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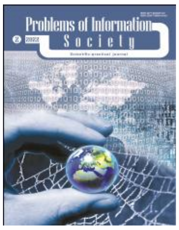

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Interaction between human-machine interface and avionics on aircraft cockpit

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ABSTRACT

The problem of the human factor, the negative impact of which is often associated with the psycho-physiological characteristics of a person, remains a priority in ensuring the safety of flight, as well as the crew in performing aircraft control operations. The study of the proposed approaches, methods and technical tools aimed at reducing the impact of the human factor on flight safety shows the insufficient effectiveness of available methodological tools in eliminating the “suddenly arising” unreliability of aviation personnel. This situation necessitates the development of an aircraft control system, taking into account the characteristics of all its components and the creation of a virtual pilot assistant interacting with the avionics system. The article discusses various aspects of the interaction of the pilot with the avionics system. It presents the concept of creating a virtual assistant to the pilot in his work on board using human-machine interfaces providing the possibility of observation, communication and flight control. The concept of a cognitive pilot-aircraft interface is proposed, which introduces knowledge-based adaptive functionality into the system to help the crew in performing important tasks which are critical in terms of flight safety.

Introduction

The safety of civil aviation is the main goal of the International Civil Aviation Organization (ICAO) and significant progress has been made in this area in recent years. However, there is still a need for further improvement of the measures taken, since any progress in this area has a significant impact on the improvement of aviation security. SA (Situational Awareness) is an important component of human information processing and is of great importance in pilot decision-making processes.

In aviation, the “human factor” is considered to be the most important condition affecting the level and state of flight safety of any kind of aircraft. A human is the most adaptable and important element of the aviation system and, simultaneously, the most vulnerable element in case of unforeseen situations.

The comfort and reliability of aircraft is growing each year, while many flight stages are performed automatically under strict control by the pilot. However, the ICAO reports that every three out of four aviation accidents have been occurring due to the pilot fault for many years up to now. The measures taken and being taken by ICAO contributed to a reduction in the total number of aviation accidents, nonetheless their causality remains the same, i.e., at least 80% of all aviation incidents, accidents and catastrophes still occur due to erroneous and incorrect actions of aviation personnel, both in the air and on the ground [1,2].

During the flight, the aircraft crew (AC), receiving data from the subsystems of the flight and navigation complex (FNC) and from multifunctional indicators, controls the aircraft by deviating the aircraft control sticks [3]. Moreover, this interaction is influenced by the features associated with the psychophysiology of the pilot. Since the crew’s ability to deflect special situations arising on board is limited, it is necessary to introduce intellectual and virtual components into the FNC, which accumulate the experience of the behavior of real experts in the field of aircraft navigation and piloting in special situations. This circumstance makes the problem of developing on-board systems equipped with these components urgent, which reduces the psycho-physiological load on the aircraft crew. This allows to conclude that the further development of FNC is closely related to the introduction of crew support systems and tools, situational awareness systems and further intellectualization of aircraft control (AC) [4].

Problem statement

Technical developments in computer hardware and software now make it possible to automate almost all aspects of human-machine systems. Technological advances in the field of avionics systems and components have facilitated the introduction of increasingly integrated and automated human-machine interfaces (HMI) and interactions on the aircraft board. Current developments in avionics have introduced a number of new systems on board civil aircraft, such as terrain and aircraft movement, warning systems, engine monitoring, flight planning and control systems, data link, communications systems, and electronic flight information systems. These technological innovations have supported higher automation, allowing the transition from manual control to flight deck supervisory control. Increasingly, machine intelligence and autonomy are driving the subsequent development of technical advances in the cockpit, especially in the field of unmanned aerial vehicles. Given these technical possibilities, the question arises. ***Which system functions should be automated and to what extent?*** This requires a thorough analysis of the receipt and processing of flight and navigation information from on-board instruments in the cockpit, as well as the engineering and psychophysiological characteristics of the human operator [5, 6].

This article is devoted to above question and highlights the issue of creating a conceptual project for a virtual pilot assistant (VPA) for his work on the aircraft board.

