ISSN 2278-3091
Volume 8, No.1.2, 2019
International Journal of Advanced Trends in Computer Science and Engineering
Available Online at http://www.warse.org/IJATCSE/static/pdf/file/ijatcse0281.22019.pdf
https://doi.org/10.30534/ijatcse/2019/0281.22019

Mathematical Model of The Implementation Process of Flight Task of Unmanned Aerial Vehicle in The Conditions of External Impact

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ABSTRACT

The method of mathematical formalization of technical processes using the graph approach of GERT-structures is investigated. It was determined that for mathematical modeling of the process of performing a UAV flight task in the conditions of external influences, it is advisable to use a stochastic GERT-network structure. The main features, advantages and disadvantages of mathematical GERT-modeling are considered. This approach allows defining arbitrary functions and probability density distributions of random variables under conditions of uncertainty of these characteristics for the system as a whole. The division of the flight process of the UAV into stages with expert evaluation of the input data at each of the stages made it possible to determine the distribution function of the random variable of the execution time of the flight task of the UAV under external influences.

A GERT-network for the performance of a UAV flight mission under external conditions is presented. Taking into account a number of the most important components of the flight task implementation process allowed to bring the prototype of the process in question as close as possible to the actual conditions for the performance of the task set by the UAV and to improve the accuracy of the simulation results.

Solved the problem of the mathematical formalization of the Gert network for the performance of a UAV flight mission under external conditions. The results of the formalization of the steel are the expressions for calculating the density and the distribution function of the random variable of the execution time of the UAV task.

The analysis and research of the obtained results of modeling. It was revealed that the practical value of the developed model is the ability to predict the process of performing the flight task of the UAV, based on the given characteristics of external influences (intensity, probability, etc.).

The results obtained allow for a more in-depth analysis of the individual stages of the flight task, and are designed to help improve the quality and efficiency of UAV control under external conditions.

Key words: unmanned aerial vehicles, cyber-attacks, mathematical model, GERT-network, autonomous flight mode.

1. INTRODUCTION

Now the pilotless aircraft is one of the most perspective directions in aviation. So according to the analytical company Teal Group, till 2020, the size of the market of unmanned aerial vehicles (UAVs) will grow to 15.1 billion US dollars [1] [23]. At the same time the increase in productivity and decrease in the sizes of the microprocessor equipment, use of perspective telecommunication tools gives the chance to pilotless development acceleration complexes and expansion spheres and industries of their use. At the same time, increase in demand for the UAV and also their use in a number of difficult and important tasks, both in civil, and in military spheres, significantly increases interest in these technical complexes by malefactors. Especially cases of cyber-attacks of active spoofing (interception of management) became frequent. This fact once again confirms need of improvement UAV protection systems.

It is necessary to notice that works in this direction are conducted, and there is a number of the productive offers directed to minimize losses of spoofing cyber-attacks. However, these works have local character, and affect the solution only of a private problem of reflection of cyber-attack. At the same time formal problem definition demands an integrated approach in the UAV's flight task solution. It's included: performance of a task in the stationary (normal) mode; solution to the problem of intellectual recognition of potential external impacts; introduction of autonomous positioning in space algorithms, etc.

To solve such complex of difficult tasks, high-quality mathematical formalization and effective information support of developers becomes one of important factors. At the same time the quality and accuracy of mathematical models in many respects depends on depth and specification of the developed model, accounting of the most important factors influencing process and also the choice of methods and tools for mathematical modeling.

2. ANALYSIS OF REFERENCES

Analysis of references [2] showed that now there is a mathematical approaches formalization set of functioning processes, performance of separate UAV flight task phases and other auxiliary algorithms.

So, for example, process of the UAV positioning in works [3] with use of a mathematical vector analysis apparatus and matrix approach to description of the photogrammetric equations. However, lack of a specification at the restrictions description and also an initial assumption of video control tools use in flight significantly limit these models application range.

In work [4] authors investigate questions of positioning and optimum control for the UAV by geometrical models. At the same time as positive features of these works it is possible to note accounting of rare updating UAV location factor. However, the limited list of the considered factors, reduce modeling accuracy in the external influences condition.

The conducted researches showed that a large number of works is devoted to modeling a cyber-attacks recognition system [5]. At the same time various mathematical modeling approaches are used (neural networks, the device of logical functions and elementary qualifiers, fuzzy logic, etc.). However, all these works do not consider features of the UAV as subject to protection and also specifics of flight performance tasks by it.

