Anthropomorphic Knowledge Structures for Cognitive Flight Safety Protection Systems: Overview of Prototypes

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INTRODUCTION

Of considerable topical interest is the problem of securing flight safety for highly automated planes in the operating conditions that involve multiple heterogeneous risk factors. 'Trouble never comes alone'. Multifactorial risk scenarios are characterized by dangerous effects of the cross-coupling compositions of non-standard events and processes on the behavior of the 'pilot (remote operator) - automaton - aircraft - operating environment' system (the System). Such situations are a priori regarded as 'theoretically improbable'. They remain 'known unknowns' or 'unknown unknowns' due to budget, time and methodological limitations. As a result, the majority of multifactorial risk scenarios cannot be included in certification and qualification requirements. However, such 'unthinkable' situations do occur in flight operations, often leading to 'chain reaction' or 'black swan' type accidents.

A solution to the problem is proposed to be sought in the imitation and reinforcement of a human operator's cognitive functions at the situational-tactical level, by bringing on board the aircraft a comprehensive synthetic knowledge backup. The goal is to help the control agent (a pilot, a remote operator, or an automaton) perform the following functions (Amiryants, 2001; Pospelov, 1986): (1) recognition and associative analysis of the current multifactorial or unknown situation, (2) parallel 'what-if' short-term prediction of the aircraft flight dynamics and safety, and (3) situational decision making to alter the control tactic if there is a danger of irreversible violation of critical constraints.

In this presentation, an overview is given of the prototypes of synthetic anthropomorphic memory structures developed for prospective cognitive systems of flight safety prediction and enhancement under multifactorial and uncertain operating conditions. The technique is aimed to generate, accommodate, map and apply comprehensive knowledge of complex accident-prone operational domains and associated remedial control tactics. Presented are experimental knowledge structures of the cognitive support model for flight safety analysis and prediction in a single situation and in a set of 'what-if' situations. Implementation algorithms, data frames and examples of key knowledge structures are introduced. The process of scripting and virtual testing of realistically complex multifactorial scenarios is exemplified for major flight phases and demanding operating conditions. Advantages, pitfalls and unresolved issues of the technique are summarized. In the conclusion, avenues for further research and potential applications of the developed flight knowledge model are outlined.

PILOT'S COGNITIVE FUNCTIONS AND SITUATIONAL-TACTICAL KNOWLEDGE BASE

Representation of situational-tactical knowledge in long-term memory

The effectiveness of cognitive functions (the level of situational awareness and tactical expertise) of a human operator depends on the available knowledge of the System dynamics and piloting techniques in very rare but dangerous multifactorial risk situations. The material carriers of the operator's situational-tactical knowledge are tree-like neural structures of professional long-term memory. These results and conclusions published by neuroscientists (Gibson et al., 2011; Quartz et al., 1997; Holtmaat et al. 2009) match observations and conclusions made by test pilots (Amiryants, 2001). The larger the volume of the 'crown' of such a knowledge tree, the deeper and broader its branching in the directions of potential infringements of operational constraints, and the less void spaces, growth defects and other structural inconsistencies in the tree's 'phenotype', the higher the practical value of the knowledge base is.

The purpose of synthetic knowledge structures

The developed structures are intended for use as 'building blocks' in the generalized framework of an open upgradable synthetic situational-tactical knowledge base for flight safety applications. These knowledge structures are aimed to automate two groups of knowledge management tasks relating to complex operating conditions:

(1) accommodation (accumulation, retention, upgrade, refinement, verification, protection, etc.) of the knowledge base on a computer, and

(2) application (search, extraction, mapping, comparison, analysis, assessment, etc.) of a subset of knowledge, derived from the knowledge base, relating to the current flight situation and its 'what-if neighborhood'.

VIRTUAL FLIGHT TESTING AND SAFETY ASSESSMENT CYCLE

'Bird's eye view' layout

Figure 1 depicts a 'bird's eye view' layout of the automated cycle of aircraft virtual flight testing, safety knowledge mapping and assessment used in the study.

