INTEGRATION - THE BASIS OF THE INTEGRATED APPROACH TO PASSENGER AIRCRAFT CONTROL SYSTEM DESIGN

S. P. Krjukov
General Director, Aviapribor corporation, Moscow
V. V. Smirnov
Chief Designer, Moscow Institute of Electromechanics

Abstract

The paper discusses the necessity to integrate the airborne flight control equipment. It is pointed out that a problem of integration can be formulated both on the system design and the corresponding elements design levels. A method of systems integration expediency evaluation is proposed: interrelationship determination between the integrated systems taking into account the whole system fail safety. Integration on the computer system level gives a considerable benefit in the equipment volume, which is confirmed by the design results. The problem of fail safety should be considered as the basis for integration. The existing and advanced equipment estimate was obtained, based on the correlation between its computational power and volume. The analog and digital implementations are compared. The paper also discusses the main principles of the integrated system digital computer architecture. The block diagrams of the Il-96-300 and Tu-204 command/stability augmentation systems are presented; these systems are designed using the comprehensive approach described in this paper. Their comparative characteristics are also discussed.

I. Flight Control Equipment Trends

Requirements for aircraft control automation have been growing continuously. Pilot control operations are being automated and, at the same time, aircraft stability and control normalized characteristics are provided owing to introduction of all-axes artificial damping, alteration of gear ratio between control levers and control surfaces, automatic trim, etc. Bulky mechanical linkage is replaced by electric wiring for fly-by-wire operation, which offers possibilities to further improve control automation processes. "Active control" systems are being tested and introduced, which allows for lowering design wing loads and artificially raising both permissible flutter speed and wing fatigue strength factor of safety.

Aircraft automatic control functions are being enhanced. Aircraft takeoff, climb, en-route flight, descent, approach and landing are being automated. Automatic protection from exceeding maximum flight parameters (Mach number, n_y, α, V_{ind}, γ) is provided.

Engine control processes are also mechanized in order to ensure optimal engine operation and achieve automatic control of an aircraft as a whole.

Much attention is paid to automation of avionics operation and maintenance as well as to in-flight monitoring of aircraft control systems, assemblies and power supplies.

As the airborne automatic systems increase in number, their complexity and pilot intellectual work load grow, while decision-making becomes much more complicated in the presence of failures or in emergencies caused by some other reasons. That is why it is necessary to put on the agenda the problem of developing and implementing expert systems generating prompts for a pilot and thus facilitating decision-making in emergencies. As the experience shows, with such an approach one could expect safe outcome of many kinds of emergencies.

To solve the automation problems from this list, which is far from being complete, requires the application of a lot of various sensors, control panels, visual aids and warning devices, computer aids, actuators and other equipment. Obviously, some of these problems can be solved using the same equipment, sensors, computers, panels, etc.

The experience confirms that when separate on-board systems solving different problems are integrated, the equipment weight and cost is reduced while its operational use is simplified.

II. Levels of Integration

Integration is a universal approach used when developing any technical device including airborne equipment. Within the flight control equipment it is possible to single out two levels of integration:

- integration of functions within one device;
- integration of devices within one system.

It should be noted that we see integration not just as simple combination of problems in a device, but as a comprehensive approach to system design when it is supposed that a designer is responsible for an optimal decision of the whole problem. Hence it becomes clear that a decision to integrate at each level depends upon decisions made at other levels.

The first level of integration, or "horizontal" integration, is typical for sensors, actuators, computers and panels. There are well-known examples of such integration: integrated sensors of strapdown inertial system/air data system, satellite navigation system / long-range navigation system, VOR/DME, etc.

The aircraft actuators can be used for damping enhancement in a manual control mode or for automatic control or in active damping systems. The ARINC-700 control panel is used in a flight management system, flight control system or thrust control system.

The second level of integration, or "vertical" integration, is typical for such systems as automatic flight control system which may include sensors as well as panels, computers and actuators. For example, some of the home-made aircraft, such as the Il-36 or An-124, have the aforesaid systems developed by one designer responsible not only for their faultless operation but also for the control modes full implementation.

As it is seen from the practice, modern aircraft still lack a common approach to the airborne equipment integration.