It is necessary to notice that all listed above works aim at mathematical formalization of separate local tasks, at the same time these models do not formalize UAV performance flight task as sets of tasks. An attempt for the solution of this problem was made in work [6]. However, use only "UML diagram" for the device description and lack of a mathematical component in model does not give researchers full information and limits a possibility of carrying out optimizing researches of this direction.

Therefore, it actual to solve an issue of mathematical formalization process of UAV flight task performance in conditions of external influences.

3. PURPOSE AND RESEARCH PROBLEMS

The purpose of article is development and a research of UAV flight task process mathematical model in the conditions of external influences.

For achievement the goal it is necessary to solve the following problems.
– offer a mathematical formalization method of UAV flight task process in conditions of external influence;
– develop Gert-network of UAV flight task performance in conditions of external influence;
– mathematically formalize developed network model of UAV flight task performance in conditions of external influence;
– conduct the analysis and researches for the received modeling results.

4. MATERIALS AND METHODS OF A RESEARCH FOR PROBLEM OF MATHEMATICAL FORMALIZATION OF UAV FLIGHT TASK PERFORMANCE PROCESS IN THE EXTERNAL INFLUENCE’S CONDITIONS

For solution of a problem of mathematical formalization of UAV flight task performance process we use graph approach of GERT structures. The expediency of such approach and adequacy of the received results of mathematical modeling is confirmed by numerous examples of GERT networks creation [7] and the techniques of preliminary regularization of complex GERT structures checked in practice. The results of modeling given in works [8] speak about increase in accuracy of the received results by 10-15%.

In the conditions of the example reviewed in article, use tools of GERT modeling allows to describe the main UAV flight task performance stages to estimate productivity of GERT network scaling possibility at increase in volume and complexity of solvable tasks and also external influences intensity.

The conducted researches showed that GERT modeling is an effective method of studying and the analysis for stochastic networks used for the description of logical interrelation between parts of the project or stages of process. A main goal of GERT is assessment of logic of network and duration of activity and obtaining the conclusion about need of performance of some activities.

GERT networks consist of AND, INCLUSIVE-OR and EXCLUSIVE-OR hubs, and two branches with two and more than parameters. The branch, has the direction, has node of the beginning and node of the end. Parameters of a branch contain:
– probability of passing of a branch (P_a) provided that the node which is a branch source was realized;
– time (t_a) or intensity (λ_a) passing’s of a branch if it will be realized (the time t_a can be a random variable).

Let's consider a branch of GERT network generally. Let duration of performance of the operation connected with a branch be described by a random variable of y_{ij}, and its conditional probability (for discrete functions) or distribution density (for continuous functions) is described by the f_{ij} function if hub *i* it is realized. Then we will enter the function $W_{ij}(s) = p_{ij}*M_{ij}$, where M_{ij} is the forming function of the moment (Moment generating function, MGF) a random variable of y_{ij} which is defined as

$$M_x(t) = \sum_{i=1}^{\infty} e^{tx_i} p_i \qquad (1)$$

for discrete functions, and

$$M_x(t) = \int_{-\infty}^{\infty} e^{tx} f(x) dt \qquad (2)$$

for continuous functions.

The W(s) function it is entered for characteristic of branches with one parameter.

Let's develop GERT network and mathematically we formalize process of UAV flight task performance in the external influence's conditions.

For this purpose, we will present the generalized block diagram of UAV flight task performance in the external influences conditions in the form of the sequence of stages in Figure 1.

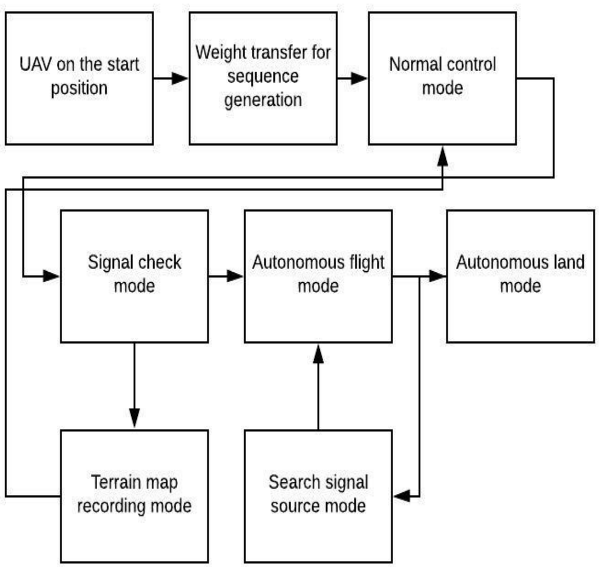

Figure 1: Block diagram of performance of the UAV task in the conditions of external influences

