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Virtual Autonomous Fast-Time Exploration of Large Domains of Complex/Unknown Flight Situations for Safety through Lifecycle: Present, Future, Benefits and Pitfalls

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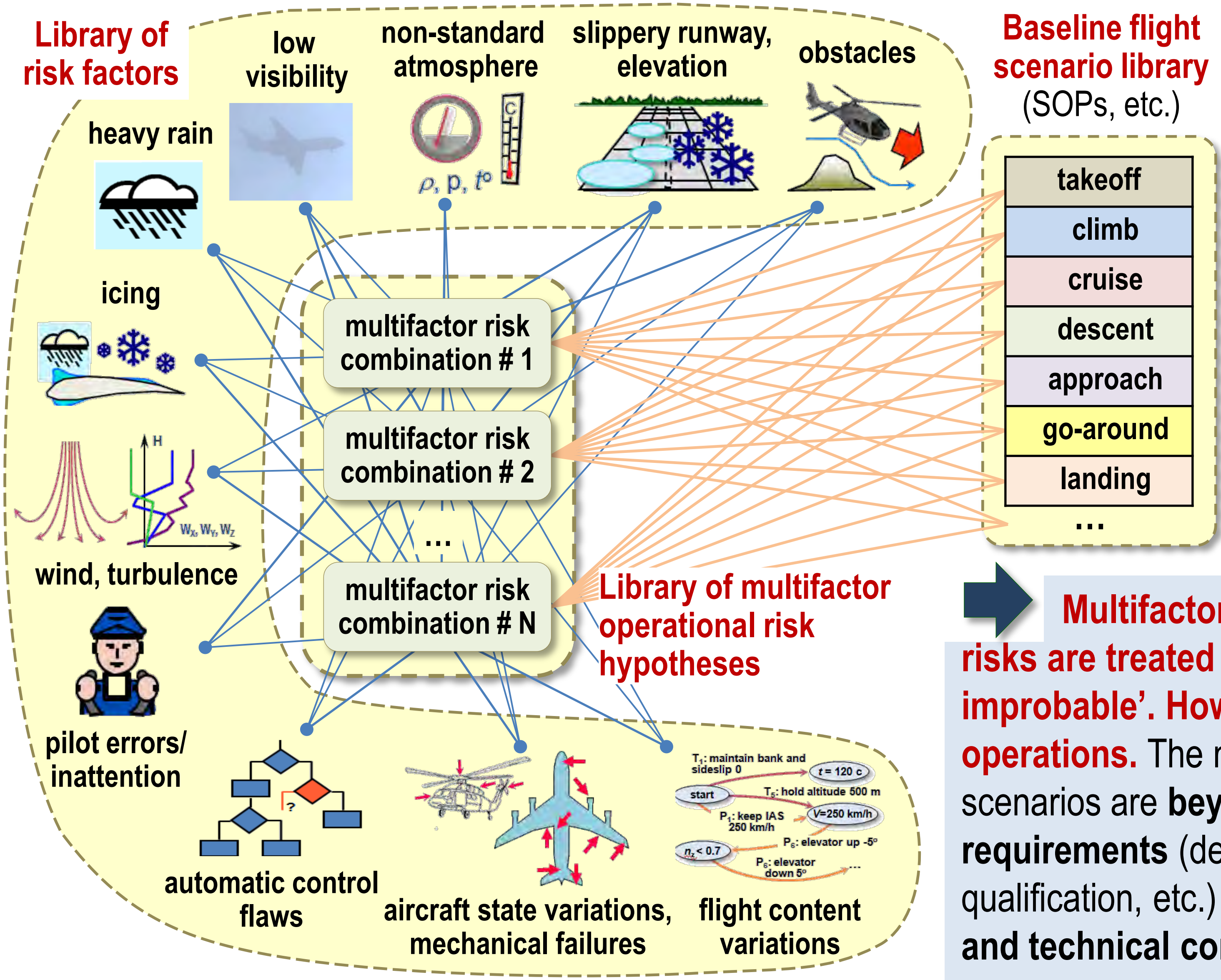
High Dimensionality of Operational Risk Space: Consequences for Flight Safety Protection through Lifecycle



Library of risk factors

heavy rain

low visibility

non-standard atmosphere

slippery runway, elevation

obstacles

icing

wind, turbulence

pilot errors/ inattention

automatic control flaws

aircraft state variations, mechanical failures

flight content variations

multifactor risk combination # 1

multifactor risk combination # 2

…

multifactor risk combination # N

Library of multifactor operational risk hypotheses

Baseline flight scenario library (SOPs, etc.)

- takeoff
- climb
- cruise
- descent
- approach
- go-around
- landing
- …

N >> 10^6

T(N) > a pilot's professional lifespan

Legend: **N** – total number of multifactor risk combinations (estimate). **T(N)** – total time of training required to learn/ refresh multifactor flight scenarios by a pilot/ engineer.

– combinatorial links.

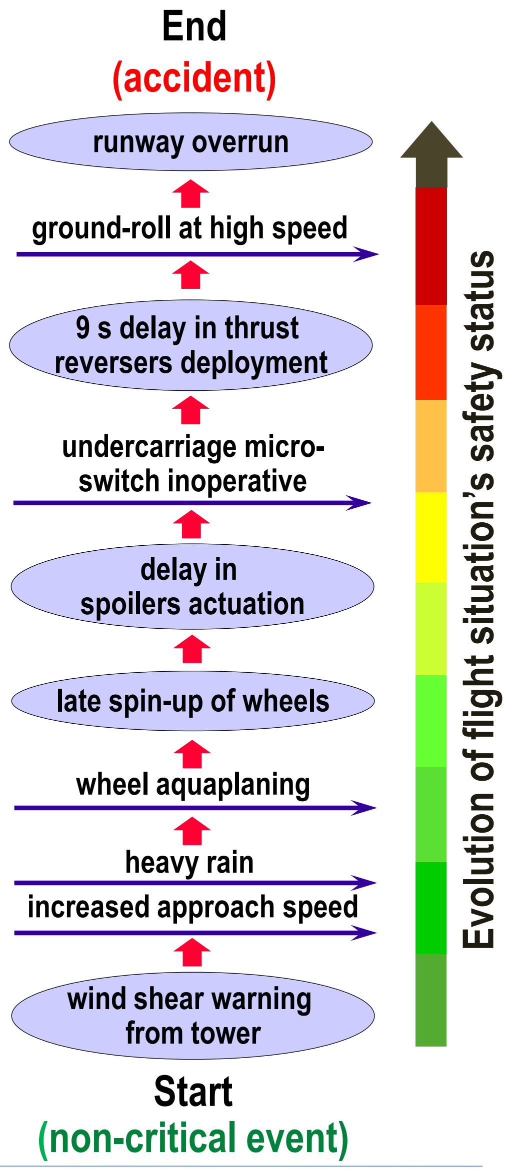
Multifactor combinations of safety risks are treated as 'theoretically improbable'. However, they do occur in operations. The majority of such off-nominal scenarios are **beyond** modern **requirements** (design, certification, qualification, etc.) – due to **time, budget and technical constraints**…

Problem: How to Explore Large Domains of Complex/ Unknown Flight Situations for Safety ?

1. Research Task Formulation

The 'pilot / automation - aircraft - operating environment' system is characterized by non-linear cross-coupling dynamics and heterogeneous logics. At the edge of the flight envelope, the system can exhibit unstable branching behavior – with bifurcations (safe/ unsafe) which are sensitive to risk factor combinations and control inputs.

Irreversible multifactor situation (example): **'Approach and landing in off-nominal conditions – wind shear warning, heavy rain, water-covered runway, pilot errors and automatic safety protection logic flaws'**


End

(accident)

runway overrun

ground-roll at high speed

9 s delay in thrust reversers deployment

undercarriage micro-switch inoperative

delay in spoilers actuation

late spin-up of wheels

wheel aquaplaning

heavy rain

increased approach speed

wind shear warning from tower

Start

(non-critical event)

Evolution of flight situation's safety status

Key challenges and solutions sought:

The **'curse of dimensionality'** ⇒ **relaxation techniques**

Non-linear **unsteady system dynamics** ⇒ **high-fidelity description**

Variety and multiplicity of scenarios ⇒ **flexible generalized scripting**

Multifactor operational **composites** ⇒ **automated planning & screening**

Safety performance ⇒ **efficient & affordable analysis through lifecycle**

System-level properties ⇒ **knowledge extraction & representation**

Legend: ⬭ - event. → - process. ⬇ - strong causal link. 🟩🟩🟨🟧🟥⬛ - safety colors.

The 'Curse of Dimensionality' in Flight Safety Research: Example for a Small Subdomain of Takeoff Cases

Flight case/ situation and examined risk factors	Number of risk factors	Number of required test scenarios
1. Normal takeoff (zero-risk or benign situation)	0	3 × 3 (*) = 9
2. Normal takeoff + 'wet runway' (one risk factor situation)	1	9 × 3 (**) = 27
3. Continued takeoff + 'wet runway' + 'engine out [in groundroll]'	2	27 × 5 (**) = 135
4. Continued takeoff + 'wet runway' + 'engine out' + 'windshear'	3	135 × 3 = 405
5. Continued takeoff + 'wet runway' + 'engine out' + 'windshear' + 'pilot error'	4	405 × 5 = 2 025
6. Continued takeoff + 'wet runway' + 'engine out' + 'windshear' + 'pilot error' + 'automatic system data/ algorithm flaw'	5	2 025 × 5 = 10 125
7. Case 6 + 'aerodrome elevation [above sea level]' + 'atmospheric temperature variation'	7	10 125 × 3 × 3 (***) = 91 125 (****)

Legend: ' …' - risk factor group name. + - operation of addition of a new risk factor to a lower-complexity scenario. (*) - three values of risk factor 'aircraft weight' { min, med, max } multiplied by three values of risk factor 'C.G. location' { front, mid, aft }. (**) - 3 … 5 is the minimal number of values of one risk factor for examination in any complex scenario. (***) - three values of risk factor 'aerodrome elevation' { 0, 1000 m, 3000 m } multiplied by three values of risk factor 'atmospheric temperature variation', e.g.: { ISA, ISA+10°, ISA+20° }. (****) - conservative estimate.

The **number of multifactor scenarios for testing increases in geometric progression** as the complexity of flight situations grows. Even for a small subdomain of takeoff cases, the total number of to-be-tested scenarios is 91125, and the net duration of these cases (each 60 s long) is equal to 1519 hours, or **190 working days**.

In overall, the total net duration of all multifactor scenarios of all flight phases for one aircraft type to test/ learn exceeds the lifespan of a pilot/ engineer.

Limitations of Classic Techniques In Studying Off-Nominal Flight Situation Scenarios

1. Desktop flight modelling and simulation software

2. Remotely controlled dynamically scaled flying model

3. Man-in-the-loop engineering/ training flight simulator

4. Experimental flight test article/ flying laboratory

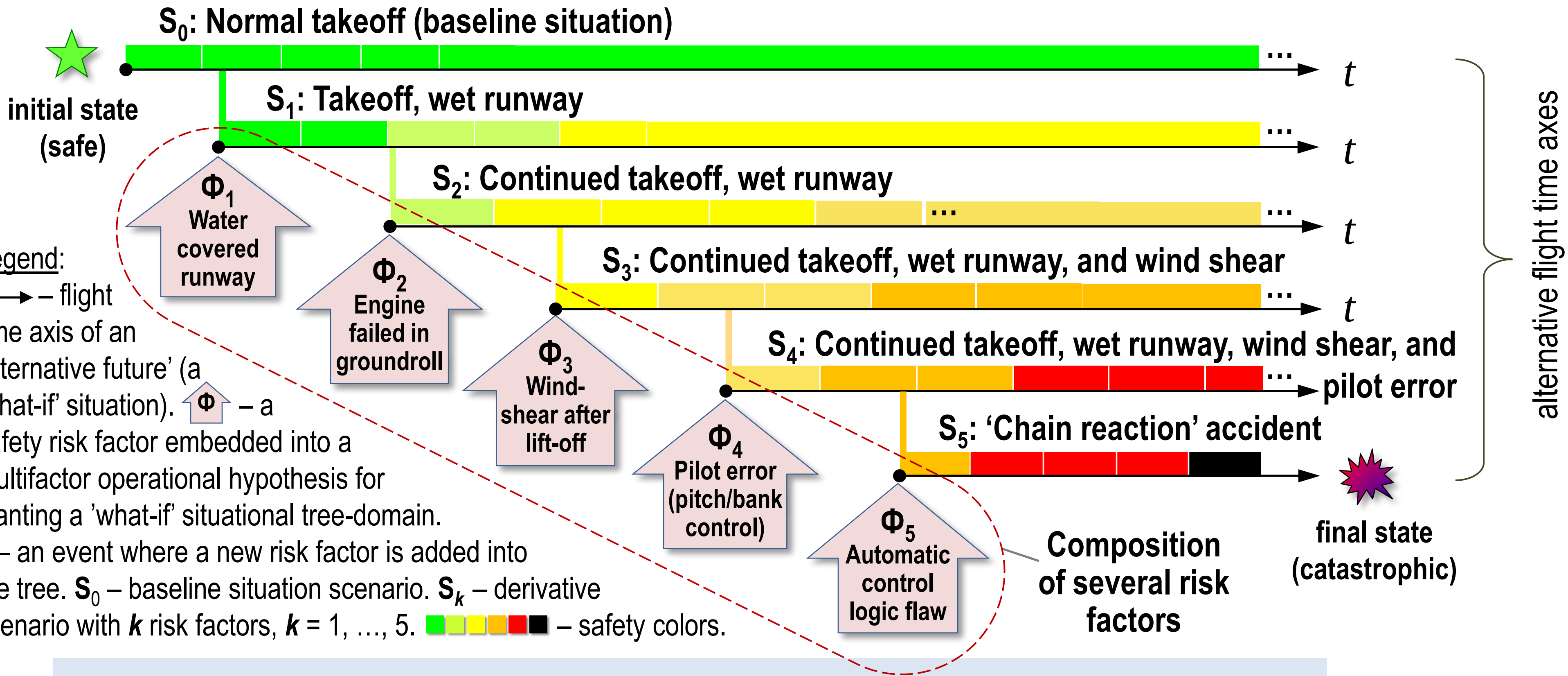
Limitation	**Technique #**			
	1	**2**	**3**	**4**
Difficulty to setup and modify the content of **multifactor scenarios**	●	●	●	●
The **‘curse of dimensionality’**: combinatorial limits on the total number of tested cases		●	●	●
Difficulty to implement and follow **multifactor scenarios** (and retain/ repeat them later)	●	●	●	●
Real-time flight **experimentation** only		●	●	●
Substantial demand for **resources** – budget, time, cadre, technology, etc.			●	●
Sparsely exemplified database of tested multifactor cases	●	●	●	●
Difficulty to **identify anomalous cases** and their precursors **in advance**	●	●	●	●

These limitations can lead to an ‘under-tested’ aircraft. As the result, **multifactor combinations of safety risks can propagate undetected into flight operations.** That is, off-nominal flight scenarios often **become known** only **after accidents**.

Solution Approach: Virtual Autonomous Fast-Time Proactive Exploration of 'Alternative Futures'

1. Research Task Formulation

The **'pilot/ automaton - aircraft - operating environment' system dynamics model serves as an autonomous high-throughput generator of multifactor virtual flight cases.** For each baseline scenario, a **tree incorporating $10^2 \dots 10^3$ 'what-if' situations**' can be simulated. Safety related knowledge is then **mined** from raw 'flight' data and **depicted** as 'a bird's eye view' **knowledge maps** for **visual analytics in parallel**.



Legend: ⟶ – flight time axis of an 'alternative future' (a 'what-if' situation). Φ – a safety risk factor embedded into a multifactor operational hypothesis for planting a 'what-if' situational tree-domain. ● – an event where a new risk factor is added into the tree. S_0 – baseline situation scenario. S_k – derivative scenario with k risk factors, k = 1, …, 5. 🟩🟩🟨🟧🟥⬛ – safety colors.

➡ A **'forest'** of such trees planted for a given phase of flight contains knowledge about the **system's 'alternative futures' available** (NB) **at present** for safety prediction.

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The 'Curse of Dimensionality': Mitigation Principle and Its Implementation

'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' [1].

Prof. Niklaus WIRTH, Swiss Computer Scientist – chief designer of programming languages Euler, Algol W, PL360, Pascal, Modula, Modula-2 and Oberon.


(*)

In order **to soften Bellman's curse of dimensionality** in complex/ unknown flight domain research, the **developed technology of Virtual Flight Test and Certification (VFTC)** harnesses Wirth's principle. Namely, the VFTC technology consists of two **highly-structured interrelated components**:

- **ISAFE methodology** – **Intelligent Situational Awareness & Forecasting Environment** (theory).
- **VATES software tool** – **Virtual Autonomous Test & Evaluation Simulator** (software tool).

The technology's exploratory power is due to the **synergy of high-fidelity mathematical modeling**, **fast-time simulation**, **situational control, artificial intelligence**, **knowledge mining and mapping**, **virtual reality** and some other techniques.

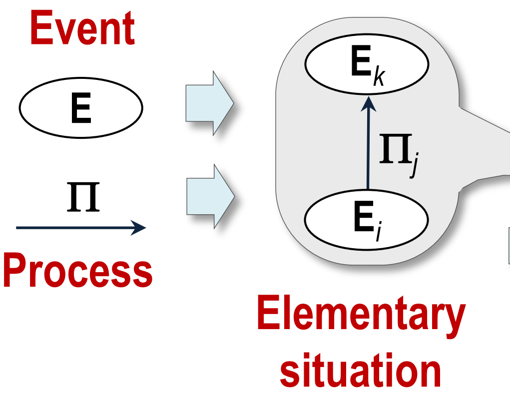
Legend: [1] - N. Wirth, Programming in Oberon, a Tutorial, ETH Zurich, Switzerland, 2004, 63 pp. (*) - image source: http://www.csag.uct.ac.za/2017/02/02/culturing-some-form-of-a-growth-mindset-for-learning-in-fractal/

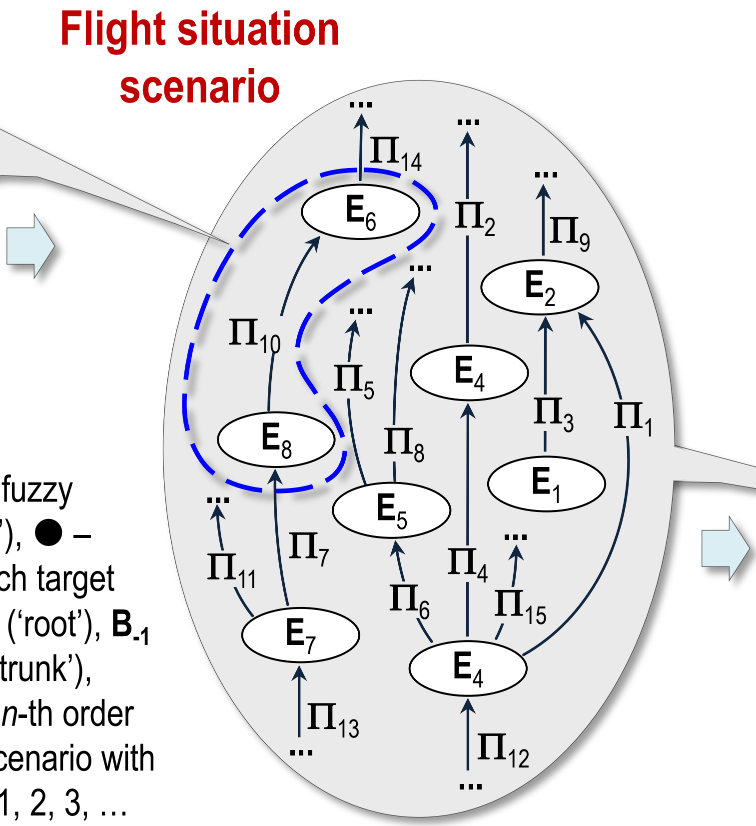
Two-Level Knowledge Structure of Complex Operational Domains of Flight - Situational/ Tactical Knowledge Base

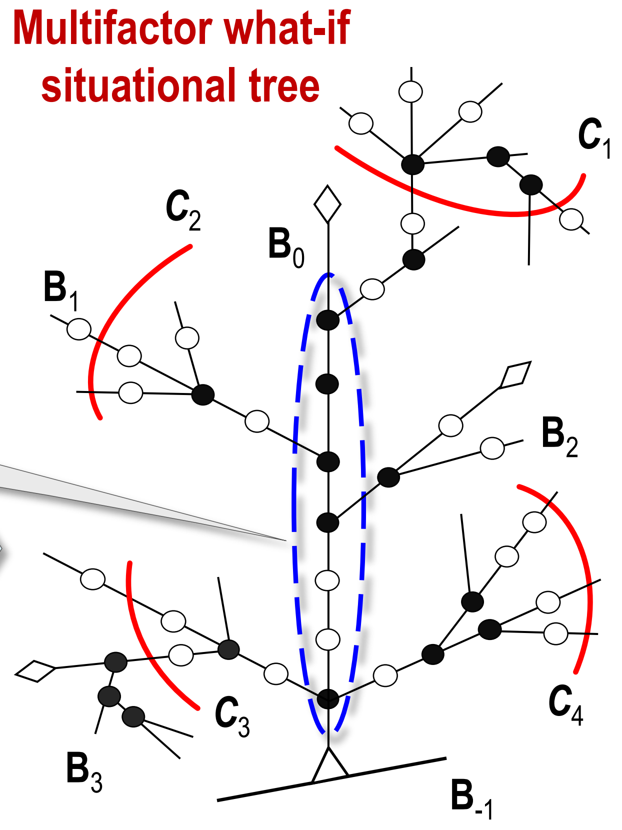
Basic formal elements

'Microstructure' of flight (Level # 1)

'Macrostructure' of flight (Level # 2)



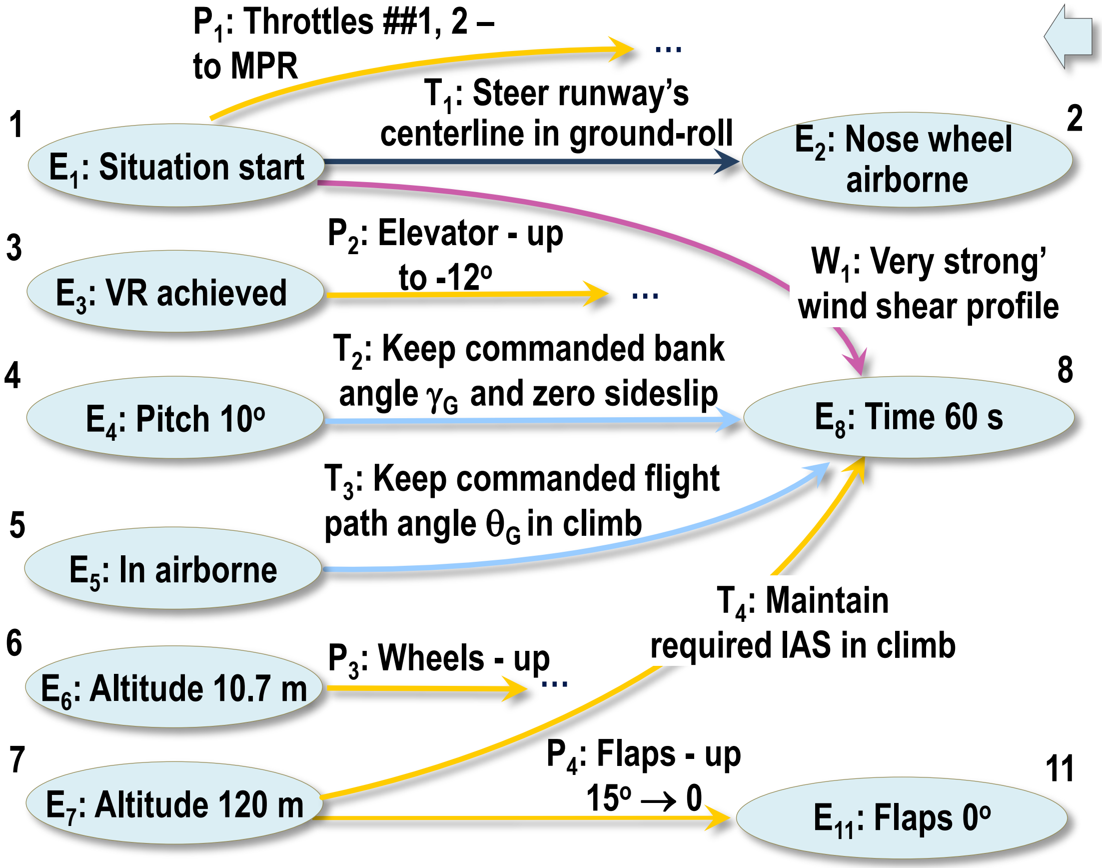




Legend: $\mathbf{E}_i$ – event, $Π_j$ – process, ***C*** – fuzzy constraint, ○ – reference state ('node'), ● – branch grafting state ('bud'), ◊ – branch target state ('leaf'), △ – branch source state ('root'), $\mathbf{B}_{-1}$ – parental branch, $\mathbf{B}_0$ – main branch ('trunk'), baseline flight situation scenario, $\mathbf{B}_n$ – *n*-th order derivative branch, complex situation scenario with *n* contributing operational factors, *n* = 1, 2, 3, …

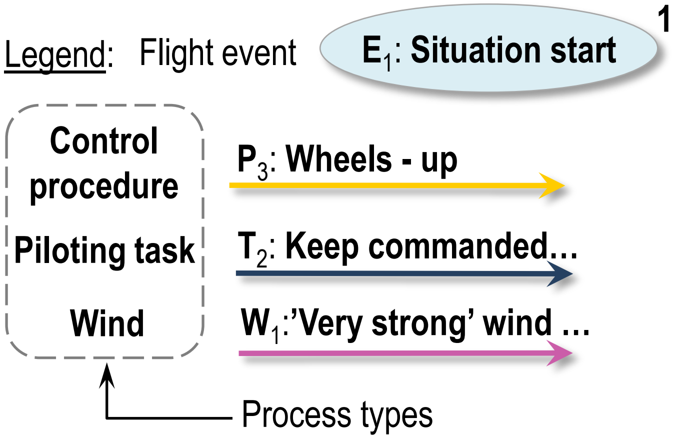
The directed graph and the tree are two **generalized mathematical structures** which are used to accumulate **knowledge about realistically complex large operational domains** of flight.

Flight Situation Scenario – Directed Graph Format (Example)



Scenario in directed graph format

Scenario $\mathbf{S_1}$: **'Normal takeoff and initial climb under 'very strong' wind shear, pilot errors in selecting commanded flight path (θ_G) and bank (γ_G) angles'** (3-factor situation)



Scenario is a **concise formal structure -** a plan of the anticipated content of a flight situation. It consists of **events and processes** linked by heterogeneous **logical relationships**: causal, temporal, instrumental, etc. **Any situation** (test, operation, incident/ accident, virtual one), **be it benign or complex**, can be formalized and simulated using this scenario scripting language.

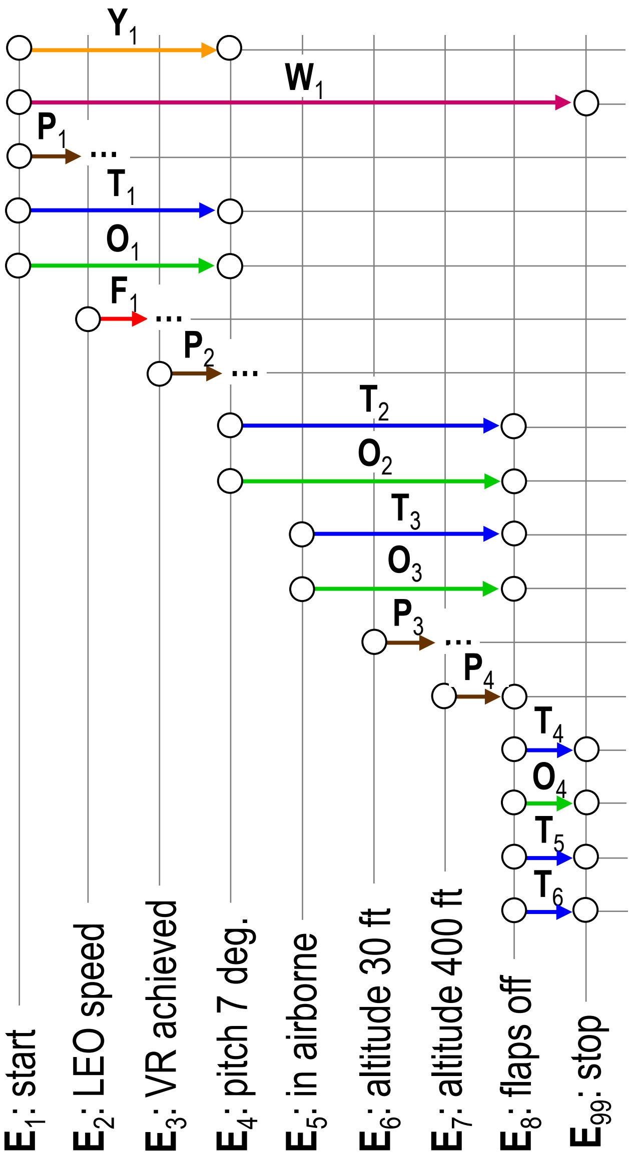
Flight Situation Scenario – Matrix Format (Example)

Scenario in matrix format

Scenario **S_3: 'Continued takeoff and initial climb, with LEO during ground-roll, wet runway and cross wind' (3-factor situation)**

$$S_3 = \{E_1, \ldots, E_8, E_{99}\} \cup \{P_1, \ldots, P_4\} \cup \{T_1, \ldots, T_6\} \cup \{O_1, \ldots, O_6\} \cup \{F_1\} \cup \{W_1\} \cup \{Y_1\}$$

The flight scenario concept is universal. It is applicable to any aircraft class, all flight phases (or the whole flight), all risk factors and all situations types: flight T&C, SOPs, accidents/ incidents, etc. Thousands of baseline scenarios were examined **for 30+** aircraft and projects **since 1984**.