The integrated system on the Tu-154, titled ABSU-154, is designed to integrate the following functions: wheel control automation, automatic attitude and altitude/velocity hold through elevators, speed hold and control through engine thrust, aircraft automatic/director approach and landing. Flight-path control is performed by another integrated system The ABSU-154 includes sensors, computers, control panels, flight/navigation information displays and actuators.

A different approach to integration was used for the Il-86. Here the integrated system does not include the Automatic Flight Control System (AFCS) or automatic control wheel system.

The airborne equipment for the Il-96 and Tu-204 aircraft was designed on the basis of the ARINC-700 principles, and the integration is performed at the ARINC-701/702 and 703 computer system level, i.e. in the same manner as on the A-310. But as for the A-320, all automatic control functions, including approach and landing, are handled within the complex system and are integrated together with navigation loop and flying mode optimization functions. Elastic vibration damping, command/stability augmentation and fly-by-wire functions are distributed among the systems containing computers FAC, ELAC and SEC.

On the B-7J7 there are a fly-by-wire system and another system which performs autopilot and command/stability augmentation functions. Flight management system operates on a stand-alone basis.

The same approach was used for the MD-11 where flight and navigation modes were realized by different systems.

Judging by the analysis, it can be said that a significant efficiency can be obtained by integration of airborne computer systems. However, the experience in the airborne flight control equipment design shows that vertical integration also gives unquestionably good results. This kind of integration allows for optimal distributing computation functions among the units, organizing more rational built-in-test systems, minimizing unit-to-unit connections and solving fail-safety problems.

III. Assessment of System Integration Optimality

If many variants of integration techniques exist, there obviously should be an optimal variant. Optimality of this variant can be evaluated by a number of criteria which define its essence.

Some main propositions may be used as the criteria of integration expediency.

The primary of these propositions may be as follows: if functional losses within achieved integration do not influence operation of a system emerging in the process of further integration, than this initial system can be developed independently, without making a part of the integrated equipment. This proposition first of all defines the expediency of vertical integration. But it can be applied to horizontal integration as well, serving as a reliable guide. A good example is the integration of the computer systems solving piloting tasks.

The use of an estimate based on system "independence" to make a decision about integration should be performed taking into consideration general problems of safety (redundancy), general approaches to research, calculations and design, general responsibility of a designer for the whole flying mode and many other items which in total determine a comprehensive approach to the integration problems.

Most of the flight modes are realized on the basis of the aircraft short-period /long-period motion loop. During dynamics researches, unique equations of motion. mathematics techniques, source data for controllable object simulation, methods of evaluating conformity with standard requirements, etc. are used.

The control loops in wheel control modes, stabilization modes including control mode M and V through engine thrust, and trajectory control modes are proved to be directly interrelated. Again, in this case vertical integration seems to be preferable.

When analog computer units of flight control systems are used, horizontal integration is inefficient. A considerable gain is achieved when digital computer systems are integrated. For example, the number of avionics units on the B-7J7 or A-320 has been dramatically reduced as compared with the A-310 equipment.

Integration of flight control systems is based not only on their functional interdependency and the common character of the dynamics of motion, but also on the safety requirements similarity. As a rule, an active fault of a system in one of the control modes can lead to dangerous situations and even to emergencies.

A navigation loop as well as flight conditions optimization loop can obviously function irrespective of an automatic control loop. Therefore further integration, connected with combining flight control and navigation modes, may be inexpedient.

Thus, as a result of a comprehensive consideration of the flight control and navigation equipment integration, it is possible to propose the following conclusions:

- both vertical and horizontal airborne equipment integration variants are equally advisable;
- the equipment supporting solution of all the piloting tasks - from command/stability augmentation up to flight-path control - should be integrated within a sole system.

IV. Computer System Integration

When integrating computer systems, a comprehensive approach is also necessary. This approach should allow for weight reduction as well as for fail-safe computer designing, a built-in-test and maintenance system optimal designing, minimizing the mutual influence of computational paths, etc. But the basis of "horizontal" integration should still be fail safety ensuring. The reason for this is that fly-by-wire systems are being widely implemented nowadays. They should meet very stringent fail safety requirements: a failure probability must not exceed 10^{-9}/h. The acknowledged way to achieve such a reliability is redundancy. The number of redundant channels depends upon the reliability of each of them. If we take into account that the reliability of a channel is defined by the reliabilities of the sensors, computers and actuators, then it can be shown that the computer reliability requirements will be high enough. At the same time, the attempt to integrate computation functions within one computer calls for increasing its computational power and therefore results in lowering its reliability. In order to solve this contradiction, it is recommended to divide all the computation functions into blocks in accordance with the required safety level. The first block will include functions providing for the level III stability and control characteristics or functions realized in the Fly-By-Wire System (FBWS). The second, third and subsequent blocks can be realized with less safety level requirements. Comparing the volumes of needed computations in these blocks, it can be seen that the number of computations in the first block is the least. When implementing this block, it is necessary to decide: whether an analog or digital computer should be used.

