Advances in Military Technology
Vol. 19, No. 2, 2024, pp. 269-285
ISSN 1802-2308, eISSN 2533-4123
DOI 10.3849/aimt.01908

Analysis of the Impact of Operator's Activity on the Control System of Unmanned Aerial Vehicles

I. Borozenec,[1] D. Parkhomenko[1], O. Nesmiian[1], N. Garmash[1], P. Open'ko[2*] and O. Martyniuk[2]

[1] *Ivan Kozhedub Kharkiv National Air Force University, Kyiv, Ukraine*
[2] *National Defence University of Ukraine, Kyiv, Ukraine*

The manuscript was received on 2 July 2024 and was accepted after revision for publication as an original research article on 11 November 2024.

Abstract:

The article describes the results of the experimental study on the influence of operator's activities on the control system of a heterogeneous unmanned aerial vehicles' group. The proposed mathematical apparatus allows to present the actions of the operator as part of the automated control system, to carry out a quantitative assessment of the efficiency of the operator's actions. It also allows to evaluate the impact of the results of this activity on the effectiveness of solving tasks in the control system of an unmanned aerial vehicles' group. The given experimental data and obtained laws of distribution of various random variables can be used in modelling the activity of the operator in complex control systems of an unmanned aerial vehicles' group. Management of operators' activity models enables to improve the quality of the development of decision support system.

Keywords:

operator, control system, unmanned aerial vehicles' group, decision support system

1 Introduction

In modern armed conflicts, unmanned aerial vehicles (UAVs) are increasingly used in heterogeneous groups. In these groups, they perform both reconnaissance and strike missions.

The use of cheap strike UAVs in groups, under the cover of heavier UAVs equipped with radar, optical-electronic reconnaissance and radio-electronic suppression, causes extremely serious losses to air defence assets. But the lack of a universal approach to the creation of easily scalable control systems for groups of UAVs, which would allow the use of a given mathematical model of control objects,

* *Corresponding author: Air Force Department, National Defence University of Ukraine, Povitrianyh Syl avenue 28, UA-030 49 Kyiv, Ukraine. Phone: +380 63 840 2192, E-mail: pavel.openko@ukr.net. ORCID 0000-0001-7777-5101.*

and for which the search for controls would be performed on a real-time scale, makes the problem of creating an intelligent control system for a group of UAVs very important [1].

The work of the operator in the automated control system of the group of UAVs includes various duties related to monitoring, management and ensuring the safe operation of unmanned systems. The need for research and evaluation of the effectiveness of the UAV group management system is growing with the steady complication of the regional air situation. At the same time, scientists do not pay due attention to the research of the activity of a human operator, as significant part of the control system of UAVs groups. Also, the results of known works [2-8] are rather of a qualitative, purely psychological nature.

Currently, quantitative assessments are used rather cautiously and hesitantly, which no longer meets the requirements of modern needs. In addition, rare studies are devoted only to some individual issues and do not consider the activity of a human operator as a whole [2-3, 5]. Such a one-sided approach neither allows to assess the efficiency of the operator's functioning at the workplace in general, nor the impact of this efficiency on the effectiveness of solving tasks in the UAVs group management system.

It is possible to assess the efficiency of the operator (a team of operators) in the UAV group management system in two ways:

- by mathematical determination of the dynamic characteristics of the operator by compiling and solving the corresponding system of differential equations,
- by determination of criteria for the efficiency of purposeful activity of a human operator through experimental research.

The mathematical approach to the study of the dynamics of the operator's functioning is associated with a number of serious problems due to the fact that human-machine systems are naturally non-linear.

It is known that the operator's characteristics change during training to perform specified functions or due to a change in the nature of his/her activity. In addition, the characteristics of the activity change as a result of fatigue and are depending on the general psychophysiological state, which is difficult and sometimes impossible to determine [2].

Therefore, the differential equations that should describe the dynamic characteristics of the operator's activity must have variable coefficients.

Further, the problem of the mathematical description of the characteristics of a human operator is even more complicated due to the extraordinary abilities of a person to adapt to changing environmental conditions, his/her operational ability to change the characteristics of his behaviour in accordance with the specific purpose and conditions of activity. That is why the second approach turns out to be more appropriate when evaluating the efficiency of the operator in complex systems.

The relevance of the investigated problem lies in solving the problem of mathematical description of the time characteristics of the human operator's activity in the complex conditions of the management process.

2 Analysis of Published Research Results and Problem Statement

It is necessary to consider the complexity of the issue, its novelty, as well as the lack of a developed and completely tested methodology for the study of operator activity in a specific automated UAV group control system. In addition, there is no single set of criteria for evaluating the efficiency of operator activity, which would make it possible to unambiguously determine the readiness of the operator to work in the human-machine system. It is also impossible to compare operators among themselves and evaluate the impact of the functional activity of the operators of the automated UAV group control system on the effectiveness of the system as a whole [9, 10].

Within the way of determining efficiency criteria, the selection of general and partial criteria is carried out as a result of scientific and theoretical studies of the peculiarities of the operator's activities. Quantification of criteria and evaluation of efficiency are solved experimentally. But even here there are difficulties, albeit of a fundamentally different nature. The main one should be considered the complexity of modelling the influence of the external environment on the nature of the behaviour of the human operator and his/her psyche during the experiment. It often turns out to be impossible to reproduce the real conditions of the operator's activity, so various kinds of artificial methods are used, which allow to simulate, with some approximation, the influence of the environment on the operator's psyche [7, 9].