E_1: start
E_2: LEO speed
E_3: VR achieved
E_4: pitch 7 deg.
E_5: in airborne
E_6: altitude 30 ft
E_7: altitude 400 ft
E_8: flaps off
E_{99}: stop

Y_1: wet runway conditions
W_1: cross wind conditions
P_1: throttles → takeoff power
T_1: steer runway centerline
O_1: observe heading & bank
F_1: left-hand engine failure
P_2: elevator → up
T_2: maintain initial climb path
O_2: observe climb path
T_3: control sideslip & bank
O_3: observe sideslip & bank
P_3: wheels → up
P_4: flaps → up
T_4: maintain IAS
O_4: observe IAS
T_5: control heading & bank
T_6: maintain initial climb path

Legend: ○ – event **E**. **...** – automatic target event. Process types: **T** – piloting task, **O** – state observer, **P** – control procedure, **Y** – runway condition, **W** – wind, **F** – mechanical malfunction. Observers {O_5, O_6} not shown.

Exploration of Multifactor Risk Space: Requirements Formulated by Test Pilots

2. Structuring Complex / Unknown Operational Domains

Characteristics of complex/ unknown domains of flight found in testimonies of test pilots [1]:

'…analytical description of aircraft behavior in various flight modes'

'…multiplicity of operational risk factors'

'…unfavorable mix of demanding conditions'

'…combination of operational circumstances'

'…domain of available decisions'

'…multiplicity of possible decisions'

'…clear understanding of margins'

'…simultaneous parallel analysis … of various, even unthinkable overlapping decisions', etc.

Requirements to safety research process in multifactor off-nominal situations:

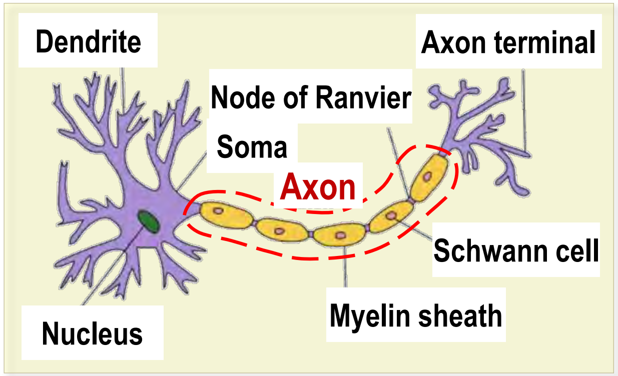
- **Accurate mathematical modeling of the physics and logic of flight**
- **Consideration of combinations of risk factors**
- **Parallel analysis of what-if branching decisions and their effects**
- **Screening operational domains for rare scenarios**.

Legend: [1] - G.A. Amiryantz, **Test Pilots. Sergei Anokhin and Co-Fellows**. Mashinostroyenie, Moscow, Russia, 2001, 448 pp. (in Russian).

Experience-Driven Branching Organization of Memory in Animals And Humans: Results of Brain and Mind Research [1-3]

2. Structuring Complex / Unknown Operational Domains

Neuron structure

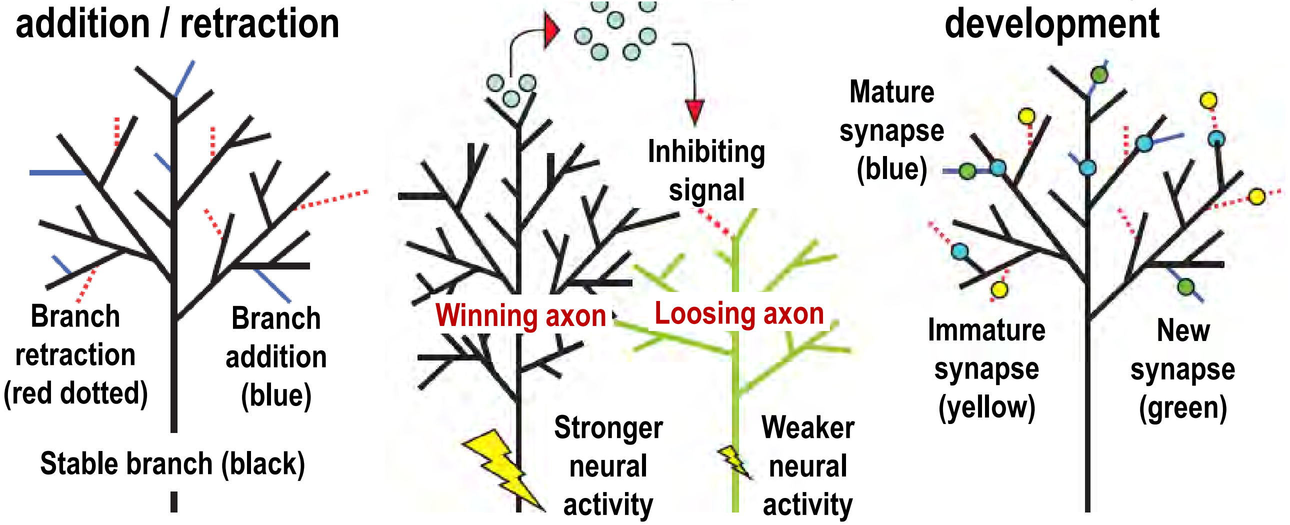


Axon branching …

…is a dynamic process of branch addition / retraction

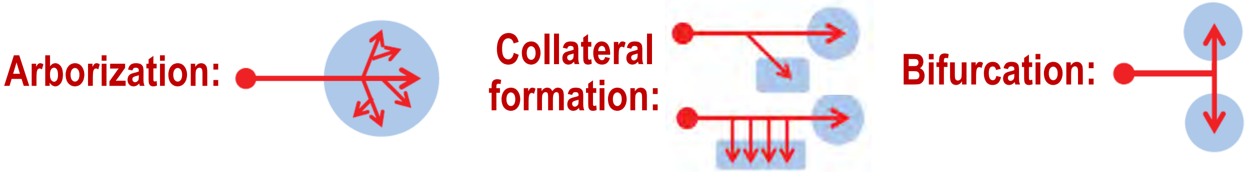
… neighbors compete for innervation ‘territory’

… is tightly coupled to other neuron’s synapse development



Underlying mechanisms in activity-dependent regulation of axon branching

Typical axon branching processes in nervous system related to human’s activity


Arborization:

Collateral formation:

Bifurcation:

Generalized concepts of ‘flight situation scenario’ and ‘situational tree’ are coherent with recent experimental research results obtained by neuroscientists and psychologists [1-3].

Legend: **[1]** - D.A. Gibson and Le Ma. Developmental regulation of axon branching in the vertebrate nervous system. *Development 138*, 2011, pp. 183-195. **[2]** - Quartz, S.R. and Sejnowski, T.J. The Neural Basis of Cognitive Development: A Constructivist Manifesto, *Behavioral & Brain Sciences*, 20:4, 1997, pp. 537-596. **[3]** - Holtmaat A., Svoboda K. Experience-dependent structural synaptic plasticity in the mammalian brain. *Nature Reviews. Neuroscience,* 10, September 2009, pp. 647-658.

The Principle of Branching in Situational Knowledge Tree – Takeoff Example

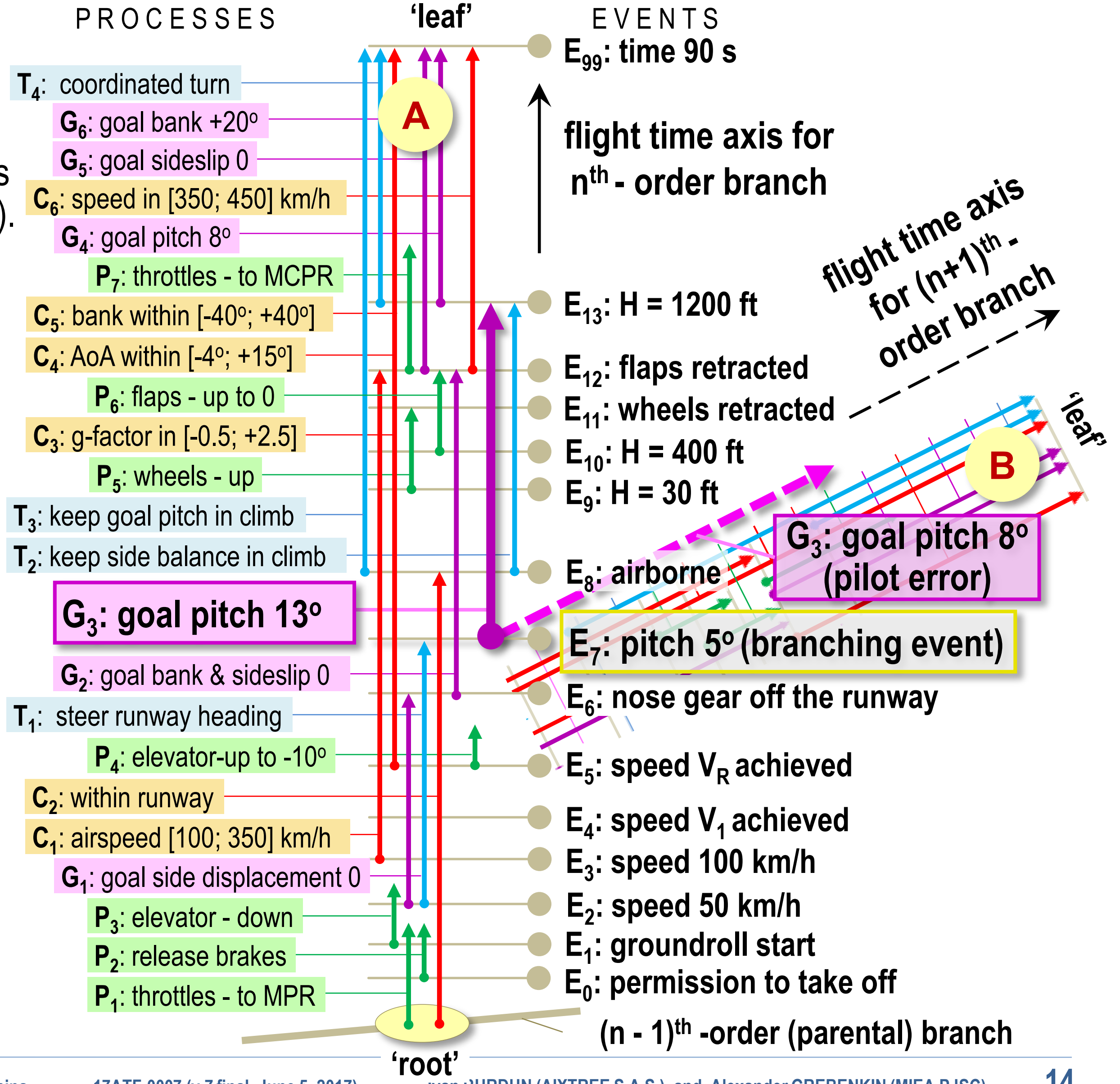
A nth -order branch: **Nominal takeoff** (**baseline scenario** or trunk, if n = 0.

The baseline scenario's events and processes are lined up along the flight time axis (upward).

B (n+1)th - order branch example: **Off-nominal takeoff with a pilot error at E_7** ('**what-if' scenario**).

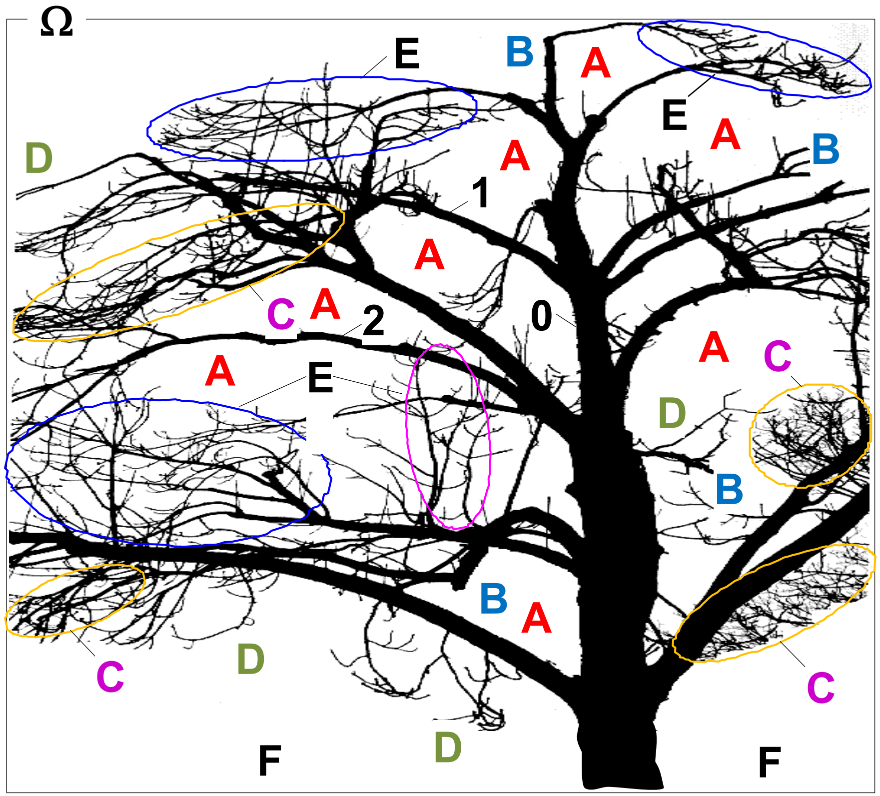
A **new risk factor** - a smaller commanded pitch angle **G_3: goal pitch 8° (pilot error)** - is implanted at event **E_7**. The time axis and the modified process (**G_3**) of the what-if scenario are shown by dashed lines.

By adding new risk factors into a baseline scenario, the process of virtual flight exploration is intentionally directed into new regions of a complex/ unknown operational domain: '**what [happens] ..., if ... ?**'.



Main Defects of a Human Pilot's Situational Knowledge Base – Natural Tree Analogy

2. Structuring Complex / Unknown Operational Domains



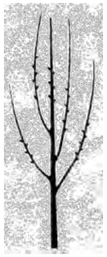
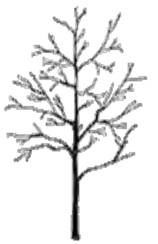
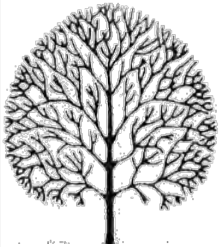
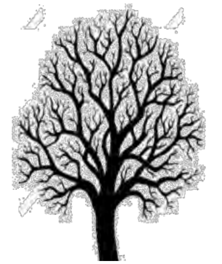
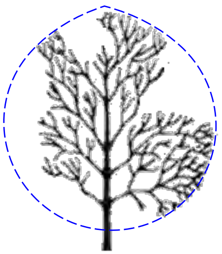
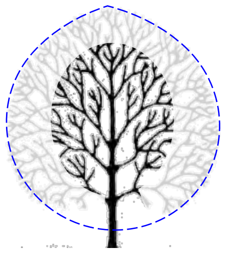
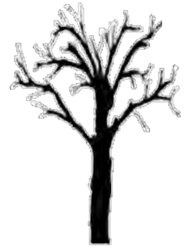
Legend:

	Characteristic subsets of a human pilot's knowledge	Natural tree analogy
Ω	Domain of possible situations	= space available for tree growth
0	Benign flight situation scenario	= tree's trunk
1	One-factor non-standard situation scenarios	= 1st-order derivative branch.
2	Two-factor non-standard situation scenarios	= 2nd-order derivative branch
A	Missing knowledge	= absent but possible branching
B	Forgotten/ shadowed knowledge	= dead/ broken branches
C	Non-systematic knowledge	= excessive/ chaotic branching
D	Fragmentary knowledge	= insufficient, sparse branching
E	Systematic knowledge	= optimally dense branching
F	Physically unattainable scenarios	= region impossible for branching

These are main defects of a human pilot's situational knowledge base to **back up** by M&S and AI techniques.

Selected Characteristic Phenotypes Of Human Pilot's Internal Situational Knowledge Base

2. Structuring Complex / Unknown Operational Domains

Total flight hours *	5 … 10	10 … 100	100 … 1000	1000 … 5000	5000 … 10000+	100 … 1000	1000 … 5000	5000 … 10000+
Piloting skills in off-nominal situations	Student pilot	'Freshly minted' pilot	Professional, mature	Highly proficient, comprehensive	Exceptional (test/ expert pilot level)	Weakened, damaged	Weakened, decayed	Substantially decayed, lost
Multifactor flight training currency	Basic	Fair	Sufficient/ good, standard	Adequate / Excellent	Up-to-date, with theoretical backup	Inadequate training method	Long breaks in training	Very long break in training
Knowledge branching pattern	Weak, basic	Sparse, immature	Dense, Systematic	Comprehensive. regular	Very dense, type-specialized	Non-systematic, with large blanks	Decayed outer (high-order) layer	Forgotten (major crown)
Thickness of trunk (of 1st … 2nd -order branches)	Tiny	Minimal	Moderate	Moderate to large	Thick (moderate)	Moderate	Moderate	Thick (moderate)
Phenotype of a pilot's 'internal situational knowledge tree'								

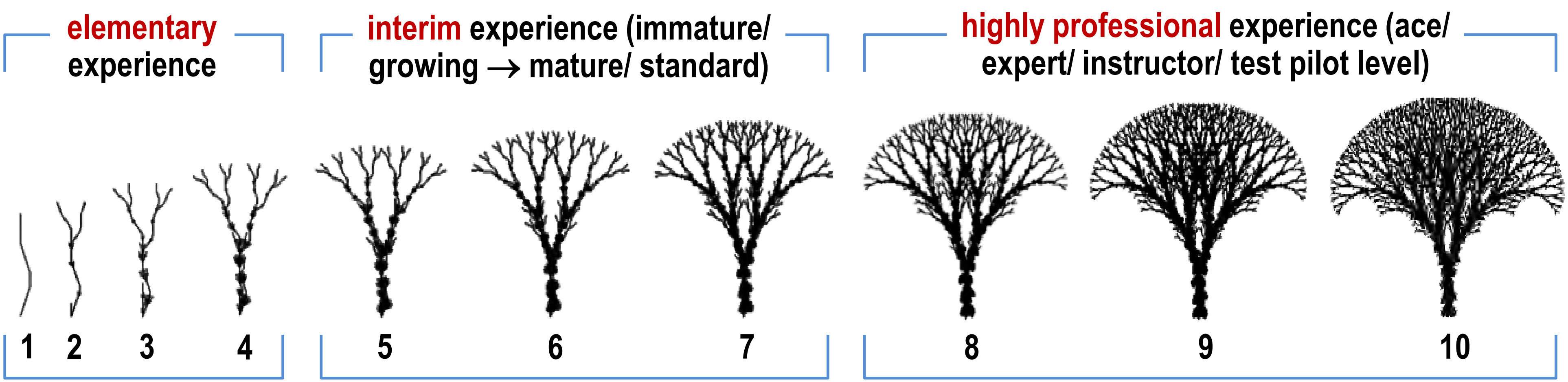
Most dangerous phenotypes of a human pilot's situational knowledge base

Without due training, hundreds or even thousands of previous total flight hours (TFH) in aircraft type accumulated by a pilot do not guarantee safe piloting in off-nominal situations.

Legend: (*) – rough estimate of a pilot's total flight hours (TFH) in type. Thickness of a trunk/ branch is proportional to a pilot's TFH in type. Thick trunk means many hours of flying in benign conditions. Dense (or sparse) crown branching denotes good (or inadequate, insufficient) training in multifactor situations. Major defects of a pilot's knowledge base include: dead/ broken branches, sparse/ chaotic crown branching, and absent branching. Image sources: http://maxpixel.freegreatpicture.com/, http://www.wildwoodsdorset.co.uk/treesurgery.asp, http://fruitandnuteducation.ucdavis.edu/generaltopics/Tree_Growth_Structure/Tree_Structure_Light_Capture/, https://www.pinterest.com/aethiopica/stencils, https://de.123rf.com/photo_17687303_sammlung-von-b-umen-silhouetten.html, https://pixabay.com, www.aixtree.com.

Fractal Tree Growth as a Model of Pilot’s Tactical Experience Development in Long-Term Memory

2. Structuring Complex / Unknown Operational Domains



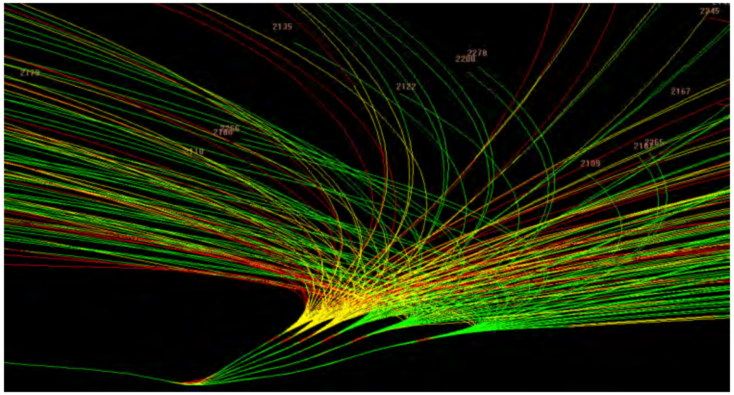
elementary experience

interim experience (immature/ growing → mature/ standard)

highly professional experience (ace/ expert/ instructor/ test pilot level)

The ideal outcome of a VFTC process is a forest-type synthetic knowledge base on the system dynamics and safety in off-nominal situations. In theory, **the volume of a such synthetic knowledge base can many times exceed the volume of situational experience acquired by all pilots for all aircraft of a given type in aviation history** since the Wright Brothers’ flight.

Legend: **1**, **2**, …, **10** – the maturity levels of a pilot’s expertise in coping with complex flight situations (a working classification): $k \in \{\mathbf{1}, \mathbf{2}, \mathbf{3}\}$ – elementary experience of a student pilot, $k \in \{\mathbf{4}, \ldots, \mathbf{7}\}$ – interim (immature/ growing → mature/ standard) states of experience, $k \in \{\mathbf{8}, \mathbf{9}, \mathbf{10}\}$ – highly professional experience of ace pilot, expert pilot, or test pilot. Fractal tree generating software: FracTree 1.0 program for MS Windows (shareware). Author: M. Schernau. Fractal name: Model of a pilot’s situational expertise growth. Number of branching directions: 20. Axiom: -----G. Tree growth rules: G → [V]+FFX-F-FFX+FX [+G][-G]F, V → XF[G], X → F[-XF][+XF] FX.



How to Represent Safety Related Information and Constraints? - Notions of Safety Palette and Fuzzy Constraint

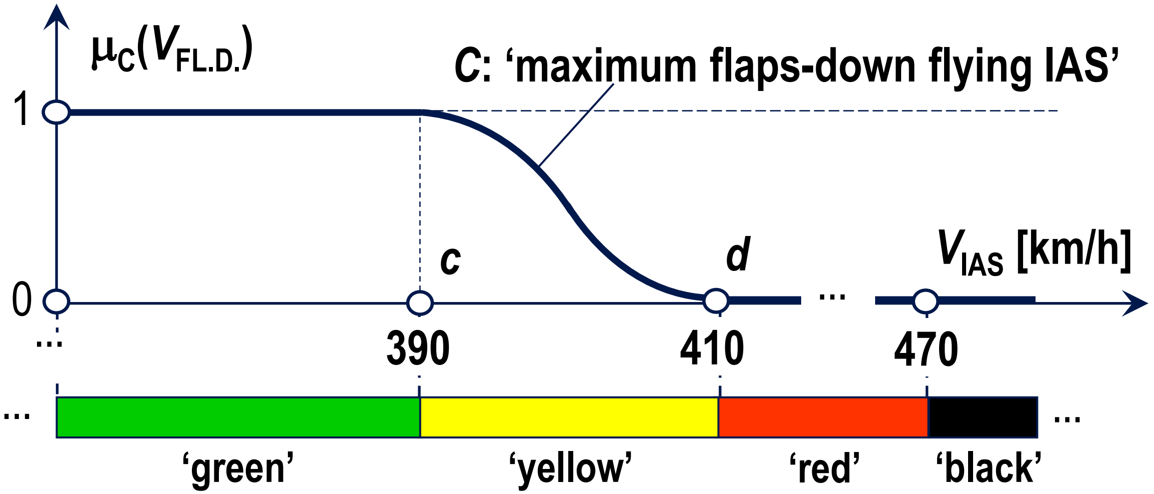
Safety Palette (π)

- 🟩 - green ('norm'), ξ_G
- 🟨 - yellow/ amber ('attention'), ξ_Y
- 🟥 - red ('danger'), ξ_R
- ⬛ - black ('catastrophe'), ξ_B
- ⬜ - grey/ white ('uncertainty'), ξ_W
- 🟦 - turquoise ('optimum'), ξ_T

$$\pi = \{\xi_W, \xi_T, \xi_G, \xi_Y, \xi_R, \xi_B, \ldots\}$$

Safety palette is a natural color-coding technique used to **denote the danger level of the current numeric value of the system state parameter** - as a function of time.

Fuzzy Constraint (*C*)

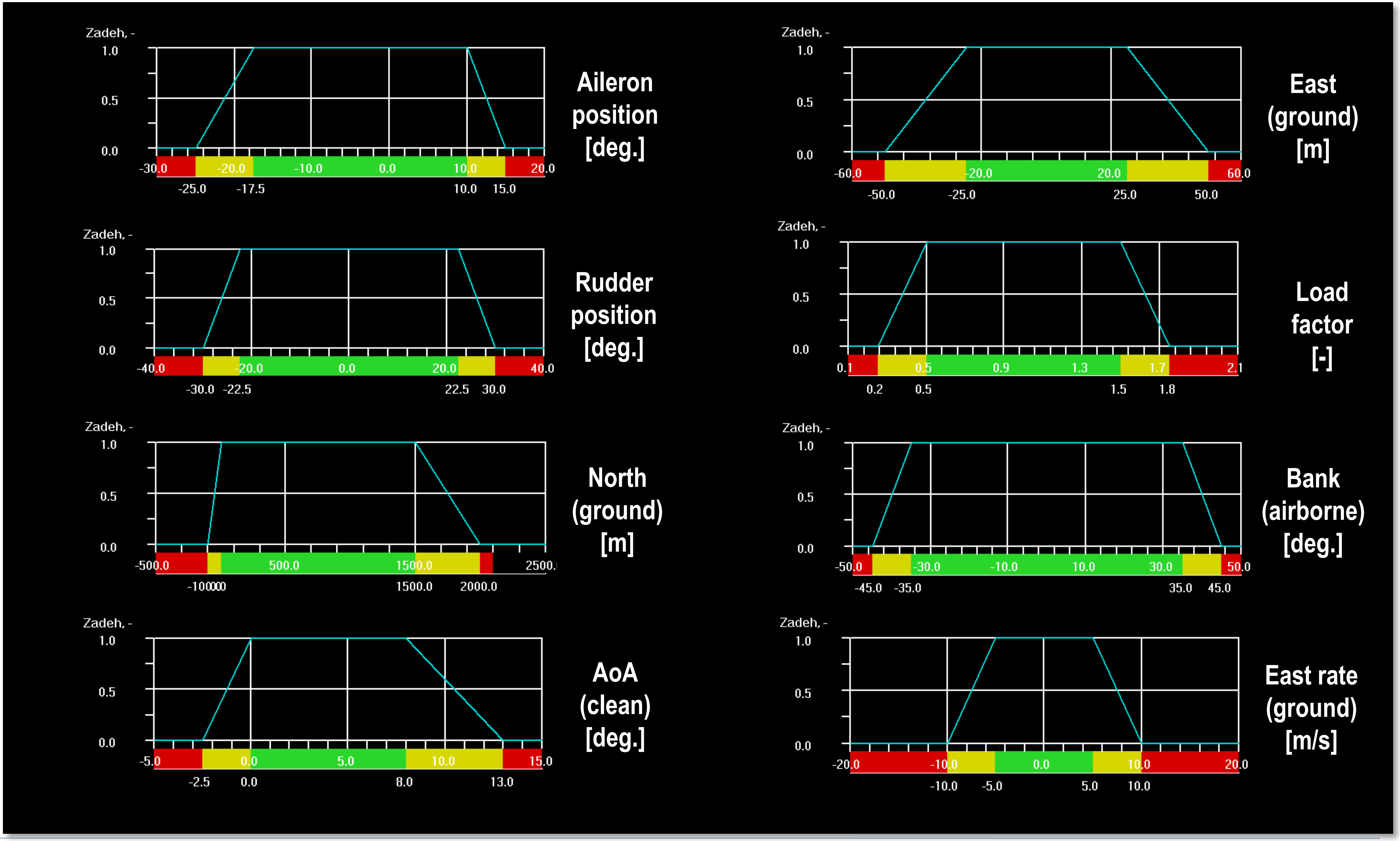


Legend: ***c***, ***d*** – characteristic points of the carrier of fuzzy set-constraint ***C***, $\mu_C(x)$ – Prof. Zadeh fuzzy set membership function. V_{IAS} – indicated airspeed ('flaps-down' flying mode).

The concept of **fuzzy constraint** is used to **formalize a real system's operational constraints**, which are characteristic to off-nominal /unknown flight domains.

