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MODELS OF OPERATOR ACTIVITY FOR A REMOTE UAV PILOT

Based on the analysis of the psychophysiological features of the activity of remote UAV pilot, a set of models of operator activity is proposed. A functional model of intellectual activity, a mathematical model of operator activity as a queuing system has been developed, and a mathematical model of Generalized Performance Characteristic of a remote pilot has been improved. These models solve a set of questions on the integral assessment of the remote pilot's activity in the UAV control loop.

Keywords: *remote pilot, UAV, Generalized Working Characteristic, psychophysiological features, intellectual activity, human factor, queuing system.*

Introduction

Unmanned aerial vehicles (UAVs), also known as drones, have become an integral part of modern technology and find applications in various fields, ranging from military operations and civilian aviation to agriculture and environmental monitoring. The use of UAVs allows for the execution of complex tasks without the direct involvement of a pilot on board, offering new possibilities and significant advantages in numerous domains. However, this new form of aviation also presents its challenges and requires special attention to the psychophysiological aspects of remote piloting and its impact on operators.

Unlike traditional manned aviation, where pilots are physically present aboard aircraft, UAV piloting is conducted remotely from specialized control stations. Remote pilots play a pivotal role in UAV operations, monitoring, controlling, and overseeing the flights of these unmanned vehicles. They are responsible for a range of functions, including observation, reconnaissance, monitoring, search and rescue, as well as conducting specialized operations.

However, the work of a remote UAV pilot entails unique psychophysiological characteristics. Operators are physically separated from the aircraft they control and lack many non-instrumental sources of information, which affects the reception of sensory inputs and creates limitations in perceiving visual, auditory, and tactile signals. Remote pilots also face unique stressors, such as making decisions based on limited information, controlling high levels of responsibility, and addressing potential system failures. All these factors necessitate a deep understanding of the psychological aspects of remote pilots' work and the development of models and approaches that can optimize their efficiency and safety [1, 2].

In light of the above, the need to develop models of UAV remote pilot activity becomes evident. Such models will contribute to a better understanding of operators' psychological profiles, their specific characteristics, stress factors, and requirements. They will also help identify the most effective methods of training and supporting these specialists. Research and development in this field can facilitate the creation of synthetic environments for UAV simulator systems that are realistic and adaptive, considering the psychophysiological aspects of remote pilots' work.

Therefore, in this article, we will focus on the considerations of the psychophysiological peculiarities of remote pilot's work, and the developing models of their activity. This will enable a better understanding of the demands and challenges faced by operators and identify avenues for further research and development in this domain.

Activities of a Remote Pilot to Control an Unmanned Aerial Vehicle

An unmanned aviation system (UAS) is an integrated system consisting of several components that interact with each other to perform unmanned flights and carry out various missions. The main components of a UAS are:

An unmanned aerial vehicle is the main element of the UAS and is an unmanned plane, helicopter, multicopter or other aircraft. The UAV is equipped with various sensors, communication systems, navigation systems, data transmission devices, and other specialized equipment that allow it to perform assigned tasks within a specific mission, such as reconnaissance, observation, monitoring, cargo delivery, and others.

Ground control station (GCS) is the central point of control and monitoring for the UAV. It is a specialized system of hardware, software and interfaces that provides communication with the UAV, data transmission, display of information about the flight and the environment, and also provides an interface for control and interaction with the system. The GCS is equipped with computers, monitors, communication equipment, and software that allow the remote pilot to control and operate the UAV, receive and analyse information from sensors, and interact with other systems [3].

Communication systems ensure the transmission of data and commands between the UAV and the ground control station, as well as between the remote pilot and other team members on the ground. They include radio communication, data transmission networks, satellite communication systems, and other technologies that provide reliable and secure interaction between the UAV and the remote pilot.

The UAV is equipped with various sensors and observation systems that gather information about the external environment and targets. These may include optical and infrared cameras, thermal imagers, radars, laser scanners, gas and chemical sensors, and others that provide information about the surrounding conditions, target detection, weather conditions, and other parameters necessary for mission execution. The collected data is transmitted to the GCS for analysis and decision-making.

The UAS may be equipped with autonomous systems and artificial intelligence that enables the UAV to perform tasks independently or make automatic decisions based on data analysis and predefined algorithms. This may include functions such as automatic piloting, object recognition, information processing, and others.

The interaction between the remote pilot and the UAS is carried out through the ground control station, where the remote pilot receives information about the flight, system states, sensor data, and makes decisions regarding UAV control. The remote pilot also exchanges commands and messages with other team members on the ground to coordinate tasks and convey important information.

It is important to note that the interaction between the remote pilot and the UAS requires high qualifications, multitasking skills, the ability to analyse real-time data, and make decisions in rapidly changing situations. This ensures flight safety and effective mission execution [4].

The remote pilot plays a central role in the process of controlling and monitoring the flight of the UAV and interacts with it in the following ways.

During flight control, the remote pilot uses control elements on the ground station, such as a joystick, steering wheel, pedals, and buttons, to control the movement and maneuvering of the UAV. He can control the flight direction, altitude, speed, change heading, and perform other actions necessary for mission execution. In the process of UAV control, the remote pilot also monitors and observes. He has access to various video streams and sensors installed on the UAV. He can observe the surrounding environment, receive images from cameras and other sensors analyse information about targets, weather conditions, and other parameters. This allows him to make informed real-time decisions.