Another, not less complex problem, is the laboriousness of the experiment and the impossibility of its reproduction with the same respondents under absolutely identical initial conditions (especially in studies on training certain skills) due to irreversible changes in the test subjects.

A fairly large number of researches [11-14] are devoted to the consideration and description of models of the operator's activity in the human-machine system. The work [11] examines the models of the operator of the human-machine system, which reveal the multifunctionality of a person in all emergency situations that occur, but there are no recommendations for their practical application.

In [12], the task of formalizing the description of the functional network regarding the algorithm of human-machine system operators' activity is considered, but performance quality indicators are not defined.

The approach to the construction of structural and functional models of the activity of a human operator in a dynamic tracking system, which is presented in [13], does not take into account the psychophysiological state of the operators. In [14], when modelling the activity of a human operator in semi-automatic control systems of dynamic objects, it is desirable to carry out a quantitative assessment of the effectiveness of the model.

Some researchers [15, 16] pay attention to the principles and theoretical foundations of the formation of activity models of decision-makers, while others consider models of simple actions or processes that are elements of the operator's complex activity.

Models of complex systems are formed, in most cases, based on the application of the theory of mass service systems. Such models make it possible to obtain generalized characteristics of the system and the operator, as links of the automated control system (average service time of applications, probability of service, error-free processing of tasks, etc.). However, the reliability of research in ergatic systems depends exclusively on the degree of detailed consideration of human activity as a whole in the system [17].

The information and software complex given in [18] allows for the assessment of working conditions at the operator's workplace in order to choose a rational system of ergonomic measures, but only the economic efficiency for various parameters of the ergonomic quality assurance system is evaluated.

According to [19-22], when modelling the activity of the operator, the automated control system must take into account:

- purposefulness of the operator's behaviour,
- heterogeneity of elements involved in the performance of each technological operation,
- presence of interruptions in the operator's work due to failures and human errors during the shift,
- presence of both conceptual and executive human actions,
- possibility of changing the choice of the algorithm of actions when other situational conditions arise (the shortage of time, emotional factors, etc.),
- variability in the characteristics of the actions of the decision-maker (fluctuations in time spent, fatigue, etc.).

The implementation of formalized models of the complex activity of a human operator into the practice of designing automated UAV group control systems has become possible in modern conditions of the use of information technologies.

3 Aim and Objectives of Research

The purpose of this work is to develop a mathematical model that provides an assessment of the efficiency of the human operator in automated control system of a UAVs group. Such a model is necessary for obtaining quantitative values when evaluating the activity of operators in complex human-machine systems.

To achieve the goal, the following tasks must be solved:

- to create an experimental module that allows to approximately reproduce the structure of the real activity of a human operator in a specific UAV group control system,
- to develop a mathematical model for determining the dynamic characteristics of a human operator by compiling and solving the appropriate system of differential equations,
- to determine a set of criteria for the measurement of efficiency of the purposeful activity of a human operator through experimental research.

4 Materials and Methods of Research on Efficiency of UAV Group Control System Operators' Activity

4.1 Researched Materials and Equipment Used in the Experiment

The basis of the experiment was the automated workstations (AWS) of the operator and supervisor. The flow of information displayed to the operator was set by a software control complex specially developed for this purpose. The management of the software complex was carried out from the control centre. All the information was displayed on the operator's AWS. The execution time of all operations for each of the messages received by the operator's AWS was automatically recorded with an accuracy of +0.02 seconds. Errors made by operators were recorded on the supervisor's AWS.

The block diagram of the device used for the experimental study is shown in Fig. 1. The software control complex provides three modes of messages to the operator's AWS:

- Individual messages. The type of messages and the moment of issuance are set by the experiment leader (supervisor),
- Semi-automatic mode. The next message is issued at the AWS only if the operator correctly and completely performs all the operations provided by the prescribed algorithm according to the previous message,
- Automatic mode of issuing messages according to a rigid program. The time interval between messages is a random value that has a uniform probability distribution law in the interval from 2 to 50 seconds. Interval limits can be changed. Two fixed programs are provided with the possibility of sudden transition to any of them at a moment unknown to the operator, determined by the manager.

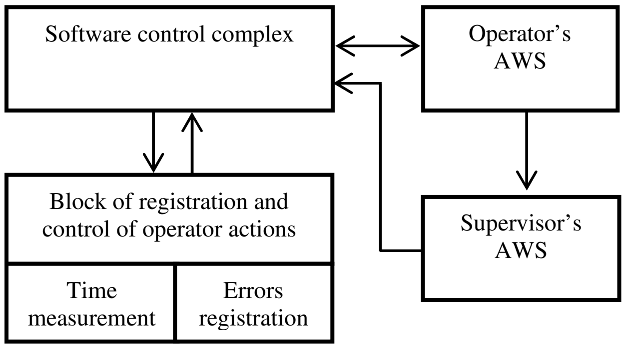

Fig. 1 Block diagram of the experimental device

Each of the two fixed programs has 25 different types of messages. The programs differ in the order of messages.

The experiment was conducted in three series. The purpose of the first series was to teach operators the skills of error-free actions using the AWS remote control. When conducting the second series, the idea was to investigate the dependence of the operators' readiness degree for emergency actions on the duration of monotonous actions. The purpose of the last series was to investigate the stability of the level of learning achieved.

The first series on teaching the skills of error-free work, in turn, had three stages:

- formation of the events input field (attributes),
- development of error-free work skills, i.e. correct behaviour determined by the selected system of events (attributes),
- formation of stationary level of education.

At the first stage, operators in the process of work select and mark the most significant tools on control panel, means of displaying information, sections of information panels, types of signals, symbols and other external stimuli.