Specification of Fuzzy Constraints in the System Dynamics Model (Commuter Airplane Example)

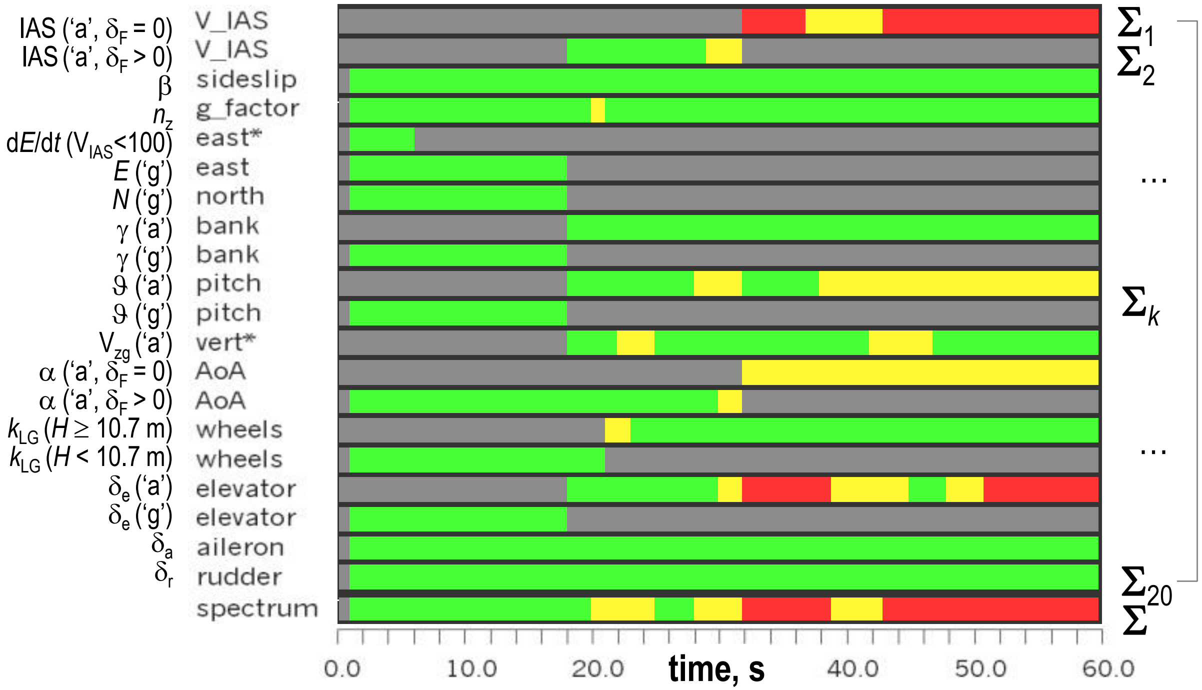
2. Structuring Complex / Unknown Operational Domains



Partial Safety Spectra and Integral Safety Spectrum Of Flight Situation

2. Structuring Complex / Unknown Operational Domains

A **partial safety spectrum is constructed for the time-history of each variable** monitored in a flight situation using safety palette and fuzzy constraints. In order to account for all monitored variables, **the hottest color from all partial spectra is selected for the integral safety spectrum at each time instant**.



'Flight' F_{2782}: **'Normal takeoff and initial climb under 'very strong' wind shear conditions'** (flight path angle $\theta_G = 16^o$ and bank angle $\gamma_G = 22.5^o$)'

Partial Safety Spectra (Σ_k)

Legend: Σ_k – partial safety spectrum for variable x_k, $k = 1, \ldots, p$, $p = 20$. Σ – integral safety spectrum. 'a' – airborne. 'g' – ground-roll. {IAS, β, …. δ_r} – system state variables. 🟩🟨🟥⬛▨ – safety palette.

Integral Safety Spectrum (Σ)

Integral Safety Spectrum (Σ) calculation algorithm

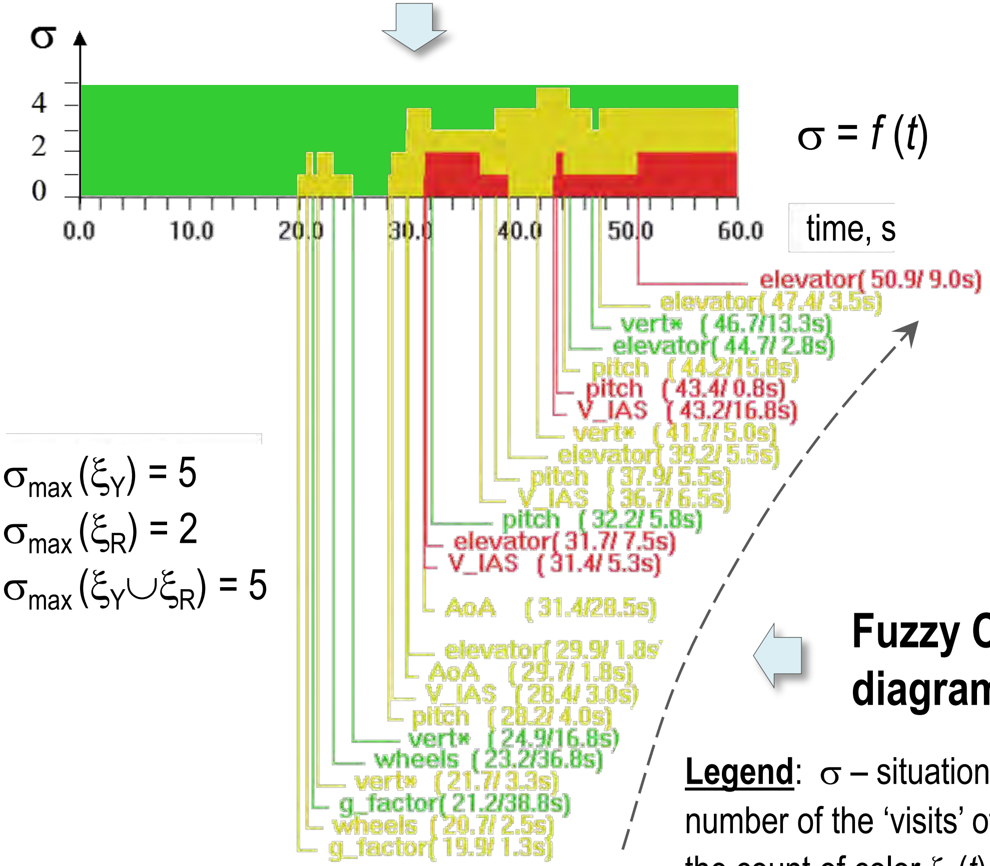
$$(\forall t)\ (t \in [t_*; t^*])\ (\exists \xi\ (x_k(t))\ (\xi(x_k(t)) \in \{\xi_W, \xi_G, \xi_Y, \xi_R, \xi_B, \ldots\} \wedge (\xi_W < \xi_G < \xi_Y < \xi_R < \xi_B))\ (\xi(t) = max\ \xi(x_k(t)),\ k = 1, \ldots, p) \Rightarrow (\xi(t) \in \Sigma \wedge \Sigma = \xi(t_*)\ \|\ \xi(t_* + \Delta)\ \|\ \xi(t_* + 2\Delta)\ \|\ \ldots\ \|\ \xi(t^*))$$

Situation Complexity Build-up Diagram

Situation complexity Index (σ) calculation algorithm

$$(\forall t)\ (t \in [t_*;\ t^*])\ (\xi_k \in \pi)\ (k = \{\mathrm{Y, R, B}, \ldots\})$$
$$(\sigma(t) = N(\xi_{\mathrm{Y}}(t)) + N(\xi_{\mathrm{R}}(t)) + N(\xi_{\mathrm{B}}(t))$$

Situation Complexity Build-up diagram



σ = f (t)

‘Flight’ F_{2782} : ‘Normal takeoff, initial climb at flight path angle θ_G = 16° and bank angle γ_G = 22.5° under ‘very strong’ wind shear conditions’

Situation Complexity Build-up diagram and Fuzzy Constraints Violation & Restoration Sequence diagram contain quantitative and qualitative information about **the severity and the order of violations and restorations** of operational constraints.

$\sigma_{max}(\xi_Y)$ = 5

$\sigma_{max}(\xi_R)$ = 2

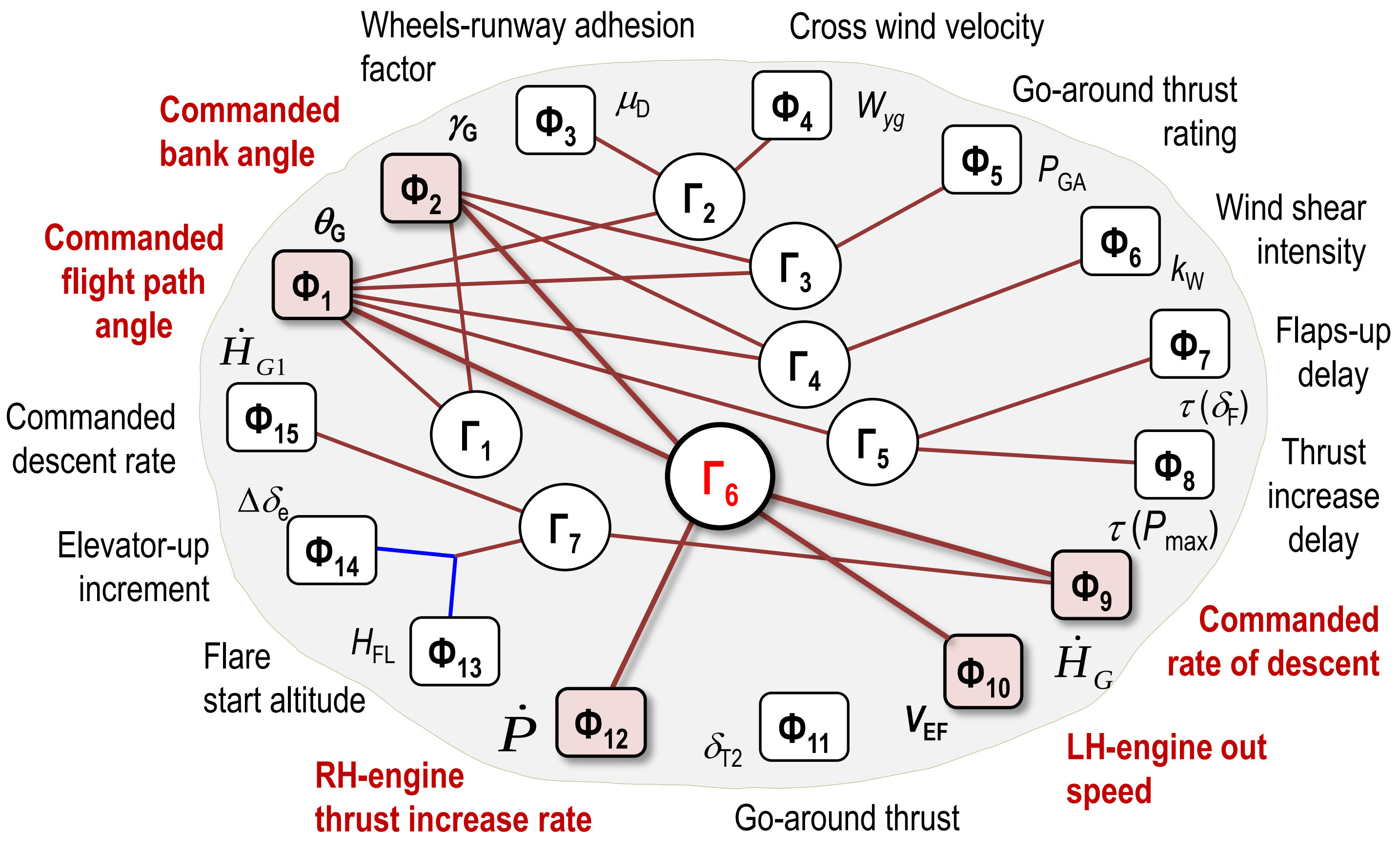
$\sigma_{max}(\xi_Y \cup \xi_R)$ = 5

Fuzzy Constraints Violation & Restoration Sequence diagram

Legend: σ – situation complexity index – the number of fuzzy constraint violations (the total number of the ‘visits’ of a monitored state variable x to zones ξ_Y, ξ_R) at a time instant t. N – the count of color $\xi_k(t)$ at a time instant t, k = {Y, R, B, …}). 🟩🟨🟥⬛ – safety palette (π).

Design Field of Multifactor Operational Risk Hypotheses

2. Structuring Complex / Unknown Operational Domains



In the system dynamics model, **heterogeneous risk factors** (associated with a pilot, automaton, aircraft technical condition and weather) **are combined and treated uniformly** - taking into account the scenario and the desired scope of safety research.

Example of a **five-factor operational hypothesis**:

$$\Gamma_6 = \Phi_9 \times \Phi_1 \times \Phi_2 \times \Phi_{12} \times \Phi_{10} \equiv \dot{H}_G \times \theta_G \times \gamma_G \times \dot{P} \times V_{EF}$$

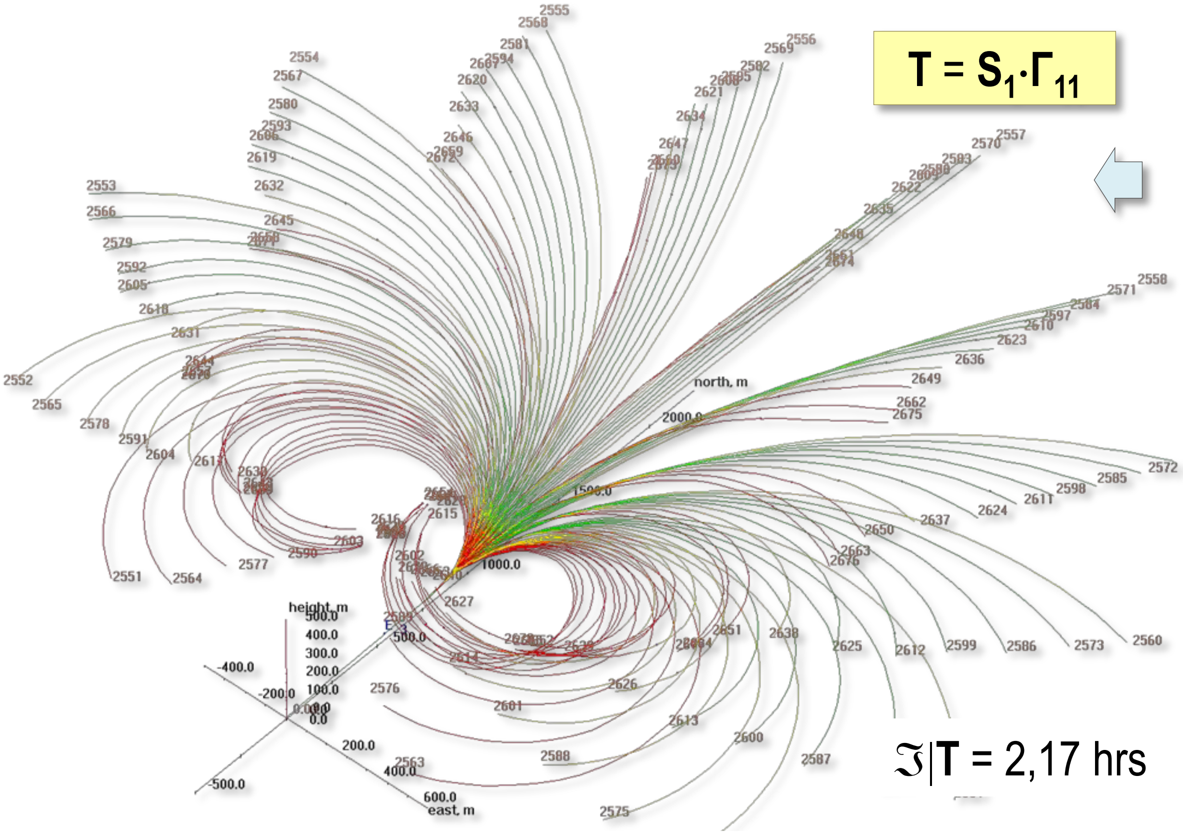
Legend:

Γ_2 - multifactor operational hypothesis.

Φ_4 - safety risk factor.

— — - link between risk factors in Γ: independent and dependent, respectively.

Situational Tree of Flight. Total Virtual Flight Test Time



$\mathbf{T} = \mathbf{S}_1 \cdot \boldsymbol{\Gamma}_{11}$

$\Im|\mathbf{T}$ = 2,17 hrs

Situational tree $\mathbf{T} = \mathbf{S}_1 \cdot \boldsymbol{\Gamma}_{11}$: 'Takeoff. Errors/ variations of selecting commanded flight path angle (θ_G) and commanded bank angle (γ_G) in initial climb' (2-factor domain)

Multifactor operational hypothesis for virtual testing:

$$\boldsymbol{\Gamma}_{11} = \boldsymbol{\Phi}_1 \times \boldsymbol{\Phi}_2$$

'Virtual flight test time' - total flight test hours (TFTH) - accumulated in tree **T**, hrs:

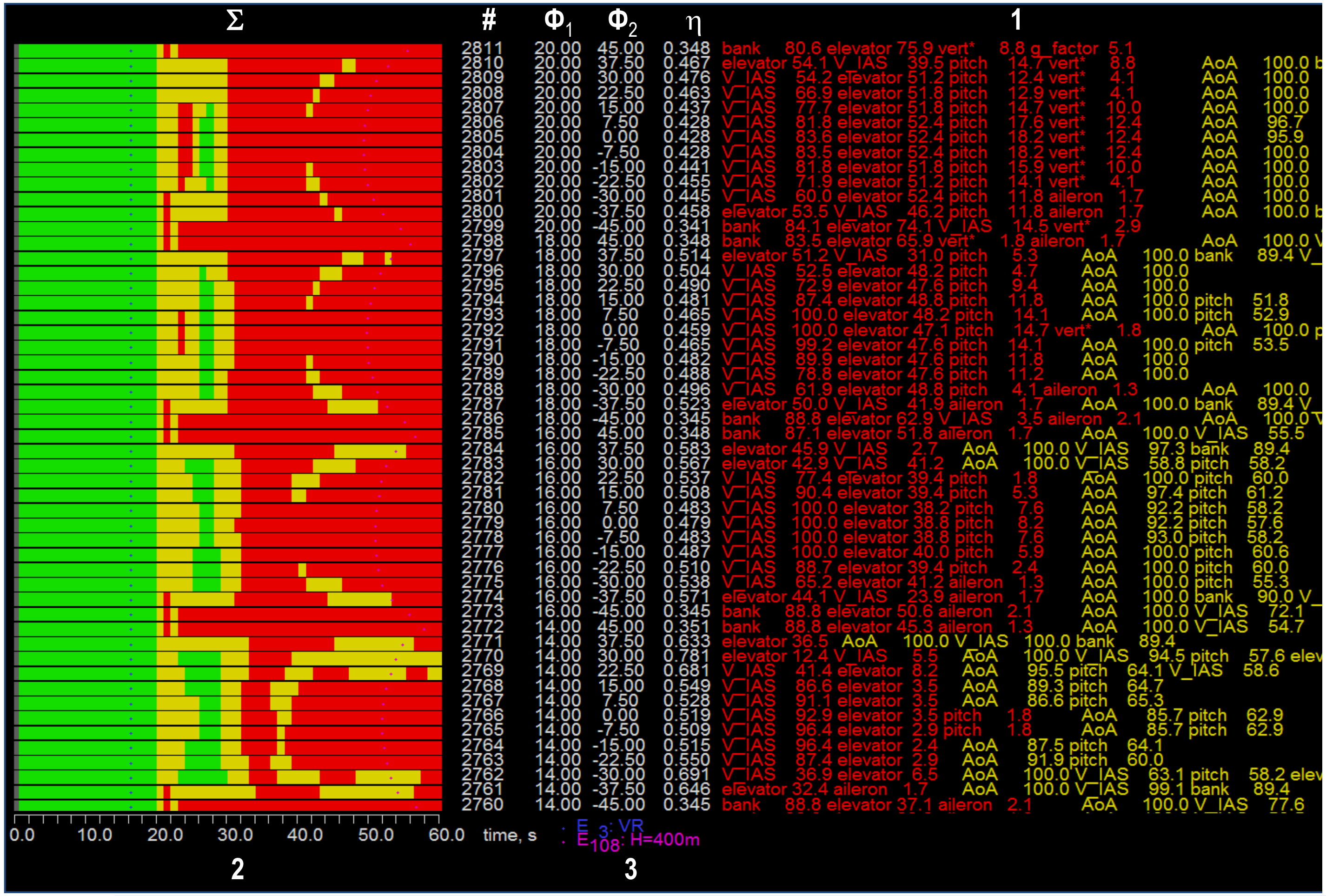
$$\Im \mid \boldsymbol{T} = \sum_{i=1}^{N(\boldsymbol{T})} \Delta t(\mathbf{B}_i) \cdot 3600^{-1}$$

Legend: $\mathbf{T} = \mathbf{S}_1 \cdot \boldsymbol{\Gamma}_{11}$ – situational tree, $\mathbf{T} = \{ \boldsymbol{F}_{2551}, \ldots, \boldsymbol{F}_{2680} \}$, $\boldsymbol{F}_k$ – 'flight', k = 2551, …, 2680, $\boldsymbol{F}_k \equiv \mathbf{B}_i$, $\mathbf{B}_i$ – branch in tree **T**, $\Delta t(\boldsymbol{B}_i)$ = 60 s – branch 'length' [s], i = 1, …, N(**T**), N(**T**) = 130 – total number of branches in tree, $\mathbf{S}_1$ – baseline situation scenario: 'Takeoff and initial climb', $\boldsymbol{\Gamma}_{11} = \boldsymbol{\Phi}_1 \times \boldsymbol{\Phi}_2$ – tree's genotype (tested operational hypothesis), $\boldsymbol{\Phi}_j$ – risk factor, $\boldsymbol{\Phi}_1 \equiv \theta_G$, $\boldsymbol{\Phi}_2 \equiv \gamma_G$, θ_G – commanded flight path angle, $\theta_G \in \{2^o, 4^o, \ldots, 20^o\}$, γ_G – commanded bank angle, $\gamma_G \in \{-45^o, -37.5^o, \ldots, +45^o\}$, (north, east, height) ≡ (N, E, H) – Earth frames, 🟩🟨🟥⬛ – safety palette.

A multifactor tree represents 'what-if neighborhood' (off-nominal derivative situations) built around a baseline situation in fast-time experiments without a real research pilot in simulation loop.

Integral Safety Spectra (‘Carpet’). Examined Risk Factors. Flight Safety Indices. Fuzzy Constraints Violation Statistics

2. Structuring Complex / Unknown Operational Domains



```
 #     Φ1     Φ2     η      1
2811  20.00  45.00  0.348  bank     80.6 elevator 75.9 vert*    8.8 g_factor  5.1
2810  20.00  37.50  0.467  elevator 54.1 V_IAS    39.5 pitch   14.7 vert*     8.8           AoA   100.0 b
2809  20.00  30.00  0.476  V_IAS    54.2 elevator 51.2 pitch   12.4 vert*     4.1           AoA   100.0
2808  20.00  22.50  0.463  V_IAS    66.9 elevator 51.8 pitch   12.9 vert*     4.1           AoA   100.0
2807  20.00  15.00  0.437  V_IAS    77.7 elevator 51.8 pitch   14.7 vert*    10.0           AoA   100.0
2806  20.00   7.50  0.428  V_IAS    81.8 elevator 52.4 pitch   17.6 vert*    12.4           AoA    96.7
2805  20.00   0.00  0.428  V_IAS    83.6 elevator 52.4 pitch   18.2 vert*    12.4           AoA    95.9
2804  20.00  -7.50  0.428  V_IAS    83.5 elevator 52.4 pitch   18.2 vert*    12.4           AoA   100.0
2803  20.00 -15.00  0.441  V_IAS    81.8 elevator 51.8 pitch   15.9 vert*    10.0           AoA   100.0
2802  20.00 -22.50  0.455  V_IAS    71.9 elevator 51.2 pitch   14.1 vert*     4.1           AoA   100.0
2801  20.00 -30.00  0.445  V_IAS    60.0 elevator 52.4 pitch   11.8 aileron   1.7           AoA   100.0
2800  20.00 -37.50  0.458  elevator 53.5 V_IAS    46.2 pitch   11.8 aileron   1.7           AoA   100.0 b
2799  20.00 -45.00  0.341  bank     84.1 elevator 74.1 V_IAS   14.5 vert*     2.9
2798  18.00  45.00  0.348  bank     83.5 elevator 65.9 vert*    1.8 aileron   1.7           AoA   100.0 V
2797  18.00  37.50  0.514  elevator 51.2 V_IAS    31.0 pitch    5.3      AoA   100.0 bank    89.4 V_
2796  18.00  30.00  0.504  V_IAS    52.5 elevator 48.2 pitch    4.7      AoA   100.0
2795  18.00  22.50  0.490  V_IAS    72.9 elevator 47.6 pitch    9.4      AoA   100.0
2794  18.00  15.00  0.481  V_IAS    87.4 elevator 48.8 pitch   11.8      AoA   100.0 pitch   51.8
2793  18.00   7.50  0.465  V_IAS   100.0 elevator 48.2 pitch   14.1      AoA   100.0 pitch   52.9
2792  18.00   0.00  0.459  V_IAS   100.0 elevator 47.1 pitch   14.7 vert*     1.8           AoA   100.0 p
2791  18.00  -7.50  0.465  V_IAS    99.2 elevator 47.6 pitch   14.1      AoA   100.0 pitch   53.5
2790  18.00 -15.00  0.482  V_IAS    89.9 elevator 47.6 pitch   11.8      AoA   100.0
2789  18.00 -22.50  0.488  V_IAS    78.8 elevator 47.6 pitch   11.2      AoA   100.0
2788  18.00 -30.00  0.496  V_IAS    61.9 elevator 48.8 pitch    4.1 aileron   1.3           AoA   100.0
2787  18.00 -37.50  0.523  elevator 50.0 V_IAS    41.9 aileron  1.7      AoA   100.0 bank    89.4 V
2786  18.00 -45.00  0.345  bank     88.8 elevator 62.9 V_IAS    3.5 aileron   2.1           AoA   100.0 V
2785  16.00  45.00  0.348  bank     87.1 elevator 51.8 aileron  1.7      AoA   100.0 V_IAS   55.5
2784  16.00  37.50  0.583  elevator 45.9 V_IAS     2.7   AoA   100.0 V_IAS   97.3 bank    89.4
2783  16.00  30.00  0.567  elevator 42.9 V_IAS    41.2   AoA   100.0 V_IAS   58.8 pitch   58.2
2782  16.00  22.50  0.537  V_IAS    77.4 elevator 39.4 pitch    1.8      AoA   100.0 pitch   60.0
2781  16.00  15.00  0.508  V_IAS    90.4 elevator 39.4 pitch    5.3      AoA    97.4 pitch   61.2
2780  16.00   7.50  0.483  V_IAS   100.0 elevator 38.2 pitch    7.6      AoA    92.2 pitch   58.2
2779  16.00   0.00  0.479  V_IAS   100.0 elevator 38.8 pitch    8.2      AoA    92.2 pitch   57.6
2778  16.00  -7.50  0.483  V_IAS   100.0 elevator 38.8 pitch    7.6      AoA    93.0 pitch   58.2
2777  16.00 -15.00  0.487  V_IAS   100.0 elevator 40.0 pitch    5.9      AoA   100.0 pitch   60.6
2776  16.00 -22.50  0.510  V_IAS    88.7 elevator 39.4 pitch    2.4      AoA   100.0 pitch   60.0
2775  16.00 -30.00  0.538  V_IAS    65.2 elevator 41.2 aileron  1.3      AoA   100.0 pitch   55.3
2774  16.00 -37.50  0.571  elevator 44.1 V_IAS    23.9 aileron  1.7      AoA   100.0 bank    90.0 V_
2773  16.00 -45.00  0.345  bank     88.8 elevator 50.6 aileron  2.1      AoA   100.0 V_IAS   72.1
2772  14.00  45.00  0.351  bank     88.8 elevator 45.3 aileron  1.3      AoA   100.0 V_IAS   54.7
2771  14.00  37.50  0.633  elevator 36.5  AoA    100.0 V_IAS  100.0 bank    89.4
2770  14.00  30.00  0.781  elevator 12.4 V_IAS     5.5   AoA   100.0 V_IAS   94.5 pitch   57.6 elev
2769  14.00  22.50  0.681  V_IAS    41.4 elevator  8.2   AoA    95.5 pitch   64.1 V_IAS   58.6
2768  14.00  15.00  0.549  V_IAS    86.6 elevator  3.5   AoA    89.3 pitch   64.7
2767  14.00   7.50  0.528  V_IAS    91.1 elevator  3.5   AoA    86.6 pitch   65.3
2766  14.00   0.00  0.519  V_IAS    92.9 elevator  3.5 pitch    1.8      AoA    85.7 pitch   62.9
2765  14.00  -7.50  0.509  V_IAS    96.4 elevator  2.9 pitch    1.8      AoA    85.7 pitch   62.9
2764  14.00 -15.00  0.515  V_IAS    96.4 elevator  2.4   AoA    87.5 pitch   64.1
2763  14.00 -22.50  0.550  V_IAS    87.4 elevator  2.9   AoA    91.9 pitch   60.0
2762  14.00 -30.00  0.691  V_IAS    36.9 elevator  6.5   AoA   100.0 V_IAS   63.1 pitch   58.2 elev
2761  14.00 -37.50  0.646  elevator 32.4 aileron   1.7   AoA   100.0 V_IAS   99.1 bank    89.4
2760  14.00 -45.00  0.345  bank     88.8 elevator 37.1 aileron  2.1      AoA   100.0 V_IAS   77.6
```

Subset of flights {F_{2760}, …, F_{2811}} from tree S_1 $\cdot\Gamma(\Phi_1\times\Phi_2\times\Phi_3)$: **‘Normal takeoff and initial climb, ‘very strong’ wind-shear, variations of commanded flight path and bank angles’**

Legend: **1** – fuzzy constraint violation messages. **2** – flight time scale. **3** – events (**E**$_3$ and **E**$_{108}$ ≡ E$_{12}$. **Φ**$_1$ – value of risk factor ‘commanded flight path angle Θ_G’, $_G\in\{14^o, …, 20^o\}$. **Φ**$_2$ – value of risk factor commanded bank angle γ_G’, $\gamma_G\in\{-45^o, …, +45^o\}$. **Φ**$_3$ – risk factor ‘wind shear (W_{xg}, W_{zg} = $f(t)$)’. # - ‘flight’ code. Σ - integral safety spectrum; η – safety index. 🟩🟨🟥⬛ – safety palette. (*) first introduced by Dr. J.-P. Cachelet, AIRBUS.

