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# The Intelligent Situational Awareness And Forecasting Environment (The S.A.F.E. Concept): A Case Study[1]

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## ABSTRACT

A knowledge-centered approach to aircraft flight safety enhancement is proposed. Using an example of modeling and simulation of a flight accident, a concept of the Intelligent Situational Awareness and Forecasting Environment (the S.A.F.E. concept) is introduced. The purpose of this type of onboard system is short-term prediction of a tree-network of possible safe and unsafe flightpaths under complex (multi-factor) flight situations. Two notional systems are discussed: the Situational Forecast Display and the Flight Safety Indicator. Potential applications include pilot-vehicle intelligent interface, automatic flight envelope protection, autonomous (robotic) flight, knowledge-centered pilot assistance and pilot training, and automatic resolution of conflicts in close 'free flight' navigation space, etc.

## INTRODUCTION

PILOT ERROR? The major problem in aviation safety is reportedly "human error, which is a factor in 60 to 70 percent of all aircraft accidents. Other major causes are mechanical problems, which account for roughly 17 per cent, and then weather at about 5 per cent…" [1].

When analyzing these statistics the following questions may arise. First, is this large percentage of "human error" related accidents fairly attributed to pilots? Did those unfortunate crews *actually* fail, in terms of skills, responsibility or self-preservation instincts in emergencies? Further, why does this type of flight accident and incident remain characteristic to modern, highly automated aircraft which are supposed to remedy the problem? Finally, concerning the share of accidents occurred due to technical failures and adversary weather conditions: was it impossible to examine such cases in advance, during aircraft design, flight test and certification?

MULTI-FACTOR FLIGHT DOMAINS. It may be argued, based on results of modeling and simulation of the "pilot - vehicle - operational conditions" system behavior in emergencies, that so called "human error" is often not a primary link in accident chain. Rather, it is an interim indication of other, root relationships, which determine the system behavior. Given a certain unusual *combination* of operational factors (demanding weather conditions, imperfect vehicle performance, mechanical problems, and inadequate control inputs), a modern vehicle may inadvertently enter an anomalous domain of the flight modes with a small safety margin and insufficient chances of recovery. Under such conditions any subsequent control input may become inadequate or inefficient.

PROPOSED SOLUTION. A knowledge-centered approach to enhancing flight safety is proposed. The principle idea is to integrate mathematical modeling and computer simulation of flight with artificial intelligence techniques [2, 3]. As a result, a more comprehensive knowledge of complex dynamics of the "pilot - vehicle - operational conditions" system can be obtained. Then this knowledge can be brought onboard to help the pilot resolve complex flight situations. The objective is to identify critical combinations of key operational factors and thus prevent the vehicle from entering irreversible flightpaths.

PAPER CONTENT. It will be demonstrated how such complex system relationships can be formalized, generated and applied to reduce the risk of a catastrophe. A concept of the Intelligent Situational Awareness and Forecasting Environment (the S.A.F.E. concept) is developed. To introduce the concept a detailed example of modeling and simulation of a flight accident is employed. The principles of construction and use of knowledge-centered media for pilot-vehicle intelligent interface are described. Two possible realizations are discussed. These are the Situational Forecast Display (SFD) and the Flight Safety (or Mission Success) Indicator (FSI/MSI). Finally, conclusions are made as to the merits and potential applications of the technique.

## "CHAIN REACTION" FLIGHT ACCIDENTS

LOGICAL MECHANISM. In recent years, statistics of flight incidents and accidents with highly automated aircraft began building up [4, 5]. These cases are difficult to correlate with some extraordinary circumstances of flight or address to a particular aircraft manufacturer or operator. Their logical mechanism appears as chain reaction: action of several operational factors, not critically dangerous alone ⇒ distortion of a standard profile of flight and control ⇒ inadequate inputs from the pilot or an automatic system ⇒ logical discrepancies in the flight control scenario ⇒ multiple infringements of operational constraints ⇒ incident/accident.

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WORK DEFINITION. The *“chain reaction” of a flight accident or incident* may be defined as quick and irreversible propagation during flight of several operational factors and their adversary effects linked by strong cause-and-effect relations. Such situations start as a relatively safe, non-critical event but often end in a catastrophe or an incident.

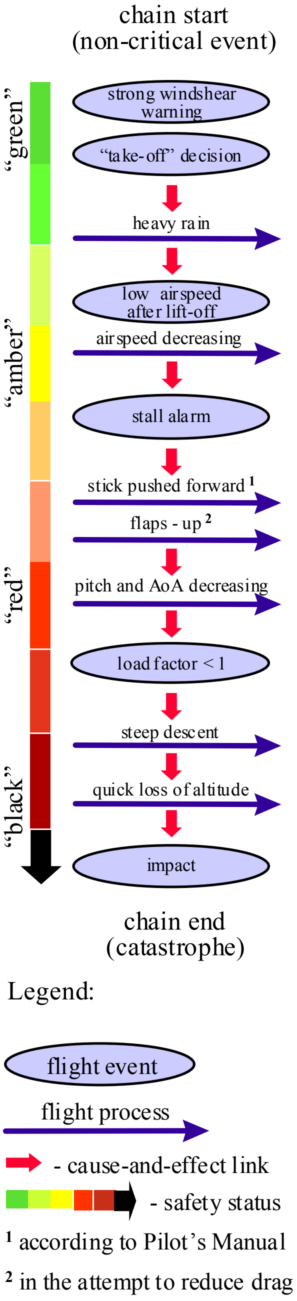


**Figure 1:** Chain reaction of a flight accident “Airplane takeoff under microburst conditions”

**Fig. 1** depicts a scheme of a “chain reaction” accident with an airliner at takeoff under microburst conditions (more detail will follow). Note that the colors, which indicate the aircraft safety status during takeoff, change from green (safe modes) and amber (approaching flight constraints) to red (constraints violation) and “black” (airframe disintegration).

HUMAN-CENTERED VS. TECHNOLOGY-CENTERED AUTOMATION. Due to the frequency of such cases, their roots ought to be searched in the methodology employed for designing flight envelope protection, flight control, and pilot-vehicle interface systems. This search results in the human-centered and technology-centered approaches to flight automation [6, 7]. Basically, these two approaches have emerged as a result of idealization of the statements that the human pilot or a computer should ultimately control the vehicle. However, aircraft safety systems based on these principles often fail under multiple conditions. Moreover, a “chain reaction” incident or accident can be triggered under non-demanding conditions.

SUMMARY. A substantial growth in global civil aviation is expected in the near future [1]. Due to the expansion of the flight envelopes, transport aircraft will be experiencing a growing number of non-standard flight modes. It is thus very likely that conditions for potential “chain reaction” accidents and incidents will continue to occur. To account for such conditions, the edge of the flight envelopes of existing and future vehicles should be tested and secured appropriately. More reliable methods are required to ensure vehicle flight safety under multi-factor situations.

## HYBRID INTELLIGENCE MODEL

SITUATIONAL KNOWLEDGE OF FLIGHT. The reliability of flight control in emergencies depends on the knowledge of complex operational domains and its quality. The *situational* (operational, tactical, or “surface”) *knowledge of flight* is a system of relationships that the operator (the pilot or an automatic system) possesses with respect to various flight situations and their transitional dynamics. Basically, the operator applies this expertise to get answers to the following questions:

- What is the current flight situation, and what are its key components?
- What are the likely alternatives for short term development of the current situation? What are the chances of its safe and unsafe outcomes?
- What operational factors will dominate under these possible safe and unsafe developments of flight in 10-25 seconds?
- Which operational constraint is the nearest (i.e. the most critical one), and how close is the vehicle to it?
- What control inputs and when should be applied (or avoided) to maintain a safe flight mode?

In the epistemological hierarchy of a pilot’s knowledge of flight [8], the situational knowledge occupies the most important position - between neuro-motor response skills and strategic mission planning relationships. Situational intelligence (i.e. the situational knowledge and processing functions associated with it) links together, respectively, the lower (reactive) and the upper (proactive) levels in a human pilot’s decision making mechanism. This type of knowledge determines the outcome of a specific maneuver or a phase of flight and thus plays a key role in securing flight safety.

KNOWLEDGE-CENTERED APPROACH. Obviously, there is a lack of onboard information about complex dynamics of the “pilot - vehicle - operational conditions” system. Given a multi-factor situation, this shortcoming may contribute, directly or indirectly, to the development of a “chain reaction” of dangerous events and processes. A *knowledge-centered approach* to flight safety enhancement means that control decisions under complex conditions should be founded on physical knowledge of the current flight situation and its possible short-term developments. In other words, the control authority under a multi-factor situation should be assigned dynamically to a most knowledgeable operator (the pilot, or an automatic system) or, perhaps, to a special safety system.

The approach is based on the following two statements:

1. Neither the pilot, nor a computer controls a flight vehicle. The vehicle is ultimately controlled by knowledge, i.e. by the laws of aerodynamics, flight mechanics, and propulsion, etc. The operator (the human pilot, or an automatic control device) acts as a carrier, processor, and/or applicator of these laws.
2. The remedial techniques (i.e. the instructions on how to avoid or rectify a particular emergency) are not new. Normally, the specialists are aware of these techniques *before* the event. The challenge, however, is how to derive a system of such knowledge and convey it to the operator before the situation may become irreversible.

To fill in this gap in flight related knowledge, an autonomous mathematical model of flight can be used as a “knowledge generator”. Special methods are also available to efficiently retain and quickly access this knowledge onboard.