During the stage of correct behaviour formation, operators first consolidate their theoretical knowledge of instructions and work algorithm, and then gradually practice the performance of each elementary operation, which gives solid skills of error-free action.

The formation of a stationary level of training consists, for example, in the fact that in each subsequent cycle of training the operator assumes a certain stable minimum of errors with a stable average value of the time for completing a given amount of work. However, learning that has been completed does not involve stereotyped behaviour in which errors will always be absent.

106 respondents were involved in the first stage of the experiment. Four training cycles were conducted with each of them. At the next stages, as well as in the second and third series of the experiment, the same respondents in the number of 30 people took part in the research.

The results of the first series of experiments on training operators in the skills of error-free work using the control panel of AWS are presented. During the research, the number of errors that were made, the time of correction, and the time of operations for each of the 25 types of messages were recorded. When processing experimental data obtained at the stage of formation of the input field of events, the laws of distribution of the following random variables were determined:

- the number of errors made during one training cycle – m,
- the time of correcting the errors – τ_{err},
- service time of resulting messages – τ_{res},
- service time for incoming digital messages – τ_{ind},
- service time for incoming messages of the type that have meaningful nature – τ_{inm}.

According to the experimental data characterizing the stationary level of learning, the laws of distribution of the last three of the listed random variables were determined: τ_{res}^{tr}, τ_{ind}^{tr}, and τ_{inm}^{tr}.

4.2 Distribution of the Number of Errors

The series of distribution of the number of errors m is given in the first two columns of Table 1. The number of errors made by the operator, as a discrete random variable, can be distributed according to Poisson's law. The Poisson distribution has the property that the mean, variance, and third central moment are the same and are determined by one value γ_{err}, which is the only parameter of this distribution:

$$\overline{m} = \sigma^2 = \mu_3 = \gamma_{\text{err}} \tag{1}$$

where $\overline{m}$ is the average value of the errors number made by operators during one training cycle, which is determined by the well-known formula [23-25]:

$$\overline{m} = \frac{\sum_{j=1}^{k} m_j n_j}{\sum_{j=1}^{k} n_j} \tag{2}$$

The probability that the operator will make m errors during one training cycle is confirmed by the expression:

$$p_m = \frac{\gamma_{\text{err}}^m}{m!} \mathrm{e}^{-\gamma_{\text{err}}} \tag{3}$$

We will check the agreement degree between the selected hypothetical distribution and the experimental data using the Pearson agreement criterion $P\left(\chi^2\right)$:

$$\chi^2 = \sum_{j=1}^{k} \frac{\left(n_j - \tilde{n}_j\right)^2}{\tilde{n}_j} \tag{4}$$

where $\tilde{n}_j$ are equalizing frequencies of the hypothetical Poisson distribution; n_j – frequencies obtained in the experiment; k is the number of bit values (digits); $j = 1,2,\ldots,k$.

Equalizing frequencies $\tilde{n}_j$ for Poisson's law are determined by the formula:

$$\tilde{n}_j = p_m \sum_{j=1}^{k} n_j = \frac{\gamma_{\text{err}}^m}{m!} \mathrm{e}^{-\gamma_{\text{err}}} \sum_{j=1}^{k} n_j \tag{5}$$

The calculation of equalizing frequencies $\tilde{n}_j$ and values χ^2 is summarized in Tab. 1. As follows from Tab. 1, $\chi^2 = 13.068$, the number of digits $k = 20$, the number of degrees of freedom is equal to $\nu = k - 2 = 18$.

Tab. 1 Calculation of equalizing frequencies $\tilde{n}_j$ and values χ^2

m_j	n_j	$m_j n_j$	p_m	$\tilde{n}_j$	$n_j - \tilde{n}_j$	$\left(n_j - \tilde{n}_j\right)^2$	$\frac{\left(n_j - \tilde{n}_j\right)^2}{\tilde{n}_j}$
0	1	0	0.0003	0.1272	–0.872	0.762	5.990
1	2	2	0.0025	1.0600	0.94	0.883	0.833
2	4	8	0.0100	4.2400	–0.24	0.057	0.013
3	13	39	0.0269	11.4000	1.60	2.560	0.224
4	24	96	0.0544	23.0600	0.94	0.883	0.038
5	35	175	0.0882	37.3900	–2.39	5.710	0.152
…	…	…	…	…	…	…	…
18	1	18	0.0011	0.4600	0.54	0.291	0.602
19	1	19	0.0005	0.2100	0.79	0.624	2.971
Σ	424	3428	$\gamma_{\text{err}} = 8.1$	$k = 20$			$\chi^2 = 13.068$

For these variables according to the table of values χ^2 [23, 24], we find that $P\left(\chi^2\right) > 0.7$.

Thus, the probability of a random cumulative discrepancy between the observed frequencies n_j and the equalizing frequencies $\tilde{n}_j$ is large enough. Therefore, the adopted hypothesis regarding the distribution of the number of errors according to Poisson's law does not contradict the data obtained during the study. The experimental distribution series (histogram) and the hypothetical Poisson distribution that describes it (probability density curve) are shown in Fig. 2.

