IEEE Access
Multidisciplinary ⋮ Rapid Review ⋮ Open Access Journal

Received 24 July 2023, accepted 9 August 2023, date of publication 15 August 2023, date of current version 22 August 2023.

Digital Object Identifier 10.1109/ACCESS.2023.3305325

TOPICAL REVIEW

AI and Blockchain Synergy in Aerospace Engineering: An Impact Survey on Operational Efficiency and Technological Challenges

YUSRA ABDULRAHMAN[1], **EDIN ARNAUTOVIĆ**[2], **VLADIMIR PAREZANOVIĆ**[1], **AND DAVOR SVETINOVIC**[2,3], **(Senior Member, IEEE)**
[1]Department of Aerospace Engineering, Khalifa University of Science and Technology, Abu Dhabi, United Arab Emirates
[2]Department of Information Systems and Operations Research, Vienna University of Economics and Business, 1090 Vienna, Austria
[3]Department of Electrical Engineering and Computer Science, Khalifa University of Science and Technology, Abu Dhabi, United Arab Emirates

Corresponding author: Davor Svetinovic (dsve@acm.org)

ABSTRACT This paper presents an exhaustive investigation into the potential of integrating blockchain and Artificial Intelligence (AI) technologies within aerospace engineering, explicitly emphasizing supply chain management and operational efficiency. Given the decentralized nature of blockchain, it has the potential to enhance diverse facets of an aircraft's lifecycle management significantly. At the same time, AI stands to revolutionize predictive supply chain models and structural fault detection. This paper provides a comprehensive overview of the current state, potential applications, challenges, and future research directions in this field based on an analysis of previous relevant literature. Further, it compares blockchain technology against traditional record management systems, underlining its data storage, security, transparency, and traceability advantages. Although these technologies promise significant advancements, many legal, regulatory, and technological readiness issues need addressing for broader acceptance within the industry. The findings highlight the importance of targeted research and development to unfold an array of new applications, driving innovation in aerospace engineering. This paper serves as a comprehensive survey for researchers, practitioners, policymakers, and industry stakeholders, illustrating the transformative potential of AI and blockchain in the aerospace sector.

INDEX TERMS Blockchain, artificial intelligence (AI), management, aerospace industry.

I. INTRODUCTION

Aerospace engineering, a specialized discipline, is concerned with designing and developing aircraft and systems for commercial and military applications. The demands for unparalleled efficiency and precision in aerospace operations necessitate the deployment of cutting-edge technologies. Despite significant technological advances, an ongoing requirement for enhanced security and reliability persists to ensure operational efficiency and safety in this sector [1].

Given its tightly regulated landscape, the aerospace industry adheres to strict safety standards that require rigorous data integrity and robust system resilience [2]. A breach in the security or reliability of aerospace operations could lead to severe consequences, potentially causing substantial financial losses or endangering human lives. Thus, exploring innovative solutions capable of addressing these challenges and enhancing the industry's overall performance is paramount.

Recently, blockchain and Artificial Intelligence (AI) have emerged as two transformative technologies with the potential to reshape various sectors, including aerospace engineering. Blockchain, initially recognized through the advent of Bitcoin cryptocurrency, has proven its unique ability to facilitate a shared economy and set the stage for the contemporary digital currency market. The true potential of blockchain lies in its robust security and privacy preservation capabilities, making it a pioneering technology in data protection and confidentiality [3].

Blockchain technology provides a decentralized, immutable ledger for secure information storage and sharing.

The associate editor coordinating the review of this manuscript and approving it for publication was Genoveffa Tortora.

As a distributed computing system, blockchain allows its databases to be spread across multiple machines, forming an indelible record of transactions [4], [5]. Given its widespread use in smart contracts and cryptocurrency, blockchain is heralded as one of the most promising information technologies [6]. Current research is actively exploring the potential applications of blockchain in areas such as supply chain management, asset management, and, specifically, the aerospace industry [7].

Conversely, AI is a transformative force capable of significantly altering various aspects of life. It involves the development of intelligent mechanisms and systems that mimic human intelligence, enabling them to perform tasks typically requiring human cognitive capacities. Enabled by advances in computational power, the availability of big data, and breakthroughs in algorithmic designs, AI has experienced rapid progress in recent years [8]. Its applications, ranging from voice assistants to autonomous vehicles, have permeated various industries, including healthcare, finance, transportation, and entertainment.

AI, a multidisciplinary field, integrates the capabilities of several technologies such as natural language processing, machine vision, and the Internet of Things [9]. Three main types of AI are recognized: narrow AI, general intelligence, and superintelligence. For narrow AI, performance improves with more data, while general intelligence (AGI) applies the same algorithm across diverse environments and contexts, retaining the same skillset. Superintelligence, however, aims to exceed human capabilities in specific tasks [10].

Moreover, AI can analyze large data volumes and distill valuable insights, contributing to improved decision-making, cost reduction, and enhanced operational efficiency. For instance, AI-powered predictive maintenance can preemptively identify potential issues, enabling preventive action to avoid downtime or safety risks. It can also optimize routing and scheduling, thereby reducing fuel consumption and operational costs [11].

Integrating AI and blockchain technology in the aerospace sector can potentially increase its operations' efficiency, safety, and security. As system complexity in this domain grows, it becomes crucial to investigate the potential benefits of these technologies [7].

This paper examines the capabilities of blockchain and AI within the aerospace sector to identify potential applications of these technologies. The contributions of this review include the following:

1) Providing an introductory overview of AI and blockchain, followed by a discussion on the motivation for their integration in the aerospace industry.
2) Exploring potential blockchain and AI technology applications in managing aerospace projects.
3) Identifying potential challenges that might impede the adoption of blockchain and AI within the engineering and management of commercial aerospace projects.
4) Conducting a survey on AI and blockchain technology utilized in the aerospace industry, analyzing their unique features and open challenges.
5) Identifying and analyzing various methods of integrating AI and blockchain.
6) Examining the challenges, potential benefits, and unresolved issues associated with integrating AI and blockchain.

The remainder of this paper is structured as follows: Section II provides a summary of the background and related work. Section III outlines the methodology used. Section IV presents and explains the qualitative results of the study. Finally, Section VI concludes the paper by summarizing the findings.

II. BACKGROUND AND RELATED WORK

Blockchain technology, characterized by a secure and immutable distributed database, is an effective solution for auditing and record-keeping [12], [13]. Its decentralized nature fosters trust and transparency. Given its ability to maintain data integrity and record transactions efficiently, blockchain technology has found wide-ranging applications [14].

The transformative potential of blockchain stems from its unique architecture and data storage methods. Each data block is linked with others through cryptographic hashes, forming a chronologically timestamped chain. Metadata and header information of these blocks are securely housed within the blockchain [15]. As the user base of the blockchain grows, so does the number of data blocks, reinforcing the system's resilience against data manipulation [16].

Blockchain technology validates transactions through two main approaches [3], [17]. The proof of work, a method utilized in systems like Bitcoin, involves solving complex mathematical problems to add a new data block to the blockchain [3]. This process, however, is energy-intensive and demands extensive computational resources.

