Basic Concepts of Building Modern Software and Hardware Systems of Aviation Training Simulators to Solve the Tasks of Training Pilots

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Abstract: The actual task of analyzing modern software and technical systems of flight simulators is solved to increase the number of training situations to improve the professional training of pilots. It is shown that it is advisable to divide all flight simulators into three classes, depending on the formation of certain components of the cognitive model of the pilot, in which his professional skills of solving problems of aircraft control and navigation are postponed. For each class of simulators, the specifics of the requirements for their main nodes are defined. In the simulators of the first and second groups, the use of modern software and hardware systems leads to a reduction in their size and energy consumption. For the simulators of the third group, the importance of forming a continuous image in flight conditions in any direction of the changeable part of the 3D-model of the flight area is shown. The latter requires the development and implementation of new algorithms for allocating image generator resources across the entire 3D-model of the flight area and solving problems of reducing or excluding control primitives from real-time processing, which should function regardless of the computers used underlying computer image generators.

1 INTRODUCTION

A flight simulator (SHukshunov, 1986) is a human-machine complex $K^{(A)} = \bigcup_{j=1}^{N^{(L+V+N_S)}} D_j^{(A)}$ that combines the j-th number of simulators $D_j^{(A)}$ (Krasovskij, Lopatin, 1992), which can be divided into three groups, according to the principle of modeling specific information for the pilot (GOST 21659-76). The total number of simulators is $L+V+N_S$. Each simulator of the three groups synthesizes information for the pilot in the m-th cycle of the real-time mode $\Delta t = 80мс$ during the flight on an aviation training simulator:

1) simulators from the first group information about the behavior of one of the l-th model of a specific aircraft unit from the list of L simulated aircraft units (which is a prototype of a specific flight simulator) (Artemov, Maksimova, SHCHerbak, Mashkin, Romanov, 2016),

$$I_j^{(A)}(m \times \Delta t) = F_j\left(D_j\left(l, m \times \Delta t\right)\right), \quad j = 1...L; \tag{1}$$

2) simulators from the second group provide information about the behavior of the v-th model of the air environment from the list of V simulated conditions of the behavior of the atmosphere in which the model of the aircraft moves (Gromov, Potapov, Ishchuk, 2022),

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$$I_j^{(A)}(m\times\Delta t)=F_j\left(D_j(v,m\times\Delta t)\right),$$
$$j=(1...L)...V; \quad (2)$$

3) simulators of the third group provide information about the visually observable part of the 3 *D*-model of the flight area (over which the aircraft model is currently moving (Ovchinnikova, Grigor'ev, Burluckij, 2019)) from previously developed 3 *D*-models of the flight area (as a rule: for observation in the visual range of electromagnetic waves through the cockpit windows of a flight simulator; for observation in the IR range of electromagnetic waves on the screen of a thermal imager simulator; for observation in the radio range of electromagnetic waves, for observation on the screen of the radar simulator), when synthesizing N_S of an image of the terrain in the observation conditions pre-determined by the Customer, taking into account the time of year – day, night, evening, morning,

$$I_j^{(A)}(m\times\Delta t)=F_j\left(D_j(s,m\times\Delta t)\right),$$
$$j=(1...L+V)...N_S. \quad (3)$$

At every moment of time, when flying a flight simulator, information $I^{(A)}(m\times\Delta t)=\bigcup_{j=1}^{L+V+N_s} I_j^{(A)}(m\times\Delta t)$ is synthesized that ensures the acquisition by the pilot of professional skills in solving problems that arise during flight on a real aircraft. The tasks of training a pilot in normal and pre-emergency conditions specified by the Customer are divided into two groups:

1) training of pilots to control an aircraft;

2) training pilots to solve aircraft navigation problems (Mamaev, Sinyakov, Petrov, Gorbunov, 2002).

To solve problems from the second group, a map or plan of a 3 *D*-model of the flight area (Sinke, Maslennikov, Selezneva, Neusypin, 2022) with the specified locations of 3 *D*-models of reference objects is needed, observing which the pilot determines the location of the aircraft model during flight on a flight simulator (Sazonova, SHelagurova, 2019), specifying it according to information from other simulators of the flight simulator (Sedova, Sedov, Bazhenov, Luchaninov, Glagolev, 2019), as well as he clarifies information from various sources during the flight (Roganov, Asmolova, Aidarbek, Esimova, Omirbekov, Kuvshinova, 2021).

