LLMs Promote Commercial Aerospace Technology Towards Innovation Intelligence

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I. Introduction

The rapid advancement of large language models (LLMs), coupled with breakthroughs in electronic information technology, has significantly accelerated progress across multiple disciplines. As a pioneering force in technological and scientific innovation, aerospace technology operates in an inherently high-risk and unpredictable domain, navigating the complexities of extreme space environments. Consequently, it demands exceptional levels of reliability, performance, integration, and cost efficiency [1], [2]. Despite over a decade of evolution, the commercial aerospace sector has established a transformative paradigm for space technology and industrial development. Nevertheless, it continues to grapple with unresolved technical constraints, many of which are uniquely distinct from challenges encountered in terrestrial applications. Within this evolving landscape, LLMs are poised to drive paradigm shifts in innovation methodologies and application frameworks, fostering a new era of intelligence-driven advancements in commercial aerospace technology. As shown below, vehicle design and Integrated Circuit design could be aid by LLM for efficiency improvement and fault tolerant, human machine interface could play a great role empowered by LLM, and LLM also could bring higher levels of autonomy to mission planning and control. (Fig. 1)

II. Core Challenges in Commercial Aerospace Technology

A. Balancing Cost Constraints and Reliability Requirements

Space missions operate within an inherently hostile environment, where extreme conditions impose substantial challenges and risks. The reliability of spacecraft and mission systems must surpass that of most other industries, necessitating rigorous engineering standards. Using decades of accumulated expertise, leading aerospace research institutions have established a comprehensive reliability assurance framework encompassing the entire life cycle from design and material selection to manufacturing, testing, and verification [7]. Despite the significant financial commitments required, these measures have been instrumental in driving the steady and sustained advancement of aerospace technology [8]. However, as the commercial aerospace sector accelerates the deployment of space missions and spacecraft, the conventional paradigm of achieving high reliability at exorbitant costs is increasingly constraining technological evolution. To enable the scalability and diversification of future space missions, striking an optimal balance between cost efficiency and system reliability has emerged as a critical engineering challenge.

B. Performance Optimization Under Resource Constraints

Commercial aerospace technologies are progressing toward higher performance benchmarks across multiple domains. In aerospace communication, advancements are driving increased transmission frequency, power, and data transfer speed. Aerospace situational awareness is benefiting from higher spatial and temporal resolution alongside expanded coverage. Meanwhile, aerospace computing is achieving greater computational power, efficiency, and system integration, while aerospace control systems are enhancing sensitivity, precision, and operational complexity. However, these performance gains come at the cost of increased resource consumption [9]. Given the stringent constraints on critical resources—such as volume, weight, power consumption, and cost—achieving an optimal balance between capability and efficiency remains a fundamental and enduring objective in aerospace technology development [10].

C. Task Execution Under Environmental Uncertainty

Despite decades of aerospace exploration, the vast repository of accumulated experience and data represents only a fraction of what is necessary for a comprehensive understanding of space's complexities. A major challenge remains in executing well-defined tasks through meticulous planning and design, particularly when boundary conditions are difficult to constrain and operational resources are inherently limited [11]. Meanwhile, the commercial aerospace sector has undergone a fundamental transformation, evolving from a high-cost, low-production, and diverse system architecture paradigm to one driven by scalability, standardization, and cost efficiency. The rapid advancement of large language models (LLMs) and the increasing integration of artificial intelligence are set to redefine this landscape, ushering in a new era of intelligent aerospace systems. Consequently, the imperative to embed intelligence across all levels—including computing, modeling, and data analytics—has become increasingly critical, driving the next wave of technological innovation in commercial aerospace.

