ISSN 1019-3316, Herald of the Russian Academy of Sciences, 2018, Vol. 88, No. 1, pp. 28–36. © Pleiades Publishing, Ltd., 2018.
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On the Rostrum of the RAS Presidium

Prospects for the Intellectualization of State-of-the-Art Aviation Systems

S. Yu. Zheltov* **and V. V. Kos'yanchuk****,#
State Scientific Research Institute of Aviation Systems, Moscow, Russia
**e-mail: zhl2604@gmail.com*
***e-mail: kos.vl.v@gmail.com*

Received March 31, 2017

Abstract—This article, based on a paper heard at a meeting of the RAS Presidium, analyzes the main problems of and trends in the intellectualization of state-of-the-art aviation complexes. The obtaining and intelligent processing of heterogeneous information, intelligent management, and aircraft "self-sensing," as well as intelligent interaction within the pilot—aircraft contour, are highlighted as key functional objectives for the foreseeable future. The primary focus is made on the intelligent processing of measuring and video information, including the automatic mutual referencing and uniting of measuring and geospatial information into a visual complex; continuous provision of an accurate, authentic, and holistic image of the surroundings to the crew, regardless of weather and time conditions; recognition and prediction of dangerous combinations of factors considering the flight path; assessment of the crew's psychophysiological condition; changes in the external environment and technical condition of the aircraft; and recommendations for the crew to escape or prevent abnormal situations.

Keywords: intellectualization, integrated modular avionics, situational awareness, 4-D path, robustness, reconfiguration, sensor networks, technical authentication, design, simulation.

DOI: 10.1134/S1019331618010136

The development of both military and civil aviation equipment is inseparably associated with meeting two key requirements: aircraft flight safety and efficacy. Although civil aviation focuses more on safety and military aviation, more on efficacy, the most crucial indicators, nevertheless, are practically the same. Safety is the reduction of the number of aircraft accidents and failures, the mitigation of their consequences, and improved robustness. Efficacy is the minimization of life-cycle cost, fuel consumption, and flight time and high-accuracy schedule and route compliance. Military aviation adds requirements associated with ensuring the maximum range of combat use, high guidance accuracy, and aircraft stealth characteristics.

The human capacities to match these requirements have practically reached their limit. An increasingly larger list of pilot functions should preferably be passed over to machines. The intellectualization of the onboard equipment set (OES) is under way; this is a step-by-step introduction of software and hardware flight support components, which have traditionally been attributed to the activity of a human operator [1–6]. The changes are taking shape thanks to significant progress in information technologies in aviation. Of key importance is the transfer from federative architecture, in which each individual aircraft function was implemented in a corresponding individual block, to an architecture built on the principles of integrated modular avionics. In our country, it was proposed by the GosNIIAS associates in the late 1990s (Academician E.A. Fedosov supervised the work) [7]. This new concept offers to convert hardware functions into software and the OES structure, into the structure of an onboard computer network. The transfer to integrated modular avionics depends primarily on a significant increase in the complexity of onboard systems, which require high performance (e.g., one of the promising aircraft navigation systems is a program consisting of 850000 lines), as well as on a substantial redistribution of software and hardware costs (at present, the software development cost may reach up to 60% of the hardware cost). The transfer to integrated modular avionics and the introduction of software at all levels of aircraft control have made it possible to switch to the phase of active aircraft intellectualization [8–11].

The following main vectors in the intellectualization of aviation complexes (ACs) can be emphasized:

[#] RAS Academician Sergei Yur'evich Zheltov is Director General of the State Scientific Research Institute of Aviation Systems (GosNIIAS). Vladislav Viktorovich Kos'yanchuk, Dr. Sci. (Eng.), is a Deputy Director General of GosNIIAS.

- acquisition and intelligent processing of heterogeneous information;
- aircraft intelligent control;
- aircraft intelligent “self-sensing”;
- intelligent interaction in the pilot—aircraft contour;
- intelligent modeling of aviation complexes.