Since it is impossible to create a complete model, each flight simulator, in addition to true information $I_j^{(A)+}(m\times\Delta t)$, synthesizes information that is considered false $I_j^{(A)-}(m\times\Delta t)$ (Slesareva, Ovchinnikov, Elistratov, 2016). The probability of the pilot being exposed to false information should be negligible (Smolyakov, Podstrigaev, 2021)

$$P_j\left(I_j^{(A)-}(m\times\Delta t)\right)<<P_j\left(I_j^{(A)+}(m\times\Delta t)\right), \quad (4)$$

provided that the full probability of synthesis for the pilot of information about the *j*-m simulator

$$P_j\left(I_j^{(A)}(m\times\Delta t)\right)=P_j\left(I_j^{(A)-}(m\times\Delta t)\right)+P_j\left(I_j^{(A)+}(m\times\Delta t)\right). \quad (5)$$

The tasks of training pilots to control an aircraft in our country and abroad were of primary importance in the development of specialized and complex flight simulators (Roganov, Remontova, Esimova, Helal, 2022). At the same time, it was believed that the quality of pilot training depends on synthesis $I^{(A)+}(m\times\Delta t)$ and is evaluated in accordance with (1-5), taking into account the one-sided orientation in the development of flight simulators for training pilots of aircraft control (Vyatkin, Dolgovesov, 2022). Such a statement of the task by the Customer was due to the need, first of all, to ensure the safe advanced training of pilots in aircraft control (the pilot acquired professional skills in aircraft control while sitting on the ground in the cockpit of a flight simulator) (Pyvovar, Kritskiy, Plastun, Kalashnikova, Popov, 2022). Secondly, this approach was due to the capabilities of the software and hardware systems underlying all flight simulators, namely, the inability to simulate for the pilot in real time a 3 *D* model of the flight area over which the controlled model of the aircraft flies. In full, the pilot could solve the problems of aircraft navigation on complex simulators only after passing the fourth turn when learning visual approach to the 3 *D*-model runway. Partially solving the problems of aircraft navigation was allowed on complex and specialized aviation training simulators only when flying along the route "in solid clouds", with orientation according to the indications of simulators of cabin equipment devices.

This approach made it possible to use visual environment simulators synthesizing for the pilot a 3*D* model of the runway visually observed through the cockpit windows with adjacent 3*D* models of reference objects) with television image generators.

In this case, a movable camera connected to the TV screen of the 3 *D* display device moved over the physical 3 *D* model of the landing area. The quality of the 2 *D*-projections of 3 *D*-models of reference objects displayed on the screen that fell into the solid angle of the mobile camera depended on the technical characteristics of the equipment used and on the quality of the designs of 3 *D*-models of reference objects painted by artists installed on the terrain layout. The overall quality of the 3 *D*-models of reference objects visually observed by the pilot (including the 3 *D*-model of the runway) and perceived by the pilot as a 3 *D*-object additionally depended on the type of 3 *D*-indication device used (single-channel, without glasses with a "narrow" pupil; single-channel, without glasses with a "wide" pupil; two-channel with disparate glasses). The use of such visual environment simulators with television image generators and 3-*D* display devices made it possible to include in the number of training situations the pilot's training in visual landing on a 3 *D* -model of the runway. However, such visual environment simulators had drawbacks:

– their service was expensive;

– it is impossible to display the change in the position of the aircraft model when performing some aerobatic elements, for example, the Nesterov loop;

– the limited size of the 3 *D*-models of the flight area, as a rule, no more than 15 × 15 km, which did not allow the pilot to train most navigation tasks, including "flight along a route with visual orientation on 3 *D*-models of reference objects during the entire flight".

Specialized simulators synthesizing information from simulators of radio-technical means of aircraft navigation during flights "in solid clouds" were developed to train navigational pilots in professional skills of solving navigation problems.

The improvement of flight simulators is associated with an increase in the number of training situations and this became possible with the introduction of inexpensive and high-performance computers (Roganov, 2022).

2 METHODS AND MATERIALS

The analysis of the directions of further improvement of the FS showed that at present an increase in the number of training situations is associated with an increase in the list of training situations allowed for a particular flight simulator related to solving problems of aircraft navigation (Zemlyanoj, 2017). This requires taking into account (1-5) to change the views on synthesis $I^{(A)}(m \times \Delta t)$ by FS simulators, taking into account the new technical characteristics of computers and new synthesis algorithms on the screen of 2 *D*-projections of 3 *D*-models of reference objects, which allows to increase overall $I^{(A)+}(m \times \Delta t)$.

Studies have shown that earlier, when analyzing the complex of technical means of flight simulators, it was taken into account that the flight simulator belongs to the category of ergatic (that is, human-machine) systems (Wu, Zhao, Gu, 2021). However, previously, when developing all flight simulators, the role of a person was determined as an outside observer for $I^{(A)}(m \times \Delta t)$, or as a decision-maker after receiving all the information to influence the control simulators in the cockpit of a flight simulator in order to direct the trajectory of the aircraft model in a given direction and at a given speed. At the same time, all flight simulators were based on the implementation of the principle of "compliance with real-time mode with the most accurate synthesis of information about the behavior of the *j*-th model from the list $j \in 1...(L + V + N_S)$". Note that due to the complexity of synchronization for the *m*-th interval, the Δ *t* of all $I_j^{(A)}(m \times \Delta t)$ was chosen differently, but in such a way as to maximize $I_j^{(A)+}(m \times \Delta t)$. This approach, taking into account the Customer's requirements, limits the number of training situations $u(b), b \in B$, where *B* is a list of training situations. At the same time, the Customer guarantees that when flying on a flight simulator, the ratio (4) is fulfilled, which ensures the formation of the *k*-th pilot of the required components of his cognitive model $C_k(b(\Delta t_m))$, in which his professional experience in controlling a specific aircraft and aircraft navigation in a given *b*-th training situation is postponed in each *m*-th cycle of real-time mode.

