Patent application No. : 2024410……_______

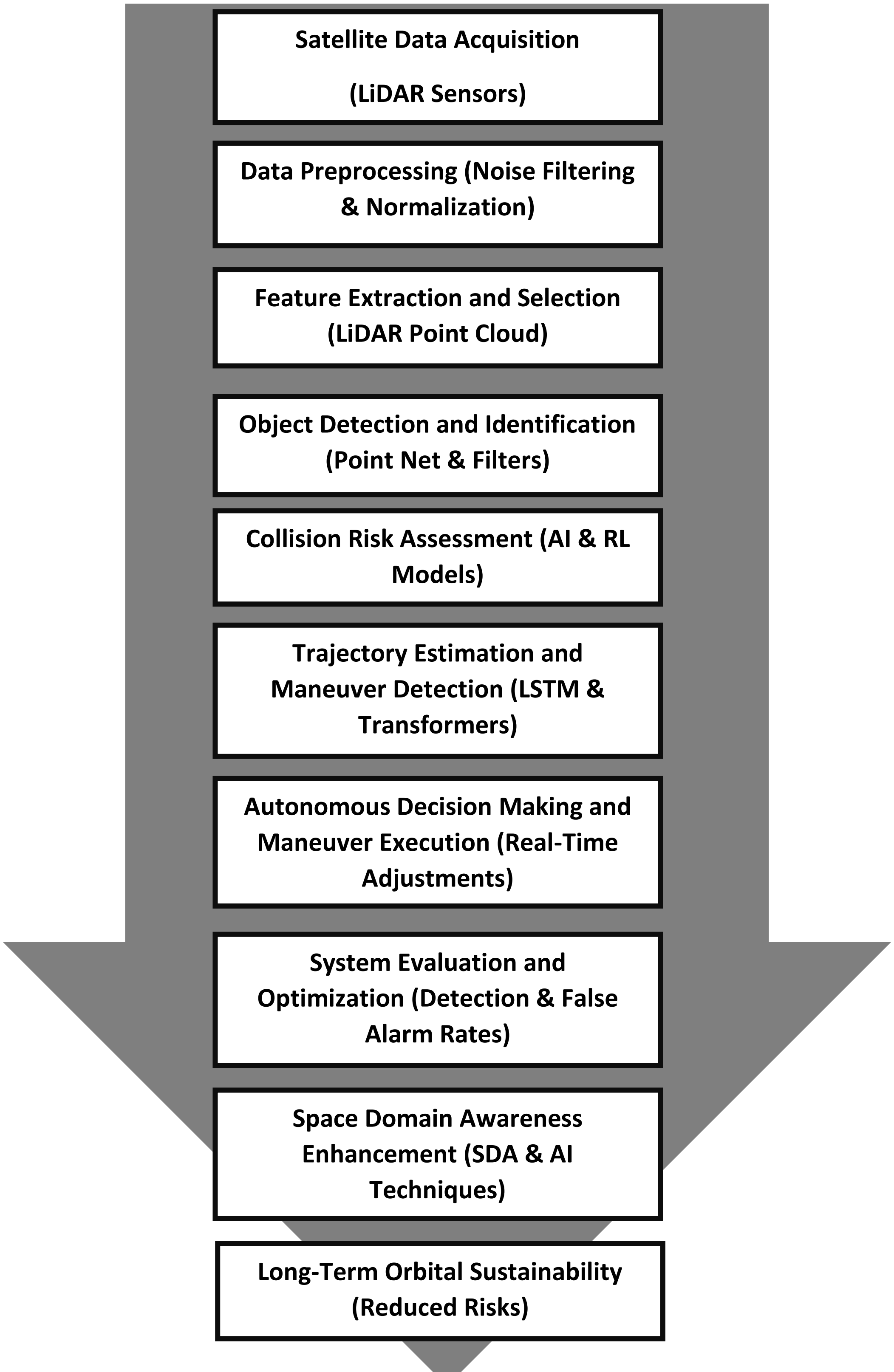

Figure 1. Schematic diagram of the methodology and flow of invention

FORM 2

THE PATENTS ACT, 1970
(39 of 1970)
&
The Patent Rules, 2003
COMPLETE SPECIFICATION
(See sections 10 & rule 13)

