential equations. The events of "RECS task execution" correspond to the states of the probability graph 10 and 12. Therefore, formula (3) takes the following form:

$$P_D(t_e) = P_{10}(t_e) + P_{12}(t_e). \quad (5)$$

The initial values of the functionality indicators of the RECS components (AS1, AS2 and OES), presented in Table 3, were selected considering the analysis of the physical principles of their functioning and technical characteristics.

The results of eight validation experiments, which are presented in Table 3, confirmed the coincidence of the values of the RECS efficiency indicator with the predicted trends of its change, namely:

a) if the values of the probabilities of task performance by acoustic and optoelectronic systems increase and decrease with respect to the initial values by 0.05, values of the probabilities of task performance by the radio-electronic complex have a corresponding increase and decrease;

b) if the mean values of the time intervals from the moments of appearance of unmanned aircraft in the far, middle and near controlled zones to the moments of their detection by the corresponding system increase and decrease relative to the initial value, the values of the probabilities of task performance by the radio-electronic complex do not change.

Table 3. Results of validation experiments with the developed stochastic model of operational functional behavior of the radio-electronic complex for detecting unmanned aerial vehicles

Validation experiments	Values of the functionality indicators of the radio-electronic complex systems								Probability of UAV detection
	in the far and middle-controlled zones in the near controlled zone				in the near controlled zones in the near controlled zone				
	P_{AS1}	T_{AS1}, sec	P_{OES1}	T_{OES1}, sec	P_{AS2}	I. T_{AS2}, II. SEC	P_{OES2}	T_{OES2}, sec	
Initial values of indicators	**0.9**	**6**	**0.8**	**60**	**0.9**	**96**	**0.9**	**60**	**0.9468**
Experiment № 1.1	0.95	"	"	"	"	"	"	"	0.9544
Experiment № 1.2	0.85	"	"	"	"	"	"	"	0.9392
Experiment № 2.1	0.9	12	"	"	"	"	"	"	0.9468
Experiment № 2.2	"	3	"	"	"	"	"	"	0.9468
Experiment № 2.3	"	1	"	"	"	"	"	"	0.9468
Experiment № 2.4	"	120	"	"	"	"	"	"	0.9468
Experiment № 2.5	"	240	"	"	"	"	"	"	0.9468
Experiment № 3.1	"	6	0.85	"	"	"	"	"	0.95535
Experiment № 3.2	"	"	0.75	"	"	"	"	"	0.93825
Experiment № 4.1	"	"	0.8	120	"	"	"	"	0.9468
Experiment № 4.2	"	"	"	30	**III.** "	"	"	"	0.9468
Experiment № 4.3	"	"	"	1	"	"	"	"	0.9468
Experiment № 5.1	"	"	"	60	0.95	"	"	"	0.9594
Experiment № 5.2	"	"	"	"	0.85	"	"	"	0.9342
Experiment	"	"	"	"	0.9	192	"	"	0.9468

№ 6.1									
Experiment № 6.2	"	"	"	"	"	48	"	"	0.9468
Experiment № 6.3	"	"	"	"	"	1	"	"	0.9468
Experiment № 7.1	"	"	"	"	"	96	***IV.*** 0.95	"	0.9468
Experiment № 7.2	"	"	"	"	"	"	***V.*** 0.85	"	0.9594
Experiment № 8.1	"	"	"	"	"	"	0.9	120	0.9342
Experiment № 8.2	"	"	"	"	"	"	"	30	0.9468
Experiment № 8.3	"	"	"	"	"	"	"	1	0.9468

Thus, the results of the validation experiments confirm that the developed stochastic model of the operational behavior of the radio-electronic complex for the detection of unmanned aircraft gives the value of its efficiency indicator with high degree of reliability.

VII. CONCLUSIONS

The article uses stochastic modeling information technology to show how to transfer from a verbal model of the virtual operational behavior of a radio-electronic complex for detecting low-flying UAVs to a system of Kolmogorov-Chapman differential equations.

The results of validation experiments illustrate the capabilities of the developed stochastic model to solve the problem of determining the functionality indicators of acoustic systems AS1 and AS2 and an optoelectronic system for a given value of its efficiency indicator at the stage of system design of a radio-electronic complex. For example, it is necessary to increase the efficiency indicator of the radio-electronic complex from 0.9468 to 0.95. The value of 0.9468 is provided by systems with the following functionality indicators: $P_{AS1} = 0.9$; $P_{OES1} = 0.8$; $P_{AS} = 0.9$; $P_{OES2} = 0.8$.

In order to achieve the required values according to Table 3, there are the following ways for improving system functionality indicators by ensuring $P_{AS1} = 0.95$, or $P_{OES1} = 0.85$, or $P_{AS2} = 0.95$, or $P_{OES2} = 0.95$.

The final choice is determined by the ability to design a system with the required functionality index value.

Further research on the topic presented in the article involves the development of a stochastic model of the operational behavior of a radio-electronic complex for detecting low-flying UAVs with a higher degree of adequacy by removing the simplifications accepted in this model.

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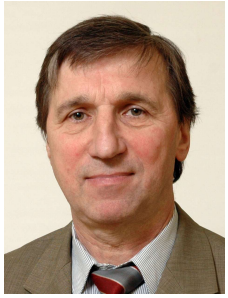

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