Let's present Gert-network of process of performance of the UAV task in the form of Figure 2. In this drawing transition (0.1) interprets normal process of performance of a flight task with an exit in the mode of near data transmission. Transition (1.2) characterizes process of an exit from a near zone management mode to the mode of UAV stationary control at the specified communication frequencies. Transition (2.3) interprets the moment of receiving a control signal and the process of verification of its compliance to normal parameters. Communications (3.4) and (4.2) characterize processes of transition on location fixing mode with return to the normal state respectively. Transition (3.5) fixes an exit to the mode of UAV autonomous flight in case of cyber-attack identification. Transition (5.6) interprets process of malefactor signal search. Transition (5.7) describes process of an exit to the autonomous landing mode. Transition (7.8) interprets process of parameters tuning for landing in difficult meteoconditions or in the conditions of other external impacts on the UAV.

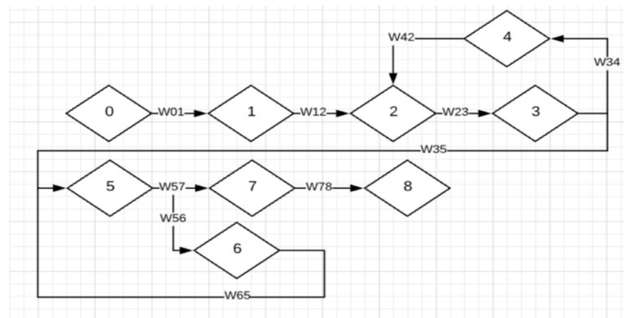

Figure 2: Block diagram 2 of performance of the UAV task in the conditions of external influences

Table 1: Characteristics of model branches

W-function	Probability	Derivative function
W_{01}	p_1	$\frac{\lambda_1}{\lambda_1 - S}$
W_{12}	p_1	$\frac{\lambda_2}{\lambda_2 - S}$
W_{23}	p_2	$\frac{\lambda_3}{\lambda_3 - S}$
W_{34}	p_3	$\frac{\lambda_4}{\lambda_4 - S}$
W_{42}	$1 - p_2 = q_2$	$\frac{\lambda_5}{\lambda_5 - S}$
W_{35}	p_4	$\frac{\lambda_6}{\lambda_6 - S}$
W_{56}	p_5	$\frac{\lambda_7}{\lambda_7 - S}$
W_{65}	$1 - p_5 = q_2$	$\frac{\lambda_7}{\lambda_7 - S}$
W_{57}	p_6	$\frac{\lambda_8}{\lambda_8 - S}$
W_{78}	p_7	$\frac{\lambda_8}{\lambda_8 - S}$

Distinctive feature of this GERT network is:
– accounting of evaluation stages of signals compliance to sample parameters with saving location of the UAV;
– accounting of opportunities for the built-in intellectual aircraft return system in the autonomous mode with use a signal bearing (malefactor) for tuning autopilot parameters;
– accounting of possible difficulties performance of UAV landing in the external influence's conditions.

The analysis of a number works [8] and also the conducted researches process of UAV flight task performance allowed to create characteristics of the branches considered in GERT model and parameters of distribution and to present them in Table 1.

According to characteristics of branches of GERT network equivalent W-function of time of performance of a flight task in the conditions of external deliberate influences can be presented as:

$$W_e = \frac{W_{01}W_{12}W_{23}W_{35}W_{57}W_{78} + W_{01}W_{12}W_{23}W_{35}W_{56}W_{65}W_{57}W_{78}}{1 - W_{01}W_{12}W_{23}W_{34}W_{42}} =$$
$$= \frac{p_1\lambda_1 \cdot p_1\lambda_2 \cdot p_2\lambda_3 \cdot p_4\lambda_6 \cdot p_6\lambda_8 \cdot ((\lambda_7 - S)^2 + p_5\lambda_7 q_2\lambda_7)}{(\lambda_6 - S)\cdot(\lambda_8 - S)\cdot(\lambda_7 - S)^2} \cdot$$
$$\cdot \frac{(\lambda_4 - S)\cdot(\lambda_5 - S)\cdot(\lambda_8 - S)}{(\lambda_1 - S)\cdot(\lambda_2 - S)\cdot(\lambda_3 - S)\cdot(\lambda_4 - S)} \cdot$$
$$\cdot \frac{1}{((\lambda_5 - S)^2 - p_1\lambda_1 \cdot p_2\lambda_3 \cdot p_3\lambda_4 \cdot q_1\lambda_5)} \quad (3)$$

