Aerospace and Intelligent Systems

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Introduction

Aerospace" can be mentioned as "aviation and space" and refers to a broad branch of engineering and science that deals with both aircraft flying in the atmosphere (such as airplanes and helicopters) and spacecraft moving in space (such as satellites, space shuttles, rockets) (Krishnakumar, 2003).

This term covers two main areas (Cohen, 2023):

Aeronautics: It deals with the design, development, and use of vehicles moving in the atmosphere. For example, airplanes, helicopters, and unmanned aerial vehicles fall into this category. Aeronautical engineering includes aerodynamics, flight mechanics, aircraft engines, and aircraft design.

Space (Astronautics): It deals with vehicles and technologies that go outside the atmosphere, that is, into space. This field includes satellites, rockets, space probes, and manned spacecraft. Space engineering covers orbital dynamics, space mechanics, rocket propulsion systems, and space mission planning.

Aviation and space are often considered together because the two fields overlap in many aspects of technology, engineering principles, and research methods. For example, aircraft and spacecraft require similar techniques in aerodynamics, materials science, propulsion systems, and control engineering. For this reason, the branch of engineering that covers these areas is called "aerospace engineering" (Keane & Scanlan, 2007).

The aerospace has various advantages and disadvantages (Chhaya, Khanzode, & Sarode, 2020; Insaurralde, 2018). This field provides great contributions to science, technology and economy in both manned and unmanned projects, but it also carries some important limitations and risks. The advantages of aerospace are like this:

Contribution to scientific progress; space research and aviation projects enable important discoveries to be made in many fields such as astrophysics, earth sciences and atmospheric science. Thanks to satellite technology, significant progress is made in vital areas such as weather forecasts, natural disaster warnings and environmental monitoring (Zhang, Chen, & Hu, 2018).

Economic returns; the aerospace sector creates high employment rates and opens up new business areas. Especially agreements made between large companies and government organizations directly contribute to the economy of countries (Tschan, Kivelevitch, & Melcher, 2013).

Developments in security and defense; aviation and space technologies are of critical importance for military and civil security. National defense systems are strengthened thanks to satellite surveillance, airspace control and other security measures (Ranasinghe et al., 2022a).

Development of new technologies; the aerospace sector is the pioneer of important innovations in areas such as new materials, Artificial Intelligence (AI), robotics and telecommunications due to its high-tech requirements. These developments also contribute to other sectors and are used in daily life (Mieloszyk, 2017).

Exploration and innovation opportunities; exploration of space seeks answers to big questions such as the possibility of life on other planets or learning about worlds outside the solar system. These discoveries open new horizons for humanity and fuel scientific curiosity (Van der Velden, Bil, Yu, & Smith, 2007).

There is some disadvantages of the aerospace (Insaurralde, 2018). The drawbacks of aerospace are like this:

High cost and economic risks; aviation and space projects require large budgets and the return on investment may be uncertain. Such high costs may lead to criticism, especially in projects carried out with public funds (Altavilla & Garbellini, 2002).

Environmental impacts; high-energy-consuming vehicles such as rocket launches and jet engines can harm the environment by releasing greenhouse gases and harmful chemicals into the atmosphere. This increases the need for environmentally friendly technologies in the sector (Mahashabde et al., 2011).

High safety and health risks; astronauts and pilots who take part in both space missions and aviation projects are at high risk. The smallest error or technical failure can pose life-threatening risks. This can lead to both physical and mental health issues for the staff (Oster, Strong, & Zorn, 2013).

Technical and legal complexity; the international and national regulations that must be adhered to in this sector are quite complex. This complexity can lead to project delays and complicate development processes. Additionally, the technology used in each project must undergo legal procedures before it can be shared with other countries (Shelukhin, Kharaberiush, Shelukhin, Tsymbalistyi, & Selevko, 2022).

