ASSESSING THE AIRCRAFT CREW ACTIVITY BASING ON VIDEO OCULOGRAPHY DATA

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Mathematical models and methods for crew training level assessing based on video oculography data are presented. The results obtained are based on comparing the studied fragments of oculomotor activity of pilots with comparable patterns of video oculography data of various types and performance quality contained in a pre-formed specialized database. To obtain estimates, a complex combination of random process analysis and multivariate statistical analysis is used. The "intelligence" of diagnostic tools is contained in empirical data and can flexibly change as they accumulate. The considered example of determining the flight mode and pilot qualification based on video oculography data allows us to talk about the possibility of significant discrimination of the gaze movement trajectories of pilots at different flight phases and significant discrimination of the gaze movement trajectories of experienced and inexperienced pilots at certain phases of flight. An important new component of the presented results is a discriminant analysis for solving the problem of flight exercises classification, based on the principles of quantum computing. The scope of the considered approach is not limited to aviation applications and can be extended to tasks that are similar in content.

Keywords: crew training level assessing, video oculography, Discriminant Analysis, Multidimensional Scaling, Cluster Analysis, oculomotor activity indexes.

ОЦЕНКА ДЕЙСТВИЙ ЭКИПАЖА САМОЛЁТА ПО ДАННЫМ ВИДЕООКУЛОГРАФИИ

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Представлены математические модели и методы оценки уровня подготовки экипажа на основе данных видеоокулографии. Полученные результаты опираются на сравнения исследуемых фрагментов глазодвигательной активности пилотов с сопоставимыми паттернами данных видеоокулографии различных типов и качества исполнения, содержащимися в заранее сформированной специализированной базе данных. Для получения оценок применяется сложная комбинация методов анализа случайных процессов и многомерного статистического анализа. «Интеллект» диагностических средств содержится в эмпирических данных и может гибко изменяться по мере их накопления. Рассмотренный пример определения режима полета и квалификации пилота по данным видеоокулографии позволяет говорить о возможности значимой дискриминации траекторий движения взора пилотов на разных фазах полета и значимой дискриминации траекторий движения взора опытных и неопытных пилотов на определенных фазах полета. Важным новым компонентом представленных результатов является дискриминантный анализ для решения задачи классификации лётных упражнений, построенный на принципах квантовых вычислений. Область применения рассмотренного подхода не ограничивается авиационными приложениями и может быть распространена на близкие по содержанию задачи.

Ключевые слова: оценка уровня подготовки экипажа, видеоокулография, дискриминантный анализ, многомерное шкалирование, кластерный анализ, показатели глазодвигательной активности.

Introduction

The relevance of the problem of effective consideration of the human factor in projecting and operating vehicles is recognized by experts and regulatory authorities of relevant industries. Today, this factor, along with the level of professional training, is becoming one of the main causes of critical situations during flight. At the same time, its impact will become even more significant in the future, thanks to a number of trends, such as increasing the level of functionality, automation and intellectualization of aircraft avionics.

Currently, this factor and its impact on the development of critical situations in flight is still not sufficiently taken into account at the stages of safety analysis and design of the cockpit. The modern approach to its accounting, as a rule, is based only on the analysis of statistics of incidents and incidents that have occurred, which is its main drawback. As a result, existing methods and recommendations that take into account the human factor are aimed only at changes in the training of flight crew or procedures for operating poorly designed systems and devices, which do not allow us to quantify the risks in specific flights and identify factors that contribute to dangerous flight situations. The problem is, firstly, the lack of acceptable mathematical models and methods, and, secondly, the lack of effective and reasonable means of assessing the condition of crews, as well as measures to reduce the risks of piloting caused by this condition.

The conducted studies [11: 12] have shown that currently the most promising and valid means of assessing the condition of crews are non-invasive technologies based on the analysis of the characteristics of the distribution of visual attention (video oculography and assessment of parameters of gaze motor activity), while non-contact technical means — *eye trackers* are used to register the movement of the pilots' gaze, which make it possible to exclude subjective assessment of the pilot's condition indicators.

This work discusses methods for assessing the level of training and condition of the crew based on video oculography data and prospects for their application to solve practical problems.

To date, a number of results have been obtained related to the identification of the level of crew training [13—22], where in the vast majority of cases only the parameters of the aircraft trajectory are considered and other characteristics are not taken into account. Limitations that make it impossible to apply these results in practice are discussed in detail in works [5; 7—10]. It should be noted that many of these limitations are caused by the use of obvious traditional metrics for comparing flight fragments.

The above problems are overcome based on mathematical models and methods for assessing the level of training of the crew, discussed in this article. As an illustration, an example of determining the flight mode and pilot qualification from video oculography data based on comparisons of the likelihood estimates of the gaze movement trajectories is presented. This example allows us to talk about the possibility of significant discrimination of the eye movement trajectories of pilots at different flight phases and significant discrimination of the eye movement trajectories of experienced and inexperienced pilots at certain flight phases, which indicates the prospects of using the presented approach for analyzing video oculography data.

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The results obtained can be used as well as in real time to: evaluate the work of crews, including quality control of their training; support the formation of instructor assessments; provide modern forms of adaptive crew training; compare various pages of the crew display system in the cockpit; optimize the layout of aircraft cockpit indicators; assess the impact of the layout of aircraft cockpit indicators and flight conditions on the risks of aviation incidents; compare various tools and training programs for flight crew; use while designing modern aircraft.