Taking into account that the sensors and actuator loop are analogous, one should not eliminate the analog implementation of the FBWS minimum functions.

Consider now some relationships between weights in the analog and digital implementations. If we take the computational procedures typical for piloting tasks, and evaluate their complexity by a number of elementary functions such as an aperiodic element, limitations, summation, etc., then we'll see that the volume of the analog hardware necessary for their implementation grows linearly. The growth rate will depend on the available components and the design perfection. There is some insignificant initial volume of the hardware. In Fig. 1 this relationship is presented by the straight line 1^a and corresponds to the state-of-the-art.

The curve 1^a was obtained for long-term designs.

The initial weight of the digital hardware is much greater. Besides, it is necessary to take into account that about 70-80% of computer power is usually spent for data recept, output and handling support. Considering the situation when the computer power growth is achieved by simply increasing the number of computers, we'll obtain the curve (2) in Fig. 1 showing the hardware volume alteration which depends on the number of functions being solved.

As appears from Fig. 1 there exists a certain cross-point "a" which can serve as a guide when choosing an implementation variant (analog or digital). The analog implementation is preferable to the left of the point "a", the digital implementation is preferable to the right of the point "a".

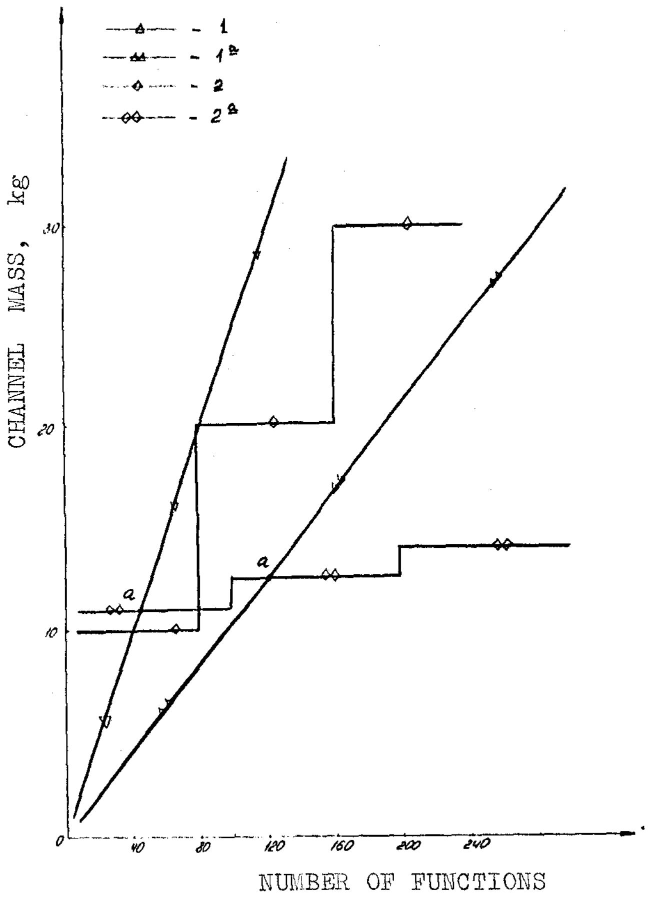

Fig. 1 Courparative assessment of the analog and digital implementations of computation functions.

As analog and digital computer technologies advance, the quantitative relationship in Fig. 1 will change, while the qualitative relationship will be preserved.

Recent advances in digital technology have enabled raising computer power without proportional growth of the computer sizing. To achieve this, the main architecture principles of such computers were defined.

