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AI-Empowered Space Traffic Management: Challenges and Strategies

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Abstract

Space traffic management (STM) has emerged as a critical field of study due to the rapid expansion of space activities, including satellites, debris, and future crewed missions. This research paper delves into the multifaceted issues and challenges associated with STM and explores innovative strategies, specifically focusing on integrating artificial intelligence (AI). It examines the pressing problems of space debris proliferation, collision avoidance, spectrum congestion, and the need for international cooperation. The paper identifies STM's primary issues, such as the exponential increase in the number of satellites and space debris, limited resources, and the absence of comprehensive regulatory frameworks. It also discusses the critical challenges posed by the rise of mega-constellations, autonomous spacecraft, and the potential for hostile actions in space. To address these issues and challenges, the research paper discusses a set of strategies that can improve STM, including the development of standardized STM protocols, enhanced tracking and monitoring capabilities, improved data sharing and communication, and the promotion of international cooperation. Moreover, the paper emphasizes the integration of AI as a pivotal strategy for improving STM, highlighting its potential to automate collision avoidance, predict and mitigate space debris collisions, and optimize satellite orbits. AI-based solutions, such as machine learning algorithms and autonomous decision-making systems, play a crucial role in enhancing situational awareness, enabling real-time data analysis, and improving space traffic prediction. The integration of AI not only provides a more efficient STM infrastructure but also aids in mitigating the growing challenges in space.

Keywords: Artificial intelligence, space debris proliferation, machine learning algorithms, spacecraft, space traffic management

INTRODUCTION

Space traffic management (STM) is a regulatory framework essential for overseeing and facilitating the safe and sustainable utilization of space, with a specific focus on Earth's orbit. With the escalating number of human activities in space, STM becomes increasingly vital to avert collisions, mitigate the generation of space debris, and encourage responsible conduct in the vast expanse of outer space. The core of STM involves the meticulous tracking and prediction of trajectories for satellites and other objects orbiting Earth, aiming to prevent potential collisions and ensure the orderly coexistence of various space entities. Additionally, STM emphasizes international collaboration to establish standardized practices, fostering a cooperative approach to address the challenges posed by the burgeoning number of objects in Earth's orbital environment. The overarching objective of STM is to preserve the safety and long-term sustainability of space activities amid the intensifying congestion in Earth's orbit.

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Increasing Congestion in Space

The growing congestion in space is a result of the escalating number of satellites, expanding space debris and upcoming space missions. As satellites launch for communications, Earth observation, and scientific endeavors, Earth's orbit is becoming increasingly crowded. This congestion increases the risk of collisions between satellites and other space objects. In addition, the proliferation of space debris, including defunct satellites and fragments from previous missions, further compounds this challenge. Adding to this congestion are upcoming space missions, powered by both government and commercial entities. Solving this problem requires effective STM strategies for monitoring, predicting and regulating the trajectories of space objects [1, 2].

The Need for Advanced Technology

The management and optimization of space traffic has become increasingly important as the space domain experiences unprecedented growth in satellite deployment, space missions, and commercial activities.

- *Autonomous decision making:* The sheer volume of space objects and the dynamic nature of space missions require rapid and autonomous decision-making capabilities. Artificial intelligence (AI) algorithms can process massive amounts of data in real time, allowing autonomous systems to make split-second decisions to optimize space traffic routes and avoid potential conflicts.
- *Mega constellation integration:* Mega constellations, comprising hundreds or thousands of small satellites, are increasingly common [3]. Coordinating the movements of these constellations and ensuring their trajectories comply with regulatory requirements requires advanced AI capabilities to manage the complexity and scale of such systems [4].
- *Effective use of resources:* AI can optimize the allocation of resources such as communication bandwidth and orbital slots by analyzing usage patterns and dynamically adjusting configurations [5]. This ensures efficient use of available resources and reduces the risk of congestion and interference.
- *Adaptability to emerging threats:* Space traffic management must be adaptable to emerging threats such as cyber-attacks on satellite systems. AI can enhance the cyber security of space facilities by constantly learning and evolving to counter new and evolving threats.

By leveraging AI, we can enhance the safety, efficiency, and sustainability of space operations while addressing the challenges posed by the growing number of satellites and space debris [6].

