Assessment of Aircraft Conditions in Flight

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Abstract When flight conditions become more difficult, the pilot needs to control a greater number of parameters than in normal modes. This results in higher workload on the pilot and an increase in the probability that some mistakes will be made when operating highly automated aircraft. The problem lies in the fact that in such situations, the pilot is to perform operations safely regarding the use of both the flight control system and the air traffic control system, even if the number of information signals exceeds that which can be processed by the pilot. The article presents the results of a study on the assessment of different methods by which the aircraft status can be determined and its control systems can be monitored. The study was conducted due to the need to meet stringent requirements in flight safety regarding pilots' ability to serve as backups when flying highly automated aircraft. In order to do this, pilots need to develop an integral skill in processing static and dynamic information coming to them from various sources.

Keywords Information · Efficiency · Status assessment · Piloting · Automation

1 Introduction

When flying a modern highly automated aircraft, the pilot does not know the position of the flight control surfaces or the aircraft's attitude. The pilot can only evaluate the position of the control stick or the side stick [1–3]. This is explained by the fact that control operations are performed by many intelligent systems that work according to the algorithms embedded in them. It is impossible for the pilot to directly monitor the operation of all these systems. However, an assessment of the state of the systems

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involved in aircraft control by indirect indicators is necessary in order to back up the automated flight systems, or for the pilot to take over the control from the autopilot.

In cases when flight conditions are difficult, the pilot needs to monitor and control a lot of different parameters. This results in higher workload on the pilot and an increase in the probability that mistakes will be made when operating highly automated aircraft [4–9]. However, the pilot needs to perform operations safely regarding the use of both the flight control system and the air traffic control system, even if the number of information signals exceeds that which can be processed by the pilot in terms of both physical and mental resources [10–12]. To solve such a problem, it is necessary to identify the number of information signals necessary for performing manual control by the crew, which, on the one hand, would satisfy the safety of the aircraft as a technical system, and, on the other hand, would not exceed the amount of information that the pilot is able to process per unit time.

Since the pilot manages his attention in a closed loop consisting of a certain group of information sources, an important part of this process is the choice of exactly that group of information sources that most fully describes the current flight phase and the status of the aircraft [13–15]. Some of the sources should display the status of the automation systems, and the other part of the information sources should display the parameters of the flight independent of the automation systems. Thus, when evaluating how well pilots control aircraft in flight, an information assessment method can be used that uses the principle of hierarchical consistency between the selected groups of instruments and the principle of controllability of the parameters included in the groups of instruments selected by the pilot. Let us consider how these two principles of selecting information coming to the pilot can work within one method. It should be noted here that in order to implement the two principles of information selection and processing in flight, the pilot needs to use cognitive converters of activity algorithms. They are the processes of regulating the algorithms of the actions performed by pilots by means of information resources selected according to the criteria of consistency and controllability of flight parameters. Using the information resources of the crew-aircraft-environment system, the algorithms of the pilot's actions are regulated by the pilot through the process of combining the sources being monitored in the algorithm. These sources are long-period and algorithmic flight parameters. The algorithms of the pilot's actions are also regulated by means of gradual strengthening of the control of information sources used in the algorithm. To increase the probability that the pilot will make the right decision concerning whether to take over the autopilot or not, the processes of regulating the algorithms are modeled. Mathematically, the decision-making process is modeled as a comparison between what the pilot should see in a situation and what he can actually see [10, 16–18]. Next, we will demonstrate how the use of cognitive converters of activity algorithms affects the efficiency of how the pilot assesses the status of the crew-aircraft-environment system.

2 Materials and Methods

Let us consider aircraft control on Boeing 737 (see Table 1) in three different flight situations (see Table 1):

1. Mode III (Autopilot, Autothrottle/Flight Guidance): climbing after takeoff, flaps extended;
2. Mode III (Autopilot, Autothrottle/Flight Guidance): activating the Vertical Speed mode (VS) and setting the vertical rate of climb with flaps extended;
3. Mode IV (Autopilot, Autothrottle, data from the Flight Management System (FMS)): the moment of being below or above the attitude profile during descent. In this case, the Autopilot Flight Director (AFDS) tries to maintain the profile parameters without using forward and vertical speed in the calculations.