HYBRID INTELLIGENCE. The basic idea of the knowledge-centered approach is to combine positive features of a human pilot’s decision-making mechanism with mathematical modeling and computer simulation of flight. Given an emergency, there is a complementary match of strengths and weaknesses between the human pilot and a computer (an automatic system) [3]. Humans in general possess strong self-preservation instincts. Human operators of complex plants are good at predicting future short-term trends in plant dynamics. Pilots can characterize various heterogeneous aspects of a complex flight situation as an integral picture, using a few approximate (fuzzy) but robust terms. They are also capable of making efficient decisions based on this information, etc.

On the other hand, computers can retain massive volumes of data in accurate, non-decaying formats. These databases can be quickly accessed during flight. Through mathematical modeling and computer simulation it is also possible to systematize and quantitatively assess extreme or rare effects upon flight of several counter-acting factors.

The strengths of both sides are proposed to integrate in a *“hybrid intelligence” model*. The model’s function is based on a complementary combination of a pilot’s and mathematical knowledge useful in emergencies. The purpose is to help the standard operator predict and avoid irreversible flightpaths under complex conditions. The concept of flight safety automation based on hybrid intelligence is called the *Situational Awareness and Forecasting Environment* (the S.A.F.E. concept).

SAFETY AS A BUILT-IN FEATURE. A common-sense synonym for air safety is “no accident” [4]. In other words, safety must become an inherent, “built-in” property of a flight vehicle, such as its aerodynamics, strength and comfort are. This objective has not been achieved yet, though the share of avionics is about 30-40% of the aircraft total cost and tends to increase and even though pilots are, probably, the best trained and highly qualified category of human operators.

A hybrid intelligence model can be specially trained to gain knowledge about multi-factor operational domains of flight. Its primary mission is to perform reliable backup control at the edge of the flight envelope. Knowledge-centered automation is suggested as a feasible and affordable means for achieving a higher level of flight safety in existing and future vehicles.

SUMMARY. Neither the pilot, nor a computer ultimately controls the flight vehicle. The vehicle is controlled by knowledge, i.e. by the laws of aerodynamics, flight mechanics, and propulsion. To secure flight safety under complex situations, a comprehensive physics-based knowledge of multi-factor operational domains is required onboard. A “hybrid intelligence” model, which combines positive features of human pilot decision-making and flight modeling, is employed to achieve this goal. The model’s purpose is to help the standard operator foresee and avoid irreversible propagation of a critical situation. The S.A.F.E. concept is a generic formulation of flight safety automation based on hybrid intelligence. The objective is to design and operate vehicles with inherent flight safety standards.

## CASE STUDY: MODELING AND SIMULATION OF AIRCRAFT TAKEOFF IN MICROBURST

INTRODUCTION. Examined is a flight accident occurred with an airliner during takeoff under severe microburst conditions. The purpose of this case study is to explain the principles of implementation and use of the S.A.F.E. concept. It will be demonstrated how complex relationships that determine behavior of the “pilot – vehicle – operational conditions” system can be identified and organized in a systematic way. Then this knowledge can be brought onboard to support flight envelope protection, pilot-vehicle interface, or other safety related functions.

DISCLAIMER. Though this study is based, to a large extent, on real accident data, it is not meant to represent any specific flight. Neither is it intended to review the results of investigation of any recorded case belonging to this class. Criticism is not aimed at any aircraft operator or manufacturer. Though this study provides a better understanding of the primary causes of such accidents, the conclusions derived from modeling and simulation reflect the author’s private opinion only. This material does not contain piloting instructions or safety recommendations for practical use.

ACCIDENT DETAILS. A three-engine airliner was taking off through an atmospheric zone of microburst (**Fig. 2**).

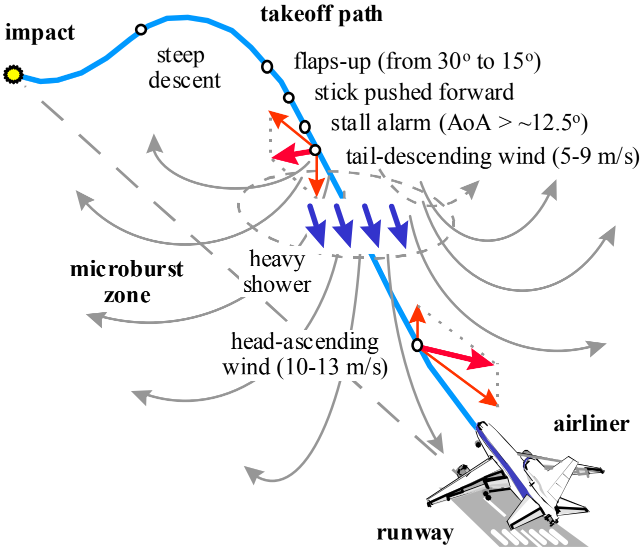


**Figure 2:** Flight accident profile

This weather condition was characterized by sharp changes in wind direction and magnitude - from head-ascending (very strong gusts, up to 10-14 m/s) to tail-descending (within 5-9 m/s). This phenomenon has created a severe wind shear situation, which in combination with a heavy shower of the intensity of about 200-250 mm/h has caused a sharp loss of the airspeed after lift-off.

After a stall alarm appeared in the cockpit (when the angle of attack had exceeded 12°-13°), the stick was pushed forward according to the Pilot's Manual. Soon after that, a flap retraction procedure (30°→15°) was commenced prematurely (probably, in the attempt to reduce drag). However, the lift force was insufficient, and the airplane went into an unrecoverable descent.

STUDY PROGRAM. This study includes the following steps:

- develop a formal scenario of the accident and reconstruct it in mathematical modeling and computer simulation
- identify a "chain reaction" mechanism of the accident
- identify weather conditions at takeoff (rain and wind)
- develop a series of scenarios to realize "neighboring" flight situations and alternative piloting methods
- examine these derivative takeoff cases and test the robustness of alternative piloting
- construct a situational tree of flightpaths to exemplify the operational domain around the accident
- calculate and draw "flight safety spectra" for the accident and its "neighbors" (derivative situations)
- draft a basic situational forecast display for the combined conditions of microburst and alternative piloting
- discuss design, implementation and application issues of S.A.F.E. systems

The results of this program are briefly described below.

ASSUMPTIONS. The accident was reconstructed in computer simulation experiments with a six-degree-of-freedom non-linear mathematical model of flight. This model incorporates a "silicon pilot" model and a generic flight situation model [2, 3]. Vehicle aerodynamics, propulsion, control, as well as the key operational factors of this flight (wheel-runway interaction, wind-shear and rain effects, C.G. location, etc.) that might have affected the vehicle motion were taken into account.

The resulting model is autonomous as it describes behavior of the entire "pilot – airliner – operational conditions" system. However, only longitudinal motion was reconstructed, because the airplane's lateral attitude did not change significantly during the takeoff (the bank angle remained within 2°-5°). This assumption was introduced for clarity and does not affect main conclusions of the study.

CASE FORMALIZATION. A *flight scenario* **$S_0$** of the accident is depicted in **Fig. 3** in the form of directed graph [2, 3]. Basically, the flight scenario is an abstract topological structure that links together discrete and continuous components of the accident's logic model. It will be used as a plan for simulating the accident and its derivatives.

A "calendar" **$\Omega_0$(E)** of the *flight events* comprising **$S_0$** represents discrete components of the situation under study and incorporates the following elements:

- **$E_1$**: "groundroll start"
- **$E_2$**: "speed VR achieved"
- **$E_5$**: "nose wheel off the runway"
- **$E_7$**: "AoA is about 6°"
- **$E_{71}$**: "AoA is about 10°"
- **$E_8$**: "altitude is about 10.7 m"
- **$E_{21}$**: "altitude is about 56 m"
- **$E_{15}$**: "flight time is 60 seconds".

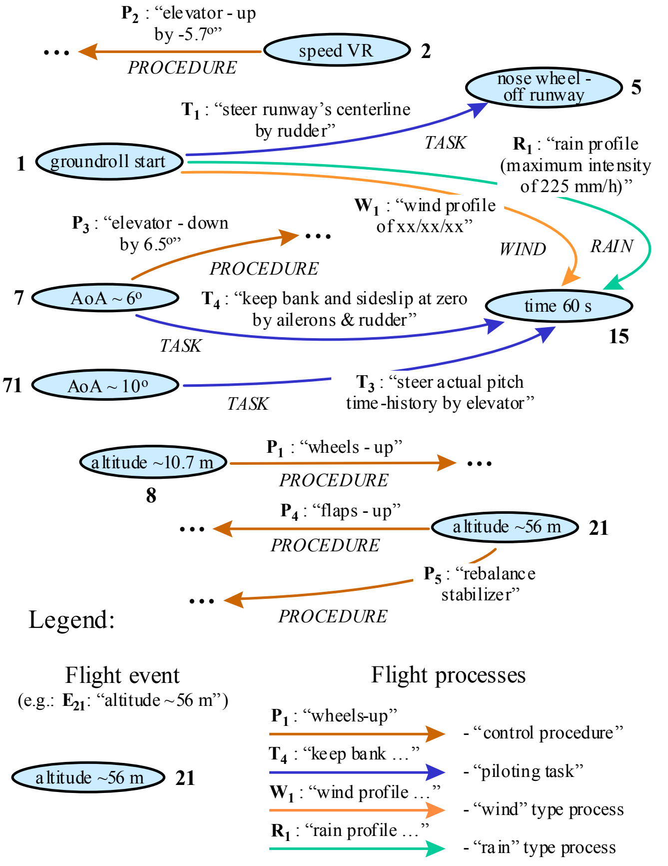


**Figure 3:** Accident scenario (**$S_0$**)

A united list **$\Omega_0$(Π)** of *flight processes* of **$S_0$**, or continuous components of flight, may be derived as follows (shown in parentheses are process type names [3]):

- **$T_1$**: "steer the runway's centerline by rudder during groundroll" (piloting task)
- **$T_3$**: "steer the pitch time-history recorded in the accident by means of elevator" (piloting task)
- **$T_4$**: "keep bank and sideslip angles at about zero in climb by ailerons and rudder" (piloting task)
- **$P_1$**: "wheels-up" (control procedure)
- **$P_2$**: "elevator-up by -5.7°" (control procedure)
- **$P_3$**: "reverse action by elevator (6.5° down)" (control procedure)
- **$P_4$**: "move flaps from 30° to 15°" (control procedure)
- **$P_5$**: "rebalance [horizontal] stabilizer" (control procedure)
- **$R_1$**: "apply a trapezoid rain profile with the maximum intensity of 225 mm/h" (rain)
- **$W_1$**: "apply a wind profile as identified in the accident of mm/dd/yy" (wind).

