

Automated Planning, Exploration and Mapping of Complex Operational Domains of Flight Using Multifactor Situational Trees

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ABSTRACT

A critical situation can suddenly develop in the 'pilot (automaton) - aircraft - operational environment' system behavior as a result of unfavorable mixing and cross-coupling of several demanding operational factors. The latter can include adverse weather effects, pilot (automaton) errors, mechanical failures and hidden design flaws. These factors are typically linked by strong cause-and-effect relationships, which can disturb the normal flow of external forces and moments acting on the aircraft. As a result, a multifactor situation can quickly propagate towards a chain reaction type accident. Specialists (designers, flight test pilots/engineers, regulators, investigators, educators/instructors, line pilots) have limited resources to address multifactor cases during the aircraft life cycle. The main difficulty is combinatorics ('the curse of dimensionality') which determines technical, time and budget constraints. Potentially unsafe complex domains of flight can be identified and screened in advance using the system dynamics model as a virtual flight test article. The developed methodology makes it possible to automatically plan, explore, analyze and map a broad set of realistic multifactor scenarios in autonomous fast-time modeling and simulation experiments. The outcome is a situational tree. This is a collection of branching (what-if) flight paths that are specially planted around a baseline situation to thread a complex operational domain of interest. Special techniques are used to mine and granulate the system level flight safety knowledge from these data structures. Multifactor situational trees can be helpful to locate potential anomalies in the system behavior, quantify critical combinations of events and processes (accident precursors), suggest available recovery options, and depict the aircraft's safety performance under multifactor conditions using 'a bird's eye view' knowledge maps. In this paper, the key concepts, algorithms, data structures, research steps and application examples of the

developed methodology are presented using realistic flight cases.

INTRODUCTION

In this section, the research task is formulated: the problem, the solution approach, input requirements and anticipated outcome.

THE PROBLEM

The System Under Study

Flight safety is an integral characteristic of the 'operator (human pilot, automaton) - aircraft - operational environment' system. This is a multi-dimensional non-linear dynamic system with essentially unsteady, stochastic properties. Under certain, very rarely observed circumstances of flight it can exhibit chaotic or even catastrophic behavior if the operational complexity of flight exceeds certain limits. The operational complexity of a flight situation is determined by the number, logic, physical nature and strength of the operational factors, which act concurrently in flight.

The Taxonomy of Operational Factors

In general, the following main groups of the operational factors (conditions, circumstances, effects, etc.), which can occur in flight, can be defined:

$$\Omega(\Phi) = \{\Omega^1(\Phi), \dots, \Omega^{14}(\Phi), \dots\}, \quad (1)$$

where: $\Omega^1(\Phi)$ - a human pilot's inattention/ carelessness, decision errors, physical incapability or functional inadequacy; $\Omega^2(\Phi)$ - mechanical failures or other malfunctions of the

onboard systems or hardware components, which can affect aircraft flight dynamics: the power plant, flight control, undercarriage, etc.; $\Omega^3(\Phi)$ - logic or data errors in automatic flight control algorithms or software; $\Omega^4(\Phi)$ - strong wind effects - including cross wind, tail wind, vertical gusts, horizontal or vertical wind shear, micro bursts, wind rotors, lee waves, etc.; $\Omega^5(\Phi)$ - atmospheric and aircraft wake turbulence; $\Omega^6(\Phi)$ - heavy rain - impacts on the aircraft aerodynamics, flight dynamics and visibility conditions; $\Omega^7(\Phi)$ - in-flight icing of the aerodynamic surfaces; $\Omega^8(\Phi)$ - non-standard surface conditions of a runway, launch or landing pad - wet, ice- (snow-, or water)-covered, uneven, sloppy, moving; $\Omega^9(\Phi)$ - unfavorable atmospheric state - high temperature or low density; $\Omega^{10}(\Phi)$ - extreme variations of the aircraft weight, moments of inertia and center of gravity location; $\Omega^{11}(\Phi)$ - non-standard changes in the aircraft aerodynamic configuration - e.g. asymmetric flaps extension, etc.; $\Omega^{12}(\Phi)$ - dangerous obstacles located along the projected flight path - terrain, other aircraft; $\Omega^{13}(\Phi)$ - low visibility conditions (nighttime, fog, smoke, etc.); $\Omega^{14}(\Phi)$ - deviations from normal flight path patterns or control tactics. The list $\Omega(\Phi)$ can be further extended and refined - depending on the aircraft class and applications. Meaningful (physics- and logic-wise) combinations of elements Φ_j from the main factor groups (1), which can theoretically occur in flight, represent the anticipated operational environment for aircraft.

Multifactor Situations: Lack of a Priori Knowledge

Normally, the effect of a single operational factor from the list $\Omega(\Phi)$ on aircraft dynamics is not critically dangerous, though there are exceptions. Flight safety of a modern aircraft is more likely to be jeopardized by a combined, snow-ball type effect of several demanding operational conditions. 'Troubles never come alone'. In the course of flight, several operational conditions can mix, adversely and spontaneously, for a very short, 10 to 100 seconds long, period of time. They are often interrelated, both physically and logically.

A multifactor flight situation typically includes a strong cause-and-effect chain of such operational conditions. For instance, in a takeoff situation this can be 'heavy rain' ($\Phi_{16} \in \Omega^6(\Phi)$) and/or 'water covered runway' ($\Phi_3 \in \Omega^8(\Phi)$), and/or 'critical engine failure during ground roll' ($\Phi_{10} \in \Omega^2(\Phi)$), and/or 'a human pilot error in lateral control' ($\Phi_2 \in \Omega^1(\Phi)$) and/or 'an automatic flight controller logic flaw' ($\Phi_{17} \in \Omega^3(\Phi)$), and so forth. This particular combination $\{\Phi_2, \Phi_3, \Phi_{10}, \Phi_{16}, \Phi_{17}\}$ represents a hypothetical yet realistic five-factor scenario, titled as follows: 'Continued takeoff with a critical engine out during ground roll in heavy rain and water-covered runway conditions, given pilot errors and possible automatic control logic flaws'. Such operational composites can unpredictably affect the external forces acting on the aircraft, the normal flow of events and processes constituting the aircraft control scenario and thus the overall system dynamics and flight safety. In spite of a negligibly small theoretical probability of

occurrence, multifactor cases do happen in flight operations, often leading aircraft to an accident or incident.