Integra Safety Spectra (‘Carpet’ (*)) knowledge map is used to quantify safety levels of ‘flights’, spot anomalies in the system dynamics, study **causal, instrumental and temporal logic links** between specific combinations of risk factors and violations of operational constraints.

Flight Situations Safety Classification Categories

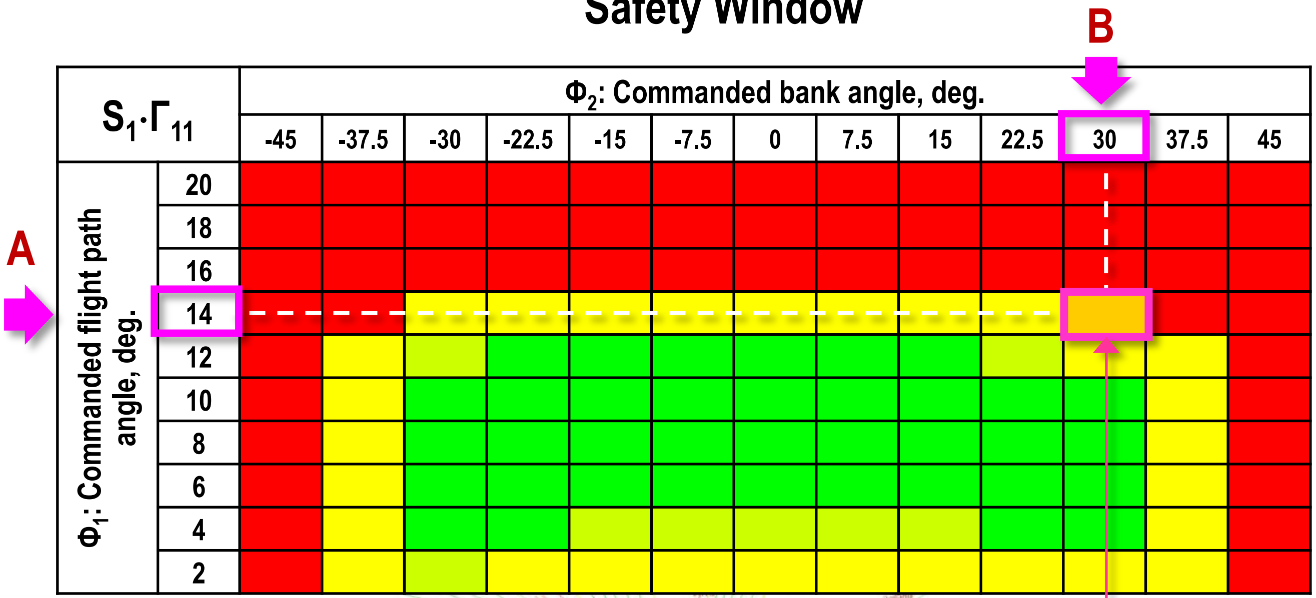
Color	Code	Name	Classification criterion
Green	I	Safe	The system state resides mainly inside the 'green' zone. The system state may stay, *for a short period of time* - as a maximum, in close proximity to the operational constraints, i.e. inside the ‘yellow’ zone.
Salad	II-A	Conditionally Safe - A	The system state may stay temporarily, *for a medium period of time* - as a maximum, in close proximity to the operational constraints, i.e. inside the ‘yellow’ zone.
Yellow	II-B	Conditionally Safe - B	The system state may stay *for a long period of time* - as a maximum, in close proximity to the operational constraints, i.e. inside the ‘yellow’ zone.
Orange	III	Potentially Unsafe	The system state may violate operational constraints, i.e. enter the ‘red’ zone, *for a short or between short and medium period of time* - as a maximum.
Red	IV	Dangerous (prohibited)	The system state may stay beyond the operational constraints, i.e. inside the ‘red’ zone, *for a medium or long period of time* - as a maximum, or till the end of the situation.
Black	V	Catastrophic (‘chain reaction’)	There is at least one (i.e. *for a very short time*) occurrence of the violation of any operational constraint on the ‘black’ level.

This safety evaluation scale enables automatic partitioning/ clustering of a tree of what-if flight situations into six safety classification categories – depending on the color-coding structure of the integral safety spectra of its branches (‘flights’).

Safety Window. Safety Chances Distribution Pie Chart

Tree T = $S_1 \cdot \Gamma_{11}$: ‘Takeoff. Errors/ variations of commanded flight path and bank angles in initial climb’

Safety Window



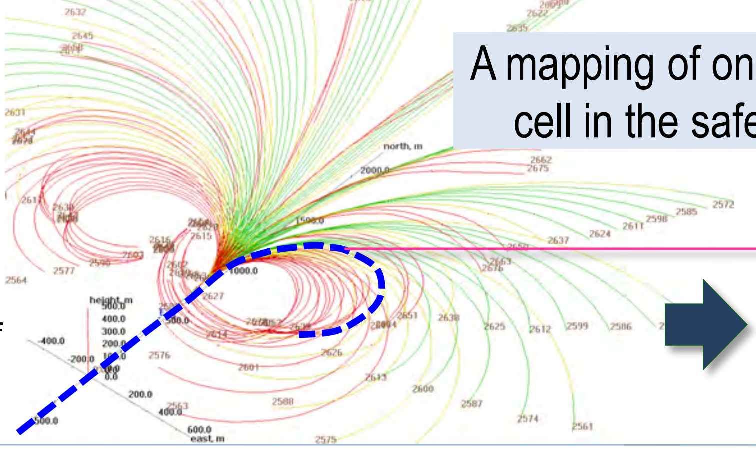
$S_1 \cdot \Gamma_{11}$		Φ_2: Commanded bank angle, deg.												
		-45	-37.5	-30	-22.5	-15	-7.5	0	7.5	15	22.5	30	37.5	45
Φ_1: Commanded flight path angle, deg.	20	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥
	18	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥
	16	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥
	14	🟥	🟥	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟧	🟥	🟥
	12	🟥	🟨	🟢	🟩	🟩	🟩	🟩	🟩	🟩	🟢	🟨	🟨	🟥
	10	🟥	🟨	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟨	🟥
	8	🟥	🟨	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟨	🟥
	6	🟥	🟨	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟨	🟥
	4	🟥	🟨	🟩	🟩	🟢	🟢	🟢	🟢	🟢	🟩	🟩	🟨	🟥
	2	🟥	🟨	🟢	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟥

Safety Chances Distribution

Category	ξ^j	n^j	χ^j, %
I	🟩	37	28
II-a	🟢	8	6
II-b	🟨	29	22
III	🟧	1	1
IV	🟥	55	43
V	⬛	0	0
$\Sigma n^j, \Sigma \chi^j \mid S_1 \cdot \Gamma_{11}$		130	100

$$\chi^j = \frac{n^j}{N(\boldsymbol{T})} \cdot 100\,[\%]$$

<u>Legend</u>: **A** – commanded flight path angle (14°) and **B** – commanded bank angle (30°) of branch $\mathbf{B}_{89}$ (‘flight’ F_{2639}) from tree **T** = $\mathbf{S_1 \cdot \Gamma_{11}}$. N(**T**) – number if flights in tree **T**. ξ^j – safety category color, j = **I**, **II**, ,,, **V**. n^j – number of ‘flights’ of category ξ^j. χ^j – percentage of n^j in N(**T**). 🟩🟢🟨🟧🟥⬛ – safety categories.



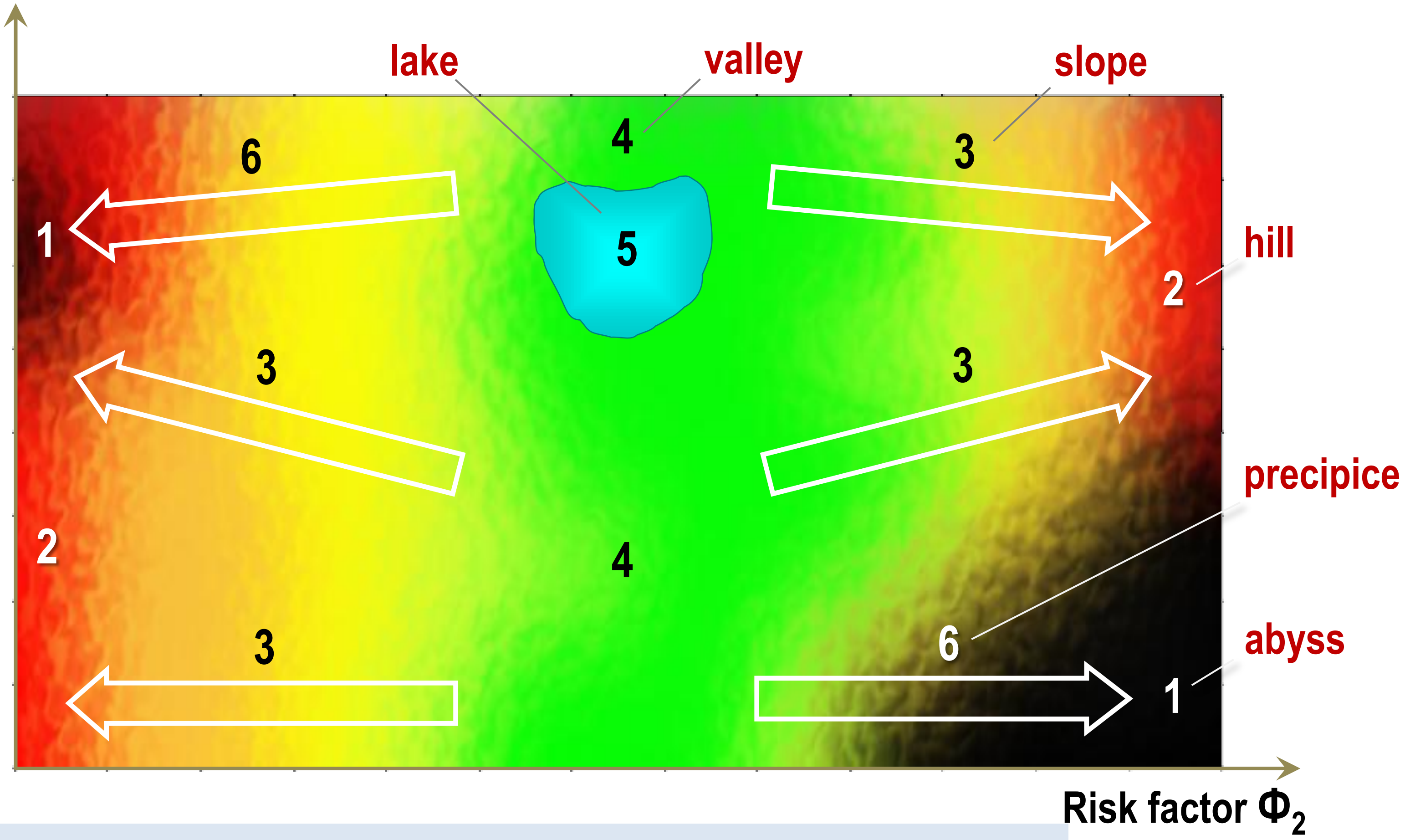
A mapping of one branch is a cell in the safety window

A mapping of safety categories of all ‘flights’ from a ‘what-if’ tree onto the plane with coordinates of two selected risk factors (in this case $\mathbf{\Phi_1}$ and $\mathbf{\Phi_2}$) is called **Safety Window**.

Safety Topology

2. Structuring Complex / Unknown Operational Domains

Safety topology of a complex flight domain is derived **from a fuzzified version of the domain's safety window**. In general, **six main object types of the safety 'topology'** can be found in a safety window:



Legend: Main object types of safety 'topology': **1** - 'abyss' (**catastrophe**), **2** - 'hill' (**danger**), **3** - 'slope' (**reversible transitions**), **4** - 'valley' (standard safety, **norm**), **5** - 'lake' (maximum safety, **optimum**), **6** - 'precipice' (chain reaction, abrupt/ **irreversible transitions**). 🟩🟨🟨🟧🟥⬛ – safety palette (color codes of flight safety categories **I**, **II-a**, **II-b**, **III**, **IV**, **V**, respectively).

Reversible transitions 3 must be known and **controlled**. **Abrupt/ irreversible transitions 6** must be known and **prevented** !

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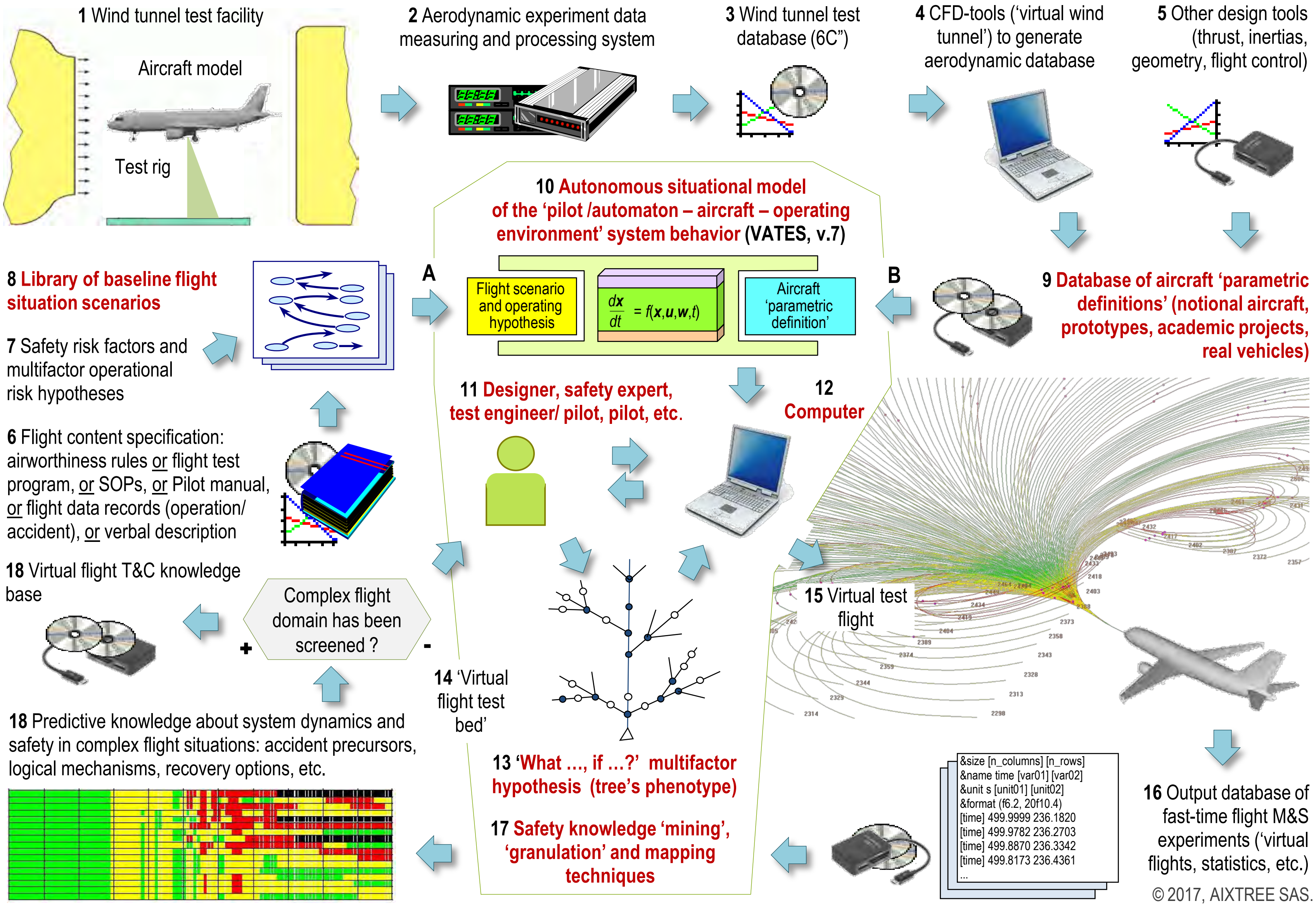
Virtual Autonomous Fast-Time Flight Exploration Cycle for Safety



1 Wind tunnel test facility

2 Aerodynamic experiment data measuring and processing system

3 Wind tunnel test database (6C")

4 CFD-tools ('virtual wind tunnel') to generate aerodynamic database

5 Other design tools (thrust, inertias, geometry, flight control)

10 Autonomous situational model of the 'pilot /automaton – aircraft – operating environment' system behavior (VATES, v.7)

Flight scenario and operating hypothesis

$$\frac{dx}{dt} = f(\mathbf{x},\mathbf{u},\mathbf{w},t)$$

Aircraft 'parametric definition'

8 Library of baseline flight situation scenarios

7 Safety risk factors and multifactor operational risk hypotheses

9 Database of aircraft 'parametric definitions' (notional aircraft, prototypes, academic projects, real vehicles)

11 Designer, safety expert, test engineer/ pilot, pilot, etc.

12 Computer

6 Flight content specification: airworthiness rules or flight test program, or SOPs, or Pilot manual, or flight data records (operation/ accident), or verbal description

18 Virtual flight T&C knowledge base

Complex flight domain has been screened ?

\+ -

15 Virtual test flight

14 'Virtual flight test bed'

18 Predictive knowledge about system dynamics and safety in complex flight situations: accident precursors, logical mechanisms, recovery options, etc.

13 'What ..., if ...?' multifactor hypothesis (tree's phenotype)