These results differ significantly from the probabilistic methods used in system management, predicting technical failures, monitoring the state and supporting pilot control actions [2].

Main components of the approach: mathematical models, methods, and connections between them

The results of the crew's work are presented as sets of time series describing the gaze motor activity (GMA) accompanying actions of the pilots. The stages of crew training level assessing based on the analysis of video oculography data, including mathematical models, methods, and relationships between them, are shown in fig. 1.

The developed concept for crew training level assessing [5; 7—10] is based on integral comparisons of the studied flight fragments with comparable fragments from a specialized database containing patterns that characterize the performance of flight exercises by crews with different levels of training, including normal and abnormal piloting. Characteristics of the nearest pattern are transferred to the fragment under study from a specialized database. At the same time, abnormal activity is recognized and flight parameters that characterize crew errors are determined in order to interpret them.

A *pattern* is a representation of a particular part of a flight, or a *flight exercise* via a set of relevant parameters. These patterns correspond to one of the recognized levels of piloting skills formation.

The anomaly of activity is detected by belonging to the corresponding clusters of patterns. The system allows you to identify parameters that are responsible for belonging to certain clusters, as well as for differences between patterns.

The information collected in a specialized database should include *the parameters of exercise performance*, as well as relevant comments containing expert assessments from various sources. Expert comments should identify weaknesses in the work of crews, including information about typical errors in terms of performance parameters and advice to the instructor on how to correct these drawbacks.

The general assumption is that crew actions performed in different styles and with different quality, as well as flight exercises of different types, are separated from each other in a multidimensional space formed in specially selected metrics. This statement is supported by the results of computational experiments using relevant empirical data. The general approach to solving the problem that follows from this assumption is based on the choice of patterns.

The developed approach involves the use of a complex combination of methods for analyzing random processes and multidimensional statistical analysis. The "intelligence" of diagnostic tools is contained in empirical data and can flexibly change as they accumulate.

Assumptions, the adequacy of which requires justification, are not used. This approach is based on experimental data, including information about the distribution of visual attention of pilots, as well as expert assessments of the flight exercises results.

The results obtained during the analysis of the comparison of the studied flight fragments and video-oculography data with comparable samples of flight fragments and video-oculography data from a specialized database are represented by estimates constructed as a result of multidimensional statistical analysis of eye movement trajectories or time series of primary GMA indicators [1].

Based on the results of sequential execution *of the principal component method, multidimensional scaling, and cluster analysis* of gaze movement trajectories, clusters of flight fragments of various types and performance quality, including abnormal ones, are formed. They are used to determine probabilistic classification rules for separating different types and quality levels of exercises performed in the scaling space, as well as abnormally performed crew actions.

The calculation of the probability profile of belonging to target clusters, which basis the conclusion is based on, is provided using *discriminant analysis*. One of the methods used to assess the crew training level is to determine the cluster and the quality of the analyzed flight fragment performance, as well as estimates of the probability of its belonging to the target clusters associated with the types of exercises and the quality of piloting.

 When working with time series of primary GMA indicators, for a meaningful analysis of the causes of detected anomalies, the parameter contributions to the differences in flight fragments are detailed in a given metric, namely: the relative contributions of the studied parameters to the elements of the mutual distance matrixes are calculated, which allow determining the parameters that characterize pilot errors in order to identify their causes.

The key element of the approach is the likelihood metric for comparing gaze movement trajectories, without which multidimensional scaling and cluster analysis would not have produced the desired results. Previously known metrics do not provide this result.

Quantitative crew training level assessing allows ***three ways to determine the skill class:***

— direct comparison of the analyzed exercises with activity patterns from the database, using the applied metric (in this case, the characteristics of the nearest pattern are transferred to the studied exercise);

— probabilistic estimates of skill class recognition using classical discriminant analysis via sample distribution functions of exercise distances to cluster centers in the scaling space, or quantum discriminant analysis [6] ;

— selecting a skill class using a probabilistic profile of staying in ranges of activity parameters, using Bayesian likelihood estimates.

This approach can be applied even for small samples of flight exercises, since even in this case you can select a pattern and calculate the contribution of parameters to mutual distances.

The expert, who takes part in the procedure of the flight exercises results analysis, is responsible for:

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— selection of clusters of abnormal exercises in the scaling space;

— identification and interpretation of anomalies and errors.

The approach used to assess the crew training level contains the following *elements of novelty*:

— the main form of the analyzed data representation is the mutual distances matrix of the studied processes in the likelihood metric;

— discriminant analysis based on the principles of quantum computing is developed and software implemented;

— representation of flight fragments in the scaling space and their distribution by type via applying multidimensional scaling to the mutual distance matrixes and subsequent cluster analysis.

When solving practical problems in case of small samples of flight exercises, it is advisable to calculate the relative contributions of parameters to the mutual distances between exercises, and in the case of large samples, either conduct a discriminant analysis (in the classical or quantum version), or evaluate the probabilities of belonging to relevant clusters using probabilistic profiles of staying in the ranges of parameter values defined by the system with detailed estimates for each parameter.