It can be stated that the root cause of certain accidents and incidents with modern aircraft is a lack of the system level knowledge about complex operational domains of flight during the design, test, certification, training and operational phases of the vehicle life cycle. Predictive knowledge about the cause-and-effect mechanisms that govern complex operational domains of flight can go beyond existing requirements. The main difficulty here is combinatorics ('the curse of dimensionality'), which determines technical, time and budget constraints. The gaps that exist in the 'internal knowledge base' of a flight specialist (designer, flight test pilot/test engineer, regulator, educator, investigator, line pilot) with respect to the logic and physics of complex flight domains increase the risk of multifactor accidents in flight operations. Physical and logical patterns of multifactor situations can be very unusual (even anomalous) and thus poorly known a priori. Therefore, a much broader set of multifactor operational scenarios must be examined in advance starting from the early design phases.

THE SOLUTION APPROACH

The Growing Role of Modeling, Simulation and Artificial Intelligence

'Knowledge is Power'. In order to be avoided (or recovered from), a potentially unsafe multifactor scenario of flight must be known in advance and timely recognized onboard. The volume and the quality of a priori knowledge about complex operational domains of flight (gained by specialists, embedded into flight automation or described in piloting manuals) may not be sufficient. Advanced mathematical modeling, computer simulation (M&S) and artificial intelligence (AI) techniques [1] should be employed to a broader extent, starting from the early phases in the aircraft life cycle. The overall goal is to help fill in the gaps of a specialist's (an automaton's) 'internal knowledge base' about multifactor flight domains. In the presented study, these techniques constitute the basis for an 'operator (pilot, automaton) - aircraft - operational environment' system dynamics model.

The system model is employed as a 'knowledge generator', or a virtual flight test article, to help explore - in advance and more thoroughly - complex operational domains of flight for a given aircraft or a project. The purpose of the model is to generate virtual flight test and accident statistics under multifactor conditions that cannot be gained in manned simulations, flight tests and operations. By means of the system model (the VATES tool [2]), various multifactor cases including potential anomalies, accident precursors and recovery options can be studied and analyzed in advance.

Main Distinguishing Feature

‘After all, complicated tasks usually do inherently require complex algorithms, and this implies a myriad of details. And the details are the jungle in which the devil hides. The only salvation lies in structure’ [3]. This guideline by N. Wirth has been implemented in the developed solution approach. The distinguishing feature of the presented methodology is the structurization and integration of all the key components of the virtual flight research cycle: concepts, mathematical models, computational algorithms, data structures, software modules, simulation output analysis techniques, and high-level knowledge maps. As a result, it enables the user to automate main labor-consuming steps of the virtual flight research process. These include preparation of the system model’s input database, planning of baseline flight scenarios, design of the situational tree structure, modeling and simulation of the aircraft control and flight dynamics, management and analysis of the simulation output database, and granulation and mapping of the system level safety knowledge.

Background and Current Status

The methodology of virtual flight research in complex conditions is based on the best expertise available in the field of mathematical modeling and computer simulation of flight - see some key publications in [4,5,6,7,8,9]. Several hundred types of flight situation scenarios have been studied for over 30 aircraft types and projects, including 21 subsonic and four supersonic airplanes, two hypersonic vehicles, three helicopters, one tilt-rotorcraft and one wing-in-ground experimental vehicle.

Using the system model, all major phases and modes of flight can be simulated for various multifactor operational conditions from $\Omega(\Phi)$ in fast-time M&S experiments without a research human pilot in the loop. The classes of simulated situations include flight tests, incidents, accidents, normal operational scenarios, as well as aerobatic, super maneuverable and hypothetical cases. At present, the model functionality is being advanced further to address emerging problems in the field of flight dynamics, control and safety for unmanned aerial and underwater vehicles, wing-in-ground vehicles, hybrid (aerodynamic plus aerostatic) aircraft, and robotic swarms.

INPUT AND OUTPUT

Input Requirements

The system model requires the following main input data sets: (1) a ‘parametric definition’ of the flight vehicle or a project of interest (the aircraft’s input characteristics - aerodynamics, moments of inertia, engine thrust, automatic control laws, landing gear kinematics), (2) a list of baseline flight situation scenarios, which will be used as trunks for situational trees, or a general description of the baseline scenarios, (3) a list of the operational factors to be tested, or a general description of the

anticipated operational domain, (4) general rules or statistics on the anticipated combinations of operational factors, (5) specifications of the operational constraints to be applied to the analysis and mapping of the system safety performance, and (6) the user general strategy for flight research.

Anticipated Output

The following list constitutes the anticipated outcome of the virtual flight research methodology: (1) a set of flight test scenarios, constraints, operational factors and multifactor operational hypotheses, which formally describe the complex operational domain of interest, (2) a database of simulated ‘flights’ - a ‘forest’ of situational trees, (3) a family of knowledge maps, which depict the aircraft safety performance for each situational tree, (4) a family of knowledge maps, which depict the individual safety performance of all the branches (‘flights’) of each situational tree, (5) generalized knowledge on the system level safety performance, including the knowledge of identified potential anomalies, accident precursors (unsafe multifactor operational composites), and safe recovery scenarios (if any), and (6) recommendations on possible control enhancement measures for securing the aircraft flight safety in the given complex operational domain.

Main Prerequisite

The main prerequisite for successful application of the system model is the availability of the flight physics characteristics for a given aircraft or project. This input database (the aircraft ‘parametric definition’) must cover the operational domain of interest including the flight regimes at and beyond constraints. However, the accuracy and ‘richness’ level of the aircraft ‘parametric definition’ does not exceed the requirements that are applicable to the input database of a manned flight simulator used for research or training.

COMPLEX FLIGHT DOMAIN MODEL

In this section, a framework of key concepts, data structures and algorithms, which constitute the developed methodology of virtual flight testing under complex operational conditions, is introduced. Then, M&S experiment setup and simulation output are described for major phases and realistic multifactor operational conditions of flight.