4.3 Distribution of Time of Errors Correction

Most errors are corrected by operators in a very short period [26-28]. Statistical series of error correction time distribution is given in the first two columns of Tab. 2. Analysis of the distribution series shows that it can be reproduced by an exponential law:

$$f\left(t\right) = \delta \mathrm{e}^{-\delta t} \text{ at } t > 0 \tag{6}$$

DOI 10.3849/aimt.01908

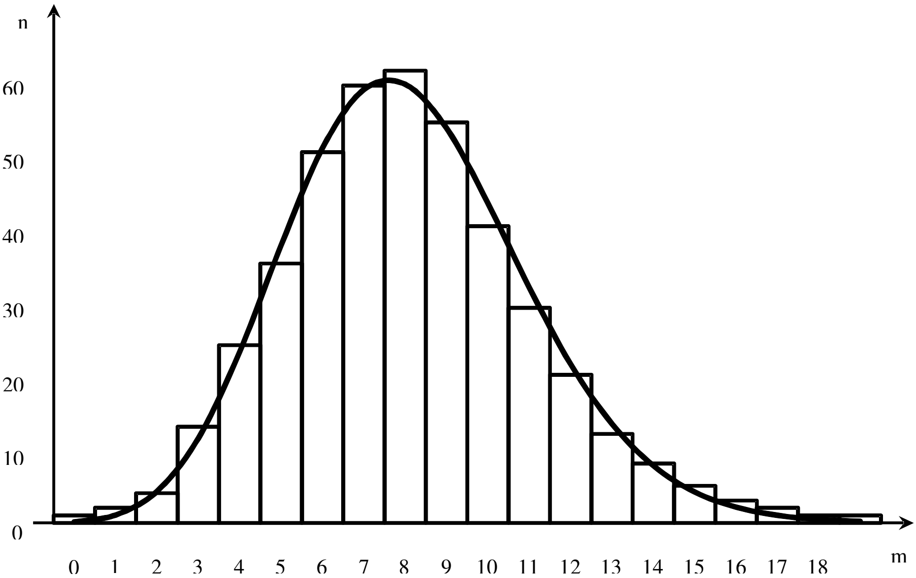

Fig. 2 Distribution curve of number of errors

where δ is the parameter of the exponential distribution law, which is equal to:

$$\delta = \frac{1}{\tau_{\mathrm{err}}} \tag{7}$$

The average time (mathematical expectation) of error correction is estimated by a well-known formula (2):

$$\overline{\tau}_{\mathrm{err}} = \frac{\sum_{j=1}^{k} \tau_{\mathrm{err}}(j) n_j}{\sum_{j=1}^{k} n_j} \tag{8}$$

where $k = 14$ is the number of digits in the distribution series. Calculation of equalization frequencies $\tilde{n}_j$ carried out according to the formula:

$$\tilde{n}_j = Cf(t) \sum_{j=1}^{k} n_j \tag{9}$$

where C is the value of one digit of the distribution series.

The degree of consistency of the experimental distribution with the theoretical one is checked by the Pearson test $P(\chi^2)$ using Eq. (4). The calculations are summarized in Tab. 2.

The histogram that describes the experimental series of the distribution, as well as the density curve of the hypothetical distribution of errors correction time is shown in Fig. 3.

Possible errors, the probability of which occurs due to the fault of a human operator, as a rule, is always greater than zero, and can lead to a sharp decrease in the effectiveness of the system or even to the failure of the management process.

Tab. 2 Degree of consistency of experimental distribution with theoretical one

$\tau_{\text{err}}(j)$	n_j	$\tau_{\text{err}}(j)n_j$	$\delta\ \tau_{\text{err}}(j)$	$e^{-\delta\tau_{\text{err}}(j)}$	$f\left[\tau_{\text{err}}(j)\right]$	$\tilde{n}_j$	$\frac{\left(n_j-\tilde{n}_j\right)^2}{\tilde{n}_j}$
1	862	862	0.1517	0.8590	0.1303	875	0.193
3	640	1920	0.4551	0.6344	0.0965	647	0.076
5	499	2495	0.7585	0.4686	0.0711	478	0.922
…	…	…	…	…	…	…	…
25	27	675	3.7925	0.0226	0.0034	23	0.529
27	20	540	4.0959	0.0167	0.0025	17	0.450
$\sum$	3361	22152	$\overline{\tau}_{\text{err}}=6.59\,s$ $\delta=0.1517$		$k=14$ $v=k-2$		$\chi^2=4.745$ $P\left(\chi^2\right)>0.9$

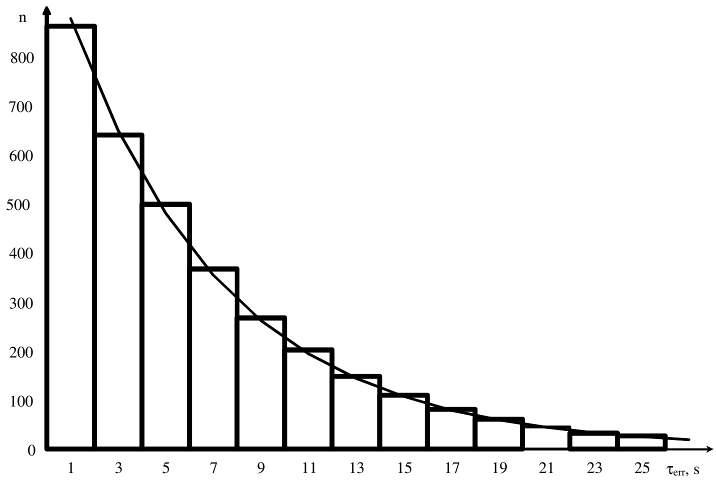

Fig. 3 Distribution curve of correction time of errors

4.4 Allocation of Service Time for Outgoing Messages

Statistical series of service time distribution of the resulting (outgoing) messages is given in the first two columns of Tab. 3. At the same time, the values τ_{res} are indicated in the divisions of the stopwatch scale. To convert the given time to seconds, each value $\tau_{\text{res}}(j)$ must be multiplied by the scale factor $m=0.02$ s/division.