The remote pilot engages in communication and command transmission. He can communicate with other team members, operators, or ground personnel through communication systems integrated into the ground station. They can transmit commands and instructions to the UAV, receive feedback, and coordinate actions with other remote pilots or staff members.

The remote pilot also has the ability to receive information about the state of the UAV, diagnose possible problems or malfunctions, and take measures to eliminate them. He can monitor systems, sensors, energy data and other aspects of the operation of the UAV.

An important aspect of the remote pilot's activity is data analysis and decision-making. He analyses the collected data, assess the situation, make decisions, and perform necessary actions according to the assigned tasks. During mission execution, he may adjust the route, change flight parameters, and respond to changes in the environment and circumstances.

The interaction of a remote pilot with a UAS requires skills in operating a ground control station, understanding the technical aspects of the system, as well as the ability to effectively analyse information and make decisions in real time. It plays a key role in the successful execution of missions and ensuring the flight safety of an unmanned aerial vehicle [5].

Features of the Intellectual Activity of a Remote Pilot when Operating UAVs

The activity of a remote pilot is impossible without the presence of professionally significant mental, physiological, and physical qualities. The operation of modern unmanned aerial vehicles (UAVs) requires significant mental and psychological effort.

When designing modern unmanned aviation systems, it is necessary to correctly take into account the so-called "human factor" with all its inherent features of functioning in conditions of remote control. Taking into account the human factor in relation to the "remote pilot-UAV" system means ensuring compatibility between the remote pilot and the spatially and temporally distributed unmanned aviation system in terms of informational, energetic, biotechnical, spatial-anthropometric, and technical-aesthetic aspects. In other words, it involves aligning the properties of the technical part of the system with the psychophysiological capabilities of the remote pilot in all operating conditions, including UAV control in the presence of technical failures and adverse environmental factors.

The analysis of erroneous actions by remote pilots shows that the main errors in UAV control are related to their mental (intellectual) activity, which includes processes occurring in the central nervous system and related to perception, information processing, and decision-making. It is based on the reflexive and heuristic activity of the brain, which, in general, represents a response to stimuli from the internal and external environment. In order

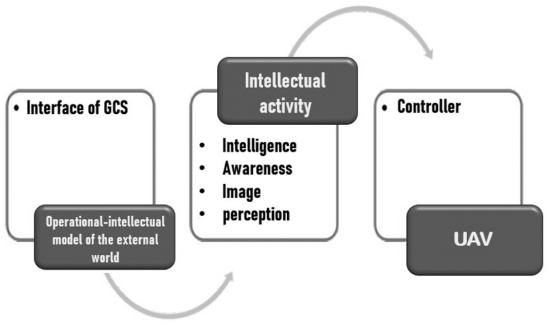

Fig. 1. Structure of the intellectual activity of a remote pilot when controlling UAVs

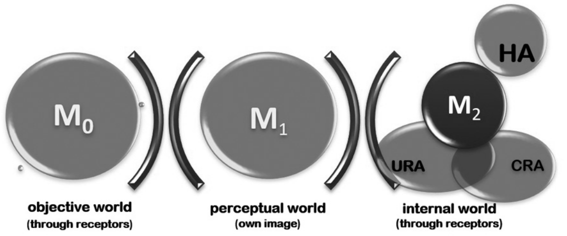

Fig. 2. Generalized functional model of the intellectual activity of a remote pilot

to formalize the process of a remote pilot's activity in controlling UAVs, let's consider the structure as shown in Fig. 1.

For most ground-based professions, it is characteristic that the operator determines the most acceptable (optimal) pace of performing work operations. In the majority of flight situations, a remote pilot has practically no opportunity to either accelerate or decelerate the course of events. When there is a mandatory and strict sequence of work operations, the pace at which they are performed by the remote pilot is dictated by the course of UAV flight development, meaning that in most cases, the remote pilot is compelled to carry out all these actions at a pace imposed by the circumstances [8]. Furthermore, the speed at which the pilot performs these operations can approach the maximum possible. These circumstances create a precondition for the occurrence of emotional and operational stress alongside pilots. Accordingly, pilots' mental state requires emotional stability and the ability to perform tasks at the imposed pace without decreasing their performance under conditions of emotional overload [9].

The role of a remote pilot in working with UAVs is crucial for ensuring safe and efficient mission execution. Psycho-physiological requirements imposed on remote pilots significantly differ from those of traditional manned aviation. Maintaining situational awareness is of paramount importance for remote pilots since they heavily rely on sensor information transmitted through UAV sensors and data streams. Limited sensor input, lack of physical presence, and dependence on visual displays and telemetry data pose challenges for the perception of the remote pilot and decision-making processes.

Distribution and management of attention also play an essential role for remote pilots due to the constant monitoring of various flight parameters, mission objectives, and potential environmental hazards. The work of a remote pilot requires simultaneous execution of individual actions, each aimed at achieving specific goals, such as UAV flight control, navigation, payload operations, coordination with ground control, mission operators, and other team members, etc.

