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INTELLECTUAL SYSTEM FOR RESEARCHING FUNCTIONAL RELIABILITY OF FLIGHT CREW MEMBERS. Part I*

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The specifics of the professional activity of a military pilot imposes very serious requirements on his functional reliability. During the flight, the pilot's body is subjected to intense multidirectional extreme influences. In aviation, the human factor plays an important role, and a potential human error can lead to an accident or even a catastrophe. The professional activity of a military pilot takes place in a combination of extreme disturbances of the internal and external environment and the need to make decisions in conditions of increased situational tension. There are a large number of mathematical models of behavioral

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reactions of flight crew members when controlling an aircraft, they are divided into three main groups — based on control theory, based on physiology and based on artificial intelligence. Typically, models based on physiology reflect the mental and psychophysiological components of the pilot's functional reliability, which, of course, is very important, but do not take into account the fact that the success of the pilot's actions will be determined by the functional reserves of his body during a stressful situation. The work contains a mathematical model of the functional respiratory system, which allows one to evaluate the current functional state of an individual's body while simulating the work of professional military personnel activities on the flight simulator. The model makes it possible to identify ongoing compensatory physiological reactions and, therefore, the number of members of crews adapt to extreme pressures when simulating professional activities in the minds of hypoxic hypoxia. Prediction of human behavior during the course of flight and similar modeling of the pilot's behavioral reactions can eliminate or change the negative consequences that result from the human factor in aviation.

Keywords: functional reliability of pilots, mathematical model of regulation of oxygen regimes in the body, adaptation to extreme storms.

Introduction

Human error is one of the most important factors contributing to serious accidents. In [1] provides an overview of human reliability analysis (HRA) methods that have been successfully used in many industries to determine the probability of errors contributing to such accidents, assess the impact of their consequences, and develop error reduction strategies. This study describes some HRA methods and their implementation in several industries, including marine, aviation, railway, space, healthcare, nuclear, petrochemical, and construction industries. Human reliability is defined as the ability of an employee to correctly perform the actions required to complete the overall task, at the specified time, and to avoid any actions that may disrupt the functioning of the system [2, 3]. The definition of human reliability is accepted as a guideline for preventing accidents caused by human errors [4].

If we consider the aircraft-pilot-environment system from the perspective of reliability theory [5] and present its model in the form of a chain with a weak link, it is quite obvious that such a «weak link» is the pilot. Due to the peculiarities of professional activity, special requirements are imposed on him, which at certain stages of professional activity exceed his physiological and psycho-emotional functional capabilities. The professional activity of flight personnel occurs under the combined influence on the body of external (hypoxic environment, change in temperature) and internal (decision-making in conditions of increased situational tension, circulatory hypoxia associated with loads) disturbing influences. The study of the relationships between various human factors and flight characteristics or activities related to flight safety is therefore an important research area. First of all, specialists must have qualities that contribute to flight safety [6]; these include, above all, spatial orientation, coordination of movements, motivation, stress resistance, cooperation skills, responsibility and leadership skills. The requirements for pilot groups form another specific area, where communication, coordination and resistance to monotony and stress are skills that every transport pilot must master. In contrast, fighter pilots must demonstrate a high speed of perception and resistance to overload and time stress.

The decrease in the functional reliability of flight crew members can be due to a number of reasons (biomechanical, physiological, psychophysiological, psychological, organizational and methodological), which in the absence of special means of optimizing the functional state of the pilot lead to the failure of the entire system.

It should be noted that a significant factor in flight safety is, on the one hand, the pilot's ability to respond adequately and in a timely manner to situations that arise through no fault of his, on the other hand, the pilot himself can make mistakes during piloting that cannot always be eliminated.

Unfortunately, in available sources [7] little attention is paid to the functional state of the body as a component of the functional reliability of flight crew members, more attention was paid to the quality of control and flight safety, which were considered as the result of the pilot's interaction with the aircraft. Review articles [8–16] show how much effort was put into developing precisely such models that consider the human-aircraft connection. Human-pilot models describe control behavior in order to understand how a person controls an aircraft. The purpose of the models is to analyze the characteristics of the pilot-aircraft system, that is, to analyze the relationships between the aircraft and the pilot.

In studies of human control of dynamic systems such as aircraft, the goal is to generalize behavioral data, provide a basis for understanding the pilot's behavior during control, and, above all, use them together with aircraft dynamics to form predictions of the behavior of the pilot/aircraft system Pilots have certain regular behavioral control patterns that usually correspond to a universal model of human behavior. Rasmussen [17] summarized the characteristics of human control behavioral patterns at three levels (Fig. 1).

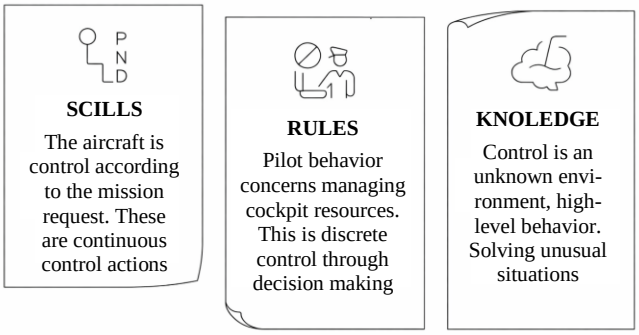


Fig. 1

There are three general approaches to pilot behavior modeling [7, 11, 12, 17–29], these approaches are graphically displayed in Fig. 2.