High risk of failure; space projects and large aviation initiatives require long-term planning, testing, and development to achieve success. However, many of these projects can face cancellation or failure due to technical or financial reasons, leading to a waste of time and resources (Harikumaran et al., 2020).

The aerospace sector significantly contributes to advancements in science and technology due to its many advantages. However, it also presents challenges, including high costs, security risks, and environmental impacts. Therefore, it is essential to develop innovative and sustainable solutions to address these issues and promote the sector's growth (Zhang et al., 2018).

The aerospace sector is highly complex and carries significant risks, continuously pushing the boundaries of technology. The main challenges faced in this field include (Baur & Silverman, 2007; Trélat, 2012): High Costs: Aerospace projects often require substantial financial investment, with research, development, and production processes costing billions of dollars, particularly for projects like rockets and spacecraft (Mahashabde et al., 2011). Technical Complexity: Aerospace vehicles incorporate intricate systems that add to their overall complexity. Overall, these factors make navigating the aerospace industry both challenging and costly. Engineers must integrate various disciplines, such as aerodynamics, materials science, software engineering, and physics, to ensure that each component functions effectively. For instance, adapting a rocket to different atmospheric conditions presents a significant engineering challenge (Oche, Ewa, & Ibekwe, 2024). Safety is one of the most critical aspects of the aerospace industry; even the smallest error can result in millions of dollars in damages or, worse, loss of life. Therefore, systems must undergo multi-layered safety protocols and controls. The aerospace industry is governed by strict regulations and compliance requirements. Compliance with the standards set by various national and international regulatory bodies often increases the cost and duration of projects. The materials and technologies developed in this field must be both durable and lightweight. Material science focuses on creating strong, lightweight materials that can withstand extreme temperatures and pressures. Research into new materials and technologies also requires substantial funding and advanced expertise.

The environmental impact of the aviation and space industries is frequently criticized, particularly concerning their carbon footprints (Mahashabde et al., 2011). Rocket launches, for instance, consume large amounts of fuel and release greenhouse gases, such as carbon dioxide, into the atmosphere. Efforts are underway to develop new, environmentally friendly technologies to mitigate these impacts.

Space exploration presents numerous uncertainties, as it involves journeys into the unknown. Conditions in space cannot be fully predicted, leading to unexpected challenges. The harsh environment of space—characterized by radiation, temperature fluctuations, and microgravity—places extreme stress on vehicles (Brevault, Balesdent, & Morio, 2020).

The implementation of AI and intelligent systems in the aerospace sector offers substantial benefits in terms of safety and efficiency. Applications such as autonomous systems, predictive maintenance, data analysis, and simulations are driving significant advancements in reliability and operational success (Bautista-Montesano, López-Valdés, Jiménez-Ríos, & Gómez-Aladro, 2019; Yang & Zhao, 2004). By utilizing these technologies, risks associated with aerospace projects are minimized, costs are lowered, and human resources are optimized effectively.

Several solutions are available to address these challenges (Léonard, Hallstedt, Nylander, & Isaksson, 2024). One of these solutions is intelligent systems, which include AI and its applications. This section explains AI applications in aerospace across four key areas. These are Remote Sensing Systems, Spacecraft Health Monitoring System, Satellite Communication System and Autonomous Robotic Systems.

Remote Sensing Systems

Remote sensing systems in the aerospace field are technologies used to collect, analyze and interpret data from the air and space. These systems use various sensors to provide information about the earth, atmosphere and space, collecting data without direct physical contact with the areas to be observed (Wang, 2007; Wu, 2024).

Remote sensing systems collect data using electromagnetic waves, which bounce off specific targets and are analyzed by sensors (Sze, Isaacs, Ko, & McElroy, 1981). Active and passive sensors can be used. These sensors are carried on satellites, spacecraft or aircraft. There are various application areas in remote sensing. Some of these are; meteorology and weather forecasting, forest fire monitoring, natural disaster management, military and defense applications, environmental monitoring and climate research.