The alternative method, proof of stake, allocates computational demands proportionately to the data block's size [3]. Widespread implementation of this method is yet to be realized. Other algorithms used for data validation include the Byzantine-fault-tolerance algorithm and the Quorum Slicing algorithm [17]. As blockchain technology finds increased application in various commercial and industrial sectors, its evolution continues [18].

AI, a subfield of computer science, has been around for over three decades and centers on drawing meaningful inferences from data [19]. This type of human-synthesized intelligence involves methodologies like fuzzy logic and support vector machines and finds uses in search engines and robotics.

A significant milestone in AI's evolution is the advent of deep learning, which involves interconnected neural networks to boost machine learning performance. The foundational algorithms and principles for AI were established during the 1980s [20]. As more industrial and commercial applications begin employing blockchain technology, the continued progression of AI becomes increasingly significant [21].

The swift emergence and evolution of innovative computing technologies, including Graphics Processing Units (GPUs) and Tensor Processing Units (TPUs), have significantly expedited the development of AI algorithms. These advancements have allowed researchers to perform computations more rapidly and efficiently. As these technologies' computational capabilities advance, AI's performance is expected to follow suit [22].

AI has also seen significant progress due to breakthroughs in deep learning, reinforcement learning, and other subfields. Deep learning, in particular, has transformed AI by facilitating the training of large neural networks on massive datasets, achieving exceptional performance in domains like image recognition, natural language processing, and autonomous driving.

AI has evolved into a powerful technology with substantial potential for industrial transformations and societal reform. By leveraging its capabilities to extract meaningful insights from enormous data volumes and perform complex tasks, AI has the potential to reshape numerous sectors, including healthcare, finance, manufacturing, and transportation. With continuous advancements in computational technologies and the emergence of innovative AI methodologies, the scope for AI applications is only set to widen, catalyzing further advancements and breakthroughs in this promising domain [8], [23].

A. CORE CAPABILITIES

Integrating blockchain technology and AI will enhance performance in distributed computational settings, potentially reducing hardware prerequisites and costs for AI development. The growing body of literature focusing on the fundamental principles of these technologies enriches our understanding of their intrinsic capabilities and potential applications within the aerospace industry.

The key advantages of blockchain technology include decentralized data storage and management, transparency, and resistance to unauthorized data alterations [24]. In contrast to traditional data management methods, blockchain eliminates a central controlling entity, significantly reducing data manipulation opportunities. Complete data access and visibility are granted to all network participants, minimizing the chance of unauthorized data modifications.

AI excels in processing extensive datasets, enabling predictive analytics and pattern recognition within the data [25]. Its applications are being explored across various engineering disciplines, with studies demonstrating its utility in structural design, flaw detection, simulation, and analysis of engineering project lifespans [26], [27], [28], [29]. AI methodologies, including fuzzy logic and neural networks, have also been employed to optimize steel structures [30], [31]. In aerospace, AI is extensively used for corrosion detection and structural integrity prediction [32], [33].

B. POTENTIAL APPLICATIONS FOR BLOCKCHAIN AND AI IN AEROSPACE

Both blockchain and AI technologies have found extensive applications in managing large databases across multiple industrial sectors. In aerospace, a study by Efthymiou et al. [34] highlighted the potential of blockchain technology in managing aircraft maintenance data effectively in maintenance, repair, and overhaul (MRO) operations.

The MRO process is heavily regulated and involves many parts and partners, complicating data management among all participating parties [35]. Implementing blockchain technology can streamline the process, ensuring enhanced data capture, sharing, and security [36]. Additionally, blockchain can prevent counterfeit and substandard aircraft components circulation, potentially improving aviation safety [34].

AI has been introduced in the aerospace industry in non-destructive testing (NDT) of aircraft components [23]. Traditional indirect defect detection methods, such as infrared and eddy current methodologies, are time-intensive and require expert handling and specific equipment [37]. In contrast, AI-based applications enhance the ability to identify corrosion and cracks from automatically captured images using computational models [32], [38]. For example, Winfree and Prabhu developed a system employing neural networks in combination with computational models to analyze images obtained from thermal sensors [39]. AI has also been used to assess the effects of corrosion on the structural integrity of aircraft fuselages and predict aircraft corrosion states using a fuzzy logic-based computational method [40], [41].

III. REVIEW METHODOLOGY

This study employs an exploratory approach, conducting a comprehensive literature review on the potential use of blockchain technology and AI in managing and engineering aerospace projects. This method is typically adopted when investigating emerging technologies or less-explored subjects [42]. The goal is to identify, analyze, and offer theoretical perspectives on these technologies' possible applications in aerospace project management and engineering. A broad search was conducted on the Google Scholar and SCOPUS databases using relevant terms to provide an in-depth understanding of the technologies and their potential uses within the field.

Triangulation was used to ensure a thorough understanding and validate the findings. This approach involves cross-checking results from different sources to provide a robust and comprehensive analysis of the potential applications of blockchain and AI in the aerospace sector [43]. The team thoroughly reviewed articles examining these technologies' past, present, and potential future applications. This comprehensive assessment of relevant literature discusses the potential applications of blockchain and AI in aerospace project management and engineering, providing a holistic understanding of the field's current state and the possible applications of these innovative technologies.

IV. RESULTS

This section presents the key findings from the preliminary literature review on blockchain and AI technologies' applications, primarily in the aerospace industry. The initial part of this section concentrates on the applications of blockchain, while the latter part centers on AI applications.

A. BLOCKCHAIN

In recent years, blockchain technology has gained significant attention due to its potential to revolutionize numerous industries, including aerospace engineering and management. This subsection provides a comprehensive overview of the current state-of-the-art applications of blockchain technology within the aerospace sector, illuminating its potential for improving efficiency, security, and operational management.

As Table 1 indicates, blockchain technology has been applied in various ways within aerospace engineering and management. A study by Ahmad et al. [44] underscores the potential of blockchain in the Aerospace and Defense industry, particularly in enhancing logistics and supply chain management due to its inherent attributes of visibility, transparency, auditability, and security. However, the research also points to privacy concerns, latency, the absence of a regulatory framework, and compatibility issues with existing blockchain technologies.

TABLE 1. Blockchain applications and potential use cases.

No.	Use cases	Key Features	Study
1	Logistics and supply chain management (traceability and supplier verification)	Visibility, security, transparency, and auditability	Ahmad et al. [44]; Treiblmaier et al. [45]; Eryilmaz et al. [46]; Calle et al. [47]
2	Records management for aircraft maintenance, repair, and overhaul (MRO)	Data quality assurance and availability	Efthymiou et al. [34][20], Kar et al. [48]; Mukkamala et al. [49]
3	Opportunities for collaboration	n/a	Walthal [50]
4	Data access control	Distributed ledger system	Martintoni et al [51]
5	Additive manufacturing	IP protection, monetization, validation	Ghimire et al. [52]; Mandolla et al. [53]
6	Centralised Business messaging platform	Transparency and security	Gunasekara et al. [54]
7	Automation of contracting and payments	Security and transparency	Gunasekara et al. [54]
8	Internet of Things (IoT) applications	Security	Gunasekara et al. [54]; Chang et al. [55]
9	Tamper-proofing production and transportation history	Immutability and transparency	Mondragon et al. [56]; Wehbe et al. [57]
10	Sharing of aerospace testing data and other industry resources	Transparency and proof of value	Dan et al. [1]
11	Positive return on investment	Competitive advantage	Sanchez Perez [58]
12	Integrating RFID and blockchain	-	Santonini et al. [59]

Research by Efthymiou et al. [34] delves into the potential of blockchain technology in managing Irish aircraft maintenance facilities. The study suggests that blockchain could boost efficiency in records management. However, it also highlights potential impediments that may inhibit organizations from fully exploiting the benefits of the technology.