Studies have shown that a further increase in the number of training situations is possible if we focus on the requirements established during the development of a flight simulator, it is also necessary to take into account the requirements to train the pilot to read correctly, $I^{(A)}(m \times \Delta t)$ taking into account the capabilities of his analyzers (Computer Vision, Visualization and Computer Graphics - Theory and Applications International Joint Conference, VISIGRAPP 2011) and the capabilities of the complex of technical means of a flight simulator (Vyatkin, Dolgovesov, Ovechkin, Chizhik, 1997) for the purposeful formation of the specified components of the cognitive model of the pilot.

Note that the information received by pilots during flights on a flight simulator in the *b*-th training situation from all simulators should approximately correspond to the information (Morozov, Dolgovesov, Mazurok, Gorodilov, 2014) received by the same pilot in a similar situation during a real flight on an aircraft (Vostryh, 2022), taking into account (4) both separately

$$I_j^{(A)}(m \times \Delta t) \approx I_j^{(Л)}(m \times \Delta t), \quad j \in 1...(L+V+N_S) \qquad (6)$$

so in general

$$I^{(A)}(m \times \Delta t) \approx I^{(Л)}(m \times \Delta t). \qquad (7)$$

The difference between $I^{(A)}(m \times \Delta t)$ and $I^{(Л)}(m \times \Delta t)$ should be less than or equal to the critical value $I^{(П)}$ in general, or $I_j^{(П)}$ for a specific *j*-th simulator forming the *k*-th pilot $C_{k_{\Delta t m}}$ in a given *b*-th training situation

$$\left|I_j^{(A)}(m \times \Delta t) - I_j^{(Л)}(m \times \Delta t)\right| \le I_j^{(П)}, \quad j \in 1...(L+V+N_S). \qquad (8)$$

In the future, we will focus on the consideration of simulators of the third group. Previously, the main reason for restrictions on the number of training situations for solving aircraft navigation problems with orientation based on visually observed 3 *D* models of reference objects was the limited performance of computer image generators both in terms of speed (no more than 16,000 primitives per 120 ms real-time cycle) and in terms of RAM (up to 32 MV) (Vyatkin, Dolgovesov, 2005). At the same time, a mathematical apparatus developed for computer image generators was used that implements machine graphics algorithms and allows synthesizing visual information $I_j^{(A)}(m \times \Delta t)$ for the pilot in the form of 2 *D*-projections of models of reference 3 *D*-objects. This mathematical apparatus developed in the middle of the XX century made it possible to replace television image generators previously used in visual environment simulators (Jane's Simulation and Training Systems 2006-2007).

The technological process of information processing in computer image generators uses the principle of sequentially processing information along a conveyor (Lemak, 2019).

At the first stage, in the scenario processor, when processing the database (which stores all primitives describing the entire 3 *D*-model of the flight area (up to 1500×1500 km in size) with all 3 *D*-models of reference objects and their 3 *D*-submodels located on it, as well as all control primitives) a part of the 3 *D*-model with reference 3 *D*-models of objects that are not visible at the moment is cut off (Roganov, 1995). At the same time, as a rule, due to the "dividing plane" control primitives, the problem is solved to exclude the transmission of the far 3 *D*-model through the near 3 *D*-model (Dolgovesov, Livshic, 1973).

At the second stage, the geometric processor projects onto the screen plane 2 *D*-projections of 3 *D*-models that have fallen into the observation camera based on the position of the mobile observer and the direction of his gaze (Vyatkin, Dolgovesov, Yesin, 2002).

At the third stage, the clipper processor cuts off parts of 2 *D*-projections that go beyond the physical dimensions of the screen (Vyatkin, Dolgovesov, 2002).

At the fourth stage, the video processor processes the mathematical model of the screen plane into television signals (*R*,*G*,*B* for each pixel of the screen) (Vyatkin, Dolgovesov, 2002).

Previously, for developers of visual environment simulators, control of the operation of the scenario processor of the computer image generator was available in the sense that it was possible to control the speed of selecting the necessary information by segmenting the 3 *D*-model of the flight area. The solution to this problem was connected with the division of the entire 3 *D*-model of the flight area into segments, sub-segments, etc., which made it possible to set the optimal database structure, allowing at the first stage to cut off part of 3 *D*-model of the flight area, which is not visible at the moment.