SCENARIO DESCRIPTION. The relationship between the events and the processes in **$S_0$** is clear from **Fig. 3**. The modeled situation lasts 60 seconds. Note this complex enough case can be mapped into a compact cause-and-effect structure, which includes only eight events and ten processes. The first event expected to occur is $\mathbf{E}_1$, and the last one is $\mathbf{E}_{15}$. The order of other events during simulation may differ from the list $\mathbf{\Omega}_0(\mathbf{\Pi})$. According to $\mathbf{S}_0$, the "silicon pilot" is instructed to maintain the pitch angle as recorded in the accident (the task $\mathbf{T}_3$). Note also that there are two specific events, $\mathbf{E}_7$ and $\mathbf{E}_{71}$, introduced for the purpose of accident reconstruction. Other events and processes represent typical components of a takeoff scenario for a turbojet transport airplane under microburst.

The graph $\mathbf{S}_0 = \mathbf{\Omega}_0(\mathbf{E})\cup\mathbf{\Omega}_0(\mathbf{\Pi})$ is convertible into a set of input data files for autonomous simulation on a computer. Also, it can be modified to generate a set of "neighboring" situations. These derivative cases differ from the accident in weather conditions and piloting methods. Note that flight scenarios of the "event-process" type are clear to the specialists.

ACCIDENT RECONSTRUCT. Accident reconstruction results are presented in **Fig. 4**.

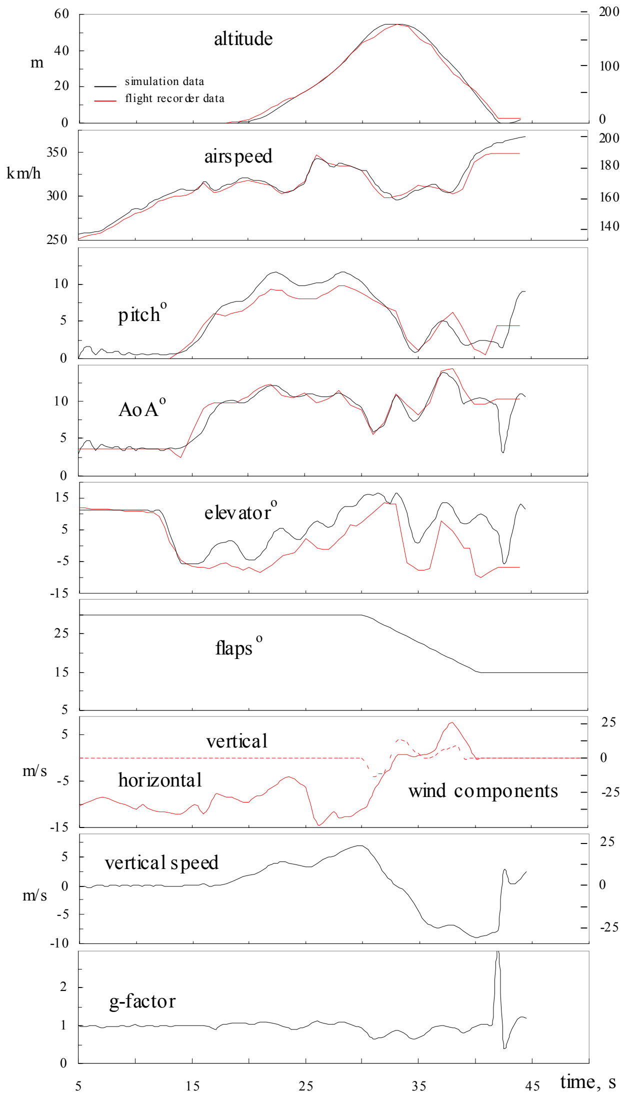


**Figure 4:** Results of accident reconstruction

Two flights are compared: results of simulation according to $\mathbf{S}_0$ and real flight accident data. The accident reconstruct is represented by a set of ten variables. It includes six main variables ($H$, $V_{IAS}$, $\theta$, $\alpha$, $\delta_e$, $\delta_{FL}$), which were also available from the flight recorder, and four additional variables ($V_z$, $n_z$, $W_{xg}$, $W_{zg}$) derived from the model. The accident is represented by the main subset ($H$, $V_{IAS}$, $\theta$, $\alpha$, $\delta_e$, $\delta_{FL}$) = f ($t$).

"CHAIN REACTION" MECHANISM. A "chain reaction" mechanism responsible for this accident has been identified based on the simulation results (**Fig. 5**). The method applied is clear from the diagram. Note that this mechanism is similar to that one depicted **Fig. 1** but now it is physics based.

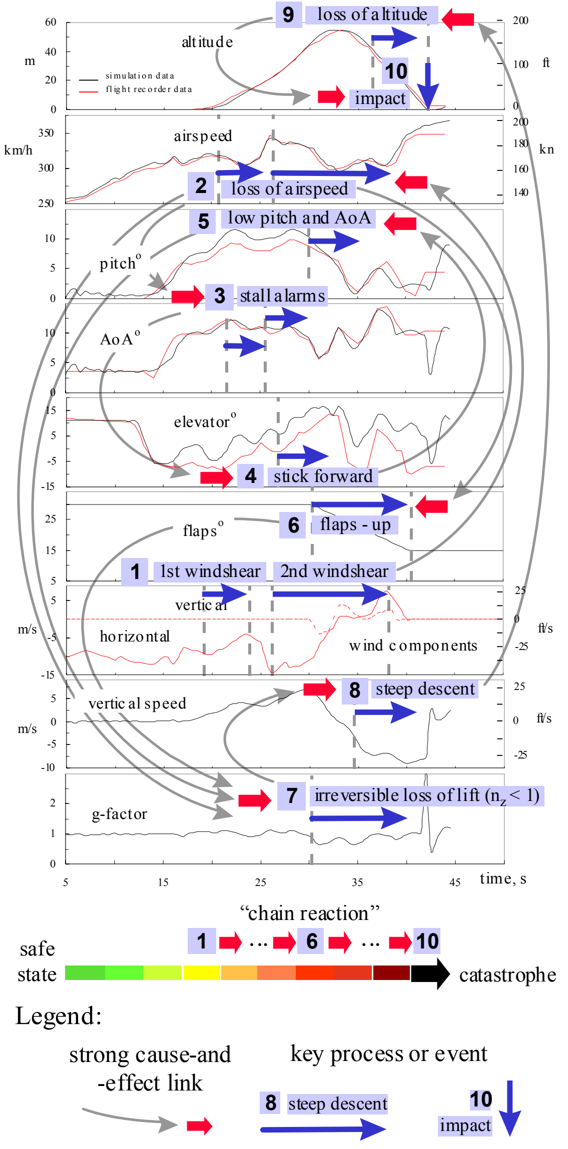


**Figure 5:** Identification of a "chain reaction" mechanism of the flight accident

OUTPUT DATA ANALYSIS. In spite of complex enough system dynamics involved in this case, there is a satisfactory fit between the flight recorder data and the accident reconstruct (see the variables $H$, $V_{IAS}$, $\theta$, $\alpha$, $\delta_e$, and $\delta_{FL}$ in **Fig. 4**). A difference between the recorded and the modeled pitch curves is due to a decoding error in the flight recorder data. A final actual pitch curve (not shown here) has matched the modeled one. Note that the "silicon pilot" executes flight control processes $\mathbf{T}_i$ and $\mathbf{P}_j$ in a manner similar to one observed in the accident. A shift between the actual and modeled time histories $\delta_e(t)$ could be eliminated by adjusting the model's horizontal stabilizer by $1^o \ldots 1.5^o$ down. It may be concluded that an irreversible trend in this takeoff began at $t$ = 28 s, i.e. approximately 13-15 seconds before the impact.

WEATHER CONDITION. The accident's wind shear profile has been identified in experiments with the model controlled by the "silicon pilot" - see the curves $W_{xg}(t)$ and $W_{zg}(t)$ in **Fig. 4**. A rain profile, J($t$), has also been derived (not shown). It has a trapezoid form with a maximum intensity $J_{MAX}$ = 225 mm/h.

SAFE TAKEOFF (EXAMPLE). A hypothetical takeoff scenario, $\mathbf{S}_3$, which demonstrates a correct piloting method possible under the given condition, is depicted in **Fig. 6**.