INTELLIGENT PROCESSING OF HETEROGENEOUS INFORMATION

Improved situational awareness of the crew. The performance efficacy and prospects for the development of aviation systems are specified by the ability to fly safely day and night, in complex and quickly changing meteorological conditions, and in poor visibility. According to the Flight Safety Foundation research, almost 75% of air crashes at landing approach and landing occur in airports that have no precision-approach instruments in conditions of poor visibility.

The appearance of new-generation sensors and computing tools has led to putting on the agenda the issue of automating several traditional information-processing functions of the pilot that were previously considered basically unavailable for automatic systems. First of all, we are speaking about the possibility to create automatic and automated systems of continuous visual representation of external space, which depends on three basic factors. First, the visual perception channel is one of the most important information sources in traditional man—machine aircraft control systems. Second, the use of high-resolution digital video sensors in state-of-the-art automatic systems has made it possible to draw the informativeness of artificial visual devices to significantly nearer to the corresponding characteristics of the human eye. Third, the hardware capabilities provided for by the latest electronics are so high that the potential capacities of advanced onboard computers should approach the characteristics of the “computing capacities,” the brain in image processing. Therefore, as the performance of onboard computers that process visual information (including 3-D graphics) increases, the creation of enhanced, synthetic, and combined vision systems becomes a topical and dynamically developing trend in the improvement of onboard avionics [12—15].

The enhanced vision system (EVS) is a hardware—software system that forms a visually enhanced image of the external environment using information from artificial vision sensors. The EVS comprises a subsystem of artificial vision, which inputs and processes video information, and a subsystem of computer visualization, which directly forms and provides graphic images of the external environment of the cockpit to the pilot. The sources of information could be television and infrared sensors of various ranges, microwave radars, laser locators, databases of terrain relief along flight routes, databases of airports and runway facilities, navigational parameters, and several others. The EVS-formed live graphic information is then passed to the pilot in real time on the corresponding display device: a head-up display or a multifunction display.

Considering the spectral limitations of human vision and the relatively low speed of processing complex and quickly changing information presented to the pilot, this information should be processed, interpreted, and prepared to the maximum for presentation in a human-readable integral form together with other graphic and textual data. This leads to the necessity to include intelligent elements of preliminary scene (object detection and recognition) analysis into the manned aircraft information support systems, which are typical of automatic control systems.

The synthetic vision system (SVS) forms in the onboard computer and outputs to the display devices the image of a topographic section observed from the cockpit; information on aircraft space orientation, flight altitude, and geographical coordinates of the aircraft; and onboard database information (Fig. 1).

Image presentation systems for navigation data as 3-D relief imagery, paths, preset limitations to flight parameters, and other characteristics, dynamically changing with the flight conditions, simplify significantly the pilot’s spatial orientation compared to the use of digital-scale indications. However, the presence of navigation errors, unaccounted hindrances and terrain relief, and database formation and updating delays, in fact, makes it impossible to operate the SVS independently.

The most promising is the use of the aircraft onboard combined vision system (CVS), which combines the best properties and characteristics of the EVS, forming an enhanced and combined image from several heterospectral sensors of the artificial vision system, and the SVS, forming the image of a virtual terrain model by its digital map, as well as navigation and pilot-centered aircraft parameters.

The CVS ensures the increased visual range of reference points and improved situational awareness of the crew by forming and displaying a unified graphic image of real and virtual images of the external environment of the cockpit using artificial vision and computer visualization tools. In addition, it is possible to use the CVS detached display mode, when the pilot, as a rule, uses the SVS imagery when flying at high altitudes and the EVS when landing and taxiing on the runway.

Covisualization of combined images in real time does not constitute special problems, since it depends on the necessary degree of mixing several images. However, this degree in the general case can be different over the entire image and can have its own value for various screen areas (display windows) and depend on the flight stage and phase. The task of choosing an