17 Safety knowledge 'mining', 'granulation' and mapping techniques

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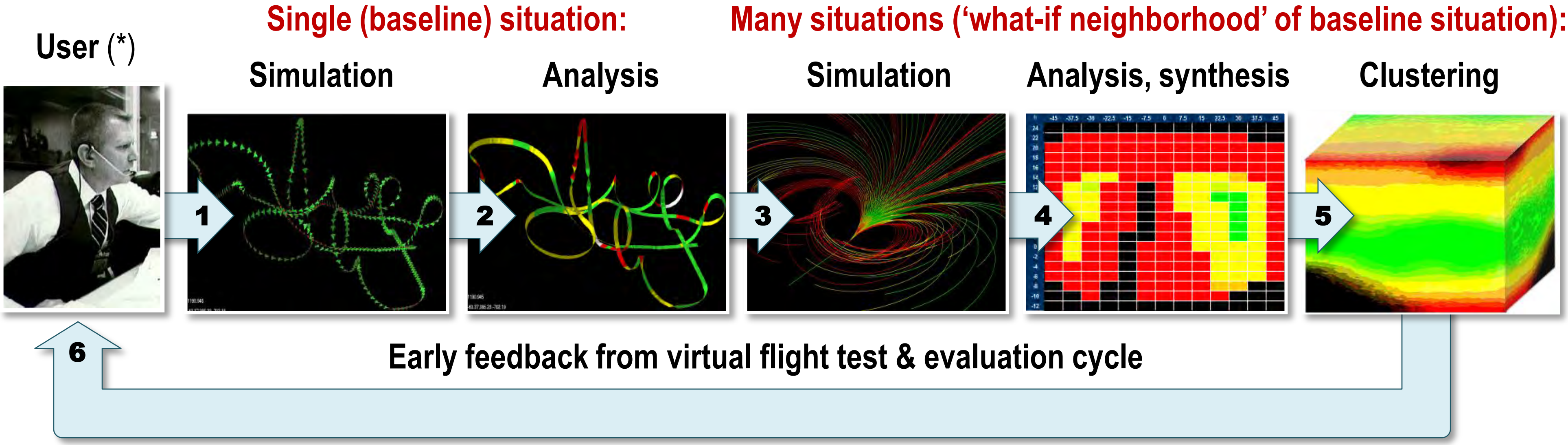
[time] 499.8173 236.4361
...
```

16 Output database of fast-time flight M&S experiments ('virtual flights, statistics, etc.)

Purpose of VFTC Technology

ISAFE methodology - **formalization of M&S and AI based approach** to predictive safety research into complex/ unknown operational domains of flight through lifecycle.

VATES software tool - **autonomous fast-time flight simulation**, knowledge extraction, generalization and representation for a large set of multifactor operational cases (‘flights’).



Single (baseline) situation:

Many situations (‘what-if neighborhood’ of baseline situation):

User (*)

Simulation

Analysis

Simulation

Analysis, synthesis

Clustering

Early feedback from virtual flight test & evaluation cycle

The purpose of VFTC technology is to help exploring off-nominal (multifactor) flight situations for safety - quickly, affordably and efficiently - before aircraft is built or flown.

Legend: (*) - major user categories: designer (aerodynamics, powerplant, flight control, etc.), test pilot/ engineer, regulator, instructor/ educator/ student/ line pilot/ operator, safety engineer/ manager, investigator/ researcher.

Photo Gallery of Aircraft and Design Projects - VFTC Technology Validation and Application Experience

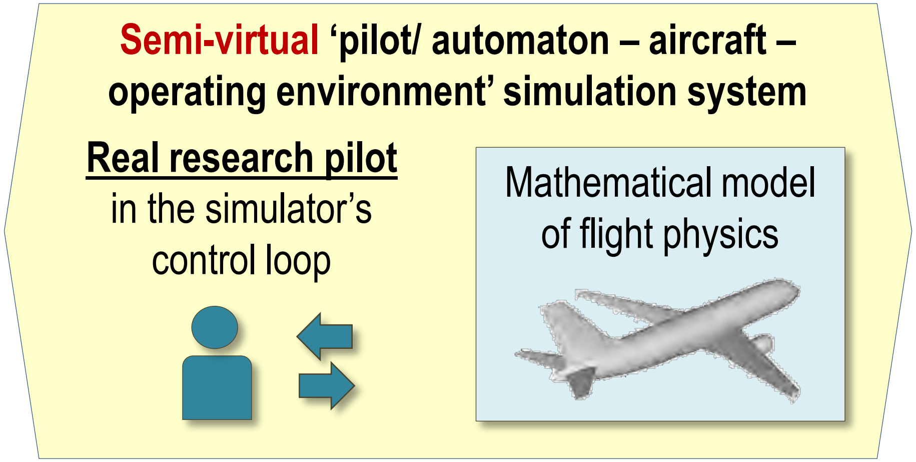
 **A400M Prototype** (FLA F-93A) Military Transport Project	 Advanced **Hypersonic Maneuvering Aerospace Plane** Project	 Notional **4++ Generation Highly-Maneuverable** (TVC) Airplane Project	 'Kasatka' Amphibious **Wing-In-Ground Experimental Vehicle** Project	 **Antonov-28** Commuter Airplane	 **Beriev-103** Amphibious General Aviation Airplane
 **Boeing-737**-300 Medium-Range Airplane	 **Buran** Hypersonic Aerospace Vehicle	 Cessna **Citation X** Business Jet	 **Concorde** Supersonic Passenger Airplane	 High-Speed Civil Transport (**HSCT**) Project	 **L-610** Let Short-Range Airplane
 **Ilyushin-114** Regional Transport/ Cargo Airplane	 **Ilyushin-62**M Long-Range Airliner	 **Ilyushin-86** Medium-Range Wide-Body Airplane	 **Ilyushin-96-300** Wide-Body Long-Range Airliner	 **Kamov-32** Multi-Purpose Helicopter	 **Mil-26** Heavy-Lift Helicopter
 **Mil-8** Medium Multi-Purpose Helicopter	 **Sukhoi-38** Agricultural Airplane	 **Sukhoi-49** Primary Training Airplane Project	 **Sukhoi-80GP** Multi-Purpose Commuter Airplane	 **SSBJ** Supersonic Business Jet Project	 **Tupolev-134A/B** Regional Airplane
 **Tupolev-154/ -154M** Medium-Range Airplane	 **Tupolev-136** Medium-Range (LNG Fuel) Airplane Project	 **Tupolev-204/ -214** Medium-Range Airplane	 **Tupolev-334-100** Regional Airplane	 **XV-15** Bell Helicopter Textron Tilt-Rotor	 **Yakovlev-40** Commuter Airplane

The VFTC technology has a proven track record of successful validations and applications for 30+ aircraft types and design projects since 1975 – see http://axtree-eng.mcdir.ru/np/01.pdf.

Manned Real-Time vs. Autonomous Fast-Time Flight Simulation In Safety Studies

3. Virtual Fast-Time Flight Exploration Process

Piloted (manned) real-time simulation of single flight situations



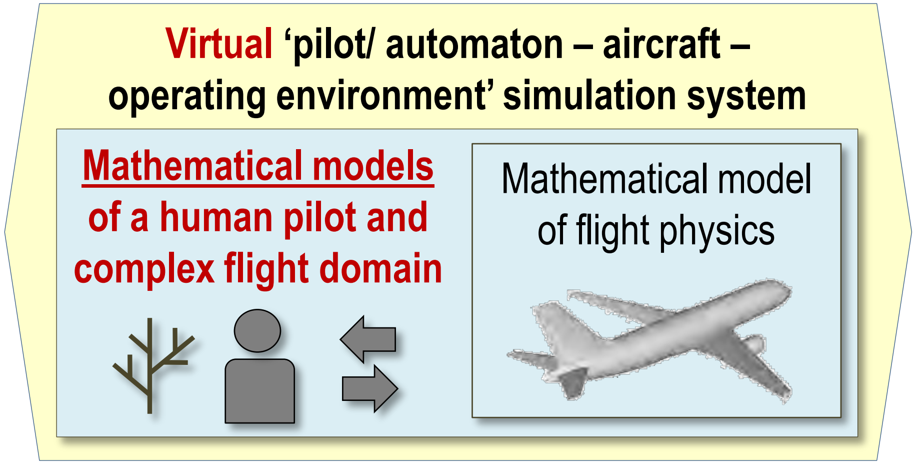
Semi-virtual 'pilot/ automaton – aircraft – operating environment' simulation system

Real research pilot in the simulator's control loop

Mathematical model of flight physics

1 hour of simulation experiment ≡ 1 hour of semi-virtual 'flight' (gaining 1 hour-equivalent new knowledge about flight safety in a single situation)

Autonomous (without a research pilot) fast-time simulation of multifactor flight domains



Virtual 'pilot/ automaton – aircraft – operating environment' simulation system

Mathematical models of a human pilot and complex flight domain

Mathematical model of flight physics

1 hour of simulation experiment ≡ 200+ hours of virtual 'flights' (gaining 200+ hours-equivalent new knowledge about flight safety in many situations)

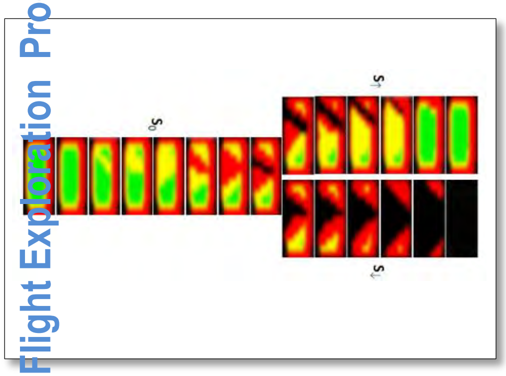
Flight research functions automated by means of VFTC technology:

- **planning** – baseline scenarios and multifactor risk hypotheses
- **piloting** – a human pilot's control according to a predefined scenario
- **exploring** – complex operational domain in the form of a what-if flightpath tree
- **mining & mapping** – safety related knowledge derived from virtual 'flights'.

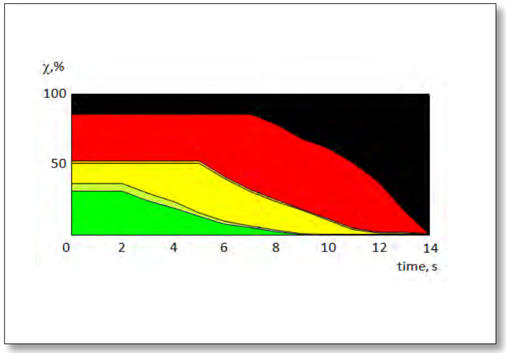
Knowledge Maps: Single Situation Analysis and Multiple Situations Analysis (Selected Examples)

3. Virtual Fast-Time Flight Exploration Process

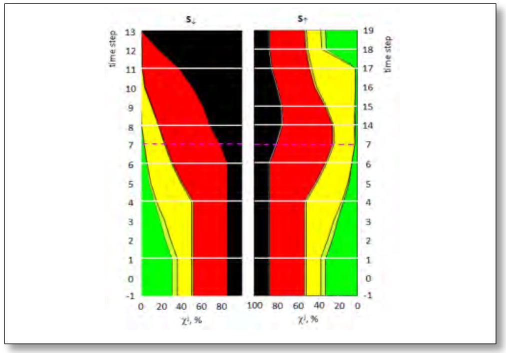
Dynamic Safety Window Tree



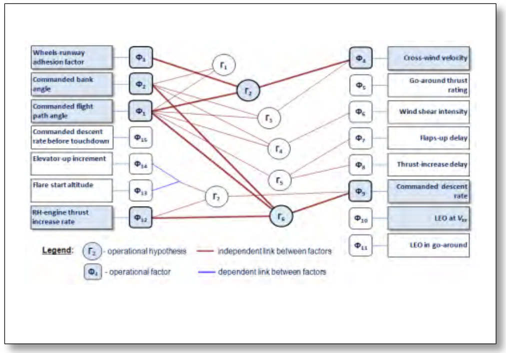
Safety Chances Distribution Time-history



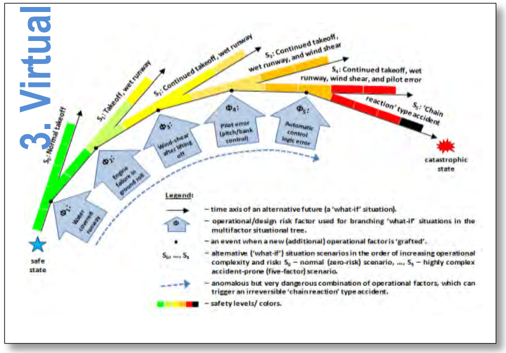
Family of Safety Chances Distribution Time-histories



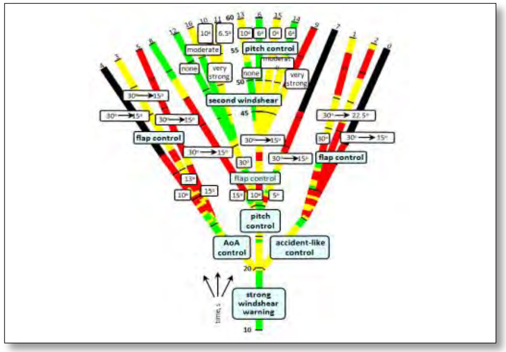
Multifactor Hypothesis Design Field



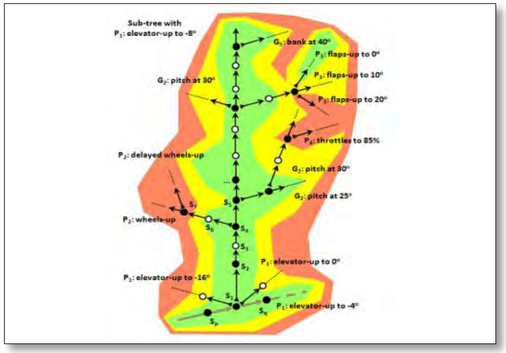
Multifactor Effect What-if Analysis Map



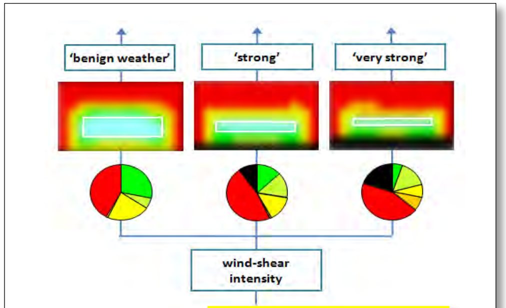
Situational Forecast Display (concept, 1998)



Situational Forecast Display (concept, 1998)



Safety-Optimal Control Advisory Display (concept)



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Single Situation In-Depth Analysis for Regional and Medium-Range Jets: Examined Risk Factors and Flight Phases (Overview)

Examined Risk Factors (Selected Examples)

SUBSETS

GROUPS

Aircraft state variations

- Weight
- Centre of gravity
- Aerodynamic configuration (takeoff, landing, interim, clean)

Onboard system failures

- Critical engine
- Wheel brakes
- Hydraulic system # 1
- Hydraulic system # 3
- Thrust reversers, including asymmetric cases

Demanding external conditions

- Cross-wind, wind shear
- Vertical gusts, vortex ring
- Aerodrome elevation
- Atmospheric turbulence
- Wet/ water-/ ice-covered/ runway

Pilot tactic errors/ variations

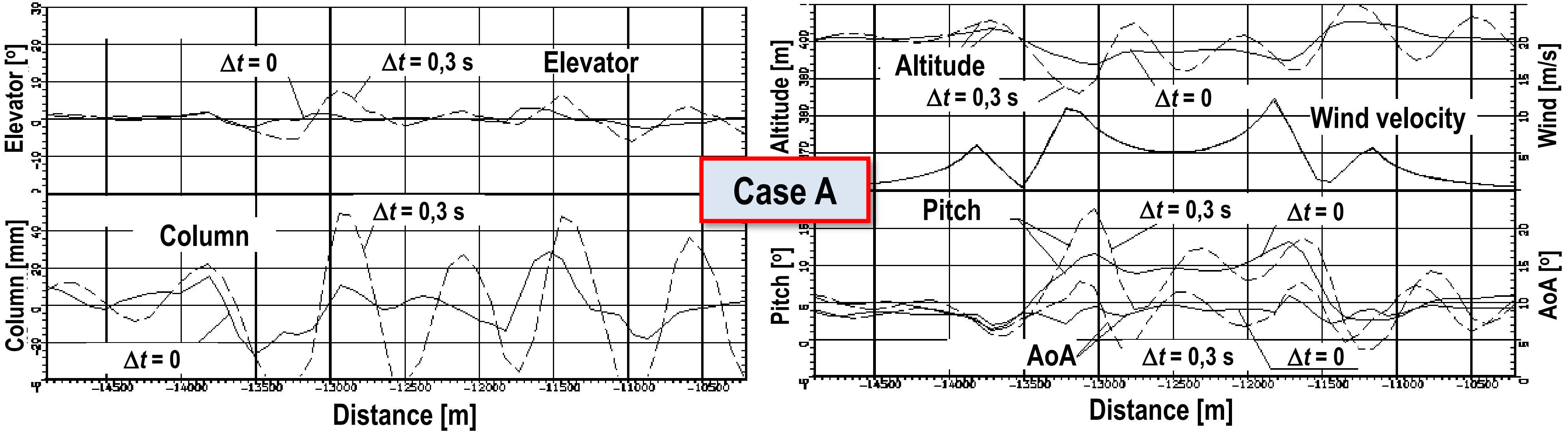
- Pilot inattention/ fatigue (attitude and thrust control)
- Delay in commencing piloting tasks
- Engine-out recognition delay
- Pilot response delay to event
- A/c observed state vector
- Use of auxiliary inputs from Electronic flight control system (EFCS - АСШУ)
- Differential control of thrust reversers
- Differential control by interceptors and wheel brakes
- Pilot Manual tactics
- Landing approach speed
- Other risk factors

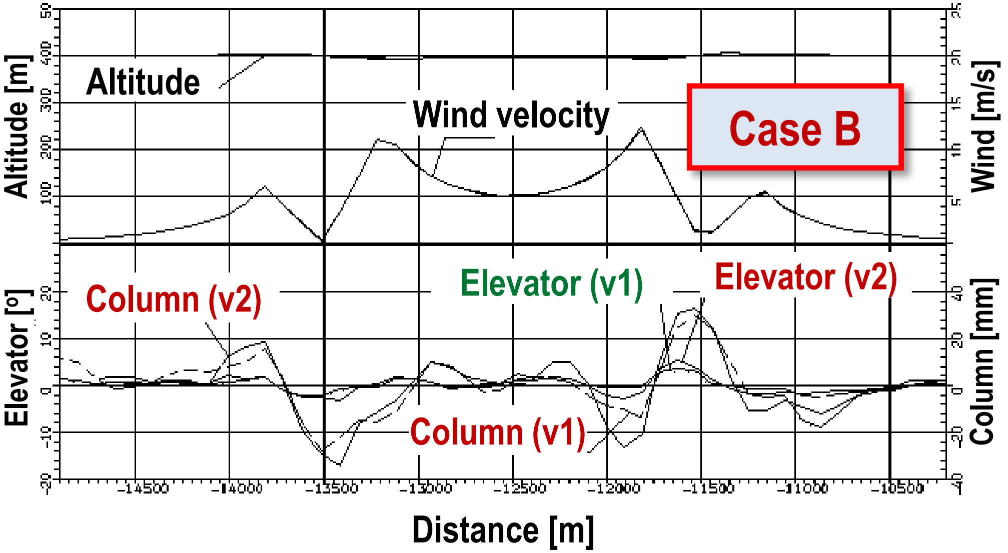
A/c types	**New regional jet. New medium-range jet**
Examined phases of flight	**All phases:** Takeoff, including groundroll. Continued takeoff. Aborted takeoff. Initial climb. Cruise/ level flight. Descent. Landing approach. Go-around. Landing, groundroll.

FSSP (VATES v.5 prototype) and VATES v.5 software tools were used in this research examples.

Medium-Range Jet. Low-Altitude Flight, Crossing Vortex Ring. Effects of Pilot Inattention/ Fatigue on Altitude-Hold Accuracy

4. Single Situation Analysis





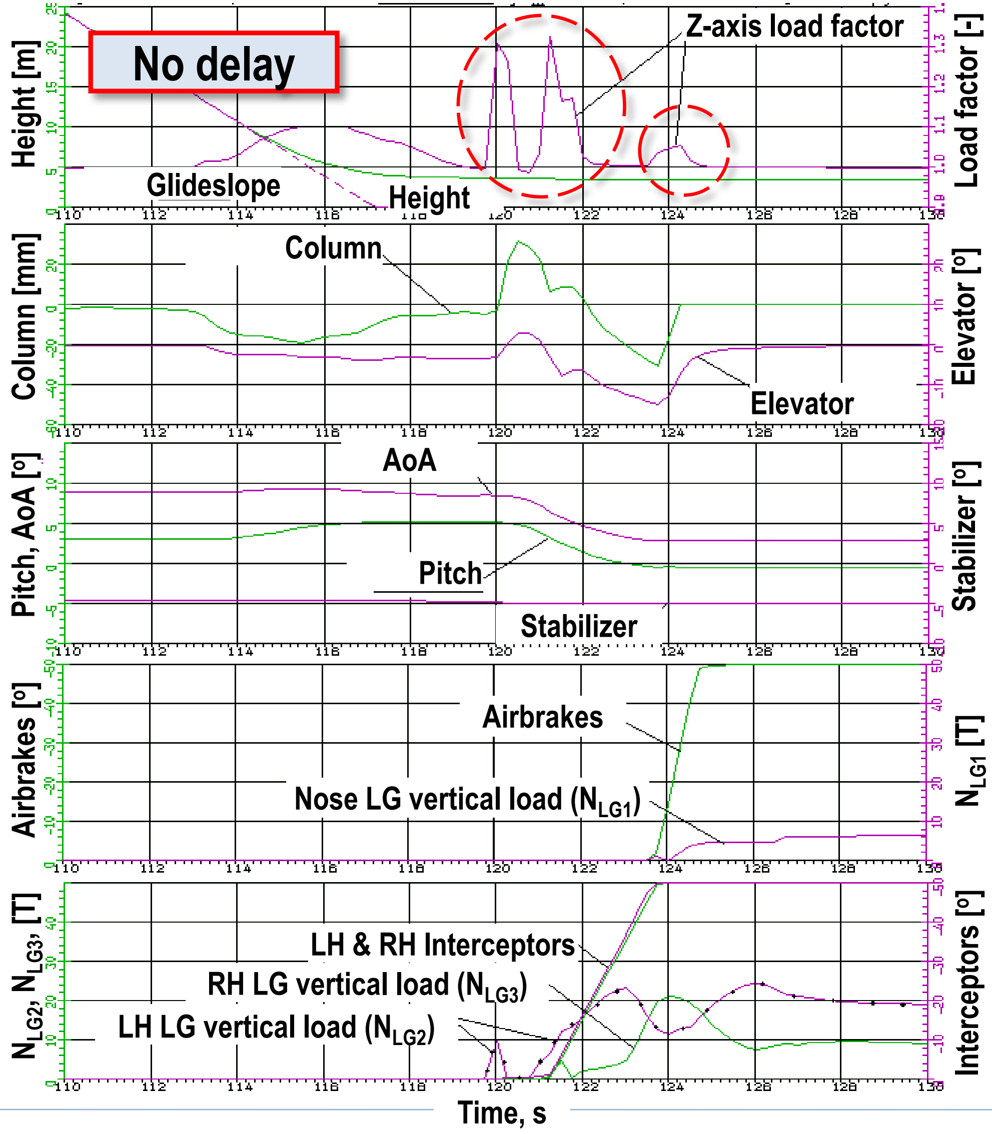
Pilot model parameters

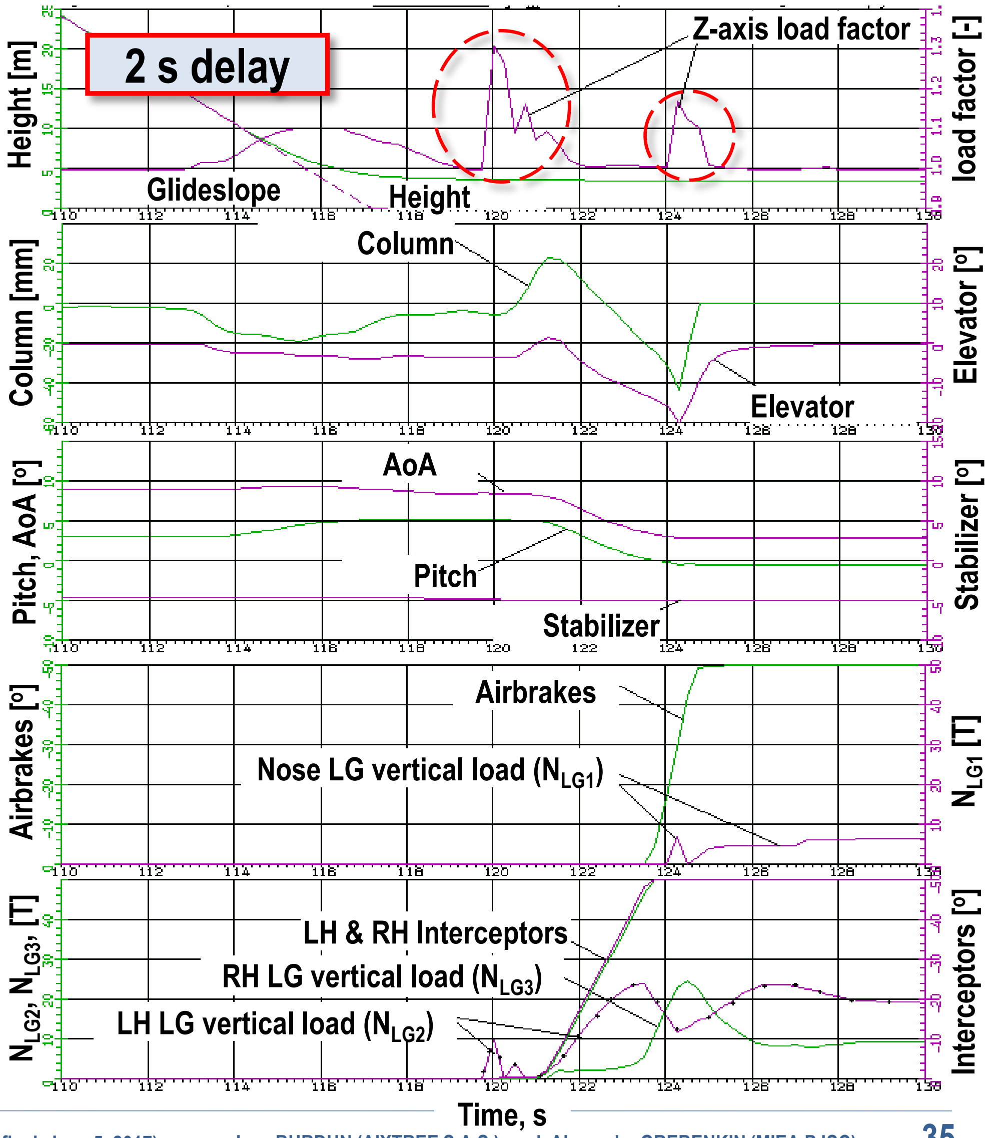
Piloting tactics	Pilot physical condition	Case A	Case B		
		Piloting model time increment, s	Vertical rate (observer), m/s		
			insensitivity margin		maximum error limit
Vigilant	Rested	0	0	v1	0
Negligent	Tired	0,3	| 0,1 |	v2	| 0,5 |

➡ The system dynamics model helps **develop/ refine quantitative recommendations on piloting goals and constraints** in off-nominal conditions.

Regional Jet. Landing: High-Elevation Aerodrome, Crosswind 15 m/s. Effect of Pilot Action Delay in Airborne-to-Ground Control

Weight = 31 tons, C.G.= 24%, δ_F / δ_S = 23°/ 27°, W_Y = 15 m/s, $H_{R/W}$ = 3000 m, dry runway



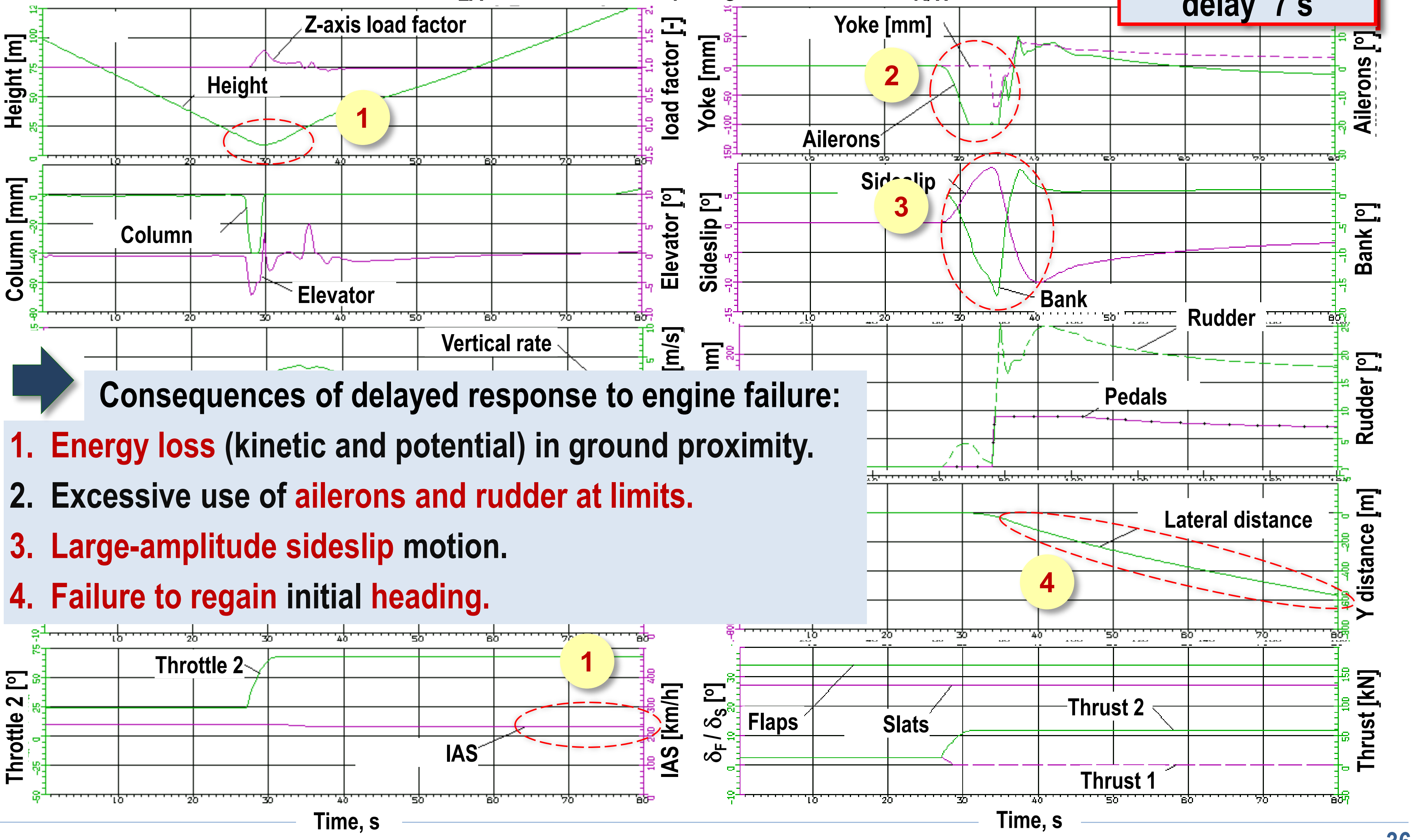


Regional Jet. Go-Around, LH-Engine Out During 'Engines to Maximum Power Rating' Procedure. Pilot Response Delay Effect

4. Single Situation Analysis

Pilot response delay 7 s

Weight = 43.5 tons, C.G.= 24%, V_{LA} = 238 km/h, δ_F / δ_S = 23°/ 27°, $H_{R/W}$ = 0 m

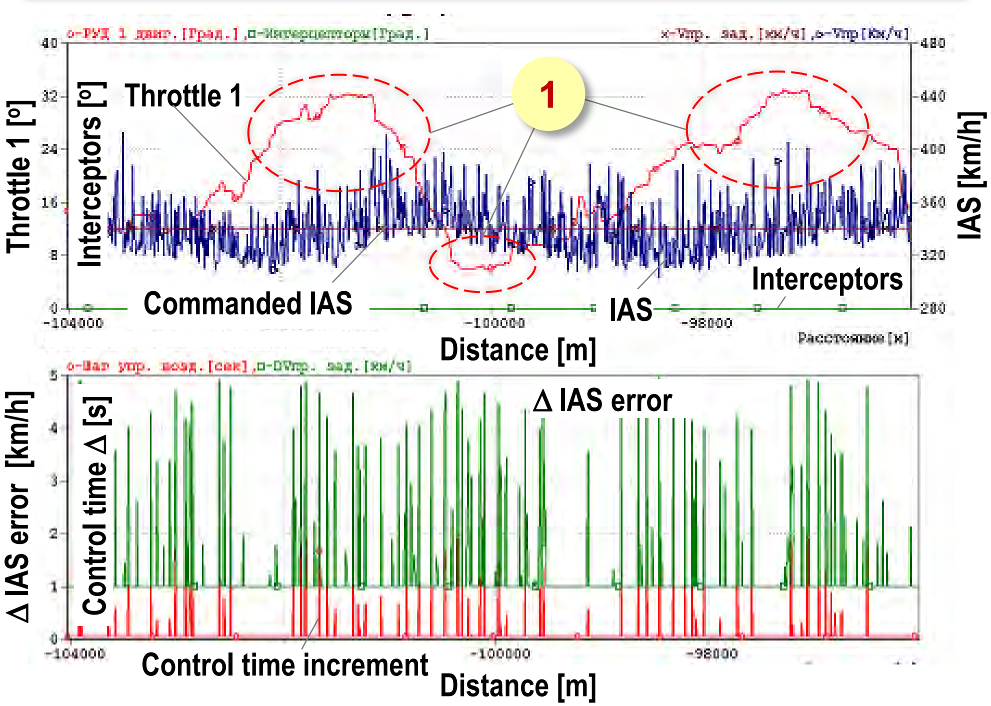


Consequences of delayed response to engine failure:

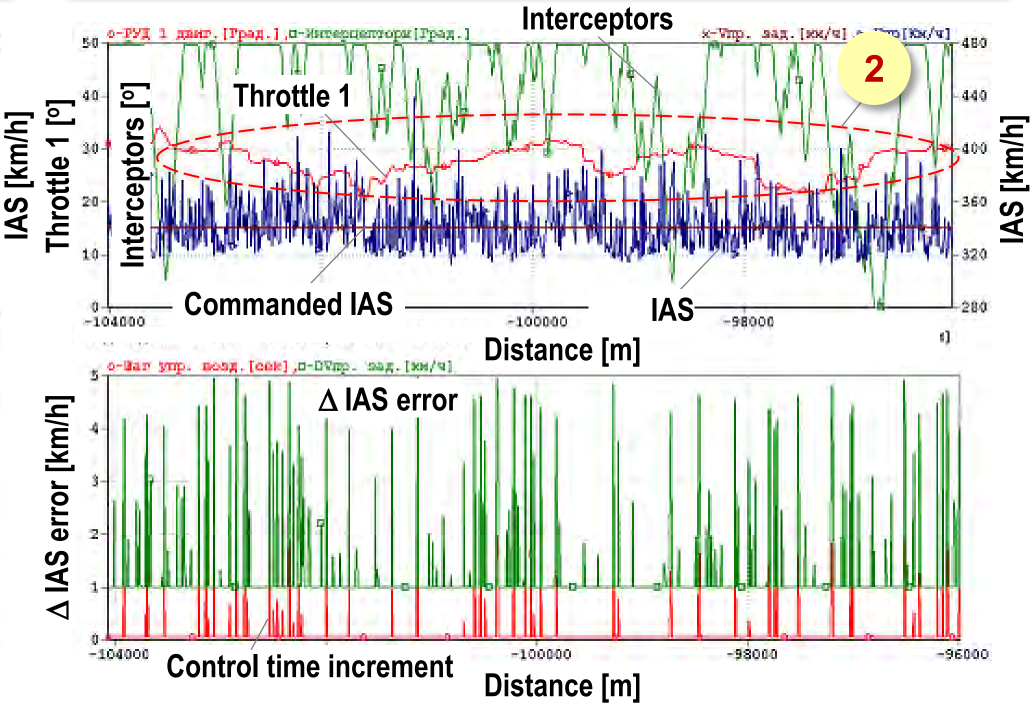
