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"SMART" AIRCRAFT: CONTROL IN CRITICAL SITUATIONS CREATED BY HUMANS IN FLIGHT

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ABSTRACT

This article addresses safety in potentially dangerous situations created by negative manifestations of human factors during aircraft flight. These manifestations include erroneous actions by the pilot, delayed reaction to rapid changes in flight conditions, inattention, fatigue, illness, inaction, suicidal intent, hijacking of the aircraft by intruders, including terrorists, who are among the passengers, panic behavior of passengers, etc. The escalation of such a situation, considered critical, into an accident can be prevented if the aircraft is designed as a "smart" human-machine system with a high level of robotization. The automatic part of this system must be able to recognize dangerous human behavior and perform autonomous measures aimed at minimizing the risks. In the most extreme case, it must block human actions and transfer aircraft control to a fully automatic mode – until the end of the flight with a safe landing. The purpose of the article is to formulate the problem of developing an onboard automatic control system that meets such tasks, and a preliminary analysis of the possibilities of its solution. The specific features of the problem under consideration determine the choice of artificial intelligence elements, in particular neural network technology, for its effective solution.

***KEYWORDS*:** *aircraft, automatic control, critical situation, human factors, neural network, safety.*

1 INTRODUCTION

In modern aircraft, a significant portion of the flight control functions is performed or can be performed automatically, without the participation of a human operator (pilot). The prospect of civil aviation moving to fully unmanned transport air vehicles or passenger planes without crews is not clear – it has both advantages and disadvantages [1, 2]. Without making any additional contribution to their consideration, it should be noted that research and development (R&D) aimed at reducing human participation in aircraft control is largely motivated by the need to minimize negative manifestations of human factors during flight and the risks associated with them. The range of these negative manifestations covers erroneous actions of the pilot, delayed reaction to rapid changes in weather or air traffic conditions, inattention, fatigue, illness, inaction, suicidal intentions, hijacking of an aircraft by intruders, including terrorists, who are among the passengers, panic behavior of passengers on board, etc. If the escalation of a critical situation caused by any of these initial events – we will call such a situation anthropogenic – is not stopped, it can lead to a serious flight accident and even a catastrophe. Some examples of catastrophes of this genesis, which resulted in the destruction of aircraft and human fatalities, are given in Table 1.

Table 1. Some aviation catastrophes caused by negative manifestations of human factors in flight

Date	Location	Aircraft, airline and flight	Probable[1] cause
2001-09-11	USA, Washington, DC	Boeing 757-223, *American Airlines*, Flight 77	Hijacking of the aircraft by terrorists [4]
2001-09-11	USA, PA	Boeing 757-222, *United Airlines*, Flight 93	Hijacking of the aircraft by terrorists [5]
2001-09-11	USA, New York	Boeing 767-222, *United Airlines*, Flight 175	Hijacking of the aircraft by terrorists [6]
2001-09-11	USA, New York	Boeing 767-223ER, *American Airlines*, Flight 11	Hijacking of the aircraft by terrorists [7]
2009-06-01	Atlantic Ocean	Airbus A330-203, *Air France*, Flight 447	Misunderstanding of critical situation by pilots and erroneous actions to get out of it [8]
2013-08-14	USA, BHM	Airbus A300F4-622R, UPS, Flight 1354	Pilot fatigue [9]
2013-11-29	Namibia, Bwabwata National Park	Embraer ERJ-190AR, *Linhas Aéreas de Moçambique* (LAM), Flight 470	The pilot's suicidal intentions [10]
2015-03-24	France, Prads-Haute-Bléone	Airbus A320-211, *Germanwings*, Flight 9525	The pilot's suicidal intentions [11]
2016-03-19	Russia, Rostov Airport (ROV)	Boeing 737-8KN, *flydubai*, Flight FZ981	Pilot fatigue [12, 13]
2021-07-06	Russia, Kamchatka, Palana	Antonov An-26B-100, Kamchatka Aviation Enterprise	Lack of time to perform the required maneuver [13, 14]

