Engineering Innovation in Aerospace Industry: Review of Technology Applications and Challenges for a Sustainable Future

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1st Ike Yuni Wulandari
Electrical Engineering
Nurtanio University
Bandung, Indonesia
ikeyuni@unnur.ac.id

2nd Heni Puspita
Electrical Engineering
Nurtanio University
Bandung, Indonesia
henipuspita@unnur.ac.id

3rd Johanes Adi Prihantono
Electrical Engineering
Nurtanio University
Bandung, Indonesia
johanesadi@unnur.ac.id

4th Andriana
Electrical Engineering
Langlangbuana University
Bandung, Indonesia
andriana6970@unla.ac.id

5th Narwikant Indroasyoko
Automation Engineering
Manufacturing Polytechnic
Bandung, Indonesia
asyoko@polman-bandung.ac.id

6th In'ya Yuri Atasi
Design Engineering
Manufacturing Polytechnic
Bandung, Indonesia
inyayuri@de.polman-bandung.ac.id

***Abstract*—The impact of technological engineering applications is crucial for the sustainable future of the aerospace industry. Advancements in maintenance activities and human reliability analysis need to be explored. Therefore, the purpose of this study is to examine the aspects that support domains characterizing future technological engineering innovations in aerospace. Relevant literature on technical information and industry development trends is explored to reveal the trends and challenges in implementing technology within the aerospace field. Challenges in the field of Human Reliability Analysis (HRA), HRA reviews, methods, and data sources are presented. This paper anticipates system failures, provides technical insights, and assesses the readiness of human resources in managing the reliability of complex aerospace industry systems. The paper also emphasizes the importance of synergy between frameworks to ensure comprehensive reliability in the aerospace industry.**

***Keywords*— aerospace industry analysis; application of reliability engineering; aerospace technology challenges**

I. Introduction

For the industry to produce equipment that aligns with its operational objectives, systems must have the ability to predict failures. Reliable systems help reduce the risk of downtime and increase productivity by identifying problems early. Previous studies have suggested that reliable systems improve production efficiency and ensure that products meet the quality and reliability standards expected by users [1]. Innovation in the aerospace industry is highly dependent on technological advancements that enhance efficiency and global competitiveness. Innovations in this field enable the development of more advanced and safer industrial equipment, lighter aircraft, and more fuel-efficient equipment [2][3]. These innovations also contribute to improving flight safety, expanding space exploration, and generating environmentally friendly solutions. All of these factors help address future challenges while meeting the growing demands of the industry.

The aerospace sector requires increased efficiency and innovation, as well as enhanced reliability and safety, as a result of technological adoption. Artificial intelligence (AI), the Internet of Things (IoT), and big data analytics are some of the technological advancements that have supported the aerospace industry. Various sensors connected to the Internet of Things (IoT) can collect real-time data from aircraft machines and systems, improving operational efficiency and reducing the risk of failure [4][5]. Data analysis for predictive maintenance helps extend component lifespan and reduce downtime. Additionally, the innovation cycle is accelerated, and aircraft components can be manufactured with greater precision using 3D printing technology. Therefore, this paper will discuss:

1. Are there any new trends emerging to address reliability in the aerospace industry sector?
2. What are the challenges faced by the aerospace industry when applying reliability science?

Therefore, research is needed to expand the scope of investigation and broaden insights with the support of previous studies. Additionally, the application of models in the industry still faces challenges in data collection techniques (both failure rates and transition probabilities) and the measurement of monetary benefits, which need to be addressed [6]. A more balanced analysis is presented regarding the reliability approach in each domain to identify them.

II. Literature Review

A. Reliability of the aerospace industry sector

Approaches to addressing the reliability of electronic devices and equipment have become a major focus for researchers, particularly due to significant paradigm shifts, starting from microelectronics and evolving into power electronics applications. Currently, approximately 70 percent of all electrical processes are heavily influenced by the use of power electronics applications [7]. This indicates that power electronics play a significant role in various modern electrical systems, whether in the industrial, transportation, or energy consumption sectors. Power electronics function to control, convert, and efficiently distribute electrical energy, thereby supporting the operation of various devices and systems that require optimal energy management.

In complex electronic systems, there are three main categories of engineering approaches: model-based, data-based, and knowledge-based approaches [8][9]. The model-based approach includes statistical techniques and Physics of Failure (PoF), which describe system degradation by considering the underlying physical understanding [10][11]. The data-based approach relies on models that learn patterns from historical system data. Its learning capabilities allow this method to detect anomaly patterns, classify failure patterns, and predict degradation trends [12][13].