Currently, the research results have shown that it is possible to modernize the algorithms of machine graphics by transferring to the database development stage the solution of the problem of eliminating the incorrect mutual closure of one 3-*D* model through another at any position of a moving observer. At the same time, it does not matter on which hardware this processor is made and which mathematical apparatus is used to synthesize the final image of 2 *D*-projections of 3 *D*-models on the screen plane. Experimental testing of new machine graphics algorithms has shown that in this way it is possible to increase the number of visual primitives processed in time by more than 30% by reducing the number of control primitives processed. Both domestic and foreign computer image generators were studied (Table 1).

Table 1: Advertising performance of some computer image generators produced by flight simulator manufacturers.

Brand of generator (manufacturer)	**Number of polygon faces processed per frame**	**Frame processing time (ms)**	**Number of lights processed per frame**
"Horizon" (NPP "Era", USSR)	400	120	The lights are implemented in the form of small faces
"Aksai" (NPP "Era", USSR)	1 000	120	4 000
"Albatross" (PKBM JSC, Russia)	4 000	80	16 000
"Twilight" (NPP "Era", USSR)	10	120	32 000
MaxWue TM (*SAE*, Canada)	16 000	80	12,000
ST 5-*A* (*Evan and Sutherland*, USA)	18,000	80	12,000
*Poligon*TM (*SAE*, Canada)	300,000	80	64,000

An increase in the number of visual primitives processed during a real-time cycle allows synthesizing a larger number of 3-*D* models of reference objects recognized by the pilot as real 3-*D* objects. To illustrate the complexity of solving this problem, we point out that it has been experimentally established that when using a computer image generator processing non-textured 3 *D* polygons, at least seven hundred and eighty 3 D polygons are required to synthesize a 3 *D* runway model with a length of 3 km and recognized by the pilot as one of the runways of Sheremetyevo airfield, or one of the runways of Vnukovo airfield. To train a pilot to visually land on the runway, in addition to the 3 *D*-model of the runway, he needs to see nearby 3 *D*-models of objects that the Customer has identified as reference – their observation next to the 3 *D*-model of the runway allows the pilot to determine the flight altitude and, if necessary, make adjustments by directing the model of the aircraft to the landing glide path. The more 3 *D* models of reference objects the pilot can see next to the 3 *D* model of the runway, the faster he acquires professional skills of visual landing of a real aircraft. Replacing controlled primitives with visual primitives allows to increase the number of 3 *D* polygons used and design the appearance of existing 3 *D* models of reference objects, bringing the probability of their recognition as real 3 *D* objects to 98% or higher accepted in aviation, or increase the number of additionally synthesized 3 *D* models of reference objects located near the runway, which allows the pilot to assume that the model of the aircraft controlled by him lands on a real airfield, taking into account its features, which, as experiments have shown, improves the pilot's ability to train the process of visual landing on the runway.

The increase in the number of visual primitives processed during the real-time cycle also allows us to add new training situations that provide training for the pilot to solve aircraft navigation problems in a more complete manner, including with the development of flight skills with visual control of the 3 *D*-models of reference objects flown at the turning points of the [P1]route. Recently, computer image generators with 3 *D* polygons painted using textures have been used, which makes it possible to improve the process of recognition by a pilot of a 3 *D* model of a reference object as a real 3 *D* object. However, a textured 3 *D* polygon is well viewed at a certain distance (when approaching or moving beyond it, the texture pattern is distorted). Then the task arises of developing several 3 *D*-submodels of the same reference 3 *D*-object to observe it at different distances, which is achieved by using nested sub-segments and placing in each sub-segment only those 3 *D*-submodels of the reference object which should be directed to processing in the event that a mobile observer finds himself at the observation distance of a particular sub-segment.

The solution of such a problem will allow to form a 3 *D*-model of the flight area (up to 1500 × 1500 km in size) with a sufficient number of observed 3 *D*-submodules of reference objects placed in accordance with their location on the map and observed at specified distances.

Studies have shown that then a flight simulator will provide conditions for training a pilot to solve navigation problems with visual orientation according to 3 *D*-models of reference objects during a training flight along an arbitrary route.

Currently, due to the unworthy number of studies conducted, training on a flight simulator with a visual environment simulator with a computer image generator, as a rule, repeats the process of training pilots with a visual environment simulator with a television image generator. Namely, the pilot controls the movement of the aircraft model on the 3 *D*–

runway model and accelerates it to the speed of separation from the ground. Then, when exceeding the height of 50 meters (the height after which the regulatory documents indicate that the process of taking off the aircraft is considered completed), the model of the aircraft "enters" into "solid cloud cover". Next, the pilot controls the model of the aircraft and solves navigation tasks according to the indications of cabin equipment simulators. After reaching the point of the fourth turn and finding the model of the aircraft on the landing glide path, a visually observed 3 *D*-model of the runway with adjacent 3 *D*-models of reference objects appears in front of the pilot (the 3 *D*-indicator allows the pilot to visually assess the distance to the 3 *D*-models selected by him), which in general allows the pilot to acquire professional skills in visual landing of an aircraft.