Fortunately, not every critical situation that arises in flight leads to catastrophe – sometimes a safe outcome is possible. It is the bifurcation nature of a critical situation that is its distinguishing feature – a control action applied rightly in spatial and temporal terms can prevent it from turning into a disaster. This is the difference between a critical situation and an emergency one – the latter, as a rule, is irreversible and results in an accident that is associated with destruction and material losses. An example of a critical situation created by humans and resolved safely is that which occurred on 17 February 2024, involving *Lufthansa* Airbus A321-231, flight LH1140. It was en route from Frankfurt to Seville. Near Madrid, the captain left the cockpit and shortly after, the co-pilot suddenly lost consciousness. The plane flew without pilot control for about 10 minutes. When the captain returned to the cockpit, he decided to divert to Madrid-Barajas Airport, where he landed without further incident [3].

Anthropogenic critical situations are characterized by uncertainty of occurrence, development and outcome. This uncertainty includes both aleatory and epistemic components. The first of them primarily encompasses pilot behavior patterns that are deviations from normal piloting but are predictable and associated with erroneous actions, delayed reactions, inattention, or fatigue. The uncertainty of the occurrence of a critical situation arising from any of these causes can be characterized by an appropriate probability estimate based on statistics accumulated in aviation. Based on the known causes of critical situations of this type and reasonable probability estimates, standard design and organizational measures can be implemented in order to minimize the risk of an accident or catastrophe.

[1] In the terminology of investigation reports.

Other negative manifestations of the human factor during aircraft flight – sudden illness of the pilot, inaction, suicidal intentions, hijacking, etc. – are more of an epistemic nature. They are difficult to predict and almost impossible to control, however, some preventative design and organizational measures are feasible.

The reversibility of critical situations provides a fundamental opportunity to cope with them and ensure a safe outcome. The purpose of this article is to explore this possibility and present the results in the form of an engineering formulation of the problem of creating a special on-board automatic control subsystem, intended to maintain safety in anthropogenic critical situations that may arise during the flight of a civil aircraft.

2 EXISTING APPROACHES TO MANAGING ANTHROPOGENIC CRITICAL SITUATIONS

2.1 TRADITIONALLY USED APPROACHES

Design measures aimed at minimizing the risk associated with aleatory uncertainty in pilot behavior (behavioral patterns of the first type – see Introduction) include constructing the cockpit interior and the human-machine interface according to ergonomic principles. These principles are established in existing standards and are being developed through ongoing research – some aspects of ergonomic design are discussed in the author's book [15]. Organizational measures are implemented in accordance with national and international regulatory documents, for example, [16, 17, 18]. These measures cover pilot education and training, selection based on professional suitability criteria upon recruitment and subsequent certification, periodic physical and mental health screening [13], pre-flight health checks of pilots, as well as the implementation of safety culture in airlines. Important elements of the latter include the private and commercial pilot responsibility to perform IMSAFE health assessment [19, 20] and mutual monitoring achieved through the presence of two pilots in the cockpit.

Regarding the second type of negative human behavior patterns, the potential manifestation of which is characterized, rather, by epistemic uncertainty, but is, in principle, predictable (see Introduction), design measures to reduce risk are limited. They mainly include protection against intruders entering the cockpit or against penetration of small arms bullets and fragments of explosive devices with specified parameters [21]. Organizational measures cover profiling carried out by airport security services to identify intruders, as well as the use of technical means for screening passengers and baggage.