Research on potential risks associated with using blockchain to manage aerospace records suggests that the technology could lead to various operational challenges and restrictions, potentially preventing full compliance with the minimal functional and regulatory requirements [34]. As per Walthall, aerospace firms have preferred incremental technological advancements over extensive blockchain innovations [50].

The application of blockchain technology to store and manage data generated from avionics health monitoring systems was proposed by Mukkamala et al. [49]. They argued that using blockchain alongside cryptography could significantly improve data quality assurance and enhance data availability, with smart contracts enabling system administrators to receive immediate alerts, facilitating the efficient and secure resolution of emerging issues.

Treiblmaier et al. [45] indicated that blockchain could offer significant capabilities for supply chain integration due to its core features, such as traceability, transparency, trust, security, and privacy. These features are particularly relevant for complex aerospace supply chains requiring high reliability and traceability. However, they also noted that regulatory, organizational, and technical barriers could hinder its adoption, and interoperability and data-sharing challenges remain.

Martintoni et al. [51] suggested using blockchain to implement data access control throughout the supply chain and between supply chain management and industrial manufacturing systems. They highlighted the distributed ledger system's ability to offer cybersecurity assurances while automating interactions between supply chain systems and manufacturing devices.

A study by Ghimire et al. [52] elucidated how blockchain technologies could be applied to additive manufacturing. They argue that blockchain can safeguard certification, industrial property, and copyright concerning the replication characteristic of additive manufacturing. However, they also identify interoperability and the regulatory framework as potential challenges.

Eryilmaz et al. [46] developed a traceability platform for the aerospace industry using blockchain technologies. The platform aims to resolve the traceability challenges of parts throughout the supply chain and certification of suppliers.

In a study by Ahmad et al. [44], they surveyed how blockchain technologies and architecture could transform aerospace and defense applications, processes, and activities. They identified numerous applications across logistics, operations, and supply chain management. In defense applications, they saw secure military communications and coordination as potential use cases for blockchain technologies.

Gunasekara et al. [54] propose using blockchain in facilities management and procurement processes. Their expert survey found that blockchain technologies could reliably verify service providers and assess supplier performance. However, they also identified the legal framework as a potential challenge.

Mondragon et al. [56] investigated potential applications for blockchain technologies in manufacturing composite materials. They concluded that blockchain technologies offered significantly higher levels of trust and integrity of supplier declarations than traditional approaches.

Dan et al. [1] developed a private blockchain network for open collaboration and sharing of aerospace industry resources. The platform ensured that aerospace test data was secure and anyone accessing such resources could be trusted.

Mandolla et al. [53] proposed a conceptual framework for using blockchain technologies for additive manufacturing. The framework outlined how blockchain could efficiently prototype aircraft components, leading to reduced lead times, lower costs, and the production of high-quality components.

Lacity [60] detailed a case study of Moog, an industrial company that supplies aircraft and spacecraft control systems. The company is gradually shifting from centralized parts manufacturing to decentralized additive manufacturing with the help of blockchain technologies.

Sánchez Pérez et al. [58] evaluated the return on investment for blockchain technology across both automotive and aerospace industries. Simulations of the model they developed showed that investment in blockchain for both industries would be highly profitable.

Santonino III et al. [59] explored the potential for integrating RFID and blockchain to modernize the Airbus supply chain. They concluded that this integration could improve customer satisfaction, better inventory control, and the ability to gather proactive feedback from supply chain partners.

Calle et al. [47] evaluated the potential for blockchain to future-proof against uncertainties that characterize most supply chains. The study showed that blockchain could resolve supply chain bottlenecks and improve efficiency when implemented alongside existing supply chain management systems, especially in highly regulated industries such as aerospace.

B. ARTIFICIAL INTELLIGENCE

AI has emerged as a transformative technology with the potential to revolutionize aerospace engineering and management fields. This section provides a comprehensive summary of critical perspectives and insights from an in-depth examination of pertinent scholarly articles. The primary goal is to present an overview of the current state of AI applications within the aerospace industry, emphasizing its potential contributions to enhancing efficiency, decision-making, and operational management. By leveraging AI techniques, aerospace engineers and managers can optimize, automate, and improve performance across various domains, including aircraft design and maintenance, air traffic management, and mission planning.

Several organizations recognize AI's potential within the aerospace industry, as summarized in Table 2. Santos et al. noted that AI could help detect and quantify unseen structural damage caused by vibrations in their study [61]. They used specialized sensors to gather ground patterns, which could be analyzed to model different strains and vibrations.

Yepes et al. [62] investigated the use of machine learning in structural maintenance and durability assessment. Their findings suggested that this technology could enhance operational efficiency and ensure structures adhere to industry standards.

Izzo et al. [63] explored the potential of AI in guiding and controlling spacecraft. The researchers found that the technology could predict a spacecraft's trajectory and optimize its landing.

Shukla et al. [64] evaluated the applications of deep neural networks in aerospace vehicle maintenance. In contrast, Izzo et al. [63] analyzed the continued evolution of various methodologies such as tree searches, deep learning, machine learning, and reinforcement learning. They found that integrating these technologies could transform spacecraft guidance and control, facilitating advancements in formation flying, docking, and automated self-assembly in orbit. However, issues related to transparency and compliance remain challenges in predictive maintenance.

Shukla et al. [64] also sought to determine the value and utility of explainable AI to adequately and accurately predict maintenance in the aerospace industry when combined with deep neural networks. They also examined the technology's adoption level among industry practitioners and the challenges they experienced. Their study showed that AI is increasingly utilized in predictive operations across various fields, such as weather forecasting, autonomous driving, and particle physics. AI is increasingly applied to evaluate technical parameters and optimize maintenance operations within the aerospace industry. However, they also noted challenges, including difficulties in debugging during testing and adjusting models for specialized scenarios due to hidden layers present in generalized models.

Ezzat et al. [65] examined the application of AI for identifying and predicting aerospace system faults. Their proposed model performed with the same level of accuracy as existing techniques.

The utilization of machine learning techniques in aerodynamics traces back to the 1970s. For instance, I. Reichenberg's experiment used evolution strategies to enhance the shape of the aerodynamic surface [66]. Reference [67] used a commercial code based on Non-Dominated Sorting Genetic Algorithm as a multi-objective optimization tool for finding the best winglet shape. Further advancements included the use of neural networks to control surface friction drag caused

TABLE 2. AI use cases and potential use cases in aerospace engineering.