BACKGROUND

Overview of the Current State of Space Traffic

Over the past 2 years, an average of 975 new streaming sites have been added to the index every 3 months. These additional items include items released into orbit independently of the launch vehicle, either as part of the routine operation of the parent aircraft or because of a separate incident, divergence, or separation.

Figure 1 shows a breakdown of the latest additions to conventional comparable covering the period between the second quarter (CY) of 2021 and the first quarter of 2023. Debris from existing satellites makes up more than a third. of all new satellites (37.8% of the total). In addition, mission-related debris (MRD), representing inert materials released by satellites during their daily operations, constitutes 4.4% of all new materials.

Historical Incidents that Emphasize the Importance of Effective Space Traffic Management

Various historical incidents underscore the crucial significance of effective STM in guaranteeing the sustainability and safety of operations within Earth's orbit. Several notable examples include:

- *Iridium-Cosmos Collision (2009):* In February 2009, an operational Iridium communication satellite collided with a defunct Russian Cosmos satellite over Siberia. This event resulted in the creation of thousands of trackable debris fragments, emphasizing the potential dangers of on-orbit collisions. Effective STM measures [4], such as collision avoidance maneuvers and improved conjunction assessments, are vital to mitigating such risks.

- *Chinese ASAT Test (2007):* In January 2007, China conducted an anti-satellite (ASAT) missile test, deliberately destroying one of its aging weather satellites. This action led to a significant increase in debris and raised concerns about intentional space debris creation [7]. STM is essential to prevent and manage the proliferation of debris, which poses risks to operational satellites and future space activities.
- *Inmarsat–Iridium Close Approach (2019):* In September 2019, two communication satellites Inmarsat GX5 and Iridium 47 came dangerously close to each other, highlighting the challenges posed by the increasing density of satellites in orbit. Effective STM protocols are crucial for coordinating maneuvers and preventing close approaches to avoid collisions [1, 2, 6].

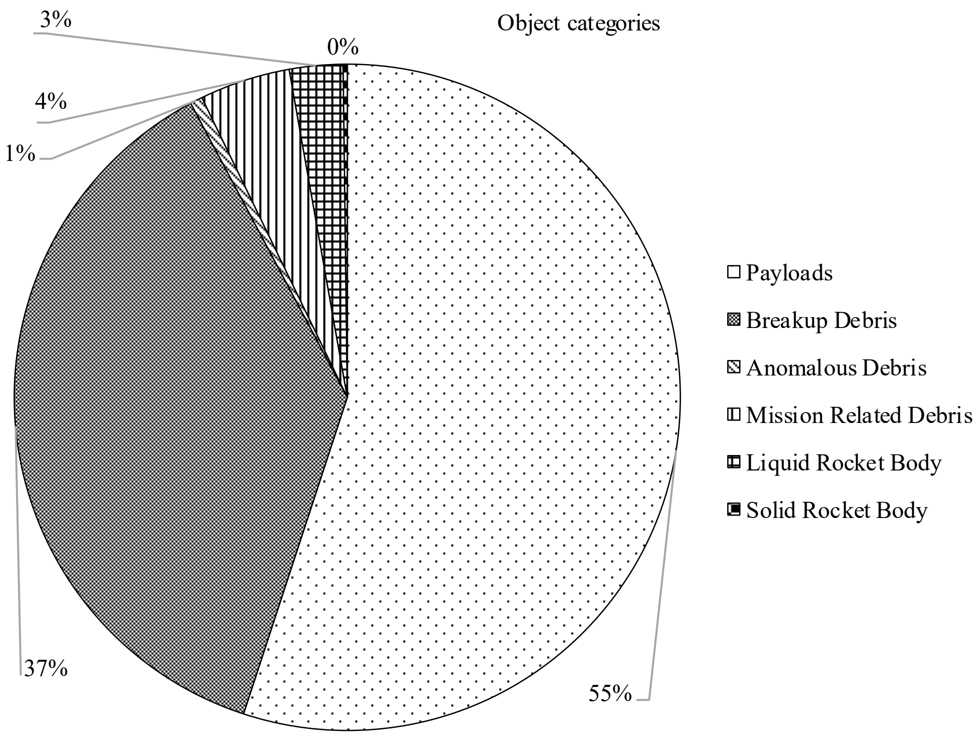

Figure 1. Object categories added to the catalogue since quarter 2 (Q2) of CY2021

These incidents collectively emphasize the necessity of robust STM frameworks to address the challenges posed by the growing congestion in Earth's orbit, minimize the risks of collisions, and ensure the long-term sustainability of space activities.