The increase in the number of tasks related to training pilots to solve navigation problems with visual orientation on 3 *D*-models of reference objects during flight on a flight simulator is due to the need to solve two tasks:

1) provide an opportunity for the pilot to train his eye professionally during the flight on a flight simulator;

2) provide the ability to fly a flight simulator in any direction at any altitude above the 3 *D*-model of the flight area with a size of at least 400 × 400 km.

The solution of the first problem is known. This is either the use of single-channel 3-*D* display devices without glasses based on collimators with a "narrow" or "wide" pupil. When using them, it is necessary that mobile 3 *D*-models of reference objects are constantly in the field of view of the pilot, or the observer himself is constantly mobile, and it is also necessary to take into account the peculiarity of such 3 *D*-indication devices – the presence of a "dead space" between the observer and the nearest observed 3 *D*-model of the reference object (depends on the design of the particular 3*D* display device). Modern 3 *D*-display devices allow to reduce the distance of the "dead space" from 300 m (produced by the Penza association "Era" 3 *D*-display device "OKU") to 10 meters (produced by Penza Video3 LLC 3 *D*-display devices "RALLY", "SVETLANA" and "ELVIRA").

The solution to the second problem is the distribution of the resources of the computer image generator over the entire area of the 3 *D*-model of the flight area. The solution of the second problem involves: modernization of the known algorithms of real-time machine graphics in order to maximize the number of visual primitives allowed to describe all segments and 3 *D*-models of reference objects placed over the entire area of 3 *D*-models of the flight area. Its solution depends on the successful solution of three subtasks.

2.1. Modernization of well-known machine graphics algorithms in order to increase the number of visual primitives used. Currently, new algorithms for the synthesis of 3 *D* models of reference objects are known and successfully tested, eliminating or reducing the number of necessary control primitives of the "separating planes" type, proposed earlier by one of the founders of machine graphics **Ivan Edward Sutherland**, which were previously used with a mobile observer to eliminate the undesirable effect of the transmission of a distant 3 *D* model of a 3 *D* object through another 3 *D* model of a 3 *D* object. "Separating planes" as well as "spanning spheres" are control primitives that organize the selection of source information from databases in real time. They are not visible, but their use allows to control the number of visual primitives processed in each clock cycle of the real-time mode during the synthesis of images of 2 *D*-projections of 3 *D*-models on the screen plane. An increase in the number of visual primitives makes it more likely to recognize 3 *D* models of 3 *D* objects as a real 3 *D* object, which creates better conditions for pilots to acquire professional skills in controlling an aircraft and solving aircraft navigation problems.

2.2. Conducting research and developing methods and algorithms for applying methods of operations research to allocate resources of a computer image generator in order to maximize the number of visual primitives in segments and sub-segments of the 3 *D*-model of the flight area in order to synthesize the most saturated 3 *D*-models of reference objects of part 3 *D*-model of the flight area caught in the surveillance camera of the simulator of the visual situation in every clock cycle of the real-time mode. Currently, a number of firms (for example, the Canadian CAE concern), due to the lack of acceptable methods and algorithms for solving the problem of resource allocation, use the following approach for this case. Several 3 *D*-models of the flight area are being developed in the center of each there is a 15×15 km segment, where the maximum allowable number of 3 *D*-models of reference objects is placed. When flying out of this area, the entry of the aircraft model into the "solid cloud cover" is simulated, and then, taking into account the direction of flight of the aircraft model, a new 3 *D*-model of the flight area is loaded from memory. In the center of each there is a 15 ×15 km segment, where the maximum allowable number of 3 *D*-models of reference objects is placed. This partially allows the pilot to learn how to solve navigation problems when flying along the route.

2.3. Solving navigation problems during a flight on a real aircraft involves visually determining the location of the aircraft in one way, then clarifying it in another way. For example, first determine the location of the aircraft using radar, then refine it by finding the required reference 3 *D* objects by examining the terrain through the cockpit windows. There may be several such options with different sequences of using a thermal imager, radar and visual examination of reference 3 *D* objects through the cockpit windows. Accordingly, in addition to the simulator of the visual environment, a thermal imager simulator and a radar simulator can be part of a modern complex of technical means. Studies have shown that in this case, the actual task is to place in the same place 3 *D*-models of the flight area 3 *D*-models of the same reference objects visible in different spectra of electromagnetic radiation. The solution of the problems of synthesis of a 3-*D* model of a large flight area with 3-*D* models of reference objects located on it observed in different ranges of light waves (8) depends on the application of new approaches and algorithms, the use of which is possible to modernize existing and develop new flight simulators, regardless of the hardware and software of computer image generators. All the proposed solutions should provide the pilot with sufficient information to solve the maximum number of tasks for training the pilot to control the aircraft and aircraft navigation during the flight on a flight simulator.