In the event of an anthropogenic critical situation of any origin during aircraft flight, the traditional approach to flight safety, cultivated in civil aviation, is applied. This approach assumes that any hazards in flight, including those caused by crew errors, must be managed by highly qualified pilots and their appropriate training [18]. However, this approach, as well as the design and organizational measures described above, cannot ensure safety across the entire range of possible anthropogenic critical situations. This disappointing conclusion is confirmed by the list of aviation catastrophes in Table 1. Moreover, the existing system of ensuring flight safety in civil aviation, while generally quite reliable, apparently cannot guarantee the prevention of any anthropogenic critical situation or a safe exit from it in the future. Such a guarantee is hindered by the very nature of human factors, which are insufficiently studied and limited in control.

2.2 ALTERNATIVES

Understanding the limitations of managing potential negative manifestations of human factors in civil aviation motivates the search for alternatives to traditionally used approaches.

In situations created by humans in flight, an alternative approach can be implemented through intervention in the process of human control, which has become inadequate, by the automatic part of the human-machine system. The form of intervention may vary depending on the specifics of the situation. For example, if the cause of a critical situation is the unintentional erroneous actions of the pilot, in particular, due to a lack of understanding of the complex flight situation, but these actions do not create an instantaneous threat of an accident, then the intervention can be "soft" – in the form of a recommendation to the pilot to correct his actions or in a slight automatic modification of the pilot's control actions to improve the flight [22].

In situations of a more serious nature and rapidly developing in a negative direction, their development can be stopped and a safe outcome ensured by blocking dangerous human behavior and transferring aircraft control to automatic mode. This "hard" intervention can also be used in a critical situation of the first category if the pilot did not follow the recommendation and (or) missed the time to correct his errors. The second type of intervention is of primary interest, since it is the most complex and applicable to the most extreme cases. For cases such as an obvious hijacking attempt or an aircraft deviation from its flight plan noticed by the air traffic control center, not attributable to the actions of the authorized flight crew, a number of technical solutions have been proposed – see, for example [23, 24, 25, 26]. These solutions are typically based on the crew's or air traffic controllers' assessment of the critical situation, as well as their involvement in control, including remote control of the aircraft from the ground. To the author's knowledge, none of the proposed solutions have been implemented in serial products.

The alternative proposed in this article is the situational replacement of human control, which turns out to be insufficiently reliable or even dangerous, with automated control. This idea goes beyond the traditional design and organizational measures used in civil aviation. It only partially overlaps with the alternative technical solutions presented in the aforementioned publications. The approach implementing this idea is aimed at ensuring safety in the entire range of the anthropogenic critical situations and is based, rather, on the philosophy of space technology. Given the extreme nature of the physical processes when launching a spacecraft into orbit or re-entering the atmosphere, as well as the complexity of maneuvers in orbit, that exceed the control capabilities of the human operator, this philosophy provides for predominantly automatic control. The participation of the human operator in control is only an option, implemented in a limited number of space operations.

For example, no cosmonaut (pilot) was present on board the Soviet aerospace vehicle (shuttle) *Buran* (Fig. 1) during its test flight and return to Earth on November 15, 1988. Its landing on the airfield runway was carried out automatically [27]. A similar concept is currently being implemented to varying degrees in unmanned aerial vehicles, including military ones. However, the approach described below differs from fully automatic control of an aircraft. Its essential distinguishing features are as follows:

– the automatic control system has a special component which works simultaneously with the pilot – it monitors not only the flight conditions, but also carries out a kind of supervision over his actions, as well as the situation in the cockpit and passenger cabin from a safety point of view;

– this component intervenes in the control performed by the pilot when a critical situation arises and carries out autonomous actions – up to the complete exclusion of the pilot from the control loop and the implementation of other protective measures.