CONCEPTUAL FRAMEWORK

Key Concepts

A generalized conceptual M&S framework has been developed for aircraft safety performance mapping, analysis, prediction and protection under multifactor conditions. These concepts are independent of the aircraft type, flight situation and operational conditions. The developed theoretical framework includes the following key concepts [11, 12]: system model, event, process, scenario, micro- and macrostructure of flight,

baseline scenario, operational (design) factor, operational hypothesis, situational tree, safety palette, partial safety spectra, integral safety spectrum, safety classification categories, safety window, family of the integral safety spectra of a situational tree, and some other.

Representation of Flight M&S Data

The ‘operator (pilot, automaton) - aircraft - operational environment’ system (the system) behavior is described as an ordered set of the system states $\mathbf{x}(t)$, $\mathbf{x}(t) = \{x_1(t), \dots, x_i(t), \dots, x_{N(x)}(t)\}$, where x_i is a system variable, $x_i \in \mathbf{x}$, $t \in [t_*, t^*]$. This data sequence is called a ‘flight’ (F_k),

$$F_k = \{\{x_1(t_*), \dots, x_{N(x)}(t_*)\}, \dots, \{x_1(t_* + (n-1) \cdot \Delta), \dots, x_{N(x)}(t_* + (n-1) \cdot \Delta)\}\}, \quad (2)$$

where n is the total number of data records in F_k , $t^* = t_* + (n-1) \cdot \Delta$, and Δ is the time increment of updating the output data file (the ‘flight’ F) in M&S experiments.

Micro-Structure and Macro-Structure of Flight

Safety knowledge of a complex flight situation domain is studied on two interconnected levels. These are the ‘microstructure’ of flight (a flight situation scenario) and the ‘macrostructure’ of flight (a situational tree). The relationship between these knowledge structures is shown in Figure 1.

The micro-structure of flight is a generalized model of a standalone (single) flight situation. It can be represented by the concept of flight situation scenario S . The latter is basically a directed graph, which consists of interconnected events and processes. In the scenario graph, a flight event (a vertex) E stands for a discrete component of the flight situation model,

whilst a flight process (a directed arc) Π stands for its continuous component. In other words, the formal scenario is a preplanned data structure designed to capture key cause-and-effect, time, instrumental and other logic relationships of flight dynamics and control in a given flight situation [1].

The macro-structure of flight is a knowledge model of a family of neighboring (what-if) situations. It can be represented, planted, stored and used in safety research as a tree. The tree trunk stands for some baseline flight situation - standard or non-standard one. Secondary (n^{th} -order derivative) branches represent multifactor situations, which implement meaningful variations of the baseline scenario or derivative scenarios of a lower level. New branches are automatically ‘implanted’ into the tree using the VATES v.7 M&S tool [2].

Operational Factor and Operational Hypothesis

The operational factor Φ is some event or process (or its attribute), which can be added to or withdrawn from a baseline (or derivative) flight situation scenario, $\Phi \cap \Omega(\Phi)$. Operational factors may vary substantially and independently in flight and thus can improve or deteriorate flight safety. Typically, an operational factor Φ is defined by a single system variable x_i , $x_i \in \mathbf{x}$. Operational factors are used in M&S experiments to generate multifactor derivative branches in a situational tree. Each derivative ‘flight’ from the tree corresponds to one combination of operational factors Φ_j .

It is important to study the effects of various combinations of operational factors on flight safety in advance. A meaningful combination (a composite) of several operational factors is called the operational hypothesis. In the model, the operational hypothesis Γ is used as a formal rule to incorporate a new

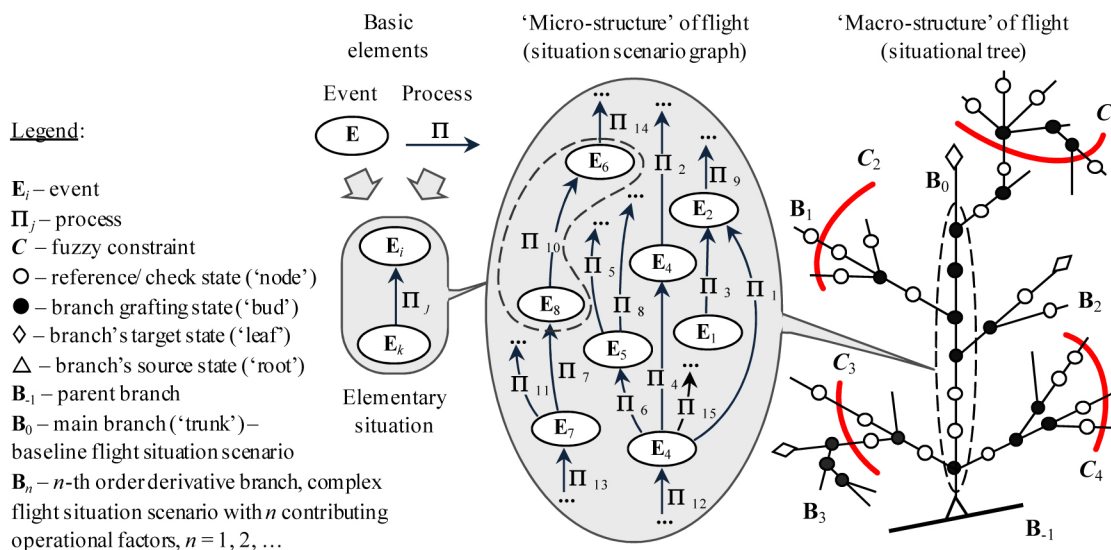


Figure 1. Two-level memory based knowledge model of complex (multifactor) flight situations domain.

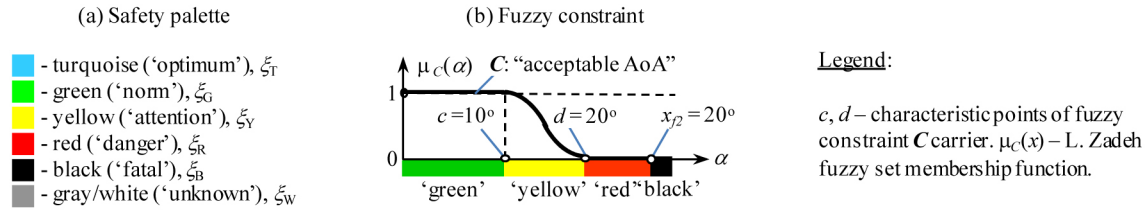


Figure 2. Safety palette and fuzzy constraint concepts.

operational composite into a baseline scenario. Formally, the operational hypothesis can be defined as follows:

$$\Gamma = \prod_{i=1}^n \left[\sum_{k=1}^m \Phi_k^i \right], \quad (3)$$

where Φ_k^i is the k^{th} dependent factor added to the baseline scenario on the i^{th} independent level of the situational tree branching process, $i = 1, \dots, n$, $k = 1, \dots, m$. In (3), Π is the symbol of Cartesian product (independent combination), and Σ is the symbol of dependent (cross-coupled) combination of operational factor values Φ_k^i on the i^{th} level.