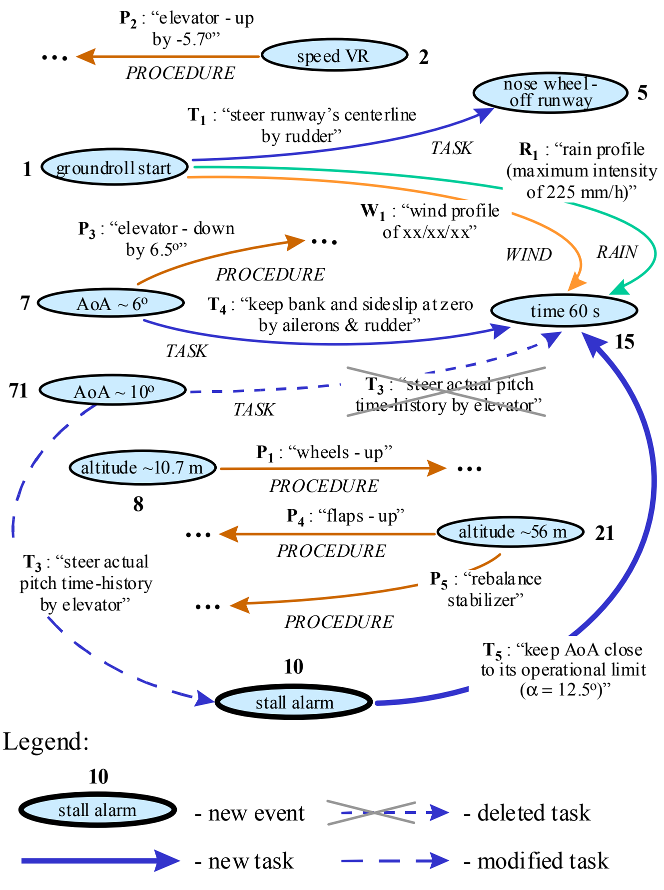
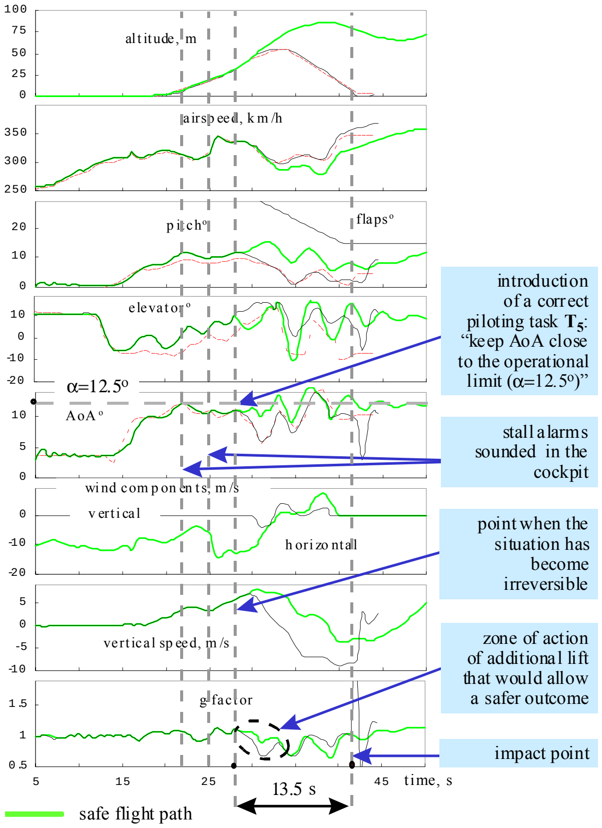


**Figure 6:** Safe takeoff scenario $\mathbf{S}_3$

Both safe ($\mathbf{S}_3$) and unsafe ($\mathbf{S}_0$) scenarios have almost identical structure. They share the same calendar of events and the majority of processes. Only one new event $\mathbf{E}_{10}$: "stall alarm in the cockpit" was added to $\mathbf{S}_3$. Also, two control processes were withdrawn from $\mathbf{S}_0$ to obtain $\mathbf{S}_3$, namely: a piloting task $\mathbf{T}_3$ to keep the pitch angle close to one recorded in the accident, and an incorrect "stick-forward" input observed in the accident after a stall alarm sounded in the cockpit. Instead, a new task $\mathbf{T}_5$: "keep AoA close to the operational limit ($12.5^o$)" was initiated at the event $\mathbf{E}_{10}$: "stall alarm in the cockpit" to employ maximum lift when crossing the wind-shear zone. The resulting instruction $\mathbf{E}_{10} \Rightarrow \mathbf{T}_5$ is in compliance with general recommendations on safe piloting in microburst. Simulation results for the safe scenario $\mathbf{S}_3$ are shown in **Fig. 7** in comparison with the accident reconstruct.



introduction of a correct piloting task $\mathbf{T}_5$: "keep AoA close to the operational limit (α=12.5°)"

stall alarms sounded in the cockpit

point when the situation has become irreversible

zone of action of additional lift that would allow a safer outcome

impact point

**Figure 7:** Safe takeoff performed according to $\mathbf{S}_3$ (example)

This flight exhibits a quite acceptable tradeoff between a loss of the vehicle's kinetic energy (measured by $V^2_{IAS}$) and a corresponding increase in the potential energy ($H$). It may be concluded that a marginally safe takeoff could have been accomplished under the given complex situation if the aircrew knew its possible consequences 10-25 seconds in advance and applied the appropriate recovery tactics.

HYPOTHESES FOR "WHAT-IF" SIMULATION. In order to explore a domain of operational modes around the accident, a series of scenarios was derived from $\mathbf{S}_0$. It represents reasonable variations in the key operational factors of flight. Then the "silicon pilot" executed these scenarios in simulation experiments. The following three hypotheses were checked.

Hypothesis 1 ("AoA control"). In several flights the "pilot" attempts to keep the angle of attack constant at various levels. Flap control is as recorded in the accident. The weather condition also remains original (one microburst zone).

Hypothesis 2 ("Pitch control"). In several flights the "pilot" attempts to maintain the aircraft's pitch attitude at certain levels. It also tries, from flight to flight, various flap settings while crossing the microburst zone. In addition, a second wind-shear (of three gradients) is added at $t$ = 40 s. The "pilot" attempts to counter this new factor by lowering the command pitch angle to preserve the airspeed.

Hypothesis 3 ("Accident-like control"). The "pilot" repeats the pitch control tactics recorded in the accident, but varying, from flight to flight, the final position of flaps during retraction (in $\mathbf{P}_4$). The weather condition remains original.

ALTERNATIVE SCENARIOS. The scenarios $\mathbf{S}_1, \ldots, \mathbf{S}_{16}$, which implement these hypotheses, are summarized in **Table 1**. The purpose of this limited flight series is to demonstrate how various operational factors could be combined and examined in a rigorous yet efficient way using the autonomous model. The subsets $\{\mathbf{S}_3, \mathbf{S}_4, \mathbf{S}_5\}$, $\{\mathbf{S}_6, \mathbf{S}_7, \ldots, \mathbf{S}_{16}\}$, and $\{\mathbf{S}_0, \mathbf{S}_1, \mathbf{S}_2\}$ represent the hypothesis 1, 2, and 3, respectively. Note that $\mathbf{S}_0$ corresponds to the accident reconstruct, and $\mathbf{S}_3$ stands for a safe takeoff depicted in **Fig. 7**. Due to a generic "event-process" formulation of flight this alternative series of experiments was planned and executed on a PC in a less than one-hour time. Neither the pilot, nor a flight simulator was involved. Software programming was not required either.

**Table 1:** "What-if" series of flight accident scenarios

| No | Scenario description |
|---|---|
| **0** | Reconstructs the accident with an airplane at takeoff under strong wind-shear and heavy rain conditions |
| **1** | Repeats the scenario **0** except that flaps are kept at 30° |
| **2** | Repeats **0** except that flaps are retracted from 30° to 22.5° |
| **3** | As **0**, except that after $t$ = 28 s the "silicon pilot" attempts to keep AoA close to its operational limit (~13°) |
| **4** | As **0**, except that the "pilot" keeps AoA at ~10° after $t$ = 28 s |
| **5** | As **0**, except that the "pilot" keeps AoA at ~15° after $t$ = 28 s |
| **6** | As **0**, except that the "pilot" keeps pitch at the level of about 10° after $t$ = 28 s |
| **7** | As **0**, except that the "pilot" keeps pitch at ~5° after $t$ = 28 s |
| **8** | As **0**, except that the "pilot" keeps pitch at ~15° after $t$ = 28 s |
| **9** | As **6**, plus second "very strong" wind-shear is added |
| **10** | As **9**, but flaps are not retracted (kept at 30°) |
| **11** | As **10**, but the command pitch is lowered from 10° to 6° if the climb rate is less than 1 m/s |
| **12** | As **6**, but no further (second) wind-shear is introduced and the flaps position remains unchanged |
| **13** | As **6**, but no further (second) wind-shear is introduced and flaps are retracted to 15° |
| **14** | As **6**, plus another half-strong wind-shear occurs, flaps are retracted to 15° and the command pitch is reduced from 10° to 6° if the climb rate is insufficient ($V_z < 1$ m/s) |
| **15** | As **6**, plus when another half-strong wind-shear hits the airplane, flaps are retracted to 15° and pitch is kept at ~10° |
| **16** | As **6**, plus another half-strong wind-shear is introduced, flaps are kept at 30°; also, the command pitch is reduced from 10° to 6° if the climb rate is insufficient ($V_z < 1$ m/s) |

SITUATIONAL TREE OF ACCIDENT NEIGHBORHOOD. The flights performed according to the scenarios $\mathbf{S}_0, \ldots, \mathbf{S}_{16}$ are depicted in **Fig. 8** in the form of a basic "situational tree" in projection on 'altitude-time' and 'airspeed-time' planes. This tree illustrates a concept of the *Fuzzy Situational Tree-Network* (FSTN) [3, 8], also schematically shown in **Fig. 9**.

A crown of the FSTN can be specially shaped to thread the operational domain under examination (in our case, the accident and its "neighborhood") - from initially safe states towards flight constraints. The purpose of branching is to reveal zones of potentially safe and unsafe flightpaths under various conditions. Each branch is a path, which incorporates the effect of a particular operational factor of flight or a combination of factors. For instance, the three first-order branches "implanted" into the tree at $t$ = 28 s (see **Fig. 8**) group the operational factors specified in the hypotheses 1-3. A more detailed introduction to the FSTN concept and its potential applications will be given in [8].