Problem solution

Concepts for implementing progressive, more integrated and automated HMIs on civil and military aircraft board include the following common elements:

- ability to assess the status of the system and the environment;
- possibility of assessing the status of the operator;
- possibility of adapting the HMI according to the first two elements.

HMI adaptation driven by human ability and knowledge can greatly improve human-machine interaction by changing system support depending on user requirements. However, one of the unsolved problems in the development of such adaptive systems is the development of suitable models and algorithms for describing human activity and cognitive states based on real-time sensor measurements [7].

HMI should be human-centric, providing relevant and timely information while avoiding human overwhelming with excessive presentation mess and redundant information. Moreover, over-automation can lead to human (pilot) under-load, leading to misuse of automation, complacency and loss of situational awareness.

The human factor in system design covers a wide range of design elements. The design of human-machine interfaces is related to physical characteristics such as content, format time and duration of the information provided to the user (visual, auditory, tactile, etc.), as well as the modality of user input to the system. The design of human-machine interaction is also related to the dynamic behavior of the system (adaptation of the interface in accordance with user input or external conditions).

The physical characteristics of the interface are used to describe the quality of the visual, auditory or tactile feedback presented to the pilot. The readability of information is affected by displays such as size, resolution, brightness, highlights, shading, contrast, color, responsiveness, and update rate. The use of color draws the pilot's attention to useful pieces of information, aiding visual retrieval on displays [7,8].

Various options for implementing the human-machine interface and the interaction of avionics on the aircraft board are considered below. Figure 1 shows the VPA architecture.

The VPA system architecture illustrated in Fig. 1 includes four major subsystems:

- Communications;
- Surveillance;
- Manual Control;
- human-machine interface (HMI)s.