The ability to perform joint operations and actions, simultaneous control over the progress of two or more processes, is achieved through the automation of remote pilot actions [10–12] – as a result of skill development, as well as through rational attention organization. Skill development can only be observed during the automatic execution of an action without control of consciousness. Consciousness only registers the final result of the action.

Another characteristic of remote pilots' work is the use of prediction and forecasting mechanisms. Like any operator working in tracking mode, a remote pilot compares and contrasts information about the current and designated modes of UAV flight [13, 14].

Based on all the above, the intellectual activity of a remote pilot, in terms of consciousness levels, can be represented as a generalized functional model of their intellectual activity (Fig. 2).

The process of processing telemetry, video, and other information by a remote pilot is directly related to their intellectual activity – mental work in solving UAV control tasks with elements of uncertainty. The foundation of human intellectual activity consists of reflexive (unconditional and conditional) and heuristic activities of the human brain, which, in general, are reactions to external and internal stimuli.

The lowest level of intellectual activity represents a combination of innate reactions to perception and information processing, as well as executive activity, and is unconditionally reflexive. The basic unit of this level is a frame, which represents basic concepts, statements, and stereotypical procedures in the form of images. Frames form the basis for unconditional reflexes. Unconditional reflexive activity (URA) is the lowest level, playing an informational and executive role, and serving as a link to the external world and higher intellectual levels. It performs three main functions: being a source of image-based information, shaping behavioural patterns, and being the level where all intellectual activity takes place.

The main working level of a remote pilot's intellectual activity in UAV control is conditional reflexive activity (CRA). It enables the modelling of the real world through the organization of temporal connections and reactions to future events. To perform these functions, natural language of images is initially used, through which a person can convey information.

The highest level of intellectual activity is heuristic activity (HA). This level involves comprehensive perception of problems and situations through the use of symbolic language, which is synthesized from natural language and the language of images.

Telemetric and other information received at the ground control station represents the objective world M0 for the remote pilot and corresponds to the current state of the UAV. In the process of intellectual activity, the remote pilot perceives a simplified model from the general objective world of tasks M0, known as the world of perceptual tasks M1. This is due to both limited receptor capabilities and the selective ability of the human brain. Additionally, the model of the remote pilot's intellectual world includes their internal world M2. The internal world is formed by:

– "Innate" unconditional reflexive tasks of URA, described in the language of frames.

– Conditioned reflexive tasks of CRA accumulated as a result of human activity and described in natural language.

– Newly formed creative heuristic tasks of HA, described in symbolic language.

In the generalized model of the remote pilot's activity, mental and sensorimotor processes of the operator's activity in UAV control can be formalized using the language of operations for different encoding methods:

– Operation of perception and information processing allows forming of a perceptual world of tasks M1 from the objective world of tasks M0.

– Operation of formation and structuring of the unconditional reflexive world of URA tasks from the perceptual world of tasks M1.

– Operation of formation and structuring of the conditional world of CRA tasks from the world of URA.

– Operation of formation and structuring of the heuristic world of HA tasks from the worlds of CRA and URA.

– Operation of forming the concept of solving the UAV control problem from the world of heuristic ED tasks.

– Operation of forming alternatives of implementation of the constructed concept of solving the UAV control from the world of CRA and selecting one of them.

– Operation of forming an algorithm for the implementation of the chosen alternative to the activity of a remote pilot to control the UAV from the world of unconditional reflex URA tasks.

– Operation of implementing the constructed algorithm for UAV control by the remote pilot.

The examination of the developed functional model of the intellectual activity of a remote pilot shows that all the listed intellectual operations align with the traditional stages of the operator's activity in UAV control, thus corresponding to the structure of the pilot's intellectual activity in UAV control (Fig. 1). The process of a remote pilot's activity in UAV control consists of the following stages:

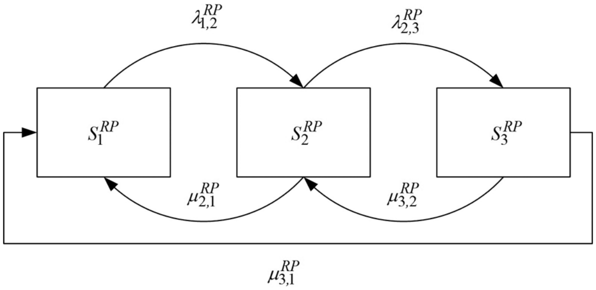

Fig. 3. State graph of the operator's activity of the remote UAV pilot in UAV control

1. Perception stage. This stage involves the direct perception and information pre-processing (corresponds to URA).

2. Image creation stage. This stage encompasses the logical processing of information and the formation of UAV control tasks (corresponds to CRA).

3. Intellect stage. This stage involves solving intellectual tasks related to UAV control and selecting an activity algorithm (corresponds to HA).

4. Awareness stage. This stage encompasses actions aimed at implementing the chosen control algorithm for the UAV.

The Construction of a Mathematical Model for the Operator's Activity of a Remote UAV Pilot

The task of mathematically describing human actions is to provide the most comprehensive formalization and consideration of human advantages in the model. The analysis of the intellectual activity of a remote UAV pilot has shown that their flight control operator activity can be represented as a queuing system S^{RP} with three states: S_1^{RP} is telemetry data reading corresponding to the level of URA (Fig. 2); S_2^{RP} is processing the read information corresponding to the level of CRA (Fig. 2); S_3^{RP} is decision-making for UAV control corresponding to the level of HA (Fig. 2). When controlling a UAV from a ground control station, the activity of the remote pilot is considered as sensorimotor tracking operator activity, expressed through the inertia of the remote pilot λ^{RP}. Fig. 3 shows the state graph of the operator's activity of the remote pilot in UAV control.