They are as follows:

- the implemented architecture should not impose any constraints on distribution of algorithms and operating programs among microcomputers; it should, if necessary, distribute the problems being solved;
- data exchange must be provided between the microcomputers;
- each microcomputer should have access to all I/O devices (IOD);
- microcomputers should be made free as much as possible from the IOD control and input data "service" processing, including: input/output message address recoding, output data array generation control and input/output data format testing;
- processing section architecture should allow for varying the number of microcomputers;
- interconnections between some of the converters and the I/O controller (IOC) should provide for the system reconfiguration in case errors occur;
- output converters should have protection elements in the output circuits to raise the operational reliability;
- built-in-test hardware and software should ensure failure detection to a separate functional module (FM);
- secondary power sources design should allow for switching to 27 VDC without breaking computations, in case of the voltage lack in the 115 VAC 400 Hz circuit;
- hardware architecture implementation should provide for reliable disconnection of the discrete command output converters and bipolar code output converters in case of a failure.

To meet such requirements, the following devices are used as the components of the Set of Digital Devices (SDD):

- digital computer consisting of one, two or three microcomputers forming a ring circuit;
- bipolar code receiver (BCR);
- discrete command receiver (DCR);
- analog signal receiver (ASR);
- bipolar code transmitter (BCT);
- discrete command transmitter (DCT);
- analog signal transmitter (AST);
- multiplex channel terminal (MCT);
- I/O controller (IOC);
- system monitor unit (SMU);
- power supply unit with a monitor.

The following conditions were analyzed before passing to structural partitioning:

- each device should be functionally complete;
- structurally each device should combine the device proper and its monitor elements;
- interconnections between the FMs should be minimized;
- high noise-immunity should be ensured.

The SDD architecture consists of the following FMs:

- micro-FM;
- IOC;
- discrete command device (DCD);
- analog signal device (ASD);
- MCT;
- power supply unit;
- integrated control system (ICS).

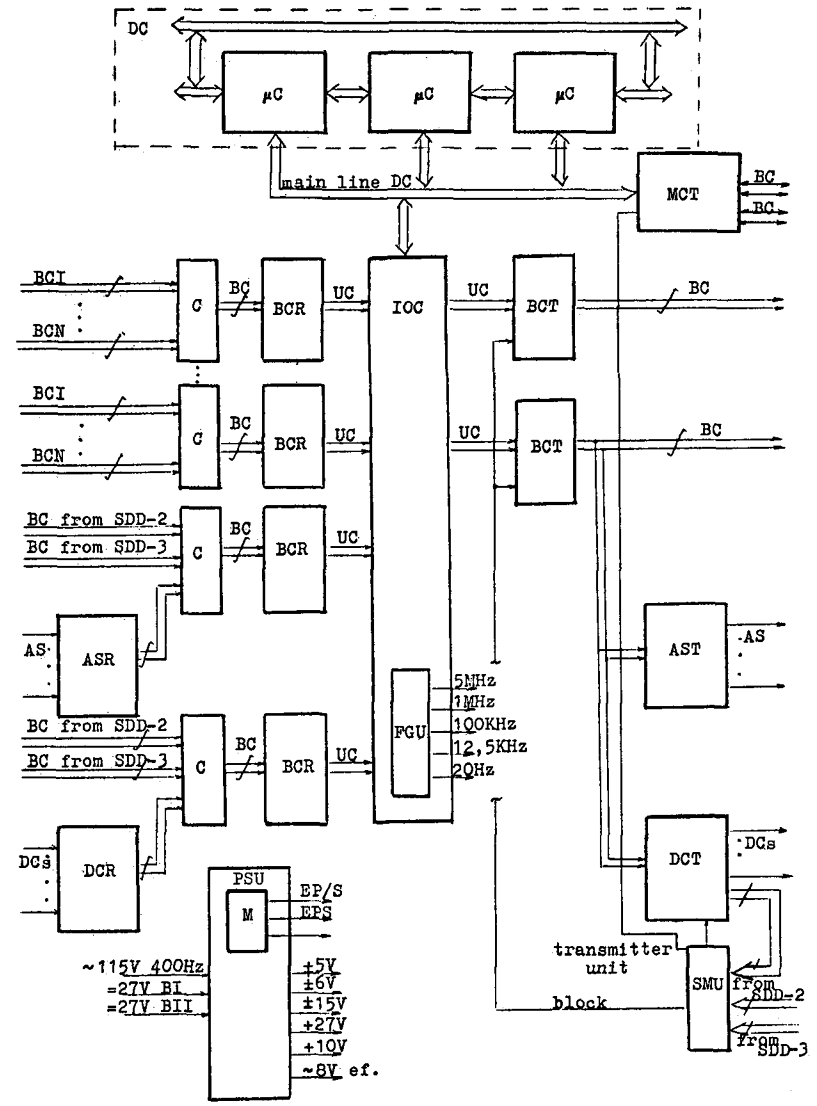

Fig. 2. SDD block-diagram.