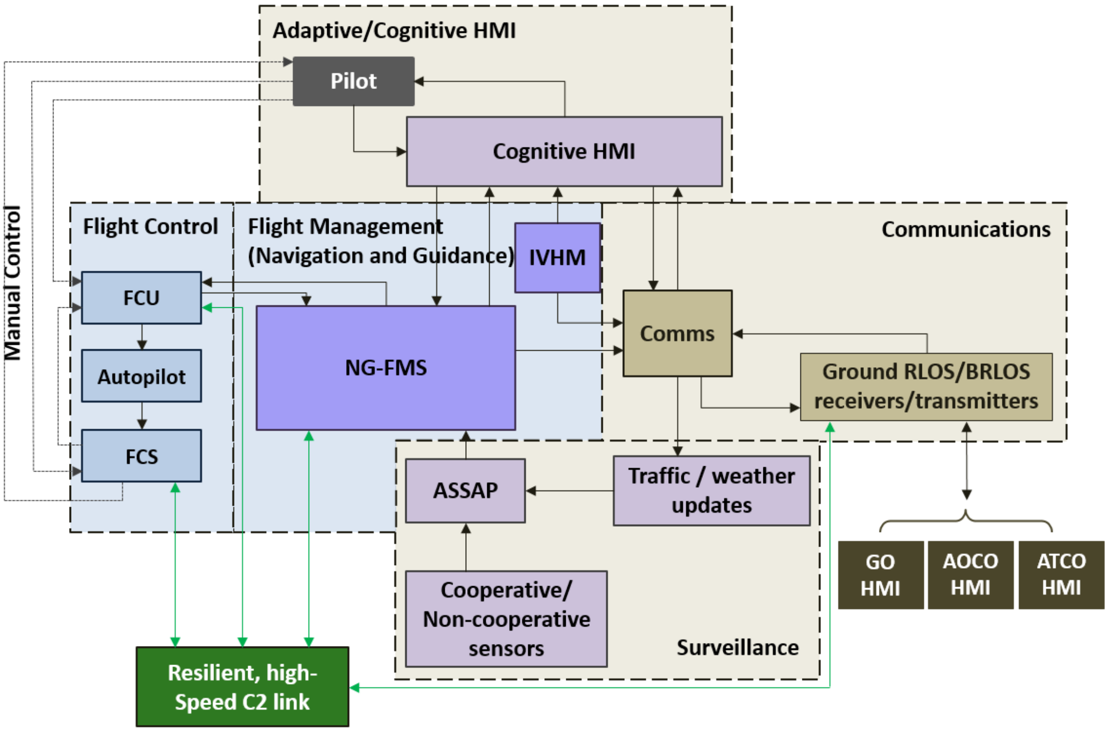

Fig.1. VPA system architecture

The communication system provides data sharing between the pilot and the pilot's on-ground support service. The proposed VPA system is an airborne autonomous pilot support system that interacts with various subsystems (including Flight Management Systems (FMS), dangerous deviation detection and prevention and communication subsystems) in the aircraft. VPA performs a real-time assessment of the aircraft condition and provides the pilot with useful and timely alerts based on relevant forecasts. Through a network containing various channels such as Radio Line of Sight (RLOS) and Beyond Radio Line of Sight (BRLOS), data is transmitted. In an emergency situation, the reliable, secure, high-speed C2 link allows on-ground personnel to take direct control of the aircraft's flight in the management and control system.

The surveillance subsystem processes the results of airborne surveillance and separation of Airborne Surveillance and Separation Assurance Processing (ASSAP). This subsystem interacts with Navigation and Guidance - Flight Management Systems (NG-FMS), in order to provide automation of SA & CA (situational awareness and capability automation) capabilities. The NG-FMS is linked to the Flight Control Unit (FCU), autopilot and flight control system. The Flight Control System (FCS) is designed to provide guidance, navigation and control, as well as optimization of the planned trajectory. The Integrated Vehicle Health Management (IVHM) automates the control and monitoring of aircraft systems, providing appropriate updates, warnings or alerts to the pilot (via the cognitive HMI) and on-ground crew.

Interface management. FMS increases the pilot's workload by automating some *internal mission loops*. These include computing navigation data, monitoring flight and engine control systems, and providing autopilot capabilities. The traditional databases associated with FMS are magnetic deviation, performance and navigation. These databases may also include weather, altitude, environmental change, and pilot's actions. NG-FMS provides increased internal loop automation for simple piloting and navigation tasks. When solving problems in more complex situations, the load on the pilot increases, which requires connection to the VPA virtual assistant pilot system.

However, the pilot is still responsible for controlling the aircraft during all phases of flight. The failure of individual subsystems or units indicates the presence of anomalies, such as deviation from the trajectory, failures on board and conflicting data, which ultimately and significantly affect the flight safety. Current aircraft control automation is generally considered rigid; thus, designers tend to favor simply implementing cockpit hardware. The aircraft's Cognitive Pilot Assistant Interface (CPAI) is being introduced into the NG-FMS, providing it with the efficient automation and, thereby, increasing the system adaptability to unforeseen events. CPAI allows NG-

FMS to evaluate the pilot's cognitive status. Through non-line-of-sight communication channels, CPAI provides periodic updates to on-ground support during the period of transition between strategic and tactical missions. Meanwhile, the CPAI monitors and assists the pilot in performing the transition. For example, in case of a pilot overloading or incapacitating, CPAI reduces the pilot's workload by assuming that the responsibility for performing some of these functions is assigned to the ground support service by redistributing their duties [8, 9].

The Cognitive Human Machine Interface (CHMI) is an important component of the VPA system, providing the necessary reduction in pilot workload and providing pilot incapacitation detection capabilities. Fig. 2 shows the CHMI architecture.