No	Use cases	Key Features	Study
1	Structural damage and durability detection	Specialised sensors and machine learning, ability to continuously conduct evaluations to detect structural damage using AI's pattern recognition capabilities	Santos et al. [61], Yepes et al. [62]
2	Spacecraft guidance and control	Ability for predicting orbits, the landing of spacecraft, and optimizing flight trajectories	Izzo et al. [63]
3	Predictive fault detection and maintenance	Deep neural networks	Shukla et al. [64], Ezzat et al. [65]
4	Aerodynamic shape optimization	Evolutionary algorithm, Non-dominated Sorting Genetic Algorithm (NSGA)	Rechenberg [66], Gavrilovic et al. [67]
5	Enhance non-invasive measurement methods in fluids	Neural networks	Lee et al. [68]
6	Control of turbulent flows	Genetic Algorithms; Genetic Programming (GP), Neural Networks for unsupervised controlled design	Lee et al. [69], Bernard et al. [70], Parezanovic et al. [71], [72], Li et al. [73], Gueniat et al. [74], Gazzola et al. [75]
7	Modelling the dynamics of hydrological systems	Reinforcement learning	Loucks et al. [76]
8	Maximizing the range of robotic gliders	n/a	Reddy et al. [77]
9	Optimizing the motion of UAVs	n/a	Kim et al. [78]; Tedrake et al. [79]
10	Automated welding and inspection for aircraft	Automated imaging powered by multilayer neural network	Tsuzuki [80]
11	IoT data analysis and modeling	IoT data analysis; order modelling, discrepancy modelling, uncertainty modelling	Brunton et al. [81]
12	Optimization of maintenance operations and technical parameter evaluation	n/a	Shukla et al [64]
13	Aero-Engine diagnosis, aerospace alloy optimization, and preliminary aircraft design	n/a	Li and Jiang [73]
14	Passenger information retrieval and augmentation	Augmented reality (AR)	Safi et al. [82]
15	Inflight entertainment	AR Smart Glasses	Safi et al. [82]
16	Airport security and surveillance	AR Simulations	Safi et al. [82]; Kulida and Lebedev [83]
17	Flight training	AR simulations	Safi et al. [82]; Kulida and Lebedev [83]
18	Auto piloting systems	Machine learning and adaptive piloting	Bakshi and Bakshi [84]
19	Demand forecasting and optimization, Production scheduling and management, Automated promotions, and pricing, Management of delivery logistics and processes, Smart manufacturing	n/a	Dash et al. [85]
20	Automated spacecraft scheduling, Identification of system and equipment failures	n/a	Kumar and Tomar [86]
21	Identification of terrains and characterisation of extra-terrestrial rocks and surfaces	n/a	Kumar and Tomar [86]
22	Cloud detection satellites	Deep neural networks and CNN	Furano et al. [87]

by a turbulent boundary layer [69] and deep neural networks to improve non-invasive fluid measurement capabilities, such as particle image velocimetry [68].

Flow control has been rendered possible by applying genetic algorithms (GAs), which optimize adjustable parameters given a known control law structure. An experiment by Benard exemplified this in controlling a backward-facing flow [70]. However, when the structure of the control law remains unknown, Genetic Programming (GP) can be deployed to discover and optimize its constants. Flow control finds application in diverse contexts, such as managing flow in a shear layer and reducing drag in a ground vehicle model [71], [72], and [73].

Reinforcement learning has catalyzed multiple breakthroughs in the field of fluid mechanics. For instance, it has enabled researchers to model the dynamics of water systems [76] and control of flow around a bluff body [74]. This technique has also facilitated studies of fish movement and the optimization of robotic glider ranges [75], [77]. Furthermore, it has been used to optimize the motion of Unmanned Aerial Vehicles (UAVs) [78], [79].

Tsuzuki [80] applied AI to automate welding and inspection procedures within the aircraft industry. Using a camera, a multi-layer neural network-based machine learning technique automated the welding and inspection of parts. The successful implementation of the prototype demonstrated an adequate emulation of a skilled inspection operator's methodology, automating imaging and decision-making processes.

Brunton et al. [81] explored the potential for integrating AI methods and technologies in aerospace engineering and identified a range of machine learning techniques applicable to aircraft engineering and operations. Digital twin technology emerged as a game-changer in aero-engineering design and distributed manufacturing. They also emphasized the necessity of AI technologies to process the vast data generated by the aerospace industry from various sensors. The study highlighted other potential areas of AI application, including reduced-order modeling, discrepancy modeling, uncertainty modeling, aero design, traditional design optimization, process standardization, and manufacturing automation. Li et al. [73] undertook a similar review of AI technologies in aerospace engineering, identifying aero-engine diagnosis, optimization of aerospace alloys, and preliminary aircraft design as active application areas.

Safi et al. [82] assessed the potential of augmented reality (AR) in the aerospace industry. They reported the extensive use of AR in training and simulation, operations monitoring, crew support, communications, and in-flight entertainment. AR has found significant applications in aerospace engineering in fabrication, repair, assembly, data analysis, and payload missions. AR enhances visualization from design to data analysis and improves situational awareness for training and navigational purposes. Safi et al. [82] highlighted how Air New Zealand uses AR and advanced algorithms to relay real-time passenger information to flight crews via HoloLens technology. They also cited using AR-powered smart glasses for in-flight entertainment and how AR aids airport security and surveillance operations, exemplified by Helsinki Airport, where AR devices animate operational data.

Bakshi and Bakshi [84] considered the potential applications of machine learning in aerospace, network analytics, and the Internet of Things (IoT). They identified viable aerospace applications, including the prediction of celestial object behavior and image analysis. They also noted the longstanding use of rudimentary AI in auto-piloting systems.

Dash et al. [85] examined the potential applications of AI in supply chain management across aerospace and other industries. They identified numerous functions within supply chains where the immediate deployment of AI could foster competitive advantages, such as demand forecasting and optimization, production scheduling and management, automated promotions and pricing, delivery logistics and processes management, and smart manufacturing. AI has demonstrated the ability to predict demand, enabling businesses to structure their manufacturing and distribution processes, reduce inventory costs, and enhance efficiency. Dash et al. [85] provided examples of deep-learning robots that streamline operational processes, identify empty shelves, and optimize item placement for efficient pick-up, leading to highly efficient maintenance, repair, and overhaul operations.

Kulida and Lebedev [83] explored the potential use of AI in both civil and military aviation, identifying various areas where AI could be advantageous. These areas include supporting critical operational decision-making, collating and analyzing traffic data, providing intelligent crew interaction interfaces, optimizing airspace structure for optimal aircraft flow, pilot training, and aircraft components diagnostics. Kulida and Lebedev [83] posited that AI, as a decision support system, could substantially shorten decision-making time and improve decision-making under pressure. They also discussed some factors limiting AI adoption in aviation, such as certification limitations, the existence of too many contingencies, and the increasing number of security requirements imposed by regulators.

Kumar and Tomar [86] analyzed the ongoing contributions of AI to space exploration. AI has been used in space exploration since 1998 when a comet probe was deployed with an AI-powered algorithm as a remote agent for scheduling and identifying failures. The Mars rovers, Opportunity and Spirit, heavily rely on AI for navigation, terrain assessment, and various operational functions, given the vast distances involved and the impracticality of real-time remote control [86]. These rovers utilize the AEGIS algorithm to identify terrains and characterize rocks, which has reduced the cost of operation and maintenance from the ground. Additionally, AI has made analyzing the vast data produced by various sensors easier and quicker.