At *the preprocessing stage*, time intervals are selected for comparing exercises and data is normalized. Subsets of time series corresponding to common time intervals that are suitable for comparing analyzed exercises of the same type are determined. Before proceeding with further calculations, the time series that characterize the history of exercise performance lead to a single scale.

The application of the considered mathematical methods and models for solving practical problems is provided by the tool "The Intelligent System for Flight Analysis" (ISFA) designed to analyze the behavior of complex systems represented by time-varying sets of parameters [5; 7—10]. This tool was originally developed for evaluating the results of flight exercises, but later became used for analyzing video oculography data. It is implemented in the graphical programming environment *LabVIEW* and officially registered in Rospatent [3].

Markov model for representing the dynamics of gaze movements associated with the likelihood metric for comparing its movement trajectories

Comparison of pilots' gaze movements dynamics across the display zones is based on *likelihood estimation that quantifies degree of the gaze movements consistency measured during various flight exercises.*

Markov processes with discrete states and discrete time (Markov chains) are used to represent dynamics of gaze movement across the display zones. In these models, the display zones correspond to certain states that form *a complete system* (i.e., these states cover all acceptable areas where the gaze can be directed). Staying in the state is determined by finding the gaze in the corresponding display zone. *Discrete time cycle* is either set by a certain (and usually small) time interval or corresponds to the time interval that determines the transition from one gaze fixation to another. The option depends on the amount of accumulated empirical data.
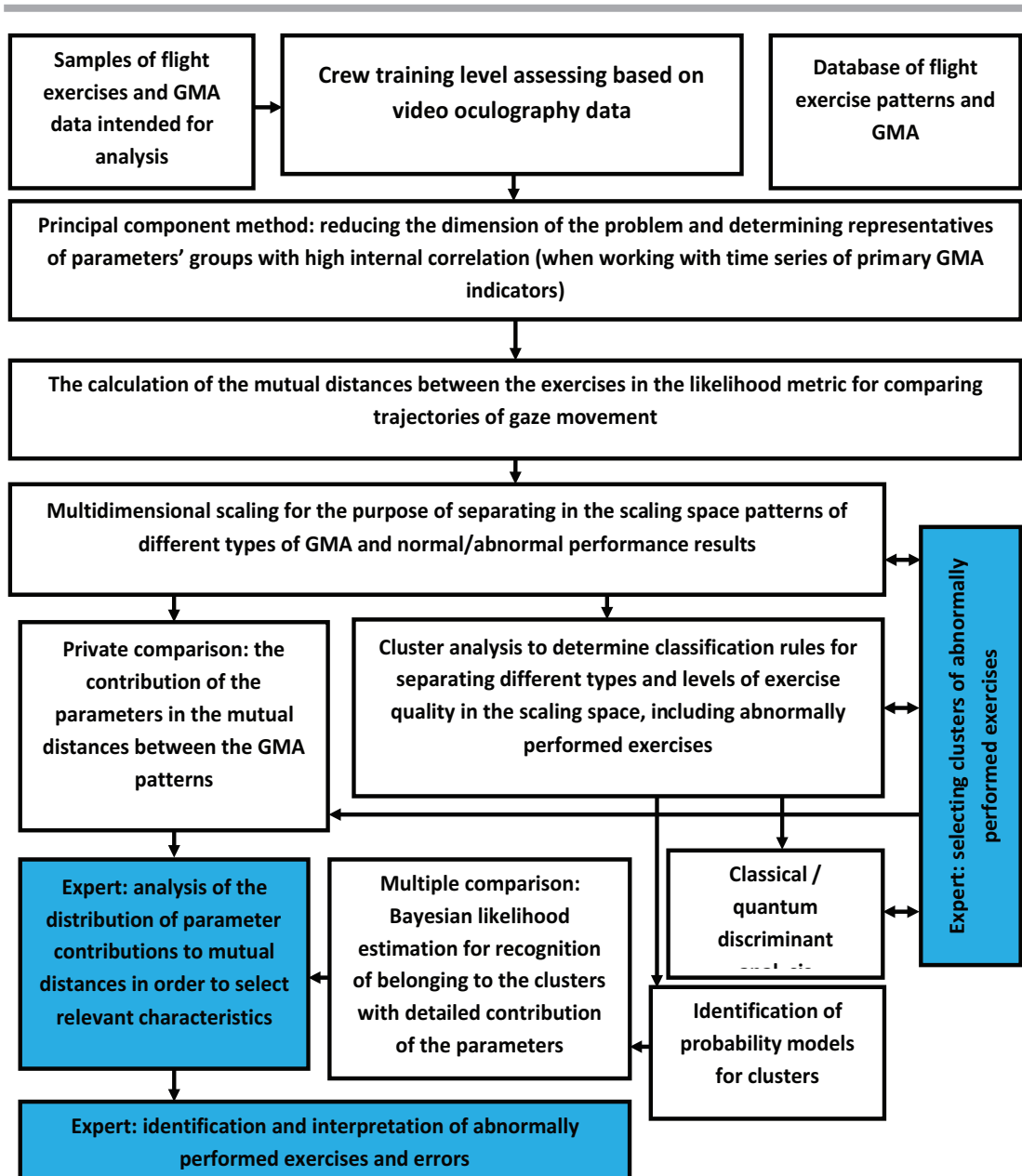
Fig. 1. Crew training level assessing based on the analysis of video oculography data: mathematical models, methods, and connections between them (the actions of experts are highlighted in color)

Probabilities of transitions between states are parameters of the model. Each flight exercise under study $l \in \{0, \dots, z\}$ has its own model with a unique set of probabilities of transitions between states.