The analysis of the distribution series shows that the empirical distribution is asymmetric unimodal and can be described by one of the Pearson curves. To determine the type of Pearson curve and the analytical expression, the initial and central moments of the empirical distribution are calculated, and then the Pearson coefficient, the parameters of the equalizing curve, and the equalization frequencies of the digit values are calculated.

The initial moments are calculated using the method of sums, for which a corresponding table of sums is created (Tab. 3) [23]. The application of the method of sums in the calculation of moments is based on the fact that between the moments and the obtained sums $S(i)$ and differences $d(i)$ there are completely deterministic relationships expressed by the formulas [6]:

$$m_1 = \frac{d_1}{n},\ m_2 = \frac{S_1 + 2S_2}{n},\ m_3 = \frac{d_1 + 6(d_2 + d_3)}{n},\ m_4 = \frac{S_1 + 14S_2 + 36S_3 + 24S_4}{n} \quad (10)$$

where n is the volume of the distribution series.

Tab. 3 Statistical series of service time distribution of resulting messages

$\tau_{\text{res}}(j)$	n_j	I	II	III	IV
170	150	150	150	150	150
270	220	370	520	670	–
370	198	568	1088	–	–
470	155	723	–	–	–
570	114	–	–	–	–
670	80	246	–	–	–
770	55	166	490	–	–
870	37	111	324	871	–
970	24	74	213	547	1258
1070	16	50	139	334	711
1170	10	34	89	195	377
1270	8	24	55	106	182
1370	6	16	31	51	76
1470	5	10	15	20	25
1570	5	5	5	5	5
Σ	1083	1811	1758	820	150
–	–	736	1361	2129	2634
–	$S(i)$	2547	3119	2949	2784
–	$d(i)$	−1075	−397	1309	2484

According to the data in Tab. 3, values of initial moments are as follows:

$$m_1 = \frac{-1075}{1083} = -0.9926$$

$$m_2 = \frac{2547 + 2 \cdot 3119}{1083} = 8.1117$$

$$m_3 = \frac{-1075 + 6(-397 + 1309)}{1083} = 4.06$$

$$m_4 = \frac{2547 + 14 \cdot 3119 + 36 \cdot 2949 + 24 \cdot 2784}{1083} = 202.394$$

Values of the central moments can be obtained based on the ratios between the initial and central moments [23-25]:

$$\mu_2 = m_2 - m_1^2$$

$$\mu_3 = m_3 - 3m_2 m_1 + 2m_1^3$$

$$\mu_4 = m_4 - 4m_3m_1 + 6m_2m_1^2 - 3m_1^4 \tag{11}$$

Using these ratios, we get:

$$\mu_2 = 7.1265\,;\ \mu_3 = 26.26\,;\ \mu_4 = 263.03\,;\ \sigma = \sqrt{\mu_2} = 2.668$$

The type of Pearson curve is determined by the value of the Pearson coefficient χ, which is calculated according to the formula [23]:

$$\chi = \frac{r_3^2 (r_4 + 3)^2}{4\left(2r_4 - 3r_3^2 - 6\right)\left(4r_4 - 3r_3^2\right)} \tag{12}$$

where $r_h = \dfrac{\mu_h}{\sigma^h}$ is the summary or main moments.

In this case, when $r_3 = 1.3953$ and $r_4 = 5.1796$, the value of the Pearson coefficient is $\chi = -1.596$.

The sign and absolute value of the coefficient indicate that the empirical distribution of the service time of the resulting messages τ_{res} can be reproduced by a Pearson curve of type III:

$$f(t) = f_{\text{III}}(0)\left(1 + \frac{t}{a}\right)^{\gamma_a} \mathrm{e}^{-\gamma t} \tag{13}$$

where

$$t = \frac{\tau_{\text{res}}(j) - M}{C} \tag{14}$$

$\tau_{\text{res}}(j)$ – the bit value of service time of resulting messages; M – the mode of distribution; $f_{\text{III}}(0)$ – the ordinate of the equalizing (theoretical) Pearson curve at the mode point; C – the length of the digit of the empirical distribution series.

Parameters of the Pearson curve of type III included in Eq. (13) are determined from the following ratios:

$$\gamma_a = \frac{4}{r_3^2} - 1\,,\ a = \frac{2\mu_2^2}{\mu_3} - \frac{\mu_3}{2\mu_2}\,,\ \gamma = \frac{2\mu_2}{\mu_3}\,,\ M = \overline{\tau}_{\text{res}} - \frac{r_3 \sigma C}{2}$$

$$\overline{\tau}_{\text{res}} = \tau_{\text{res}}(0) + m_1 C \tag{15}$$

where $\tau_{\text{res}}(0)$ is the time value for which the initial moments were calculated (in Tab. 3 $\tau_{\text{res}}(0) = 570$); and $\overline{\tau}_{\text{res}}$ is the average value of the distribution series.

The ordinate of the equalizing curve is determined by the formula:

$$f_{III}(0) = \frac{1}{a} \cdot \frac{\gamma_a^{\gamma_a + 1}}{\mathrm{e}^{\gamma_a}\Gamma(\gamma_a + 1)} \tag{16}$$

where $\Gamma(\gamma_a + 1)$ is the gamma function.