Furano et al. [87] also examined potential applications of satellite AI technologies, outlining an AI architecture that could potentially be used in cloud detection using deep neural networks for hyperspectral image analysis. However, Kumar and Tomar [86] also pointed out some challenges associated with AI use in space exploration, including reliability issues and the risks of erroneous predictions. The recent disaster of the Japanese HAKUTO-R lunar lander [88] is a stark warning against relying too much on narrow AI routines for critical decision-making without extensive testing.

Soroka and Kurkova [89] examined the technological, ethical, and legal issues linked to AI adoption in aerospace. Despite highlighting numerous exciting AI applications in aerospace, they noted that regulatory and risk management frameworks lag. Additionally, critical ethical issues remain unaddressed. However, operationalization issues persist, such as addressing AI mistakes and biases. They argued that regulating evolving self-learning models and applications is challenging. Ethical issues, such as privacy intrusions, also exist. As such, broad-based, internationally-driven regulation designed to minimize AI's downsides without stifling technological development in the field is recommended [90], [91]. Soroka and Kurkova [89] advocate for specific laws based on solid technical standards to safeguard human rights as AI evolves.

Martin and Freeland [92] delved into the legal and ethical challenges AI technologies present. Their study aimed to understand the context of AI systems and usage in space exploration within the existing legal framework and established standards. A key concern they identified is the lack of transparency in AI technologies, primarily due to their autonomous nature. The European Union and the United Nations have developed operational guidelines for AI, including maintaining human oversight, ensuring reliability, security, and robustness of AI algorithms, controlling public data, ensuring traceability of AI functions, and establishing mechanisms for responsible and accountable AI systems [92]. However, these guidelines have not been codified into specific laws with clear monitoring frameworks. As such, Martin and Freeland [92] recommend further research and stakeholder engagement to regulate, monitor, and improve transparency in AI applications.

Kavasidis et al. [93] reveal a novel platform, harmonizing multi-blockchain technology with federated learning, enabling the formation of globally trained AI models on distributed datasets, notably in pharmaceutical manufacturing. A unique feature of this research is a blockchain-based system preserving details of the training process, ensuring its immutability, traceability, and reproducibility. Advanced federated learning algorithms were deployed on a pharmaceutical industrial dataset to demonstrate the platform's effectiveness. The results showed increased generalizability and rapid convergence time, underscoring the proposed approach's practical utility. This research marks a significant step forward, marrying federated learning and blockchain technology, addressing the challenge of maintaining training process integrity and exact model reconstruction, which is vital in highly regulated industries such as aerospace.

Vaiyapuri et al. [94] have developed an innovative approach, termed Blockchain Assisted Data Edge Verification with Consensus Algorithm for Machine Learning (BDEV-CAML), targeted at IoT Fault Detection. This technique amalgamates the advantages of blockchain, IoT, and ML models, significantly improving IoT networks' security, efficacy, and trustworthiness. Notably, their blockchain application empowers IoT devices with substantial decentralized decision-making, facilitating intra-block transaction efficiency. They employed a deep directional gated recurrent unit (DBiGRU) model, optimally tuned using the African vulture optimization algorithm (AVOA), for enhanced fault detection. This study contributes valuable insights into integrating blockchain, AI, and IoT, with potential applications in the aerospace industry, especially for improved network reliability and fault detection.

Amari et al. [95] present a thorough review of Vehicle Ad-Hoc Networks (VANETs) and trust management's fundamental concepts. Key security challenges, privacy concerns, and the need for trustworthy communication within VANETs are identified, highlighting the importance of efficient trust management mechanisms to bolster their reliability. A novel classification of trust management approaches, which includes emerging technologies like Cloud Computing, Software-Defined Networking (SDN), Edge/Fog Computing, Blockchain, and AI techniques, is proposed. The paper thoroughly evaluates these trust management approaches, providing comparative analyses and suggesting potential future research directions. In the context of aerospace, these findings are significant. VANETs share similarities with aerospace networks, such as the need for robust and reliable communication. Hence, trust management approaches developed for VANETs could be adapted for use in AI and blockchain-enabled aerospace networks. For instance, blockchain's distributed nature can enhance data integrity and security in aerospace systems, and AI can optimize decision-making and network management. These technologies, coupled with the power of cloud, edge/fog computing, and SDN, can help overcome some of the inherent complexities and challenges in aerospace networks, paving the way for safer and more efficient aerospace operations.

TABLE 3. **Challenges of blockchain in aerospace engineering.**

No.	Identified Challenges	Study
1	Privacy, latency, absence of regulatory framework, and interoperability of existing blockchain technologies	Ahmad et al. [44]; Treiblmaier et al. [45]; Ghimire et al. [52]; Gunasekara et al. [54]
2	Lack of readiness and unwillingness to transition to a new records management	Efthymiou et al. [34]
3	Risks to operational workflow and meeting the minimum regulatory and functional requirements	Kar et al. [48]
4	Lack of requisite skills for	Calle et al. [47]
5	Preference for incremental and as opposed to revolutionary technologies such as blockchain	Walthal et al. [50]

Truong et al. [96] delve into the symbiosis of blockchain and the metaverse, an envisaged 3D immersive successor to the internet. They highlight blockchain's transformative power in decentralizing the metaverse, thus fostering a democratic virtual society with unique economic and governance systems, and spotlight its role in managing digital assets. The research explores how blockchain can shape various facets of the metaverse, from user applications and virtual services to a blockchain-enabled economic system. Furthermore, it investigates blockchain's potential to bolster security and privacy in the metaverse and proposes decentralized governance and data management solutions. Integrating blockchain and AI into a potential aerospace metaverse could revolutionize communication, data management, and operations in aerospace. Decentralization could enhance security and trust, while a blockchain-enabled economic system could facilitate new transaction models. However, like the general metaverse, privacy, security, and governance challenges must be even more critically addressed in the aerospace metaverse.

C. IDENTIFIED CHALLENGES

The potential of blockchain and AI to enhance efficiency and security in aerospace engineering is significant. Nevertheless, successfully integrating these technologies poses various challenges that require careful consideration. This section thoroughly analyzes the barriers to incorporating blockchain and AI in aerospace engineering, derived from a comprehensive review of relevant literature.

By examining critical impediments identified in academic research, we seek to fully understand the difficulties that hamper the smooth adoption and implementation of blockchain and AI within the aerospace industry. From the blockchain-related challenges, such as latency, regulatory limitations, and privacy concerns, to the complexities of AI integration, including issues of trust, compliance, and reliability, we discuss the constraints and complexities underscored by researchers. Identifying and tackling these challenges is crucial for devising efficient strategies to mitigate them, enabling the aerospace industry to fully benefit from blockchain and AI's increased efficiency, security, and operational capabilities.

Implementing blockchain technology within aerospace engineering poses considerable challenges that must be addressed to ensure its successful integration. Table 3 summarizes the critical challenges identified in various studies on using blockchain in aerospace engineering. These challenges encompass latency, lack of established regulatory frameworks, privacy concerns, and interoperability issues with current blockchain technologies. A prevalent reluctance and unpreparedness to transition to an entirely new records management system pose significant obstacles.

The capacity to meet the minimum regulatory and functional requirements and the potential risks to the operational workflow warrant careful consideration. Moreover, the shortage of skills necessary for blockchain implementation adds further complexity to the adoption process. Finally, the existing preference for incremental over revolutionary technologies, such as blockchain, presents challenges. By proactively tackling these challenges, the aerospace industry can set the stage for the successful integration of blockchain technology, thus enhancing efficiency, security, and operational effectiveness.

