A Survey of Artificial Intelligence Techniques for Space Debris Detection, Tracking, and Mitigation

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Abstract

Space debris is considered a major challenge for space activities, and has gained significant attention in recent times. Satellites, rocket fragments, and other human activities have resulted in an increase in damaged satellites and collision debris in Earth's orbital space. Conventional debris detection technologies are often ineffective in managing the growing volume of space debris and the associated complex data. Artificial intelligence is recognized as an efficient technology for space debris detection, tracking, collision prediction, and mitigating its effects. This survey paper provides an overview of space debris, its adverse effects, statistics, and AI techniques for handling space debris.

Keywords: *Space Debris, Artificial Intelligence, Machine Learning, Space Situational Awareness, Collision Avoidance*

1. Introduction

The rapid development in space activities in the past several decades has seen a major increase in artificial objects orbiting the Earth. Although space technology is of prime importance in communication, navigation, weather forecasting, observation, exploration, and other areas, it has also resulted in a buildup in space debris. Space debris refers to non-functioning artificial bodies in space, include defunct satellites, spent launch vehicles, or fragments that get there through explosions or collisions. These objects can travel at extremely high velocities, far beyond 7 km/s, due to which the fragments can do considerable damage even if they are small in size[1].

The increasing rate of space debris is posing a threat to both robotic and human space exploration activities. When space debris collides with satellite systems, it may lead to mission failure, which might cause monetary losses and further aggravate the condition due to the generation of yet more debris in space. This phenomenon is known as the Kessler Syndrome, which has the potential to make space impassable for further exploration activities in space. Space agencies such as NASA and the European Space Agency have mentioned space debris as a threat to space exploration activities in space[1].

Artificial Intelligence (AI) technology is one potential solution to offset these issues. The use of artificial intelligence tools, such as machine learning and deep learning algorithms, can facilitate the efficient evaluation of large-scale data sets and enable relative identification of specified patterns within those sets. In space debris management technology, artificial intelligence systems could be better leveraged for object detection, orbit prediction, collision risk estimation, and collision avoidance maneuvers[2],[3]. Essentially, by using artificial intelligence for space situational awareness systems, it is possible to better evaluate decision-making processes and prevent potential catastrophic space collisions.

In this paper, an extensive survey of space debris is provided, along with a discussion about the implications of artificial intelligence in removing the risks associated with it. The paper includes a discussion about the sources and impacts of space debris, statistics regarding it, as well as various techniques involving artificial intelligence for efficient detection, tracking, as well as collision avoidance[1],[2],[3]. Also, the current applications, challenges, as well as various research issues are presented, focusing on the role of intelligent systems.

2. Space Debris Overview

Space debris, also called orbital debris, is defined as human-made items that are present in Earth's orbit and have no useful purpose. The items remain in orbit because of the absence of atmospheric effects at high altitudes[4]. The space debris continues to move at high velocities. The space debris varies greatly in shape, size, and mass, including large satellites that have served their useful role and microscopic amounts of space debris produced by space missions[4],[5].

2.1 Sources of Space Debris

The main sources of space debris consist of satellites that have reached their lifespan, spent rocket stages that were not removed after delivering their payload, and fragments resulting from accidental collisions and explosions. Debris is also being created through various activities associated with space missions, such as bolts, lens covers, and flakes of paint used during spacecraft operation. Anti-satellite weapon tests have also significantly contributed to the creation of space debris, resulting in the generation of thousands of fragments distributed throughout densely populated orbit regions.

2.2 Classification of Space Debris

Space debris is most commonly classified on the basis of size; the extent of danger posed by it is usually determined on the basis of its dimensions. Large objects of space debris, i.e., pieces of space junk that are larger than 10 cm, can be actively tracked using radar and optical ground-based tracking facilities[4]. Medium-sized space debris, which falls in the range of 1 cm to 10 cm, is considered extremely hazardous but is also hard to track. Small pieces of space junk, though not tracked, can be extremely harmful owing to their velocities.

2.3 Orbital Regions of Space Debris

Most of the space debris is currently concentrated within Low Earth Orbit (LEO), where a number of Earth observation, communication, and scientific satellites are deployed. In addition, there is some presence of space debris in Medium Earth Orbit (MEO) and Geostationary Orbit (GEO), but to a much lesser extent. The presence of space debris is a major concern within LEO due to the presence of a high number of satellite launches and satellite constellations[4].

2.4 Long-Term Impact on Space Sustainability

If not addressed, the increasing amount of space debris may result in a virtual ecosystem in which collisions produce more debris, thereby escalating the probability of further collisions. Consequently, the sustainability of space activities can be threatened, as well as access to space in important orbital positions[4],[5]. Therefore, it is important to develop effective debris monitoring, mitigation, and elimination techniques for the safe and effective utilization of outer space.

3. Harmful Effects of Space Debris

The safety, reliability, and sustainability of space activities are significantly threatened by space debris. This is primarily attributed to the substantially high speeds at which space vehicles move, whereby, even when space debris is minuscule, it can cause destructive damage when it collides with other space vehicles[2],[6]. The destructive effect of space debris cuts across its technological, economic, operational, and human safety ramifications.