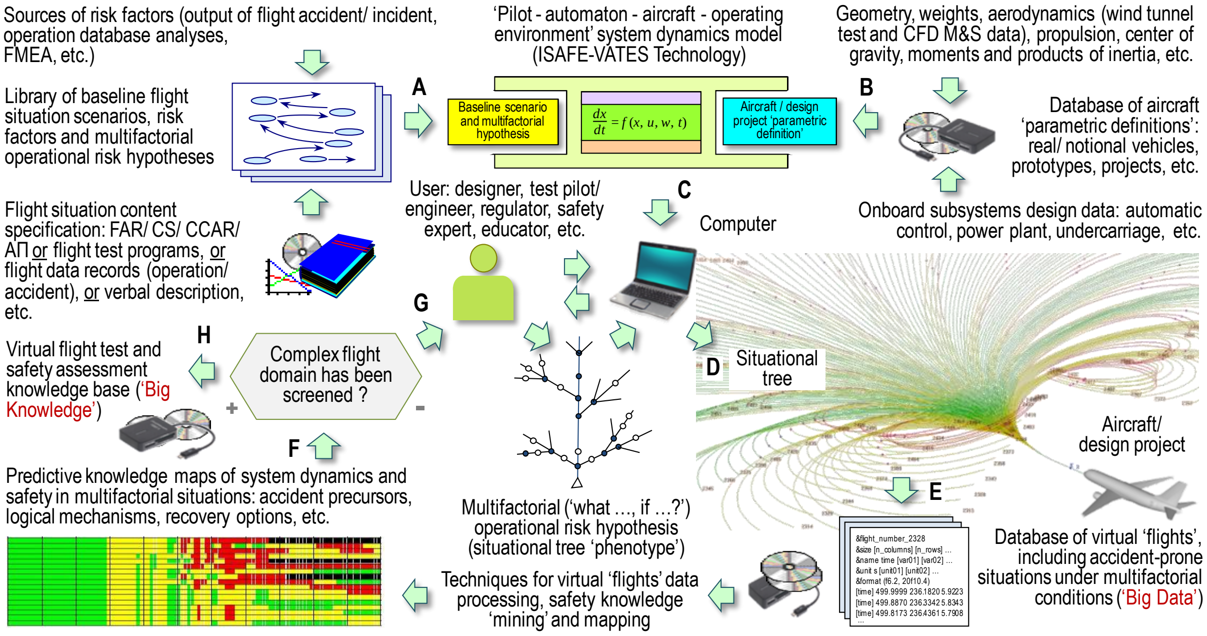

Figure 1: Virtual cycle of flight testing, safety knowledge mining, mapping and assessment.

Transforming 'Big Data' into 'Big Knowledge'

First, the scenario of a baseline situation and its multifactorial 'what-if' cases are formalized using the Flight Scenario Scripting Language, a list of the risk factors selected for testing, and a multifactorial risk hypothesis (Amiryants, 2001; Pospelov, 1986; Burdun, 2011).

The resulting set of multifactorial scenarios is then screened in autonomous fast-time (~1:200) simulation experiments using a high-fidelity mathematical model of the System dynamics and a special software tool for virtual autonomous flight testing and safety evaluation (the ISAFE-VATES technology (Burdun, 2019)).

SCREENING LARGE COMPLEX OPERATIONAL DOMAINS OF FLIGHT FOR SAFETY

Situational trees

As a result of composition of the baseline scenario and the designed multifactorial risk hypothesis, a situational tree of flight can be generated automatically, without a real research pilot in the simulation loop (see Figure 1). Such a tree can incorporate 10^2 ... 10^5 simulated branches (flight paths), which represent derivative variants (a 'what-if neighborhood') of the baseline situation (Burdun, 2011). For each phase of flight, a 'forest' of situational trees is 'planted' in accordance with comprehensive multifactorial risk hypotheses (tree 'phenotypes'). The multifactorial risk hypothesis can account for a specific aircraft type or design project, a control agent, an air route network, an operating environment, a pilot training syllabus, and/or a database of historic accidents and incidents.

Then, by using the output database of virtual 'flights', high-level information about the System dynamics and safety under tested operating conditions is 'extracted', 'granulated' and displayed on suitable knowledge maps for specific applications (Burdun, 2010). The developed knowledge structures are aimed to use in real time for monitoring flight state evolution and safety decision making. The latter two processes can be carried out by a human operator via a visual analytics interface, automatically by a cognitive system or jointly (Burdun, 2019).

Knowledge model of a large domain of complex flight situations

Figure 2 depicts anthropomorphic structures which constitute the conceptual framework of the generalized knowledge model of a large domain of complex flight situations.

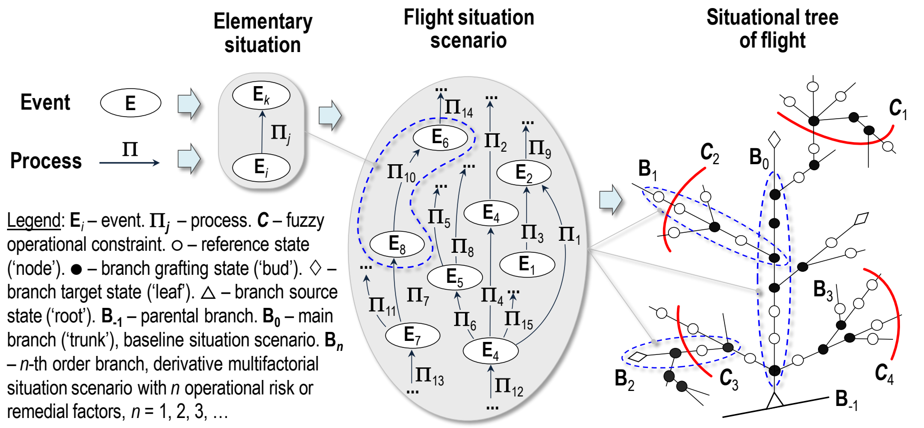

Figure 2: Generalized knowledge model of a large domain of complex flight situations.