Situational Tree as Knowledge Base

A situational tree $\mathfrak{S}$ is a composition of a baseline situation scenario S and a multifactor operational hypothesis Γ :

$$\mathfrak{S} = S \cdot \Gamma \equiv \Omega(F). \quad (4)$$

The tree $\mathfrak{S}$ is generated in M&S experiments with the system model. It can be viewed as a 'what-if neighborhood' of the baseline situation, i.e. as a structured set of branching situations F_k that surround S . In other words, the rule (4) is the situational tree 'genotype' that determines its shape, size, branching properties and safety characteristics. Each situation-branch B (a 'flight' F_k), $B \in \mathfrak{S}$, is defined by a combination of contributing operational factors Φ_j (the rule Γ), the baseline scenario S , and the system dynamics.

The goal of constructing a situational tree is to examine the combined effect of demanding operational conditions on the aircraft's safety performance and thus to generate in advance missing statistics on possible multifactor accident patterns. The overall goal of virtual flight test research process is to construct a 'forest' of such trees and to analyze safety properties of the complex flight situation domain it threads based on available design, test, operation or incident data.

Safety Palette. Fuzzy Flight Constraints

Color is a natural and efficient medium for storing and communicating safety-related information. Five basic colors green ξ_G , yellow ξ_Y , red ξ_R , black ξ_B and grey/white ξ_W) are

used to denote respectively 'normal', 'warning', 'dangerous', 'catastrophic' and 'uncertain' levels of the system safety performance for each measured system variable x_i from (2) and each time instant t recorded in flight - see Figure 2 (a).

Operational constraints of flight under multifactor conditions are not known precisely. They are inherently fuzzy. In the system model, the notion of fuzzy constraint introduced by L.A. Zadeh is employed for approximate measurement of the compatibility of current system states, measured at time instants t , with operational constraints using key system variables (monitored flight parameters). A notional example of the fuzzy constraint for the angle of attack α is presented in Figure 2 (b), together with a scheme for coloring its numeric definition domain using the safety palette from Figure 2 (a).

Safety Spectra

For each flight situation from a situational tree, its current safety levels can be measured at all recorded time instants for all monitored variables x_k . As a result, for each situation, a family of partial safety spectra Σ_k , $k = 1, \dots, N$, and an integral safety spectrum Σ can be constructed using the following general algorithm:

$$\begin{aligned} & (\forall t) (t \in [t^*; t^*]) (\exists \xi(x_k(t)) (x_k \in \mathbf{x} \wedge x_k(t) \in F) \\ & (\xi(x_k(t)) \in \{\xi_G, \xi_Y, \xi_R, \xi_B, \xi_W, \dots\} \wedge (\xi_B < \xi_R < \xi_Y < \xi_G < \xi_W)) \\ & (\xi(t) = \max \xi(x_k(t)), k = 1, \dots, N) \Rightarrow (\xi(t) \in \Sigma \wedge \\ & \Sigma = \xi(t^*) \parallel \xi(t^* + \Delta) \parallel \xi(t^* + 2 \cdot \Delta) \parallel \dots \parallel \xi(t^*)) \end{aligned} \quad (5)$$

where $\max$ denotes the operation of selecting the 'hottest' color from the safety colors recorded for all monitored variables x_k at a time instant t , $<$ is the operation of comparing safety colors, and $\parallel$ is the operation of geometric concatenation for two sequential safety color bars [11, 12].

The integral safety spectrum is basically a color-coded time-history of the situation safety status, which maps all cases of the violation and restoration of monitored fuzzy constraints during a flight situation at the 'hottest' level taking into account the available partial safety spectra. A more detailed introduction to the technique of flight safety spectra construction and applications can be found in [11, 12]. Examples of partial safety spectra and an integral safety spectrum are shown in

Legend:

$F_{2237} \in S_2 \cdot \Gamma_1$, $\{\beta, E, N, \gamma, \vartheta, V_{zg}, \alpha, \delta_N, \delta_e, \delta_a, \delta_r, H, \dots\}$ – system state variables
 $x_k, x_k \in \mathbf{x}$, Σ_k – partial safety spectrum calculated for variable $x_k, k = 1, \dots, N$;
 $N = 19$, Σ – integral safety spectrum.
 See Figure 2 for safety colorcodes.
 Phases of flight: a – airborne, g – ground-roll.

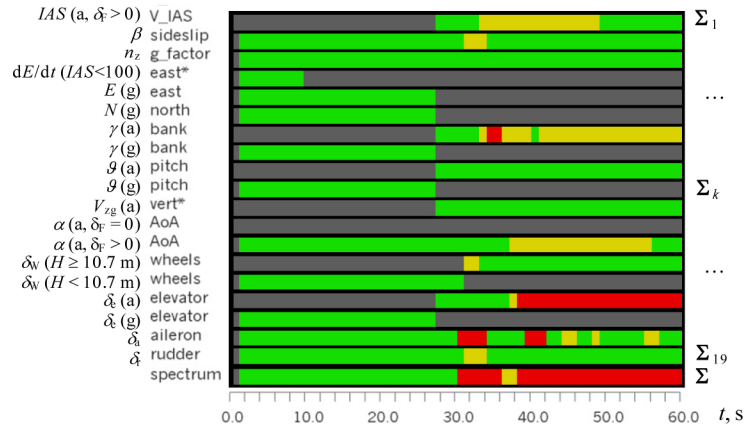


Figure 3. Safety spectra for flight F_{2237} : ‘Continued takeoff and initial climb at commanded flight path angle $\theta_G = 5^\circ$ and commanded bank angle $\gamma_G = -42^\circ$ with left-hand engine out during ground roll’.