Gaze movements are characterized by sequences of passed display zones, which are interpreted as sequences of states in terms of this model.

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Dynamics of the probabilities of staying in the model states as functions of discrete time is determined by the following matrix equation:

$p\,(t+1) = M_l p\,(t)$,

where t is discrete time; $0 \le t \le T$; $t, T \in N$; T is final time; N is a set of natural numbers; vector $p\,(t) = (p_0\,(t), ..., p_n\,(t))^T$ represents the probabilities of being in the model states at time t; n is the number of states of the Markov process; $M_l = \| m_{ij,i} \|$ is a stochastic matrix of transition probabilities between states of the Markov chain of order n, in which $m_{ij,i}$ is the probability of transition from state j to state i for the flight exercise under study l.

Identification of the considered Markov models for the exercises under study $l \in \{0, ..., z\}$ is performed via experimental data on the frequency of transitions from one display zone to another. Each exercise under study l has its own identified matrix M_l.

To calculate probabilities $P\,(v_r \mid C_l)$ of passing a sequence of the Markov process r states under the condition of belonging to the exercise under study l, where C_l is a fact of belonging to the exercise under study l, and v_r is an event representing the passage of a sequence of states, matrix M_l elements are used:

$$P(v_r | C_l) = \prod_{k=1}^{r-1} m_{s_{k+1} s_k, l}$$

The values $ln\,P\,(v_r \mid C_l)$ are used as *likelihood estimation* of passing the sequence from states, provided that it belongs to the exercise under study l. The use of likelihood estimation instead of the corresponding probabilities when analyzing the dynamics of passing model states is caused by the low orders of these probabilities, which are inconvenient for machine calculations.

Formation of the matrix of mutual distances in the likelihood metric in the notation of the graphical language G of the LabVIEW graphical programming environment is presented in fig. 2 .

Practical application example: determination of flight mode and pilot qualification based on video oculography data by comparisons of likelihood estimates of gaze movement trajectories

The gaze movement trajectories were measured during experiments on the Aircraft Cockpit Universal Prototyping Bench, developed at GosNIIAS [4]. A large group of specialists from FGUP GosNIIAS and Moscow State University of Psychology and Education took part in the experiments. Flight modes and pilot qualifications were determined based on comparisons of the likelihood estimates of gaze movement trajectories. Video oculography data was recorded using the *Gazepoint GP3 (Gazepoint Research Inc.) eye tracker* represented in fig. 3. This device is a non-contact technical tool and allows you to exclude subjective assessment of the pilot's condition indicators.

During the experiments, the gaze movement trajectories were recorded on the indicators on the windshield (IW). The display content adaptively changed depending on the flight altitude
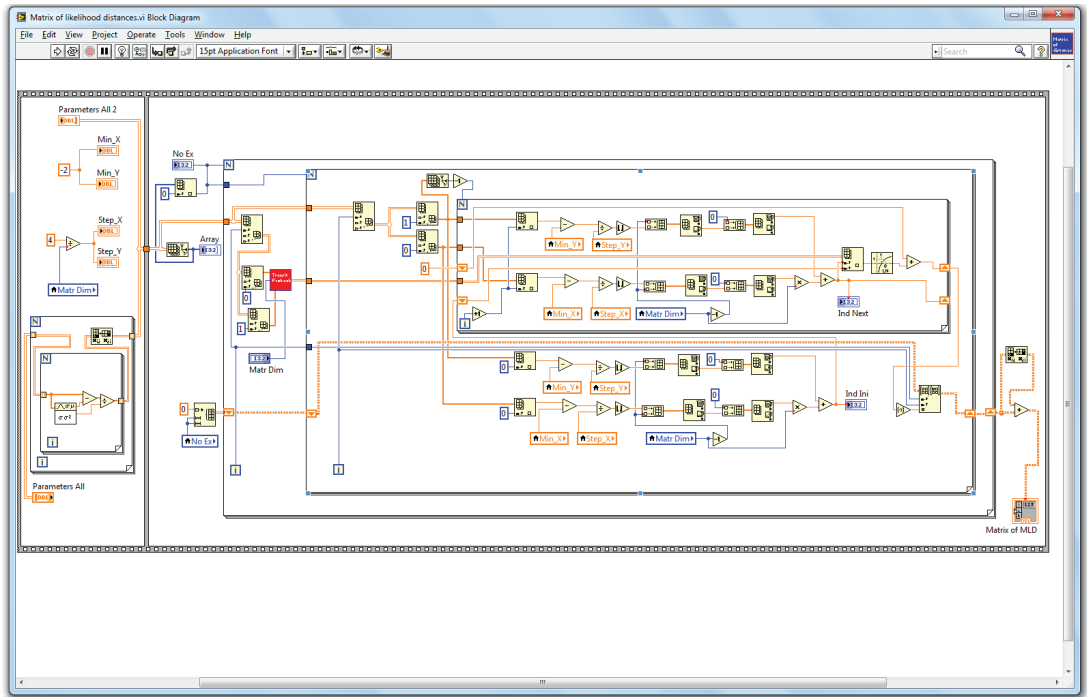
Fig. 2. Formation of the matrix of mutual distances in the likelihood metric in the notation
of the graphical language G of the LabVIEW graphical programming environment

Fig. 3. Gazepoint GP3 (Gazepoint Research Inc.) tracker, which was used for recording
ideo oculography data

when passing through the altitude of 1500 ft and 100 ft, so the video oculography data was compared for the "Landing" exercise, which includes three flight phases represented by the following altitude ranges:

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— more than 1500 ft (descent before 1500 ft);
— from 100 to 1500 ft (descent after 1500 ft);
— less than 100 ft (landing).