Main structures of the flight knowledge model are: the event, the process, the elementary situation, the situation scenario, the fuzzy operational constraint, the baseline situation, the derivative situation, the multifactorial risk hypothesis, and the situational tree. These concepts are employed in concert to build a database of flight physics and control and a synthetic knowledge base of flight safety prediction and enhancement for a large set of multifactorial scenarios generated and screened in fast-time simulation experiments.

Safety assessment metrics

The following metrics are introduced to measure and compare technical characteristics of a synthetic knowledge base: the total virtual flight time on type (in hours), the distribution of the total flight time by risk factors, the distribution of flight situations by safety categories, etc. Several metrics are also used to assess and compare safety performance of single flight situations: safety index, safety category, level of complexity, etc.

EXAMPLES OF FLIGHT SAFETY KNOWLEDGE STRUCTURES

Selected examples of experimental anthropomorphic structures designed for mapping and analysis of safety related knowledge of complex flight domains are presented in Figure 3.

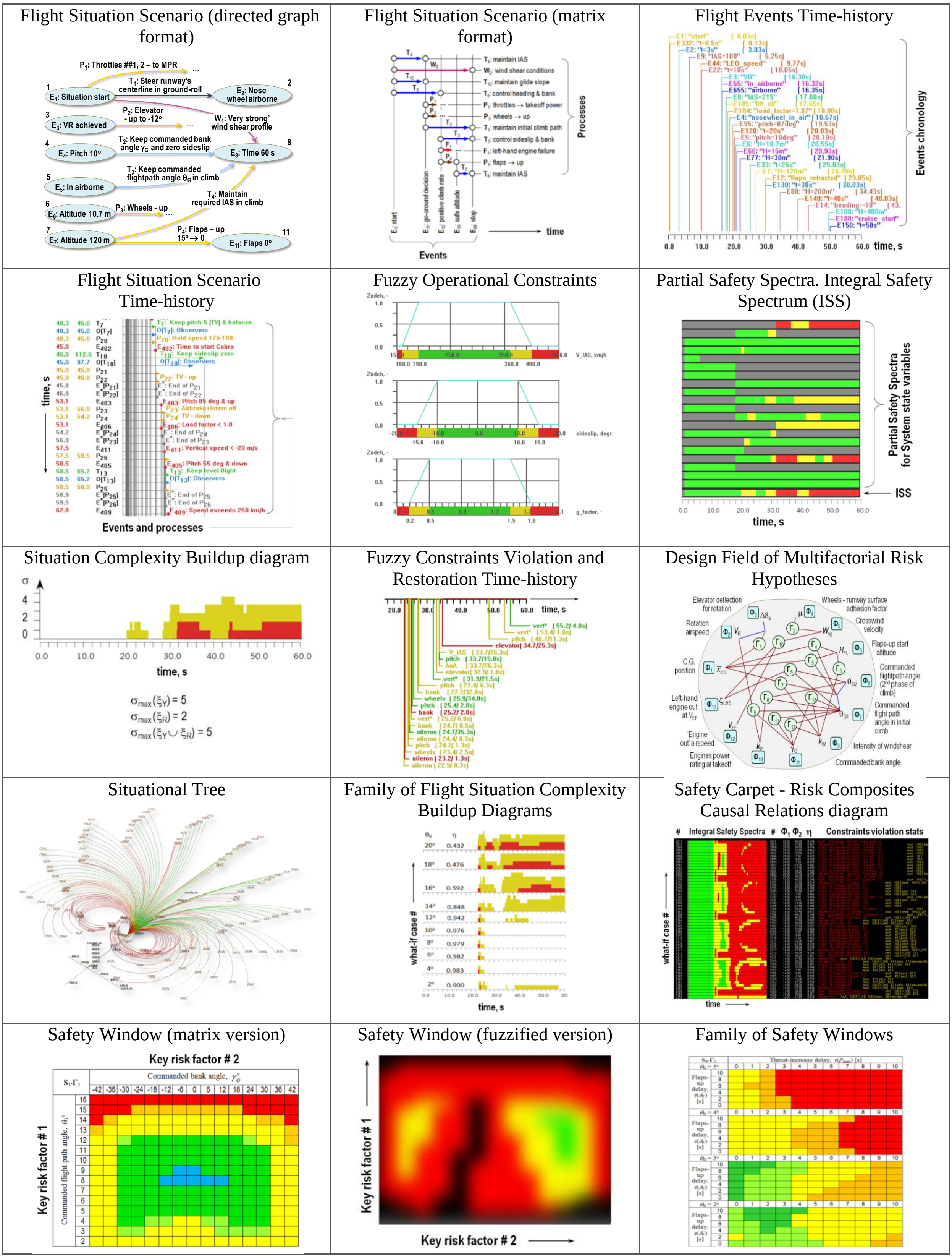

Figure 3: Examples of knowledge structures for flight safety mapping and analysis.