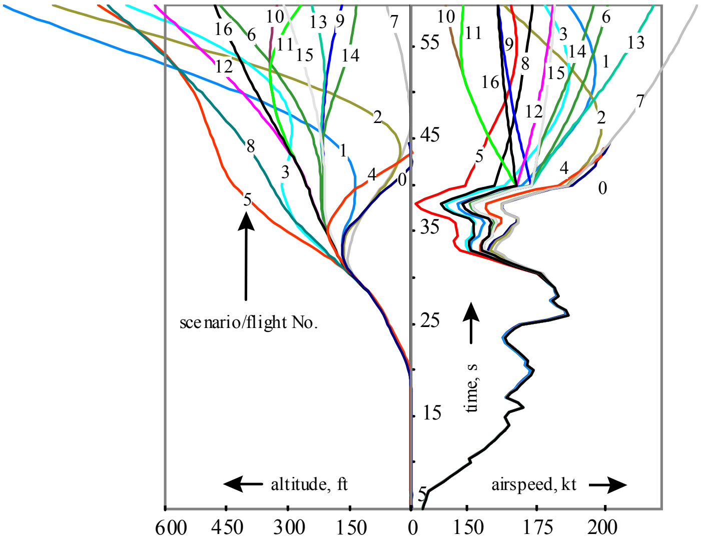


**Figure 8:** A situational tree of flight accident's "neighborhood"

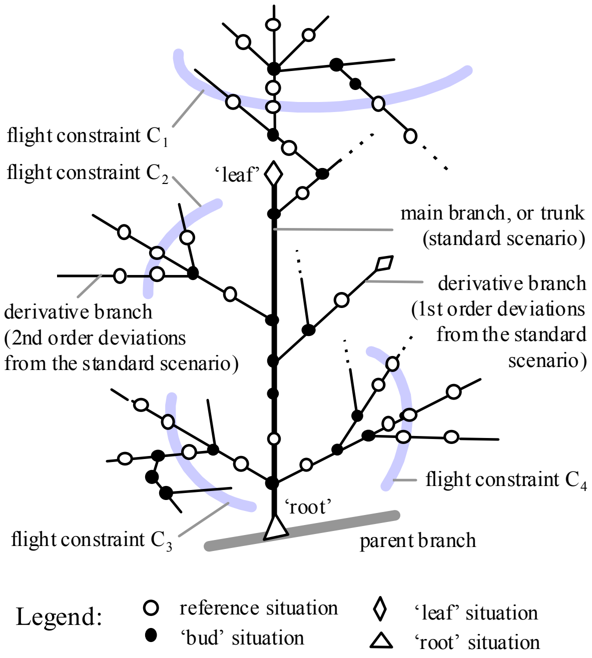
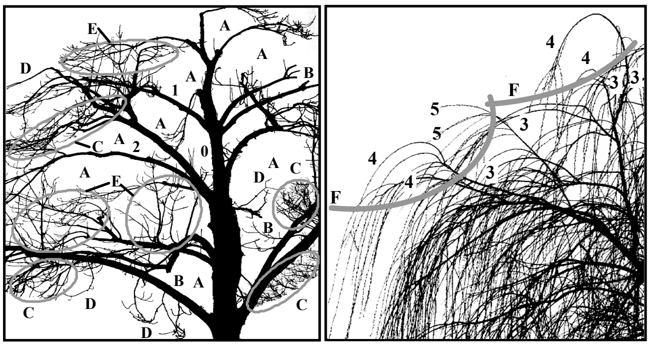


**Figure 9:** Fuzzy situational tree-network

Nature gives perfect examples of structure of artificial knowledge trees for various applications. A tree, which may be used as a model of a human pilot's tactical experience, is depicted in **Fig. 10, a**. A whipping willow tree (**Fig. 10, b**) may be helpful to specify the properties of a situational tree for flight envelope protection and pilot assistance (see [3, 8]).

FUZZY CONSTRAINTS. In order to assess flight safety of the seventeen takeoffs (the scenarios $\mathbf{S}_0, \ldots, \mathbf{S}_{16}$) the compatibility of flight variables with 13 operational constraints was checked. A formulation of the fuzzy constraint [9] was used to account for the uncertainty of our knowledge of actual system's limits under complex conditions.



(a) "internal FSTN"
of the human pilot

(b) flight envelope
protection

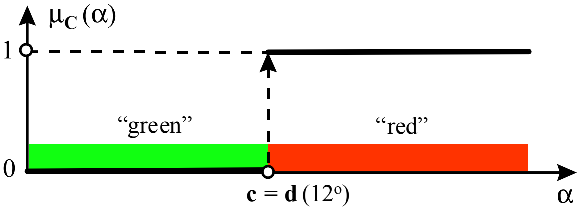
Legend:

**0** - main branch (trunk), **1** - first-order branch, **2** - second-order branch,
**3** - unsafe path (branch), **4** - recovery path, **5** - irreversible path
**A** - absent knowledge (empty space)
**B** - decayed, shadowed or unused knowledge (dry/cut branches)
**C** - non-systematic knowledge (excessive/chaotic branching)
**D** - fragmentary knowledge (sparse branching)
**E** - systematic knowledge (normal branching)
**F** - fuzzy flight constraint

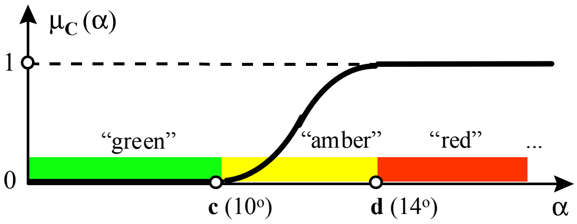
**Figure 10:** Some useful patterns of natural trees

Basically, the *fuzzy flight constraint*, **C**, is an extension of the notion of a "precise" constraint (**Fig. 11, a**). Instead of putting an artificially sharp border between the fully acceptable and the fully unacceptable numeric values of a flight variable, an interim interval [**c**; **d**], which admits partial membership of a value to the constraint, is introduced (**Fig. 11, b**).

(a) "Precise" flight constraint **C**: "α > 12º"



(b) Fuzzy flight constraint **C**: "high AoA"



Legend:

🟩 "green" 🟨 "amber" 🟥 "red" - safety colors

**Figure 11:** "Precise" constraint vs. fuzzy constraint

A "precise" constraint **C** is defined using a binary criterion, e.g.: ($\alpha(t)>12^o$) ⇒ (**C**: "$\alpha(t)>12^{o}$" ⇔ $\alpha(t)\in$ **C**). But under this assumption the following non-evident statements have to be admitted: $\alpha(t)=11.9^o$ is an acceptable value of α, i.e. $\alpha(t)\notin$ **C**, and $\alpha(t)=12.1^o$ is not, i.e. $\alpha(t)\in$ **C**. On the contrary, a fuzzy constraint **C**: "high_AoA" can be defined mathematically in such a way that if the angle of attack increases, say, from $10^o$ to $14^o$, its membership function (i.e. the degree of non-acceptance), $\mu_C(\alpha)$, gradually changes from 0 to 1.

The concept of fuzzy constraint is important to specify an interrelated system of constraints of a complex flight domain. By means of fuzzy sets physical and other uncertainties of non-stochastic nature can be modeled more adequately. Fuzzy flight constraints applied to this case are defined in **Table 2**.

**Table 2:** Fuzzy flight constraints

| Name | Definition | c | d |
|---|---|---|---|
| Low speed[1] | ($V_{IAS} \lesssim 130$ kn) & airborne[3] | 130 | 135 |
| High speed | ($V_{IAS} \gtrsim 200$ kn) & flaps-on[2] | 190 | 200 |
| Low AoA[1] | ($\alpha_F \lesssim -5^o$) | -5 | -2 |
| High AoA | ($\alpha_F \geq 14^o$)& flaps-on & airborne | 11 | 14 |
| Steep descent[1] | ($V_z \lesssim -6$ m/s) | -6 | -4.5 |
| Steep climb | ($V_z \gtrsim 20$ m/s) | 15 | 20 |
| Insufficient lift[1] | ($n_z \lesssim 0.8$) & airborne | 0.8 | 0.85 |
| High g-factor | ($n_z \gtrsim 2.5$) | 2 | 2.5 |
| Elevator at minimum[1] | ($\delta_e \lesssim -25^o$) & airborne | -25 | -22 |
| Elevator at maximum | ($\delta_e \gtrsim 15^o$) & airborne | 12 | 15 |
| Small pitch[1] | ($\theta \lesssim -8^o$) | -8 | -5 |
| Large pitch | ($\theta \gtrsim 25^o$) | 20 | 25 |
| Ground proximity[1] | ($H \lesssim 20$ m) & Steep descent | 20 | 25 |

Note:

1. $\mu_C$ is a mirror image of the function shown in **Fig. 11, b**
2. flaps-on ⇔ ($\delta_{FL} = 15^o$)
3. airborne ⇔ ($N_z = 0$) & ($\tau = 2$ s)

FLIGHT SAFETY SPECTRUM. Basically, the flight safety spectrum is a color strip, which graphically indicates changes of the flight safety status through a flight situation. It is formed along the time axis using the following *flight safety* (or mission success) *colors* or levels and their definitive criteria **Cr** for a flight variable (see **Fig. 11, b**):

- *"green"*, $\xi_G$, if the current value (at a time instant *t*) of the variable is within acceptable limits
- *"amber"*, $\xi_A$, if the variable enters the uncertainty interval [**c**; **d**]
- *"red"*, $\xi_R$, if the variable violates its constraint beyond **d** for a right hand constraint or **c** for a left hand constraint
- *"black"*, $\xi_B$, if the flight cannot be continued due to airframe disintegration, collision, or other fatal cause.