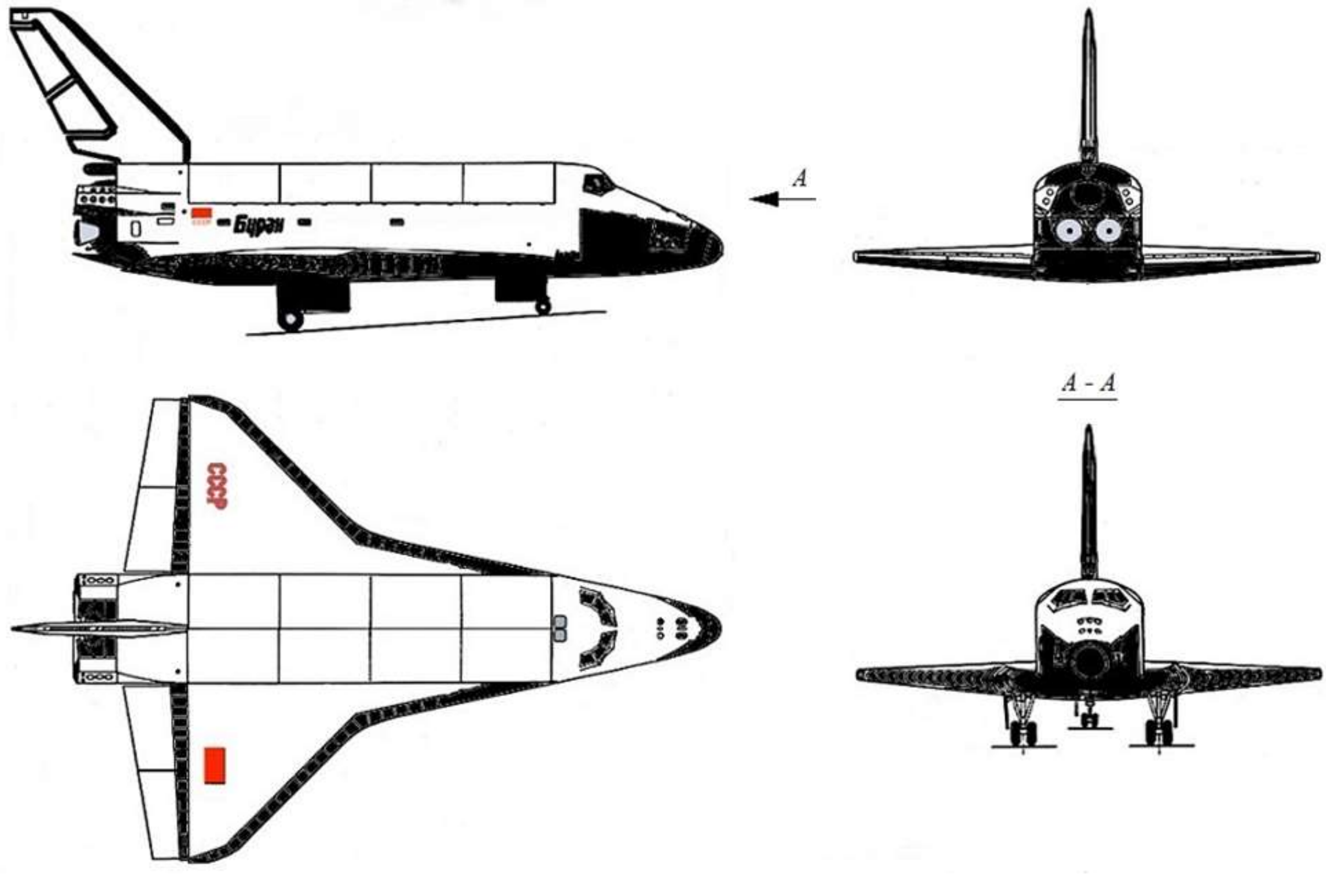

Fig. 1 Aerospace vehicle *Buran*. Reproduced from the image by Lee Brandon-Cremer: https://en.wikipedia.org/wiki/Buran_(spacecraft)#/media/File:04_OK-1.01.png, CC BY-SA 4.0

To ensure this situational takeover of control, an aircraft – plane, helicopter or airspace vehicle – should be designed as a human-machine system with a high level of robotization. The special component of the automatic control system should be capable to recognize critical situations (in the context under consideration, anthropogenic), determine an automatic control algorithm adequate to a specific situation and aimed at a safe outcome from it, and also perform appropriate control actions. All these functions must be carried out in real flight time. The current level of science and technology makes it possible to implement the component in question as part of an on-board automatic control system.