In the first situation, the crew needs to monitor four information sources: Flight Mode Annunciator (FMA), which checks whether the autopilot operation mode corresponds to the specified one; Primary Engine Display (PED), which demonstrates the key parameters of the engine and is used to compare the operation of the engines with the parameters set in FMS; FMS compares the thrust displayed on PED with the pre-calculated climb thrust; kinesthetic control of the thrust levers to check the change in thrust. However, by applying cognitive converters of activity algorithms to combine the kinesthetic control of the thrust levers and thrust control using the data displayed on PED, the pilot will need to work with three rather than four parameters. Mathematically, the control process will be expressed as a ratio of one to three (see Table 3), and not one to four (see Table 2).

In the second situation, AFDS and the autothrottle (A/T) work separately, maintain their own parameters. AFDS maintains the vertical rate of climb by changing the pitch, and A/T maintains forward speed by changing the mode of operation of the engines. Naturally, in the V/S mode, a conflict situation may arise between the autopilot and the autothrottle, which will lead to the aircraft going beyond critical

Table 1 Types of control modes of a highly automated aircraft for a Boeing 737

I	Hand flown/raw data	Manual piloting with flight directors off/FMA and directors off
II	Hand flown/flight guidance	Manual piloting with flight directors on/FMA control while flying; flight modes are set on the mode control panel (MCP) by the pilot monitoring (PM)
III	Autopilot, Autothrottle/flight guidance	Autopilot mode using AFS with AFDS and autothrottle (A/T) on/mandatory FMA control, where the pilot flying (PF) himself sets the flight mode on the MCP
IV	LNAV, VNAV/flight guidance	Autopilot mode with AFDS and autothrottle (A/T) on/using data entered into the Flight Management Computer (FMC)

Table 2 Parameters of incorrect (F) and correct (T) information presented to the pilot during the specified flight phases without the pilot using cognitive converters

Aircraft status	Flight situation No. 1	Flight situation No. 2	Flight situation No. 3
F	1/4	1/3	1/5
T	3/4	2/3	4/5

Table 3 Parameters of incorrect (F) and correct (T) information presented to the pilot during the specified flight phases with the pilot using cognitive converters

Aircraft status	Flight situation No. 1	Flight situation No. 2	Flight situation No. 3
F	1/3	1/2	1/3
T	3/4	2/3	4/5

flight speeds. According to an expert survey conducted among instructors, the pilot in such situations only controls the compliance of the FMA mode with the specified piloting mode, which usually includes a long-period parameter that depends on an algorithm (for example, the airspeed parameter on the flight display and the airspeed parameter on the autopilot panel). However, if the pilot understands that conflict situations may arise between the control systems of the aircraft and what they can lead to, then he or she will understand that the flight situation may become more complicated and the application of cognitive converters is necessary. Therefore, the pilot needs to use such operations as combination and step-by-step control in order to maintain awareness of the aircraft status in flight and not exceed the limits on the amount of information being processed.

Thus, the probability that the pilot is presented with information requiring intervention if cognitive converters are not used will be one in three (see Table 2), and if they are used, it will be one in two (see Table 3).

In the third situation, the crew needs to control five information sources: wind direction and speed on the navigation display (ND); compliance of the current piloting mode with the one set by FMA; control of the forward speed for increase according to the commands on the FMS display (THRUST REQUIRED or DRAG REQUIRED); kinesthetic control of the position of the thrust levers; monitoring the atmospheric situation based on the comments of the crews in the air. The probability that the information received by the pilot in this mode without the use of cognitive converters does not require intervention in the control will be equal to one in five (see Table 2). And when using cognitive converters, the pilot will control the other four modes after moving to the current flight phase and making sure that the FMA displays the correct autopilot mode. Thus, the probability that the information coming to the pilot in this mode requires intervention in the control will be equal to one in three when the pilot uses cognitive converters (see Table 3).