Characteristic function $\Phi_E(s)$ is on the basis of the topological equation of Mason [9] by replacement in the equivalent function the moments $W_E(s)$ of a variable s to $i\varsigma$ where ς – the real variable.

The conducted researches showed that in complex GERT networks with possible cycles there are no simple methods of function special points finding of $\Phi_E(z)$ replacement of the valid variables $(z = -s = -i\varsigma)$. It is connected with the fact that for finding of special points it is necessary to solve the nonlinear equations, and the more difficult structure of GERT network, the more complex the initial equation [8]. Therefore, during modeling carrying out complex transformation we will receive:

$$\Phi(z) = \frac{-z^4 + rz^3 - yz^2 + uz - k}{\left(-z^5 + az^4 - bz^3 + cz^2 - dz + g\right)} \cdot \frac{1}{(\lambda_6 + z)(\lambda_8 + z)(\lambda_7 + z)^2} \quad (4)$$

where

$r = -(2\lambda_7 + \lambda_5\lambda_4)$;

$y = \lambda_7 + \lambda_4\lambda_5 + p_5 q_2 \lambda_7{}^2$;

$u = -\left(2\lambda_4\lambda_5\lambda_7 - \lambda_5\lambda_7 - \lambda_4\lambda_7 + p_5 q_2 \lambda_5 \lambda_7{}^2 + p_5 q_2 \lambda_4 \lambda_7{}^2\right)$;

$a = -(\lambda_5 - \lambda_1 - \lambda_2 - \lambda_3 - \lambda_4)$;

$b = -(\lambda_1\lambda_5 - \lambda_2\lambda_5 - \lambda_3\lambda_5 - \lambda_4\lambda_5 - \lambda_1\lambda_2 -$
$-\lambda_1\lambda_3 - \lambda_1\lambda_4 - \lambda_2\lambda_3 - \lambda_2\lambda_4 - \lambda_3\lambda_4)$;

$c = -(\lambda_1\lambda_2\lambda_5 + \lambda_1\lambda_3\lambda_5 + \lambda_1\lambda_4\lambda_5 +$
$+\lambda_2\lambda_3\lambda_5 + \lambda_2\lambda_4\lambda_5 - \lambda_3\lambda_4\lambda_5 + \lambda_1\lambda_2\lambda_3 +$
$\lambda_1\lambda_2\lambda_4 + \lambda_1\lambda_3\lambda_4 + \lambda_2\lambda_3\lambda_4)$;

$d = -\lambda_1\lambda_2\lambda_3\lambda_5 - \lambda_1\lambda_2\lambda_4\lambda_5 - \lambda_1\lambda_3\lambda_4\lambda_5 -$
$-\lambda_1\lambda_2\lambda_4\lambda_5 - \lambda_1\lambda_2\lambda_3\lambda_4$;

$g = -(\lambda_1\lambda_2\lambda_3\lambda_4\lambda_5 - p_1^2 p_2 p_3 q_1 \lambda_1\lambda_3\lambda_4\lambda_5$;

Then distribution probabilities density of flight task performance time

$$\phi(x) = \frac{1}{2\pi i}\int_{-\infty}^{\infty} e^{zx} \frac{-z^4 + rz^3 - yz^2 + uz - k}{\left(-z^5 + az^4 - bz^3 + cz^2 - dz + g\right)} \cdot \frac{1}{(\lambda_6 + z)(\lambda_8 + z)(\lambda_7 + z)^2}, \quad (3)$$

where integration is carried out on Bromvich's contour [9]. Function $\Phi(z)$ except the simple poles determined by roots of the equations $\left(-z^5 + az^4 - bz^3 + cz^2 - dz + g\right) = 0$, and $(\lambda_7 + z)^2 = 0$ can have also poles of the second – the third order. It is possible when values λ_6, λ_8 either coincide among themselves, or are equal to values of roots z_8, z_9. Distribution density fly time of UAV $\phi(x)$ is in these cases on a formula of finding of deductions γ_{-1} from poles z_n in power m

$$\gamma_{-1} = \frac{1}{(m-1)!}\lim_{z \to z_n} \frac{d^{m-1}\left[(z - z_n)^m e^{zx}\Phi(z)\right]}{dz^{m-1}}.$$