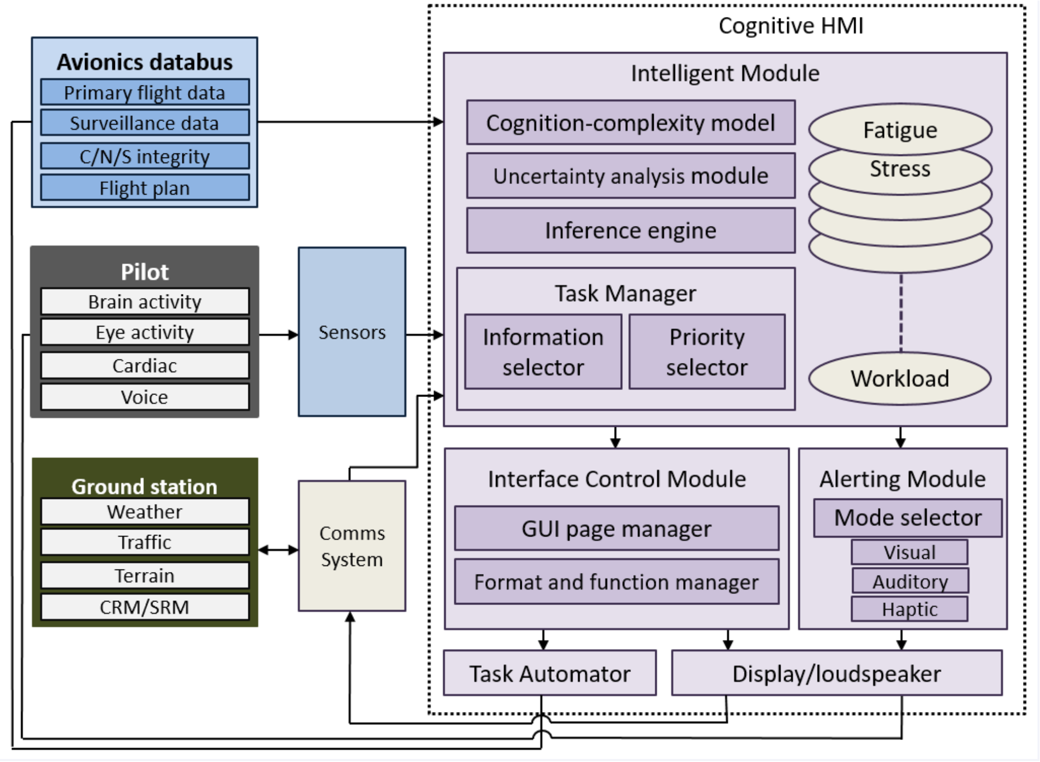

Fig.2. CHMI architecture

CHMI assists the pilot with several intelligent features such as control information, adaptive alerting, situational assessment, and dynamic task allocation. CHMI uses physiological sensors constructed into the cockpit to monitor the pilot's condition in real time. *Cognition models* are used to evaluate the pilot's cognitive state such as fatigue, stress, attention and mental workload based on collected physiological data. Important physiological measures include brain activity (e.g., blood oxygenation), cardiac activity (e.g., heart rate, heart rate variability), and eye activity (e.g., blink rate, eye movements, and pupil diameter). Brain activity provides information about cognitive load and can be monitored using appropriate electrical or optical instruments. The inference engine manages the distribution of tasks between automation systems (e.g., NG-FMS) and human operators (flight and ground) based on the external environment and their cognitive states. If the system concludes that the pilot is losing situational awareness at a high level of automation, then the CHMI suggests lowering the automation level or triggers appropriate alerts to keep the pilot in control. Adaptive notification is designed to provide hints that supplement the cognitive state of a human pilot, based on the assessment of the situation by the system [10].

The proposed CPAI architecture is primarily based on a core functionality, namely:

- assessment of the physiological state,
- assessment of the external state
- dynamic distribution of tasks.

This set of functions uses appropriate models of human cognition and intentions of the operators, as well as situations.

The article proposes a new concept of CPAI. The proposed implementation of the CPAI system based on the real-time detection of the physiological and cognitive states of the pilot, avoids errors and maintains enhanced synergy between human and avionics systems.

These synergies provide significant

improvements in overall performance and security. The CPAI workflow, consisting of the stages of perception, evaluation and reconfiguration, is designed to support the assessment of physiological and environmental conditions, dynamic task allocation and adaptive pilot alerting. Appropriate mathematical models are introduced to estimate the mental load associated with each piloting task and evaluate the cognitive abilities of the pilot. Properly implemented decision logic ensures continuous and optimal adjustment of automation levels depending on the estimated cognitive states. By constantly adapting, the automation successfully maintains the pilot's workload within the optimal range, mitigating the occurrence of dangerous levels of fatigue.

During flight, the cockpit allows pilots to perform their tasks of piloting, navigating, communicating and controlling the aircraft [12]. The pilot interacts with the avionics systems through interfaces, some of which are highlighted in Fig. 3. The following units are available:

- Navigation Display (ND),
- Multifunction Control Display Unit (MCDU),
- Engine indicators and crew alerts,
- Engine Indication and Crew Alerting System (EICAS)
- Primary Flight Display (PFD).