1. TITLE OF THE INVENTION

SYSTEM AND APPARATUS FOR AI-ENHANCED SATELLITE DEBRIS DETECTION AND COLLISION MITIGATION

2. APPLICANT(S)

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3. PREAMBLE TO THE DESCRIPTION

COMPLETE SPECIFICATION

The following specification particularly describes the invention and the manner in which it is to be performed

SYSTEM AND APPARATUS FOR AI-ENHANCED SATELLITE DEBRIS DETECTION AND COLLISION MITIGATION

FIELD OF INVENTION

[001] This invention relates to an AI-driven collision avoidance system for satellites in Low Earth Orbit (LEO) and Geostationary Earth Orbit (GEO). It integrates LiDAR sensors, reinforcement learning (RL), and AI models to detect and track space debris in real-time, enhancing Space Domain Awareness (SDA) and optimizing trajectory adjustments. Additional strategies include differential drag, adjusting satellite orientation to reduce collision risk, and using thrusters for propulsive maneuvers. Ephemeris data sharing with other operators improves coordination and situational awareness. Effective implementation involves planning during mission design, incorporating necessary hardware and software, and selecting optimal orbits to balance operational requirements with collision risks.

BACKGROUND OF INVENTION

[002] Background description includes information that may be useful in understanding the present invention. It is not an admission that any of the information provided herein is prior art or relevant to the presently claimed invention, or that any publication specifically or implicitly referenced is prior art.

[003] The increasing proliferation of satellites in Low Earth Orbit (LEO) and Geostationary Earth Orbit (GEO) has led to a significant rise in space debris, posing a serious threat to satellite operations. Space debris, including defunct satellites, spent rocket stages, and fragments from collisions, can cause catastrophic damage to operational satellites. Traditional methods of tracking and avoiding space debris, which rely on ground-based radar and optical telescopes, are becoming increasingly insufficient due to the sheer volume and velocity of the debris.

[004] These traditional tracking systems, while valuable, often lack the real-time precision required for immediate and accurate maneuver decisions. Additionally, they struggle to detect smaller debris, which, despite their size, can cause significant damage because of their high-velocity impacts. The growing number of satellites in orbit, coupled with the increasing volume of space debris, necessitates the development of more advanced and autonomous solutions for effective collision avoidance. Also the project having scope of differential sized LiDAR's as per satellite sizes.

[005] Recent advancements in LiDAR (Light Detection and Ranging) technology have shown promise in enhancing space debris detection capabilities. LiDAR sensors can provide high-resolution, real-time data on the position and movement of objects in space. This technology, when combined with advanced data processing

techniques, can effectively detect and track space debris, including those smaller than 10 cm.

[006] The integration of artificial intelligence (AI) and reinforcement learning (RL) models further enhances the capability to analyze and predict potential collisions, enabling satellites to autonomously adjust their trajectories in real-time. Reinforcement learning, a subset of AI, allows systems to learn and make decisions based on the analysis of past data and current conditions. By applying RL to satellite collision avoidance, the system can continuously improve its decision-making algorithms, optimizing for both safety and efficiency.

[007] The use of AI models, such as neural networks, in conjunction with LiDAR data, provides a robust framework for accurate debris tracking and collision risk assessment. This integrated approach not only reduces the need for manual interventions by satellite operators but also lowers operational costs and enhances the sustainability of satellite missions. As the risk of Kessler Syndrome—a scenario where the density of objects in low Earth orbit is high enough to cause a cascade of collisions—grows, the implementation of AI-driven collision avoidance systems becomes increasingly critical.

[008] This invention aims to integrate these advanced technologies to create a comprehensive collision avoidance system for satellites. By leveraging LiDAR sensors, reinforcement learning, and sophisticated AI models, the system offers a

real-time, autonomous solution to the growing problem of space debris, ensuring the long-term safety and operational efficiency of satellites in crowded orbits.

[009] Additionally, the system incorporates several collision mitigation strategies. Differential drag can modify the satellite's trajectory without using propellant by reorienting the satellite to change its frontal area in the velocity direction, altering the atmospheric drag experienced by the spacecraft, and resulting in a trajectory change over time. For spacecraft lacking propulsion or unable to use differential drag effectively, changing the attitude to present a minimal cross-section can reduce collision risk by reorienting the satellite so that its smallest projected area faces the direction of the approaching object.