Calculations carried out according to Eqs (15) and (16) give the following values of the parameters of the Pearson equalizing curve of type III:

$$\gamma_a = 1.0546\,;\ a = 1.9429\,,\ \gamma = 0.5428\,,\ M = 280\,,\ \overline{\tau}_{\text{res}} = 470.7$$

$$f_{\mathrm{III}}(0) = 0.1949 \tag{17}$$

To construct an equalizing curve and determine the degree of consistency between the observed data and the hypothetical equalization distribution, the equalization bit frequencies are calculated – $\tilde{n}_j$. The formula for calculating equalization frequencies is as follows:

$$\tilde{n}_j = \tilde{n}_0 \left(1 + \frac{t}{1.9429}\right)^{1.0546} \mathrm{e}^{-0.5428t} \tag{18}$$

where

$$\tilde{n}_0 = n f_{\mathrm{III}}(0) = 1083 \cdot 0.1949 = 211.1 \tag{19}$$

The degree of agreement between the empirical distribution series and the hypothetical equalization series is determined by the value of the Pearson test $P(\chi^2)$ based on Eq. (4).

The obtained value of the Pearson test $P(\chi^2) > 0.3$ indicates that the accepted hypothesis regarding the Pearson equalizing curve of type III with parameters (17) does not differ from the research data. The equation of the distribution curve has the form:

$$f(t) = 0.1949 \left(1 + \frac{t}{1.9429}\right)^{1.0546} \mathrm{e}^{-0.5428t} \tag{20}$$

where $(-1.9429 \le t < \infty)$.

The histogram that describes the empirical series of the distribution, as well as the curve of the density of the distribution that equalize it, are shown in Fig. 4.

The method of analysis and processing of research data at time τ_{ind}, τ_{inm}, τ_{res}^{tr}, τ_{ind}^{tr}, and τ_{inm}^{tr} is similar to the method of analysis and processing of research data for time τ_{res}. We only note that the listed random variables are distributed according to the law, which is also described by the Pearson curve of type III.

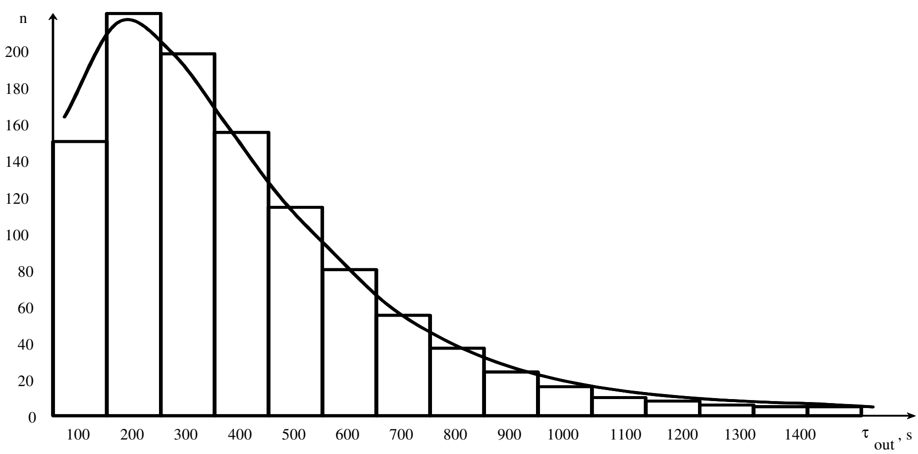

Fig. 4 Allocation of service time for resulting messages

Analytical expressions for the equalizing curves of the distribution density have the following forms:
for time τ_{ind}, at $(-2.396 \le t < \infty)$

$$f(t) = 0.21\left(1 + \frac{t}{2.396}\right)^{1.742} \mathrm{e}^{-0.727t} \tag{21}$$

for time τ_{inm}, at $(-2.686 \le t < \infty)$

$$f(t) = 0.2226\left(1 + \frac{t}{2.686}\right)^{2.404} \mathrm{e}^{-0.895t} \tag{22}$$

for time τ_{res}^{tr}, at $(-3.13 \le t < \infty)$

$$f(t) = 0.3358\left(1 + \frac{t}{3.13}\right)^{7.06} \mathrm{e}^{-2.249t} \tag{23}$$

for time τ_{ind}^{tr}, at $(-9.15 \le t < \infty)$

$$f(t) = 0.1665\left(1 + \frac{t}{9.15}\right)^{14.68} \mathrm{e}^{-1.604t} \tag{24}$$

for time τ_{inm}^{tr}, at $(-4.7 \le t < \infty)$

$$f(t) = 0.217\left(1 + \frac{t}{4.7}\right)^{5.768} \mathrm{e}^{-1.225t} \tag{25}$$

Fig. 5 shows the distribution of digital message service time τ_{ind}.

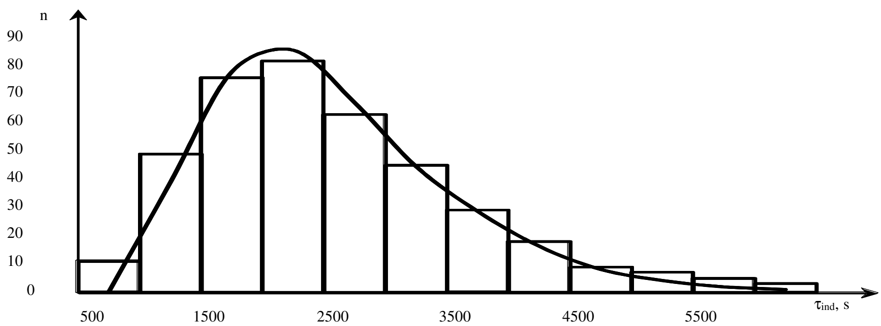

Fig. 5 Allocation of service time for digital messages

Histograms describing the statistical series of the distribution of τ_{inm}, τ_{res}^{tr}, τ_{ind}^{tr}, and τ_{inm}^{tr} and the equalizing distribution density curves are given similarly to Fig. 5.