μC - microcomputer; DC - digital computer; MCT - multiplex channel terminal; BC - bipolar code; C - commutator; BCR - bipolar code receiver; IOC - I/O controller; BCT - bipolar code transmitter; UC - unipolar code; ASR - analog signal receiver; FGU - frequency generation unit; AST - analog signal transmitter; AS - analog signals; DCs - discrete commands; DCR - discrete command receiver; M - monitor; PSU - power supply unit; EP/S - emergency power supply; EPS - emergency power system; DCT - discrete command transmitter; SMU - system monitor unit; SDD - set of digital devices; BI - board I; BII - board II

The SDD block-diagram is shown in Fig. 2. One, two or three microcomputers are interconnected forming the ring circuit. Data exchange between the microcomputers is organized through a two-port internal memory with a common field for two microcomputers 1Kx16, the internal memory field of each microcomputer being 2Kx16.

In order to lower the digital computer power spent during data exchange with users in the control devices and data processing in such FMs as IOC, ASD, DCD, MCT, the *microprogramming* control was established while input/output data address recoding/generation as well as user foregrounding was realized via the hardware.

The microprogramming control devices in each of these FMs work independently and asynchronously with respect to each other. That helps, together with making the control process unparallel, to raise the hardware speed in whole, improve its noise immunity and expand its functional possibilities.

The microprogramming control application has made it possible, owing to the microprograms specialization, to make the most of the available microcomputer computational resources running the main program as well as to reduce the hardware volume and overall dimensions, to preserve the advantages of programming, viz. universality and simplicity of algorithm alteration without changing the hardware, and, in addition, to retain the possibility of varying programming problem distribution among the microcomputers.

Curve 2 in Fig. 1 indicates the parameter variations of such a computer depending on the volume of the problems being solved.

Table 1. Comparative characteristics of special computers

Designation \ Computer			FCC	TCC	CSAC	Total	SDD
IOD	BCR	In	I8	I8	I8	54	23
		Out	2	4	4	I0	2
	DCD	In	56	52	52	I60	II4
		Out	33	23	23	79	72
	ASD	In	I2	32	36	80	37
		Out	4	4	5	I3	I3
	MCT		-	-	-	-	I double

FCC - flight control computer; TCC - trust control computer; CSAC - command/stability augmentation computer; SDD - set of digital devices; BCR - bipolar code receiver; DCD - discrete command device; ASD - analog signal device; MCT - multiplex channel terminal; IOD - "I/O" devices

Basing on these conclusions, a request for proposal for an integrated digital computer was formulated. This computer must have the same functions as the flight control, thrust control and command/stability augmentation computer systems installed on the Il-96. The characteristics showing a considerable gain in the hardware weight, overall dimensions, volume and, consequently, reliability are given for comparison in Table 1.

V. Integrated Computer System Architecture

Taking into account the qualitative relationship between the digital and analog methods of implementing the computation functions, it is possible to draw a conclusion about the necessity to build a computer with analog components which ensures the level III stability and control characteristics. The analog implementation of the most important functions also has some additional advantages:

- improved noise immunity (as compared with the digital implementation);
- absence of the software errors, undetected during testing;
- absence of time lags in the damping loop due to time-slotting. Hence, the requirements for the time-slotting frequence of other control loops based on digital computers can be reduced.

The rest of the integrated flight control system computation functions can be realized in digital computers, the redundancy rate of which is defined proceeding from safety requirements. The experience shows that tripple redundancy is sufficient to meet the safety requirements for such critical flying modes as approach, landing and takeoff. In this case, the output data from the digital computer are transferred to the inputs of the FBW analog computer via a majority circuit which excludes their influence over the FBW computer when a failure occurs.

The proposal to use a high-reliable airborne computer consisting of analog components was realized when developing the command/stability augmentation system for the Il-96 and Tu-204 aircraft.