TABLE 4. Challenges of AI in aerospace engineering.

No.	Identified Challenges	Study
1	Still at an experimental stage, with deep learning models still being tested	Izzo et al. [63]
2	There are still challenges with compliance, transparency, and trust of AI models	Shukla et al. [64]; Kumar and Tomar [86]; Martin and Freeland [92]
3	Inability to debug during testing and inability to adjust models to suit specialized scenarios due to hidden layers present in generalized models	Shukla et al. [64]
4	Legal, ethical and regulatory shortcomings	Henderson and Harbour [90]; Soroka et al. [89]; Martin and Freeland [92]
5	Human rights violations	Soroka et al. [89]
6	Challenges with diagnosing wrong predictions and reliability issues	Kumar and Tomar [86]
7	Certification limitations, the existence of too many contingencies, and increasing number of security requirements by regulators	Kulida and Lebedev [83]

Integrating AI into aerospace engineering also presents numerous challenges that must be addressed to exploit its potential fully. Table 4 delineates the critical challenges identified in various studies on AI use in aerospace engineering. These challenges cover multiple areas, including the experimental nature of AI, as deep learning models continue to undergo testing and refinement. AI models' trust, compliance, and transparency issues pose significant hurdles that need surmounting. Debugging during testing and adjusting models to specialized scenarios is also complex due to the hidden layers in generalized models.

Legal, ethical, and regulatory deficits further compound the challenge of AI adoption in aerospace engineering. Concerns about human rights infringements and the necessity to ensure AI systems' adherence to ethical principles add further complexity. Diagnosing incorrect predictions and tackling reliability issues remain substantial challenges to address. Certification limitations, multiple contingencies, and increasing security demands by regulators pose hurdles to integrating AI in aerospace engineering.

Overcoming these challenges is paramount to unlock AI's full potential in enhancing efficiency, safety, and decision-making within the aerospace industry. By surmounting these obstacles, aerospace engineers and industry stakeholders can harness AI's power to stimulate innovation, augment operational capabilities, and achieve sustainable growth in the rapidly evolving field of aerospace engineering.

V. EVALUATION AND LIMITATIONS

This section provides an exhaustive synthesis drawn from an extensive review of the scholarly literature on the application of blockchain and artificial intelligence (AI) in the aerospace sector. The analyzed literature underscores potential applications, presents formidable challenges, and forecasts future trajectories of these innovative technologies within aerospace engineering. By assimilating and elucidating these scholarly works' key findings and recommendations, we delineate the prevailing scenario, unearth prospective opportunities, and identify potential enhancement pathways for integrating blockchain and AI in the aerospace domain. This comprehensive examination contributes significantly to the discourse on advancing technology integration in the aerospace industry.

The importance of the research outlined in IV, pertaining to blockchain technology, is depicted visually in Figure 1. The wide-ranging potential applications of blockchain within aerospace engineering and management underscore the urgent need for a more in-depth investigation of this topic. Furthermore, the influence of blockchain-enabled record-keeping on conventional cost-modeling practices in aerospace applications [97] necessitates a thorough assessment.

The increasing number of commercial space engineering ventures, exemplified by entities such as *SpaceX* and *Blue Origin*, indicates a burgeoning demand for comprehensive, robust, and secure protocols for component tracking and logistics management. Frequently, spacecraft and their launch vehicles incorporate off-the-shelf components, the reliable operation of which is paramount to mission success. In some instances, a selected subset of these components is subjected

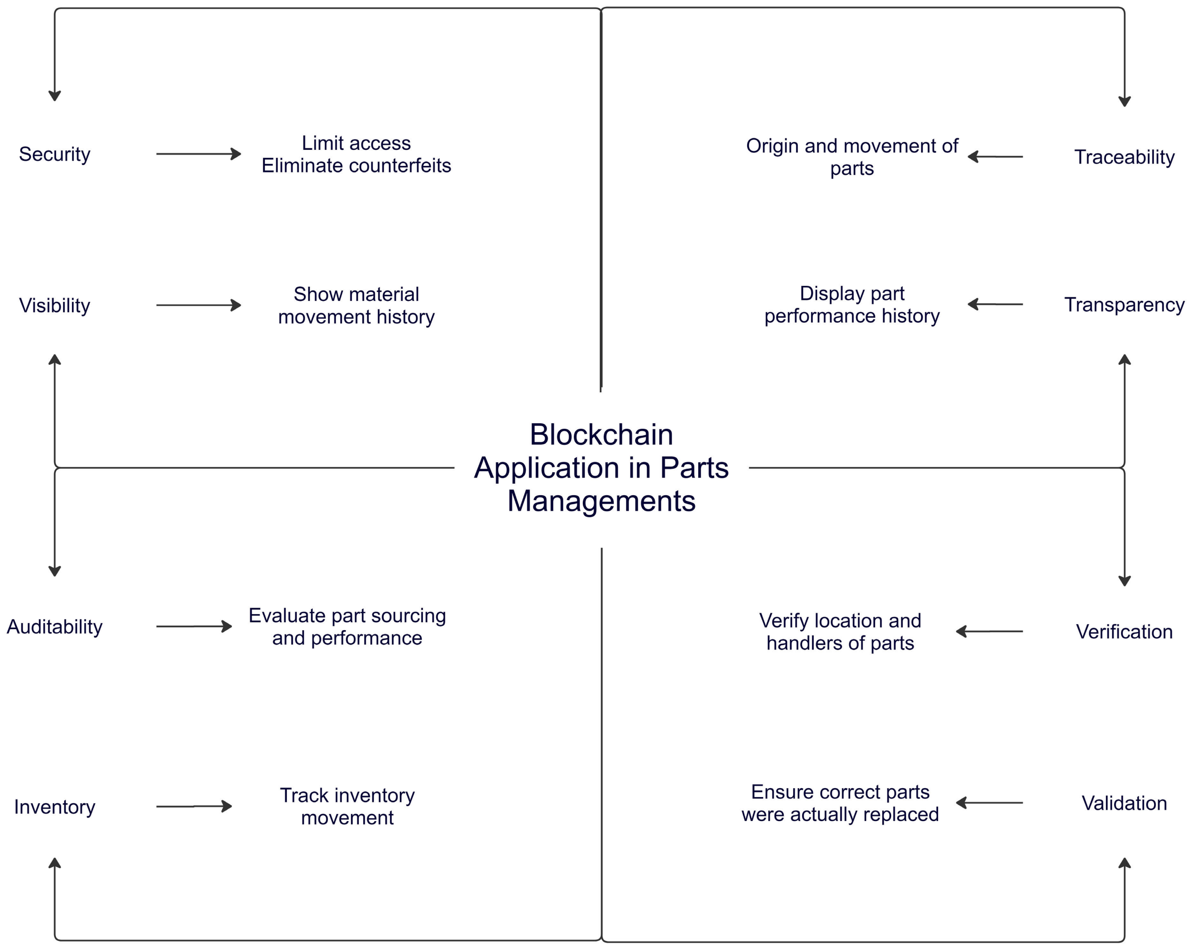

FIGURE 1. Blockchain's application in management and maintenance of parts.

to rigorous testing for performance and resilience under the austere conditions of space. If these components pass the necessary benchmarks in the test, a batch from the same manufacturing unit and production line is procured without further testing based on the assumption of uniformity in the manufacturing process.