In particular, the MCDU is the pilot's interface for monitoring flight management systems (FMS). The FMS is primarily responsible for providing automated navigation and guidance services from takeoff to landing. The software component has a built-in processor and performs the following functions [12]:

- Algorithmizing for positioning and navigation, including multimedia methods for merging sensory data.
- Algorithmizing for constructing optimal trajectories.
- Algorithmizing for calculating short-term and long-term performance.
- Calculation of targeting horizontally and vertically, targeting algorithmizing.
- Processing, sorting and selecting databases.
- Built-in test equipment (BITE) and monitoring.

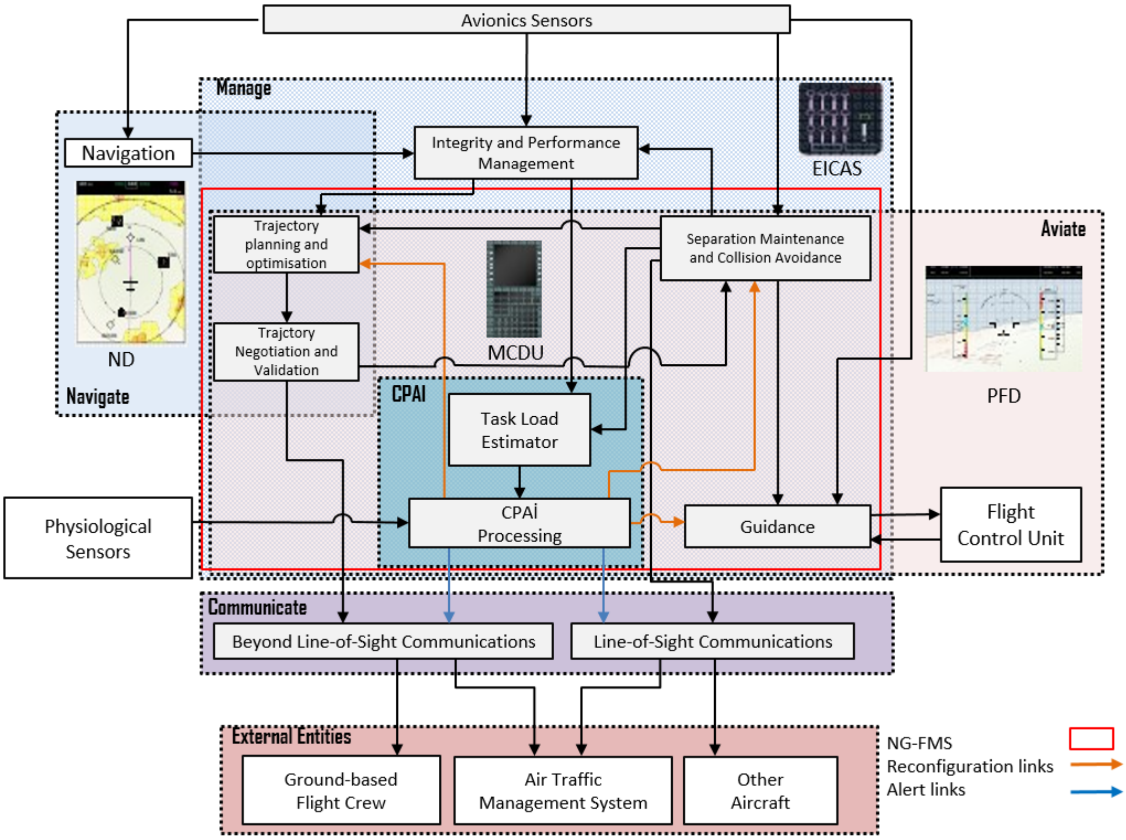

Fig.3. Interaction of the pilot with the avionics system

CPAI is integrated into NG-FMS through a network consisting of various RLOS and BRLOS data links. In an emergency, the reliable, secure high-speed C2 link allows ground personnel to take control of the aircraft's control systems and flight.

To assess the human factor, it is proposed to use computer modeling of human behavior. This model will allow:

- understanding the interaction between pilot and aircraft
- finding out the requirements for the characteristics of the aircraft dynamics.