Expression (3), according to works [8,9], can be presented as fractional and rational function relatively z with degree of a denominator bigger, than numerator degree, therefore for it conditions of a Lemma of Jordan are satisfied. Function $\Phi(z)$ has poles in points $z_8 = -\lambda_6$, $z_9 = -\lambda_8$. The polynomial $(\lambda_7 + z)^2$ generates two poles, the polynomial $\left(-z^5 + az^4 - bz^3 + cz^2 - dz + g\right)$ generates five more poles. Solution of the equation

$$-z^5 + az^4 - bz^3 + cz^2 - dz + g = 0 \quad (5)$$

it can be found any numerical method. Then we will receive five more special points $z_1 - z_5$.

Let's conduct pilot studies of the presented mathematical model of UAV flight task performance process.

5. RESULTS OF THE STUDY OF MATHEMATICAL MODEL OF THE UAV FLIGHT TASK IMPLEMENTATION PROCESS UNDER EXTERNAL INFLUENCES

Find the probability density function $\phi(x)$ the execution time of flight of the UAV tasks under external influences. At the same time, we define the following branches GERT-network as the initial data:

$p_1 = 0{,}9999$. $p_2 = 0{,}55$. $p_3 = 0{,}6$. $p_4 = 0{,}1$. $p_5 = 0{,}55$. $p_6 = 0{,}9$. $\lambda_1 = 1$. $\lambda_2 = 0{,}9$. $\lambda_3 = 0{,}8$. $\lambda_4 = 0{,}1$. $\lambda_5 = 0{,}91$ $\lambda_6 = 0{,}9$. $\lambda_7 = 0{,}9999$. $\lambda_8 = 0{,}9999$.

For this case in Figure 3 is a density graph of the probability distribution of the UAV mission execution time.

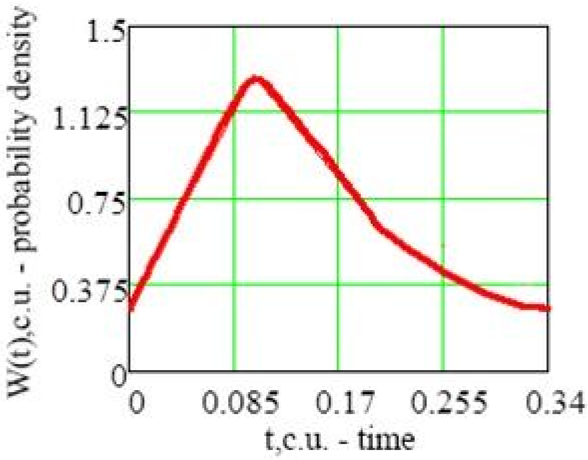

Figure 3: Schedule a probability density runtime task UAV

As can be seen from this graph, the maximum probability density values are time performance UAV flight task under external influence, taking into account the possibility of an autonomous return to given territory accounted for the interval from 0.08 to 0.17 c.u.

For this example, function $\Phi(z)$ has simple poles:

$$z_1 = 0;$$
$$z_2 = -2;$$
$$z_3 = 0{,}049 + i \cdot 0{,}23*10^{-6};$$
$$z_4 = -0{,}135 - i \cdot 0{,}9;$$
$$z_5 = -0{,}135 + i \cdot 0{,}9;$$
$$z_6 = -0{,}83 - i \cdot 0{,}8;$$
$$z_7 = -0{,}83 + i \cdot 0{,}8;$$
$$z_8 = -0{,}9;$$
$$z_9 = -0{,}9999.$$

In view of the assumptions stated above, for the case when one considers the pole $z_4 = -0{,}135 - i \cdot 0{,}9$ and $z_5 = -0{,}135 + i \cdot 0{,}9$ function $\phi(x)$ the probability distribution of the UAV task flight execution time under external influences defined as

$$\phi(x) = 2e^{-0{,}135x}\left[\left(14{,}9\cos(0{,}9x)\right) - 14{,}3\sin(-0{,}9x)\right] / 985.6 .$$

For this case, in Figure 4 is a graph of the density distribution $\phi(x)$ Probability runtime UAV flight tasks under external influences to the above conditions.