Let's write the Kolmogorov equations for the state graph of the operator's activity of the remote UAV pilot (Fig. 3).

$$\begin{gathered}
\frac{dp_1^{RP}}{dt} = -\lambda_{1,2}^{RP} p_1^{RP} + \mu_{2,1}^{RP} p_2^{RP} + \mu_{3,1}^{RP} p_3^{RP}, \\
\frac{dp_2^{RP}}{dt} = -\left(\lambda_{2,3}^{RP} + \mu_{2,1}^{RP}\right) p_2^{RP} + \\
+\lambda_{1,2}^{RP} p_1^{RP} + \mu_{3,2}^{RP} p_3^{RP}, \qquad (1) \\
\frac{dp_3^{RP}}{dt} = -\left(\mu_{3,2}^{RP} + \mu_{3,1}^{RP}\right) p_3^{RP} + \lambda_{2,3}^{RP} p_2^{RP}.
\end{gathered}$$

The intensities $\lambda_{i,j}^{RP}$ and $\mu_{i,j}^{RP}$ of transition from one state to another in the state graph depend on the time spent by the remote pilot on performing operations related to information perception, processing, and decision-making: $\lambda_{1,2}^{RP} = \frac{1}{T_r}$ is intensity of information perception by the human operator (URA) associated with telemetry information reading time, T_r; $\lambda_{2,3}^{RP} = \frac{1}{T_{dp}}$ is transition intensity associated with telemetry information processing time, T_{dp}; $\mu_{2,1}^{RP} = \frac{1}{T_u}$ is transition intensity associated with the time required for refining telemetry information, T_u (corresponds to the stage of immediate perception through sensory organs and previous information processing (URA)); $\mu_{3,2}^{RP} = \frac{1}{T_{lp}}$ is intensity associated with the time required for returning to telemetry information processing, T_{lp} is time for logical information processing by the remote pilot (corresponds to the stage of logical information processing and formation of UAV control tasks, CRA); $\mu_{3,1}^{RP} = \frac{1}{T_{dm}}$ is intensity associated with the time required for decision-making in UAV control, T_{dm} (corresponds to the stage of sol-ving the intelligent task of UAV control and choosing the activity algorithm, (HA), and the stage of action directed at implementing the selected UAV control algorithm).

The obtained model (1) allows determining the time $T_{i,j}$ required by the remote pilot for telemetry information reading, processing, and decision-making in UAV control, taking into account the characteristics of human intelligence. It represents the transition time of the S^{RP} system when it transitions to state S_3^{RP}, indicating that the pilot has made a decision regarding the control. This can be solved as a system of equations (1) with initial conditions $p_1^{RP}=1,\ p_2^{RP}=0,\ p_3^{RP}=0$.

Experimental Obtaining of the Generalized Performance Characteristic Using the Developed Queuing System Model

In [16], a Generalized Performance Characteristic (GPC) was proposed for analysing human operator activities as part of an ergatic system. Let's consider a system that has an object with a control device and is studied within a certain mathematical model M:

$$M=\left\langle A, P_r, y=f\left(x,u\right)\right\rangle \tag{2}$$

where $\left(A, P_r\right)$ is the basis of the system over which the relation $y=f\left(x,u\right)$ of the controlled system is defined, A specifies the sets $X,\ Y,\ U$ of possible values $x,\ y,\ u$ respectively;

$x\in X$ is the state vector of the output variables of the control object;

$u\in U$ is the state vector of control parameters;

$y\in Y$ is the vector of output variables of the control object;

f is a transformation function that defines the relation of the variable y over the variables x and u.

$P_r=\{P_0,K,P_l,K\}$ is set of rules for the formation of relationships .

When a mathematical model of the system (2) is chosen, it determines the basis of the system $A,\ P_r$, on which the relationship $y=f\left(x,u\right)$ is defined. This basis defines the sets $X,\ Y$ and the language used to describe the relationships $y=f\left(x,u\right)$ in the mathematical model M. This basis serves as the foundation for describing the human operator as a component of the control system "indicator device – human operator – human operator-machine communication device." In this approach, the human operator is considered together with the devices that convert (translate) information from the language of the mathematical model M to a "human-readable" language and vice versa, from the "human language" to the language of the entire system M_i. To the human operator as an element of a closed purposeful system, requirements are put forward to carry out operator activities, characterized by the triple:

$$\left\langle R, Q\ , \varepsilon\right\rangle \tag{3}$$

where Q is the operator of relationships carried out by the human operator as part of the system, between indicator variables x_i and input variables x_{h0} introduced into the system by the human operator:

$$x_{h0}=Q_{xi}; \tag{4}$$

R is the operator of relationships between a reference signal Ψ_{rs} common to all systems and an indicator signal

$$x_i : x_i = R\psi_{rs}\ ; \tag{5}$$

ε – is the permissible accuracy of executing the relationships Q over the signal x_i, characterized by the operator R.