Taking into account the results of research on the main directions of modernization of existing flight simulators and the development of new ones, we note that each simulator is part of an ergodic optical-software-technical system. We will determine the areas of improvement of all three groups of simulators in accordance with their participation in the formation of individual components of the cognitive model of the pilot. In the future, the parameters related to the simulators of the first group will be marked with an upper index $^{(1)}$, to the simulators of the second group we will mark with an upper index $^{(2)}$, to the simulators of the third group we will mark with an upper index $^{(3)}$.

The first group of flight simulators includes simulators that during the real-time interval $\Delta^{(1)}t$ update information about the simulation of physical processes in the *l*-th nodes of the aircraft $l \in 1...(L+V)$. Synthesized information from simulators of this group is reflected on the instrument panels of cabin equipment simulators. Formation of the components of the cognitive model of the *k*-th pilot from the *j*-th simulator of this group

$$C_{k_b}^{(1)}(j) = F_{j_b}^{(1)}\left(T_k, I_j^{(A)}\right),$$

$$\lim_{T_k \to \infty} C_{k_{b_j}}^{(1)}(T_k) \to const_j^{(1)}, \tag{9}$$

where $F_{j_b}^{(1)}\left(T_k, I_j^{(A)}\right)$ is the function of the change in the *b*-th situation of the components of the cognitive model of the *k*-th pilot receiving information from the *j*-th simulator of the first group;

T_k is the total flight time of the pilot both on the FS and on the aircraft in the *b*-th situation;

$const_j^{(1)}$ – the limit of information that the pilot can get from the *j*-th simulator.

$I_j^{(A)}(m \times \Delta t)^{(1)}$ the information synthesized by the simulators of the first group is perceived by the pilot as absolutely reliable. The formation of the components $C_{k_b}^{(1)}(j)$ is reduced to training the pilot to correctly read the synthesized information, which is achieved by training both during flights on the FS and during flights on the aircraft. $I^{(A)}(m \times \Delta t)^{(1)}$ creates conditions for training a pilot to control an aircraft.

The second group of flight simulators includes simulators that during the real-time interval $\Delta^{(2)}t$ update information about models of interaction of simulators of aircraft radio navigation equipment with simulators of ground-based radio beacons, the location of which is indicated on the map 3 *D*-models of the flight area. The synthesized information from the simulators of this group is reflected on the instrument panels of the simulators of aircraft radio navigation equipment. Formation of the components of the cognitive model of the *k*-th pilot from the *j*-th simulator of this group

$$C_{k_b}^{(2)}(j) = F_{j_b}^{(2)}\left(T_k, I_j^{(A)}, F_k^{(2)}(S)\right),$$

$$\lim_{T_k \to \infty} C_{k_{b_j}}^{(2)}(T_k) \to const2_j^{(2)}, \tag{9}$$

where $F_{j_b}^{(2)}\left(T_k, I_j^{(A)}, F_k^{(2)}(S)\right)$ is the function of the change in the *b*-th situation of the components of the cognitive model of the *k*-th pilot receiving information from the *j*-th simulator of the second group;

$F_k^{(2)}(S)$ – the ability of the *k*-th pilot to work with the model map of the flight area *S*;

$const2_j^{(2)}$ – the limit of information that the pilot can get from the *j*-th simulator.

$I_j^{(A)}(m\times\Delta t)^{(2)}$ the ability of the *k*-th pilot to use information from the simulators of the second group to solve problems of aircraft navigation, in addition to the information directly received, also depends on the pilot's ability to work with the model map of the flight area *S*. The formation of the components $C_{k_b}^{(2)}(j)$ involves training the pilot to read synthesized information from the simulators of the second group and training to work with the map of the flight area model *S* to determine the location and direction of movement of the aircraft model over the 3 *D*-model of the flight area. Formation $C_{k_b}^{(2)}(j)$ is determined by training flights on a flight simulator on an aircraft. The simulators of the second group are focused on solving the problems of aircraft navigation during "flights in solid clouds". When developing a flight simulator, in addition to the simulators of the second group, it is also necessary to develop a model map of the flight area *S*.

$$S=\bigcup_{d=1}^{D_R} R_d\left(x_d, y_d, z_d\right), \qquad (10)$$

where D_R is the number of ground-based beacons, $R_d\left(x_d, y_d, z_d\right)$ are the characteristics of the beacon and the coordinates of its location on the 3 *D*-model of the flight area.