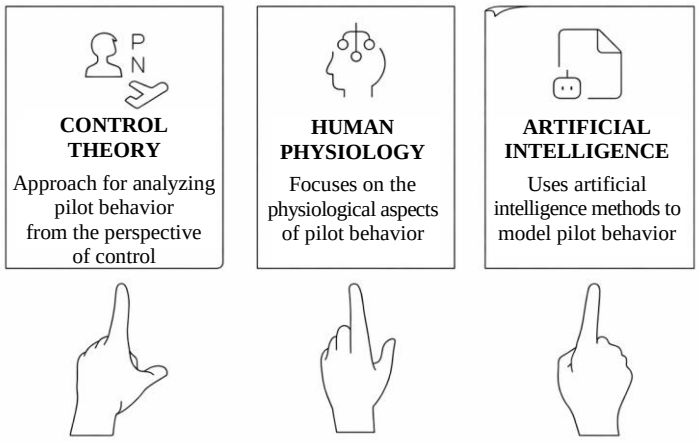


Fig. 2

In flight, the main task is to adapt to unusual circumstances, such as emergency decision-making to avoid dangerous flight zones [17]. The above types of models focus on the pilot's behavior, which is based on skills, which are used to provide accurate

tracking of the pilot and analyze the interaction of the pilot with the aircraft, especially in fly-by-wire manual control systems. As a means of understanding and evaluating the qualities of controllability, this modeling technology provides useful information about the actions of the manual control.

Existing models of the human pilot, based on physiology, cover such areas as the central nervous system, the neuromuscular system, the visual system, and the vestibular apparatus. They reflect the dynamics of the human sensory and control effectors.

The structural model of the pilot [12] was developed to understand the perception and behavior of the pilot during control, it takes into account the additional internal loop generated by the pilot as a result of his response to the kinesthetic signal. The inner loop of the model is a feedback loop for velocity and can be used to describe the adaptive behavior of a human pilot to the dynamics of the aircraft.

To understand the influence of the visual and vestibular systems on the behavior of a human pilot, a descriptive model was developed to simulate the behavior of a pilot during a tracking task [11, 24, 25].

The biodynamic model reflects the influence of how the body moves in an accelerated environment. It can provide predictions of the effects of movement on human health, comfort or performance [11], in particular vibration.

A separate review article [22] should be highlighted, which provides an overview of the current state of virtual pilot modeling. A virtual pilot is a mathematical model of the behavioral responses of a professional pilot performing a vehicle piloting task. These models are fundamental for implementing closed-loop simulations. The models presented in this article are divided into frequency and time-based models, and for each of them the advantages and disadvantages are discussed to help choose the appropriate model for a given task. In the author's opinion, time-based models are more adaptive and suitable for online characteristics, while frequency-based models are easier to adjust, but in manual mode.

All these models reflect the mental and psychophysiological components of the pilot's functional reliability, which, of course, is very important, but they do not take into account the fact that the success of the pilot's actions will be determined by the functional reserves of his body during a stressful situation. In [30, 31] it is shown on the basis of the reliability theory that if the human body is presented as a chain with a «weak link», then such a link will be the functional respiratory system.

The ability of a human/pilot to fly an aircraft is to process large amounts of information and translate it into appropriate movements of the aircraft controls (the fork, pedals, and throttle lever). This information can change suddenly, its level of importance can change, and it can often change with an inappropriate signal-to-response ratio. The ability of a human/pilot to receive and process input is also significantly limited by the specific flight situation in which the pilot receives this information (quiet flight, complex flight, aerobatic flight, etc.). The pilot's greatest enemy is the lack of time to process all the input. This results in time delays, sometimes quite long, between the point of the initial input signal and the pilot's corresponding response to that input signal.

In [30, 32], a mathematical model of the functional respiratory system shows that even a slight increase in the oxygen demand of brain tissue requires a nonlinear increase in the work of compensatory self-regulation organs — respiratory and cardiac muscles, even without taking into account circulatory hypoxia, which occurs during overload.

That is why, first of all, to determine the functional reliability of flight personnel, one should take into account the possibilities of adapting their respiratory system to the combined effects of extreme disturbances when performing professional loads.

The article [6] summarizes the results of many years of development and modeling. Based on knowledge about human behavior during an airplane flight from the point

of view of flight automation, options for obtaining parameters with which a pilot's behavior model can be built are described. The results of experimental tests are presented, which are a study of the pilot's reaction to a visual stimulus, and also partially to a motion stimulus — a step change in flight altitude, where the pilot's task is to return the flight to the initial flight altitude as quickly as possible. Then, an analysis of the pilot's reaction is presented, obtained as a result of many tests on two simulators (stationary and mobile). The authors conducted many tests on flight simulators, obtaining the necessary data to identify the parameters of the transfer functions for the pilot's behavior model. These parameters are used as input for the mathematical model of the pilot's behavioral reactions [33]. If a sufficient amount of test data from a particular pilot is obtained on a flight simulator (Fig. 3), it is possible to determine statistical errors in the development of the pilot's behavior during the flight of the aircraft, determine the level of his training, fatigue, lack of concentration, etc. Predicting human behavior during the flight of the aircraft is mandatory for the successful reduction of the undesirable impact of the human factor in air transport. Predicting human behavior during the flight of the aircraft is mandatory for the successful reduction of the undesirable impact of the human factor in air transport.

The authors [34], based on the obtained test data and the created models of pilot behavior, conducted a statistical analysis, focusing on comparing the time constants of the transfer function for the pilot's behavior model with information on the pilot's professional qualities. Such data include: the training phase, the level of training of individual groups of pilots, the number of real flight hours, the actual level of theoretical knowledge. Also, the relationships between these parameters and time constants were revealed, the stage of pilot training and their experience were assessed. All these data have a graphical and tabular interpretation.

The authors of the development emphasize that changes in parameters over time, depending on the level of training, indicate the possibility of providing relevant information about the impact of training on pilots. Conversely, statistical assessment of pilot parameters at different stages of training provides useful data on the capabilities or abilities and limitations of a human controller to perform a specific task. Such knowledge is also important for the purposes of general modeling of human behavior. It is concluded that the engineering installation of a flight simulator can serve as a test station for assessing the current state of the pilot. in conditions that are as close as possible to the conditions of a training flight and real flight mode. The parameters of the transfer function make it possible to determine whether the pilot is fit to fly or needs further training. These parameters are quite easy to obtain and relate to the parameters that determine the functional state of a person during training on a flight.