The pilot in this model is a complex multi-channel, adaptive and self-learning control system. During the control process, it adapts to the aircraft to ensure the stability and controllability of the system. The adaptation of the pilot in this case is reduced to the adjustment of his neuromuscular and central nervous system.

When studying the "pilot-aircraft" system in the semi-automatic control mode by the methods of the theory of automatic control, such an analog pilot model, as the transfer function is often used:

$$W_{\Pi}(P) = \frac{k_{\Pi} e^{-p\tau_n} (\tau_1 p + 1)}{(T_1 p + 1)(T_2 p + 1)} \tag{1}$$

where , τ_n is the time delay constant characterizing the formation of a response to the input signal; T_1, T_2 - time constants characterizing the inertia in signal transmission; τ_1 - time constant, taking into account experience, training, fatigue; n - the number of sources from which the pilot receives information.

The delay time τ_n is often in the range of 0.1 ... 0.25 s. The time constant T_1 determines the integrating (filtering) properties of a person and, according to experimental data, reaches 10 ... 20 s. Time constant T_2=0.1…0.2 s. represents the delay of the human motor (muscular) system. The time constant $\tau_1 \le 1$ characterizes the ability of a person to respond to the speed of the input signal. The pilot's gear ratio k_{Π} depends on the force required to deflect the control unit.

The block diagram of the pilot model is presented in Fig.4.

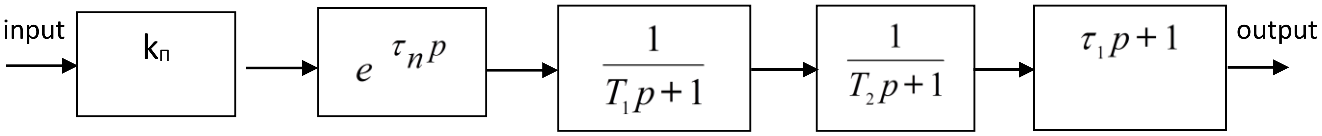

Fig. 4. Structural diagram of the pilot model

The first link characterizes the pilot's delay in forming a reaction to the received instrumental or auditory information. The second link determines the pilot's inertia, due to the need to develop a solution as a result of generalizing the information received. The third link represents the inertia of the human motor (muscular) system. The fourth link takes into account the formation of pre-emptive signals. The fifth link characterizes the pilot's transmission coefficient, which depends on the gradient of the load force on the deflection of the control device.

The main tasks of monitoring the crew's activities in flight include assessing the quality of their activities, identifying dangerous trends in actions, and determining the causes of deviations from the requirements of guidance.

Solution of the problems listed is based on the results of flight information (FI) processing with the help of special devices, which represent a set of parameter values at controlled flight points x_i and (or) information about detected deviations:

$$\{r_i, x_j\},$$

where r_i is the number of the detected deviation; x_j is the extreme value of the controlled parameter.

As the integral characteristics of the crew activity for a certain period of time, the followings can be taken:

- deviation frequency ν = n / N,
- deviation intensity λ = n / T

where n is the number of deviations detected in flights N during flight hours T.

The quality of following a particular parameter x_i by the crew can be characterized by the form of the distribution law of deviations of the parameter from the nominal value and the moments of this distribution. Distributions of aircraft parameters, such as barometric altitude, bank angle, airspeed, aircraft elevation, etc. can be modeled by a symmetrical exponential law. This law is characterized by the position of the distribution center, the standard deviation and the exponent.

For an approximate estimation, the mean and standard deviation can be used:

$$\overline{x_i} = \frac{\sum_{j=1}^{N} x_{i,j}}{N}; \qquad \sigma_{x_i}^2 = \frac{\sum_{j=1}^{N} \left(x_{i,j} - \overline{x_i}\right)^2}{N-1},$$

where $x_{i,j}$ is the deviation of the i-th parameter in the j-th measurement.

These indicators can be used to assess the quality of the crew's activities over a certain period of time.

To prevent possible deviations, it is necessary to identify dangerous trends in the crews' actions that can be caused by fatigue, loss of professional skills and other reasons. To solve this problem, the methods of regression analysis and other forecasting methods can be used.