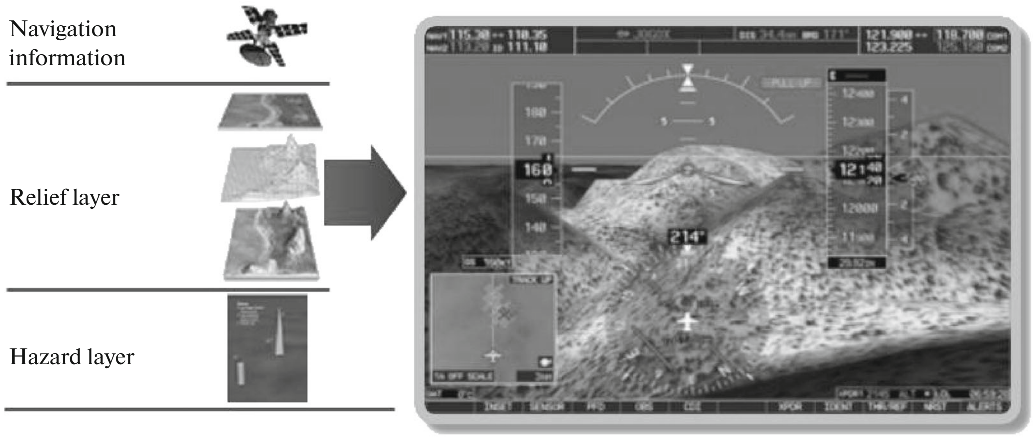


Fig. 1. An example of a synthetic image.

image fusion option efficient for the crew is difficult and should be solved considering (a) the specific phase of flight mission execution, (b) the spatial image error of image fusion imparted under the given conditions, and (c) the visibility conditions.

The highest temporal complexity characterizes the task of combining EVS images with the image of the virtual terrain model obtained from the digital terrain map and navigation data: the current position coordinates and the positioning angles of sightlines of the artificial vision sensors. This is due to uncertainty in choosing the section and perspective for building the virtual terrain model because of the high error of the coordinate and angular positioning of the artificial vision sensors. To solve the problem of alignment in real time by the method of full enumeration of possible perspectives of the virtual terrain model requires building about 10^5–10^6 perspectives of this model per second, which exceeds at least 10^3 times the capacity of the state-of-the-art onboard computing platform.

The main problem that arises during preliminary image processing is the development of methods and algorithms of "understanding" images received from various sensors. The difficulty of "understanding" can be explained by the fact that its intelligent (algorithmic) component turned out to be much more complex than traditional problems, which had served as the field of application for artificial intelligence methods. The difficulty of the information contents of images is the infinite variety of brightness and geometric structures, the generation models of which are unknown a priori or can be simply absent. In this sense, it is hard to "understand" even individual objects present in the observation scene. The detection and identification of many types of such objects, for example, buildings and roads on air photographs, have become the subject matter of new trends in intellectualization studies. Solutions to the above problems will help create a next-generation CVS, which will significantly exceed the currently known systems in the set of combining functions, especially in intelligent image processing.

Pilot's Associate information systems. The Pilot's Associate intelligent information systems are designed

- to display continuously to the crew accurate, authentic, and holistic images of the environment regardless of weather and time conditions;
- to recognize in real time dangerous combinations of aircraft external and internal factors fraught with abnormal situations, rate the identified factor combinations by hazard, and display them audiovisually to the crew;
- to predict future hazardous combinations of factors considering the flight plan (path) and assess changes in the external and technical conditions of the aircraft;
- to work out recommendations for the aircraft crew to cope with, mitigate, or prevent abnormal situations;
- to make individual decisions and automatically exit abnormal situations, mitigate or prevent them, and block pilots' actions entailing abnormal situations or increasing the degree of hazard.

The above tasks have been investigated to different degrees. For example, the first two of them are already implemented today aboard aircraft. As for predicting the evolution of the environment and hazardous factor combinations, this requires special databases. The function of making recommendations is associated with the creation of a knowledge base, which accumulates the practical experience of pilots in abnormal situations. Finally, the function of decision making implies maximum responsibility and can be initiated in the future only after a certain period of successful operation of a system with a simpler functionality.

