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An integrated graphic–taxonomic–associative approach to analyze human factors in aviation accidents

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Abstract Human factors are critical causes of modern aviation accidents. However, existing accident analysis methods encounter limitations in addressing aviation human factors, especially in complex accident scenarios. The existing graphic approaches are effective for describing accident mechanisms within various categories of human factors, but cannot simultaneously describe inadequate human–aircraft–environment interactions and organizational deficiencies effectively, and highly depend on analysts' skills and experiences. Moreover, the existing methods do not emphasize latent unsafe factors outside accidents. This paper focuses on the above three limitations and proposes an integrated graphic–taxonomic–associative approach. A new graphic model named accident tree (AcciTree), with a two-mode structure and a reaction-based concept, is developed for accident modeling and safety defense identification. The AcciTree model is then integrated with the well-established human factors analysis and classification system (HFACS) to enhance both reliability of the graphic part and logicality of the taxonomic part for improving completeness of analysis. An associative hazard analysis technique is further put forward to extend analysis to factors outside accidents, to form extended safety requirements for proactive accident prevention. Two crash examples, a research flight demonstrator by our team and an industrial unmanned aircraft, illustrate that the integrated approach is effective for identifying more unsafe factors and safety requirements.

1. Introduction

Rapid development in technology has remarkably reduced rates of aviation accidents attributable to aircraft failures; thus, human factors, which have been implicated in 70%–80% of all aviation accidents,[1] become prominent in modern aviation accidents.[2–4] Among the research studying human factors in aviation, accident and accident causation analysis remain worldwide concerned themes.[5] Two key problems on accident causation analysis are: (a) how to identify unsafe factors from

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accident processes as completely as possible, and (b) how to define and represent accident mechanisms, or relations, among the unsafe factors.

In terms of unsafe factors, Edwards classified accident causes by human individual, hardware, software, and environment in his software–hardware–environment–liveware (SHEL) model.[6] Hawkins further modified the SHEL model into software–hardware–environment–liveware–liveware (SHELL) model by introducing another liveware element.[7] In the Domino model by Heinrich,[8,9] the man-made disaster theory by Turner,[10] and the Swiss cheese model by Reason,[11] management and organizational perspectives were taken into account. Based on Reason's framework, Wiegmann and Shappell further extracted systematic human error taxonomy from U.S. Navy aviation accidents, and set up the human factors analysis and classification system (HFACS).[1] Instead of examining how accidents happen, Roberts adopted a positive point of view and studied the characteristics that make high reliability organizations (HRO) perform safely.[12] Effects of legislation, government management, and regulation were further considered in the accident map (AcciMap) approach by Svedung and Rasmussen,[13] and also in the systems-theoretic accident model and processes (STAMP) method by Leveson.[14] Recently, the original SHELL model was modified into software–hardware–environment–liveware–liveware–organization (SHEL-LO) model by Chang and Wang through incorporating an organizational block into the SHELL framework.[15] Among all aforementioned approaches, the HFACS is most extensively used in current aviation industrial community due to the wide coverage and high reliability rising from its inductive nature.[1,16–20]

In view of the relations among accident factors, Edwards[6] and Hawkins[7] viewed accidents as results of inappropriate interactions among human, aircraft, and environment in the SHEL and SHELL model. Heinrich, in his Domino model, considered accidents as consequences of single-channel sequential chains from society to individual.[8,9] Differently, Reason defined accident mechanism as failures of safety defenses in socio-technical system layers.[11] Perrow, in his normal accident theory, believed that accidents of complex and tight-coupling systems are normal and unavoidable.[21] In contrast, Roberts considered that patterns and characteristics of safe operations in HROs could be understood and applied to safety management of other hazardous industries.[12] Nielsen, in his cause-consequence chart (CCC), viewed accident mechanism as cause-consequence relations among multiple unsafe events.[22] Svedung and Rasmussen further introduced control concept into CCC and established their AcciMap approach.[13] Leveson, in her STAMP, defined ''control'' as ''constraint'' and believed that accidents are caused by failures of safety constraints in socio-technical control structures.[14] More recent studies by Bakolas and Saleh further introduced control theory like controllability into system-perspective models.[23] A systematic review of accident causation studies can be found in a review paper by Saleh et al.[24]

As for representation of accident mechanisms, the SHELL framework and the Swiss cheese model use language-based narration to describe accident causes and mechanisms. Moreover, these two model schematics are concise to illustrate the model concepts, but not practicable enough for modeling the complex, interactive evolvements of accidents.[1,4,7,11] Among graphic accident analysis approaches, the fault tree analysis is effective for studying aircraft failures,[25,26] rather than identifying human factors.[24,27] The STAMP adopts control structure charts to describe the normal safety constraints between socio-technical levels, and represents the evolvements of accident factors by system dynamic charts.[14] Using system dynamic charts, Marais et al.[28] and Kontogiannis[29] further proposed archetypes modeling dynamic organizational behaviors and human processes that lead to accidents. The CCC and AcciMap use a network structure to describe the cause-consequence relationships among unsafe events of multiple socio-technical levels.[13,22] Recently, Debrincat et al. tried to integrate the Swiss cheese framework into the AcciMap model to identify safety defense failures inside unsafe events of the AcciMap model.[30]

Some Chinese scholars have applied the SHELL model[31] and the HFACS[32,33] to aviation accident analyses. Based on the SHELL model, Zhang and Wang developed a multi-level fuzzy method for aviation safety evaluation.[34] Ma et al. developed a Chinese civil aviation human error analysis system (CN-HFACS) based on multiple Chinese civil aviation accidents.[35] Wang Y G and Wang Y integrated business process management into the HFACS, and developed a multidimensional model for human factor analysis.[36] Xiang et al. integrated the triggers event result (TER) and the SHELL model into Reason's model, and developed an R-S-TER model for analyzing human factors in unsafe aviation events.[37] Wang J and Yang proposed an ontology-based approach for human factors analysis of unsafe events in air traffic systems.[38] Gong et al. developed a method for hazard identification of turbofan engine digital control systems based on functional hazard analysis (FHA).[39] Recently, Sun and Zhao developed an event classification analysis and recommendation (ECAR) model for human error analysis of aviation occurrence.[40]

A limitation we encountered when applying previous approaches to aviation accident analyses is that most aviation accidents involve both inadequate human–aircraft–environment interactions and organizational deficiencies; while among existing approaches, only the AcciMap model addresses both aspects simultaneously, which is based on a parallel hierarchical structure with less effective description of human–aircraft–environment interactions and interfaces between any two parts of human–aircraft–environment integration. The second limitation is that the current graphic approaches adopt entirely subjective ways to determine unsafe events for accident modeling,[5,13,14,25,26,30,41] showing a need for identification of complete unsafe factors with less dependence on analysts' skills and experiences.[5,13,30] The third concern is that the existing approaches help identify accident factors in a reactive way, or focus on factors that have been indicated in accidents. Obviously, proactive approaches for identification of potential hazards outside the accidents and preventive control of risks are preferred for future operations.

Starting from a new graphic approach named AcciTree for accident modeling, this paper is dedicated to progress through the above three limitations in aviation accident analysis and prevention.