Nowadays, large amounts of data from remote sensing systems are analyzed with AI algorithms. Machine learning and deep learning techniques provide great benefits, especially in the analysis of satellite images, target detection, change monitoring and classification. With these analyses, faster and more accurate results are achieved in areas such as disaster prediction, plant health assessment or pollution monitoring (Merhav, 2012).

Aerospace remote sensing systems are vital in air, space and ground observations. With the development of sensors and the increase in AI-supported data analysis, remote sensing systems provide more comprehensive and reliable solutions by collecting and analyzing data in various scientific and practical fields. These systems play an important role in both daily life and solving global problems.

Spacecraft Health Monitoring System

Spacecraft health monitoring systems are designed to oversee the condition of various components within a spacecraft, ensuring both safety and operational efficiency. These systems continuously track the status of all vehicle systems, identify potential issues, and facilitate preventive maintenance. By playing a crucial role in mission success and prolonging vehicle lifespan, health monitoring systems are essential for the overall effectiveness of space missions (Ranasinghe et al., 2022b; Tipaldi & Bruenjes, 2014).

Spacecraft have the ability to assess their own status and communicate this information to ground control using onboard AI and machine learning algorithms. These systems analyze different situations, evaluate performance data, and make decisions based on historical information. AI models enhance data analysis and can predict potential failures or maintenance needs by examining the spacecraft's current performance.

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Health monitoring systems are essential components of aerospace technologies, playing a crucial role in both the operational and safety aspects of space missions. When combined with AI and machine learning applications, these systems enhance the efficiency, safety, and long-term operation of spacecraft (Herrera & Chura, 2005).

Software-Based System Health Management (SHM) employs software solutions to monitor the status of spacecraft, predict potential failures, and ensure safe operation throughout the mission. SHM consists of algorithms and software that continuously assess the complex structure of spacecraft and recommend or implement the most suitable interventions when problems arise. These systems optimize vehicle performance using built-in software algorithms and AI techniques, minimizing the need for human intervention (Bao, Bao, & Qiu, 2022).

Sensor Data Collection and Monitoring

Sensors installed throughout the spacecraft continuously monitor essential parameters such as temperature, pressure, vibration, radiation, and voltage. The data collected from these sensors is transmitted to software-based system health management units. This software instantly analyzes the sensor data. For instance, if an abnormality is detected in the engine temperature, the software can identify it and assess the likelihood of a failure (Harris, Bailey, & Dodd, 1998).

Data Analysis and Anomaly Detection

The sensor data collected is meticulously compared to well-defined normal operating conditions. By leveraging advanced machine learning algorithms and statistical analysis methods, the software identifies any anomalies present in the data. For example, it scrutinizes unusual patterns like pressure fluctuations or temperature spikes, enabling it to forecast and alert on the likelihood of failures before they occur. This proactive approach ensures that preventive maintenance can be strategically planned, safeguarding operations and preventing costly disruptions (Basora, Olive, & Dubot, 2019).

Fault Detection and Diagnostics (FDD)

FDD (Fault Detection and Diagnosis) plays a crucial role in managing the health of software-based systems. FDD software analyzes data from sensors to predict potential failures. By using machine learning or deep learning algorithms trained on historical data, these systems can improve their failure predictions. Predictive systems not only anticipate when failures might occur but also pinpoint the locations of the problems. This capability enables the vehicle control center or onboard systems to automatically take corrective actions (Ezzat et al., 2021).

Autonomous Response Systems and Intervention

SHM has the ability to respond immediately in the event of a failure. When a problem is detected, the system can either automatically intervene or notify the control center, depending on the severity of the situation. For instance, if high temperatures are detected in a section of the vehicle, the software system activates cooling units or temporarily reduces power. Autonomous response systems are especially critical during deep space missions, where communication latency can be significant (Bautista-Montesano et al., 2019).