1. **Energy loss** (kinetic and potential) in ground proximity.
2. Excessive use of **ailerons and rudder at limits.**
3. **Large-amplitude sideslip** motion.
4. **Failure to regain** initial **heading.**

Medium-Range Jet. Cruise Flight, Strong Atmospheric Turbulence. Effect of EFCS Interceptor Signals on Speed-Hold Control

Without auxiliary interceptor signals from EFCS



With auxiliary interceptor signals from EFCS



Auxiliary interceptor signals from Electronic Flight Control System (EFCS) help **minimize throttle application for maintaining commanded IAS in** cruise flight **in strong turbulence conditions:**

Case 1. Intensive throttle control inputs (no auxiliary interceptor signals from EFCS).

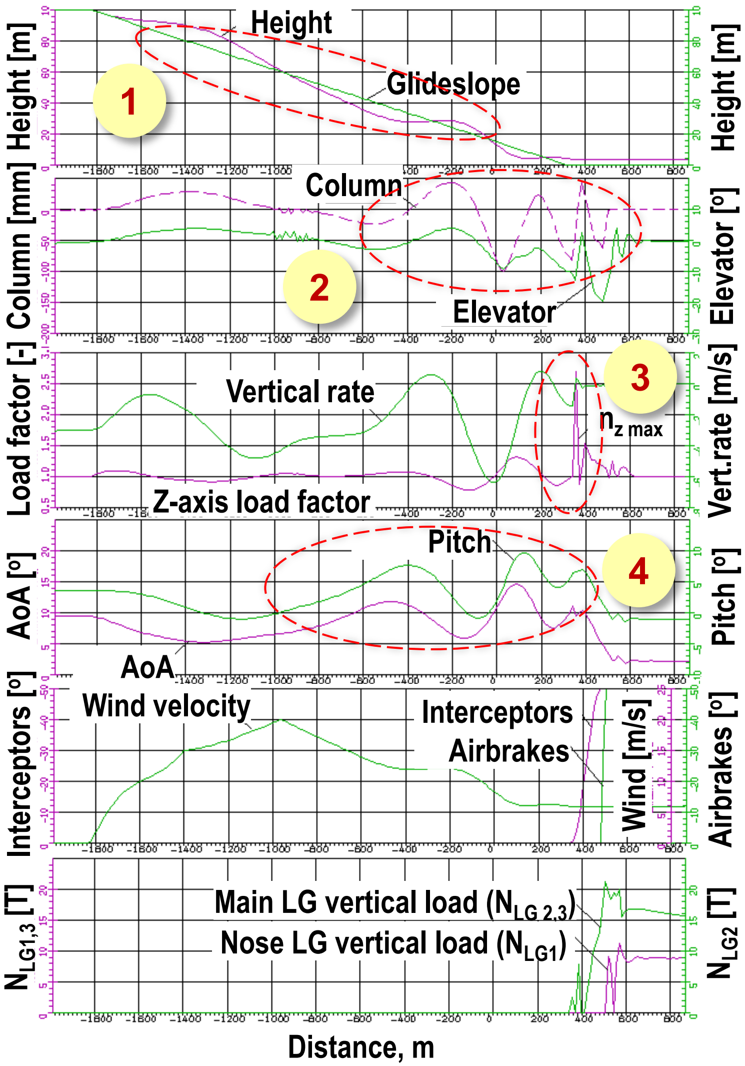
Case 2. Minimal throttle control inputs (with auxiliary interceptor signals from EFC).

Benefits: higher fuel efficiency, lower emissions and extended service life of engines.

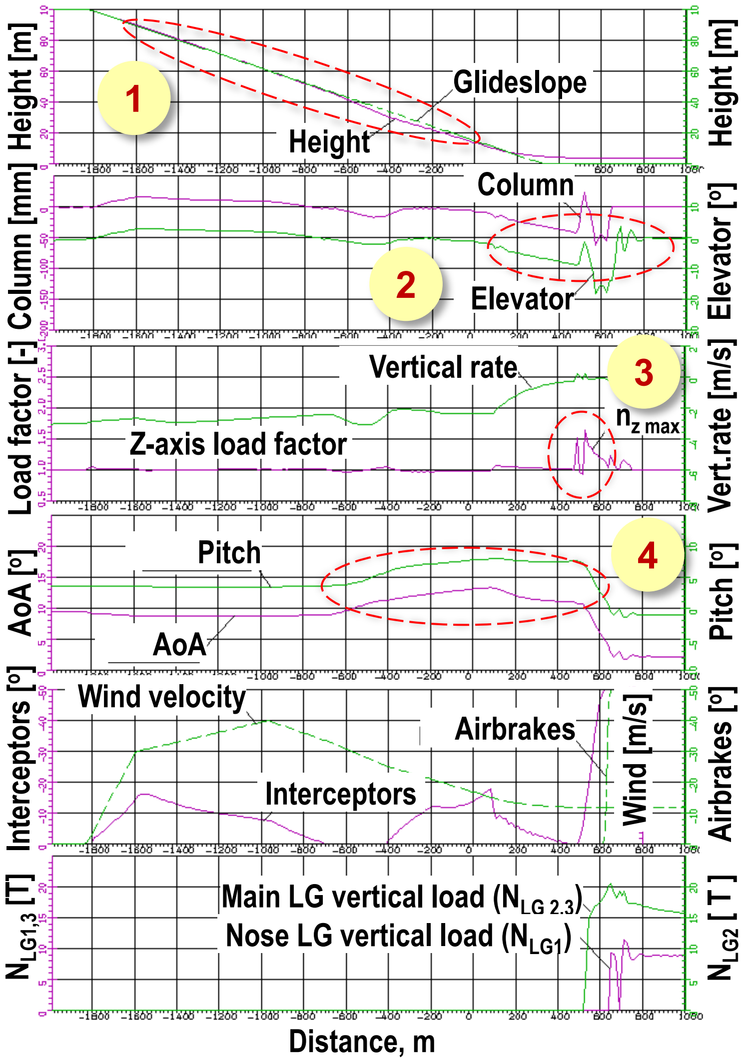
Regional Jet. Landing, Head-Tail Wind. Effect of Flightpath Active Correction (EFCS Interceptors Signals) on Descent and Flare

4. Single Situation Analysis

Without flightpath active correction



With flightpath active correction



Active Flightpath Correction technique advantages:

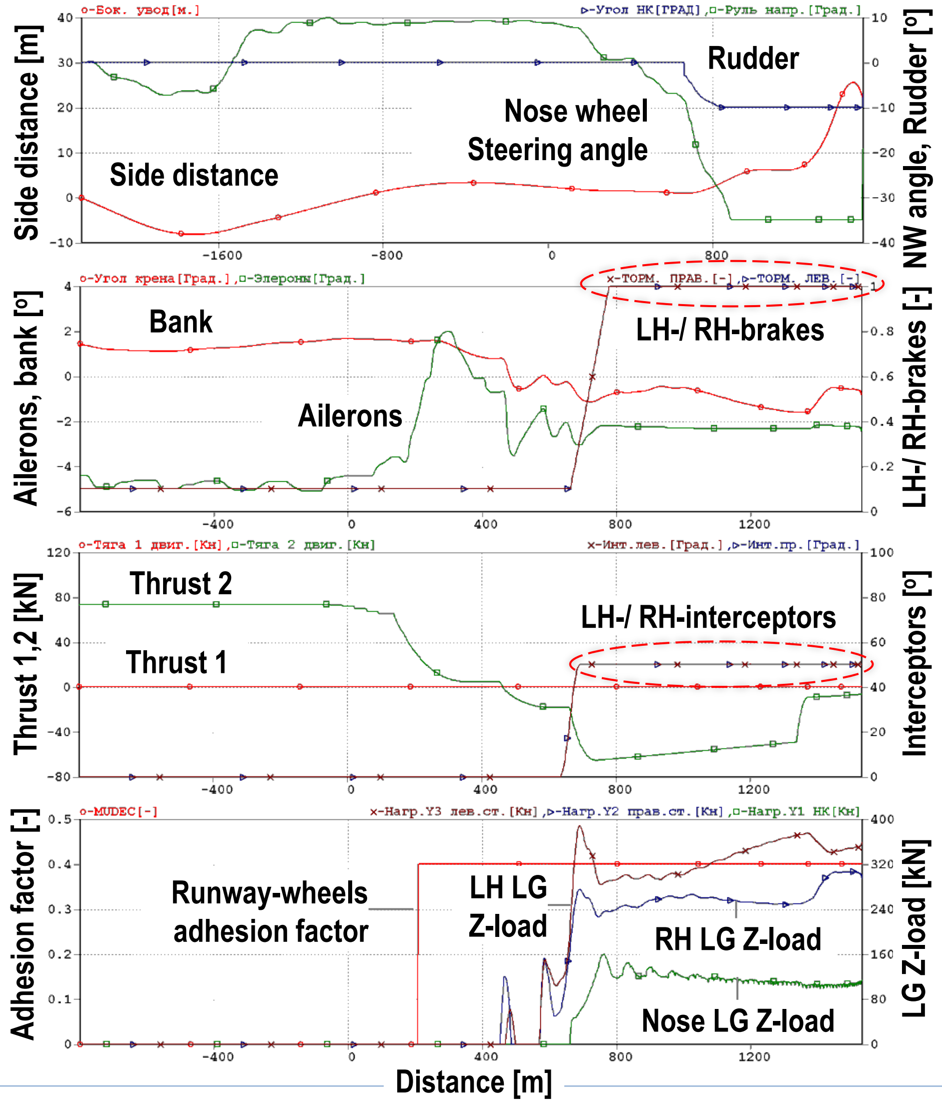
1. Minimal errors in steering glideslope.
2. Reduced workload on pilot.
3. Much lower z-axis load factor at touchdown.
4. Smooth pitch and AoA profiles.

This is an example of a **piloting technique which has been studied at low budget and time expenses** (‘at the ‘click of a mouse’).

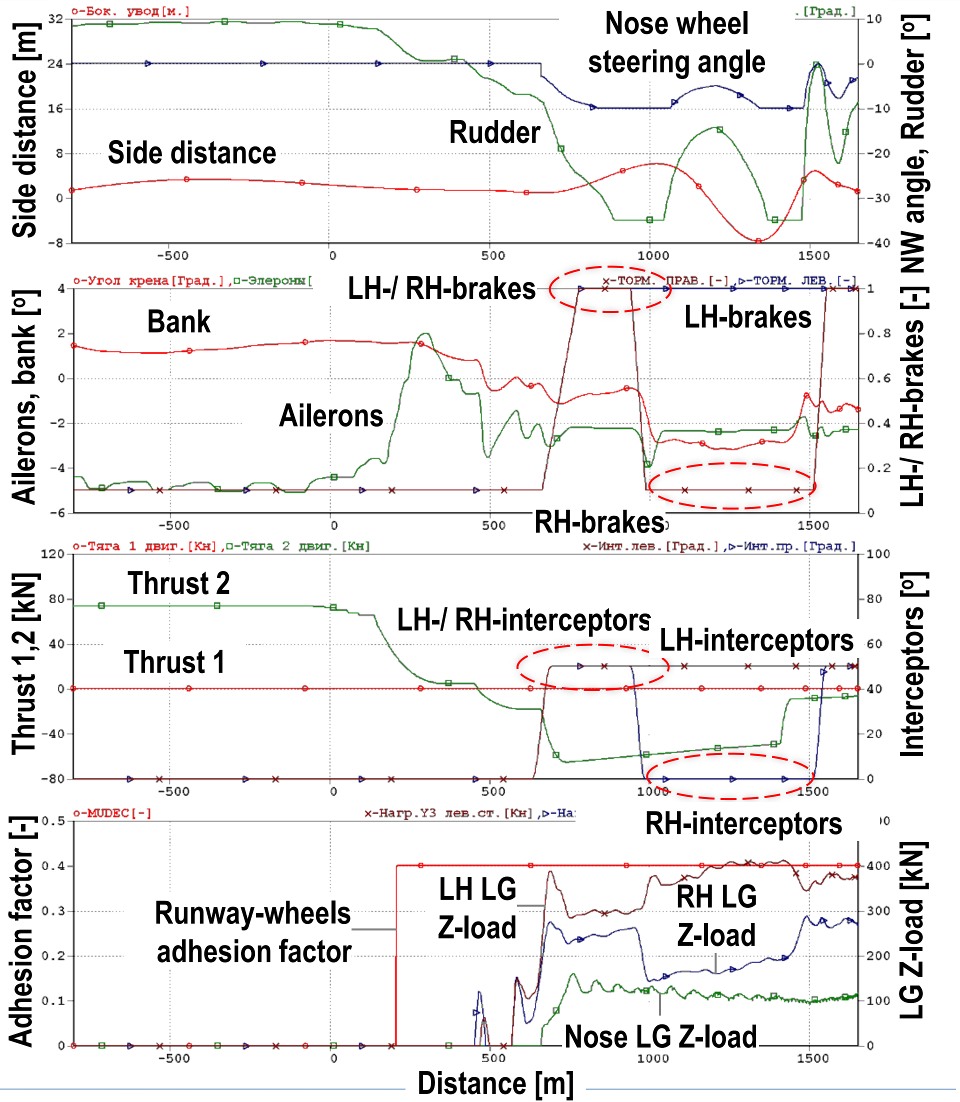
Medium-Range Jet. Landing, RH-Engine Out, Wet R/W, W_y = 15 m/s. Effect of Differential (Interceptors + Brakes) Control on Groundroll

4. Single Situation Analysis

Without auxiliary signals from EFCS

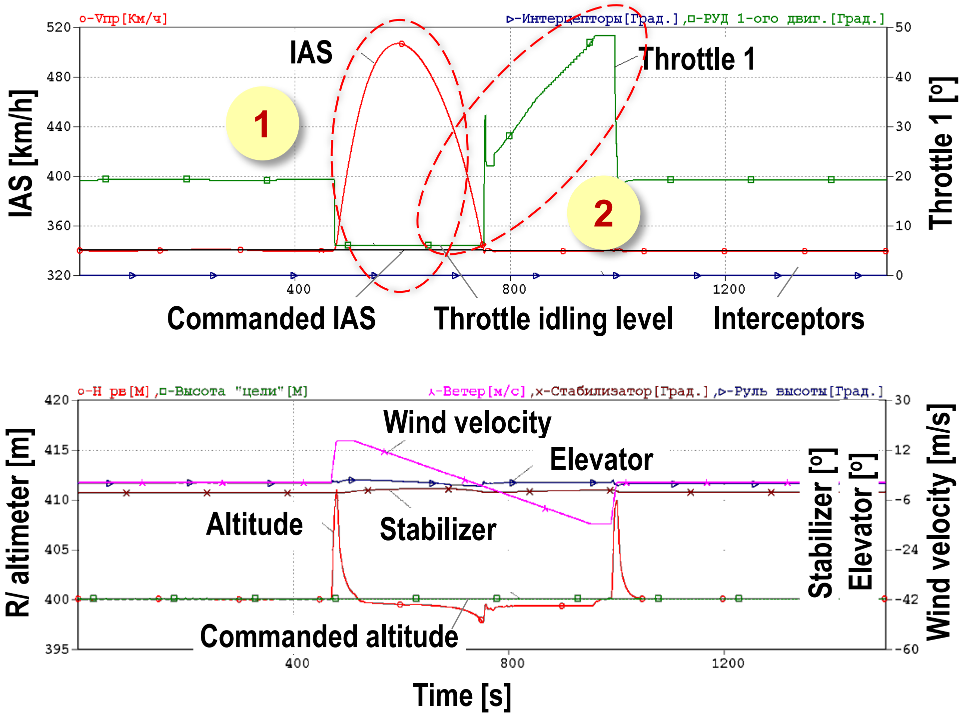


With auxiliary signals from EFCS (ΔL_{LD} = +121 m)

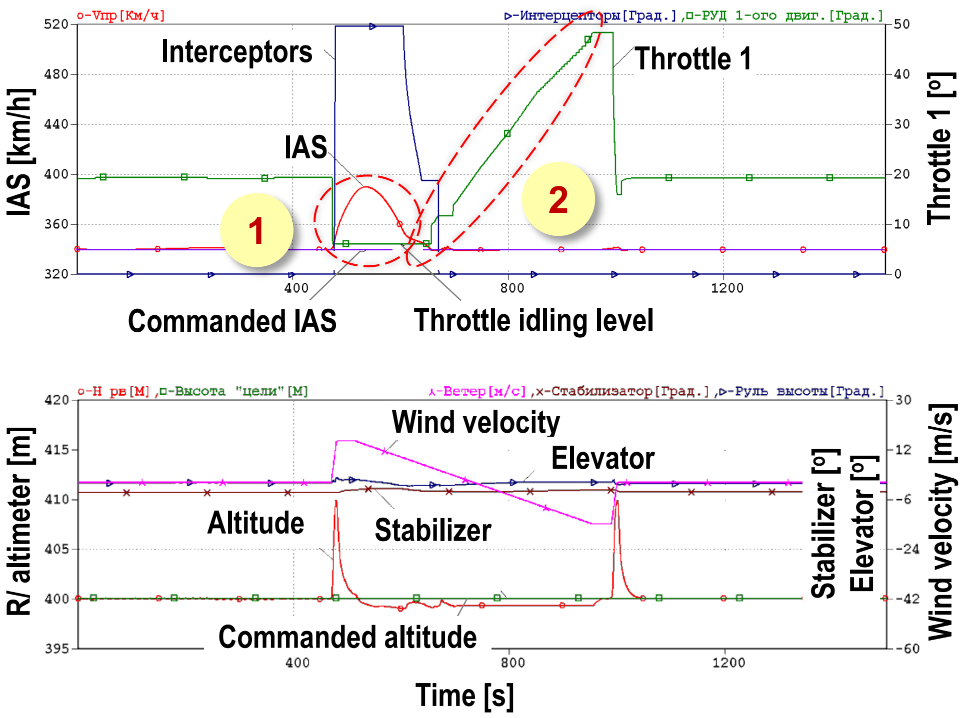


Medium-Range Jet. Level Flight, Strong Vertical Windshear. Effect Of EFCS Auxiliary Interceptor Signals on IAS Hold Control

Without auxiliary interceptor signals from EFCS



With auxiliary interceptor signals from EFCS



Advantage of IAS hold control by interceptor auxiliary signals from EFCS:

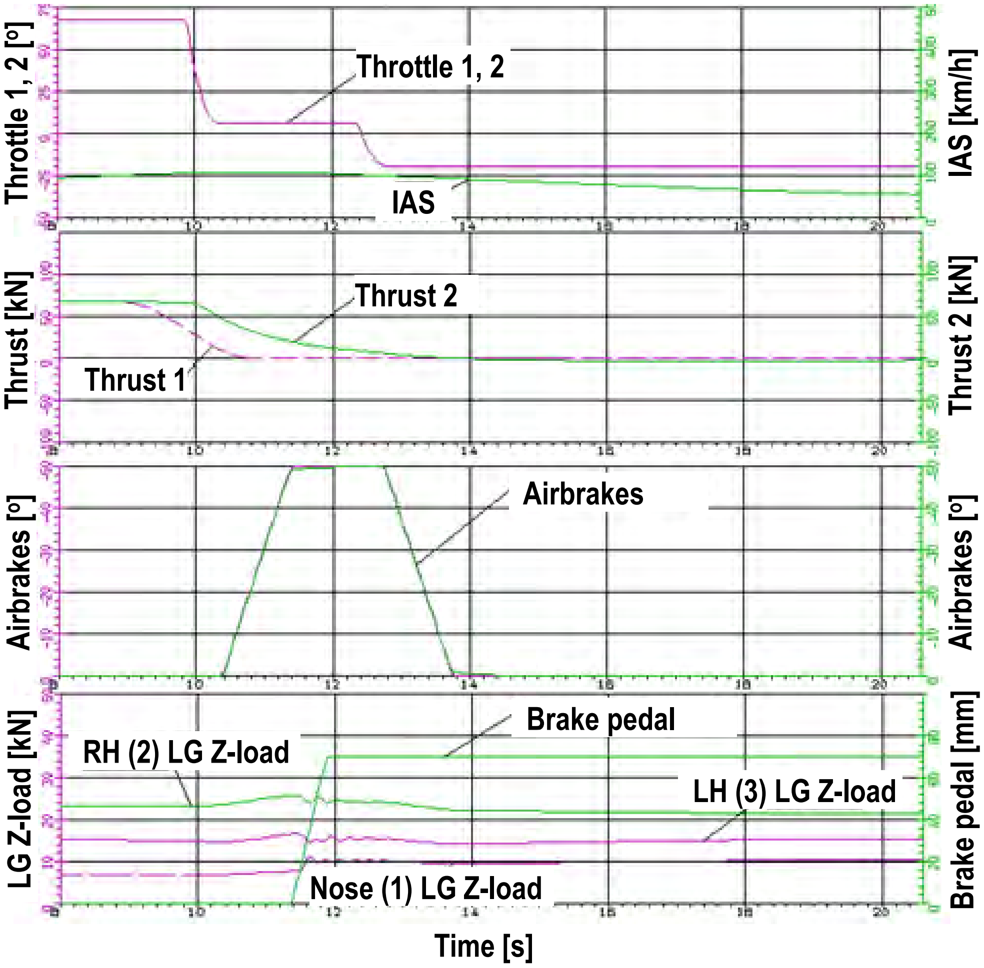
1. **Minimal fluctuations of IAS** (about three times) while crossing windshear zone.
2. **Smoother throttle** control (no 'spikes').

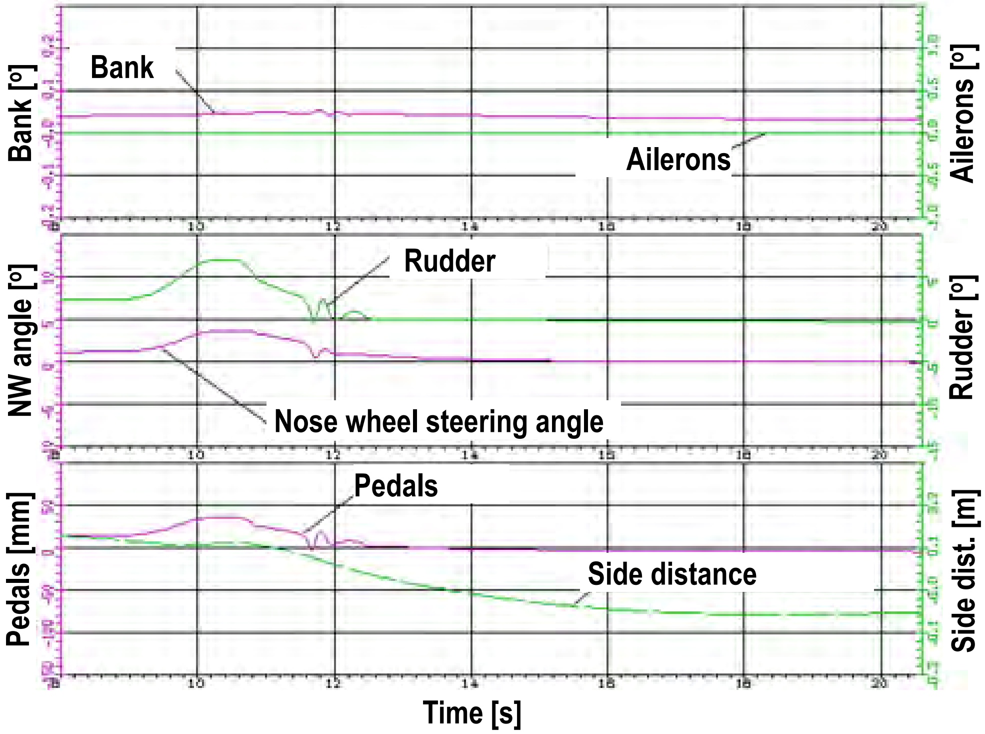
This off-nominal scenario and piloting technique have been studied 'at the 'click of a mouse' - **within a low budget and a short time schedule**).

Regional Jet. Aborted Takeoff, Crosswind 15 m/s, Critical Engine-Out Below V_1 During Groundroll

4. Single Situation Analysis

Weight = 47.9 tons, C.G.= 24%, δ_F / δ_S = 15°/ 22.5°, W_y = 15 m/s, V_{EF} = 100 km/h, $H_{R/W}$ = 0 , μ_D = 0.6



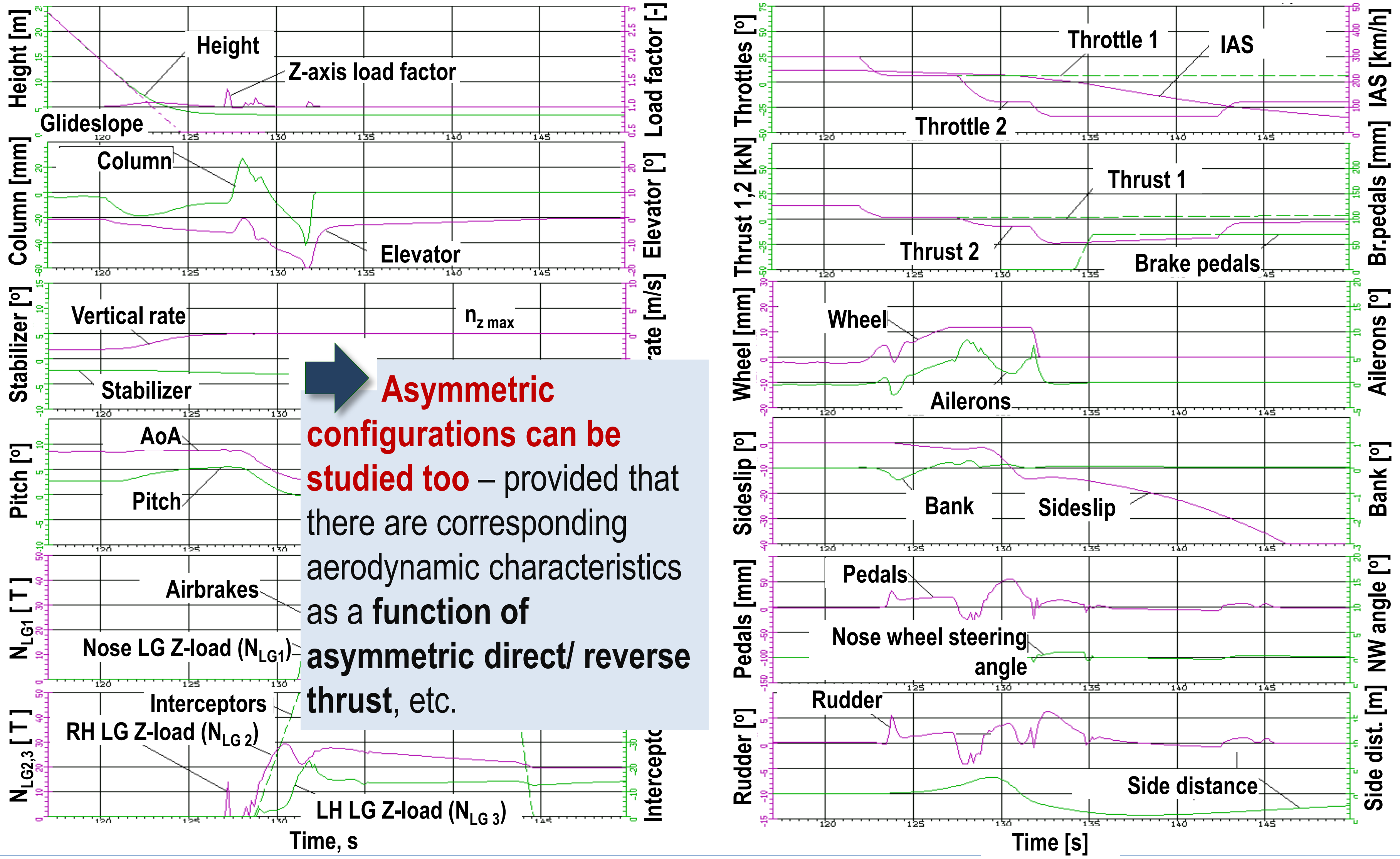


Legend: LG – landing gear. LH – left-hand. RH – right-hand. IAS – indicated airspeed.

The system dynamics model and scenario scripting language enable **quick in-depth analysis and parametric tune-up of piloting tactics** (flight tests, SOPs, etc.) in multifactor operating conditions – **by a non-pilot**.

Regional Jet. Continued Landing, Critical Engine-Out, Crosswind 15 m/s, Thrust Reverser Inoperative during Groundroll

Weight = 43.5 tons, C.G.= 35%, V_{LA} = 248 km/h, δ_F / δ_S = 34°/ 27°, W_y = 15 m/s, $H_{R/W}$ = 0 , μ_D = 0.6

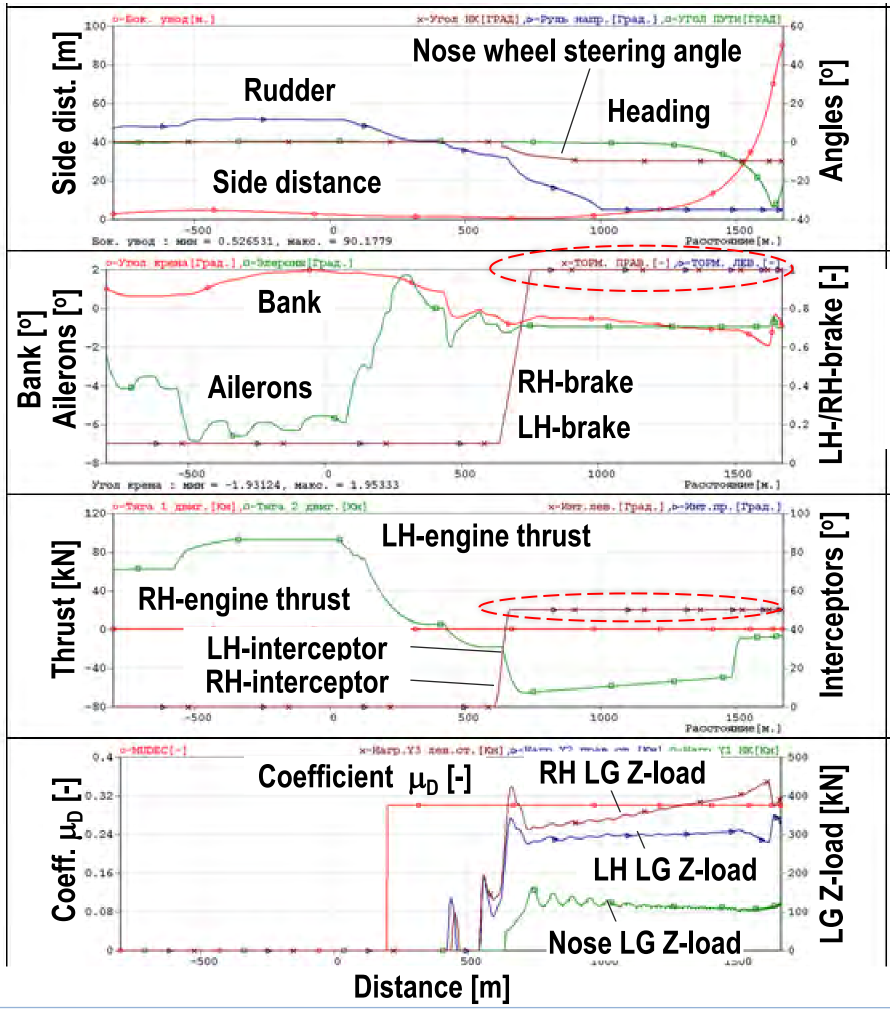


Asymmetric configurations can be studied too – provided that there are corresponding aerodynamic characteristics as a **function of asymmetric direct/ reverse thrust**, etc.

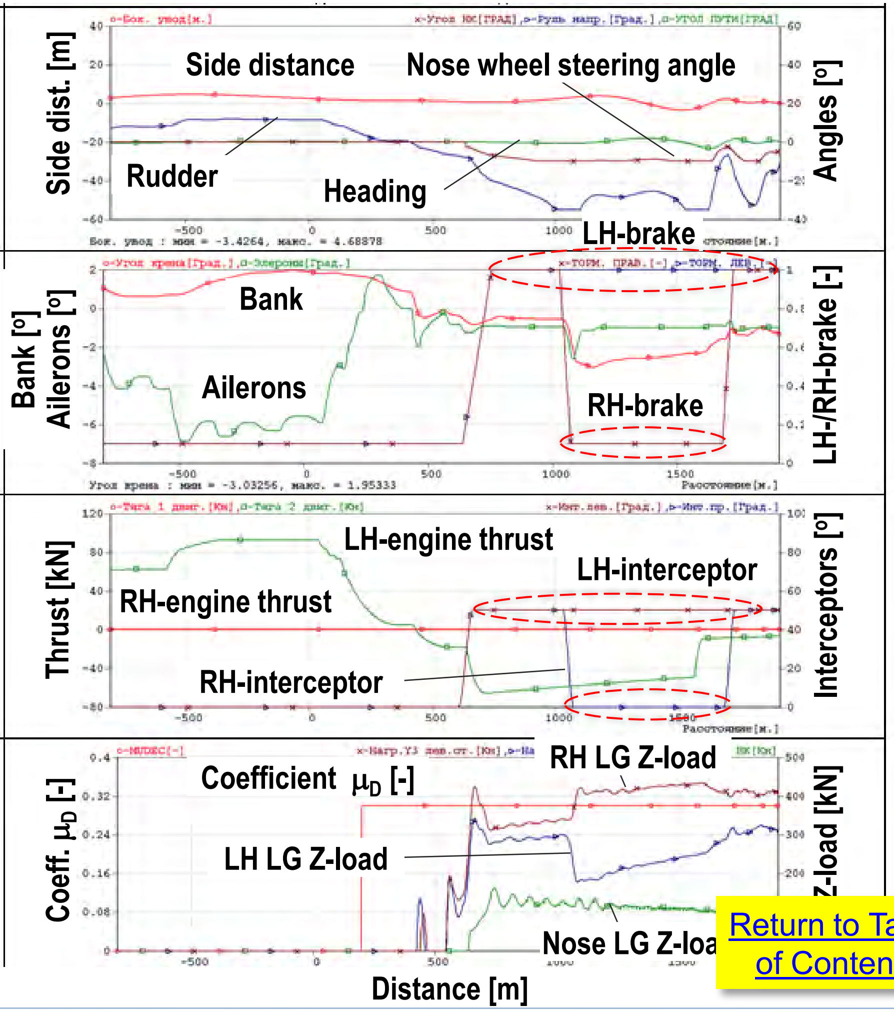
Medium-Range Jet. Landing, RH-Engine, Icy R/W, Crosswind 15 m/s, Out, Differential Control by Interceptors + Brakes in Groundroll

4. Single Situation Analysis

Without differential control by interceptors + brakes (L_{LD} = 1672 m)



With differential control by interceptors + brakes (L_{LD} = 1909 m, ΔL_{LD} = 237 m)



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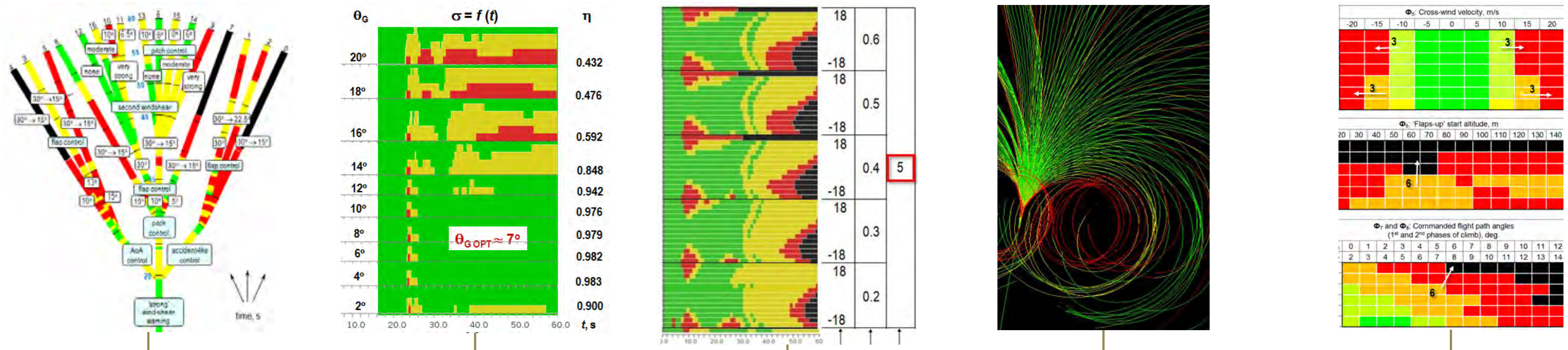
Parallel Analysis of Multiple Situations Using Knowledge Maps (Overview Slide)

5. Multiple Situations Analysis

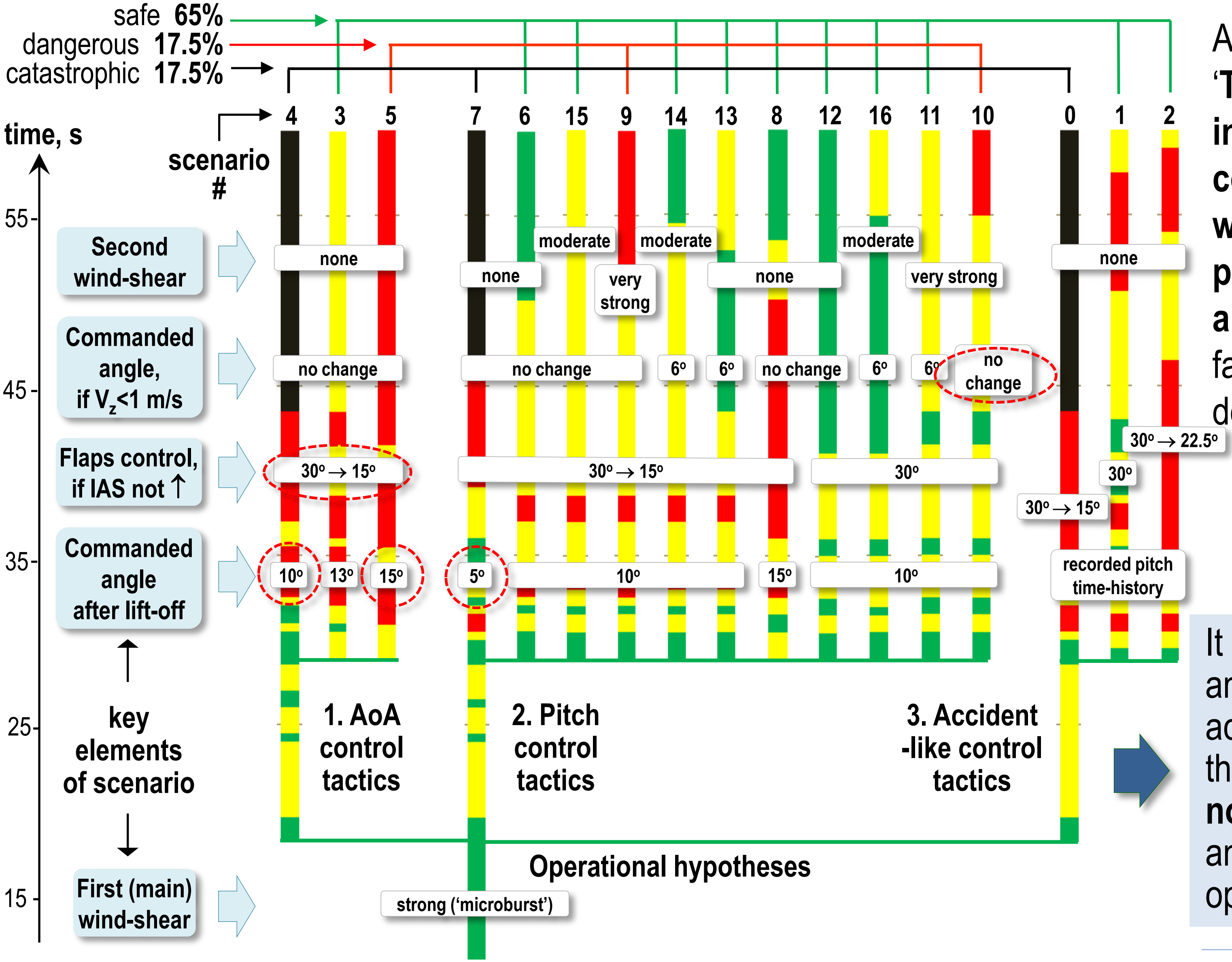
Parallel analysis case studies (selected examples)

- Accident reconstruction and ‘what-if analysis of its neighborhood’ under uncertainty
- Determination of optimal/ safest values of goal/ commanded flight parameters
- Analysis of cross-coupling effects of multiple risk factors on system dynamics/ safety
- Exploration of limited-capacity local airspaces situational trees and other knowledge maps
- Safety topology analysis and anomaly identification in multifactor domains using safety windows



Examples of knowledge maps

Accident Reconstruction and ‘What-if Neighborhood’ Analysis Under Uncertainty

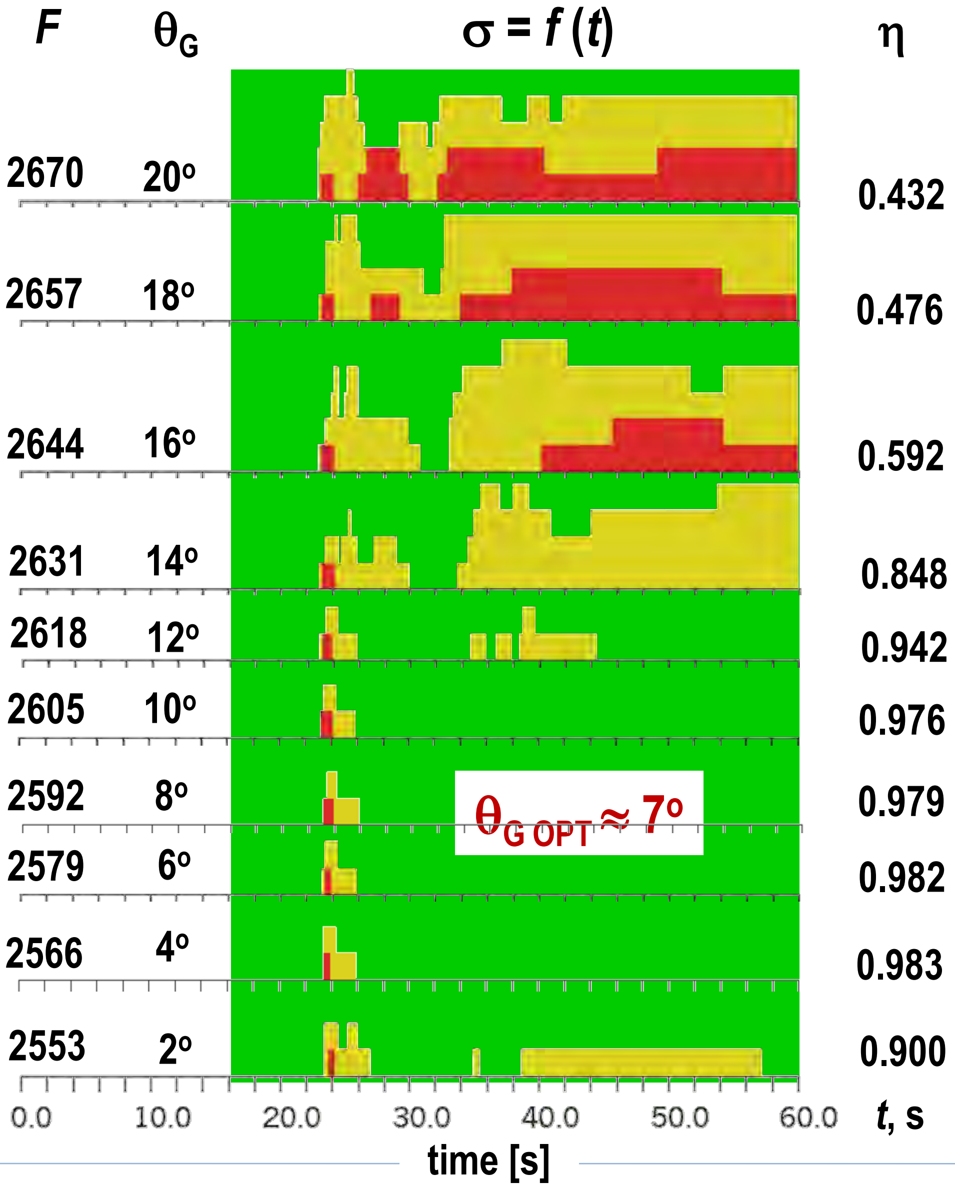


Accident‘s what-if tree: **‘Takeoff and initial climb in ‘microburst’ conditions. Variations of wind shear intensity, pilot errors in flaps, AoA and pitch control’** (5-factor operational domain).

It follows from ‘what-if’ analysis of this accident’s ‘neighborhood’ that the catastrophe **was not inevitable** in given and close complex operating conditions.

Determination of Optimal (Safest) Flight Path Angle in Steep Turn Using Situation Complexity Build-up Diagrams

5. Multiple Situations Analysis



F	θ_G	η
2670	20°	0.432
2657	18°	0.476
2644	16°	0.592
2631	14°	0.848
2618	12°	0.942
2605	10°	0.976
2592	8°	0.979
2579	6°	0.982
2566	4°	0.983
2553	2°	0.900

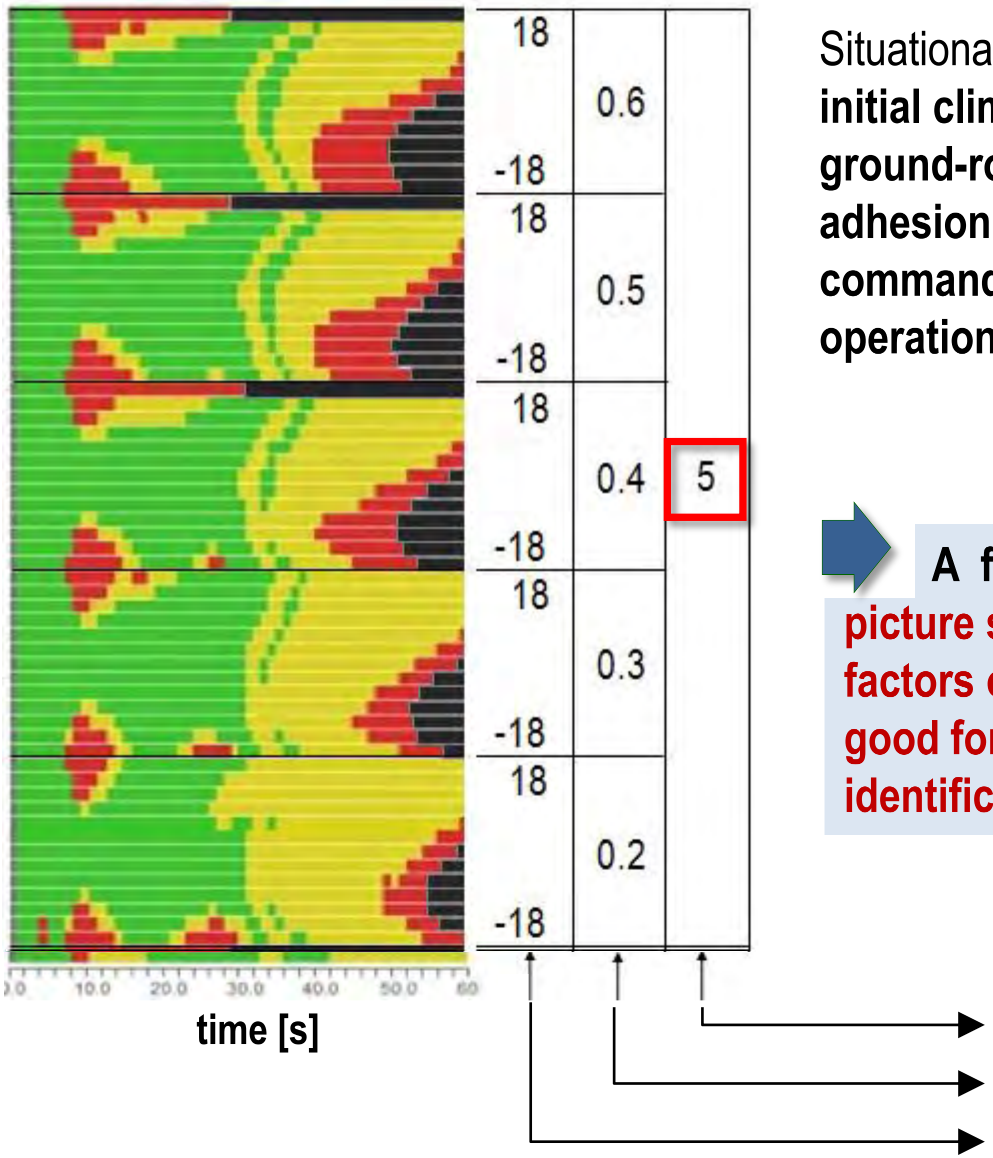
Situation Complexity Build-up Diagram

Situational tree ***T* = S·Γ: ‘Takeoff and initial climb, variations/ errors of selecting commanded flight path angle θ_G and commanded bank angle γ_G’ (2-factor domain, sub-tree with θ_G = *var* and γ_G = -30°)**

Optimal flight path angle ($\theta_{G\,OPT} \approx 7^o$) can be easily identified: This is an interim scenario between ‘flights’ ## 2579 and 2592. It is **equally distanced (safety-wise)** between boundary ‘flights’ ## 2553 and 2618.

Legend: **S** – normal takeoff scenario. **Γ** – multifactor hypothesis, **$\Gamma = \Phi_1 \times \Phi_2$**. **$\Phi_1$** – commanded flight path angle θ_G. **Φ_2** – commanded bank angle γ_2. ***F*** – ‘flight’ number. σ – situation complexity index. η – flight safety index. *t* – flight time [s]. 🟩🟨🟥⬛ – safety palette.

Analysis of Cross-Coupling Effects of Multifactor Risks on System Dynamics and Safety Using Integral Safety Spectra Carpets



Commanded flight path angle Φ_1, [deg.]

Wheels-runway adhesion coefficient Φ_3 , [-]

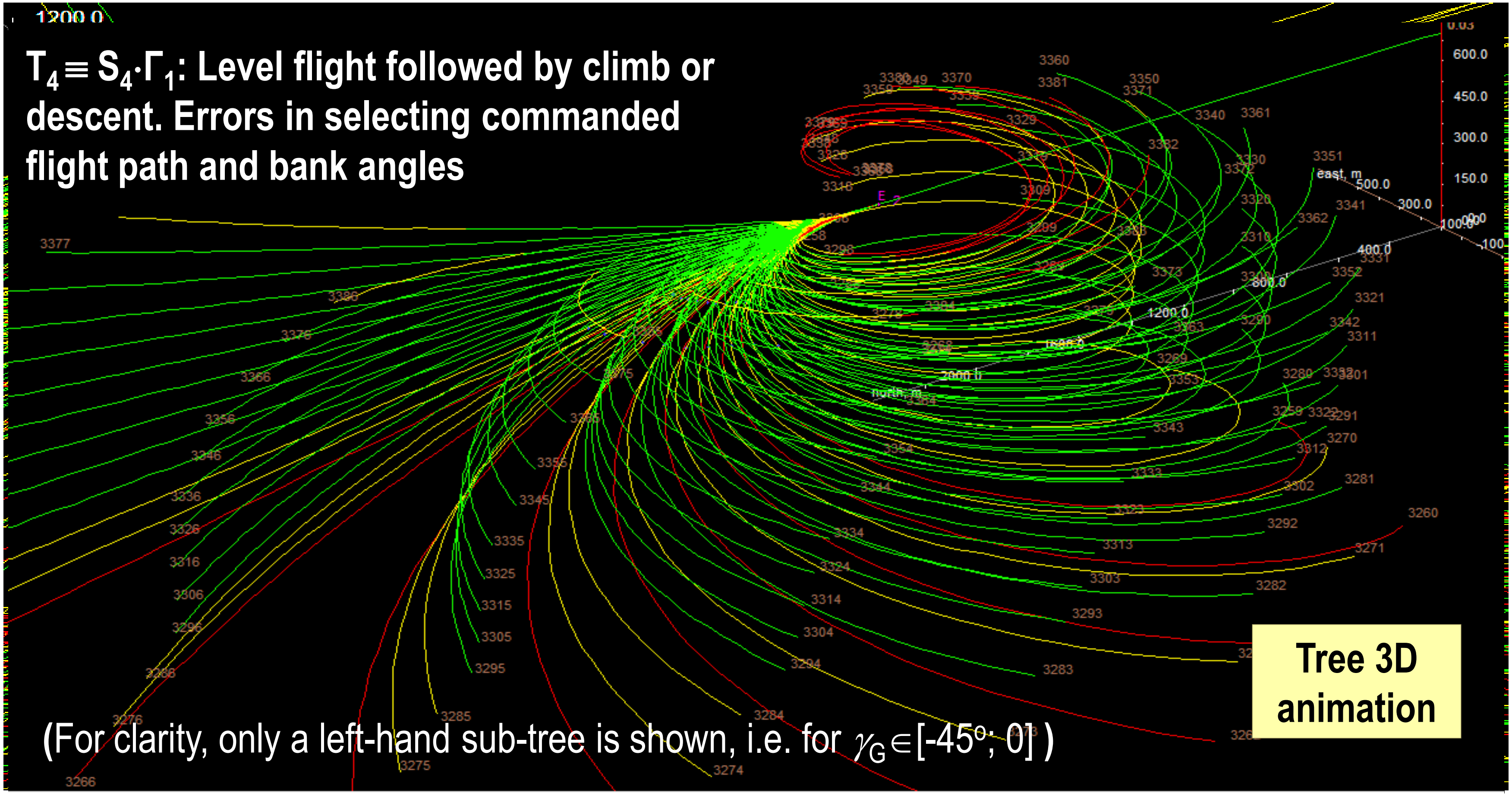
Cross wind velocity Φ_4, [m/s]

Situational tree $T_3 \equiv S_3 \cdot \Gamma_2$: **Continued takeoff and initial climb, with left-hand engine our during ground-roll with variations of wheels-runway adhesion coefficient Φ_3, cross wind velocity Φ_4, and commanded flight path angle Φ_1 (four-factor operational domain)**

A family of safety carpets is a 'bird's eye view picture showing the integrated effect of four risk factors on continued takeoff and initial climb – good for visual analytics and anomalies identification.

Virtual Exploration of Congested/ Limited Local Airspace Using Situational Trees and Safety Spectra

5. Multiple Situations Analysis



$T_4 \equiv S_4 \cdot \Gamma_1$: Level flight followed by climb or descent. Errors in selecting commanded flight path and bank angles

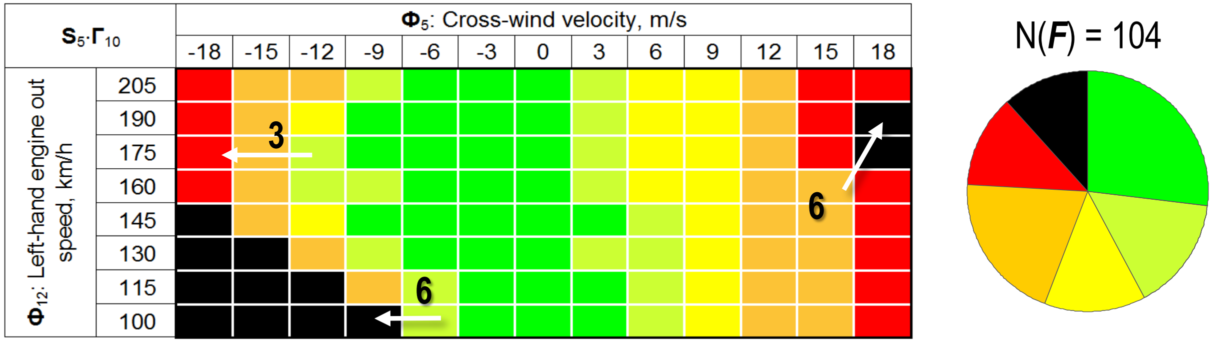
(For clarity, only a left-hand sub-tree is shown, i.e. for $\gamma_G \in [-45^o; 0]$)

Tree 3D animation

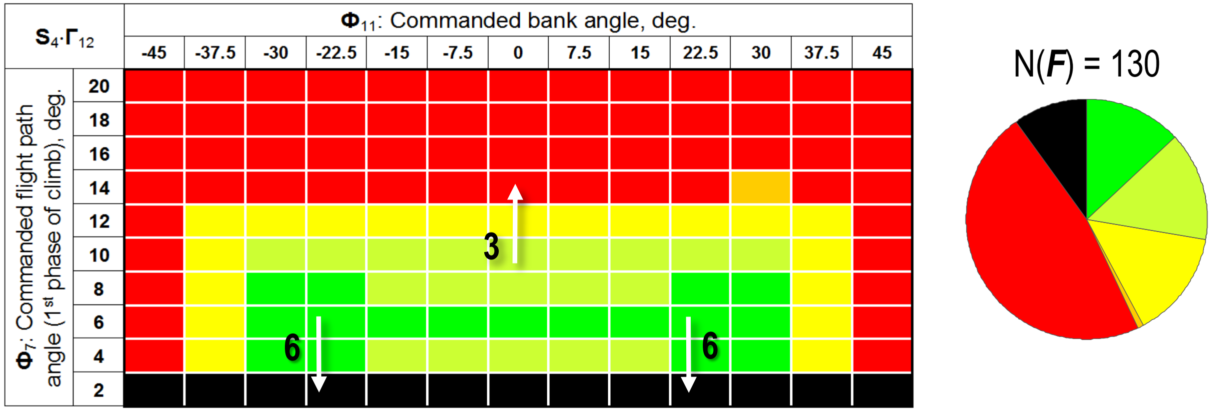
Analysis of Safety Topology and Identification of Anomalies In Multifactor Operational Domains Using Safety Windows

5. Multiple Situations Analysis

$S_5 \cdot \Gamma_{10}$: Continued takeoff with LH-engine out during ground-roll in cross-wind conditions. Variations of engine failure speed and cross-wind velocity (3-factor domain)



$S_4 \cdot \Gamma_{12}$: Normal takeoff in 'strong' wind-shear conditions. Variations/ errors in maintaining commanded flight path angle (1st phase of climb) and commanded bank angle (3-factor domain)