Figure 3 for a ‘flight’ F_{2237} : ‘Continued takeoff and initial climb of an airplane at a commanded flight path angle (θ_G) of 5° and commanded bank angle (γ_G) of -42° with the left-hand engine out during ground-roll’.

Safety Classification Categories

One more level of flight safety knowledge generalization is needed in addition to the notion of safety spectra. The goal is to measure the aircraft’s safety performance in a particular flight situation as a whole. With this purpose, a generalized safety ruler’ that consists of six safety classification categories is introduced (Table 1).

This classification algorithm (Table 1) takes into account the palette, the ‘weight’ and the position of the four basic safety colors $\{\xi_G, \xi_Y, \xi_R, \xi_B\}$ in the integral safety spectrum Σ of a flight situation $F_k, F_k \in \Omega(F)$. Two new colors (‘salad green’ and ‘orange’) have been added to the original safety palette to denote interim categories: II-a and III, respectively. In general, the proposed total number of the flight safety classification categories in Table 1 (six) corresponds to a human expert’s ability to reliably recognize and utilize five to ten levels of a complex, difficult-to-formalize system property. This technique is based on the concept of ‘information granulation’ introduced by L.A. Zadeh [10].

The main criterion for assigning a safety category ξ_k from Table 1, $\xi_k \in \{\xi_I, \xi_{II-a}, \xi_{II-b}, \xi_{III}, \xi_{IV}, \xi_V\}$, to a flight situation F_k is the relative residence time of the system state, respectively, in the ‘green’, ‘salad green’, ..., and ‘black’ zones of this situation’s integral safety spectrum. As a result, for each situation-branch from a tree $\mathfrak{F}, \mathfrak{F} \equiv \Omega(F)$, a qualitative safety level (safety category) can be assigned. Such generalized safety color codes or grades are expedient to have for predictive and post-event flight safety analysis and in-flight decision-making support in complex operational domains.

Table 1. Flight situation safety classification categories

Code	Name	Definition
I	Safe	The system state resides mainly inside the ‘green’ zone. As a maximum, the system state may stay, for a short time in close proximity to the operational constraints, i.e. inside the ‘yellow’ zone, but must leave it by the end of the situation
II-a	Conditionally Safe – a	As a maximum, the system state may stay temporarily, or for a medium time, in close proximity to the operational constraints, i.e. inside the ‘yellow’ zone
II-b	Conditionally Safe – b	As a maximum, the system state may stay for a long time in close proximity to the operational constraints, i.e. inside the ‘yellow’ zone
III	Potentially Unsafe	As a maximum, the system state may violate operational constraints, i.e. enter the ‘red’ zone, for a short or between short and medium time, but must leave it by the end of the situation
IV	Dangerous (Prohibited)	As a maximum, the system state may stay beyond the operational constraints, i.e. inside the ‘red’ zone, for a medium or long time or till the end of the situation
V	Catastrophic (‘Chain Reaction’)	There is at least one (i.e. for a very short time) occurrence of the violation of any operational constraint at the ‘black’ level

Safety Window

Let us have a situational tree of ‘flights’ $\Omega(F), \Omega(F) = \{F_{(1),(1)}, \dots, F_{(i),(j)}, \dots, F_{(m),(n)}\}$ with the following pairs of values for two key operational factors Φ_a and Φ_b :

$$\{(\Phi_{a(1)}, \Phi_{b(1)}), \dots, (\Phi_{a(i)}, \Phi_{b(j)}), \dots, (\Phi_{a(m)}, \Phi_{b(n)})\}, \quad (6)$$

where $\Phi_{a(1)} > \Phi_{a(2)} > \dots > \Phi_{a(m)}$ is a top-to-bottom vertical ordering relation for the values of the first factor Φ_a and $\Phi_{b(1)} < \Phi_{b(2)} < \dots < \Phi_{b(n)}$ is a left-to-right horizontal ordering relation for the values of the second key factor Φ_b . Then, a flight safety window can be defined as a $m \times n$ matrix $W(\Phi_a, \Phi_b)$ with the

coordinates Φ_a and Φ_b , where w_{ij} is a cell located on the crossing of the row $\#i$ and column $\#j$,

$$w_{ij} = [(\Phi_{a(i)}, \Phi_{b(j)}), \xi_{ij}^k], \quad (7)$$

$i = 1, \dots, m, j = 1, \dots, n, k \in \{\mathbf{I}, \dots, \mathbf{V}\}$. The cell w_{ij} contains the following information: $\Phi_{a(i)}, \Phi_{b(j)}$ - a pair of values of factors (Φ_a, Φ_b) , where $\Phi_{a(i)} = \text{const}$ for $(\forall i)$ ($i = 1, \dots, m$) and $\Phi_{b(j)} = \text{const}$ for $(\forall j)$ ($j = 1, \dots, n$), and ξ_{ij}^k - the color of the k^{th} cluster, which the 'flight' $F_{(i,j)}$ belongs to, $k \in \{\mathbf{I}, \dots, \mathbf{V}\}$, $\xi_{ij}^k \in \{\xi^{\mathbf{I}}, \dots, \xi^{\mathbf{V}}\}$. The VATES tool incorporates an algorithm for automatic mapping of all the 'flights' from a tree $\Omega(F)$, $\Omega(F) = \mathbf{S} \cdot \Gamma$, on to a safety window plane $W(\Phi_a, \Phi_b)$.

SIMULATION EXPERIMENT SETUP

Virtual Flight Research Process

The developed virtual flight test process is carried out as a sequence of the following main research steps:

1. Develop the aircraft 'parametric definition' and implement the system dynamics model using VATES.
2. Plan and debug the baseline flight situation scenarios.
3. Formalize a subset of the operational factors selected for testing in M&S experiments.
4. Plan a situational tree's 'genotype' - a multifactor operational hypothesis.
5. Select a subset of the output color-coded graphic maps to be used for flight safety knowledge mapping.
6. Debug and validate the system model using available real or simulated flight data for the given vehicle or prototype.
7. Run a series of autonomous flight M&S experiments to test the multifactor operational hypothesis and construct a situational tree.
8. Map time-histories of the what-if 'flights' from the tree by means of the selected knowledge maps.
9. Screen the multifactor situational space of flight using the selected knowledge maps.
10. Mine new knowledge 'granules' of the system safety performance in multifactor situations from M&S experiment data and knowledge maps.
11. Identify and quantify possible anomalies, unsafe control scenarios and accident precursors in the system dynamics.
12. Identify and quantify safe situations, their precursors and control scenarios.
13. Explore in depth accident avoidance or recovery control techniques (or remedial design solutions) to avoid chain reaction type accidents (anomalies) under multifactor operational conditions.