The parameters of incorrect (F) and correct (T) information presented to the pilot during the specified flight phases without the pilot using cognitive converters and with the use of these converters are shown in Figs. 2 and 3.

There is an equation for calculating the probability of the expected gain of any process related to human activity in the control loop of a technical system [16]:

$$E = p(T)\big[p(t|T)V_t - p(f|T)C_f\big] + p(F)\big[p(f|F)V_f - p(t|F)C_t\big] \quad (1)$$

Let us assume that the probability of gain for the study of the control of a highly automated aircraft will be the efficiency of the pilot's assessment of the aircraft status in flight when controlled in automatic mode. Then the values of the components in Eq. (1) will be as follows:

- $p(T)$—a priori probability that the aircraft will be in the correct status, i.e., not in the status that the pilot set through automation;
- $p(F)$—a priori probability that the aircraft will be in the wrong status, i.e., in the status that the pilot set through automation;
- $p(t|T)$, $p(f|T)$, $p(f|F)$, $p(t|F)$—conditional probabilities f (control intervention) and t (no control intervention) for the corresponding statuses of the aircraft F (different from the set one) and T (set one);
- V_t—gain with the correct non-intervention in the current piloting situation;
- V_f—gain in the case of necessary intervention in the automatic control in the current piloting situation;
- C_f—loss in the case of unnecessary intervention in the automatic control in the current piloting situation;
- C_t—loss due to the inaction of the pilot in the case when it is necessary to intervene in the control.

3 Discussion

In order to find the probabilities $p(f|T)$, and $p(f|F)$, it is necessary to perform a number of transformations with the data presented in Tables 2 and 3. We will first discuss the data in Table 2. Let us reduce all the fractions in the table to a common denominator, which is $g = 60$. Next, we will compile a new table (see Table 4), which will contain data on the values of the numerators of all fractions previously reduced to the common denominator, each written in its own row and column but without a denominator. This table also presents the ratios of these observed values or the so-called cutoff $L(x)$.

The next step is to search for the values of the likelihood ratio criterion (K). To do this, it is necessary to know a priori probabilities $p(T)$ and $p(F)$, as well as gains and losses V_t, V_f, C_f, C_t. Since the pilot's behavior is unknown before any action is performed, it is assumed that $p(T) = p(F) = 0.5$. Gains and losses are distributed in this case as follows: $V_t = 1$, $V_f = 4$, $C_f = 1$, $C_t = 1$. This distribution is explained by the fact supported by the results of expert surveys that when the autopilot system is on, pilots rely on automatic controls when making decisions on performing control actions [19]. Therefore, the gain V_f in the case when there is necessary intervention in the control in the current piloting situation is the key criterion for the safe control

Table 4 Observed values of conditional probabilities for various flight modes, with corresponding flight modes presented in Table 2

Conditional probabilities	Flight situation No. 1	Flight situation No. 2	Flight situation No. 3
$P(x\|F)$	15	20	12
$P(x\|T)$	45	40	48
$L(x) = \frac{P(x\|F)}{P(x\|T)}$	0.33	0.5	0.25

of the aircraft for the pilot. In this case, as in all subsequent cases, reliance on the visual channel is inevitable, and all actions that pilots perform in flight are checked by monitoring instruments and other information sources. Therefore, intervention in control follows only after the pilot has processed information by means of the visual channel. This is why V_f has such a high value.

According to [15], the value of the K-criterion will be as follows:

$$K = \frac{p(T)}{p(F)} \times \frac{V_t + C_f}{V_f + C_t} = \frac{0.5}{0.5} \times \frac{1+1}{4+1} = 0.4.$$

The next step in our calculations is to find the values $p(t|T)$, $p(f|T)$, $p(f|F)$, $p(t|F)$:

$$p(f|F) = \frac{\sum p(x|F)}{g} = \frac{20}{60} = 1/3,\ p(f|T) = \frac{\sum p(x|T)}{g} = \frac{40}{60} = 2/3,$$
$$p(t|T) = 1 - \frac{2}{3} = 1/3,\ p(t|F) = 1 - \frac{1}{3} = 2/3.$$

It should be noted here that the sum of all values $\sum p(x|F) u \sum p(x|T)$, It should be noted here that the sum of all values $L(x) = \frac{P(x|F)}{P(x|T)}$, that is greater than or equal to the value of the K-criterion (see Fig. 1).