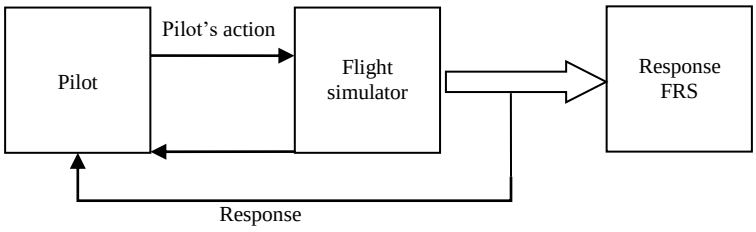


Fig. 3

Similarly, the simulator can measure indicators to determine the current state of the functional respiratory system.

In [33], an algorithm for studying the pilot's behavioral reactions on a simulator is described. To obtain the values of the time constant v, it is necessary to test/measure the pilot's reactions to a predetermined aircraft movement, and then pass the obtained reactions using the appropriate mathematical algorithms — identifications. The scheme of the complex is shown in Fig. 4.

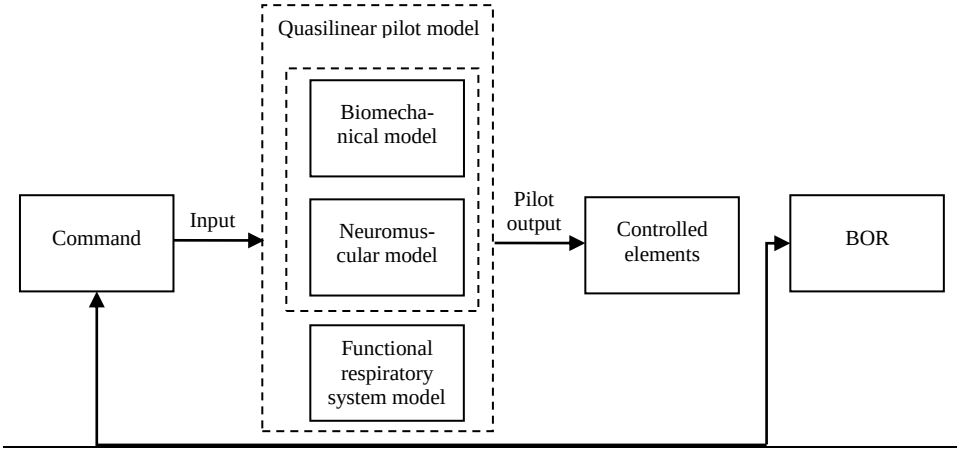


Fig. 4

The analysis of the pilot's behavioral reactions data according to the specified algorithm is carried out according to the scheme shown in Fig. 5

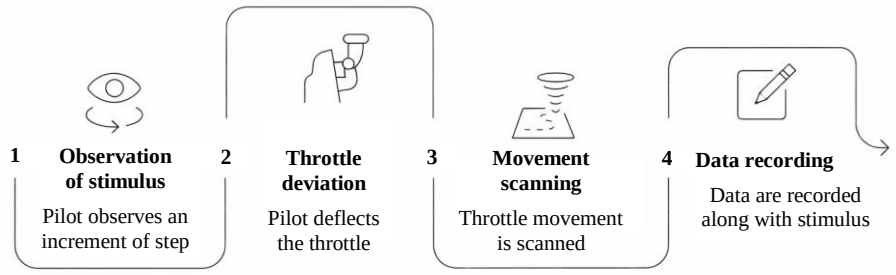


Fig. 5

The initial idea of measuring the pilot's response to a suitable stimulus that would at least partially reflect the flight control is given in [33]. This approach can be described by the schematic diagram in Fig. 6.

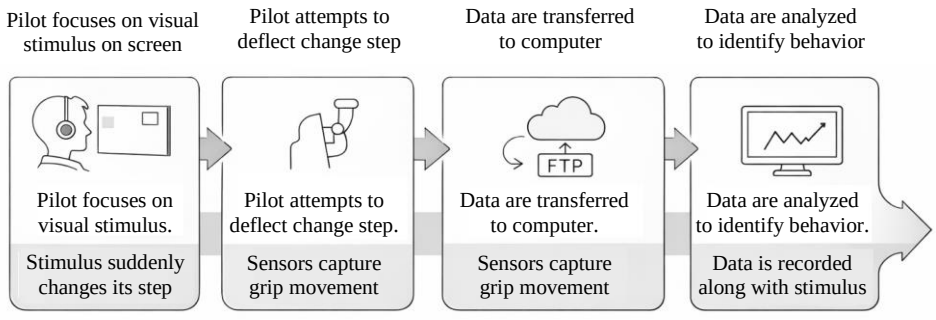


Fig. 6

The following basic mathematical model of the dynamic characteristics of the pilot is proposed [34].

$$F_{(p)} = K\frac{(T_3 p+1)}{(T_1 p+1)(T_2 p+1)}e^{-\tau p}, \quad (1)$$

where $F_{(p)}$ — transfer function; K — pilot gain coefficient, reflecting the pilot's habits for a given type of aircraft control. If the pilot does not intervene for too long or during the adjustment process there is a sudden change in the system gain, the system may become unstable. It is measured as an increase in the force on the rudders relative to their

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deviation (from 1 to 100); T_1 — delay time constant, associated with the implementation of learned stereotypes and pilot procedures. When a pilot repeats certain situations several times, this leads to stereotypes and learned habits. This causes the pilot to gradually lose the activity of his brain; T_2 — neuromuscular delay time constant reflects the pilot's delay in his activity, caused by the neuromuscular system. The neuromuscular system includes muscles and sensory organs operating at the level of the spinal cord (spinal cord). The brain receives information through the spinal cord and then reacts to the external environment. The central nervous system and the peripheral nervous system provide the body's information connections with the external environment and continuously regulate processes in the body. T_3 — the lead time constant is related to the pilot's experience. It reflects the pilot's ability to anticipate control inputs in the near future, that is, to anticipate a situation that may arise. Assessing and predicting the future situation is the ability to plan future steps in the surrounding circumstances. This level represents the highest level of situational awareness. The pilot has knowledge of the state and dynamics of individual system elements. He also has the ability not only to understand the current situation, but also to predict the future situation. The pilot acquires this ability through training and experience. — a time constant that indicates the delay between the perception by the eye and the brain's reaction through the pilot's musculoskeletal system. This transport delay depends on the current state of the neuromuscular system, as well as the physical and mental state of the pilot. Fatigue can significantly increase the delay in transportation, and the regulatory system can become unstable.