The current stage of R&D carried out in this direction with the participation of the author includes an engineering formulation of the problem and an analysis of the possibilities of its solution.

3 THE PROBLEM STATEMENT

The problem of situational takeover of control when an anthropogenic critical situation arises in flight in order to ensure a safe way out of it can be formulated as follows: it is necessary to equip the onboard automatic control system with a special component that must solve three tasks, or lower-level problems, in real time:

1) recognition of the situation;
2) determination of the algorithm for managing the situation and
3) implementation of this algorithm.

The first task is essentially similar to that solved during the investigation of an aviation accident post-factum, but differs from it because it must be solved directly in flight, and the result of the solution must be unambiguous – in the form of an algorithm of automatic actions that would ensure a safe way out of the situation. Reliable recognition of the situation in both cases requires information obtained through several channels: sound recordings, video data, and sensor data characterizing the flight parameters, as well as control actions and the state of the aircraft systems. All sounds in the aircraft cockpit are currently gathered by the cockpit voice recorder (CVR) and sensor data by the flight data recorder (FDR). These recordings assist accident investigators. Video recordings of the cockpit or passenger cabin are not generally made.

Automatic recognition of the situation in real time is possible using electronic processor devices capable of identifying certain markers (or patterns) in the data coming through each channel that characterize its occurrence and course, and of generating integrated judgments about the nature and probable development of the situation. The solution to this task (the first of the low-level problems in our list) is, according to available information, in the early stages of research and development in global civil aviation. No serial-produced electronic devices of this kind were found.

The second low-level problem that requires a solution after recognizing an anthropogenic critical situation is to determine the algorithm for managing it in order to achieve a safe outcome (a safe way out of the situation). Such algorithm should provide for the following groups of operations:

– blocking dangerous or potentially threatening actions of pilots and (or) passengers;

– transferring aircraft control exclusively to automatic mode and

– performing the automatic control with a certain spatial scheme of force application and time profile.

The solution to this problem may not be easy, given the variety of critical situations that may arise in flight due to human fault. For the second problem, as for the first, no ready-made solutions applicable to the entire range of possible situations were found in the available sources of information. It is reasonable to assume that the algorithm appropriate to a particular situation can be determined by selecting from a pre-developed set of algorithms, taking into account established criteria of applicability and effectiveness.

The selected algorithm must be implemented (the third of the low-level problems in the list above) by the relevant control circuits including actuators and secondary flight controls, that are capable of generating the necessary control forces. Air vehicles are currently equipped with control circuits that use mechanical, hydraulic or electromechanical actuators and movable aerodynamic surfaces (rudders, ailerons, elevons, flaps, etc.). These elements can produce the control actions needed to manage some critical situations. However, in the event of failure of the aerodynamic secondary controls, their actuators, or the entire control loop, there are no proven technical solutions that guarantee a safe outcome. In such cases, other design solutions are required.

The absence of ready-made technical solutions on a number of issues indicates the significant novelty of the problem at hand. There is an obvious need to develop appropriate practical proposals for solving these issues in order to create the required component of the automatic control system for an aircraft. The proposals should cover solutions to the following tasks:

1) implementation of video recording of the situation in the cockpit and passenger cabin;
2) development of methods for recognizing anthropogenic critical situations in real time using all three data recording channels: CVR, FDR and video;
3) an experimental study of the sufficiency of information received through these channels, and in case of

insufficiency, a proposal to obtain additional information;

4) embodiment of recognition methods in on-board electronic devices (including the choice of the most effective combination of software and hardware);
5) development of control algorithms for a conceivable set of anthropogenic critical situations, including all three groups of operations that must be performed in real time, and a technique for selecting the best algorithm for a specific situation using certain selection criteria;
6) development of appropriate control circuits for the implementation of these algorithms, including actuators and elements generating control forces;
7) development of the architecture of an on-board automatic control system for anthropogenic critical situations, and linking it with the flight control systems currently in use or under design.