ROLE OF ARTIFICIAL INTELLIGENCE IN SPACE TRAFFIC MANAGEMENT

How Artificial intelligence Can Enhance STM by Analyzing Large Dataset, Predicting Trajectories and Optimizing Space Traffic

AI has become a transformative force in the New Space sector, revolutionizing STM with its advanced capabilities [8]. New Space, characterized by innovative technologies and business models in space exploration, benefits significantly from AI in optimizing various aspects of space traffic operations:

1. *Optimizing Space Traffic Planning and Operations:* AI utilizes sophisticated algorithms to analyse extensive datasets encompassing orbital dynamics, atmospheric conditions, and launch vehicle performance. This analysis optimizes space traffic planning by selecting launch windows, calculating fuel consumption, and planning trajectory adjustments for efficient resource utilization and cost-effectiveness [9, 10].

2. *Autonomous Systems for Space Traffic:* AI enables the development of autonomous systems for spacecraft, equipped with decision-making capabilities. These systems leverage real-time analysis to autonomously adjust trajectories and orbits, particularly crucial for satellite constellations requiring continuous monitoring and rapid response to changing space traffic dynamics.
3. *Space Debris Tracking and Management:* AI's predictive capabilities are harnessed for tracking and managing space debris, minimizing collision risks with operational satellites and spacecraft. It aids in developing effective strategies for debris mitigation and removal, ensuring the safety of space traffic operations.
4. *Artificial Intelligence in Design and Simulation for Space Traffic:* AI-powered simulations model intricate interactions among spacecraft components, enhancing the reliability and safety of space traffic operations by identifying potential issues before physical manufacturing.

In summary, AI's multifaceted contributions play a transformative role in optimizing STM within the New Space sector, enhancing efficiency, safety, and overall success in space traffic operations.

KEY COMPONENTS OF ARTIFICAL INTELLIGENCE–EMPOWERED SPACE TRAFFIC MANAGEMENT

Enhancing Real-Time Data Processing and Analysis Through Artificial Intelligence Algorithms

To our knowledge, there is no public repository containing such information. Therefore, we created a method to create this library that can be applied to both real and virtual scenarios.

Real Scenario

The goal here is to find collisions between active satellites and orbital debris and create evasive maneuvers to avoid collisions, based on real tracking data of objects in space.

a. Input Data and Object Categorization:
   - Utilize JSON files containing space object measurements with Two-line Element Set (TLE) orbital elements.
   - Categorize objects into primary satellites and secondary debris based on TLE names.
b. Critical Point Computation:
   - Compute critical points for squared Keplerian distance between orbits for all possible object pairs.
   - Accept only critical points with miss distances below a defined threshold (D = 10 m).
c. Time Analysis at Critical Points:
   - Determine arrival times of primary and secondary objects at accepted critical points.
   - Identify potential high probability collisions by comparing time differences (using threshold T = 1 s).
d. Collision Probability Calculation:
   - Set the time of possible conjunction (tC) as the midpoint between primary and secondary object arrival times.
   - Calculate collision probability through sampling within a set of one million samples at tC.
e. Collision Avoidance Maneuver:
   - If collision probability exceeds the accepted collision probability level (ACPL), compute avoidance maneuvers.
   - Determine direction and magnitude of the maneuver to reduce collision probability below the ACPL.
f. Maneuver Application and Analysis:
   - Apply computed maneuver to the primary object and update its state.
   - Recalculate potential collisions with secondaries and analyze subsequent maneuvers needed.
   - Perform this process recursively for future time intervals.

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g. Save into Maneuver Database:
   - Store information about collisions, maneuvers, and subsequent actions in a MongoDB database.
h. Size and Radius Considerations:
   - Set primary object radius as 9 m and secondary object radius as 1 m, summing up to a combined radius of 10 m.
   - Adjust covariance matrix values based on object size assumptions.
i. Parameters and Thresholds:
   - Set thresholds for miss distance (D), time difference (T), and ACPL.
   - Consider specific ratios for standard deviations in the covariance matrix.
j. Iterative Process:
   - The entire process involves an iterative approach to continuously analyze and update collision avoidance strategies based on real-time tracking data.