To determine the functional reliability of the respiratory system of flight personnel, a simple but quite informative model of the respiratory system can be used — regulation of oxygen regimes of the human body [35, 36]. The use of such an approach seems possible if the simulator is equipped with the equipment necessary for functional diagnostics Fig. 7.

The following indicators of the respiratory system are determined — lung ventilation, gas composition of exhaled and alveolar air, respiratory rate, heart rate, blood pressure, etc. These data can be input for calculating the parameters of the respiratory system when the pilot works on the simulator. It is planned to calculate more than fifty indicators that characterize the economy, efficiency, intensity of the body's oxygen regimes, data on oxygen transport at individual stages of its path in the body (upper respiratory tract, alveolar space, arterial blood, mixed venous blood). To process and analyze the information received, an automated information system was developed, which is based on a mathematical model of the regulation of the body's oxygen regimes (BOR).

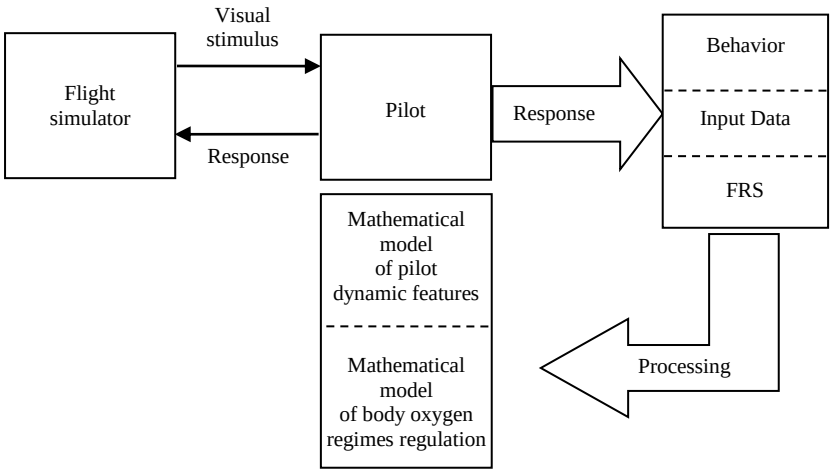


Fig. 7

The mathematical model of regulation of oxygen regimes of the organism is based on the concept according to which two groups of parameters are interconnected in the human body — the speed of oxygen transport and its partial pressures and tensions at the main stages of the path in the organism (lungs, alveoli, arterial blood, mixed venous blood). Analysis of the combination of these two groups of parameters allows us to characterize the function of the system of providing the organism with oxygen quantitatively and qualitatively. The algorithm of the BOR model is shown in Fig. 8.

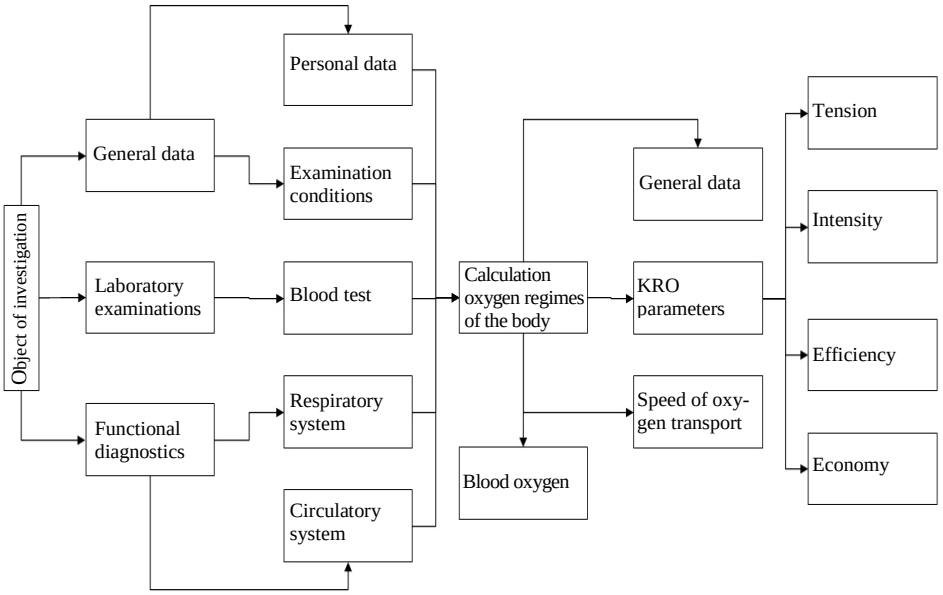


Fig. 8

Fig. 9 shows the structural hierarchy of the physiologist's automated workplace

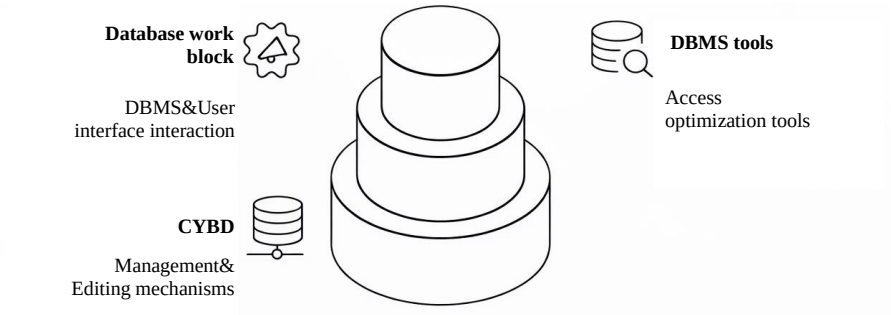


Fig. 9

The system works as follows. After logging into the system at the laboratory assistant's workplace, general data about the subject is entered, such as last name, age, qualification, height and body weight. The system automatically forms groups by age or qualification. Then, applications for examination of a certain group on a date are formed on the physiologist's AWP. The full algorithm is shown in Fig. 10

Fig. 11 presents information system diagram.