The exercises were performed by two specialists who had piloting skills, but different qualifications (one of them was considered as an experienced pilot, and the second — as an inexperienced pilot).

"Heat" maps of attention distribution for different flight modes and pilots of different qualifications are shown as illustrations in fig. 4. Direct qualitative comparisons of "heat" maps allow us to conclude that there is no reason to hope to identify any significant discrimination between flight modes and pilots, relying only on this form of representation of the GMA.
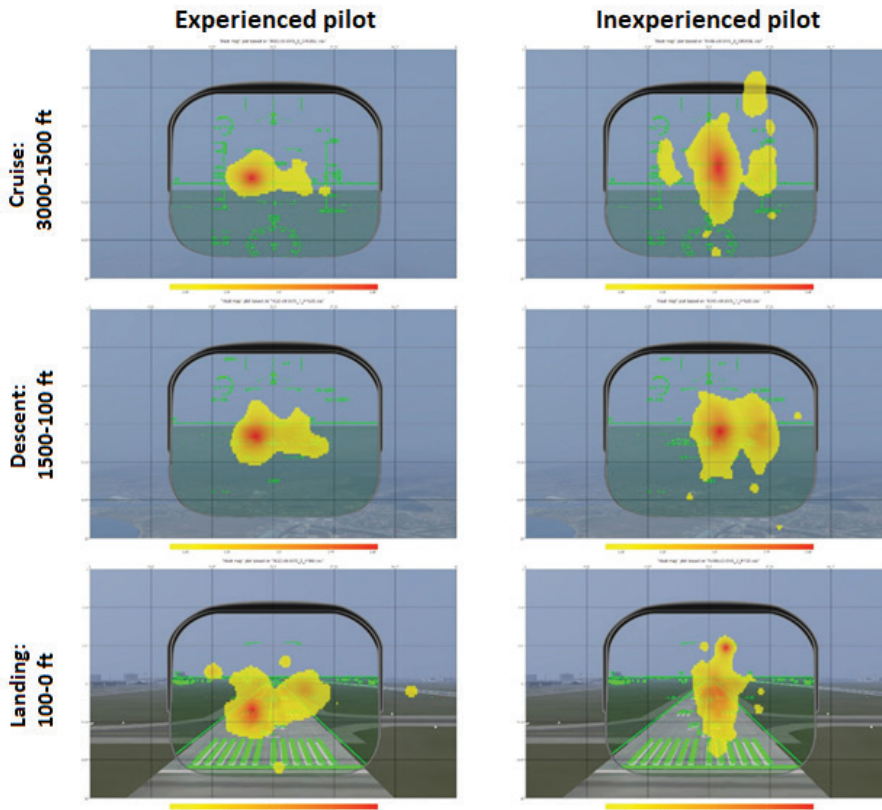

Fig. 4. "Heat" map of the distribution of attention for different modes of flight and pilots with different skills

The GMA analysis of the pilots was performed based on comparisons of eye movement trajectories in the likelihood metric using the *Intelligent System for Flight Analysis (ISFA 3.0) tool*.

The results of Fischer's preliminary discriminant analysis of gaze trajectories representations in scaling spaces presented in tables 1, 2 with verification of hypotheses about the insignificance of differences in gaze trajectories at different flight phases and for different pilots with the calculation of *F*-statistics revealed that:

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— there is no significant discrimination between experienced and inexperienced pilots when flying above 1500 ft and below 100 ft;

— for both pilots there is a highly significant discrimination between different phases of flight;

— there is a significant discrimination between experienced and inexperienced pilots when flying at altitudes from 1500 to 100 ft.

Therefore, in the subsequent analysis, four groups of gaze movement trajectories were compared:

— both pilots when flying at altitudes above 1500 ft;

— experienced pilot when flying at altitudes from 1500 to 100 ft;

— inexperienced pilot when flying at altitudes from 1500 to 100 ft;

— both pilots when flying at altitudes below 100 ft.