Next, let us find the efficiency of assessing the aircraft status by the pilot when performing a flight in the automatic mode using Eq. (1):

$$E = 0.5\left[\frac{1}{3} \times 1 - \frac{2}{3} \times 1\right] + 0.5\left[\frac{1}{3} \times 4 - \frac{2}{3} \times 1\right] \cong 0.20.$$

Let us find the efficiency of the pilot's assessment of the aircraft status when flying in the automatic mode when the pilot uses the processes of cognitive converters of activity algorithms (see Table 5 and Fig. 2).

In accordance with [16], the value of the likelihood criterion will be as follows:

$$K = \frac{p(T)}{p(F)} \times \frac{V_t + C_f}{V_f + C_t} = \frac{0.5}{0.5} \times \frac{2+1}{4+2} = 0.5.$$

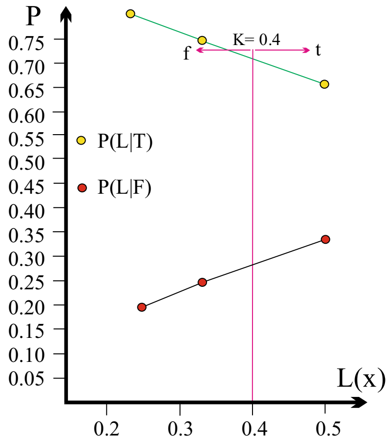

Fig. 1 Distribution of conditional probabilities for likelihood ratios without the pilot's reliance on cognitive converters of activity algorithms

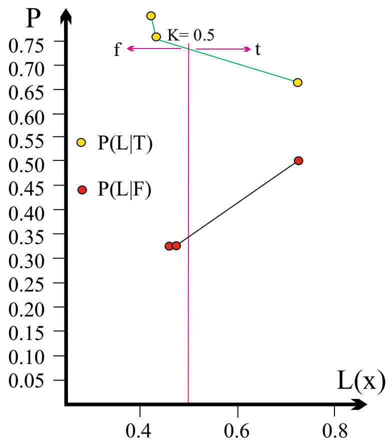

Fig. 2 Distribution of conditional probabilities for likelihood ratios with the pilot's reliance on cognitive converters of activity algorithms

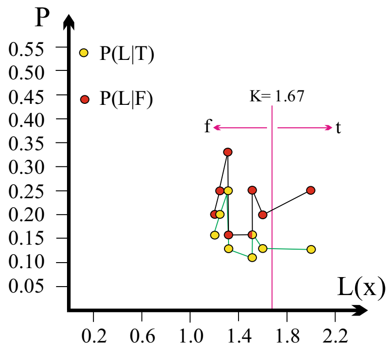

Fig. 3 Distribution of conditional probabilities for likelihood ratios with the pilot's reliance on cognitive binding to current information

Table 5 Observed values of conditional probabilities for various flight modes, with corresponding flight modes presented in Table 3

Conditional probabilities	Flight situation No. 1	Flight situation No. 2	Flight situation No. 3
$P(x\|F)$	20	30	20
$P(x\|T)$	45	40	48
$L(x) = \frac{P(x\|F)}{P(x\|T)}$	0.44	0.76	0.41

The values of gain with correct non-intervention and those of loss with incorrect non-intervention grow since the processes of cognitive converters of activity algorithms, as it were, return the pilot to the control loop. In this case, when assessing the status of the aircraft, the pilot relies not only on the results provided by the visual channel but also on mental activity, which involves a forecast of how the situation will develop. Therefore, in accordance with [19], the risks of non-intervention in any of the two considered cases (C_f, C_t) increase.