The algorithms of the Pilot's Associate intelligent information systems in the future onboard equipment set can be implemented using general computing resources, as well as by creating an individual compu-

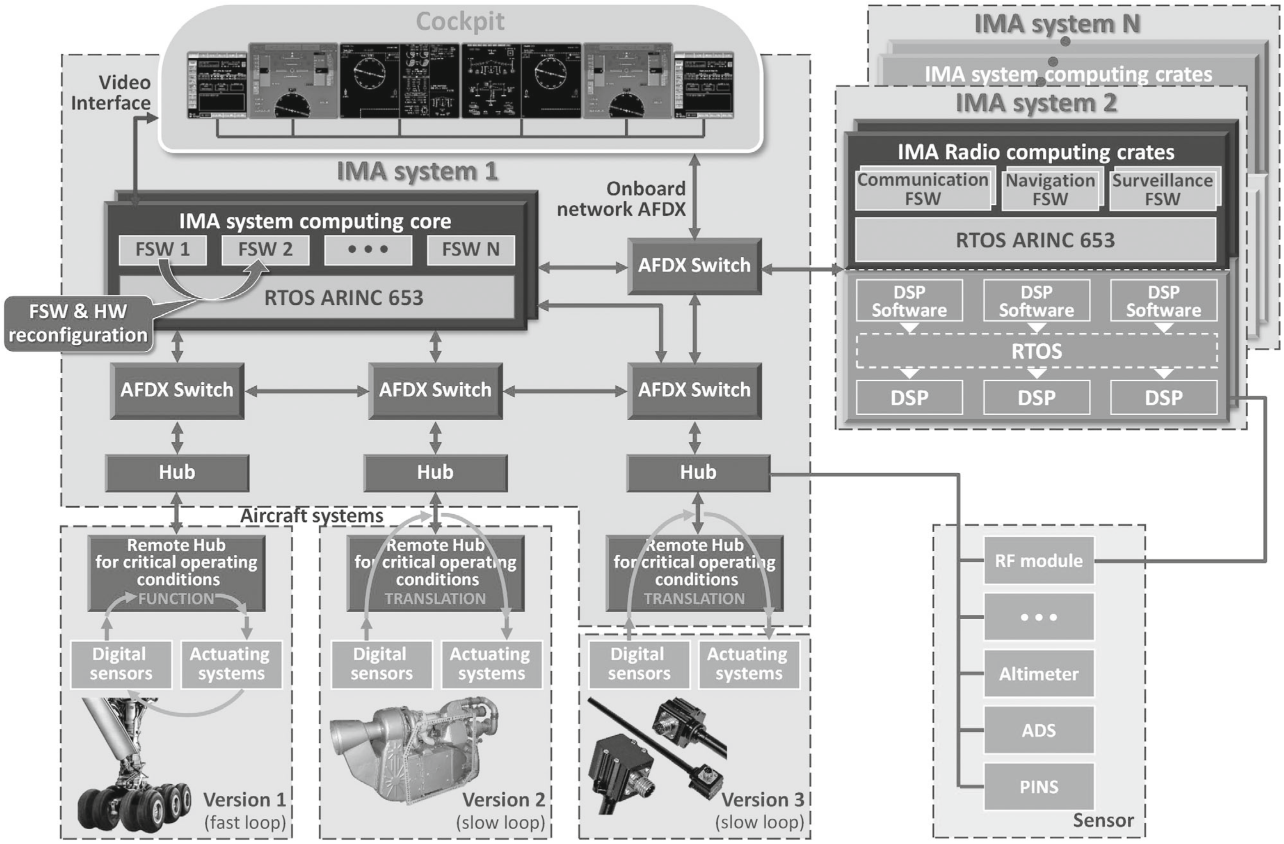


Fig. 2. Computation process control.

tational platform within integrated modular avionics [16]. At the same time, in many spheres of aviation equipment application, the point is not to improve separate characteristics of single aircraft but to find the most effective ways of building and using holistic control, communication, and information acquisition and processing systems. These systems may include many aircraft, as well as several subsystems, services, and networks, including those associated with imaging and geographical data. They may include space and aviation data acquisition platforms; geographical support services; ground-based information acquisition systems; and systems of operational planning, modeling, navigation, traffic control, and targeting, among others [17].