The redundant control loop was realized using this computer. The redundant loop on the Tu-204 supports the fly-by-wire operations, command/stability augmentation and successful completion of the flight after the main loop fails. The modern component technology has made it possible to achieve full disconnection of the redundant loop at level $P \leqslant 10^{-7}$ with the triple redundancy. The main loop provides for the normalized stability and control characteristics, fly-by-wire, limitation of aircraft maximum flight parameters such as Mach number, n_y, α, γ, $V_{ind.}$ and is realized on the basis of a digital computer. The probability of the main loop full disconnection and transition to the redundant loop is $P = 10^{-5} \div 10^{-6}$. The architecture of the command/stability augmentation system is shown in Fig. 3.

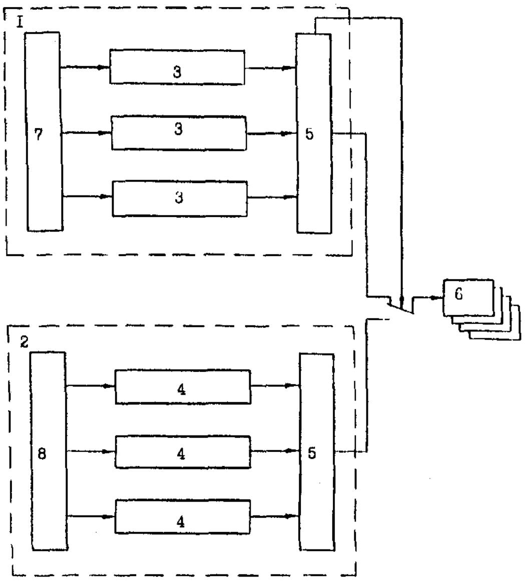

Fig. 3. Selection of the redundant control loop on the Tu-204.
1. Main control loop; 2. Redundant control loop; 3. Digital computer; 4. Analog computer; 5. Majority component; 6. Servo; 7. Main control loop sensors; 8. Redundant control loop sensors.

The redundant control loop with similar tasks is installed also on the Il-96-300. Unlike the command/stability augmentation system on the Tu-204, it is a quadruplex system with the redundant loop full disconnection probability on the level of 10^{-9}. Another difference is that the Il-96-300 command/stability augmentation system lacks the possibility of switching over from the main loop to the redundant one, which definitely offers some advantages (absence of a switch reducing the channel reliability, the requirement for dynamic control during digital computer operations are not so stringent, and the effects of possible failures in the digital computer can be compensated with more effectiveness). The probability of disconnecting digital computers which implement a full set of functions in accordance with the specifications was $P = 10^{-6}$ with the quadruple redundancy.

The Il-96-300 command/stability augmentation system architecture is presented in Fig. 4.

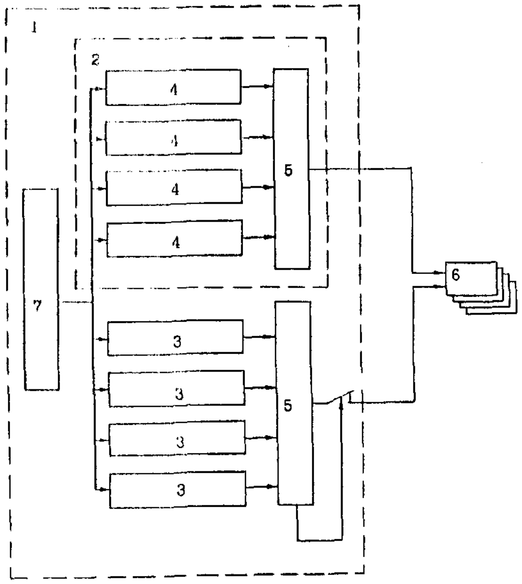

Fig. 4. Selection of the redundant control loop on the Il-96-300.

1. Main control loop; 2. Redundant control loop; 3. Digital computer; 4. Analog computer; 5. Majority component; 6. Servo; 7. Sensors.

It is worth pointing out in conclusion that the solution of the integrated flight control system development problem is still to be completed. The striving for ordering various approaches to integration together with the results presently available give every reason to suppose that it is possible, moving in this direction, to get a considerable gain in reliability, weight and safety of the airborne flight control equipment.