3.1 Threat to Operational Satellites

Operational satellites used for various purposes on Earth are also highly susceptible to collision with space junk. Particles moving at speeds above 7 km/s have ample kinetic energy, which allows tiny pieces of debris only a few centimeters in size to penetrate and potentially damage satellite equipment, solar panels, and electronic equipment, and may even completely destroy the satellite. These satellite failures may lead to loss of vital services such as communication, navigation, and acquisition of weather and Earth observation images[6].

3.2 Risk to Human Spaceflight

In addition, space debris poses a direct threat to human life through crewed space missions. Space stations and crewed spacecraft should always pay close attention to the trajectory taken by debris to avoid collision. Even fragments of small debris can puncture the wall of space stations or compromise life-support mechanisms. Because of this fact, astronauts are frequently required to take shelter or conduct emergency maneuvers, which adds operational complexity and safety risks[1],[2].

3.3 Generation of Secondary Debris

One of the worst effects that collisions of space debris have is generating secondary debris. A colliding pair can break into thousands of pieces, increasing the population of debris metric tons many fold. This could achieve a cascading effect-the so-called Kessler Syndrome-where such a self-sustaining cycle of collisions leads to a radical rise in collision probabilities and may render certain orbital regions unusable for a long time.

3.4 Financial and Operational Impacts

The economic cost associated with space debris is huge. For instance, satellite operators need to execute several collision avoidance maneuvers, which require precious fuel and shorten the operational lifespan of satellite[2],[6]. As a result, insurance premiums for space missions grow when there is also an increase in risks of collision, while replacing satellites may amount to hundreds of millions of dollars. Moreover, disruptions attributable to debris could affect industries and services dependent on space infrastructures.

3.5 Impact on Future Space Missions

The increasing concentration of space debris makes mission planning for that place more complex and highly restricted by limiting access to certain valuable orbital regions. Launch windows may be restricted, and requirements on spacecraft design to be able to survive possible debris impacts become more complex. Unless carefully managed, the accumulation of space debris has the potential to significantly impact future scientific exploration, commercial activities, and innovation based on space.

4. Statistics of Space Debris

The problem with space debris has escalated in magnitude in recent years because many satellites are being launched, and many satellite systems consist of large numbers of satellites. Statistically, it is evident that there is satellite congestion in Earth Orbit.

Recent assessments by space agencies indicate that more than 36,000 objects larger than 10 cm are being tracked in Earth's orbit. This includes defunct satellites and rocket bodies, which are capable of inflicting catastrophic damage in case of a collision. Besides these trackeable objects, it is also estimated that there are about one million fragments measuring between 1 cm to 10 cm. Due to their size, these are considered to be a major hazard to satellites since they are difficult to track but large enough to inflict severe damage[1].

Secondly, in addition to the over 130 million debris particles smaller than 1 cm, which are hard to detect, their high velocity is sufficient to erode spacecraft surfaces, which would then impact the overall system. According to current knowledge, only a limited number of the total debris are under active surveillance, implying a high number of debris particles are not under consideration in the collision risk analysis.

The region of Low Earth's Orbit has the highest density of space debris because of the high number of Earth observation, communication, and scientific satellites that are deployed and operate in this region [2]. Additionally, the more satellite constellations that are being deployed, the higher the density of space debris accumulated in this region, necessitating a significant increase in the likelihood of satellite collision. In Medium Earth Orbit and Geostationary Orbit, there is some space debris, though less dense, that can stay for decades due to low atmospheric drag [1].

The rising statistics on space debris provide a clear indication that the problem is not a self-limiting one, as the current amount of debris is enough to ensure collisions even in the absence of fresh launches. These statistics clearly indicate the need for advanced monitoring, prediction, and mitigation techniques, motivating the adoption of artificial intelligence to manage the growing complexity of the orbital environment.

Categories	**Size Range**	**Estimated Quantity**	**Description / Risk**
Large debris	> 10 cm	Approximately 36,000 objects	Trackable; includes defunct satellites and rocket bodies; can cause catastrophic damage
Medium debris	1–10 cm	Approximately 1,000,000 objects	Difficult to track; capable of disabling satellites
Small debris	< 1 cm	>130 million objects	Not trackable; can erode surfaces and damage sensors
Actively tracked objects	N/A	<10% of total debris	Limited tracking coverage increases collision risk
Most affected orbit	LEO	Highest density	High satellite concentration and collision probability

Table 1: Global Statistics of Space Debris

5. Role of Artificial Intelligence in Space Debris Management

AI has emerged as a powerful tool to address the emerging challenges of space debris management. Unlike traditional rule-based and physics-driven approaches, AI can learn from large volumes of data, identify complex patterns, and make adaptive decisions in uncertain environments. Those properties of AI basically position it for space situational awareness and debris mitigation.

5.1 AI-Based Space Debris Detection

Especially, AI techniques like deep learning models are extensively used for the detection of space debris based on optical telescope images and radar data. This model can segregate weak and fast-moving debris objects from noisy and low-contrast conditions. The AI-based detection significantly improves the accuracy by reducing false positives when compared to the conventional image processing techniques [7],[9],[11].