The accuracy parameter ε, along with the relationship operators R and Q, is the main characteristic of the human operator's operator activity.

The operator activity of the human operator is determined by this triplet (3), related to time and space, providing a basis for characterizing the human operator as a component of a closed control system with the concept of a Generalized Performance Characteristic. It relates the time and space of the existence of operator activity $\left\langle R, Q\ , \varepsilon\right\rangle$ to each point in the functional spaces (M_R, M_Q, M_e) of the mathematical model M.

A quasi-stable functional state of a human operator in the region D of the space $T\cap B$ of independent variables $\tau=\left(t,\beta_1,\ldots,\beta_n\right)$ is his state when working in a closed control system with fixed values of the relational operator R, and a fixed instruction regulating the work a human operator, which makes it possible to compose a relational operator Q that is unique for all subdomains $D_i\subseteq D$, connecting signals x_{h0} and x_i with accuracy ε. In this case, Q is called a quasi-operator of functional transformations performed by a human operator in a closed control system.

Each specific type and composition of operator activity $\left\langle R, Q\ , \varepsilon\right\rangle$ is associated with a fully defined distribution probability law $f\left(t,\beta\right)$ or a fully defined

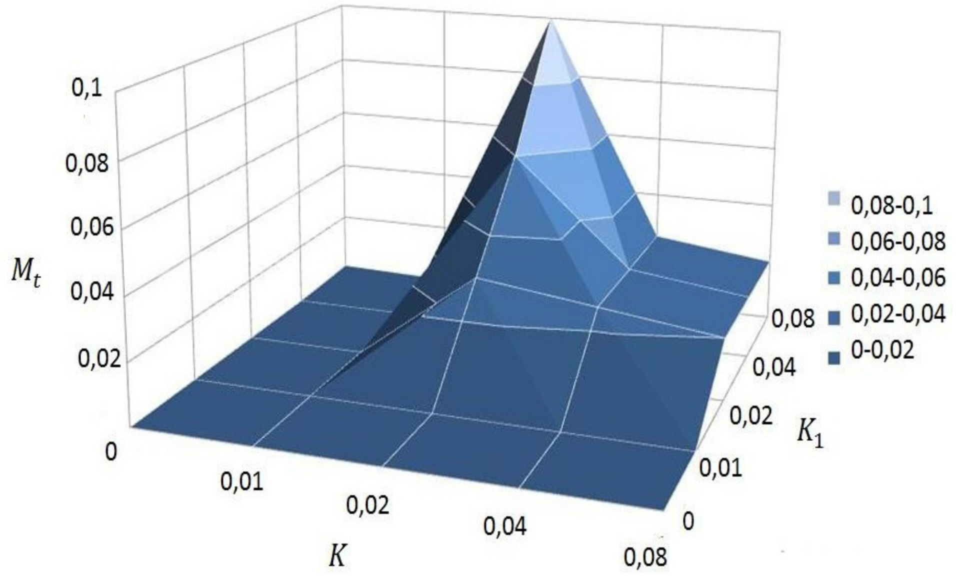

Fig. 4. Experimentally constructed *Q*-characteristic

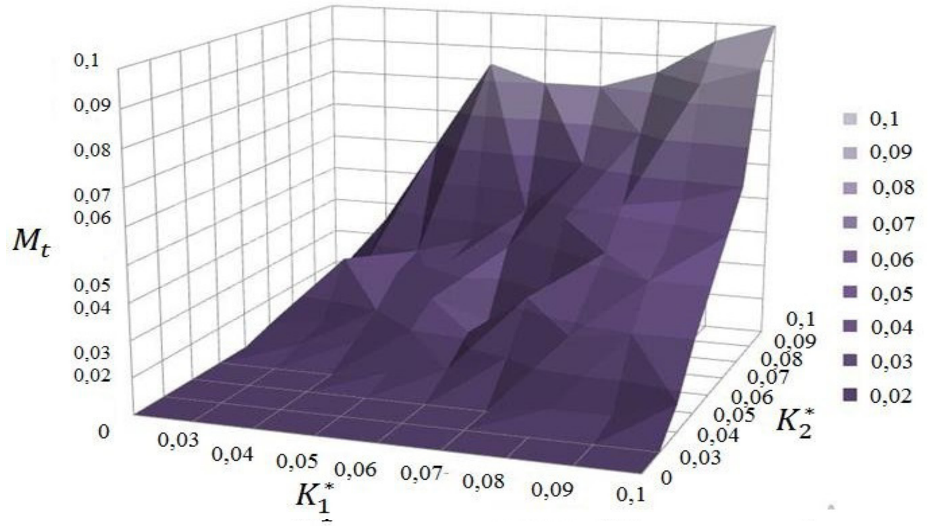

Fig. 5. Experimentally obtained *R*-characteristic

set of numerical characteristics $\left\langle m, \left\| k_{ij} \right\| \right\rangle$ of random variables $(t, \beta_1, \ldots, \beta_n)$, where $m = (m_t, m_{\beta 1}, \ldots, m_{\beta n})$ are mathematical expectations that characterize the average values of the time parameter *t* and spatial parameters β; $k_{i,j}$, $i \neq j$; $i, j = 1, \ldots, n+1$ are correlation moments cha-racterizing the pairwise correlation of all parameters $t, \beta_1, \ldots, \beta_n$.