High-quality components support consistent, safe, and disturbance-free system performance. Unlike the manufacturing or energy industries, which focus on efficiency and minimizing downtime, in aerospace, reliability has an additional dimension due to operation in extreme conditions and a higher level of risk that necessitates redundancy, precision, and rigorous testing to ensure flight safety. Both sectors require preventive maintenance and continuous monitoring approaches to ensure that vital components function according to specifications under varying operational conditions.

B. Maintenance Management

In light of the complexity of the aerospace industry, maintenance concepts must be updated. Maintenance actions refer to the activities carried out in the field, such as preventive or corrective maintenance. Maintenance policies that need to be implemented include time-based or condition-based maintenance, encompassing actions, policies, and decision frameworks that aid in the planning and execution of maintenance activities [20]. In the literature, there are two categories of maintenance management models: declarative models and process-oriented models [21]. Declarative models consist of maintenance system components that are disconnected from one another, meaning the flow of information between parts is not visible. Declarative models also lack a clear implementation methodology and do not utilize advanced maintenance techniques. Responsibility, authority, and communication should be the main focus of management. In contrast, process-oriented models provide a clearer flow of information among their components, where system inputs and outputs are sometimes represented. Both models consider human resource management as a central focus.

The purpose of maintenance optimization models is to ensure that investments made in assets and maintenance activities can be optimized. These models can be limited or unlimited, static or dynamic, deterministic or probabilistic, and continuous or discrete. Researchers and practitioners have developed specific performance models tailored to various performance standards to evaluate maintenance performance. Several approaches include economic and technical approaches, strategic approaches, system audits, and functional approaches that focus on statistics, reliability, and maintenance.

High expectations are placed on the use of e-maintenance, which integrates information and communication technologies into maintenance strategies, aligning with the current data revolution. E-maintenance enables remote operations such as collaborative decision-making or expert interventions, as well as more efficient reporting once implemented [22]. Additionally, an emerging trend in aerospace maintenance that is relevant to general maintenance industries is the reassessment of maintenance procedure errors. Due to collaboration between researchers and industry practitioners, interest in this topic has grown since 2000 [23]. Organized maintenance design will reduce both maintenance costs and time [24].

In addition, skill and communication training programs need to be integrated into employee training programs [25][26]. These findings are part of a broader context, which explores how employees can apply safety, influenced by the organization's overall commitment to safety and the level of employee satisfaction [27][28]. Communication has been identified as one of the most fundamental human factors contributing to human errors [29]. Communication is critical in aviation [30][31], as poor communication can lead to accidents [32]. Recent studies on flight maintenance have shown that communication and trust are closely related to safety [33][31].

Systems cannot be effectively addressed without considering the analysis of human resources as key actors. Several studies show that 24% of major errors are caused by human factors, while errors in tasks such as design, inspection, testing, calibration, and maintenance account for nearly 57% of total errors over the past decade [34]. Human error, combined with equipment failure, can lead to significant damage, even when the design has been well-executed and complete safety measures are in place [35]. Researchers propose several additional policies, such as age-replacement policies (ARP), preventive maintenance policies, and repair policies. [36] suggests that removing aged components is the best way to implement an ideal timed replacement plan.

C. Challenges

At present, there are many difficulties in applying reliability science in the aerospace industry. In this article, we attempt to identify the most common issues, particularly those related to the interactions between systems and their components. With distributed, interconnected service systems, it has become increasingly challenging to analyze the potential failure of components and their effects on the network. Moreover, the theoretical assumptions underlying risk analysis and reliability engineering are often misaligned with the current state of systems. This misalignment creates challenges related to the discipline of complexity science [37]. Some key issues that need attention include the lack of research on human error behavior and limitations in its implementation, the mismatch between factors affecting human behavior in specific industries, and the difficulty in obtaining relevant data sources [38].

Risk management and the representation of uncertainty in complex systems remain relevant topics of debate among researchers. In the context of interconnected and dynamic systems, the challenges of identifying, analyzing, and managing risks have become increasingly complex [39]. Researchers continue to strive to develop effective methods and models to understand how uncertainty can affect system performance and how risk management strategies can be implemented to mitigate negative impacts. This discussion encompasses a range of perspectives, from data-driven quantitative approaches to more holistic qualitative frameworks, resulting in diverse viewpoints on the best ways to address uncertainty and risk in complex systems.