14. Issue recommendations on the aircraft flight safety performance and refine operational constraints, human piloting tactics and automatic control laws for the given (multifactor) operational domain.

Aircraft 6-DOF Flight Dynamics Model

Using the methodology and research process described above, a series of M&S experiments has been planned and carried out with the system model to study takeoff, climb, level, descent, landing approach, go-around and landing phases of flight in multifactor conditions for a notional commuter airplane. The quality and the 'richness' of the vehicle 'parametric definition' used to build its 6-DOF non-linear flight dynamics model matches the input data requirements applicable to engineering and training flight simulators.

Baseline Flight Situation Scenarios

Seven baseline flight situation scenarios $\{S_1, \dots, S_7\}$ have been developed for demonstration. These are as follows (Table 2): S_1 : 'Normal takeoff and initial climb', S_2 : 'Continued takeoff and initial climb with left-hand engine out during ground-roll', S_3 : 'Continued takeoff and initial climb in cross wind conditions with left-hand engine out during ground-roll on wet runway', S_4 : 'Level flight followed by climb or descent', S_5 : 'Landing approach and go-around in wind shear conditions', S_6 : 'Landing approach and go-around in wind shear conditions with left-hand engine out', and S_7 : 'Landing approach, landing and ground-roll'. Note that the scenario subset $\{S_2, S_3, S_5, S_6\}$ already represents non-standard cases with non-empty subsets of operational factors.

Table 2. Baseline flight situation scenarios, $\Omega(S)$

Symbol and name	$\Omega_0(\Phi)$	$N(\Omega_0(\Phi))$
S_1 : Normal takeoff and initial climb	$\emptyset$	0
S_2 : Continued takeoff and initial climb with left-hand engine out during ground-roll	$\{\Phi_{10}\}$	1
S_3 : Continued takeoff and initial climb in cross wind conditions, with left-hand engine out during ground-roll on wet runway	$\{\Phi_3, \Phi_4, \Phi_{10}\}$	3
S_4 : Level flight followed by climb or descent	$\emptyset$	0
S_5 : Landing approach and go-around in wind shear conditions	$\{\Phi_6\}$	1
S_6 : Landing approach and go-around in wind shear conditions with left-hand engine out	$\{\Phi_6, \Phi_{11}\}$	2
S_7 : Landing approach, landing and ground-roll	$\emptyset$	0
Note. See Table 9 for definitions of Φ_i .		

These baseline situations represent central branches ('trunks') of the multifactor situational trees, which will be generated and tested in M&S. The scenarios S_1 , S_2 and S_3 stand for normal and continued takeoff situations under benign and demanding (cross wind) conditions. The scenario S_4 consists of a level flight phase followed by descent or climb after a decision-making point. The scenarios S_5 and S_6 begin with a landing approach phase, followed by climb after reaching a 'go-around' decision point - either in benign weather or wind

shear conditions. Finally, the scenario S_7 represents a standard landing situation and is composed of the approach, landing and ground roll phases. Specified below are the lists of the events and processes (control procedures, mechanical failures, piloting tasks, state observers, and demanding weather conditions), which constitute $\Omega(S)$, $\Omega(S) = \{S_1, \dots, S_7\}$.

Flight Events

A united calendar $\Omega(E)$ of all the flight events that form a discrete framework for the scenarios $\Omega(S)$ is defined in Table 3. It is essential that the recognition criteria developed for the events from $\Omega(E)$ are sufficiently general to formalize realistic flight situations, manual piloting and automatic control tactics. Note that about 30 events are sufficient to formalize all major phases of flight for a civil airplane - from takeoff to landing.

Table 3. Flight events, $\Omega(E)$

Symbol and name	E^{IF}	Recognition criterion			
		x	$\square$	A	U
E_1 : start		t	$\geq$	t_*	s
E_2 : LEO speed	E_1	IAS	$\geq$	V_{EF}	km/h
E_3 : VR achieved		IAS	$\geq$	V_R	km/h
E_4 : pitch 7 degr.	E_3	ϑ	$\approx$	7	$^\circ$
E_5 : in airborne	E_3	$R_{LG2} + R_{LG3}$	$=$	0	kN
E_6 : altitude 10.7 m		H	$\geq$	10.7	m
E_7 : altitude 120 m		H	$\geq$	120	m
E_8 : flaps retracted		δ_F	$=$	0	$^\circ$
E_9 : decision point		t	$\geq$	30	s
E_{10} : high speed	E_9	IAS	$\geq$	390	km/h
E_{11} : go-around decision		H	$\leq$	30	m
E_{12} : positive climb rate	E_{11}	$\dot{H}$	$\geq$	0.5	m/s
E_{13} : safe altitude	E_8	H	$\geq$	150	m
E_{21} : altitude to flare		H_W	$\leq$	9	m
E_{22} : load factor ≥ 1.15	E_{21}	n_z	$\geq$	1.15	-
E_{23} : small descent rate		$\dot{H}$	$\geq$	-1.0	m/s
E_{24} : touchdown	E_{21}	$s_2 \vee s_3$	$\geq$	0.01	m
E_{25} : touchdown + 5s delay		t	$\geq$	$t(E_{24}) + 5$	s
E_{26} : IAS 100 km/h	E_{24}	IAS	$\approx$	100	km/h
E_{27} : IAS 30 km/h	E_{26}	IAS	$\approx$	30	km/h
E_{99} : stop		t	$>$	t^*	S

Note. More complex (compound) recognition criteria, such as $(x \square A), \nabla (x \square A)_2 \nabla \dots \nabla (x \square A)_m$, are not shown. $\nabla \in \{\wedge, \vee\}$, $x \in \mathbf{x}$.