Let $\{x_1, x_2, \ldots . x_n\}$ be a deviations sample from the nominal value of the controlled parameter obtained from flight portraits N of the given crew. It is necessary to determine the trends in the change of the controlled parameter *x* aimed to predict the possibility of going beyond the limits. The duration of the analyzed period is that there are no significant qualitative changes in the crew's activities. We use a linear model of the dependence of the deviation $\dot{x}$ on the flight time τ:

$$\dot{x}_i = a + b\tau_i \qquad (2)$$

where a, b are the parameters; τ_i – flying time to the i-th flight.

The parameters a, b can be determined by the least squares method from the equations system:

$$\begin{cases} a = \bar{x}_N - b\bar{\tau}_N \\ b = \dfrac{\sum\limits_{i=1}^{N} x_i \tau_i - N\,\bar{x}_N \tau_N}{\sum\limits_{i=1}^{N} \tau_i^2 N\,\bar{\tau}_N^2} \end{cases},$$

$$\text{where} \quad \bar{x}_N = \frac{1}{N}\sum_{i=1}^{N} x_i \qquad \bar{\tau}_N = \frac{1}{N}\sum_{i=1}^{N} \tau_i \,. \quad (3)$$

The rate of deviation change over flights N during flight time τ_N can be determined by the relation:

$$R_x^N = \frac{\hat{x}_N - \hat{x}_1}{\bar{\tau}_N}.$$

Using model (3), it is possible to predict the change in deviations and analyze the possibility of going beyond the allowable limits.

The block diagram of the algorithm for calculating the deviation changes according to the above method using model (3) is presented in Fig.5. The results of programming and calculations are illustrated in tables 1 and 2.