Virtual Scenario

The real scenario, while computationally intensive, has a low probability of identifying high-risk collisions, making it inefficient. To address this, a simplified virtual scenario is proposed. In this scenario, primary objects are identified from a TLE set database, and virtual secondary objects are generated by perturbing the state of primaries. Collision scenarios are simulated by randomly choosing conjunction times within a given interval. If the collision probability exceeds a threshold, a collision avoidance maneuver is computed. This process is repeated for subsequent maneuvers, allowing a cost-effectiveness comparison. The virtual scenario offers computational efficiency for analyzing collisions and generating avoidance maneuvers, presenting a practical alternative to the resource-intensive real scenario.

Description of a Maneuver Record

a. Maneuver Record Description:
   - Computed maneuvers, for both real and virtual scenarios, are stored in a database.
   - Comprehensive data associated with each maneuver is saved to allow for in-depth analysis and result reproduction.
b. Maneuver Record Fields:
   - *ID:* Unique identifier for the maneuver record.
   - *Collision:* Information about the collision avoided, including covariance matrices, mean states, miss distance, and details about the involved objects.
   - ΔV: Computed maneuver expressed as a 3D vector in the tangent–normal–h reference frame, containing direction and magnitude.
   - *Object to maneuver:* Information about the primary object on which the maneuver will be applied.
   - *Posterior collision probability:* Probability of collision after applying the avoidance maneuver.
   - *Scenery type:* Indicates whether the maneuver was computed in a real or virtual scenario.
   - *Subsequent maneuvers after application:* Array of collision avoidance maneuvers needed in the future in case the current maneuver is applied to the primary object.
   - *Subsequent maneuvers no application:* Array of collision avoidance maneuvers needed in the future if the current maneuver is not applied.
   - *Time of application:* Indicates the time when the maneuver must be applied.
c. Collision Field Details:
   - *o1 and o2:* General information about object 1 and object 2 in the collision, including mass, measurements, name, and radius.
   - *Probability:* Probability of collision, always exceeding the ACPL.
   - *Screening time:* Moment when the collision was detected.

- *State o1st and state o2st:* Mean state of objects 1 and 2 at screening time.

d. Additional Information:
- The database stores not only the ΔV but also every piece of data associated with it, enabling thorough analysis and result reproduction.

Autonomous Collision Avoidance: Artificial Intelligence–Predicted Trajectories and Maneuver Planning

In this section, we delve into the intricate details of autonomous collision avoidance for satellites, emphasizing the utilization of AI-enhanced trajectory predictions. These advancements in maneuver planning play a pivotal role in ensuring the safety and efficiency of satellite operations in space.

Trajectory Prediction Leveraging Neural Networks

A key mathematical foundation for satellite trajectory prediction lies in the application of neural networks. These networks, a subset of machine learning algorithms, utilize input data comprising position, velocity, and acceleration information collected from diverse sensors. Through a process of iterative learning, the network discerns complex relationships within this data, enabling accurate forecasts of the satellite's future position at distinct time intervals.

Mathematically, the neural network's predictive function can be represented as:

$$P(t+\Delta t) = NeuralNetwork(P(t), (V(t), A(t)) \tag{1}$$

Here, the AI model function encapsulates the learned relationships within the neural network.

Probabilistic Approaches to Collision Prediction

To enhance the precision of collision prediction, probabilistic models come into play. These models consider uncertainties in trajectory predictions, assigning probabilities to potential collision events. Bayesian methods, for example, facilitate the calculation of posterior probabilities for collision scenarios, integrating prior knowledge with real-time sensor data.

The collision probability (PoC) can be expressed as:

$$PoC = P\ (Collision\ Features) \tag{2}$$

Here, features encompass parameters like relative speed, miss distance, and historical collision data.

Optimization Techniques for Safe Maneuvers

Upon identifying a potential collision, the AI system engages in optimization for maneuver planning. Optimization techniques, such as convex optimization or genetic algorithms, are employed to determine the optimal change in velocity (ΔV) that minimizes future risk and associated costs.