The central block is the main menu, which is determined by the tasks of the user's workstation. All the Help, Help, and Exit blocks are common to both workstations. In other blocks, there is a division depending on the tasks solved by this workstation.

Thus, in particular, the mathematical problem solution block does not participate in the work of the laboratory assistant and is exclusively part of the physiologist's workstation, as well as the regular data entry and personal data entry blocks

for the laboratory assistant's workstation. On the other hand, the report saving, results submission, and output data saving blocks work for the workstations according to the same principle, but with different data.

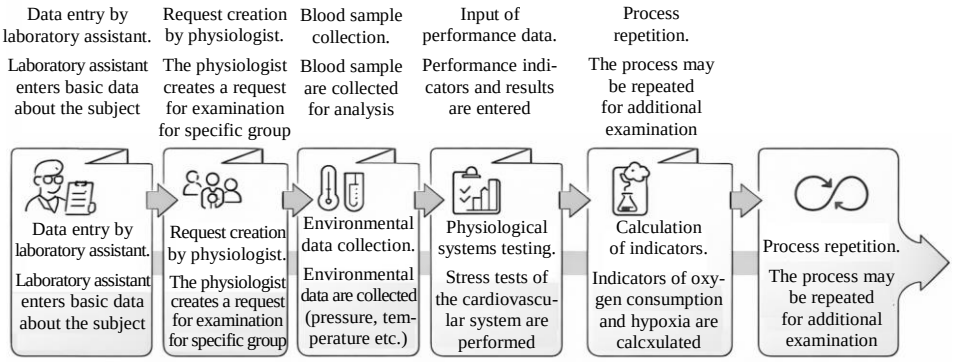


Fig. 10

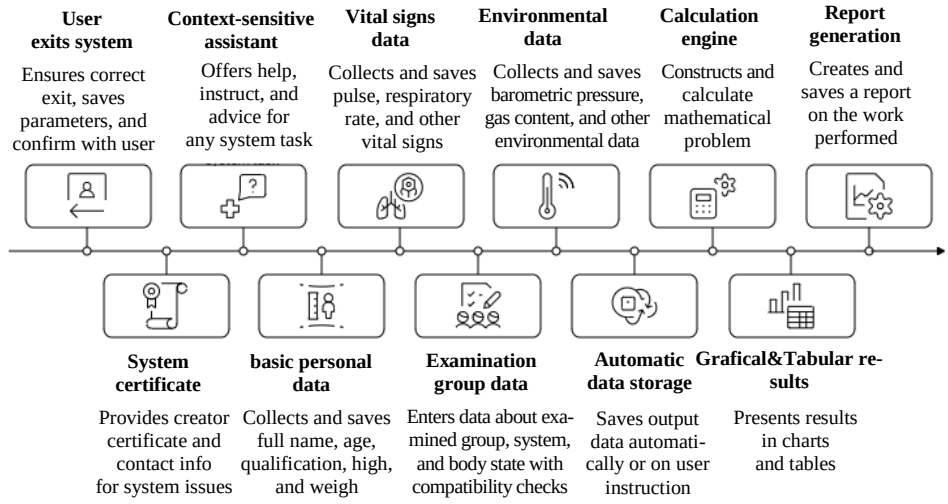


Fig. 11

Unlike existing developments, this system should primarily contain means for processing and saving individual data, and also contain information on the results of professional training.

The system should contain three «working» places (Fig. 12), two of which are fully automated, information comes directly from the sensors, only manual entry of blood parameters (hemoglobin, acidity, oxygen and carbon dioxide tension) is required.

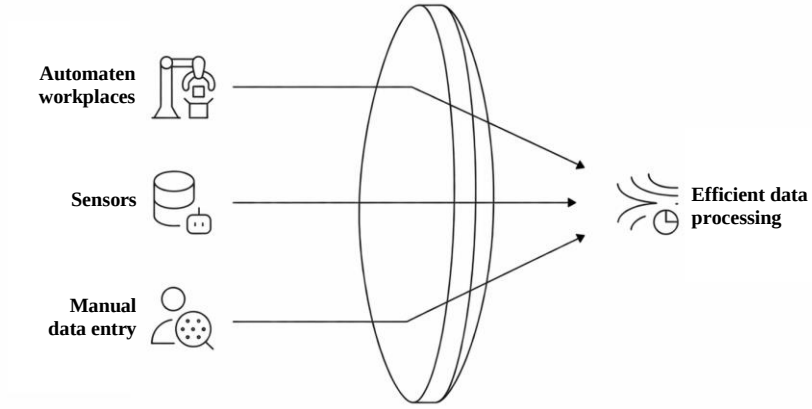


Fig. 12

Systematic accumulation of data, their systematization with subsequent processing and analysis provide the ability to recognize and objectify the characteristics of a large number of persons being examined, make it possible to track the dynamics of changes in the main indicators in the process of general physical training, which contributes to the improvement of the body and the development of general physical qualities and special training, which is professionally oriented and aimed primarily at increasing the body's resistance, as well as track the dynamics of changes in the main parameters of the respiratory and circulatory systems of flight crew members (Fig. 13).

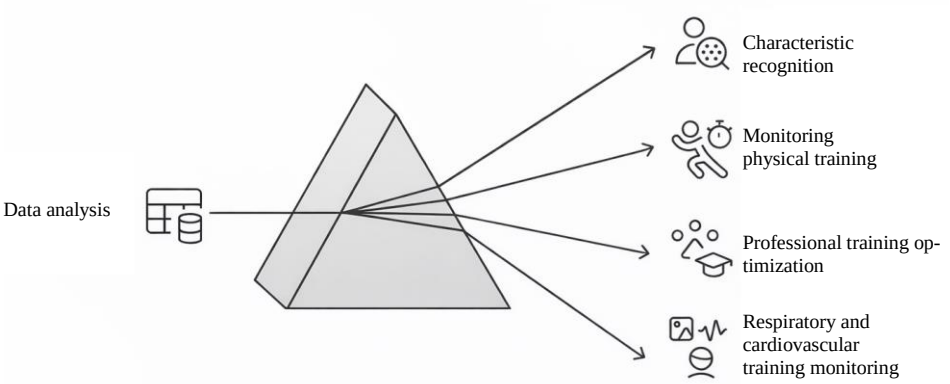


Fig. 13

To improve the means and methods of operational collection, processing and analysis of data of a comprehensive study based on the Interbase 7 DBMS and the Delphi programming system, an automated information system (AIS) was developed and implemented, which allows: to significantly accelerate the processing of data obtained during the examination, to implement a diagnostic algorithm for assessing the functional state of flight personnel, to centrally accumulate information for its preliminary processing, storage and collective use; to create an algorithmic apparatus to ensure the possibility of proving scientific propositions, developing options for optimizing solutions when assessing professional suitability or forming crews Fig. 14.