Flight Processes

In addition to the calendar of events $\Omega(E)$, the following lists of flight processes have been compiled to fill in the baseline scenarios $\Omega(S)$: $\Omega(P) \cup \Omega(F)$ - a united list of control procedures and mechanical malfunctions, $\Omega(T)$ - a list of piloting tasks, $\Omega(O)$ - a list of system state observers, and $\Omega(Y) \cup \Omega(W)$ - a united list of weather related processes. The control procedures and mechanical malfunctions, $\Omega(P)$ and $\Omega(F)$, are formalized in Table 4. The piloting tasks $\Omega(T)$ and the associated system state observers $\Omega(O)$ that represent manual flight control with continuous feedback are defined in Tables 5 and 6. Weather related processes, $\Omega(Y) \cup \Omega(W)$, which simulate demanding (wet) runway conditions, cross wind and wind shear conditions, are specified in Tables 7 and 8. It follows from the presented

examples that M&S scenarios for major phases of flight can be formalized in a uniform fashion for the purpose of complex flight domains analysis using a simple ('events-processes') description language.

Table 4. Control procedures and mechanical malfunctions, $\Omega(P)$ and $\Omega(F)$

Symbol and name	Control vector, $\mathbf{u}$	Goal, u_G	U	Rate of change
P_1 : throttles $\rightarrow$ takeoff power	δ_{T1}, δ_{T2}	100	$^\circ$	s
P_2 : elevator $\rightarrow$ up	δ_e	-8	$^\circ$	m
P_3 : wheels $\rightarrow$ up	δ_W	0	-	n
P_4 : flaps $\rightarrow$ up	δ_F	0	$^\circ$	n
P_5 : airbrake $\rightarrow$ on	$\delta_{A,BR}$	60	$^\circ$	n
P_6 : elevator $\rightarrow$ down	δ_e	15	$^\circ$	s
P_7 : throttles $\rightarrow$ idle	δ_{T1}, δ_{T2}	7	$^\circ$	n
P_8 : ground spoilers $\rightarrow$ on	$\delta_{GR,SP}$	50	$^\circ$	n
P_9 : wheel brakes $\rightarrow$ on	$\delta_{W,BR}$	1	-	n
P_{10} : throttles $\rightarrow$ reverse	δ_{T1}, δ_{T2}	-60	$^\circ$	n
P_{11} : throttles $\rightarrow$ idle	δ_{T1}, δ_{T2}	7	$^\circ$	n
P_{12} : wheel brakes $\rightarrow$ off	$\delta_{W,BR}$	0	-	n
P_{13} : ground spoilers $\rightarrow$ off	$\delta_{GR,SP}$	0	$^\circ$	n
P_{14} : ailerons & rudder $\rightarrow$ neutral	δ_a, δ_r	0	$^\circ$	m
F_1 : left-hand engine failure	δ_{T2}	-5	$^\circ$	f

Note. $\mathbf{u} \subset \mathbf{x}$; s - slow, m - medium, n - normal, f - fast.

Table 5. Piloting tasks, $\Omega(T)$

Symbol and name	Control vector, $\mathbf{u}$	State observer	Main observed variables, $\mathbf{y}$
T_1 : steer runway centerline	$\delta_{N,W}/\delta_r$	O_1	Ψ
T_2 : maintain initial climb path	δ_e	O_2	θ
T_3 : control sideslip & bank	δ_r, δ_a	O_3	β, γ
T_4 : maintain IAS	δ_{T1}, δ_{T2}	O_4	IAS
T_5 : control heading & bank	δ_r, δ_a	O_5	Ψ, γ
T_6 : maintain initial climb path	δ_e	O_6	θ
T_7 : maintain level flight	δ_e	O_7	$\dot{H}$
T_8 : maintain IAS	δ_{T1}, δ_{T2}	O_8	IAS
T_9 : maintain flight path	δ_e	O_9	θ
T_{10} : maintain glide slope	δ_e	O_{10}	$\dot{H}$
T_{11} : maintain tangent path	δ_e	O_{11}	$\dot{H}$

Note. $\mathbf{u} \subset \mathbf{x}$, $\mathbf{y} \in \mathbf{y}$, $\mathbf{y} \in \mathbf{x}$. See Table 6 for definitions of O_i .

Table 6. System state observers, $\Omega(O)$

Symbol and name	State observation vector(s), $\mathbf{y}$	Goal, y_G	U
O_1 : observe heading & bank	$(\Psi, \dot{\Psi}, r), (\gamma, \dot{\gamma}, p)$	0	$^\circ$
O_2 : observe climb path	$(\theta, \dot{\theta}, q)$	8	$^\circ$
O_3 : observe sideslip & bank	$(\beta, \dot{\beta}, r), (\gamma, \dot{\gamma}, p)$	0	$^\circ$
O_4 : observe IAS	$(IAS, \dot{V})$	250	km/h
O_5 : observe heading & bank	$(\Psi, \dot{\Psi}, r), (\gamma, \dot{\gamma}, p)$	0	$^\circ$
O_6 : observe climb path	$(\theta, \dot{\theta}, q)$	5	$^\circ$
O_7 : observe flight path	$(\dot{H}, \ddot{H}, q)$	0	m/s
O_8 : observe IAS	$(IAS, \dot{V})$	300	km/h
O_9 : observe flight path	$(\theta, \dot{\theta}, q)$	5	$^\circ$
O_{10} : observe descent rate	$(\dot{H}, \ddot{H}, q)$	-3.5	m/s
O_{11} : observe descent rate	$(\dot{H}, \ddot{H}, q)$	-0.2	m/s

Note. $\mathbf{y} \subset \mathbf{x}$.

Table 7. Weather related processes, $\Omega(Y)$ and $\Omega(W)$

Symbol and name	Variables	Function
Y_1 : wet runway conditions	μ_D	$f(F)$ – see Table 13
W_1 : cross wind conditions	W_{yg}	$f(t)$ – see Table 8
W_2 : wind shear conditions	W_{yg}, W_{zg}	$f(t)$ – see Table 8
Note. $(\forall t)(t \in [t^*; t^*])(W_1 \Rightarrow W_{yg}, W_{zg} = 0; W_2 \Rightarrow W_{yg} = 0)$.		