AIRCRAFT INTELLIGENT CONTROL

4-D flight path control. Flight path formation considering destination arrival time, i.e., 4-D paths that will become a significant element of the next-generation air traffic control system, is becoming a key trend in control intellectualization [18, 19]. It is assumed that airplanes will fly by accurate four-dimensional paths, where time is the fourth dimension. It will require coordinating the 4-D flight path from takeoff to landing and tracking and updating it considering, for example, factors such as wind shift or limitations within the air traffic control system. Let us assume that the dispatcher appoints the target time of arrival for the aircraft crew with an accuracy of 5 s. As the aircraft approaches the airport of destination, the flexibility in determining the target time of arrival decreases. The implementation of this approach will require optimizing the aircraft performance characteristics by the cost index considering all limitations based on an expanded model of the atmosphere (multilayered wind and temperature) and a 4-D path built simultaneously for each type of flight plan (active, changed, additional).

Simultaneously, integrated information processing, identification of spacecraft characteristics, assessment of disturbing vectors, and prediction and control tasks should be solved aboard aircraft. This approach will help reduce flight costs significantly.

Computation control is becoming most topical due to the fact that the advanced OES has an open network fault-tolerant function-oriented architecture based on scalable integrated modular avionics using a common computing environment [20]. The functions of the systems in this case are performed by software applications, which share common computing and information resources. An important characteristic feature of this architecture is the absence of rigid, hard and fast links between the sensors of onboard equipment (information channels) and computing facilities. This opens the opportunity to reconfigure dynamically the OES structure, redistributing resources correspondingly [21]. Structures for optimal execution of each preset function are formed (and connected to the necessary information channels of the system) within the computing environment. The common configuration of the computing environment is restructured dynamically during operation of the system. This feature becomes key at faults. Reconfiguration decreases the effect of the computing platform's faults on overall flight safety (Fig. 2). The future OES requires a minimal nomenclature of unified interchangeable open standard items (modules, systems) with a high capacity and energy efficacy. Highly integrated multifunctional systems, for example, a single software-controlled radio communication, navigation, and observation system, can be imbedded into this structure. General aircraft systems also use the system's common computing resources to the maximum.

Reconfiguration of control systems. State-of-the-art aircraft control systems are complex, highly reliable, and multiply redundant. Nevertheless, under contingency conditions, the consequences of their faults cannot be eliminated by backing up; therefore, failures of control systems are critical. An example is the breakdown of control-surface drivers, damage to all communication lines of the control computing system with drivers because of fire, the destruction of control-surface consoles, etc. To ensure fault tolerance when such problems arise, advanced aircraft have the capacity to reconfigure the control system [22]. Aircraft controllability is ensured by redistributing the functions of failed control channels among the remaining intact channels. For example, the failure of the aileron channel is counteracted by a differential deflection of the elevators and the failure of the stabilizer channel, by the agreed deflection of the ailerons and elevators.

A promising trend in control system reconfiguration is the use of analytical approaches that yield multiple possible solutions symbolically only through algebraic (arithmetic) operations [23]. Analytical methods help trace the effect of initial data on the final results, helping significantly to solve problems for nonstationary dynamic aircraft models, especially in critical flight modes. Analytical expressions, including those for optimal and robust solutions, help improve the accuracy by minimizing the number of numerical computations [24, 25]. Intelligent failsafe control systems are being developed to use various reconfiguration algorithms depending on the accurate (erroneous) solution of problems to identify intact or defective aircraft models (predictive maintenance) and to reconfigure control proper [26].

