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Abstract

Aircraft incident reconstruction plays a pivotal role in aviation safety by enabling comprehensive analysis of accident sequences, identification of causal factors, and formulation of effective preventive strategies. Increasing aircraft system complexity, extensive onboard sensing, and the availability of large-scale flight operational data have exposed the limitations of conventional reconstruction approaches that rely primarily on deterministic models and manual investigation. Reinforcement learning has emerged as a promising computational paradigm capable of learning sequential decision-making policies through continuous interaction with high-fidelity simulation environments. This chapter presents a comprehensive review of reinforcement learning for simulated scenario reconstruction of aircraft incidents, emphasizing its potential to generate realistic flight trajectories, optimize reconstruction policies, and model complex interactions among pilots, aircraft systems, and environmental conditions. Fundamental concepts of aircraft incident reconstruction, reinforcement learning principles, deep reinforcement learning architectures, aircraft simulation environment design, reward function engineering, and intelligent flight data processing are systematically examined. Recent developments in digital twin technology, multi-agent reinforcement learning, explainable artificial intelligence, and counterfactual scenario generation are discussed to highlight their contributions to improving reconstruction fidelity, operational interpretability, and decision support. Current research challenges, including simulation-to-reality transfer, sparse reward optimization, computational scalability, safety constraints, and regulatory considerations, are critically analyzed. The chapter concludes by outlining future research directions toward autonomous, interpretable, and high-fidelity reconstruction frameworks that strengthen aviation accident investigation, enhance pilot training, improve operational risk assessment, and support the continuous advancement of global aviation safety.

Keywords: Reinforcement Learning, Aircraft Incident Reconstruction, Deep Reinforcement Learning, Digital Twin, Multi-Agent Reinforcement Learning, Aviation Safety.

Introduction

Aircraft incident reconstruction has become an indispensable component of modern aviation safety because it provides a systematic understanding of the sequence of events that precede abnormal flight operations, serious incidents, and accidents [1]. Every aviation occurrence results from a complex interaction among aircraft systems, pilot decisions, environmental conditions, operational procedures, and organizational factors rather than a single isolated event. Accurate reconstruction of these interactions enables investigators to determine causal relationships, evaluate aircraft performance under adverse conditions, and formulate recommendations that improve operational safety [2]. Continuous advances in aircraft technology have transformed commercial and military aviation into highly integrated cyber-physical systems equipped with sophisticated avionics, digital flight control systems, advanced navigation technologies, and intelligent monitoring capabilities. Such technological evolution has significantly increased the volume, diversity, and complexity of operational data generated during every phase of flight [3]. Flight Data Recorders, Cockpit Voice Recorders, Automatic Dependent Surveillance–Broadcast systems, onboard health monitoring units, weather sensing platforms, and air traffic management infrastructures collectively generate extensive datasets describing aircraft behavior and operational environments. Extracting meaningful information from these heterogeneous data sources requires computational techniques capable of identifying intricate temporal relationships and dynamic interactions among numerous operational variables. Conventional accident investigation procedures have relied primarily on engineering analysis, expert interpretation, and deterministic simulation models that reproduce recorded flight events based on predefined assumptions [4]. Although these methodologies have established strong foundations for aviation safety investigations, increasing aircraft automation and operational complexity demand intelligent analytical frameworks capable of reconstructing realistic scenarios with greater adaptability, precision, and computational efficiency. Such developments have created substantial interest in advanced artificial intelligence techniques that support comprehensive incident reconstruction while strengthening evidence-based aviation safety analysis [5].

Artificial intelligence has transformed numerous engineering disciplines by enabling computational systems to learn complex relationships directly from data rather than relying exclusively on manually designed analytical rules [6]. Aviation has benefited considerably from this technological progress through intelligent applications in predictive maintenance, air traffic management, autonomous navigation, flight trajectory prediction, anomaly detection, weather forecasting, aircraft health monitoring, and operational decision support. Machine learning and deep learning algorithms have demonstrated remarkable capability in processing large-scale aviation datasets characterized by high dimensionality, nonlinear behavior, and temporal dependencies [7]. These technologies have improved the detection of operational anomalies, optimized maintenance scheduling, enhanced flight efficiency, and supported proactive safety management across diverse aviation domains [8]. Even with these achievements, many existing artificial intelligences approaches primarily address classification, regression, or prediction tasks using supervised learning paradigms that depend on labeled historical datasets. Aircraft incident reconstruction presents a fundamentally different computational challenge because accident progression evolves through continuous interactions among pilots, aircraft systems, environmental disturbances, and operational decisions over extended periods [9]. Successful reconstruction requires computational models capable of understanding sequential dependencies, evaluating long-term consequences of control actions, and adapting to continuously changing flight conditions. Such requirements extend beyond the capabilities of conventional supervised learning models and establish the need for learning frameworks specifically designed to solve sequential decision-making problems within complex and uncertain operational environments [10].