Each flight $\Im$ belonging to the situational tree (**Fig. 8**) was colored accordingly. Safety levels of all the key variables of $\Im$ were measured along the constraints from **Table 2** at recorded time instants $t$, $t\in[t_*;\ t^*]$. The *flight safety spectrum* of $\Im$, $\mathbf{\Sigma}$, can be obtained by applying a computational algorithm, which implements the following formal relationship:

$$\begin{aligned}&(\forall\Im)\ (\Im = \{x(t_*),\ \ldots,\ x(t^*)\},\ x(t) = (x^1(t),\ \ldots,\ x^p(t)),\\ &t\in\ [t_*;\ t^*])\ (\exists\mathbf{\Sigma})\ (\mathbf{\Sigma}\equiv \text{flight\_safety\_spectrum}\wedge\\ &\mathbf{\Sigma} = \xi(t_*)\,|\ldots|\,\xi(t)\,|\ldots|\,\xi(t^*))\ (\forall t)\ (\forall x^k)\ (\mathrm{k} = 1,\ \ldots,\ \mathrm{p}) \qquad (1)\\ &(\exists\xi(x^k(t)))\ (\xi(x^k(t))\equiv \text{safety\_color}\wedge\xi(x^k(t))\therefore\mathbf{Cr},\\ &\xi(x^k(t))\in\{\xi_G,\ \xi_A,\ \xi_R,\ \xi_B,\ \ldots\},\ (\xi_B<\xi_R<\xi_A<\xi_G))\\ &(\xi(t) = \mathit{max}\ \xi(x^k(t)),\ \mathrm{k} = 1,\ \ldots,\ \mathrm{p})\Rightarrow(\xi(t)\in\ \mathbf{\Sigma})).\end{aligned}$$

The relationship (1) means that the “hottest” color is to be left in the resulting spectrum $\mathbf{\Sigma}$ at a point $t$ if variables $x^k$, k = 1, …, p exhibit different colors $\xi(x^k(t))$ at $t$. Safety spectra for the flights $\Im_0$, …, $\Im_{16}$ are compared in **Fig. 12**.

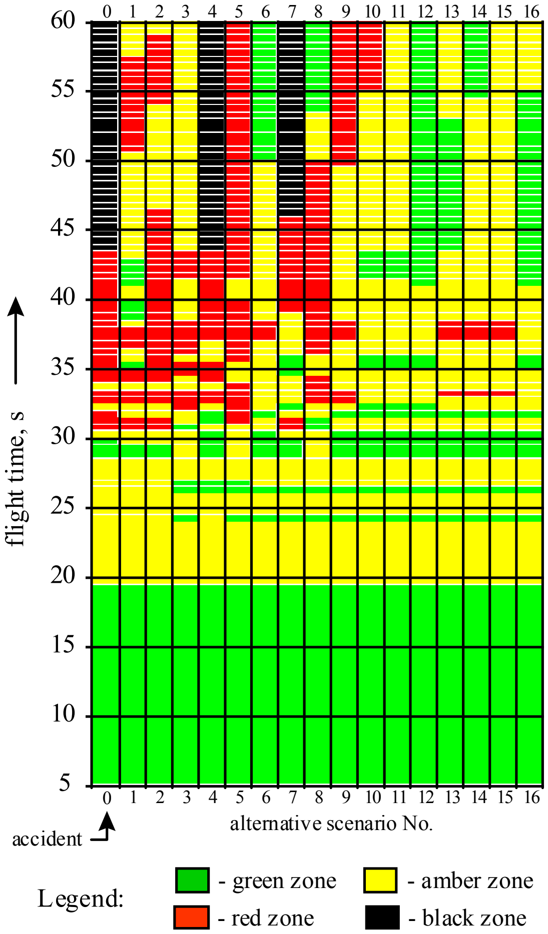


**Figure 12:** Flight safety spectra of the flight accident and its “neighborhood”

It follows from the diagram that even a small subset of alternative scenarios helps reveal possible safe and unsafe flightpaths under the given and similar non-standard conditions. Safe alternatives are colored in green or amber in their final segments (see the flight safety spectra for $\mathbf{S}_1$-$\mathbf{S}_3$, $\mathbf{S}_6$, $\mathbf{S}_8$, and $\mathbf{S}_{11}$-$\mathbf{S}_{16}$).

BASIC SITUATIONAL FORECAST DISPLAY. A notional Situational Forecast Display (**Fig. 13**) was designed using the results obtained from the study. This hypothetical instrument maps a situational flight domain around the examined accident. Its purpose is two fold:

- visualization of a sub-tree of possible takeoff options and short-term prediction of the airplane’s safety status along these trajectories
- dynamic evaluation and selection of safe piloting tactics during takeoff under severe microburst conditions.

Note. The graphic format and the color code used in **Fig. 13** should not be viewed as a final onboard layout. Several important ergonomic and design issues are beyond the scope of this study. The only purpose of the constructed situational knowledge tree is to exemplify a complex operational domain to illustrate the S.A.F.E. concept. However, much more comprehensive trees can be obtained and displayed using the developed technique.

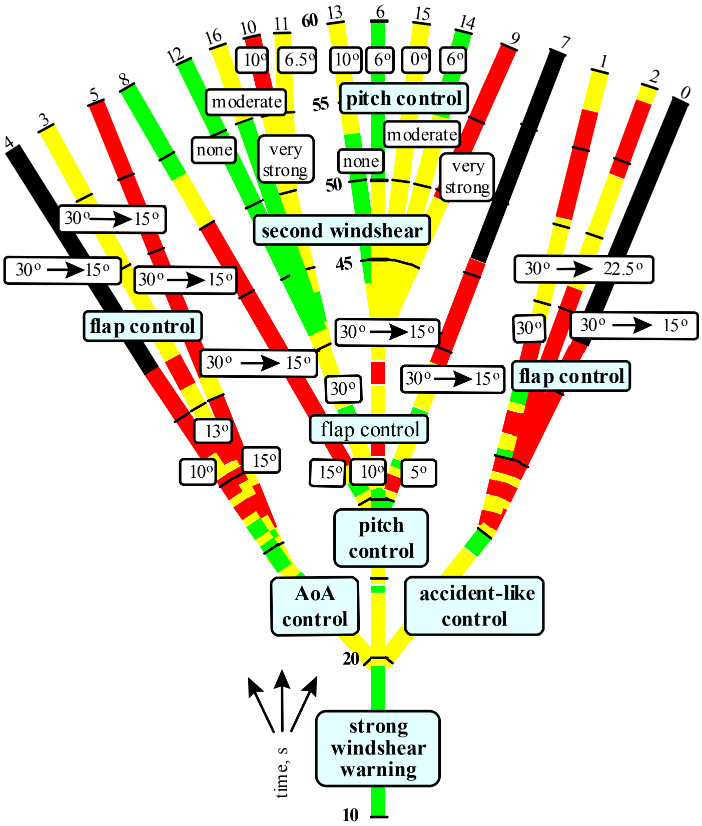


**Figure 13:** Basic situational forecast display “Takeoff under microburst conditions”

CONSTRUCTION PRINCIPLES. Basically, knowledge of three kinds is required to construct a SFD. First, a FSTN, which encapsulates the operational domain under study, should be generated. Second, genetic properties of the FSTN are to be known as well to obtain structure of a displayed sub-tree. Third, an agreement regarding the use of safety colors $\{\xi_G, \xi_A, \xi_R, \xi_B, \ldots\}$ for pilot-vehicle interface and the algorithm (1) for calculating flight safety spectra are required to assign the rate of safety or danger to the sub-tree’s branches.

In our case, the SFD is a result of composition of a tree of the flights $\Im_0$, …, $\Im_{16}$ (**Fig. 8**) and their safety spectra $\mathbf{\Sigma}_0$, …, $\mathbf{\Sigma}_{16}$ (**Fig. 12**). Basic geometric transformations (grouping, bending, and cutting) and color blending with respect to the source safety spectra were applied. Note that the sub-tree branches at the events where the scenario deviates from $\mathbf{S}_0$ or its subsequent modifications (see **Table 1**). The black dashes across the branches mark the flight time relative to some reference or current state of the system during takeoff.

SFD STRUCTURE AND UPDATE. The SFD exhibits a sub-tree of various possible flightpaths to follow or avoid in the subsequent 10-25 seconds of flight. When performing takeoff in microburst, the pilot may find it helpful to refresh in mind an integral “what-if” picture of possible scenarios. The sub-tree’s branches stand for the key operational factors, which currently affect, may affect, or are expected to affect takeoff. In our case (see **Fig. 13**), these options are grouped according to the hypotheses 1, 2, and 3 as three first-order branches (the left, the central and the right one, respectively). There are also a few second- and third-order derivative branches, which represent flap and pitch adjustments to possible fluctuations of wind after exiting the main wind-shear zone.

The SFD is updated as follows. Given a wind-shear warning at takeoff, an appropriate sub-tree is loaded from the FSTN, displayed and updated on the screen. The type and the level of depicted information can be pre-selected by the pilot to meet his (her) specific needs (e.g.: to account for a lack of knowledge of some strong operational factors and their effects). As the takeoff develops, obsolete branches are dropped off the screen, and new ones are added or extended automatically. The current situation also changes, but its location on the SFD remains the same. These updates are correlated with actual changes in flight and its virtual trends or factors, which the pilot wants to monitor.