[0010] Propulsive maneuvers, which involve using the satellite's thrusters to alter its trajectory, are typically planned about three days before the time of closest approach (TCA). A maneuver trade-space plot is used to determine the optimal burn intensity and timing, aiming to reduce the probability of collision by at least one and a half orders of magnitude below the mitigation requirement of 1E-04. Different propulsion modes may be used depending on the required velocity change.

[0011] Ephemeris data sharing with other spacecraft operators is a crucial part of collision avoidance strategies. This allows the operator of the other spacecraft to perform their own risk assessment, enabling coordinated avoidance maneuvers if necessary, and improving overall space situational awareness and safety. Effective implementation of these mitigation strategies requires considering collision avoidance capabilities during the mission planning and spacecraft design phases, selecting an appropriate mission orbit that balances operational requirements with collision risks, and incorporating necessary hardware (thrusters and attitude control systems) and software for supporting collision avoidance operations.

[0012] Further limitations and disadvantages of conventional approaches will become apparent to one of skill in the art through comparison of described systems with some aspects of the present disclosure, as outlined in the remainder of the present application and concerning the drawings. As used in the description herein and throughout the claims that follow, the meaning of “a,” “an,” and “the” includes plural reference unless the context dictates otherwise. Also, as used in the description herein, the meaning of “in” includes “in” and “on” unless the context dictates otherwise.

[0013] Groupings of alternative elements or embodiments of the invention disclosed herein are not to be construed as limitations. Each group member can be referred to and claimed individually or in any or a combination with other members of the group or other elements found herein. When any such inclusion or deletion occurs, the specification is herein deemed to contain the group as modified thus fulfilling the written description of all groups used in the appended claims.

SUMMARY OF INVENTION

[0014] This invention relates to an AI-driven collision avoidance system for satellites in Low Earth Orbit (LEO) and Geostationary Earth Orbit (GEO). It integrates LiDAR sensors, reinforcement learning (RL), and AI models to detect and track space debris in real-time, enhancing Space Domain Awareness (SDA) and optimizing trajectory adjustments. Additional strategies include differential drag, adjusting satellite orientation to reduce collision risk, and using thrusters for propulsive maneuvers. Ephemeris data sharing with other operators improves coordination and situational awareness. Effective implementation involves planning during mission design, incorporating necessary hardware and software, and selecting optimal orbits to balance operational requirements with collision risks.

[0015] The invention revolves around an AI-driven collision avoidance system for satellites operating in Low Earth Orbit (LEO) and Geostationary Earth Orbit (GEO). This system addresses the growing threat posed by space debris, which includes defunct satellites, spent rocket stages, and fragments from collisions. The accumulation of such debris poses a serious risk to operational satellites, necessitating more advanced and autonomous solutions to ensure the safety and efficiency of satellite operations.

[0016] At the core of this invention are LiDAR sensors mounted on satellites. These sensors provide high-resolution, real-time data on the position and movement of space debris, including objects smaller than 10 cm. The use of LiDAR technology allows for precise detection and tracking of debris, overcoming the limitations of traditional ground-based radar and optical telescope systems that often lack real-time precision and struggle with smaller debris.

[0017] The system's capabilities are further enhanced by integrating artificial intelligence (AI) and reinforcement learning (RL) models. Reinforcement learning, a subset of AI, enables the system to analyze and make decisions based on real-time data and past experiences. By continuously learning and improving its algorithms, the system can optimize satellite trajectory adjustments in response to detected debris, ensuring both safety and efficiency. AI models, such as neural networks, are used to analyze collision risks and predict potential threats, providing a robust framework for accurate debris tracking and collision risk assessment.

[0018] Additionally, the invention utilizes advanced data processing frameworks such as Open3D and the Point Cloud Library (PCL) for LiDAR point cloud processing. Object detection is facilitated by PointNet, implemented in TensorFlow, while FilterPy integrates Kalman and Unscented Kalman Filters for tracking debris trajectories.

[0019] These technologies work together to filter noise, segment, and cluster LiDAR data, extracting debris features for accurate analysis. Residuals derived from observational noise are used for maneuver detection, validated through Random

Forest and deep neural network classifiers to optimize detection and reduce false alarms.