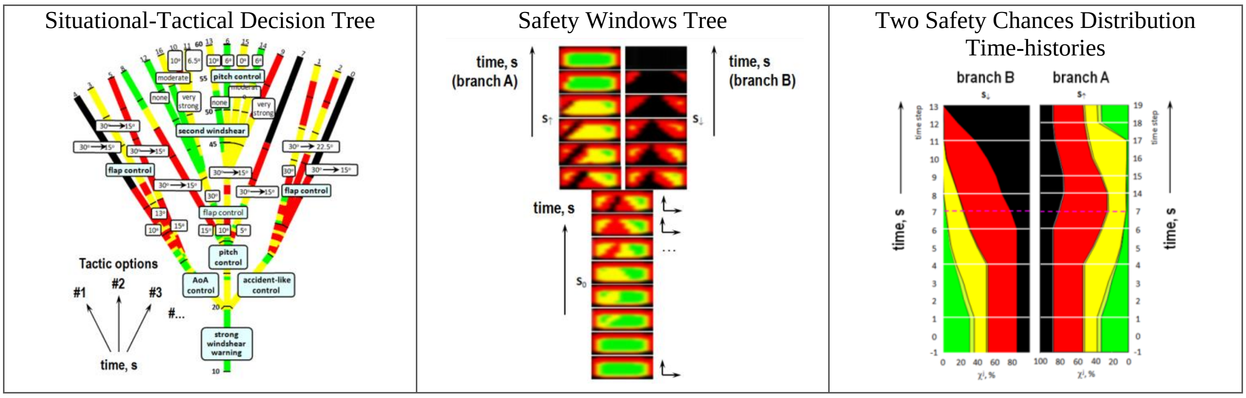

Figure 3: Examples of knowledge structures for flight safety mapping and analysis (continued).

CONCLUSION

The results of the study make it possible to formulate prospective application sectors and avenues of further research into anthropomorphic structures of situational-tactical knowledge for flight safety. These include: (1) automation of training, upgrade and validation of a knowledge base, (2) prototyping of a highly competent knowledge base with the total virtual flight time ~10^5 ... 10^6 hours on type, (3) development of 'artificial intelligence - natural intelligence' cognitive interface, (4) theoretical training and professional development of line pilots, test pilots/engineers and instructors, (5) demonstration and 'what-if' analysis of historic accidents and incidents on a manned flight simulator.

REFERENCES

Amiryants, G. A. (2001). *Test pilots. Sergei Anokhin and Associates*. Mashinostroyeniye Publishing House [in Russian].

Pospelov, D. A. (1986). *Situational Control. Theory and Practice*. Nauka Publishing House [in Russian].

Gibson, D. A., and Ma, Le. (2011). Developmental Regulation of Axon Branching in the Vertebrate Nervous System. *Development*, *138*. 183-195.

Quartz, S. R., and Sejnowski, T. J. (1997). The Neural Basis of Cognitive Development: A Constructivist Manifesto. *Behavioral & Brain Sciences*, *20(4)*. 537-596.

Holtmaat, A., and Svoboda, K. (2009). Experience-dependent Structural Synaptic Plasticity in the Mammalian Brain. *Nature Reviews. Neuroscience*, *10*. 647-658.

Burdun, I. Y., and Mavris, D. N. (1997). A Technique for Testing and Evaluation of Aircraft Flight Performance in Early Design Phases (Paper 975541). *Proceedings of the World Aviation Congress (WAC'97), October 1997, AIAA-SAE, USA.*

Burdun, I. (2011). Automated Planning, Exploration and Mapping of Complex Operational Domains of Flight Using Multifactor Situational Trees. *SAE International Journal of Aerospace*, *4(2)*, *USA*. 1149-1175.

Burdun, I. Y. (2019). *Aircraft Virtual Flight Testing and Certification in Off-nominal Multifactorial Situations* [Professional Development Course C1892]. SAE International, USA. Retrieved March 19, 2022, from https://www.sae.org/learn/content/C1892/

Burdun, I. (2010). Safety Windows: Knowledge Maps for Accident Prediction and Prevention in Multifactor Flight Situations (Paper 723). *Proceedings of the 27th Congress of the International Council of Aeronautical Sciences (ICAS 2010), 19-24 September 2010, ICAS, Nice, France.*