The optimization problem is formulated as:

$$Minimize\ J(\Delta V) = Future\ Risk\ (\Delta V) + Future\ Cost\ (\Delta V) \tag{3}$$

Subject to constraints related to available thrust, energy consumption, and time of application.

Real-Time Decision-Making Algorithms

Integration of predictive models into real-time decision-making algorithms proves vital for the dynamic space environment. Recursive estimation methods, such as Kalman filters, continuously update predictions based on incoming sensor data. This ensures that the satellite adapts to unforeseen changes in its trajectory or the trajectories of other space objects.

Continuous Learning and Adaptation

Satellite collision avoidance AI systems undergo continuous learning and adaptation. Reinforcement learning mechanisms enable satellites to adjust their behaviors based on the outcomes of past decisions, ensuring ongoing improvement in the system's ability to predict, plan, and execute collision avoidance maneuvers. This amalgamation of advanced mathematical models and AI techniques empowers satellites with the autonomy and intelligence required to navigate complex orbital environments securely.

CHALLENGES IN DEVELOPING SYSTEMS AND TECHNOLOGIES

Mission Design and Planning

The meticulous design and planning of space missions demand a wealth of knowledge and expertise from both human and computational resources. AI plays a crucial role in managing information, knowledge, procedures, and operations throughout a space mission.

Space Exploration

The impact of AI on shaping and advancing the future of space exploration is noteworthy, with diverse applications spanning planetary navigation, robot exploration, and the exploration of celestial bodies in deep space. A compelling example is the utilization of a Bayesian algorithm to obtain the first image of a black hole, employing deconvolution on radio astronomy images. Ongoing research efforts are focused on developing more sophisticated AI algorithms to achieve more precise images of black holes, aiding scientists in the identification and classification of various deep-space objects. A case in point involves the discovery of two Kepler Exoplanets, Kepler 80g, and Kepler 90i, orbiting the Kepler 80 and Kepler 90 star systems, respectively. The challenge for astronomers lies in autonomously identifying exoplanets in these regions, necessitating advanced AI techniques are as mentioned in Figure 2.