The third group of flight simulators includes simulators that $\Delta^{(3)}t$ synthesize a visually observable image of a 3 *D* model of the flight area around the cockpit of an aircraft simulator in the specified electromagnetic wave ranges for the pilot during the real-time interval.

In this group of simulators, the visual environment simulator has a significant difference from the other simulators of the third group. The visual environment simulator is an ergatic optical-software-technical simulator that allows a person, when observing through special optics a video sequence of 2 *D*-projections of 3 *D*-models, to see a 3 *D*-object and at the same time professionally train his eye. This effect is achieved by including in the synthesis process 3 *D*-images of 3 *D*-display devices that activate while viewing on the screen a video sequence of 2 *D*-projections of 3 *D*-models of the specified components of the human visual apparatus, forcing him to believe that he sees not a 3 *D*-model, but a 3 *D*-object, which allows him to train his eye professionally. (The appearance of high-definition screens of level 5K and higher with the simultaneous improvement of avionics, which facilitates the pilot to solve the problem of landing a real aircraft on the runway, allow the Customer to give back to the development of visual environment simulators, where the main criterion is to keep the model of the aircraft in a horizontal position, taking into account the information received from the avionics simulator. This led to the possibility of using display devices synthesizing "non-planar" images of 3 *D* models for the pilot to train pilots in the process of landing an aircraft on the runway with maximum use of information from avionics).

The remaining simulators of the third group synthesize video sequences from 2 *D*-projections of 3 *D*-models observed on the screens of simulators of real devices (for example, on the screen of a thermal imager simulator).

All simulators of the third group use computer image generators designed to synthesize and display colored 2 *D*-projections of 3 *D*-models on the screen. The synthesis process uses primitives extracted from the corresponding database of a computer image generator per cycle $\Delta^{(3)}t$.

The formation of the components of the cognitive model of the *k*-th pilot from the *j*-th simulator of this group for the simulator of the air situation is described by the expression

$$C_{k_b}^{(3)'}(j)=F_{j_b}^{(3)}\left(T_k, I_j^{(A)}, A_k(o), F_k^{(3)}(S)\right), \quad \lim_{T_k\to\infty} C_{k_{b_j}}^{(3)\prime}(T_k)\to\infty_j, \qquad (11)$$

where $F_{j_b}^{(3)}\left(T_k, I_j^{(A)}, A_k(o), F_k^{(3)}(S)\right)$ is the function of the change in the *b*-th situation of the components of the cognitive model of the *k*-th pilot who received information from the *j*-th simulator of the third group;

$A(o)$ – the ability of the pilot's visual apparatus to activate the specified components (accommodation and convergence when using glasses-free 3*D* display devices, or disparity when using two-channel 3*D* displays with disparity glasses) by observing in real time changeable 2*D*-projections of 3*D*-models, which makes a person believe that he sees 3 *D*-object and at the same time has the opportunity to train his eye professionally;

$F_k^{(3)}\left(S^{(3)\prime}\right)$ – the ability of the k-th pilot to work with the model map of the flight area $S^{(3)\prime}$, waiting for the appearance of the next reference 3 D-object.

Flight area models

$$S^{(3)'} = \bigcup_{d=1}^{D'_V} R'_V\left(x_d, y_d, z_d\right), \qquad (12)$$

where D'_V is the number of reference objects visible to the naked eye placed on the entire $3D'_V$ model of the flight area,

$R'_V\left(x_d, y_d, z_d\right)$–characteristics of $3D'_V$-models of a reference object visible to the naked eye and coordinates of its location on $3D'_V$-models of the flight area.

For the rest of the simulators from the third group we have

$$C_{k_b}^{(3)}(j) = F_{j_b}^{(3)}\left(T_k, I_j^{(A)}, F_k^{(3)}\left(S^{(3)}(P)\right)\right),$$

$$\lim_{T_k \to \infty} C_{k_{b_j}}^{(3)}\left(T_k\right) \to \infty_j, \qquad (13)$$

where $F_{j_b}^{(3)}\left(T_k, I_j^{(A)}, F_k^{(3)}\left(S^{(3)}(P)\right)\right)$ is the function of the change in the b-th situation of the components of the cognitive model of the k-th pilot who received information from the j-th simulator of the third group.

The expression $F_k^{(3)}\left(S^{(3)}(P)\right)$ describes the ability of the k-th pilot to work with a model map of the flight area $S^{(3)\prime}$ where $3D'_V$ models of reference objects observed in the visual range of light waves are placed, most of which are usually visible in another range of electromagnetic waves. For this group of flight simulators, its own $3D_V(P)$ is being developed. Most 3 D-models of reference objects developed for $3D_V(P)$ should be combined with 3 D-models of reference objects observed in the visual range of light waves and with 3 D-models of reference objects observed in the IR image.