III. Technical Foundations for LLM Integration in Aerospace

The intelligent development with LLMs of commercial aerospace field also needs a new ecology like other indus-

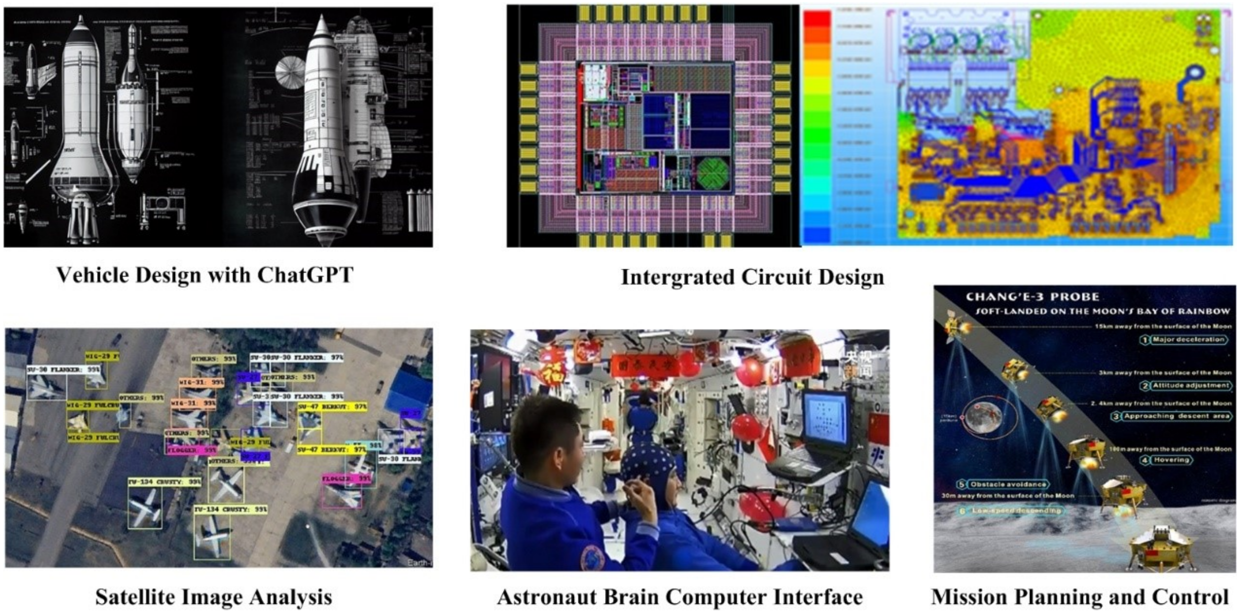

Fig. 1. Typical Applications of LLMs in the Commercial Aerospace Field. [3]–[6]

tries, which including Open Structure Digital Development Platform, Intelligent hardware, OS, Services and Intelligent Facilities and Application. The differences are evident in the personalized content of computational infrastructure, algorithms, and data. (Fig. 2)

A. Computational Infrastructure for Space Applications

Contemporary advancements in electronic technologies are rapidly approaching the fundamental limits of Moore's Law, posing significant challenges for the deployment of terrestrial computing chips in the extreme conditions of space. The constraints of current semiconductor manufacturing processes and material properties exacerbate these challenges, particularly for silicon-based chips utilizing sub-7 nm fabrication processes, which are highly susceptible to space radiation effects such as single-event latchup (SEL), single-event upset (SEU), and total ionizing dose (TID). While emerging technologies—including Silicon-On-Insulator (SOI) architectures, quantum computing, photonic computing, quantum spin memory, and neuromorphic computing—offer potential advancements in radiation resistance, they have yet to fully satisfy the stringent reliability and durability requirements for space-grade applications. Furthermore, the integration of ultra-high-performance intelligent chips necessitates significant power consumption and complex thermal management, introducing substantial operational risks and escalating costs in the harsh space environment. Addressing these limitations requires a paradigm shift in space-optimized chip design, prioritizing high reliability, efficiency, and resilience, while reducing development costs through scalable production and breakthrough innovations. These advancements are critical to the integration of LLMs in commercial aerospace, facilitating the development of the next generation of intelligent space systems.