Machine Learning and AI Applications

Structural Health Monitoring (SHM) utilizes AI and machine learning models to analyze data more effectively. These systems can learn from historical datasets to detect anomalies with greater accuracy and predict potential failures. By analyzing thousands of hours of operational data, machine learning can assess failure probabilities. This capability enables SHM to enhance vehicle performance in real time (Ezzat et al., 2021; Sathyan, n.d.).

Preventive Maintenance and Performance Optimization

SHM offers preventive maintenance recommendations that aid in planning maintenance before failures occur. As a result, most issues can be addressed before they happen, ensuring system safety throughout the mission and reducing costs. Additionally, these systems conduct analyses to optimize vehicle performance, promoting long-term and efficient operation (Herrera & Chura, 2005).

Benefits of Software-Based System Health Management

System Health Management (SHM) enhances mission reliability by continuously monitoring the status of systems and preventing unexpected failures that could disrupt mission operations. Early detection of issues allows for intervention before a failure occurs, ultimately reducing maintenance costs (Tipaldi & Bruenjes, 2014).

Software-based SHM is particularly crucial for ensuring astronaut safety, as it identifies potential safety risks in advance and implements necessary precautions. Additionally, SHM can make autonomous decisions without requiring human intervention, which is a vital advantage for deep space missions where communication delays may occur.

In aerospace projects, SHM technology is of great significance. Powered by AI and machine learning, these software systems enable spacecraft to carry out their tasks safely and efficiently while minimizing risks and ensuring cost-effectiveness.

Satellite Communication Systems

Satellite communication systems use satellites to transmit data between various locations around the World (Kodheli et al., 2020). They are essential in numerous fields, including communication, television broadcasting, internet connectivity, military communication, and emergency services. AI (AI) applications within these systems enhance data transfer speed and reliability, improve fault management, optimize network traffic, and enhance the overall user experience.

These algorithms used to optimize network traffic analyze traffic patterns to predict which network paths are busiest and optimize traffic management (Fourati & Alouini, 2021). This increases data transmission speed and minimizes delays. Additionally, AI algorithms increase the efficiency of satellite communication systems by identifying unused or low-density frequencies and prevent signal interference. Also, for healthy communication and maintenance management, AI analyzes data from sensors to predict possible malfunctions in satellites. In this way, satellite maintenance and repair operations can be carried out before malfunctions occur.

In data transmission, image, audio and data packets are compressed by AI algorithms and sent (Abdulwahid & Kurnaz, 2024). This provides faster and higher quality data transfer, especially in video or high data volume transmissions. AI algorithms ensure that the satellite position remains stable and make automatic route adjustments when needed, thus ensuring precise and appropriate orbit management, especially for satellites in low Earth orbit.

In addition, AI provides optimum data transmission by filtering out unwanted harmonics and making the signal stronger (Keane & Scanlan, 2007; Kim, Kennedy, & Gürdal, 2008; Van der Velden et al., 2007). This application is especially useful in very bad weather conditions or in areas with heavy electromagnetic pollution. AI analyzes users' connections and their needs, adjusting frequency, bandwidth, and data flow accordingly. It offers users a faster and uninterrupted connection, especially in internet services.

The benefits of AI in Satellite Communication Systems can be listed as follows: AI increases efficiency in communication systems by performing traffic management, data compression and frequency optimization. In addition, satellites/aircrafts become more effective with predictive maintenance and failure management (Nickels, 2015). With AI, satellite communication systems are more sensitive to user needs and thus service quality increases.

As a result, AI applications play an important role in satellite communication systems to provide faster, more efficient and more reliable communication. These applications improve satellite communication in the next generations by providing advanced communication solutions for both personal and industrial use.

Autonomous Robotic Systems

In the aerospace field, AI applications in autonomous robotic systems are used to perform many critical tasks such as space exploration, data collection, maintenance/repair, vehicle motion control and ensuring life safety. These systems have the advantages of reducing costs, ensuring mission continuity and easily adapting to tiring space situations by reducing the need for manual space missions (Bautista-Montesano et al., 2019).