Then the visually observed models of reference objects are described by the functional

$$3D_V(P) = \bigcup_{d=1}^{D_V(P)} R_v^{(P)}\left(x_d, y_d, z_d\right), \qquad (14)$$

where $D_V(P)$ is the number of reference objects visible on the screen of the P-th device (for example, a thermal imager) placed in the cockpit of a real aircraft, located throughout the flight area:

$R_V^{(P)}\left(x_d, y_d, z_d\right)$– characteristics of $3D_V(P)$-models of the reference object visible on the screen of the P-th device and the coordinates of its location on the $3D_V(P)$-model of the flight area.

$I_j^{(A)}\left(m \times \Delta t\right)^{(3)}$ describes the possibility of the k-th pilot using information from the simulators of the third group to solve problems of aircraft navigation, with the exception of information received directly during the flight with FS. Note that in general, the information used by the pilot also depends on his ability to work with the model map of the flight area S.

The components of the cognitive model of the pilot in which his professional skills are postponed to calculate in advance when the model of the aircraft will be located above the place from where you can see the next reference 3 D-object and adjust, if necessary, the flight route (as well as during a real flight on a real aircraft) depends on the ability of the pilot to read the necessary information considering the images of 3 D-terrain models and simulators of cabin equipment. At the same time, the formation $C_{k_b}^{(3)\prime}(j)$ involves training the pilot's visual apparatus to see a 3 D-object, while he considers a video sequence from his 2 D-projections (when observing such objects synthesized by a visual environment simulator, it is assumed that the pilot can determine the distance to it with the help of an eye (through the use of optics activating the specified components of his visual apparatus). The formation $C_{k_b}^{(3)}(j)$ using the remaining simulators involves training the pilot to recognize on the screen of the P-th device a 3 D-model of a reference object, synthesized taking into account the peculiarities of highlighting the image of the terrain on the screen of the prototype device installed on the aircraft. Formation $C_{k_b}^{(3)\prime}(j)$ and $C_{k_b}^{(3)}(j)$ is determined by training flights on an aircraft simulator on an aircraft.

The simulators of the third group are focused on solving the problems of aircraft navigation from orientations according to the observed 3 D-models of reference objects. When developing an aviation simulator, developing simulators of the third group, it is necessary to develop maps of flight area models for each simulator of the third group. When training on an aircraft simulator, the pilot uses only a map designed for a visual environment simulator.

Thus, the use of modern software and hardware systems in the development of simulators of the first and second groups leads to a reduction in their dimensions and a reduction in energy consumption. When developing simulators of the third group, a significant increase in the number of processed primitives per clock cycle in real time (see Table 1) gives an effect due to an increase in the number of training situations related to the solution of aircraft navigation problems only when solving:

– tasks of resource allocation of a computer image generator for the synthesis of a continuously changing image of a 3 *D*-model of the flight area when flying in any direction;

– when reducing or eliminating the processing of control primitives, when using any programs for the machine synthesis of 3 *D*-images (as a rule, this applies only to the operation of the first scenario processor included in the computer image generator).

3 CONCLUSIONS

1. A flight simulator should be considered an ergodic optical-software-technical complex focused on the formation of individual components of the pilot's cognitive model in which his experience of solving aircraft control problems and solving navigation problems is postponed, depending on the total time spent by the pilot in preparation for flights, when flying on a real aircraft and when flying on an aircraft simulator.

2. The division of all flight simulators into three groups is proposed, depending on the participation of synthesized information in the formation of specific components of the pilot's cognitive model in which his experience of controlling an aircraft and solving navigation problems is postponed.

3. The solution of navigation problems became possible after the advent of high-performance computers and the reduction in the cost of RAM, which stores in the form of primitives all information about all 3 *D*-models of reference objects and their submodels located on the entire area of 3 *D*-models of the flight area with a size of at least 400 × 400 km.

4. The simulator of the visual situation differs from other simulators synthesizing for the pilot a 3 *D*-model of a section of the flight area caught in their surveillance camera in that the pilot believes that he sees not *3D*-models of reference objects, but real 3 *D*-objects and at the same time can professionally train his eye by estimating the distance to any visible 3 *D*-objects, while the rest of the simulators of this group synthesize images of video sequences from 2 *D*-projections of 3 *D*-models of reference objects, painted in accordance with the colors adopted on their real counterparts.

5. The possibility of solving navigation problems when flying on an aviation simulator implies the need to solve two problems:

– to provide an opportunity for a pilot to train his eye professionally during a flight on a flight simulator;

– to provide an opportunity to fly a flight simulator in any direction at any altitude above the 3 *D*-model of the flight area with a size of at least 400 × 400 km.

6. The basic concepts of building modern software and hardware systems of flight simulators to solve the tasks of training pilots assume at the design stage of simulators of any group to take into account that they are developed taking into account the need to form specific components of the cognitive model of the pilot in which his professional skills of solving aircraft control problems and solving navigation problems are postponed during the preparation for flights, as well as when flying on a real aircraft and on a flight simulator.

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