4 ANALYSIS OF THE SOLVABILITY OF THE PROBLEM

The analysis of the solvability of the problem of creating a component of an aircraft automatic control system for managing anthropogenic critical situations is carried out by considering the individual tasks within this problem, which are listed at the end of the previous section.

The first of these tasks (implementation of video recording) seems quite simple from a technical point of view. However, as attempts to equip cockpits with video cameras have shown, pilots are opposed to such measures, and overcoming their resistance can be a significant organizational challenge. The solution lies in the intersection of industrial and organizational psychology and maintaining a safety culture in airlines.

Methods for recognizing anthropogenic critical situations based on available flight records from CVR and FDR (see the second task in our list) have so far been developed mainly for use in aviation accident investigations. In particular, it is possible to recognize the mental state of pilots by analyzing the recording of their conversations in the cockpit [28]. There are also attempts to identify abnormal pilot behavior based on data from FDR, characterizing the process of manual control through deviations of the aerodynamic secondary controls in an emergency situation [29]. The key issue for the use of these methods in flight conditions is their applicability on board an aircraft and in real time.

Information obtained from the CVR, FDR, and video (if video recording is feasible) may be insufficient to recognize critical situations caused by certain unhealthy conditions of the pilot, his inaction, or suicidal intention, especially when these conditions have no audible or visible signs of manifestation. If the pilot is alone in the cockpit, and if he loses consciousness, remains silent, or shows no visible intention, it is extremely difficult to determine what is happening to him based on this information. Given such situations, it may be necessary to conduct experimental studies to find additional sources of information that can fill this gap (the third task). The best source of information is the one that provides a clear picture of the processes in the pilot’s mind that initiated the anthropogenic critical situation.

Methods for identifying processes occurring in pilots’ minds, which are used by aviation psychologists in accident investigations and professional suitability assessments [13, 28, 30], are unlikely to be applicable to recognizing critical situations in flight. However, these processes must inevitably manifest themselves in some physical, but non-mechanical, phenomena, which, if identified, can be considered diagnostic signs. Such signs could include, for example, specific patterns in the electromagnetic field emitted by the brain. Despite the weak intensity of the electromagnetic field generated by neurophysiological processes, modern technology makes it possible to record it using instrumental methods. It is possible that additional sources of information required for reliable recognition of some anthropogenic critical situations in real time should be based on the development of these methods and their implementation in the automatic control systems of aircraft.

The solution to the fourth task (embodiment of recognition methods in on-board electronic devices) should involve the choice of a combination of software and hardware based on the criteria of their seamless inclusion in the automatic control system of aircraft and the minimum time spent on recognizing a critical situation.

When solving task 5 (development of control algorithms for a conceivable set of anthropogenic critical situations and a technique for selecting the best algorithm for a specific situation), it is necessary to take into account:

- the nature of each critical situation in question and the human behavioral parameters characterizing it;
- variables describing the current flight conditions;
- the current state of the aircraft in terms of operability and safety (integrity, controllability, degradation of the properties of elements, etc.);

- the control forces necessary to implement a safe way out of the situation;
- available characteristics of control circuit elements;
- changeability of the situation over time and the time reserve available for control actions;
- the emergence of additional loads at a certain combination of spatial scheme of control forces and their time profiles with the dynamic properties of the aircraft;
- limitations imposed by the environment (flight altitude, terrain, meteorological conditions, etc.).