Further calculations produce the following result:

$$p(f|F) = \frac{30}{60} = 1/2,\ p(f|T) = \frac{40}{60} = 2/3,\ p(t|T) = 1 - \frac{1}{2} = 1/2,$$
$$p(t|F) = 1 - \frac{2}{3} = 1/3,\ E = 0.5\left[\frac{1}{2} \times 2 - \frac{2}{3} \times 1\right] + 0.5\left[\frac{1}{2} \times 4 - \frac{1}{2} \times 1\right] \cong 0.50.$$

The proposed method for determining the efficiency of assessing the aircraft status by a pilot in flight is based on the static regularity of attention distribution between groups of information sources and certainly affects the quality of piloting. However, it can be added here that the method does not explain how to maintain the pilot's skill of assessing the current situation, although it reflects the laws of interaction between information provided by instruments and other information received in flight.

There is also a pattern in the dynamic behavior of the aircraft, which the pilot can identify through the order of change of certain flight parameters both relative to the set values and relative to changes in other related flight parameters. Let us consider in more detail the method of assessing of the aircraft status taking into account the dynamic relationship between aircraft flight parameters.

When considering how the pilot assesses the aircraft status by means of dynamic parameters in contrast to the static assessment, the relationship between long-period and algorithmic parameters is no longer considered, but the relationship between long-period and short-period parameters is considered. In this case, cognitive converters cannot be used. Therefore, the pilot needs to use other cognitive processes that allow for keeping control over the flight parameters when any of the parameters escape the pilot's attention by comparing the rate of change of the parameters remaining in the pilot's attention focus. Such processes are called processes of cognitive binding to current information.

The dynamic approach is based on the pilot's assessment of the status of a highly automated aircraft through monitoring the relationship of the rate of change in aircraft flight parameters. There are two such rates of parameter change for each source of information. One of them is to the difference between the current change in the observed parameter and its set value, and the other is the change in the observed value of the parameter relative to another dependent parameter. For example, the rate of speed change depending on the amount of power supplied to the engines can have different values. Therefore, if the pilot sets aircraft engine power in the manual mode, he or she expects that there will be a corresponding rate of increase in speed. However, in automatic modes with kinesthetic control, it is difficult for the pilot to track whether the change in speed is as predicted because the pilot's processes of perception are distorted due to overload and control is performed by the automation system. Therefore, the control in the autopilot mode should be guided by information coming from indirect indicators. For monitoring speed, such indicators apply as the rate of change of speed on the PFD depending on the engine speed value demonstrated on the PED and the rate of change of pitch (or angle of attack) on the PFD depending on the change in speed.

Thus, the processes of cognitive binding to current information are reduced to the detection of signals coming to the pilot and are based on determining and comparing two parameters:

- the rate of change of the parameter being monitored relative to its own set value;
- the rate of change of the parameter being monitored relative to another, which is most closely related to it.

Let us consider several flight operations: maintaining speed and altitude in level flight, maintaining speed and altitude in climb or descent, and maintaining heading at various flight phases. The conditions for maintaining the flight speed at a constant for the case of determining the correct aircraft status (F) are as follows: (1) constant pitch; (2), (3) change in pitch to the side contributing to an increase or decrease in speed that tends to a given value; (4), (5) increase or decrease in engine speed in the direction corresponding to the specified speed value. The conditions for maintaining the flight speed at a constant for the case of determining the incorrect aircraft status (T) are as follows: one more parameter is added to the parameters for determining the correct aircraft state (F)—a constant value of engine speed (see Table 6). The remaining parameters of the modes considered in the table are determined according to the same principle. In order to develop a mathematical model of the conditions for assessing the aircraft status using cognitive converters, it is first necessary to represent the process as a fraction whose numerator is one and whose denominator is the number of conditions that determine the aircraft status at the current time. The unity in the numerator means that the pilot determines the aircraft status by one of the selected parameters in the denominator of the fraction (see Table 6).