5 Results and Discussion

A quantitative evaluation of the operator's functioning efficiency at the workplace in the automated UAV group control system was carried out. Analytical expressions were obtained for the smoothing curves of the density distribution for τ_{inm}, τ_{res}^{tr}, τ_{ind}^{tr}, and

τ^{tr}_{inm}. These expressions form the basis of the mathematical model for determining the dynamic characteristics of a human operator.

Analysis of Research Results. The proposed mathematical model for evaluating the efficiency of the functioning of a human operator in the automated control system of a UAVs group can be used:

- to ensure the design of complex automatic control systems using the step-by-step modelling method; to substantiate the requirements for a set of automation tools, composition and structure of the information support subsystem,
- to optimize operators' work modes and develop recommendations for improving the existing ergatic management systems, as well as to obtain comparative assessments of the operator's activity efficiency when using different types and configurations of means for interaction,
- to justify requirements for the operator's capabilities,
- to ensure training of operators during the development of new systems or modernization of existing ones.

Advantages and Disadvantages of the Conducted Research. The mathematical apparatus, which was proposed in the work, allows to present the actions of the operator as a block of the automated control system of UAVs' group. The advantage of this approach is the universality of application for any human operator. The disadvantage of such an approach and its limitation is the high computational complexity (which requires farther simplification), of the given mathematical models of operator activity in complex control systems of large groups of UAVs.

The obtained results make it possible to assess the impact of the efficiency of the operator's functioning on the effectiveness of solving tasks in the UAV group control system. The obtained laws of distribution of various random variables can be used in the modelling of operator activity in complex control systems of groups of UAVs.

6 Conclusions

The experimental study of the influence of operator activity on the functioning of UAV group control systems shows that the operator, with his/her presence in the UAV group control system as one of the links, in addition to errors, also introduces significant time delays that slow down the processes of information exchange between the components of the control system.

The mathematical apparatus that was proposed in the paper allows to present the actions of the operator as a link of the automated UAV group control system, to carry out a quantitative assessment of the efficiency of the operator's functioning at the workplace, as well as to evaluate the impact of this efficiency on the effectiveness of solving tasks in the UAV group control system. The fact that the optimal system of ergonomic improvements can be chosen based on the proposed mathematical models is of practical importance.

As far as the criteria for the efficiency of the purposeful activity of a human operator are concerned, the probability of error-free and timely decision of the operator of the automated UAV group control system to the emerging situation was defined. A graph-analytical system was used to present the performance evaluation criteria in a structured form.

The given experimental data and the obtained laws of distribution of various random variables will be useful for modelling the operator's activity in complex control systems of a UAVs' group.

The developed approach is universal, so, the given results can be used in practical, scientific, educational and research work, and are appropriate for further utilization by institutions engaged in the development, modernization and operation of UAV group control systems, and the development of future systems for solving specific tasks.

References

[1] PARKHOMENKO, D., O. RYSOVANYI, V. BURTSEV, V. VORONIN, V. STARTSEV and V. PANCHENKO. A Method for Targeting Unmanned Aerial Vehicles for a Distributed Intelligent Control System for a Group of Dissimilar Unmanned Aerial Vehicles. In: *2023 IEEE 4th KhPI Week on Advanced Technology (KhPIWeek).* Kharkiv: IEEE, 2023. DOI 10.1109/KhPIWeek61412.2023.10312902.

[2] HARRIS, D., V. DUFFY, M. SMITH and C. STEPHANIDIS, eds. *Human-Centered Computing: Cognitive, Social, and Ergonomic Aspects*, *Volume 3*. Boca Raton: CRC Press, 2019. ISBN 0-367-81336-X.

[3] KHURTENKO, O., K. BEREZIAK, R. KHAVULA, O. VDOVICHENKO, N. ONISHCHENKO and S. LIEBIEDIEVA. Psychological Analysis of Occupational Conditions in Extreme Environments and the Structure of Non-Standard Situations. *Broad Research in Artificial Intelligence and Neuroscience*, 2020, **11**(4), pp.132-148. DOI 10.18662/brain/11.4/145.

[4] KONZ, S. and S. JOHNSON. *Work Design: Occupational Ergonomics*. 7th ed. Boca Raton: CRC Press, 2018. ISBN 1-351-40412-1.

[5] KROEMER, K., H. KROEMER and K. KROEMER-ELBERT. *Ergonomics: How to Design for Ease and Efficiency*. 2nd ed. Englewood Cliffs: Prentice Hall, 2001. ISBN 0-13-752478-1.

[6] MACLEOD, D. *The Rules of Work: A Practical Engineering Guide to Ergonomics*. 2nd ed. Boca Raton: CRC Press, 2013. ISBN 1-4398-9906-1.

[7] MCCAULEY-BUSH, P. *Ergonomics: Foundational Principles, Applications, and Technologies*. Boca Raton: CRC Press, 2012. ISBN 0-429-11264-5.

[8] STACK, T., L.T. OSTROM and C.A. WILHELMSEN. *Occupational Ergonomics: A Practical Approach*. Hoboken: Wiley, 2016. ISBN 1-118-81421-5.

[9] LIN, S.C., J.C. CHEN and W.C. LI. The Analysis of Human Error Prevention Strategies in Military Aviation. In: *12th International Conference Engineering Psychology and Cognitive Ergonomics 2015 (EPCE 2015)*. Coventry: Springer, 2015, pp. 428-435. ISBN 3-319-20372-X.