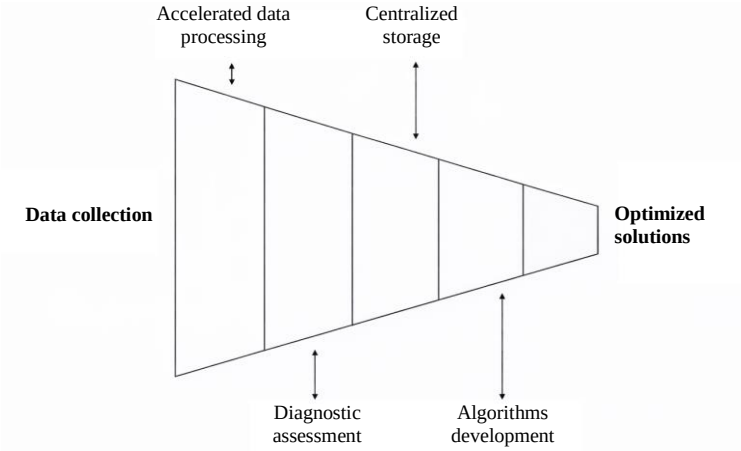


Fig. 14

The data obtained as a result of the model of regulation of the body's oxygen regimes will provide information on the current functional state of flight personnel when performing their professional activities. These data can be correlated with data obtained using the basic mathematical model of the pilot's dynamic characteristics.

Accumulation of structured information in the database provides effective means for: collective use of information in multi-user mode; obtaining information on all information arrays or on individual fragments, including on an arbitrary set of conditions set by the user; constructing series of values of indicators from the database structure and transferring them for statistical processing of results; automating the process of evaluating test results with subsequent integration of indicators of various aspects of preparedness; forming source documents, tables, graphs, reports, histograms for different categories of users; conducting a retrospective analysis of the training of flight crew members who have achieved significant results in special training to generalize psychological, physiological, sociological factors, experience of initial basic training, which provided the foundation and growth of professional skills (Fig. 15).

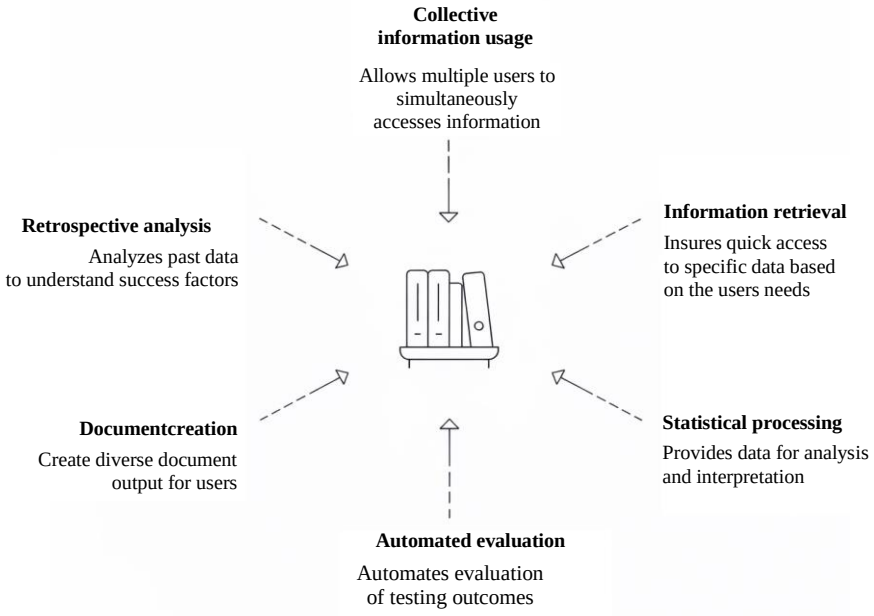


Fig. 15

This information is also input for the mathematical model of the functional respiratory system, which makes it possible to predict the process of adaptation of the body of flight crew members to internal and external disturbing influences in accordance with their specialization.

Conclusion

When determining the functional reliability of flight crew members, it is necessary to take into account, on the one hand, personal characteristics, such as speed, the ability to perceive and process information under various disturbing influences, reliability and accuracy of actions, psychophysiological stability, and, on the other hand, the ability of functional respiratory and circulatory systems to adapt to extreme internal and external disturbing influences that accompany the professional activities of flight crew members. The proposed complex makes it possible to track the behavioral reactions of the pilot under the complex influence of hypoxic hypoxia conditions and increased situational stress when making decisions. Further research in this area involves more experimental tests with a large group of pilots, obtaining, analyzing and comparing changes in pilot parameters over time and changes depending on the level of training. Further research will also include the use of more advanced models of human behavior or the use of other types of simulators. The proposed engineering installation of the flight simulator can be used to assess the current state of the pilot. Also, the data obtained on the current functional state of flight crew members can be used in the future as input for predicting the regulatory reactions of their functional respiratory system when simulating certain disturbances.