In such circumstances, having a detailed component history embodied in a manufacturer-assigned blockchain could greatly expedite the component identification process and significantly streamline the logistics and tracking of these batches. Moreover, the considerable influx of new spacecraft and launcher designs necessitates meticulous record-keeping for future reference. This requirement stems from logistical and safety considerations and preserving vital engineering knowledge.

The past has witnessed substantial losses of critical technical information; for instance, various aspects of rocket engine designs from the 1960s were irretrievably lost due to inadequate documentation of the specific design and manufacturing processes. Such losses, though unfortunate, were perhaps tolerable when the annual number of space launches was relatively low (138 worldwide in 1965). However, such information losses are untenable in the contemporary era, with a staggering 2000 plus launches recorded in 2022 alone, according to data from the United Nations Office for Outer Space Affairs (UNOOSA) [98].

Apart from these, several other technical issues warrant consideration. The integration of blockchain with existing tracking systems, the potential latency added by blockchain protocols in time-sensitive operations, and the cybersecurity aspects of implementing blockchain technology in space logistics, among others, are areas of potential research and development. Thus, the advent of blockchain promises a new era of secure, transparent, and efficient tracking and archiving, thereby meeting the growing demands of the rapidly evolving space industry.

Figure 1 demonstrates how blockchain technology could supervise parts sourcing, transportation, replacement, and performance. This system could provide all stakeholders, including suppliers, engineers, technicians, customers, purchasing managers, and auditors, with comprehensive visibility of the entire system. This approach ensures the accurate replacement of parts with traceability of each component's journey from the supplier to its final disposal. Furthermore, it could simplify the evaluation of parts' performance and facilitate auditing maintenance processes and procedures.

As the aerospace industry delves into the potential of blockchain technology, understanding its benefits over conventional record management systems is crucial. Figure 2 underlines blockchain technology's key distinctions and advantages in contrast to traditional record management systems. This visual comparison illuminates how blockchain can revolutionize data storage, security, transparency, and traceability, providing valuable insights into blockchain technology's potential to augment efficiency and reliability in aerospace record management.

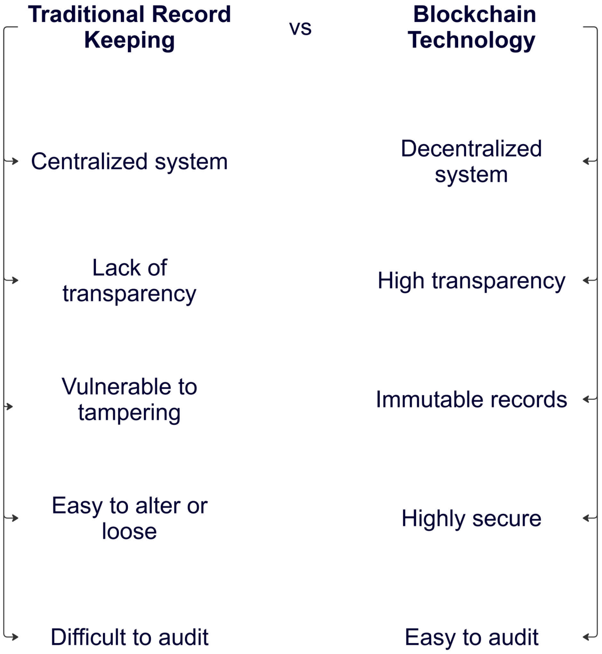

FIGURE 2. **Comparison between traditional record management vs. blockchain technology.**

Figure 3 visually encapsulates AI's critical advantages to the aerospace sector, illustrating its multifaceted applications. These range from predictive maintenance and fault detection to optimizing production schedules and implementing smart manufacturing processes. By graphically portraying these benefits, Figure 3 provides an all-encompassing understanding of AI's capacity to augment efficiency, fortify safety measures, and enhance decision-making processes in aerospace engineering and management.

In the aerospace industry, the convergence of AI and blockchain technology carries immense potential to stimulate innovation and revolutionize various operational aspects. Figure 4 emphasizes the potential benefits of integrating AI and blockchain in the aerospace industry. The figure demonstrates how merging AI and blockchain can improve efficiency, security, and reliability across predictive maintenance, supply chain management, data sharing, and autonomous systems. These visual representations serve as an invaluable resource for stakeholders and decision-makers, illuminating the transformative impact of blockchain and AI technologies in the aerospace industry.

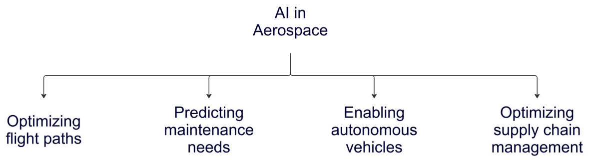

FIGURE 3. **AI benefits in the aerospace industry.**

As we delve deeper into integrating blockchain and AI technologies in the aerospace industry, it becomes increasingly clear that further research and regulatory support are vital for developing a comprehensive, robust regulatory framework. With these technologies rapidly evolving and permeating critical aerospace operations, addressing privacy, interoperability, data security, and compliance concerns is imperative.

Privacy challenges arise as the nature of these technologies necessitates the sharing of potentially sensitive information. Therefore, it's crucial to devise mechanisms that protect privacy while ensuring smooth operation.

Interoperability, another critical concern, refers to the ability of systems to work together coherently. As different systems employ blockchain and AI solutions, ensuring they can interoperate effectively and reliably is paramount.

Data security, a common concern across any technology-driven industry, becomes even more significant with the integration of blockchain and AI. Safeguarding data from potential breaches and ensuring the integrity of the information processed by these technologies is a must.

Lastly, compliance with industry standards and regulatory norms presents another significant challenge. Adherence to potentially conflicting rules and regulations can be difficult with no one-size-fits-all regulation for these technologies.

We must increase research efforts and foster collaboration among industry stakeholders, policymakers, and regulatory bodies to navigate these challenges. These entities must collaborate to formulate guidelines and standards that ensure blockchain and AI's safe, ethical, and responsible implementation. By doing so, we can promote trust and confidence in using these transformative technologies within the aerospace sector.

A. LIMITATIONS

While this study contributes substantially to our understanding of the integration of AI and blockchain technologies within the aerospace industry, it acknowledges certain limitations that present opportunities for future research.