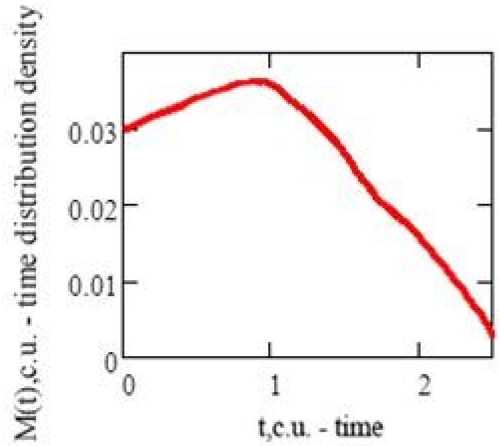

Figure 4: Time distribution density of the UAV flight performance tasks in terms of external actions for the case when one considers the pole $z_4 = -0{,}135 - i \cdot 0{,}9$ and $z_5 = -0{,}135 + i \cdot 0{,}9$.

Similarly, conduct of research and submit a schedule the density distribution of the UAV task flight execution time in terms of external actions for the case when one considers the pole $z_6 = -0{,}83 - i \cdot 0{,}8$ and $z_7 = -0{,}83 + i \cdot 0{,}8$.

Function $\phi(x)$ the probability distribution of the execution time of flight of the UAV task in terms of external actions in this case is defined as

$$\phi(x) = 2e^{-0{,}83x}\left[\left(-140{,}6\cos(0{,}8x)\right) + 137{,}5\sin(-0{,}8x)\right] / 2.5\times10^{4}$$

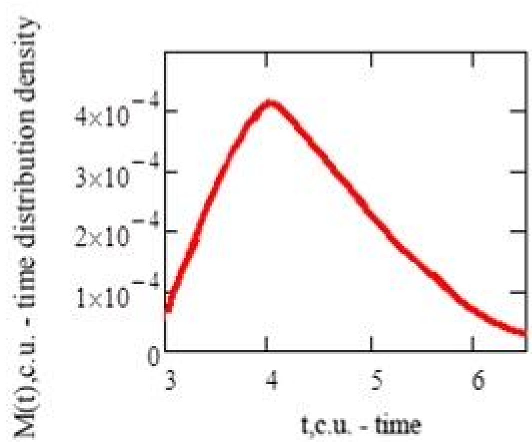

Figure 5: Density performance timing of the flight of the UAV tasks under external influences for the case when the pole $z_6 = -0{,}83 - i \cdot 0{,}8$ and $z_7 = -0{,}83 + i \cdot 0{,}8$

Appearance curves curves in Figures 4 and 5 gives reason to assume that the random variable execution time of flight of the UAV task under external influences distribution has a "heavy tail".

Similarly, you can conduct research for cases of simple poles of the equation 3.

It is necessary to notice that change of input data, and adaptation them under characteristics of external influences (intensity, probability, etc.) will allow to predict time frames of UAV flight task performance process directly for areas.

5. CONCLUSION

Researches are conducted and the mathematical formalization method of UAV flight task performance process in the conditions of external influences is offered. Graph approach of GERT structures is taken as a basis of mathematical modeling. This approach allows to formalize mathematically difficult technical processes and to define any functions and distribution densities of random variables probabilities. For the considered practical case this approach allowed to define function of random variable distribution of UAV flight task performance time in the conditions of external influences.

The Gert-network of UAV flight task performance in the conditions of external influences is developed. Its distinctive feature is accounting of very important components of flight task performance process (an evaluation stage of compliance of signals to sample parameters with fixing of UAV location; a stage of return the aircraft in the autonomous mode; a stage of UAV landing performance in the conditions of external influences).

The network model of UAV flight task performance in the conditions of external influences is mathematically formalized and described. The output data of modeling, is presented in the form convenient for the analysis and researches.

The analysis and researches of the modeling received results are conducted. For the set entrance values density and functions of random variable distribution of UAV flight task performance time in the conditions of external influences are found. The assumption that the random variable of UAV flight task performance time in the conditions of external influences has distribution with "a heavy tail" is made. It is also noted that the practical value of this model consists in a possibility of forecasting for UAV flight task performance process, proceeding from the set characteristics of external influences (intensity, probability, etc.).

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