Table 1

Results of Fischer's preliminary discriminant analysis of representations of gaze trajectories in scaling spaces: testing hypotheses about the insignificance of differences in gaze trajectories at different flight phases and for different pilots with the calculation of F-statistics (F-statistics)

F-statistics (df = 2,16)	Inexperienced: cruise 3000-1500ft	Experienced: cruise 3000-1500ft	Inexperienced: descent 1500-100ft	Experienced: descent 1500-100ft	Inexperienced: landing	Experienced: landing
Inexperienced: cruise		**0,109**	7,614	21,602	4,121	5,342
Experienced: cruise	**0,109**		8,133	27,583	5,334	7,000
Inexperienced: descent	7,614	8,133		15,338	25,337	29,037
Experienced: descent	21,602	27,583	15,338		55,494	59,916
Inexperienced: landing	4,121	5,334	25,337	55,494		**0,128**
Experienced: landing	5,342	7,000	29,037	59,916	**0,128**	

Table 2

Results of Fischer's preliminary discriminant analysis of representations of gaze trajectories in scaling spaces: testing hypotheses about the insignificance of differences in gaze trajectories at different flight phases and for different pilots with the calculation of F-statistics (p-values)

p-values	Inexperienced: cruise 3000-1500ft	Experienced: cruise 3000-1500ft	Inexperienced: descent 1500-100ft	Experienced: descent 1500-100ft	Inexperienced: landing	Experienced: landing
Inexperienced: cruise		**0,898**	0,005	0,000	0,036	0,017
Experienced: cruise	**0,898**		0,004	0,000	0,017	0,007
Inexperienced: descent	0,005	0,004		0,000	0,000	0,000
Experienced: descent	0,000	0,000	0,000		0,000	0,000
Inexperienced: landing	0,036	0,017	0,000	0,000		**0,881**
Experienced: landing	0,017	0,007	0,000	0,000	**0,881**	

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After entering GMA fragments into a specialized database for various flight modes and pilots, a matrix of mutual distances between the gaze movement trajectories was calculated in the likelihood metric (fig. 5).
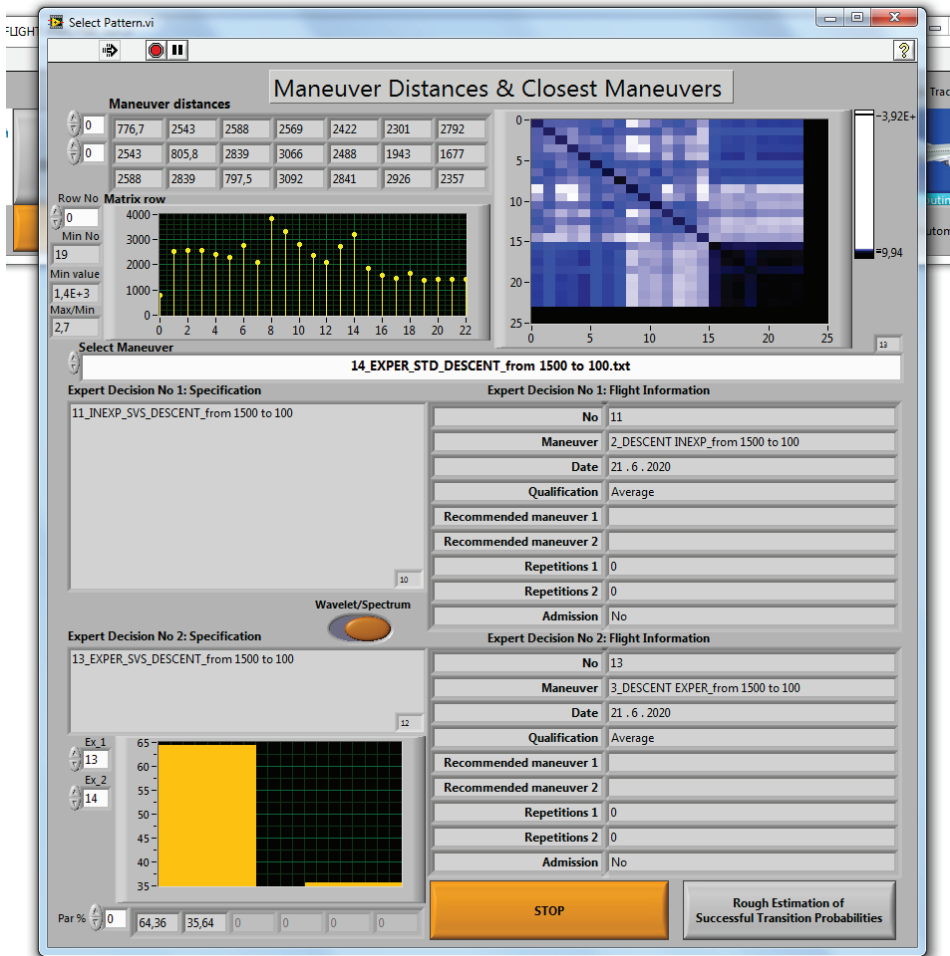

Fig. 5. Results of calculating the matrix of mutual distances between the gaze movement trajectories in the likelihood metric together with related information

As a result of multidimensional scaling, the studied GMA fragments were ordered in two-dimensional space, demonstrating a high degree of discrimination (fig. 6).

Illustrations on fig. 7 and 8, respectively, show a comparison of the "raw" (i.e. unprocessed) gaze paths of an experienced pilot when flying at altitudes above 1500 ft and below 100 ft and both experienced and inexperienced pilots when flying at altitudes from 1500 ft to 100 ft.