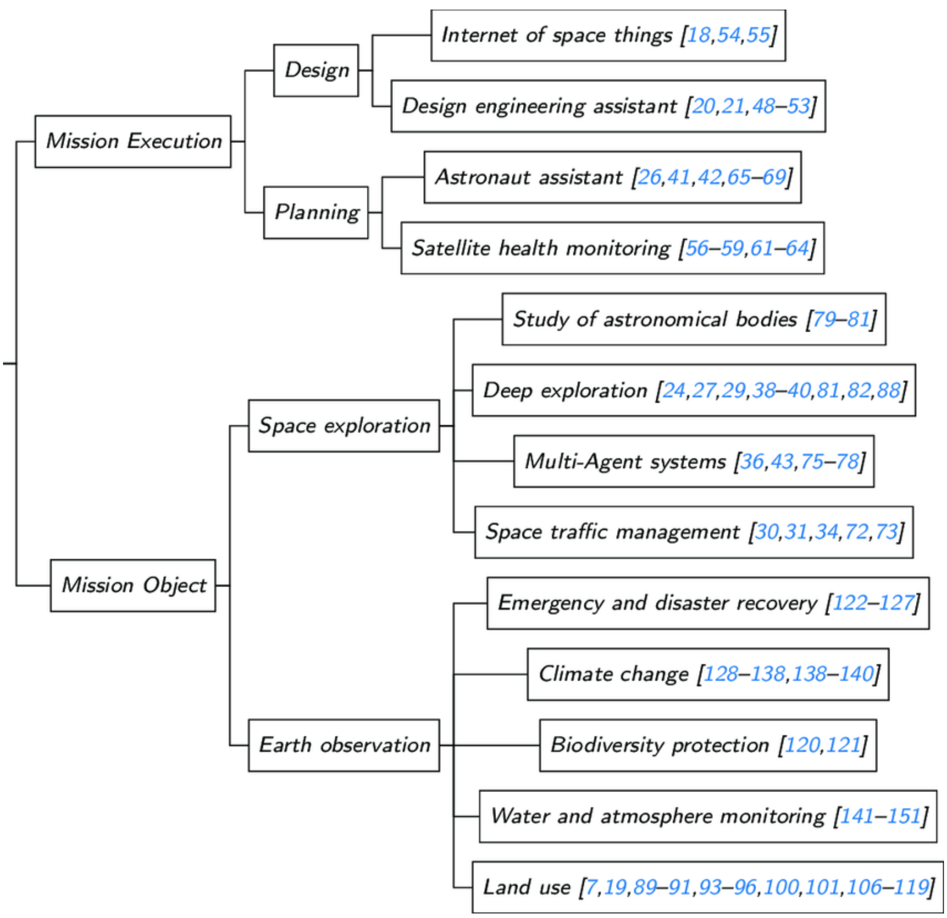

Figure 2. Challenges in space applications.
Source: https://www.researchgate.net/figure/Challenges-in-Space-Applications_fig1_360747595

FUTURE TRENDS AND DEVELOPMENT

Upcoming Technologies and Advancement in Artificial Intelligence

Swarm Intelligence

Utilizing AI algorithms inspired by swarm intelligence could enable groups of satellites to coordinate and optimize their movements collectively. This approach mimics the behavior of natural swarms to improve overall system efficiency and adaptability.

Explainable Artificial Intelligence

Given the critical nature of space operations, incorporating explainable AI (XAI) techniques can help in understanding and interpreting the decisions made by AI systems. This is crucial for building trust and facilitating human oversight in STM.

Deep Reinforcement Learning

Deep reinforcement learning (DRL) can be applied to train AI systems for autonomous decision making in space. DRL allows AI to learn optimal strategies through trial and error, which can be beneficial for complex and dynamic space environments.

Quantum Machine Learning

As quantum computing technology advances, there is potential for quantum machine learning to address complex optimization problems more efficiently than classical algorithms. This could have applications in trajectory planning and collision avoidance in space.

Interoperability and Standardization

AI systems for space traffic management could be designed with a focus on interoperability, allowing different systems to communicate and share information seamlessly. Standardization efforts can play a crucial role in ensuring compatibility between diverse space systems.

Integration with Space Weather Forecasting

Integrating AI with space weather forecasting can enhance predictive analytics for space traffic management. Space weather events, such as solar flares, can impact satellite operations, and AI can help in predicting and mitigating these effects.

Advanced Computer Vision Techniques

Advancements in computer vision, such as improved object recognition and tracking algorithms, can enhance the accuracy of identifying and monitoring objects in space. This is crucial for maintaining a comprehensive and up-to-date space situational awareness [1, 4].

CONCLUSION

In conclusion, the incorporation of AI into STM emerges as a transformative strategy to tackle the escalating challenges presented by the intricacies of modern space operations. This study has extensively explored the various dimensions of AI's contribution to STM, encompassing predictive analytics, autonomous decision making, adaptive spectrum management, and collaborative communication networks.

The findings underscore the imperative for advanced technologies in navigating the increasing congestion and dynamism of space environments. Traditional STM systems, foundational though they may be, are facing strain amid rapid technological advancements and the proliferation of satellites and debris. The constraints of human-centric decision making and conventional methods necessitate the adoption of AI-driven solutions to ensure the safety, efficiency, and sustainability of space activities.

Illustrative case studies presented here spotlight instances where successful integration of AI in STM has yielded tangible improvements in collision avoidance, resource optimization, and adaptability to dynamic scenarios. These practical applications offer valuable insights into the real-world implications and potential challenges associated with infusing AI into operational space environments.

Moreover, the examination of ethical and legal considerations underscores the importance of establishing a comprehensive framework that addresses privacy, security, and international regulations. As AI becomes an integral component of STM, establishing guidelines and standards becomes crucial to ensuring responsible and ethical use, promoting international collaboration and adherence to shared principles.

Looking ahead, the prospects of AI-empowered STM appear promising, with ongoing advancements in AI technologies poised to enhance predictive capabilities, decision-making autonomy, and adaptability to evolving space environments. The recommendations articulated in this study emphasize the necessity for proactive policy development, the encouragement of collaboration among spacefaring nations, and the maximization of AI's potential.

In essence, this study contributes to the expanding body of knowledge on AI-empowered STM, shedding light on the potential of these technologies to revolutionize the navigation and management of space traffic. As humanity continues its exploration of the cosmos, the integration of AI stands as a crucial ally, ensuring that the final frontier remains accessible, secure, and sustainable for generations to come.

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