Firstly, our study does not evaluate the current technological readiness level (TRL) of AI and blockchain technologies in the aerospace sector. Understanding their readiness for practical application is critical. For instance, future studies could analyze these technologies' maturity and performance in real-world aerospace scenarios. This could involve assessing the stability and scalability of blockchain solutions or

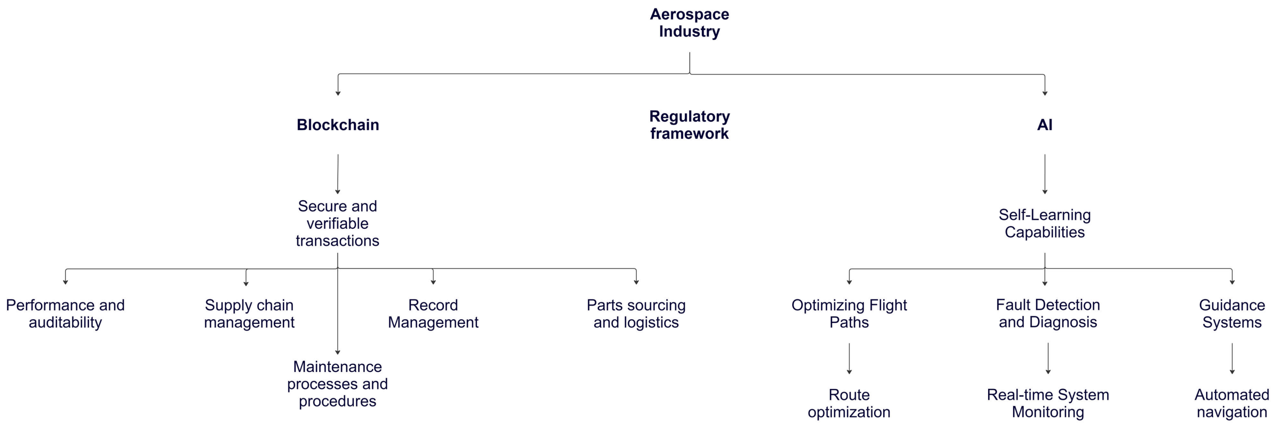

FIGURE 4. **AI and blockchain potential benefits in the Aerospace industry.**

the precision and resilience of AI algorithms under varied conditions.

Secondly, this work does not explore the financial implications associated with adopting AI and blockchain technologies. Given the potential for high initial and ongoing costs, future research could examine the return on investment models and cost-benefit analyses. This would provide a fuller picture of the economic viability of these technologies within the aerospace industry.

Thirdly, while we acknowledge standardization and interoperability issues across different AI and blockchain platforms, we have not delved into these concerns in depth. Interoperability – the ability for diverse systems and organizations to work seamlessly – is critical as aerospace projects often involve multiple stakeholders. Future studies might explore existing standardization efforts or propose new protocols for facilitating interoperability. The interoperability should include a systematic evolution plan and understanding of strategically managing the changes with the rapid evolution of these complex technologies and systems [99].

Fourthly, while we acknowledge the importance of privacy and data security, our study does not sufficiently elaborate on the cybersecurity risks inherent in using AI and blockchain in aerospace. Future work could conduct a rigorous threat analysis, investigating the susceptibility of these technologies to various forms of cyber-attacks and proposing potential mitigations. We will conduct this work along the lines of enhanced SQUARE approach [100].

Finally, the lack of specific case studies or real-world examples demonstrating successful applications of AI and blockchain in the aerospace industry limits the practical scope of our paper. Future studies might include an examination of real-world deployments of these technologies, offering insights into their operation and effectiveness in actual aerospace contexts. Moreover, it would be beneficial to explore the robustness of AI algorithms and blockchain networks against adversarial attacks or malfunctions, as this is a critical aspect to consider for their successful implementation in aerospace.

VI. CONCLUSION AND PROSPECTS FOR FUTURE RESEARCH

Integrating blockchain and AI technologies in the aerospace industry offers many potential solutions that could profoundly augment its functioning, particularly concerning supply chain efficiency. Blockchain technology, with its decentralized architecture, has the potential to significantly enhance diverse aspects of an aircraft's lifecycle, possibly streamlining aircraft material and repair operations. Additionally, the exploration of additive manufacturing within blockchain applications is gathering momentum.

Concurrently, AI possesses substantial potential to evolve predictive supply chain management models and advance aircraft design techniques. While the effectiveness of AI in optimizing flight paths and identifying structural faults has been established, there remains a pressing need for more comprehensive research to further cement its applications within the aerospace industry. For instance, in-depth case studies are essential to fully understand the utility of blockchain technology in supply chain logistics management.

Despite these promises, numerous regulatory and legal challenges must be surmounted before AI and blockchain technologies can achieve broad acceptance within the aerospace industry. Conducting additional research is of utmost importance to unlock the full potential of AI applications within this sector, which extends beyond predictive maintenance and fault diagnosis to encompass the regulatory aspects of these technologies.

The potential of blockchain and AI within the aerospace industry remains largely untapped and is in its early stages. With focused research and development efforts, we can anticipate the emergence of further applications, thereby opening new avenues for innovation in this field.

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YUSRA ABDULRAHMAN received the B.Sc. degree from The University of Arizona, in 2004, the M.Sc. degree from the Masdar Institute of Science and Technology, in 2016, and the Ph.D. degree from MIT, in 2020. Her expertise lies in robotics, artificial intelligence (AI), and non-destructive testing (NDT). With considerable industrial experience, she is currently a Faculty Member with the Department of Aerospace Engineering, Khalifa University. Her research interests include robotics, AI, and NDT. She received the awards from the UAE Ministry of Energy and Industry.

EDIN ARNAUTOVIĆ received the Ph.D. degree from the Vienna University of Technology, in 2009. He studied electrical engineering, with a major in computer technology, with the Graz University of Technology, ETH Zürich, and the Vienna University of Technology. From 2009 to 2012, he was a Postdoctoral Researcher with the Vienna University of Technology. From 2012 to 2013, he was a Senior Scientist with the Masdar Institute, Abu Dhabi. He has been involving in the industry as a Research and Innovation Activities Manager, since 2013. He is currently the Deputy Director of the Institute for Distributed Ledgers and Token Economy, Vienna University of Economics and Business, Vienna, Austria, where he conducts research and teaching in blockchain technology.

VLADIMIR PAREZANOVIĆ received the Dipl.-Ing. degree in aeronautical engineering from the University of Belgrade, Belgrade, in 2005, and the M.Sc. and Ph.D. degrees in fluid mechanics from École Polytechnique, Paris, France, in 2008 and 2011, respectively. He is currently a Faculty Member with the Department of Aerospace Engineering, Khalifa University of Science and Technology. His research interests include experimental and theoretical aerodynamics and flow control. He has helped pioneer genetic programming in flow and turbulence control.

DAVOR SVETINOVIC (Senior Member, IEEE) received the Ph.D. degree in computer science from the University of Waterloo, Waterloo, ON, Canada, in 2006. He was with the TU Wien, Austria, and Lero—The Irish Software Engineering Center, Ireland. He was a Visiting Professor and a Research Affiliate with the MIT, USA, and the MIT Media Laboratory, MIT. He is currently a Professor of computer science with the Department of Electrical Engineering and Computer Science, Khalifa University, Abu Dhabi, and the Department of Information Systems and Operations Management, Vienna University of Economics and Business, Austria (on leave), where he is also the Head of the Institute for Distributed Ledgers and Token Economy and the Research Institute for Cryptoeconomics. He has extensive experience working on complex multidisciplinary research projects. He has published more than 100 papers in leading journals and conferences. His research interests include security, privacy, trust, decentralized systems, blockchain, and software engineering. His career has furthered his interest and expertise in developing advanced research capabilities and institutions in emerging economies. He is a Lifetime Senior Member of ACM. He is an Affiliate of the Mohammed Bin Rashid Academy of Scientists. He is a highly cited researcher in blockchain technology.

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