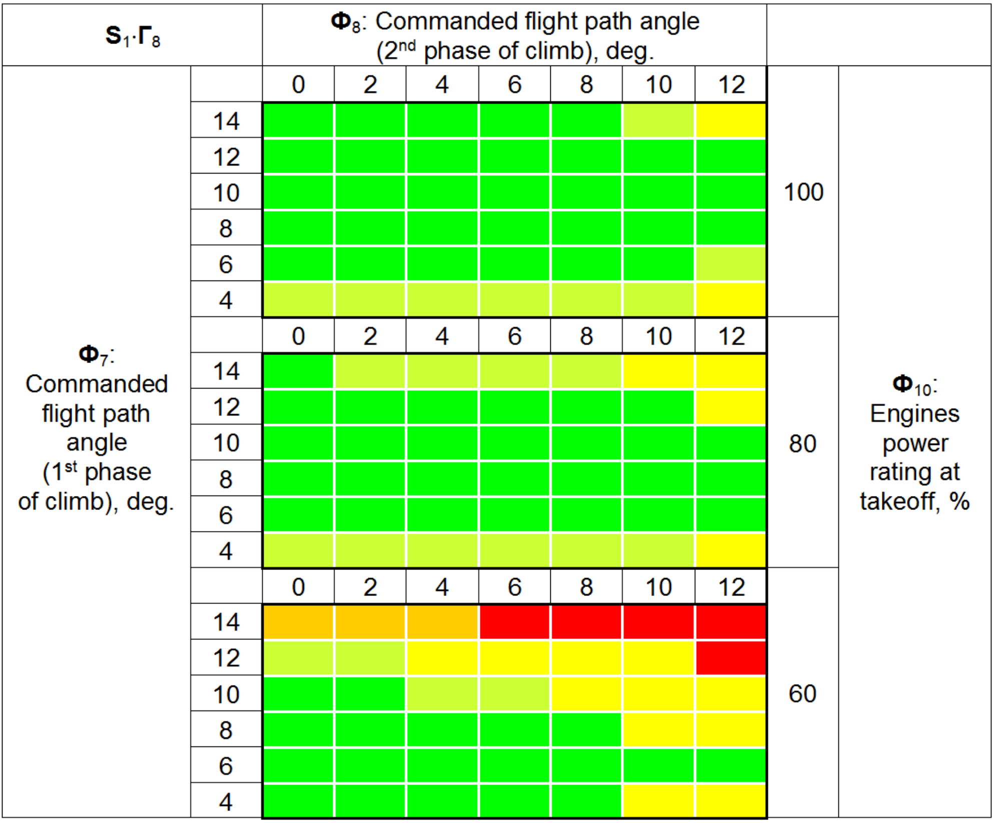


Legend: **S** - baseline scenario, **Γ** - multifactor hypothesis, **N(*F*)** – number of 'flights' in situational tree. **3** (**6**) – gradual (abrupt) transition from a safe state to an unsafe (catastrophic) state. : 🟩🟩🟨🟧🟥⬛ – safety categories.

Visual Analytics using 3D Safety Windows and Safety Chances Distribution Pie Charts

Situational tree: '**Normal takeoff and initial climb. Pilot errors/ variations of commanded flight path angle θ_{G1} (1st phase of climb, flaps on), commanded flight path angle θ_{G2} (2nd phase of climb, flaps off), and engine power rating**' (3-factor operational domain)

3D safety window



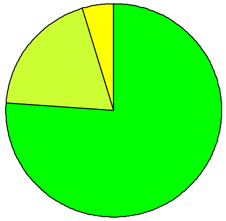
$S_1{\cdot}\Gamma_8$		Φ_8: Commanded flight path angle (2nd phase of climb), deg.								
Φ_7: Commanded flight path angle (1st phase of climb), deg.		0	2	4	6	8	10	12		Φ_{10}: Engines power rating at takeoff, %
	14	🟩	🟩	🟩	🟩	🟩	▨	🟨	100	
	12	🟩	🟩	🟩	🟩	🟩	🟩	🟩		
	10	🟩	🟩	🟩	🟩	🟩	🟩	🟩		
	8	🟩	🟩	🟩	🟩	🟩	🟩	🟩		
	6	🟩	🟩	🟩	🟩	🟩	🟩	▨		
	4	▨	▨	▨	▨	▨	▨	🟨		
		0	2	4	6	8	10	12		
	14	🟩	▨	▨	▨	▨	🟨	🟨	80	
	12	🟩	🟩	🟩	🟩	🟩	🟩	🟨		
	10	🟩	🟩	🟩	🟩	🟩	🟩	🟩		
	8	🟩	🟩	🟩	🟩	🟩	🟩	🟩		
	6	🟩	🟩	🟩	🟩	🟩	🟩	🟩		
	4	▨	▨	▨	▨	▨	▨	🟨		
		0	2	4	6	8	10	12		
	14	🟧	🟧	🟧	🟥	🟥	🟥	🟥	60	
	12	▨	▨	🟨	🟨	🟨	🟨	🟥		
	10	🟩	🟩	▨	▨	🟨	🟨	🟨		
	8	🟩	🟩	🟩	🟩	🟩	🟨	🟨		
	6	🟩	🟩	🟩	🟩	🟩	🟩	🟩		
	4	🟩	🟩	🟩	🟩	🟩	🟨	🟨		

Legend: 🟩▨🟨🟧🟥⬛ – safety categories.

Safety Chances Distribution Pie Charts

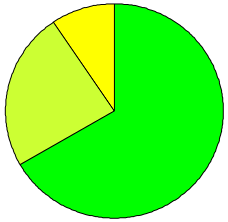
Φ_{10}, %

Category	ξ^j	n^j	χ^j, %
I	🟩	32	76
II-a	▨	8	19
II-b	🟨	2	5
III	🟧	0	0
IV	🟥	0	0
V	⬛	0	0
$\Sigma n^j, \Sigma\chi^j$ | $S_1{\cdot}\Gamma_8$		42	100



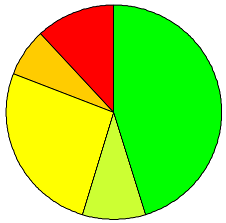
100

Category	ξ^j	n^j	χ^j, %
I	🟩	28	66
II-a	▨	10	24
II-b	🟨	4	10
III	🟧	0	0
IV	🟥	0	0
V	⬛	0	0
$\Sigma n^j, \Sigma\chi^j$ | $S_1{\cdot}\Gamma_8$		42	100



80

Category	ξ^j	n^j	χ^j, %
I	🟩	19	45
II-a	▨	4	10
II-b	🟨	11	26
III	🟧	3	7
IV	🟥	5	12
V	⬛	0	0
$\Sigma n^j, \Sigma\chi^j$ | $S_1{\cdot}\Gamma_8$		42	100



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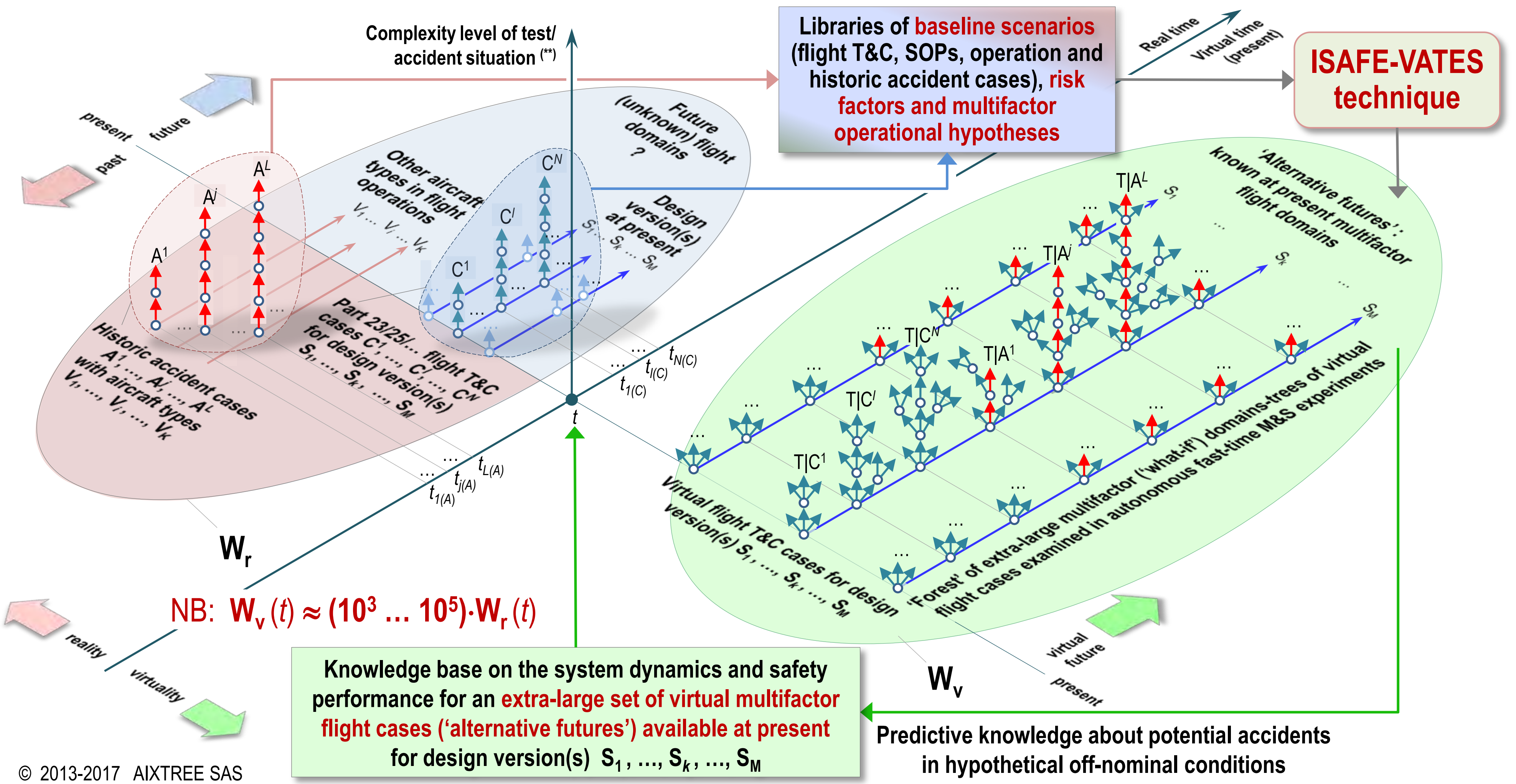
Adaptive Virtual Fast-Time Flight Test and Operation Cycle For Early Exploration of Project's 'Alternative Futures'



Libraries of **baseline scenarios** (flight T&C, SOPs, operation and historic accident cases), **risk factors and multifactor operational hypotheses**

ISAFE-VATES technique

NB: $\mathbf{W_v}(t) \approx \mathbf{(10^3 … 10^5)\cdot W_r}(t)$

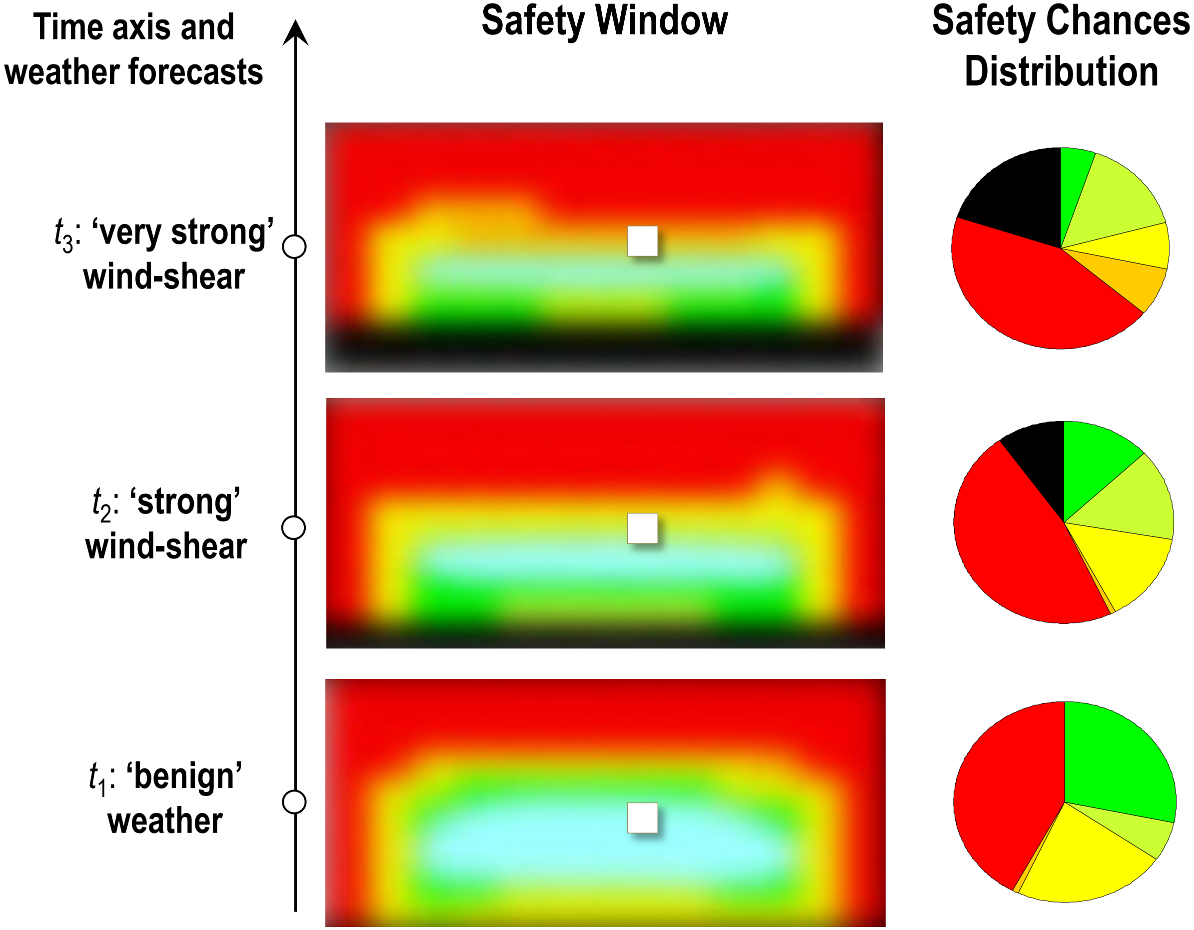
Knowledge base on the system dynamics and safety performance for an **extra-large set of virtual multifactor flight cases ('alternative futures') available at present** for design version(s) $S_1, …, S_k, …, S_M$

Predictive knowledge about potential accidents in hypothetical off-nominal conditions

Legend: (*) – lifecycle phase: conceptual/ preliminary/ detailed design (CD/ PD/ DD), flight test and certification (T&C), pilot training, introduction into service, operations. (**) – proportional to the number of risk factors in a flight scenario. *t* – current time (present). $V_1, …, V_i, …, V_K$ – existing aircraft types. $S_1, …, S_k, …, S_M$ – new aircraft project design versions at present. ○→○→ – cause-and-effect scenario of a historic accident situation. ○→○→ – cause-and-effect scenario of a flight test case. $A^1, …, A^j, …, A^L$ – flight accidents recorded in the past. $C^1, … C^i, …, C^N$ – Part 23/ 25/ … flight T&C cases. $t_{1(A)}, …, t_{j(A)}, …, t_{L(A)}$ – time instants of flight accidents. $t_{1(C)}, …, t_{I(C)}, …, t_{N(C)}$ – time instants of flight test cases (at present and in the future). W (*t*) - volume of knowledge about system dynamics and safety available at present (at time *t*). r – reality. v – virtuality. T – situational tree. $(T|C^i)$ – multifactor 'what-if' domain-tree built around a flight T&C case C^i. $(T|A^j)$ – multifactor 'what-if' domain-tree built around a flight accident scenario A^j.

Pilot Cognitive Assistance: ‘Tactical Goals - Constraints’ Real-Time Management Using Safety Windows

Situational tree: **‘Normal takeoff under uncertain wind-shear conditions and possible pilot errors/ variations in flight path angle and bank angle control ’** (3-factor operational domain)



Time axis and weather forecasts

Safety Window

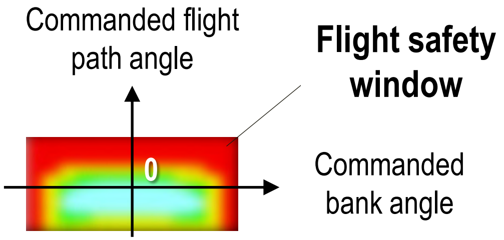
Safety Chances Distribution

t_3: **‘very strong’ wind-shear**

t_2: **‘strong’ wind-shear**

t_1: **‘benign’ weather**

Legend: t_1, t_2, t_3 – time instants of wind-shear forecasts (notional examples). ↑– time axis. 🟩🟩🟨🟧🟥⬛ – flight safety colors. Flight Safety Window’s axes: vertical (horizontal) - commanded flight path (bank) angle:



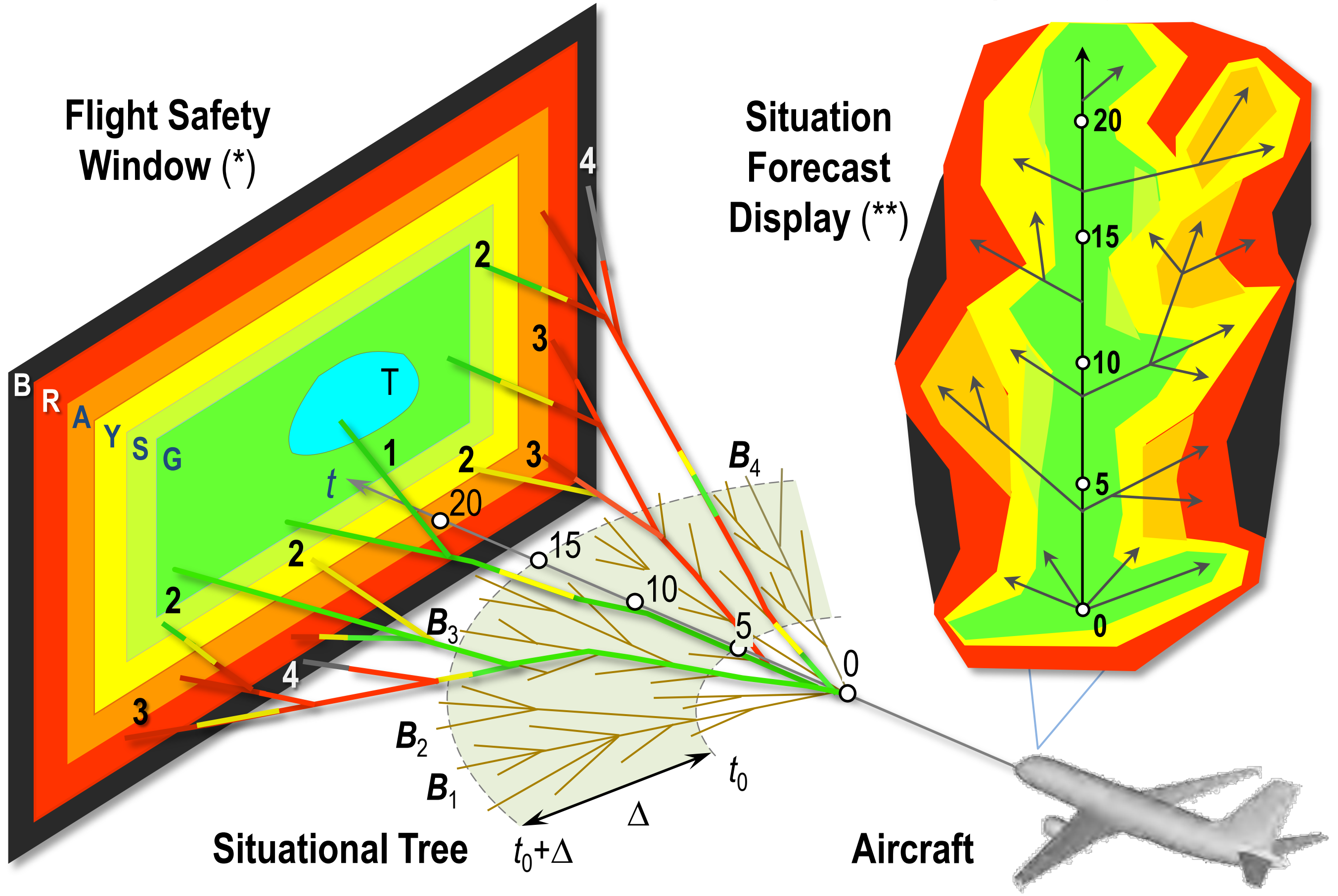
☐ - cell of current tactical goal.

Safety windows can be used in flight **for projecting the ‘pilot/-automaton-aircraft – operating environment’ system’s tactical goals and constraints as a function of time and /or important flight events** (wind-shear warning, etc.).

Prediction and Enhancement of Aircraft Flight Path Safety In Multifactor/ Unknown Situations

Present capability: virtual fast-time flight testing (prior to mission, off board)

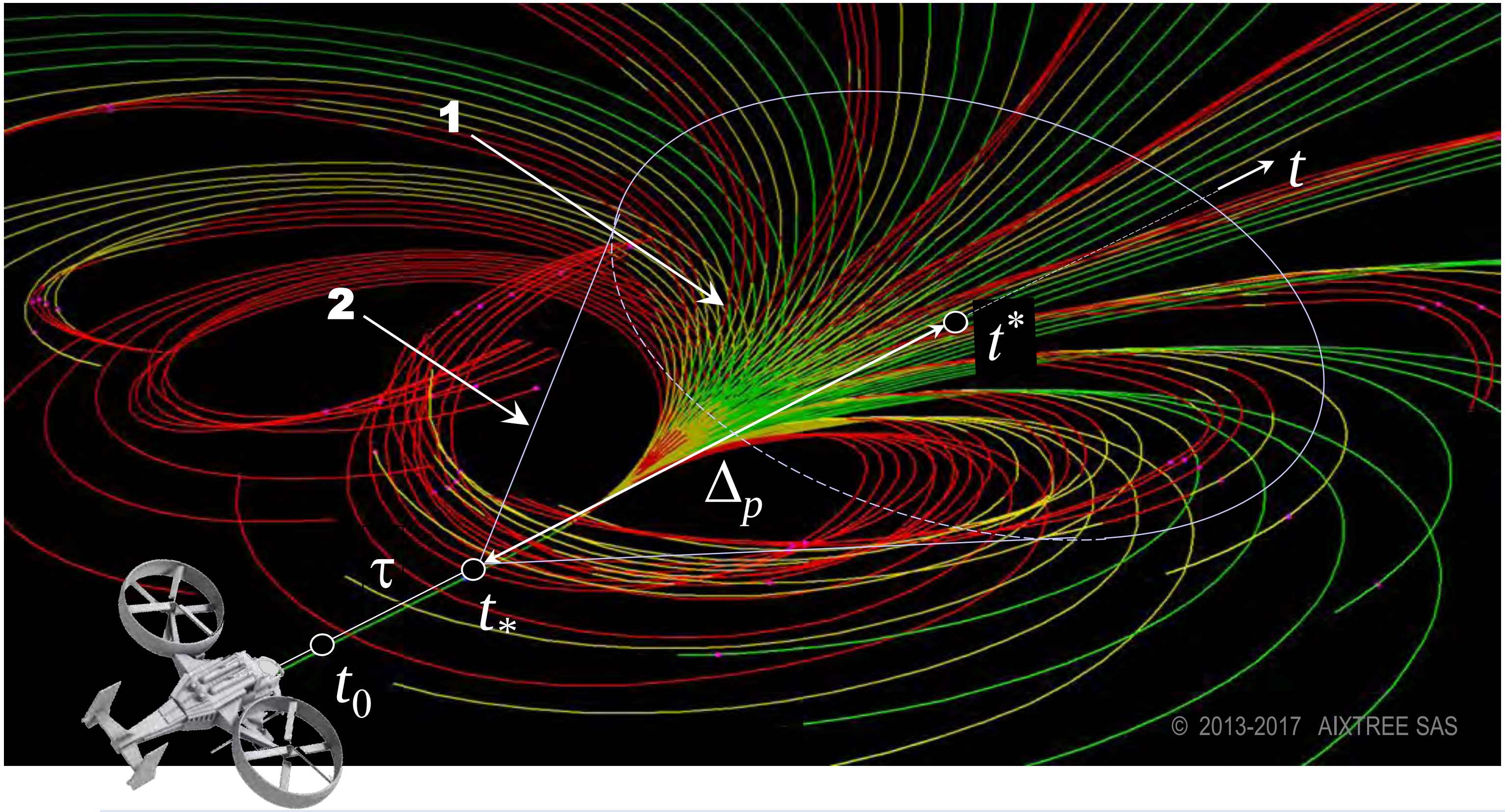
Future capability: safety prediction and protection (during mission, on board)



Legend: Not to scale. t – relative time of safety prediction, $t \in [t_0; t+\Delta]$ (t = 0 – current flight time, Δ – depth of safety prediction). Examples of situational tree's branches: 'stuck rudder' (***B***$_1$); 'left-hand engine out' (***B***$_2$); demanding weather conditions: 'strong' wind shear' (***B***$_3$), 'low visibility' (***B***$_4$). 🟦🟩🟩🟨🟧🟥⬛ – flight path safety colors: T – turquoise, G – green, S – salad, Y – yellow, A – amber, R – red, B – black). Flight path categories: optimal (**1**), safe (**2**), dangerous (**3**), catastrophic (**4**). (*) – see implementation examples in this presentation. (**) – conceptual layout.

Flight Safety Window and **Situational Forecast Display** maps can be used to prototype future ATM system's functions for flightpath prediction and envelope protection in complex/ uncertain conditions.

‘Intelligent Safety Suit’: Real-Time Prediction and Avoidance of Collisions for Small Autonomous Vehicles



Legend: Not to scale. **1** – situational tree used for short-term prediction of vehicle safety. **2** – multifactor domain/ cone for safety screening (forecast sub-tree). t_o – current flight time. t_* – forecast start time. t^* – forecast stop time. $\tau = (t_* - t_o)$ – decision making delay. $\Delta_p = (t^* - t_*)$ – time depth of safety screening. 🟩🟨🟥⬛ – integral safety spectrum colors.

The ‘Intelligent Safety Suit’ (ISS) is a concept of affordable onboard safety protection systems for autonomous vehicles, **including small UXVs**. It is based on Situational Tree, Integral Safety Spectra and Safety Window knowledge maps. The ISS system incorporates a **comprehensive situational knowledge base and real-time inference engine**. It is aimed at **flight path prediction and collision avoidance** in complex/ unknown operational domains.

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Comparison of Flight Research Techniques

7. User Benefits

Metric	Technique				
	FT	DM	MS	DS	SM
Insensitivity to the complexity level of a flight situation under study	-	-	-	-	+ *
Flexible 'what-if' flight **experimentation**	-	-	-	-	+
Easy **combining of several risk factors** in a flight scenario	-	-	+ **	+ **	+ *
System level exploration of complex cause-and-effect relationships of flight	+ **	+ **	+ **	+ **	+
Affordability of flight experiments	-	+	-	+	+
Autonomy (**independence of research pilot** and hardware)	-	+ **	-	+ **	+
Availability during lifecycle	+ **	+ **	+	+	+
Fast-time flight **experimentation**	-	-	+ **	+	+
Fidelity of flight research results	+	+ **	+ *	+ *	+ *

Legend: **FT** – flight test. **DM** – dynamically scaled flying model. **MS** – manned (piloted) flight simulator. **DS** – commercial desktop flight M&S software. **SM** – System Dynamics Model (**VFT&C** technique). **+** ('YES') or **-** ('NO') in matching the criterion. **(*)** – depends on the 'parametric definition' fidelity and completeness. **(**)** – limited capability.