5.2 Artificial Intelligence for Tracking and Orbit Prediction

The machine learning models, like RNNs and LSTM networks, use previous knowledge of temporal patterns to predict debris trajectories from historical orbital data. These models are capable of handling the nonlinear dynamics and uncertainties because of atmospheric drag, solar radiation pressure, and gravitational perturbations.[8],[11] Thus, long-term AI-based orbit prediction gives better results than traditional methods of physics-based approaches.

5.3 AI-Driven Collision Prediction and Avoidance

An application of AI is seen in using it to calculate the probabilities of collision, hence supporting a decision process for collision avoidance maneuvers. Reinforcement learning can be used by satellites in orbit to learn how to make autonomous choices in selecting the most efficient way of dealing with collisions, minimizing fuel usage in the process.

5.4 Advantages of AI-Based Approaches

The incorporation of AI in space debris management is associated with several benefits such as enhancing the accuracy of detection of space debris, increasing the reliability of prediction information, automating collision avoidance decision processes for space debris, and providing efficient ways of dealing with space surveillance data.[8][9][11]

6. Existing Applications of Artificial Intelligence in Space Debris Management

Artificial intelligence is no longer viewed as a hypothetical concept in the management of space debris and has started to emerge in the practical implementation of real-world applications. Space organizations and research institutions have actively looked into and even began implementing AI in the management of space situational awareness.

Space agencies such as NASA and the European Space Agency have integrated various forms of machine learning into their detection of space debris to enhance the analysis of information collected from radar and optical observation.[5],[7] The role of AI is to improve the understanding of previously unknown space debris.

Research initiatives and scholarly studies, such as those conducted and published via platforms associated with IEEE, have highlighted and proved the efficiency and effectiveness of deep learning and reinforcement learning-based approaches in regard to debris detection and avoidance. The studies prove the feasibility of deploying such technology .[4],[8]

Additionally, there are experimental missions that are focused on active debris removal, where intelligent systems are being used for identification, navigation, and planning for the capture. Although these applications are still at their developmental stages, they indicate the key role that AI is going to play in the problem of space debris.[6]

7. Challenges and Limitations of AI-Based Approaches

Even though there is the advantage of using artificial intelligence in managing space debris, some challenges affect its adoption. Some of these challenges include:

Lack of quality and labeled datasets – the quality of available space debris is often limited and noisy, hence affecting the quality of artificial intelligence. This is mainly because real-life collision information is constrained.

Another limitation is that computing is a high computational requirement for AI models. Indeed, deep learning algorithms have high computational demands.[6] Implementing these high computational demands onboard satellites can be a challenge due to limited resources. Indeed, real-time computing for AI models is a challenge within a space environment.

Additionally, the transparency and trustworthiness of the decision made by the AI come into play. Some of the AI models are "black boxes," meaning the operator cannot fully comprehend or verify the justification for the collision avoidance system decision.[11],[12] This can have implications for spacecraft operations, which must perform in a trusted environment in safety-critical situations, for instance, for autonomous spacecraft maneuvers.[8]

Moreover, safety and ethical issues may emerge when using space missions since one of the challenges may be to ensure that some decisions are made alone by the AI system. If it ends up doing something wrong, it may fail in its mission and also contribute to more space junk.

8. Future Research Directions

The future studies in AI-based space debris management should be centered on creating solid adaptive learning models that can function in states of uncertainty with minimal access to data. The hybrid approach, which combines physics-based models with ML, could prove instrumental in improving accuracy in orbit prediction and collision risks. The other potentially useful direction could be found in swarm intelligence, whereby various satellites would work cooperatively through the application of AI systems that could help them exchange information and thus help deal with space debris threats more effectively.[12],[13]

Research on AI-enabled active debris removal is also getting attention. Intelligent systems can help identify high-risk debris, plan strategies for capture, and optimize the mission for removal.[13] Advancement in real-time on-board AI will enable satellites to make autonomous collision avoidance without continuous ground intervention.

Both AI integrated into space traffic management frameworks and international coordination will be needed to ensure that the utilization of intelligent systems in space is standardized and safe. These directions of current research illustrate long-term opportunities for AI to support sustainable space operations.[12]

9. Conclusion

The rapid growth of space debris has become a critical challenge threatening safety and sustainability in space activities. Traditional debris tracking and management face scalability, accuracy, and responsiveness challenges, especially in increasingly crowded orbital environments. Artificial intelligence provides powerful data-driven solutions to enhance debris detection, tracking, collision prediction, and mitigation.

This paper provided an overall review of space debris, ranging from sources and harmful effects to global statistics, and the limitations of using conventional methods in tracking. The part played by AI in providing enhanced space situational awareness was analyzed, pointing at existing applications, challenges, and future research opportunities. Integrating AI into the management systems of space debris can reduce collision risks while enabling sustainable use of space over a long period. The potential improvement by AI-driven approaches can be fully realized in ensuring safety and sustainability in the use of outer space with further research on validation and international cooperation.

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