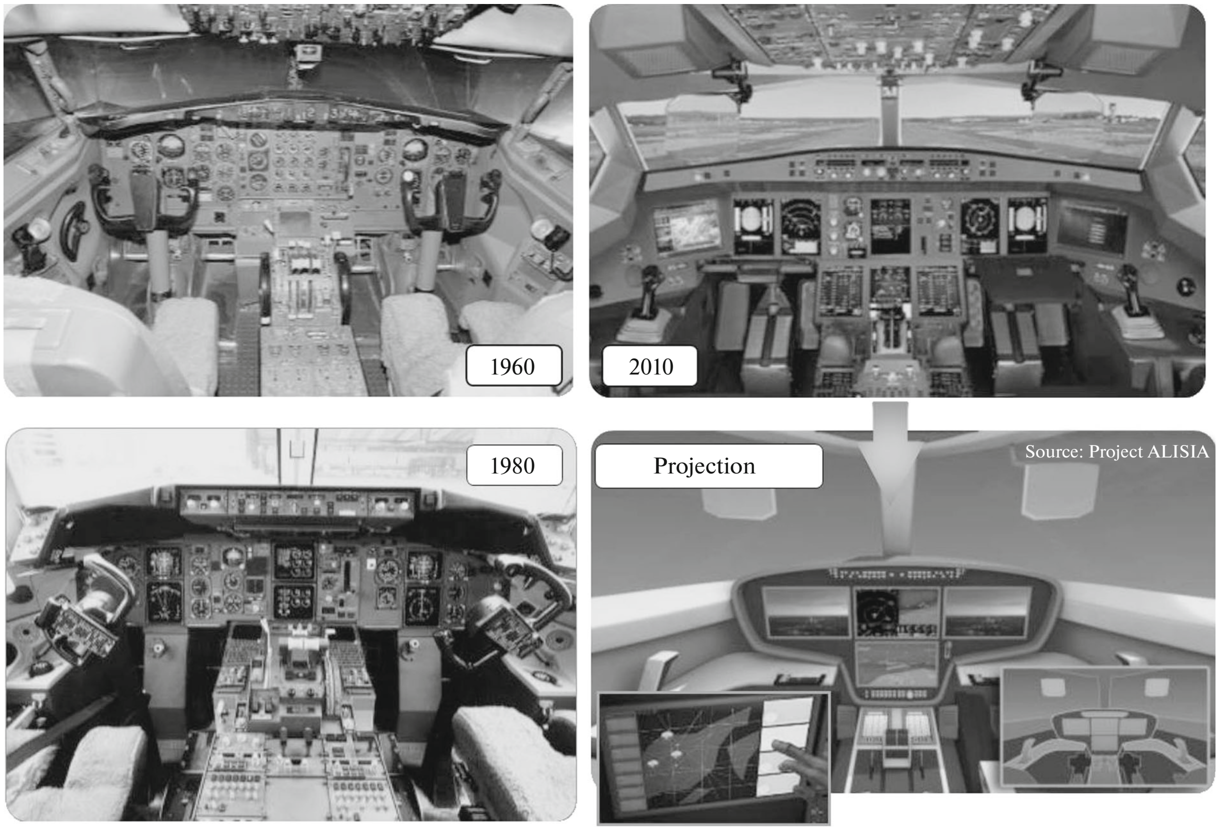
INTELLIGENT AIRCRAFT "SELF-SENSING"

Wireless sensor networks. The OES functionality of advanced aircraft is substantially expanded by onboard wireless distributed systems, built using energy-saving technologies, for observation and control over resources and processes. Such systems may include tens of thousands of relatively closely located and networked miniature intelligent nodes, capable of measuring and adjusting various physical parameters, as well as preprocessing and transferring information [27, 28]. These systems are designed to solve the following tasks: to monitor the technical condition of aircraft elements; to monitor loads on the aircraft structure and elements, cargo, passengers, and the crew; to monitor the microclimate in the cockpit and cabin; to monitor and control the airfoil of aircraft elements; to control the distributed actuation devices of the aircraft control system; to monitor the psychophysiological condition of the crew and passengers; and so on.

Energy-saving and maintenance- and special installation–free (vibratory, infrared, electrochemical, electromechanical, acoustic, and optical fiber) sensors; micro- and nanoelectromechanical actuators; thermoelectric, vibratory, kinetic, and electromagnetic generators; and power accumulators (supercondensors) will form the technological basis for such systems. Distributed self-organized and failsafe systems of big data acquisition, processing, and transmission, which form the "nervous system" of the aircraft are based on various data transfer technologies with a dynamically reconfigurable topology and low energy consumption.

Technical authentication. Safe operation of aircraft largely depends on the authenticity of information about the technical condition of the aircraft and its components, especially its actualization when it is time to decide whether to continue operation or not. Important conditions for the successful solution of this problem are the use of information system technologies designed to automate the procedures of current information acquisition when assessing the authenticity of the life cycle of aircraft components, the organization of a fully paperless model of document processing, and full-scale remote control over the flight worthiness of aircraft components [29, 30].