Comparison of Flight Research Techniques

Metric	Technique				
	FT	DM	MS	DS	SM
Repeatability of flight scenarios. **Retention of scenarios** for future reuse	-	+ **	-	+ **	+
Generalized formal description of any baseline flight situation and its multifactor ('what-if') neighborhood'	-	-	-	-	+
Automatic exploration of 'what-if' neighborhood of a baseline situation	-	-	-	-	+
Automation of flight scenario planning task	-	+ **	-	-	+
Safety of flight experimentation	+ **	+ **	+	+	+
Suitability for training of line pilots, test pilots and test engineers	+ **	-	+ *	+ *	+ *
Automation of **safety knowledge mining and mapping**	-	-	-	-	+
Monitoring multiple operational constraints in flight experiments	-	-	+ **	+ **	+

Legend: see previous slide.

The VFTC technology is complementary to 'classic' flight research techniques, such as manned simulations, flight testing, wind tunnel testing, CFD, etc.

User Benefits

Benefit	User category					
	Designer (*)	Test Pilot / Engineer	Regulator	Educator / Instructor	Line Pilot / Operator	Investigator / Safety engineer
more **options of configuration/ equipment** (*) **'flown'** during design	🟦					
more thoroughly **verified algorithms** of automatic flight control and safety protection systems	🟦	🟦	🟦			
lower cost and shorter schedule of flight T&C cycle	🟦	🟦	🟦	🟦		🟦
less rework (redesign, retesting, rehearsal, retraining, etc.)	🟦	🟦		🟦		🟦
better preparedness of pilots & engineers for multifactor unknowns		🟦		🟦	🟦	
better focused programs of manned flight simulations and real tests		🟦	🟦	🟦	🟦	🟦
more ***ab initio*** **knowledge gained about a 'what-if off-nominal neighborhood'** of fight situations	🟦	🟦	🟦	🟦		🟦
enhanced flight safety in unusual/ unfamiliar operating conditions		🟦		🟦	🟦	
more thoroughly **screened complex operational domains** and more reliably validated aircraft airworthiness	🟦	🟦	🟦	🟦	🟦	

Legend: (*) - Aerodynamics, Flight Control, Powerplant, etc.

User Benefits

Benefit	User category					
	Designer (*)	Test Pilot / Engineer	Regulator	Educator / Instructor	Line Pilot / Operator	Investigator / Safety engineer
more **intelligent aids** for training (didactics, demonstration , etc.)		🟦		🟦	🟦	🟦
more **flexible flight scenario planning** and broader **scenario library**	🟦	🟦	🟦	🟦	🟦	🟦
more **efficient training** process (more affordable, shorter and deeper)		🟦		🟦	🟦	
better understood **safety margins** and accident precursors	🟦	🟦		🟦	🟦	🟦
deeper **knowledge about unsafe sub-domains** and their topology	🟦	🟦		🟦	🟦	
more **reliable identification of** a potential accident's causality		🟦		🟦	🟦	🟦
better **recommendations** on accident prevention/ reoccurrence		🟦				🟦
Legend: (*) - aerodynamics, flight control, powerplant, etc.						

Core benefits include: shorter **schedule**, lower **costs**, lower demand for **other resources** (materials, cadre, technology, etc.), higher **throughput**, and **much larger volume of a priori knowledge** about flight safety in off-nominal operating conditions.

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Pitfalls

Pitfall	Consequence
Imbalanced accuracy of component models in the system dynamics model, e.g. a mix of very detailed and simplistic components	Invalid simulation results
Lack of reference flight data for system model validation: flight test/ operation/ accident/ manned simulation data records	Impossible to validate system dynamics model
Errors in component models or in aircraft parametric definition	Invalid simulation results
Sensitive **data protection**. **Timely update** of a/c parametric definition.	Delayed/ slowed process
Use of the aircraft **flight physics model as a 'black box'**, without understanding its assumptions and limitations	Invalid simulation results
Errors in the aircraft '**parametric**' **definition**	Invalid simulation results
Incorrect setup of **operational constraints**	Distorted safety performance
Technology use outside the arguments range of aircraft 'parametric definition'	Invalid results of simulation and safety analysis
Inadequate setup of a baseline situation (**events/ processes**)	Incorrectly planted trees
Too sparse or too dense grid for quantification of risk factors	Missed/ overlooked safety flaws
Automatic flight control/ safety protection **algorithms not available**	Impossible to use technology

➡ At this stage, it is important to have **close cooperation links between the technology developers, users and customer management**.

Scientific and Technical Challenges

Problem/ challenge
Data standards for Information exchange: 'aircraft parametric definition owner – VFTC technology user'.
Information protection and exchange: 'aircraft flight test/operation/ simulation data owner – VFTC technology user'.
Availability/ accuracy of **mathematical description of unsteady aerodynamics** for boundary flight cases: high AoA, large sideslip, stall modes, spin, etc.
Availability of input data for **aero-elasticity effects** on flight physics
Availability of input data for **asymmetric aerodynamic configurations**
Availability of **mathematical description of automatic flight control system functions** for examined conditions and modes of flight.
Identification of a human **pilot model's parameters** for specific flight modes and conditions.
Development of **virtual/ augmented reality tools** for complex domain exploration (onboard/ off-board).
Accreditation of the **system dynamics model.**
Certification of the VFTC technology.
Other challenges.

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Conclusions

1. The internal situational knowledge base of a pilot has a **branching memory structure**, which is **subject to growth and decay for multifactor off-nominal operational sub-domains**.

The VFTC technology demonstrates the **potential to back up and/or reinforce a human pilot's situational awareness and decision-making** in non-standard flight situations for safety.

2. The technology is **complementary to classic flight research techniques in predicting aircraft/ project flight and safety performance** in complex/ unknown operational domains.

3. **Application sectors** (recommended):

- **design, in-depth analysis and rehearsal of off-nominal scenarios**: flight T&C, SOPs, accidents, etc.
- **a priori screening of large complex domains** of flight for unsafe anomalies.
- design and **validation of automated/ automatic flight control systems**.
- **accident/ incident** reconstruction and **'neighborhood' analysis** under uncertainty.
- **theoretical training** of pilots and engineers in branching system dynamics.
- **component prototyping of intelligent systems** – for autonomous missions, operator-vehicle interface, pilot training/ aiding/ cognitive backup, collision avoidance, flight envelope protection.

Conclusions

4. **Benefits**:

- **increased (10^3 …10^5 times) volume of predictive knowledge** (not data) about complex system dynamics and safety available early in the lifecycle (steeper learning curve).
- **better focused programs** of manned simulation research, flight test and certification.
- **substantially reduced volume** of manned flight simulations and flight tests.
- **essential savings of other resources** (time, etc.) on design, flight T&C and training.

5. **Pitfalls**:

- aircraft **'parametric definition'** - availability, 'richness' and validity ('rubbish in – rubbish out')
- **imbalanced component models** in the system dynamics model – mathematical fidelity, etc.
- **real flight/ simulator data records** for model validation – for a prototype, older type, etc.

6. **Challenges**:

- Aircraft type/ design project **information exchange**
- System dynamics model/ **technology accreditation**
- Mathematical **description of flight modes at the edge** of operational envelope - post-stall, large sideslip, aero-elasticity effects, asymmetric configurations, etc.

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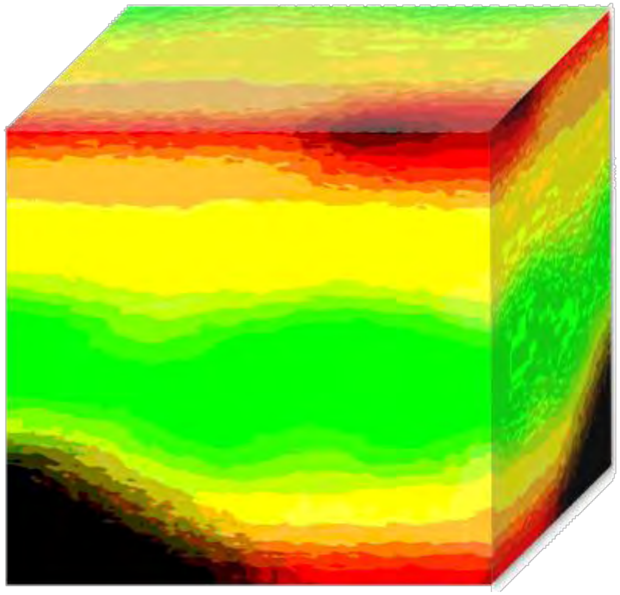
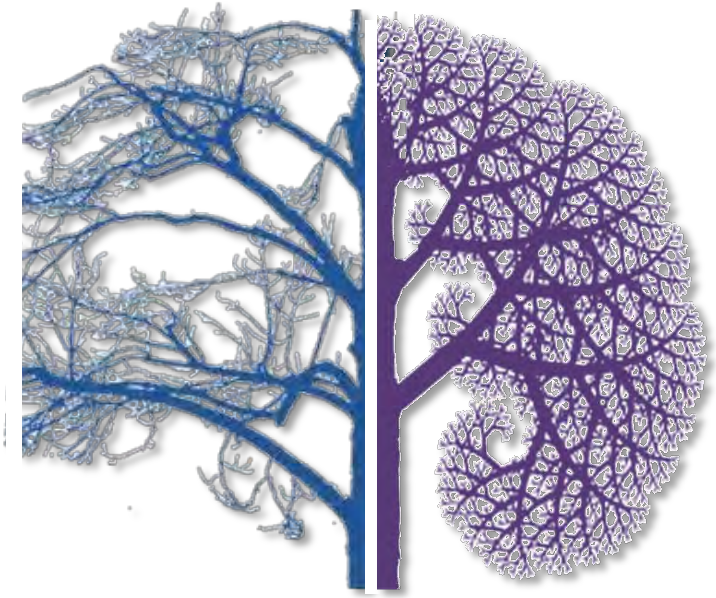
Thank You Very Much for Your Attention!





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