AI, which uses image processing techniques in space missions, is used for robots to identify and analyze the environment (Valasek, 2018). In this way, they can analyze the surface, detect environmental problems, craters or geological formations. For example, a rover that investigates the surface components of the planet can provide data to researchers by classifying mineral and rock types with machine vision. In this way, research is done more effectively.

In deep aerospace research, a large number of data sets must be analyzed (Badea, Zamfiroiu, & Boncea, 2018). By analyzing this data quickly, AI can find anomalies, provide information about the planet, or predict different variables such as weather. Especially in long-term missions, AI analyzes large amounts of data from outside. It optimizes data transmission by sending only the important findings to the ground control center.

Planning and management in aerospace missions are critical to the completion of tasks. AI is preferred in functions that allow the grading of tasks, determination of the movement route of the robots and optimization of energy consumption (Yang & Zhao, 2004). In this way, tasks are completed faster and safer. For example, algorithms have been developed that select the most useful paths to optimize the battery life used by rovers for their energy needs.

AI enables robots to make decisions on their own in aerospace missions where there is a delay due to communication (Shekhar, 2019). These systems analyze the conditions of the external environment and make decisions accordingly. They contribute to the successful implementation of tasks. Learning algorithms are applied to autonomous robots, allowing them to easily adapt to environmental changes throughout the tasks they perform. In this way, they determine the best route and movements to reach their goals.

AI analyzes data received from sensors to predict failures in robotic systems. In this way, maintenance requirements can be made before the robots fail and mission continuity is ensured. Data that can be determined in advance in robotic systems are energy consumption, motor temperatures or vibration (Monteiro, Carmona-Aparicio, Lei, & Despeisse, 2022). By analyzing this data, failures can be detected before they occur. Moreover, unexpected situations are minimized.

As a result, these systems and AI applications in the aerospace field increase both reliability and enable adaptation to demanding space conditions. In subsequent aerospace exploration and missions involving researchers, these technologies will provide safer, more efficient and lower-cost solutions.

Conclusion

AI applications in the aerospace field provide a major transformation in the industry by exploring space, performing satellite communication, carrying out maintenance and repair activities, and increasing the efficiency of autonomous functions. With AI-supported systems, data is analyzed quickly and accurately, preserving the operational continuity of aerospace vehicles. In this way, mission success is increased. As a simple example, thanks to autonomous robots and intelligent navigation systems, robotic vehicles conducting research on planetary surfaces can detect obstacles and determine their own routes. These systems, which do not require humans, can successfully perform their tasks. It is of critical importance, especially in important and sensitive space missions where communication-based delays are high. With similar applications of AI, it is ensured that even long-range missions progress without any problems and that all collected data is analyzed.

AI-based autonomous systems offer more sustainable solutions for the current and future industry by reducing the costs of aerospace missions. In areas such as remote satellite communication, AI is involved in many stages, starting from spectrum analysis to signal processing processes and frequency management, optimizing communication quality. In addition, AI algorithms used in maintenance/repair and failure management can continuously monitor the health status of aerospace vehicles and detect possible failures in advance. In this way, maintenance operations that need to be performed before failures occur can be planned. In this way, functional continuity is maintained and operational interruptions are minimized. Thanks to applications such as predictive maintenance, the working life of aerospace vehicles is extended and costly failures are prevented.

In the future, AI will become a key component of more complex and long-term missions in the aerospace industry. AI applications will play an important role in tasks such as autonomous exploration and discovery on distant planets or asteroids, defining and even mapping planetary surfaces, and developing suitable habitats for human life. AI-based analyses and algorithms will accelerate the pace of experimental/scientific discoveries by rapidly processing large amounts of data sets. It will make aerospace functions safer and more efficient by making intelligent optimizations for business management plans. Thanks to all these technological developments, the aerospace industry will not only improve life on Earth, but also provide new, safe and stable exploration opportunities for the future of human existence in space.

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