B. Domain-Specific Algorithmic Adaptations

As a general-purpose technology, universal LLMs lack the specificity required to fully address the unique demands of commercial aerospace applications [12]. To support specialized tasks such as intelligent spacecraft design, mission planning, and data governance, the development of domain-specific LLMs is essential. This requires the implementation of advanced techniques, including model compression, quantization, knowledge distillation, and lightweight architectures to ensure optimal performance in aerospace environments [13], [14]. While the adaptation of LLMs mirrors trends in other industries, aerospace presents distinctive challenges that necessitate a deeply specialized and systematic approach. The complexity and mission-critical nature of aerospace systems demand the active involvement of senior experts, ensuring that AI-driven solutions align with stringent operational and safety requirements. Moreover, as real-time performance, safety, and interpretability become increasingly critical, the development of aerospace-specific LLMs must emphasize robustness, reliability, and transparency, making these considerations fundamental to their design and deployment.

C. Data Acquisition and Quality Challenges

The commercial aerospace sector faces a significant disparity in data generation, accessibility, and storage compared to other industries, posing substantial challenges for the integration of LLMs. The rate at which aerospace data is produced and becomes available remains insufficient to meet the demanding computational requirements of existing LLMs, while inherent limitations in data quality and credibility impede the development of robust evaluation and verification frameworks.