Further calculations are performed according to Eq. (1). The results of reducing the values of the characteristics of incorrect (F) and correct information (T) to a common denominator and finding the definition of the cutoff $L(x)$ are presented in Table 7. The distribution of conditional probabilities for likelihood ratios in the case of using the processes of cognitive binding to current information is shown in Fig. 3. The a priori probabilities of both incorrect and correct states $p(F)$, $p(T)$ were chosen

Table 6 Parameters of incorrect (F) and correct (T) information presented to the pilot when performing specified flight operations using cognitive binding to current information

Aircraft status	Maintaining speed in level flight		Maintaining altitude in level flight		Maintaining speed in climb or descent		Maintaining altitude in climb or descent		Maintaining heading at various flight phases	
	V const	V ↓ or ↑	H const	H ↓ or ↑	V const	V ↓ or ↑	H const	H ↓ or ↑	hdg| const	hdg ↓ or ↑
F	1/5	1/4	1/5	1/4	1/6	1/4	1/6	1/4	1/4	1/3
T	1/6	1/5	1/6	1/6	1/9	1/8	1/9	1/8	1/5	1/4

equal to 0.25 due to the high load on the visual channel when assessing changes in flight parameters. Gains and losses, in this case, are distributed as follows: $V_t = 3$, $V_f = 2, C_f = 2, C_t = 1$. This distribution is explained by the fact that the loss in the case of unnecessary intervention in automatic control is equal to the gain in the case of necessary intervention in automatic control since the dynamic assessment of the current information equates these two processes as they do not require an element of prediction.

On the contrary, the gain from correct non-intervention implies a forecast of changes in the parameter being monitored, which makes it bigger than the loss from non-intervention. Therefore, the likelihood criterion is:

$$K = \frac{p(T)}{p(F)} \times \frac{V_t + C_f}{V_f + C_t} = \frac{0.25}{0.25} \times \frac{3+2}{2+1} = 1.67.$$

Further calculations produce the following result:

$$p(f|F) = \frac{180}{360}, p(f|T) = \frac{90}{360}, p(t|T) = \frac{180}{360}, p(t|F) = \frac{270}{360}$$

$$E = 0.25\left[\frac{270}{360} \times 3 - \frac{90}{360} \times 2\right] + 0.25[0.5 \times 2 - 0.5] \cong 0.81.$$

Table 7 Conditional probabilities and likelihood ratios for various flight situations, with their mode correspondence probabilities presented in Table 6

Conditional probabilities	Maintaining speed in level flight		Maintaining altitude in level flight		Maintaining speed in climb or descent		Maintaining altitude in climb or descent		Maintaining heading at various flight phases	
	V const	V ↓ or ↑	H const	H ↓ or ↑	V const	V ↓ or ↑	H const	H ↑ or ↑	hdg cons t	hdg ↓ or ↑
$P(x\|F)$	72	90	72	90	60	90	60	90	90	120
$P(x\|T)$	60	72	45	60	40	45	45	45	72	90
$L(x)$	1.20	1.25	1.6	1.5	1.5	2	1.33	2	1.25	1.33

4 Results

It follows from the calculations that the efficiency of the method for assessing the aircraft status by the pilot when piloting in automatic mode without relying on cognitive converters of activity algorithms is approximately 20%. The efficiency of the pilot's assessment of the aircraft status when piloting in automatic mode using the processes of cognitive converters of activity algorithms increases by approximately 30% relative to the situation in which cognitive converters are not used. The efficiency of the pilot's assessment of the aircraft status when piloting in automatic mode using the processes of cognitive binding to current information increases by approximately 30% relative to when cognitive converters are used.

5 Conclusion

The results of the theoretical study presented in this article show that the efficiency of assessing the status of the aircraft and its automated control systems by means of indirect indicators increases significantly when using methods that include the processes of cognitive converters of activity algorithms and processes of cognitive binding to current information. This allows for combining the static and dynamic parameters of the assessment of the current flight situation.

However, the application of cognitive converters and cognitive binding processes requires that pilots have an integral skill needed to operate modern highly automated aircraft. In order to develop such an integral skill in the area of processing static and dynamic information in flight, it is necessary to design and apply new flight training methods.

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