The expanded use of information technologies entails the need to develop and introduce special electronic tools to be deployed directly on aircraft components, which contain data for their unambiguous identification and are capable of recording and storing data accumulated during aircraft operation. At present, the global aviation industry uses radio frequency tags as such special tools. The radio frequency identification (RFID) complex ensures their functioning and includes the necessary hardware and software components. Encoded information about the current state of aircraft components is entered automatically into RF tags; they permit reading it during aggregate authen-



Source: Project ALISIA

Fig. 3. Aircraft cockpits of various generations.

ticity monitoring procedures and repetitive rewriting. Then information flows are processed, systematized, and stored for a specified time; the analysis and formation of reports at the request of controllers are based on state-of-the-art database technologies, analysis tools, and telecommunications.

RFID enables transmission and reception of information from identifiable objects by the radio channel and does not require a visual line of sight or physical contact between the reader and the identifier. Thanks to these two advantages, RFID is gradually ousting bar coding and magnetic cards. RFID identifiers are not only convenient in use but can also store more information and allow various data coding systems for copy and falsification protection. RFID technologies are widely used in logistics, in access monitoring and control systems, and in electronic document flow. Another advantage of introducing them in the aviation industry is the improved quality of control over the aircraft life cycle and prevention of the use of inauthentic spare parts. The use of RF tags implies their fixation on aircraft components and accompanying documentation, covering manufacturers, assembly and repairs factories, and warehouses of aircraft operators.

INTELLECTUAL INTERACTION WITHIN THE PILOT–AIRCRAFT CONTOUR

Improvement of aircraft onboard equipment is inseparably associated with the expansion of its functionality. This, on the one hand, increases the amount of information coming to the pilot, simplifies flight control, and helps improve the level of flight safety and, on the other hand, significantly increases the load on the crew. Figure 3 shows aircraft cockpits of various generations. Obviously, the main trend is transfer to wide-format sensor displays, which show information in the form most acceptable for the pilot.

Two problems exist in intelligent interaction between the pilot and the aircraft: the presentation of information necessary for the pilot and information control [31]. What is the most optimal way of presenting heterogeneous information, perceived with auditory, visual, and tactile receptors, considering the psychophysiological condition of the crew? The solution is seen in infusing new qualities, based on integration of situational awareness systems and recommendations following the analysis of multiple flight factors, to the human–machine interface (Fig. 4).

During the control of the information field, increasingly important become new approaches that enable adaptation to the pilot's needs, his psychophysiological condition, and the specifics of the job done.

Fig. 4. Integration of situational awareness and rule-making systems.

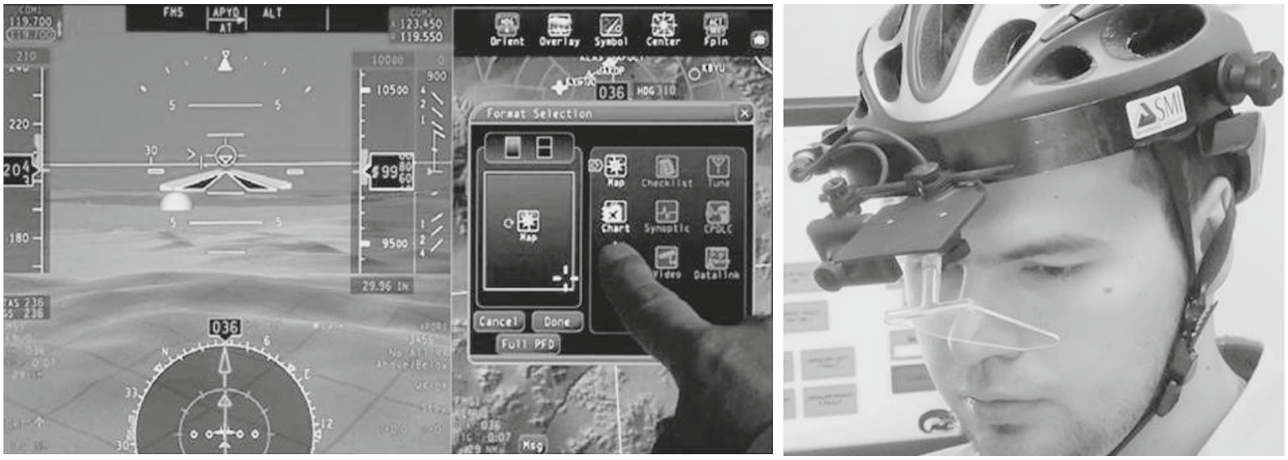


Fig. 5. An example of information field control.