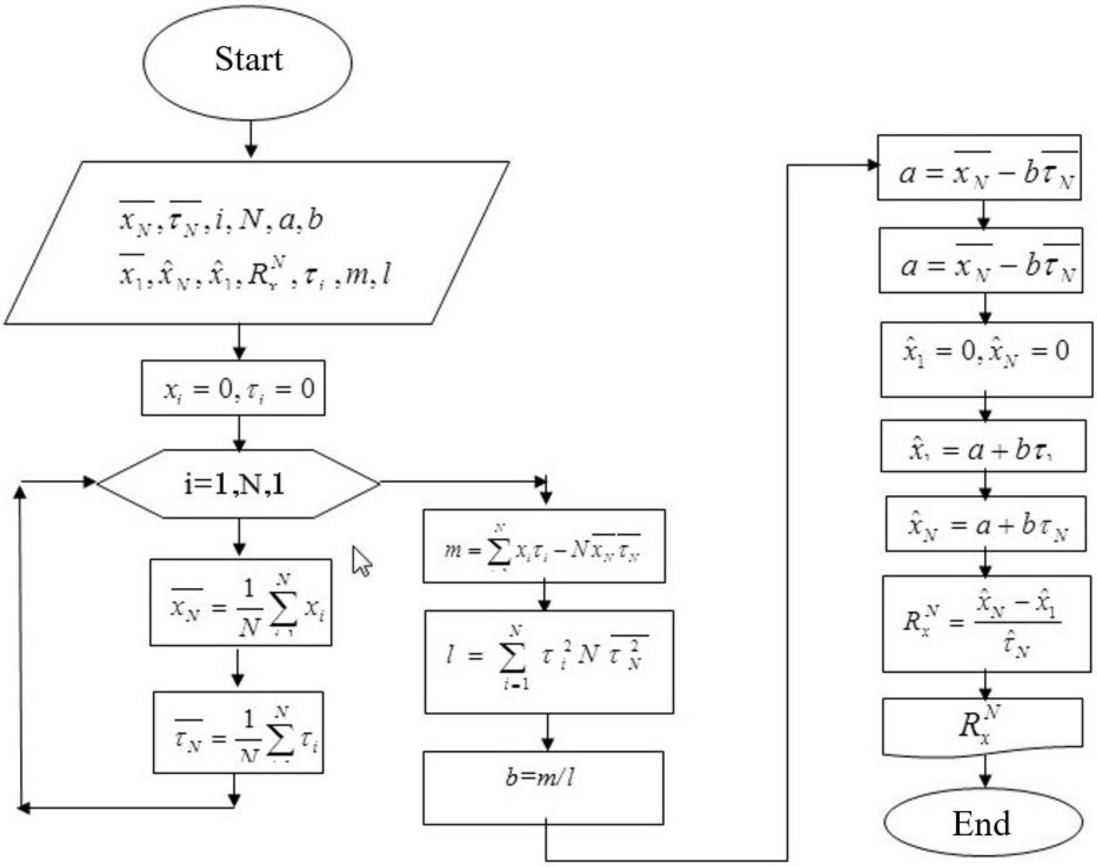

Fig.5. Block diagram of the deviation calculation algorithm

Table 1. Calculation results

Barometric altitude			
Number of measurements	Measured values input	Time moments t, sec	Deviation changes rates
N_3	$X_1 = 14$	$t_1 = 72$	Result: 5,10854E-9
	$X_2 = 12$	$t_2 = 69$	
	$X_3 = 10$	$t_3 = 66$	

Bank angle			
Number of measurements	Measured values input	Time moments t, sec	Deviation changes rates
N_3	$X_1 = -0,2$	$t_1 = 72$	Result: 1,27713E-10
	$X_2 = 0,15$	$t_2 = 69$	
	$X_3 = -0,1$	$t_3 = 66$	

Aircraft elevation			
Number of measurements	Measured values input	Time moments t, sec	Deviation changes rates
N_3	$X_1 = -5$	$t_1 = 72$	Result: 2,55427E-9
	$X_2 = -4$	$t_2 = 69$	
	$X_3 = -3$	$t_3 = 66$	

Airspeed			
Number of measurements	Measured values input	Time moments t, sec	Deviation changes rates
N_3	$X_1 = 45$	$t_1 = 72$	Result: 6, 38568E-9
	$X_2 = 42$	$t_2 = 69$	
	$X_3 = 40$	$t_3 = 66$	

Table 2

Barometric altitude			
Number of measurements	Measured values input	Time moments t, sec	Deviation changes rates
N_3	$X_1 = 985$	$t_1 = 0,8$	Result: 0,003123001
	$X_2 = 990$	$t_2 = 0,9$	
	$X_3 = 987$	$t_3 = 0,85$	

Bank angle			
Number of measurements	Measured values input	Time moments t, sec	Deviation changes rates
N_3	$X_1 = -3,0$	$t_1 = 1,2$	Result: 0,00411679
	$X_2 = 3,0$	$t_2 = 1,0$	
	$X_3 = 3,1$	$t_3 = 1,1$	

Aircraft elevation			
Number of measurements	Measured values input	Time moments t, sec	Deviation changes rates
N_3	$X_1 = 1,2$	$t_1 = 0,80$	Result: -0,0033235
	$X_2 = -1,2$	$t_2 = 0,95$	
	$X_3 = 1,1$	$t_3 = 0,90$	
Airspeed			
Number of measurements	Measured values input	Time moments t, sec	Deviation changes rates
N_3	$X_1 = 850$	$t_1 = 1,2$	Result: 0,01207655
	$X_2 = 832$	$t_2 = 1,1$	
	$X_3 = 845$	$t_3 = 1,4$	

Conclusion

The article presented a new concept of creating a virtual assistant to a pilot for his work on an aircraft board using human-machine interfaces. The safety and human factors issues associated with this concept were assessed and technical considerations were proposed to address these problems, as well as an assessment of the status of current certification standards.

VPA is a viable system providing enhanced surveillance, communication and flight control capabilities as well as adaptive task allocation and human-machine interfaces. This system contributes to the optimization of the flight path, and also performs the functions of separation and collision avoidance.

The proposed concept included a cognitive pilot-to-aircraft interface that introduced knowledge-based adaptive functionality into the system to assist the pilots perform important missions critical to flight safety.

The implementation of the CPAI system based on the real-time detection of the physiological and cognitive states of the pilot avoided piloting error and enhanced the synergy between human and avionics systems.

The results of computer simulation of the assessment of the crew’s activity during the flight were presented.

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