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ІНТЕЛЕКТУАЛЬНА СИСТЕМА ДОСЛІДЖЕННЯ ФУНКЦІОНАЛЬНОЇ НАДІЙНОСТІ ЧЛЕНІВ ЛЬОТНИХ ЕКІПАЖІВ. Частина 1

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Специфіка професійної діяльності потребує від військового льотчика високого рівня функціональної надійності, оскільки у процесі польоту його організм зазнає інтенсивного різноспрямованого екстремального впливу. В авіації людський фактор відіграє важливу роль, і потенційна людська помилка може призвести до аварії або навіть катастрофи. Професійна діяльність військового льотчика відбувається за обставин, коли екстремальні збурення внутрішнього та зовнішнього середовища поєднуються з необхідністю приймати рішення в умовах підвищеної ситуаційної напруги. Існує велика кількість математичних моделей щодо поведінкових реакцій членів льотних екіпажів під час керування літаком, які можна розподілити на три основні групи, що ґрунтуються на теорії керування, фізіології та штучному інтелекті відповідно. Зазвичай моделі, засновані на фізіології, відображають психічну та психофізіологічну компоненти функціональної надійності пілота, що, звісно, є дуже важливим, але у них зовсім не враховується той факт, що успішність дій льотчика буде обумовлюватися функціональними резервами його організму під час стресової ситуації. У статті запропоновано математичну модель функціональної системи дихання, за допомогою якої у осіб льотного складу оцінюється поточний функціональний стан організму за умови імітації здійснення ними професійної військової діяльності на авіасимуляторі. Модель дає можливість відстежити поточні компенсаторні фізіологічні реакції і, відповідно, здатність членів

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льотних екіпажів адаптуватися до екстремальних навантажень у разі імітації професійних дій за умови гіпоксичної гіпоксії. Прогнозування поведінки людини під час керування літаком та відповідне моделювання поведінкових реакцій пілота можуть сприяти запобіганню або зменшенню негативних наслідків, що виникають через людський фактор в авіації.

Ключові слова: функціональна надійність льотчиків, математична модель регулювання кисневих режимів організму, адаптація до екстремальних збурень.

REFERENCES

1. Yalçın E., Ciftcioglu G., Güzel B. Human reliability analysis methods. *Pamukkale University Journal of Engineering Sciences*. 2024. Vol. 30, N 2. P. 282–292. DOI: https://dx.doi.org/10.5505/pajes.2023.33958
2. Emami K.H. Human reliability data banks. *International Journal of Occupational Hygiene*. 2019. Vol. 11, N 3. P. 232–246. URL: https://ijoh.tums.ac.ir/index.php/ijoh/article/view/416
3. Applying analytic hierarchy process (AHP) to choose a human factors technique: choosing the suitable human reliability analysis technique for the automotive industry / A. Petruni, E. Giagloglou, E. Douglas, J. Geng, M.C. Leva, M. Demichela. *Safety Science*. 2019. Vol. 119. P. 229–239. DOI: https://doi.org/10.1016/j.ssci.2017.05.007
4. A bibliometric analysis of human reliability research / J. Tao, D. Qiu, F. Yang, Z. Duan. *Journal of Cleaner Production*. 2020. Vol. 260. ID: 121041. 11 p. DOI: https://doi.org/10.1016/j.jclepro.2020.121041
5. Lloyd D.K., Lipov M. Reliability: organization of research, methods, mathematical apparatus. M. : Publishing House «Soviet radio», 1964. 699 p. (in Russian). URL: https://ikfia.ysn.ru/wp-content/uploads/2018/01/LlojdLipov1964ru.pdf
6. Boril J., Jirgl M., Jalovecky R. Using aviation simulation technologies for pilot modelling and flight training assessment. *Advances in Military Technology*. 2017. Vol. 12, N 1. P. 147–161. DOI: https://doi.org/10.3849/aimt.01179
7. Review of control models for human pilot behaviour / S. Xu, W. Tan, A.V. Efremov, L. Sun, X. Qu. *Annual Reviews in Contro*l. 2017. Vol. 44. P. 274–291. DOI: https://doi.org/10.1016/j.arcontrol.2017.09.009
8. Entzinger J.O. The. role of binocular cues in human pilot landing control. *Proceedings of the Thirteenth Australian International Aerospace Congress (AIAC13)*. Australia : Melbourne, 09–12 March 2009. 15 p.
9. Gerlach O.H. Developments in mathematical models of human pilot behaviour. *The Aeronautical Journal*. 1977. Vol. 81, N 799. P. 293–305. DOI: https://doi.org/10.1017/S000192400003284X
10. Grant P., Schroeder J. Modeling pilot control behavior for for flight simulator design and assessment. *AIAA Modeling and Simulation Technologies Conference*. Canada : Toronto; Ontario; 02–05 August 2010. 33 p. DOI: https://doi.org/10.2514/6.2010-8356
11. Griffin M.J. The validation of biodynamic models. *Clinical Biomechanics (Bristol*). 2001. Vol. 16. Suppl. 1. P. S81–S92. DOI: https://doi.org/10.1016/S0268-0033(00)00101-7
12. Hess R.A. Feedback control models — manual control and tracking. *Handbook of Human Factors and Ergonomics* / ed. by G. Salvendy. 2nd ed. New York : Wiley and Sons, Inc., 1997. P. 1249–1294.
13. Lone M., Cooke A. Review of pilot modelling techniques. *48th AIAA Aerospace Sciences Meeting Including the New Horizons Forum and Aerospace Exposition.* USA : Orlando, 04–07 January 2010. 16 p. DOI: https://doi.org/10.2514/6.2010-297
14. McRuer D.T., Jex H.R. A review of quasi-linear pilot models. *IEEE Transactions on Human Factors in Electronics*. 1967. Vol. HFE-8, N 3. P. 231–249. DOI: https://doi.org/10.1109/THFE.1967.234304
15. Palmer J. Large scale systems: systems, man, and cybernetics overview. *IEEE Transactions on Circuits and Systems*. 1983. Vol. 30, N 6. P. 340–347. DOI: https://doi.org/10.1109/TCS.1983.1085375
16. Adverse rotorcraft pilot couplings — past, present and future challenges / M.D. Pavel, M. Jump, B. Dang-Vu, P. Masarati, M. Gennaretti, A. Ionita, L. Zaichik, H. Smaili, G. Quaranta, D. Yilmaz, M. Jones, J. Serafini, J. Malecki. *Progress in Aerospace Sciences*. 2013. Vol. 62. P. 1–51. DOI: https://doi.org/10.1016/j.paerosci.2013.04.003
17. Rasmussen J. Skills, rules, and knowledge: signals, signs, and symbols, and other distinctions in human performance models. *IEEE Transactions on Systems, Man, and Cybernetics*. 1983. Vol. SMC-13, N 3. P. 257–266. DOI: https://doi.org/10.1109/TSMC.1983.6313160