Then, given the set $M_m \cap M_k$ of values of mathematical expectations and correlation moments, it is possible to give a definition of the Generalized Performance Characteristic of a human operator.

The Generalized Performance Characteristic of a human operator as a link in a control system is called the operator *W* mapping points in the space $(M_R \cap M_Q \cap M_\varepsilon)$ points in the space $M_m \cap M_k$.

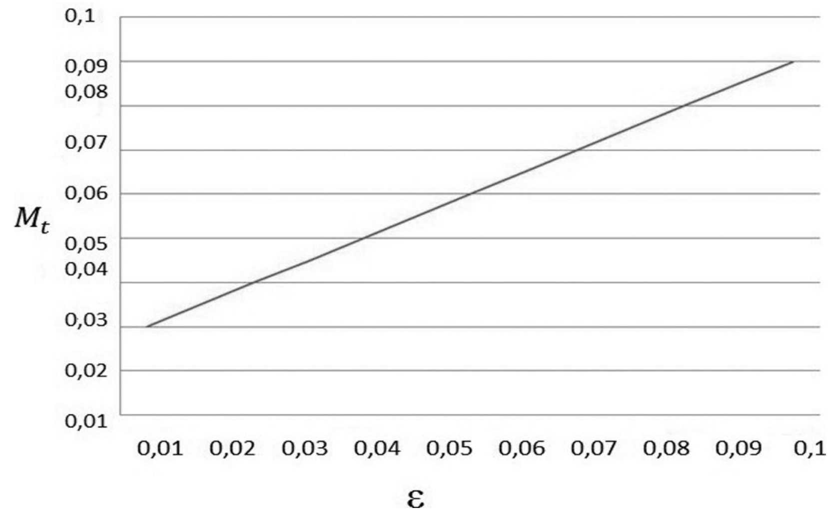

Fig. 6. Experimentally obtained ε-characteristic

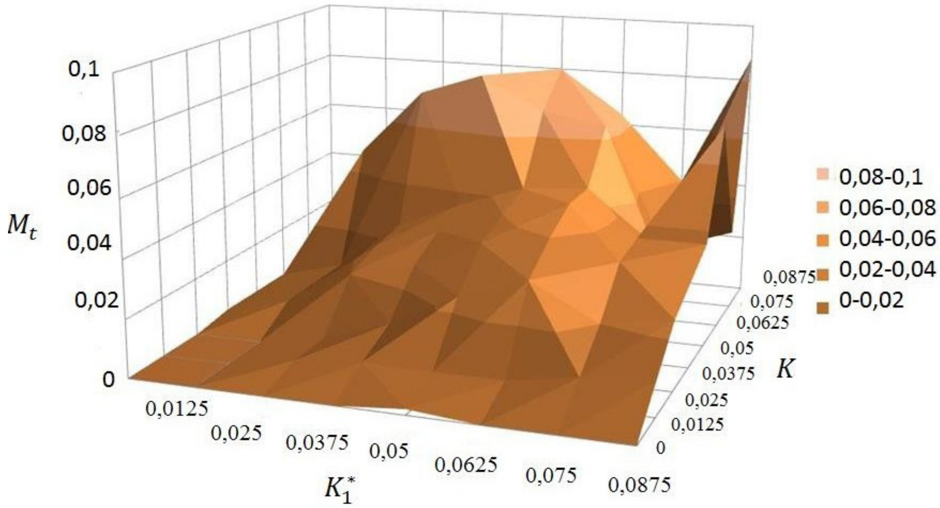

Fig. 7. Experimentally obtained *QR*-characteristic

For the operator *W*, the corresponding mathematical model must be chosen with a basis that does not contradict the basis of the mathematical model of the ergatic system. In our case, a queuing system is chosen as the basis of the mathematical model.

The functional transformation operators are selected within the class of linear operators, as they are widely used in the practice of operating ergatic control systems, where the human operator performs functions in compensatory tracking mode. The parameters of the generalized performance characteristic are associated with the parameters of the developed mathematical model in the form of a queuing system:

Q is processing of telemetry information by the remote pilot $\lambda_{2,3}^{RP}$, $\mu_{3,1}^{RP}$ corresponds to the CRA;

R is characteristic of the indicator signal of the ground control station corresponds to the URA;

ε is accuracy of the remote pilot in executing the *Q* signal with respect to *R*, $\mu_{3,1}^{RP}$, $\lambda_{2,3}^{RP}$ corresponds to the HA.

The experimental dependencies were obtained for the following pair of functional transformation operators *Q* and the observed signal *R*.

The ***Q-characteristic*** is formed from the stages of image creation, intellect and awareness. Here is the formation of an operative image of the situation. An operative image is understood as a mental unit obtained by bringing together disparate information from receptors (corresponding to the CRA in Fig. 2). This is the stage of logical processing of information and the formation of UAV control tasks. Based on the generated operative image of the situation, the solution of the intellectual problem of the UAV control and the choice of the activity algorithm (corresponding to the HA) and then the implementation of the selected UAV control algorithm are carried out.