Discriminant analysis performed on the basis of approaches used in quantum computing (fig. 9) resulted in 5 errors, which is 22% of the sample size and suggests a significant difference
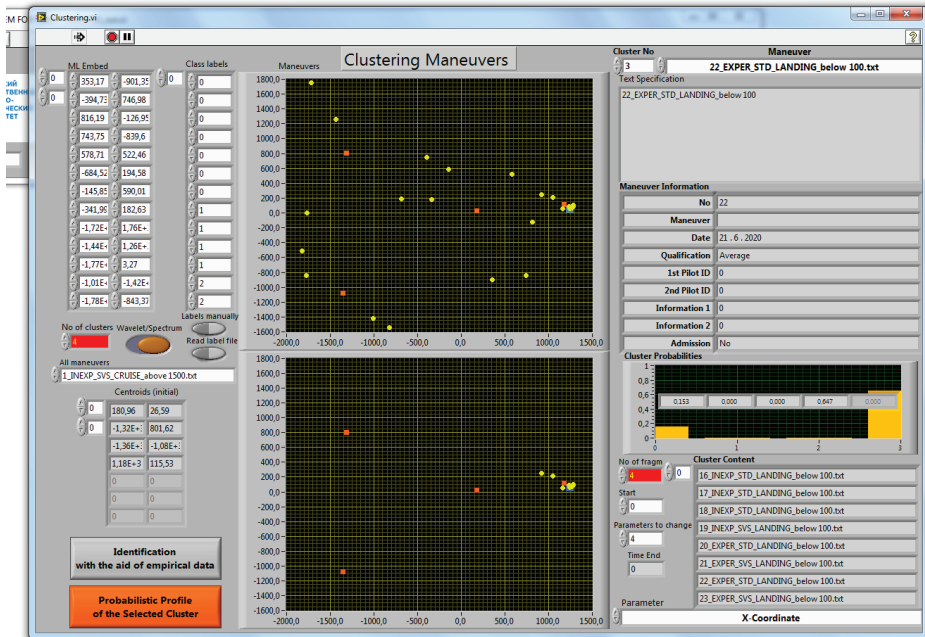
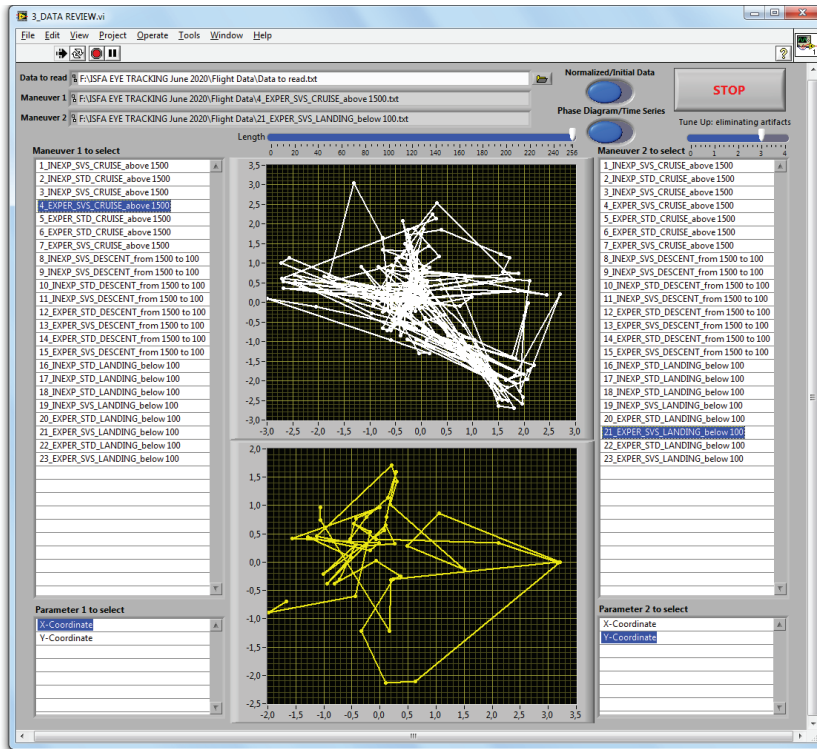*Fig. 6.* GMA fragments under study ordered in a two-dimensional scaling space

Fig. 7. Comparison of "raw" (unprocessed) gaze paths of an experienced pilot when flying at altitudes above 1500 ft and below 100 ft

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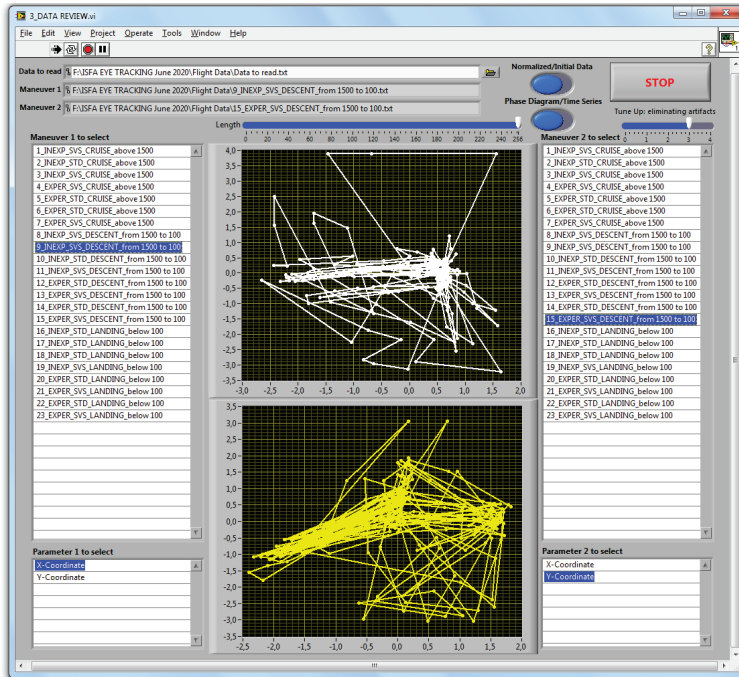Experimental Psychology (Russia), 2021, vol. 14, no. 1