18. McRuer D.T., Graham D., Krendel E.S. Manual control of single-loop systems: part I. *Journal of the Franklin Institute*. 1967. Vol. 283, N 1. P. 1–29. DOI: https://doi.org/10.1016/0016-0032(67)90112-3
19. McRuer D.T., Graham D. Pilot-vehicle control system analysis. *Guidance and Control* – II / ed. by R.C. Langford, C.J. Mundo. *Progress in Astronautics and Rocketry*. New York : Academic Press, 1964. Vol. 13. P. 603–621. DOI: https://doi.org/10.1016/B978-0-12-395587-6.50025-9
20. Kleinman D.L., Baron S., Levison W.H. An optimal control model of human response part I: theory and validation. *Automatica*. 1970. Vol. 6, N 3. P. 357–369. DOI: https://doi.org/10.1016/0005-1098(70)90051-8
21. Baron S., Kleinman D.L., Levison W.H. An optimal control model of human response part II: prediction of human performance in a complex task. *Automatica.* 1970. Vol. 6, N 3. P. 371–383. DOI: https://doi.org/10.1016/0005-1098(70)90052-X
22. Roncolini F., Quaranta G. Virtual pilot: a review of the human pilot's mathematical modeling techniques. *Aerospace Europe Conference 2023: Joint 10th EUCASS — 9th CEAS Conference.* Switzerland : Lausanne, 9–13 July 2023. 14 p. DOI: https://doi.org/10.13009/EUCASS2023-589
23. Hess R.A. A rationale for human operator pulsive control behavior. *Journal of Guidance and Control*. 1979. Vol. 2, N 3. P. 221–227. DOI: https://doi.org/10.2514/3.55864
24. Hosman R. Pilot's perception and control of aircraft motions : PhD thesis, Faculty of Aerospace Engineering, Delft University of Technology. Holland : Delft University Press, 1996. 160 p.
25. Hosman R., Stassen H. Pilot's perception in the control of aircraft motions. *Control Engineering Practice.* 1999. Vol. 7, N 11. P. 1421–1428. DOI: https://doi.org/10.1016/S0967-0661(99)00111-2
26. Scibilia A., Pedrocchi N., Fortuna L. Human control model estimation in physical human-machine interaction: a survey. *Sensors (Basel*). 2022. Vol. 22, N 5. ID: 1732. 26 p. DOI: https://doi.org/10.3390/s22051732
27. Gestwa M., Bauschat J.M. On the modelling of a human pilot using fuzzy logic control. *Computational Intelligence in Control* / M. Mohammadian, R.A. Sarker, X. Yao. Hershey; London; Melbourne; Singapore; Beijing : Idea Group Publishing, 2003. P. 148–167. DOI: https://doi.org/10.4018/978-1-59140-037-0.ch009
28. Extracting fuzzy control rules from experimental human operator data / G.A. Zapata, R. Kawakami, H. Galvao, T. Yoneyama. *IEEE Transactions on Systems, Man, and Cybernetics. Part B: Cybernetics.* 1999. Vol. 29, N 3. P. 398–406. DOI: https://doi.org/10.1109/3477.764875
29. Wenqian T., Efremov A.V., Xiangju Q. A criterion based on closed-loop pilot-aircraft systems for predicting flying qualities. *Chinese Journal of Aeronautics*. 2010. Vol. 23, N 5. P. 511–517. DOI: https://doi.org/10.1016/S1000-9361(09)60248-X
30. Aralova N.I. Mathematical models of functional respiratory system for solving the applied problems in occupational medicine and sports. Saarbrücken : LAP LAMBERT Academic Publishing GmbH&Co, KG, 2019. 368 p. (in Russian).
31. Aralova N.I. Respiratory system self-organization parameters of an operator of the system of continuous interaction for decision making under complicated situational conditions. Research on mathematical model. *Journal of Automation and Information Sciences*. 2020. Vol. 52, N 3. P. 33–47. DOI: https://doi.org/10.1615/JAutomatInfScien.v52.i3.30
32. Mathematic methods for investigation of reliability problem of organism functioning in extreme high mountain conditions / P.V. Beloshitsky, Y.N. Onopchuck, D.I. Marchenko, N.I. Aralova. *Physiological Journal*. 2003. Vol. 49, N 3. P. 139–143 (in Ukrainian). URL: https://fz.kiev.ua/journals/2003_V.49/Fiziologichnyi%20Zhurnal%2049(3)_2003/Fiziologichnyi%20Zhurnal%2049(3)_2003_139-143.pdf
33. Jirgl M., Jalovecky R., Bradac Z. Models of pilot behaviour and their use to evaluate the state of to evaluate the state of pilot training. *Journal of Electrical Engineering*. 2016. Vol 67, N 4. P. 267–272. DOI: https://doi.org/10.1515/jee-2016-0039
34. Jirgl M., Boril J., Jalovecky R. Statistical evaluation of pilot's behaviour models parameters connected to military flight training. *Energies.* 2020. Vol. 13, N 17. ID: 4452. 13 p. DOI: https://doi.org/10.3390/en13174452
35. Automated information system for athletes functional diagnostics / A.A. Aralova, N.I. Aralova, L.A. Kovalchuk-Khimyuk, Yu.N. Onopchuk. *Control Systems and Machines.* 2008. N 3. P. 73–78 (in Russian).
36. Information system for the examination of organism adaptation characteristics of flight crews' personnel / A.A. Aralova, N.I. Aralova, O.M. Klyuchko, V.I. Mashkin, I.V. Mashkina. *Electronics and Control Systems*. 2018. Vol. 2, N 56. P. 106–113. DOI: https://doi.org/10.18372/1990-5548.56.12944

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