Table 8. Specification of wind type processes, $\Omega(W)$

Π	Variable		Piecewise linear function node #										$\mathfrak{Z}_i$
	x	U	1	2	3	4	5	6	7	8	9	10	
W_1	t	s	0	3	10	20	t^*	-	-	-	-	-	$\mathfrak{Z}_3$
	W_{yg}	m/s	0	10	10	10	10	-	-	-	-	-	
W_2	t	s	0	10	15	19	27	35	41	46	53	t^*	$\mathfrak{Z}_5$
			0	10	12	16	24	32	42	47	55	t^*	$\mathfrak{Z}_6$
			0	10	12	16	24	32	38	43	50	t^*	$\mathfrak{Z}_7$
			0	10	15	25	37	45	55	60	64	t^*	$\mathfrak{Z}_8$
	W_{yg}	m/s	0	-7	-12	-8	-14	-12	2	6	3	2.5	$\mathfrak{Z}_k$
	W_{zg}	m/s	0	0	0	0	-1	-1	-2.5	-3	-1	0	
<u>Note.</u> See Table 11 for definitions of $\mathfrak{Z}_i$; $k \in \{5, ..., 8\}$.													

Scenario Graphs and Description

Scenario S_1 : ‘Normal takeoff and initial climb’ (Figure 4). The situation begins at the event E_1 , with the aircraft positioned on the runway ready for takeoff. At this point, both throttles (δ_{T1}, δ_{T2}) are moved to a takeoff power setting by means of the control procedure P_1 . Simultaneously, the ‘silicon pilot’ begins to monitor and control the ground roll path by means of the two interrelated processes - the state observer O_1 and the

piloting task T_1 . The observer O_1 is employed to measure the aircraft heading angle (Ψ) error with respect to the runway centerline and the aircraft bank angle (γ) error. In the piloting task T_1 , the ‘pilot’ maintains the runway centerline using rudder and nose wheel steering. When a rotation speed V_R is reached (at E_3), elevator is deflected up by -8° using the process P_2 to rotate the aircraft. Once the nose wheel is off the runway (at E_4), the processes of ground roll motion observation and control (O_1, T_1) are terminated. At a pitch attitude (θ) of about 7° nose up (E_4), the pilot commences the processes of monitoring and maintaining the initial climb path; these are the observer O_2 and the task T_2 . Here, the commanded initial climb path is attained and maintained by means of elevator (δ_e) using the flight path angle (θ) error measurements. Shortly after lift-off (at E_5), the process of monitoring the aircraft sideslip (β) and bank (γ) angles begins (O_3). It is used to provide real-time system state error feedback for the process T_3 of the aircraft lateral control by means of rudder (δ_r) and ailerons (δ_a). At an altitude of 10.7 meters (E_6), the wheels are retracted ($\delta_w: 1 \rightarrow 0$) using the procedure P_3 . When a safe altitude of 120 m is reached (E_7), flaps are retracted (P_4). Once the aircraft is in clean configuration (at E_8), the following pairs of state observers and piloting tasks are commenced: (O_4, T_4) - to maintain a commanded value of indicated airspeed (IAS) by means of throttles, (O_5, T_5) - to steer commanded heading and bank angles by means of rudder and ailerons, and (O_6, T_6) - to maintain a new commanded flight path angle by means of elevator during the second phase of initial climb after flaps retraction. The situation is ended at the stop event E_{99} ($t > t^*$).

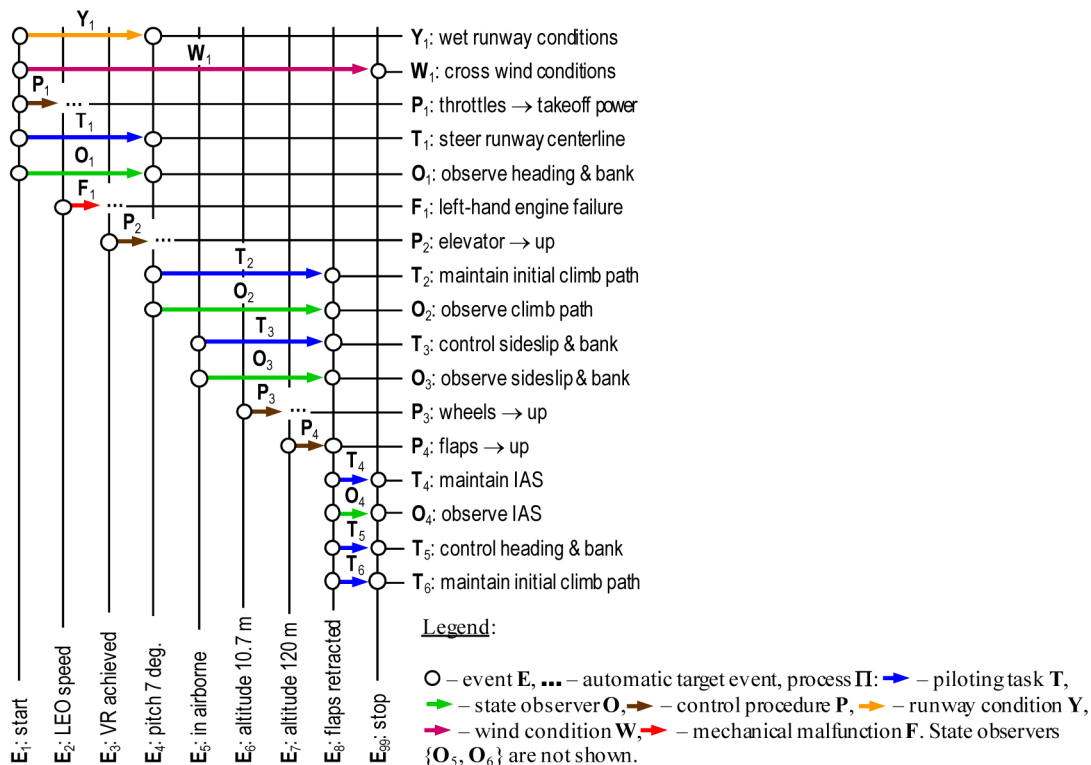


Figure 4. Baseline scenarios S_1 : ‘Normal takeoff and initial climb’, S_2 : ‘Continued takeoff and initial climb, with left-hand engine out during ground-roll’ and S_3 : ‘Continued takeoff and initial climb, with left-hand engine out during ground-roll, in wet runway and cross wind conditions’ (joint graph).