Fig. 8. Comparison of "raw" (unprocessed) gaze paths of experienced and inexperienced pilots when flying at altitudes from 1500 ft to 100 ft
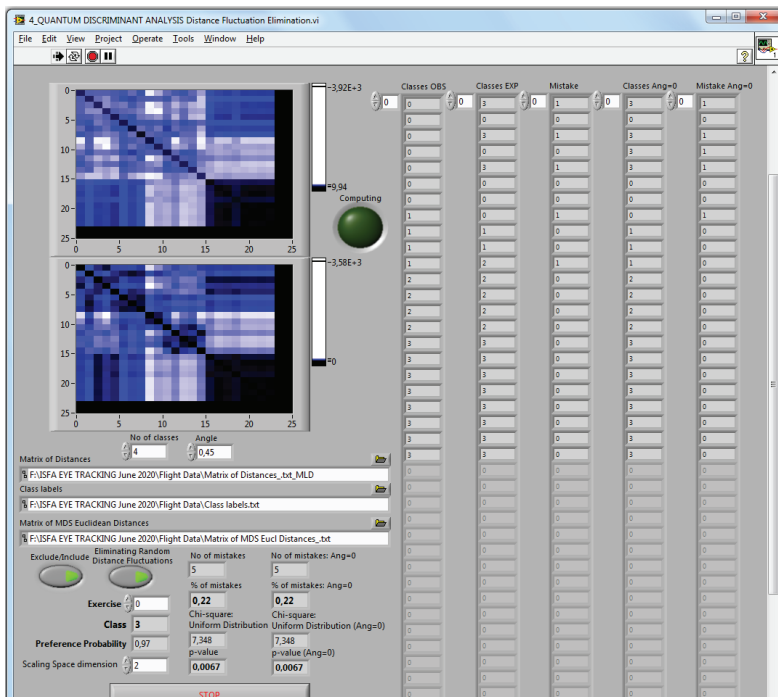

Fig. 9. Panel with the results of the discriminant analysis performed based on the approaches used in quantum computing

in the recognition result of the above four groups of gaze movement trajectories from the uniform distribution according to the Pearson criterion ($X_1^2 = 7,35$; $p < 0,007$).

The classical discriminant analysis of the distribution of the studied GMA fragments in the scaling space led to the same result: 5 errors (22% of the sample size). Discrimination of GMA fragments is a statistically highly significant value (Wilks Lambda=0.04; associated statistics F (6.36) = 22.83; p<0.0001).

Thus, the considered example allows us to talk about the possibility of:

— significant discrimination of the pilots' gaze trajectories at different flight phases;

— significant discrimination of the gaze movement trajectories of experienced and inexperienced pilots at certain flight phases, which indicates the prospects of using the presented approach for analyzing video oculography data, especially when classical methods do not allow us to get useful conclusions.

In the future, the revealed significant discrimination of gaze movement trajectories will allow identifying both the flight modes performed and the level of training of pilots based on their oculomotor activity in automatic mode in real time. It is obvious that the scope of the considered approach is not limited to aviation applications and can be extended to tasks that are similar in content.

MAIN RESULTS AND CONCLUSIONS

Mathematical models and methods for crew training level assessing based on video oculography data, which are based on comparing the studied fragments of pilots' gaze motor activity with comparable video oculography data patterns of various types and performance quality contained in a pre-formed specialized database, have been developed. To obtain estimates, a complex combination of random process analysis and multivariate statistical analysis is used.

The considered example of determining the flight mode and pilot qualification based on video oculography data allows us to talk about the possibility of:

— significant discrimination of the pilots' gaze trajectories at different flight phases;

— significant discrimination of the gaze movement trajectories of experienced and inexperienced pilots at certain flight phases, which indicates the prospects of using the presented approach for analyzing video oculography data, especially when classical methods do not allow obtaining useful results.

In the future, the revealed significant discrimination of eye movement trajectories will allow identifying both the flight modes performed and the level of training of pilots based on their oculomotor activity in automatic mode in real time.

The results obtained are a significant development of tools for predicting risks and identifying factors that contribute to the occurrence of dangerous flight situations, including real time ones, and can be used for:

— assessing the crews' work, including quality control of their training;

— support for the formation of instructor assessments;

— provision of modern forms of adaptive crew training;

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— comparison of various pages of the cockpit display system and control panels;

— optimization of the cockpit indicators layout taking into account the GMA;

— assessment of the cockpit indicators layout impact and flight conditions on the risks of aviation incidents;

— comparison of various flight training tools and programs for air crew in the design of modern aircraft.

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