SFD FUNCTION. By means of the SFD the pilot can identify potentially safe and potentially dangerous flightpaths *in advance*. This identification process is fast as it is based on direct mapping of a human pilot's mental model of flight. The system does not require having precise data on future flight conditions in real time. The most preferable scenario may be dynamically selected and implemented through the display.

In that accident, unfortunately, the pilot had applied an incorrect control scenario from a subset $\{\mathbf{S}_0, \mathbf{S}_4, \mathbf{S}_7\}$ that led to catastrophic outcomes, i.e. the flightpath-branches colored in black at their ends (see **Fig. 13**). Given the seventeen options modeled, the share of unsafe tactics is about 23 per cent. The remaining 13 scenarios produce non-fatal outcomes and could have been employed. Therefore, the presence, on board that airplane, of a more comprehensive system of microburst related knowledge could have helped the crew avoid the catastrophe. The logic of the flight processes and flight events specified in the scenarios $\mathbf{S}_j$ which form safe branches is also important, as they contain instructions for correct piloting.

POTENTIAL PROPERTIES. SFD systems exemplified in **Fig. 13** are expected to add new useful properties to flight safety automation and pilot-vehicle interface.

1. The SFD is a knowledge-centered medium for pilot-vehicle communication in complex flight situations. It is technically feasible to construct a FSTN, which accumulates more comprehensive knowledge of multi-factor flight domains compared with the relevant human pilot's experience [8]. This instrument type supports flexible, adaptive interface between the pilot and the vehicle. At any time during flight the pilot can modify the nomenclature of operational factors for monitoring and the depth of flight forecasts. Thus, the SFD may serve as a knowledge backup for a particular pilot.

2. Pilot-vehicle interface via a SFD system is direct and intelligent. This is because the FSTN, in structure and learning principles, fits memory models of a human's tactical experience [10]. A part of this artificial knowledge associated with a current situation is displayed for pilot's reference in natural, "brain mapping" formats.

3. Finally, the SFD represents a tool for "what-if" analysis of flight in real time. Using this technology, the pilot can dynamically group and compare various sets of safe and unsafe flightpath options available under the actually present and anticipated conditions. The pilot can also change the graphic scale and the focus of these mappings during flight.

SUMMARY. Physics based knowledge of the behavior of the "pilot – vehicle – operational conditions" system under complex situations is important to achieve a higher level of flight safety. It is feasible to generate such complex system relationships, using autonomous modeling and computer simulation of flight. Inherently, this knowledge has a tree structure and appropriate evolution principles. "Chain reaction" accidents or incidents may be inadvertently pre-programmed in system behavior, if this fundamental property of flight is under-represented in flight safety design.

The "event-process" formulation of flight is a flexible means for exploring various combinations of flight modes, operational conditions and control tactics. The notions of situational tree, fuzzy flight constraint and flight safety spectrum can be applied together to identify logical structure and safety characteristics of a complex flight domain. Based on this formulation, a Situational Forecast Display can be designed to enhance a pilot's decision-making capabilities under multi-factor situations.

The SFD is a knowledge-centered bio-technical medium for supporting pilot-vehicle intelligent communication. It provides a "what-if" experimentation capability for real-time evaluation of the combined effect of multiple operational conditions. It is believed that the presence of a SFD system on board that airliner could have helped the pilots avoid the catastrophe: within the examined domain of flight modes the share of non-fatal outcomes was 77%.

## S.A.F.E. TECHNOLOGIES

POSSIBLE APPLICATIONS. There are several potential avenues for implementing the S.A.F.E. concept onboard. These include (but not limited to) the following [8]:

- pilot-vehicle intelligent interface
- automatic flight envelope protection
- automatic resolution of conflicts in a close 'free-flight' navigation space
- autonomous (robotic) flight, including multiple intelligent UAV systems
- knowledge-centered pilot assistance and pilot training
- virtual testing and certification of a vehicle's flight envelope in design (the "intelligent" flight envelope).

Following is an introduction to the first two applications.

PILOT-VEHICLE INTERFACE. By means of the S.A.F.E. concept the pilot-vehicle communication process can be organized on the level of knowledge, not data. This task may be accomplished through a *Situational Forecast Display* system depicted in Fig. 14. This diagram represents a more general layout of the system than one in Fig. 13.

The SFD is a 2-D color graphic mapping (e.g.: on a FMS screen, etc.) of a subset of situational knowledge of flight from the FSTN. Shown in **Fig. 14** is a sub-tree of interrelated fuzzy flightpaths, which may originate from a current or other reference situation, *if* certain operational factors step into action. This is why the SFD may be called a "what-if" flight analysis tool. The operational factors for monitoring purposes can be specified and modified dynamically by the pilot to backup his (her) knowledge of complex domains of flight.

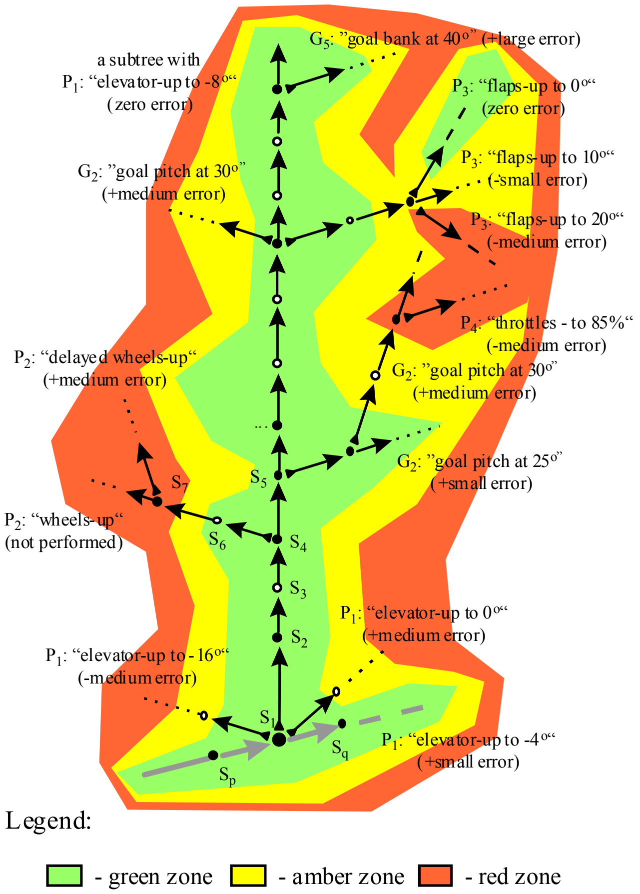


**Figure 14:** A notional layout of the Situational Forecast Display (SFD)

Unlike an ordinary instrument, which measures aircraft states, the SFD provides the pilot with knowledge of *future* flightpaths and the associated operational factors. Note also that the SFD represents a non-geometric, abstract mapping of this knowledge. There is no direct correlation between the location of a branch on the SFD and the vehicle position in earth or other physical frames. The current or reference situation is normally depicted in the bottom.

A green-amber-red-black color code is used to attenuate the safety level of branches under examination (respectively, safe, alert, unsafe, and fatal). The display is updated with a frequency as low as 0.5-2 Hz, depending on the system dynamics and instrument's mode. As a result, the pilot receives an integrated, physics based picture of possible flight paths for subsequent several (5-25) seconds. Because of this feature the S.A.F.E. concept differs from the expert system approach, which is based on the avialable pilots' experience.

The resulting image may also be considered as a virtual "safety valley". Red and black "hills" in this "valley" indicate pre-critical and critical flight modes to avoid (i.e. no collision is allowed with the "hills"). The pilot examines its topology and selects a safe flightpath-branch (scenario) to follow. This process can be implemented through a tactile display by applying a finger touch control to the desired tree's segment. Alternatively, a laser scanning system could be used to locate the pilot's eye focus point within the tree. After choice confirmation (e.g.: by pressing a button or via a voice command), the selected path is taken for realization. The associated scenario may be engaged automatically. Alternatively, the model may advise the pilot the sequence and the timing of appropriate manual control inputs.

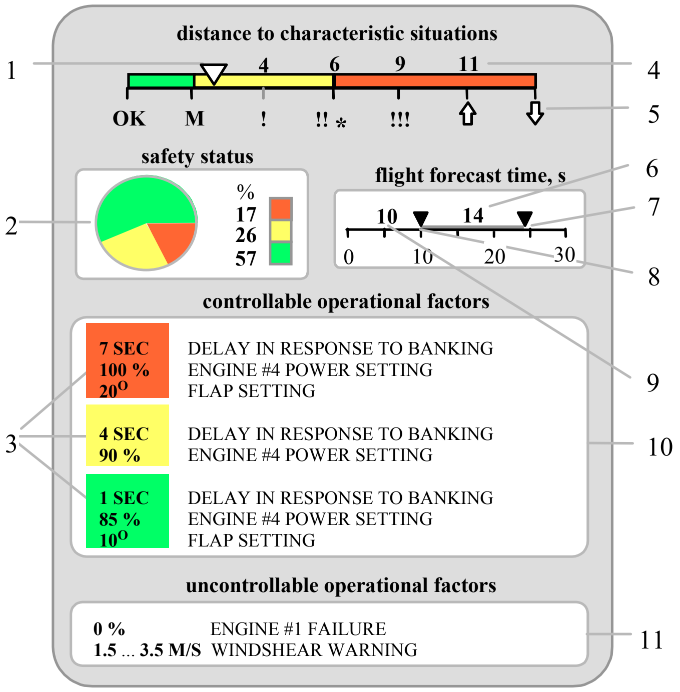
The SFD function is in coherence with the principles of human pilot decision making and with the organization of a human pilot's tactical experience in long-term memory. This allows pilot-vehicle interface to be implemented on a higher level. Pilot's decisions are situation-based and situation-driven, as the SFD accounts for actual and anticipated operational factors, vehicle dynamics, flight constraints and relationships. As a result, it is expected that a more thorough dynamic planning of flight can be achieved under complex (multi-factor, extreme, hostile, unknown, etc.) situations.