This characteristic is the dependence of the mathematical expectations of the time for the remote pilot to maintain a quasistable functional state on the parameters $K = \lambda_{2,3}^{RP}$, $K_1 = \mu_{3,1}^{RP}$ (Fig. 3) of the functional transformation operator *Q*, in this case $R = \text{Const}$, $\varepsilon = \text{Const}$. Based on the results of modelling the "remote pilot – UAV" system using the model (1) of the operator's activity, the settling time was determined for each state probability of the system, and their mathematical expectations were calculated. Based on the experimental results, the surface of the function $M_t = t(K, K_1)$ was constructed and depicted in Fig. 4.

According to the figure, in the operator activity model of a remote pilot, the maximum value of the mathematical expectation M_t of the time of transition from state to state is located in the region $0{,}015 \le K \le 0{,}025$ and tends to increase with increasing K_1. It should be noted that the extreme of the function $M_t = t(K, K_1)$ in the selected region are pronounced.

This fact indicates that the function $M_t = t(K, K_1)$ in the region $0{,}01 \le K \le 0{,}1$ is sensitive to changes in the parameters *K* and K_1. Thus, with possible changes in *K* and K_1, the time of quasi-stable functional state for the remote pilot significantly decreases. Hence, the parameter range $0{,}015 \le K \le 0{,}025$; $0{,}08 \le K_1 \le 0{,}1$ is optimal since the function $M_t = t(K, K_1)$ is almost invariant to changes *K* and K_1 in this range.

The ***R-characteristi***c is formed during the perception process. Perception is the lowest level of intellectual activity (corresponds to URA in Fig.2) and is characterized by the ability to reflect reality not in the form of separate object forms, as in sensations, but in the form of reflecting objects through the integration of their influencing properties into a unified and holistic object image. It is through the level of perception from the multifunctional interface of the ground control station that the operational-information model of the outside world is provided, which is perceived by the remote pilot using the receptors of various analysers. The more qualitative the information transmitted on the ground station interface is for perception, the more accurately the remote operator perceives it.

R-characteristic represents the dependence of the mathematical expectation of the time for the remote operator to maintain a quasi-stable functional state on the coefficients: $K_1^* = \mu_{3,1}^{RP}$, $K_2^* = \lambda_{1,2}^{RP}$ (Fig. 3) of the operator of transformation of the reference input signal of the system. In this case: $Q = \text{Const}$, $\varepsilon = \text{Const}$.

Based on the experimental results, the surface of the function $M_t = t(K_1^*, K_1^*)$ was constructed and depicted in Fig. 5.

From the provided dependency, it is evident that it has a monotonic nature and with an increase in the coefficients K_1^*, K_1^*, in operator activity model of a remote pilot the value of the mathematical expectation M_t of the transition time from one state to another Increases. This can be confirmed by the fact that with an increase in the coefficients K_1^*, K_1^*, transient processes at the output of the converter acquire a smoother character, passing from the region of oscillatory processes to aperiodic ones. The time of the quasi-stable functional state of the remote pilot during operation increases.

The ε***-characteristic*** (accuracy of operation execution) is formed at the level of intelligence, where comparison, memorization, and sorting of images take place. There is a certain set of basic UAV control techniques outlined in the instructions. For an experienced remote pilot, solving a specific operative task is reduced to finding a modification of one of the basic control techniques that accurately reproduces the conditions of the given situation, and only in some cases does the pilot encounter a problem. The training process can be interpreted as the development (assimilation) of basic techniques, as well as learning as components of the highest level of intellectual activity and finding the corresponding control techniques. As the pilot undergoes training, they associate the operational-information model with different classes stored in long-term memory, based on different control techniques.

This characteristic represents the dependence of the mathematical expectation of the time for the remote pilot's quasi-stable functional state on the acceptable accuracy of executing transformations Q of the input signal (accuracy of describing the remote pilot's activity by the Q operator within the time interval $[0,t]$). In this case, $Q = \text{Const}$, $R = \text{Const}$.

Based on the experimental results, the dependency $M_t = t(\varepsilon)$ was constructed and depicted in Fig. 6. From the provided dependency, it can be inferred that it has a linear nature, and with an increase in the accuracy ε, in the model of the operator's activity for the remote pilot the maximum value of the mathematical expectation M_t of transition time from one state to another increases.

The ***QR-characteristic*** occurs at the level of awareness, which is the highest level of human intellectual activity. It encompasses the levels of URA, CRA, and HA and serves as the mechanism for controlling and adjusting operative UAV control tasks. This level encompasses willpower, purposefulness, and decision-making. The formalizing this level is quite challenging due to its individuality in each person. However, awareness unites the previous three levels, which is why its influence should be conducted through perception, images, and intellect (Fig. 1, Fig. 2). The level of awareness acts as a correcting and controlling link at all levels of mental activity. It is the result of labour, so only after accumulating sufficient experience does the remote pilot begin to consciously control the UAV, acquiring components such as freedom, purposefulness, and awareness of necessary behaviour.

This characteristic depends on the coefficient $K = \lambda_{2,3}^{RP}$ of the Q operator and the coefficient $K_1^* = \mu_{3,1}^{RP}$ of the operator observing the signal R. In this case, $\varepsilon = \text{Const}$. Based on the experimental results, the surface of the function $M_t = t(K, K_1^*)$ was constructed and depicted in Fig. 7.