In addition, aviation faces challenges posed by future technologies. Various studies have highlighted the roles examined in ensuring safety in the aviation field. Advanced technologies that are currently developing, such as machine learning (ML), the Internet of Things (IoT), and cloud computing, have also been integrated to enhance aviation safety. One of the necessary technologies is eye-tracking technology. Currently, advancements in materials, sensors, artificial intelligence (AI), and other technologies have driven significant progress in eye-tracking hardware and software [40]. Eye movements are used to monitor the operator's mental condition in real-time and provide a reference for efforts to improve operator awareness during flight. However, the broader use of eye-tracking technology, encompassing various roles in aviation, has yet to be fully optimized. Furthermore, the real-time application of this technology is still limited, as raw data preprocessing requires a considerable amount of time [41].

III. Discussion

In this section, we will address the questions posed at the beginning of the paper.

A. Are there any emerging trends in addressing reliability in the aerospace industry?

Ongoing advancements in technology and innovation have sparked the discovery of new solutions to address reliability issues in the aerospace industry. With the development of technologies such as big data analytics, artificial intelligence, and advanced sensors, the aerospace sector is now capable of predicting component failures and proactively responding to them before problems arise [42][2]. These solutions not only enhance the reliability of aircraft and aerospace systems but also reduce operational costs and improve flight safety. Furthermore, the implementation of condition-based maintenance and Internet of Things (IoT) technologies enables real-time monitoring of component performance, providing deeper insights into operational conditions and potential risks.

Power electronics also plays a significant role in various modern electrical systems, making it a key component in the industrial, transportation, and energy consumption sectors [43][1]. In the aerospace industry, power electronic devices enable high efficiency and energy savings in production processes. In transportation, this technology supports the development of electric vehicles and more efficient propulsion systems, contributing to emissions reduction and enhanced sustainability. Furthermore, in the context of energy consumption, power electronics plays a crucial role in energy management and distribution, particularly in renewable energy systems.

B. What are the challenges faced by the aerospace industry when applying reliability science

There are still many unresolved challenges, particularly regarding human reliability. According to [44], humans are significant contributors to system failures, primarily due to human weaknesses. Nonetheless, humans remain a vital component for the overall performance of aerospace missions. Human involvement encompasses all aspects of the system, from design, construction, and maintenance to testing, operation, and decommissioning. Even in automated systems, human errors can still occur and significantly impact system performance. In the aerospace industry, this can lead to catastrophic consequences, such as damage to hardware, loss of scientific knowledge, or even loss of life. The main challenges faced by the aerospace industry are summarized in Table 1.

Table 1. Challenges in the Aerospace Industry

No	Theme	Challenges
1	HRA [44]	Human errors The use of HRA methods to measure error probability Probabilistic Risk Assessment Human Error Rate Prediction Techniques Accident Sequence Evaluation Program Human Cognitive Reliability Experiment Human Error Analysis Techniques
2	Method [45][46]	digital human-system interface (HSI) relevant performance shaping factors (PSFs) quantitative empirical studies
3	HRA Study [37][38]	psychological and spiritual factors have a significant impact on human error processes and mechanisms causing human error
4	Data [47][48]	Fuzzy Virtual

IV. Conclusion

This study investigates the trends and challenges of reliability engineering applications through the analysis of the aerospace industry. New application areas result in more stringent requirements in reliability and drive the sophistication of the discipline. Recent innovations respond to the reliability of the aerospace industry sector to reduce operational failures and reduce greater potential risks. Challenges in the aerospace industry can be anticipated through the Human Reliability Analysis (HRA) approach and an in-depth study of the factors that affect human performance in operations. Engineering approaches such as the Fuzzy Logic method can be used to analyze and measure the level of human performance more accurately. Performance data presented in the form of fuzzy values allows for more comprehensive and flexible decision making under conditions of uncertainty, thus providing better predictions of potential risks and improving the reliability of the aerospace system as a whole.

This paper provides an overview of the concepts and challenges in reliability engineering; however, a more in-depth discussion of specific applications in the aerospace industry still needs to be developed. Illustrations and practical implications also require further exploration. Including empirical evidence would strengthen the findings of this paper and help guide future research.

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