FLIGHT ENVELOPE PROTECTION. This task is to prevent the vehicle from entering a zone of irreversible flightpaths under a multi-factor situation. It can be realized by means of a *Flight Safety (Mission Success) Indicator,* FSI/MSI. A notional layout of the FSI is depicted in **Fig. 15**. Onboard implementation may differ from the proposed scheme.

The instrument's input includes: a set of key operational factors and a set of flight variables, which the pilot wants to monitor (not shown), the depth **6** of future flightpath analysis, and the relative time **9** with respect to a current time when forecasts should begin. Based on this data, a sub-tree is loaded from the FSTN for real-time processing. Given the key operational factors and the desired forecast time span **6**, the overall chances of safe, marginal, dangerous, and (if applicable) fatal outcomes of the current situation are calculated and displayed onto the sector diagram **2**.

The indicator depicts a current position **1** of the vehicle at the critical (nearest) constraint $\mathbf{C}_{crit}$. Also indicated are the distances **4** to the main types of *characteristic flight situations* **5** at $\mathbf{C}_{crit}$: the border of the operator's "comfort zone", **OK**; the beginning of constraint monitoring, **M**; the warnings – the first (**!**), the second (**!!**), and the last (**!!!**); the constraint infringement situation, *; the beginning of automatic recovery, ⇑; the irreversible situation ⇓; the catastrophic situation, ⊗; and the safe return (to the flight envelope) situation, ®. More detail on the concept of "intelligent flight envelope" which includes these notions will be given in [8].

Also displayed are the main flight events and flight processes of the scenarios, which are likely to bring the vehicle to the



Legend:

1 - marker of the vehicle current position with respect to a critical constraint
2 - current chances of 'red', 'amber' and 'green' outcomes of flight
3 - processes leading to the 'red', 'amber' and 'green' zone, respectively
4 - time (in seconds) to characteristic situations
5 - characteristic safety types of flight situation
6 - depth of future flightpaths analysis
7 - forecast end time marker (with respect to the reference/current situation)
8 - forecast start time marker (with respect to the reference/current situation)
9 - relative time when forecasts start
10 - aiding messages (controllable operational factors) also produced by audio means
11 - aiding messages (uncontrollable factors) also produced by audio means

**Figure 15:** A notional layout of the Flight Safety (Mission Success) Indicator (FSI/MSI)

edge of the flight envelope (i.e. to a "red zone" [**!!**; ⇓] - see **Fig. 15**). Alternatively, an automatic speech synthesizer may be used to convey these messages to the pilot. The instructions the pilot should follow to recover from a pre-critical situation (i.e. to reach the "amber" or "green" zone) are available as well. Thus, this system type complements the SFD, since it emphasizes more quantitative, rather than qualitative and topological, information on the expected safety status of the flight and its contributing factors.

The flight envelope protection function may be executed automatically. Before or during flight, the pilot or other entity specifies the circumstances, under which the control authority should be transferred to the hybrid model. This may happen, for instance, if a critical combination of operational factors occurs, or when the vehicle "hits" the surface of automatic recovery situations ⇑ in the "safety valley", i.e. the chances of "green" and "amber" outcomes displayed on the diagram **2** (**Fig. 15**) are below some safety margin. The operator is disengaged, and instead the model applies a recovery scenario to bring the vehicle back into the safe flight envelope.

SUMMARY. The S.A.F.E. concept may be used to address a number of flight safety related issues. This variety emerges from the FSTN's property as a generic framework to organize, retain and apply a systematic knowledge of a multi-factor domain of flight. In particular, the SFD depicts the topology and safety characteristics of a subtree of possible flightpaths that may emerge from a given situation, if a certain combination of key operational factors occurs. The FSI/MSI provides more quantitative and instructional information on the future flight safety status. This includes positive and negative effects of key operational factors of flight and the remedial control tactics available under complex situations.

## CONCLUSIONS

Given a complex, multi-factor flight situation, uncontrollable cause-and-effect links ("chain reaction") may be spontaneously triggered in the "pilot – vehicle – operational conditions" system. This may compromise flight safety.

Neither the pilot, nor a computer, ultimately controls a flight vehicle. The vehicle is controlled by physical knowledge, i.e. by the laws of aerodynamics, flight mechanics, and propulsion. The system behavior in emergencies is a dynamic superposition of these laws. The outcome of these complex relationships has a branching structure, which is very sensitive to the contributing factors. Flight incidents or accidents of a "chain reaction" type may be pre-programmed in the system's logic, if this important branching property of the system behavior is ignored in flight safety design.

More physics based knowledge of multi-factor operational domains of flight is therefore required onboard. The purpose of this information is to help the operator predict the system behavior at the edge of the flight envelope and under multiple operational conditions. The flight modeling and artificial intelligence techniques offer a feasible solution to this problem. By means of a fuzzy situational tree-network of flight it is possible to predict short-term flightpaths, both safe and unsafe, which may originate from a given situation under the effect of a combination of key operational factors.

The concept of Situational Awareness and Forecasting Environment (the S.A.F.E. concept) may be used as a formal framework of new intelligent technologies for implementing flight safety as an inherent property of the vehicle. Two notional instruments are proposed for prototyping; these are the Situational Forecast Display and the Flight Safety Indicator. The purpose of these systems is to timely identify and avoid propagation of a "chain reaction" type flight accident under the effect of multiple operational conditions.

Possible application sectors include: pilot-vehicle intelligent interface, automatic flight envelope protection, autonomous (robotic) flight including multiple intelligent vehicle systems, automatic resolution of conflicts in a close free-flight navigation space, knowledge-centered pilot assistance and pilot training, and virtual testing and certification of an aircraft's flight envelope in design. In general, the role of a S.A.F.E. system can be thought of as a kind of "future-looking knowledge radar" on board the flight vehicle.

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## DEFINITIONS, ACRONYMS, ABBREVIATIONS

| | |
|---|---|
| **!** | “First warning” situation type |
| **!!** | “Second warning” situation type |
| **!!!** | “Last warning” situation type |
| ∗ | “Constraint infringement” situation type |
| ⇔ | Logical equivalence |
| ⇒ | Logical implication |
| → | State transition |
| $\vert$ | Geometric concatenation of color bits $\xi$ in **Σ** |
| ∴ | “Defined by” relation (reverse to ≡) |
| ℑ | Flight-record (as a recorded time history of *x*) |
| ⇑ | “Beginning of automatic recovery” situation type |
| ⇓ | “Irreversible” situation type |
| ⊗ | “Catastrophic” situation type |
| ® | “Safe return to the flight envelope” situation type |
| • | “Bud” situation type |
| ◊ | “Leaf” situation type |
| o | “Reference (ordinary)” situation type |
| Δ | “Root” situation type |
| ∧, & | Logical ‘and’ |
| ≡ | “Is”, or definition, relation |
| < | “Hotter color” relation (in conjunction with $\xi$ only) |
| ≲ | Fuzzy “less than” relation |
| ≳ | Fuzzy “greater than” relation |
| AI | Artificial intelligence |
| **c** | Characteristic point of a fuzzy constraint carrier |
| **C** | Fuzzy flight constraint |
| **Cr** | Definitive criteria for flight safety colors |
| crit | Critical [constraint] |
| **d** | Characteristic point of a fuzzy constraint carrier |
| **E** | Flight event |
| FMS | Flight management system |
| FSI | Flight Safety Indicator |
| FSTN | Fuzzy situational tree-network |
| **G** | Tactical objective of flight |
| *H* | Altitude of flight |
| J | Rain intensity, mm/h |
| **M** | “Beginning of constraint monitoring” situation type |
| *max* | “Hottest color” operation (for safety colors $\xi$ only) |
| MAX | Maximum value |
| MSI | Mission Success Indicator |
| $n_z$ | Vertical load factor (earth) |
| $N_z$ | Vertical reaction load on wheels (body) |
| **OK** | “Border of the operator’s comfort zone” situation type |
| **P** | Control procedure |
| **R** | Rain type process |
| **S** | Flight situation, or flight [situation] scenario |
| S.A.F.E. | Situational Awareness and Forecasting Environment |
| SFD | Situational Forecast Display |
| *t* | Current flight time |
| $t_*$ | First time instant in a flight-record |
| $t^*$ | Last time instant in a flight-record |
| **T** | Piloting task |
| UAV | Unmanned Aerial Vehicle |
| $V_{IAS}$ | Indicated airspeed |
| $V_z$ | Vertical speed (earth) |
| **W** | Wind type process |
| $W_{xg}$ | Horizontal wind component (earth) |
| $W_{zg}$ | Vertical wind component (earth) |
| *x* | Vector of flight variables, $x = (x^1, \ldots, x^k, \ldots, x^p)$ |
| $\alpha_F$ | Fuselage angle of attack |
| α, AoA | Angle of attack |
| $\delta_e$ | Elevator position |
| $\delta_{FL}$ | Flap position |
| $\mu_C$ | Membership function of a fuzzy constraint **C** |
| θ | Pitch angle |
| τ | Delay with respect to some event |
| ξ | Flight safety level |
| $\xi_A$ | “amber” safety color/grade |
| $\xi_B$ | “black” safety color/grade |
| $\xi_G$ | “green” safety color/grade |
| $\xi_R$ | “red” safety color/grade |
| **Ω(Π)** | United list of flight processes |
| **Ω(E)** | Calendar of flight events |
| **Π** | Flight process |
| **Σ** | Flight safety spectrum |