According to Fig. 3, this dependence is quite complex and exhibits pronounced extrema. This statement highlights the need for a careful approach to organizing the operational activity of the remote operator. Thus, the choice of the operating point on the characteristic with a high and sharp maximum value of the mathematical expectation time M_t strongly depends on the fluctuations of the parameters K and K_1^*. This means that the functioning time of the entire system with a given quality is highly sensitive to changes in the corresponding parameter. To ensure more favourable conditions for the entire system's operation, it is necessary to adjust (if possible) the parameters of the ground control station interface and the operator's training level (K, K_1^*) in such a way that the remote operator works not at a critical maximum but at a more stable and less sensitive maximum, which also satisfies the condition for the integral system's existence. Thus, the nonfailure execution time of transformations t must be no less than the time required to solve the task assigned to the system. The time t was measured until the first error of the remote pilot, that is, until the equilibrium was disrupted at the given value of ε.

Conclusions

The article examines the psychophysiological features of the remote pilot in UAV control loop, and these features are summarized in the form of a functional model of the remote pilot's intellectual activity. This allowed the authors to develop a mathematical model of the remote pilot's operational activity in UAV control from the perspective of a queuing system. This stochastic mathematical model of deterministic states of the remote pilot's intellectual activity in UAV control formalizes the processes of information perception, processing, and decision-making as states of a queuing system.

The model enables analysis of the time costs of the remote pilot in executing the processes of reading and processing telemetry information and making decisions on UAV control, taking into account the peculiarities of human intellectual activity.

Furthermore, this model serves as the basis for an improved mathematical model, "Generalized Performance Characteristic of the Remote Pilot," by introducing a new basis – operators of the remote pilot's activity – as a queuing system. This allows for the examination of the system characteristics of operational activity in the "remote pilot – UAV" system during UAV control.

The model of operator activity in the form of a generalized performance characteristic has a significant advantage over the known ones, since it directly takes into account a very important parameter of the model, namely, the lifetime of this model. This allows a more flexible use of the model of operator activity in the analysis of the psychophysiological characteristics of a remote pilot and in the organization of education and training of future remote pilots.

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МОДЕЛІ ОПЕРАТОРСЬКОЇ ДІЯЛЬНОСТІ ВІДДАЛЕНОГО ПІЛОТА БПЛА

Вступ. Безпілотні літальні апарати (БПЛА) стали невід'ємною частиною сучасних технологій та знаходять застосування у різних галузях, починаючи від військових операцій та цивільної авіації, й закінчуючи сільським господарством та екологічним моніторингом. Використання БПЛА дає змогу виконувати складні завдання без прямої участі пілота на борту, що відкриває нові можливості та привносить суттєві переваги до багатьох областей. Проте ця нова форма авіації також має власні виклики і вимагає особливої уваги до психофізіологічних особливостей віддаленого пілотування та його впливу на операторів.

Мета статті. У цій статті розглянуто особливості діяльності віддаленого пілота БПЛА та його психофізіологічні характеристики, запропоновано моделі його операторської діяльності. Це уможливить краще розуміння вимог і викликів, з якими стикаються оператори, та позначить напрями для подальших досліджень і розробок у цій галузі.

Методи. Для розробки математичної моделі операторської діяльності віддаленого пілота БПЛА використовувалися методи теорії масового обслуговування. При вдосконаленні моделі узагальненої робочої характеристики використовувалися методи теорії ймовірності. Експериментальні залежності на основі узагальненої робочої характеристики віддаленого пілота було отримано завдяки комп'ютерному моделюванню з використанням чисельних методів. Для аналізу отриманих залежностей використовувалися методи теорії автоматичного керування.

Результат. За підсумками аналізу психофізіологічних особливостей діяльності віддалених пілотів БПЛА запропоновано набір моделей операторської діяльності. Розроблено функціональну модель інтелектуальної діяльності, математичну модель операторської діяльності як систему масового обслуговування, а також удосконалено математичну модель «Узагальнена робоча характеристика віддаленого пілота».

Висновки. Запропоновані у статті моделі операторської діяльності вирішують комплекс питань щодо інтегральної оцінки діяльності віддаленого пілота в контурі управління БПЛА. Дані моделі формалізують процеси сприйняття інформації, її обробки та прийняття рішення з керування, що дає змогу аналізувати тимчасові витрати віддаленого пілота БПЛП на здійснення процесів зчитування та обробки телеметричної інформації й прийняття рішення з керування БПЛА з урахуванням особливостей інтелектуальної діяльності людини, а також уможливлює дослідження системних характеристик операторської діяльності в системі «віддалений пілот-БАС» під час керування БПЛА. Модель операторської діяльності у формі узагальнено робочої характеристики має істотну перевагу перед відомими, тому що безпосередньо враховує дуже важливий параметр моделі, а саме час існування цієї моделі. Це уможливлює гнучкіше використання моделі операторської діяльності при аналізі психофізіологічних характеристик віддаленого пілота й організації навчання та тренування майбутніх віддалених пілотів.

Ключові слова: *віддалений пілот, БПЛА, узагальнена робоча характеристика, психофізіологічні особливості, інтелектуальна діяльність, людський фактор, система масового обслуговування.*