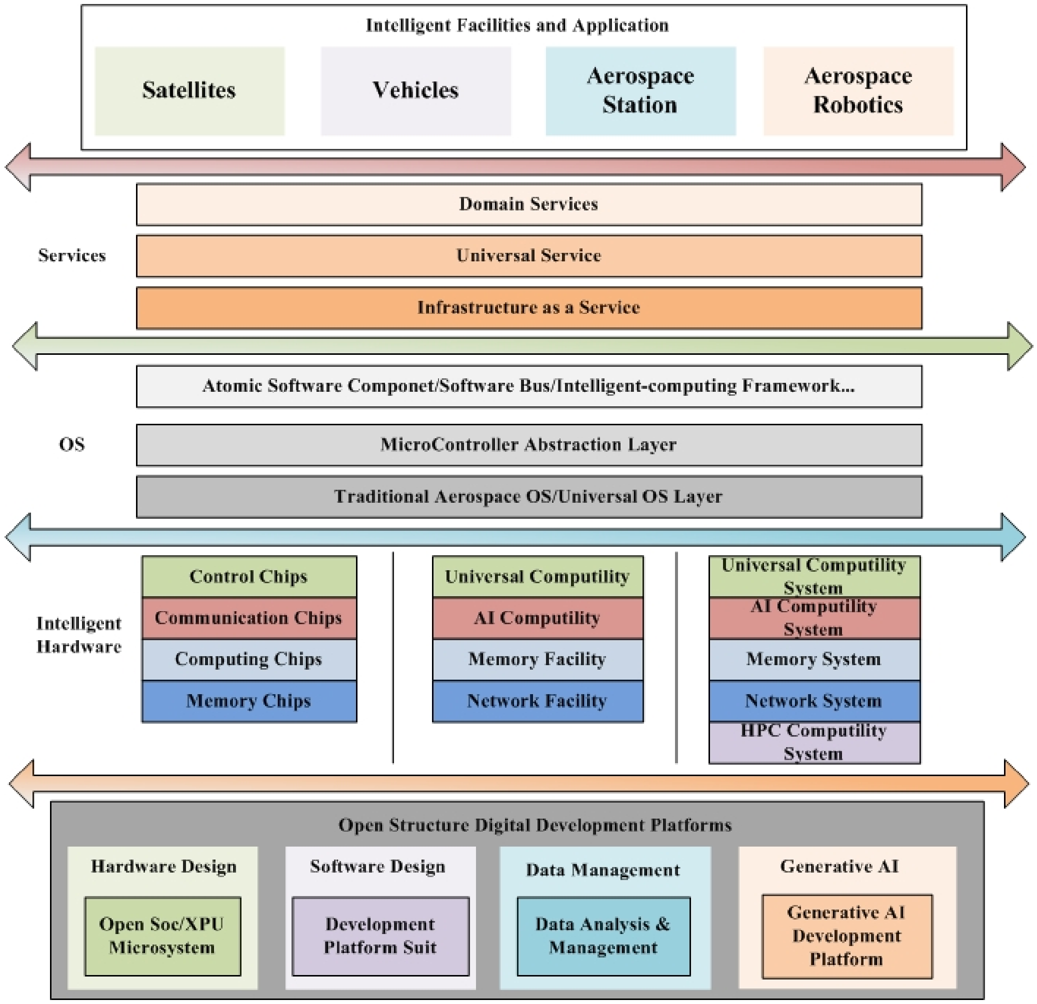

Fig. 2. LLMs Application under Intelligent Development Foundation.

Additionally, the uncertainty associated with small-sample datasets presents formidable obstacles, far exceeding those encountered in other domains [15]. Although some space missions attempt to simulate data acquisition and training environments on Earth to assess feasibility, these methods are primarily effective for deterministic tasks. In contrast, mission scenarios characterized by high uncertainty exacerbate the decline in data collection efficiency and model training effectiveness. Addressing these challenges necessitates a fundamental paradigm shift in theoretical frameworks, emphasizing innovative methodologies for data acquisition, processing, and model optimization. Advancing next-generation theoretical approaches to bridge these gaps remains a critical research priority in the evolution of commercial aerospace AI applications.

IV. Applications of Large Language Models in Commercial Aerospace

A. *Spacecraft Design and Optimization*

Harnessing their ability to process vast datasets and extract complex patterns, LLMs introduce innovative methodologies for spacecraft design, significantly enhancing the optimization of subsystems and components. By leveraging data-driven insights and advanced computational techniques, LLMs accelerate design iterations and achieve optimization levels beyond those attainable through traditional manual engineering approaches [16]. Their application extends to architectural design and optimization of ultra-large-scale high-reliability aerospace chips, nanoscale sensor structures, and large-scale phased-array composite antennas, enabling next-generation advancements in aerospace engineering. Furthermore, through adaptive design frameworks, LLMs facilitate real-time parameter adjustments in response to dynamic operational constraints, ensuring that spacecraft maintain optimal performance across complex and unpredictable environments. This AI-driven approach not only enhances design efficiency and innovation cycles but also contributes to a substantial reduction in research and development costs, paving the way for the development of more cost-effective and scalable aerospace technologies.

B. Mission Planning and Control

The integration of LLMs has the potential to revolutionize mission planning and control, significantly enhancing both efficiency and operational safety. Unlike traditional task planning methods, which depend heavily on human expertise and are prone to challenges arising from environmental complexity and uncertainty, LLMs enable the development of data-driven, adaptive, and comprehensive mission strategies. By analyzing historical mission data alongside real-time environmental inputs, LLMs facilitate multi-objective optimization, simultaneously balancing factors such as energy efficiency, time constraints, and safety considerations [17]. Moreover, through onboard intelligent deployment, LLMs support real-time task scheduling and dynamic adjustments, enhancing operational agility and decision-making in collaboration with human operators [18]. This advanced capability marks a critical milestone in the advancement of intelligent and autonomous aerospace missions, paving the way for more adaptive, efficient, and resilient space operations in the future.

C. Data Analysis and Decision Support Systems

In the commercial aerospace sector, the collection, analysis, and strategic utilization of data are fundamental to informed decision-making and operational efficiency. Using comprehensive aerospace datasets, user feedback, and robust data governance frameworks, LLMs introduce a transformative approach to decision support systems, allowing the identification of underlying inefficiencies and hidden patterns. This capability drives breakthrough advancements in real-time system monitoring, fault diagnosis, lifespan prediction, anomaly detection, and target forecasting—all of which are critical to spacecraft operations and mission management [19]. Through the integration of these intelligent capabilities, LLMs enhance analytical precision and predictive insights, significantly improving the reliability, safety, and success rate of space missions. Ultimately, this technological evolution paves the way for a future defined by autonomous and intelligent aerospace operations.

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