In many respects, this task is similar to that which must be solved when ensuring the safe emergency landing of an aircraft [31]. Therefore, a solution should likely be sought within the SPARS (Smart Pro-Active Resilient System) design concept described there. The functions of the component of the aircraft automatic control system in question, which is intended to provide control in anthropogenic critical situations, fall within the range of functions of the Critical and Emergency Control System (CECS) (ibid). At this stage of R&D, it is difficult to determine whether it should be implemented as an autonomous subsystem within CECS or integrated into this system as a set of additional options.

In any case, the component that provides control in anthropogenic critical situations will use, among many onboard equipment elements, actuators and elements generating control forces – both aerodynamic secondary flight controls and new ones not yet used in aviation. The latter could include, for example, small solid-fuel rocket engines similar to those applicable in emergency rescue systems (launch escape systems) or soft landing systems for spacecraft. Technical proposals for these elements can be prepared as a result of solving task 6. These proposals, as well as results of solving task 7, which should determine architecture of the component in question and its interface with the integrated Flight Control System (FCS) or Intelligent Flight Control System (IFCS) equipped with artificial intelligence [32, 33], can form the content of the corresponding conceptual design.

5 PREFERENCE FOR NEURAL NETWORK TECHNOLOGY

The key features of the problem of creating a component that provides control in anthropogenic critical situations from the point of view of information technology are the following:

1) the heterogeneous nature and multiplicity of data required to recognize the situation and determine an effective control algorithm and, thus, subject to processing;
2) continuous updating of these data during the development of a critical situation, and, accordingly, the need to process them and obtain results in real time;
3) requirement for installation of the component on board the aircraft.

Similar features are inherent in the problem of ensuring safety during an aircraft emergency landing. To solve that problem, the choice was made in favor of neural network technology [31]. This technology also appears preferable for control in anthropogenic critical situations. Indeed, effectively recognizing such situations is unlikely to be possible without the use of a neural network. The challenge lies in training it. Given the variety of situations, training is not an easy task, but it will be carried out not in flight conditions, but on the ground and in advance.

Recognizing patterns based on a set of characteristic elements is a typical task that a neural network can solve. In our context, the pattern to be identified is a set of data of different modalities (audio, video and sensor signals). Determining an algorithm for control in an anthropogenic critical situation is possible using classical methods of applied mathematics and mechanics, including solving the differential equations of aircraft motion. However, this requires extensive computational resources unavailable onboard the aircraft and is not applicable under the time constraints typical of a developing critical situation. Using a neural network, pre-trained on a representative set of examples corresponding to a conceivable set of anthropogenic critical situations and flight conditions, ensures the algorithm can be determined with minimal time expenditure.

Another preferred area of application of neural network technology is the processing of the results of experimental study aimed at discovering additional channels of information for the purpose of more reliable recognition of an anthropogenic critical situation.

An important argument in favor of neural network technology is the ability to process fuzzy data, which will inevitably be present in information flows of various natures.

It remains to be added that the development of a neural network and its training for the above-mentioned applications should be an integral part of the project to create the control system component in question. An aircraft that implements the control in anthropogenic critical situations acquires the properties of a robotic system and can be called a "smart" aircraft. The idea described is reminiscent of the first of the three fundamental Rules of Robotics, formulated by Isaac Asimov in his book *I, Robot*: "A robot may not injure a human being, or, through inaction, allow a human being to come to harm."

CONCLUSION

The presented research shows that the design and organizational measures currently used in civil aviation do not ensure safety across the full range of critical situations that may arise during an aircraft flight due to negative manifestations of human factors. Aviation accident statistics confirm the existence of the problem. The proposed solution to it is to give the aircraft the properties of a "smart", i.e. highly robotic system, capable of recognizing the emergence of an anthropogenic critical situation on board and taking control to ensure a safe outcome. The article describes the engineering formulation of the problem of creating a special on-board automatic control subsystem intended to perform the corresponding functions. The formulation of the problem is accompanied by an analysis of its technical feasibility.

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