These approaches are based on speech, ocular motility, and tactile sensations (Fig. 5). The use of virtual reality systems is also possible, but they must still be assessed on benches and tested in actual flight conditions.

SIMULATION AS A KEY TECHNOLOGY FOR TUNING AVIATION SYSTEMS

The design of state-of-the-art aviation complexes and systems is impossible without simulation technologies. GosNIIAS has been using them, including conceptual, mathematical, hardware-in-the-loop, and physical simulation, since the early 1950s [32–35]. Conceptual, or external, design is a special type of simulation, from which the technological process of product development begins and which can test and assess various options of the OES architecture. Conceptual design represents a methodology of forming and justifying the main AC characteristics at the initial stages of their development to minimize the temporal and input costs of their creation and reduce the risks of making erroneous technical decisions. Note the importance of this stage: although it requires only 2% of the total costs of AC creation, this is the stage that sets up to 70% of decisions made. Then follow avionics models: physical, hardware-in-the-loop, and mathematical. They generate models of aircraft control and navigation instrumentation, computing systems, etc. At the stages of mathematical and hardware-in-the-loop AC simulation, the correctness of decisions made at the conceptual design stage is verified and the AC technical layout is detailed.

Experience shows that, at the early stages of AC design, mathematical simulation methods are most effective. They help replace adequately the system or process under investigation with the corresponding mathematical model following its investigation using the methods of computational mathematics. To answer questions concerning an aviation system described by a mathematical model, it should be determined how to build this model. When a model is simple, it is possible to obtain an accurate analytical solution. However, many aviation systems are

Fig. 6. Prospective cockpit demonstrator.

extremely complex, and the opportunity of finding an analytical solution is practically absent. In this case, the model is investigated using simulation modeling, i.e., by multiple testing with various input data to determine their effect on the indicators of the system's operation.

GosNIIAS effectively uses the method of hardware-in-the-loop simulation. It implies study of aviation systems using simulation complexes. Along with real equipment, they can comprise, for example, impact and noise simulators and mathematical models of the environment and processes for which a precise mathematical description is unknown. The inclusion of real equipment or real systems in the complex process simulation contour makes it possible to reduce the a priori uncertainty of tasks at hand. During hardware-in-the-loop simulation, the advantages of mathematical and full-scale simulation blend gracefully, possibly attaining the optimal interaction between computational and full-scale experiments.

At present, observable is an increase in the role of virtual prototyping systems, which help save significant resources, because they make it possible to avoid inefficient operating modes of the onboard complex, which are identified at an early stage of simulation. GosNIIAS created virtual prototyping benches that, in fact, serve as virtual complexes of hardware-on-the-loop simulation (Fig. 6). A typical bench represents a cockpit simulator and a computing center where real onboard equipment and weaponry is represented by mathematical models. The virtual external world includes mathematical models of enemy aircraft simulating their onboard radio electronic equipment and weaponry and enemy air defense models. The external environment of the cockpit is simulated as 3-D scenes on the screens installed around the cockpit.

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The development of aviation equipment will always be a priority task for our country with its huge territory and a necessarily high mobility of the population. Russia can reach a new level of safe and efficient aviation operations only if it introduces advanced technologies of "intellectualization" of aviation complexes. Competitive advantages are reached if the most advanced and science-intensive developments are introduced. A breakthrough in intellectualization issues is attainable only under active interaction between the Russian Academy of Sciences and leading centers of applied science. This will help consolidate efforts to create a basic scientific groundwork, as well as ensure interindustry and interdisciplinary integration of breakthrough technologies.

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Translated by B. Alekseev