[10] RAMOS, R.A., M.C. HEIL and C.A. MANNING. *Documentation of Validity for the AT-SAT Computerized Test Battery* [online]. 2001 [viewed 2024-04-22]. Available from: https://rosap.ntl.bts.gov/view/dot/15411

[11] BOY, G.A., ed. *The Handbook of Human-Machine Interaction: A Human-Centered Design Approach*. London: CRC Press, 2017. ISBN 1-315-55738-X.

[12] GRIF, M.G., O. SUNDUI and E.B. TSOY. Methods of Designing and Modeling of Man-Machine Systems. In: *Proceedings of International Summerschool*

Computer Science 2014. Chemnitz: Chemnitzer Informatik-Berichte, 2014, pp. 38-40. ISSN 0947-5125.

[13] DI PASQUALE, V., S. MIRANDA, R. IANNONE and S. RIEMMA. A Simulator for Human Error Probability Analysis (SHERPA). *Reliability Engineering & System Safety*, 2015, **139**, pp. 17-32. DOI 10.1016/ j.ress.2015.02.003.

[14] BENNOUR, M. and D. CRESTANI. Formalization of a Process Activity Performance Estimation Approach Using Human Competencies. *International Journal of Production Research*, 2007, **45**(24), pp. 5743-5768. DOI 10.1080/ 00207540600654459.

[15] LAVROV, E., N. PASKO, A. KRIVODUB and A. TOLBATOV. Mathematical Models for the Distribution of Functions Between the Operators of the Computer-Integrated Flexible Manufacturing Systems. In: *Proceedings of the XIIIth International Conference TCSET'2016 "Modern Problems of Radio Engineering, Telecommunications, and Computer Science"*. Lviv-Slavske: IEEE, 2016, pp. 72-77. ISBN 617-607-806-7.

[16] BOLTON, M. L., E.J. BASS and R.I. SIMINICEANU. Using Formal Verification to Evaluate Human-automation Interaction: A review. *IEEE Transactions on Systems, Man, and Cybernetics: Systems*, 2013, **43**(3), pp. 488-503. DOI 10.1109/TSMCA.2012.2210406.

[17] ASKARPOUR, M., D. MANDRIOLI, M. ROSSI and F. VICENTINI. Formal Model of Human Erroneous Behavior for Safety Analysis in Collaborative Robotics. *Robotics and computer-integrated Manufacturing,* 2019, **57**, pp. 465-476. DOI 10.1016/j.rcim.2019.01.001.

[18] LU, T., D.M. POOL, M.M. VAN PAASSEN and M. MULDER. Quantifying the Effects of Added Dynamics with Human Operator Control Behavior Measurements and Simulations. In: *AIAA Modeling and Simulation Technologies Conference*. *AIAA-2017-3667.* Denver: AIAA, 2017. DOI 10.2514/6.2017-3667.

[19] YEMELYANOV, A.M. Unified Modeling of Human Operator Activity in a Real-World Environment. In: *2005 IEEE International Conference on Systems, Man and Cybernetics*. Waikoloa: IEEE, 2005, pp. 2476-2481. DOI 10.1109/ICSMC.2005.1571520.

[20] ÁLVAREZ-CASADO, E., B. ZHANG, S. TELLO-SANDOVAL and P. MONDELO. Using Ergonomic Digital Human Modeling in Evaluation of Workplace Design and Prevention of Work-Related Musculoskeletal Disorders Aboard Small Fishing Vessels. *Human Factors and Ergonomics in Manufacturing & Service Industries,* 2016, **26** (4), pp. 463-472. DOI 10.1002/hfm.20321.

[21] HOLLNAGEL, E. Reliability Analysis and Operator Modelling. *Reliability Engineering & System Safety*, 1996, **52**(3), pp. 327-337. DOI 10.1016/0951-8320(95)00143-3.

[22] DUFFY, V.G., ed. *Handbook of Digital Human Modeling: Research for Applied Ergonomics and Human Factors Engineering*. Boca Raton: CRC Press, 2008. DOI 10.1201/9781420063523.

[23] VON MISES, R. *Mathematical Theory of Probability and Statistics*. New York: Academic Press, 2014. ISBN 0-12-727356-5.

[24] OLVER, F.W.J., D.W. LOZIER, R.F. BOISVERT and C.W. CLARK. *NIST Handbook of Mathematical Functions*. New York: Cambridge University Press, 2010. ISBN 0-521-14063-3.

[25] OTT, R.L. and M.T. LONGNECKER. *An Introduction to Statistical Methods and Data Analysis*. 7th ed. Pacific Grove: Brooks Cole, 2015. ISBN 0-495-01758-2

[26] ENNIS, R.H. Critical Thinking Assessment. *Theory Into Practice*, 1993, **32**(3), pp. 179-186. DOI 10.1080/00405849309543594.

[27] BOROZENEC, I., O. DMITRIIEV, M. MELNICHUK, M. PAVLENKO, G. SHCHERBAK and S. SHYLO. Method Development of the Information Models' Design and Synthesis for Infocommunication Systems of Air Traffic Control. *Advanced Information Systems*, 2019, **3**(3), pp. 37-42. DOI 10.20998/2522-9052.2019.3.05.

[28] DMITRIIEV, O., I. BOROZENEC, S. SHILO and T. KALIMULIN. Imitation Model of Support for Decision-making Based on Assessment of the Situation by Operators of the Automated Air Traffic Control System. *Advanced Information Systems*, 2018, **2**(3), pp. 30-35. DOI 10.20998/2522-9052.2018.3.05.