[0020] When a collision threat is detected, a maneuver detection algorithm, supported by models like Long Short-Term Memory (LSTM) and Transformer architectures, predicts necessary trajectory adjustments. The satellite autonomously executes these maneuvers to avoid debris and returns to its operational orbit post-threat. This real-time, autonomous decision-making capability significantly reduces operator workload and maneuver estimation costs, enhancing overall operational efficiency and sustainability.

[0021] The system also includes additional mitigation strategies. Differential drag can modify the satellite's trajectory without using propellant by reorienting it to change its frontal area in the velocity direction, altering the atmospheric drag experienced, and resulting in a trajectory change over time. For spacecraft lacking propulsion or unable to use differential drag effectively, changing the attitude to present a minimal cross-section reduces collision risk by reorienting the satellite to present the smallest area to the approaching object. Propulsive maneuvers involve using thrusters to alter the trajectory, planned a few days before the closest approach, optimizing fuel usage and minimizing collision risk. Sharing accurate orbital data with other operators enhances coordinated avoidance maneuvers and improves overall situational awareness. Effective implementation involves planning collision avoidance features during mission design, incorporating necessary hardware and software, and selecting optimal orbits.

[0022] In summary, this invention integrates advanced LiDAR technology, AI, and RL models to create a comprehensive, autonomous collision avoidance system for satellites. It addresses the limitations of existing technologies, offering a sophisticated solution to the growing problem of space debris, ensuring the long-term safety and operational efficiency of satellites in increasingly crowded orbits.

[0023] Further limitations and disadvantages of conventional approaches will become apparent to one of skill in the art through comparison of described systems with some aspects of the present disclosure, as outlined in the remainder of the present application and concerning the drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

[0024] The accompanying drawings are included to provide a further understanding of the present disclosure and are incorporated in and constitute a part of this specification. The drawings illustrate exemplary embodiments of the present disclosure and, together with the description, serve to explain the principles of the present disclosure.

[0025] Figure 1. Schematic diagram of the methodology and flow of invention

DETAILED DESCRIPTION

[0026] The following is a detailed description of embodiments of the disclosure depicted in the accompanying drawings. The embodiments are in such detail as to communicate the disclosure. However, the amount of detail offered is not intended to limit the anticipated variations of embodiments; on the contrary, the intention is to cover all modifications, equivalents, and alternatives falling within the spirit and scope of the present disclosure as defined by the appended claims.

[0027] Figure 1. Schematic diagram of the methodology and flow of invention. This figure represents the flow of the AI-driven collision avoidance system for satellites, starting from data acquisition to long-term orbital sustainability. The process begins with Satellite Data Acquisition, where multiple LiDAR sensors mounted on the satellite collect raw data in real-time. This data provides detailed information on the position and movement of space debris within a range of specified kilometers, including objects smaller than 10 cm. The acquisition of high-resolution data is crucial for the accurate detection and tracking of space debris.

[0028] Following data acquisition, the system performs Data Preprocessing to clean and normalize the collected data, filtering out noise and ensuring consistency and accuracy. This step is essential for preparing the data for further analysis. Once preprocessed, the system proceeds to Feature Extraction and Selection, utilizing frameworks such as Open3D and the Point Cloud Library (PCL) to process the LiDAR point cloud data. Key features of the detected objects, such as size, shape, and movement, are extracted and selected for further analysis.

[0029] The next phase, Object Detection and Identification, involves implementing PointNet in TensorFlow to identify and classify space debris. The system validates the detected debris using Kalman Filters and Unscented Kalman Filters (UKF) through FilterPy, ensuring accurate tracking of debris trajectories. Following identification, the system conducts Collision Risk Assessment using reinforcement learning (RL)-based AI models. These models analyze collision risks and predict potential threats, optimizing the assessment using deep neural networks (DNN) and Random Forest classifiers.

[0030] In the Trajectory Estimation and Maneuver Detection phase, the system estimates debris trajectories and predicts necessary collision avoidance maneuvers using models like Long Short-Term Memory (LSTM) and Transformer architectures. The satellite autonomously decides and executes these maneuvers, adjusting its trajectory in real-time to avoid collisions and returning to its operational orbit post-threat. This autonomous decision-making capability is crucial for reducing operator workload and improving operational efficiency.

[0031] The system also includes additional mitigation strategies, Differential Drag: Some spacecraft can utilize differential drag to modify their trajectory without using propellant, particularly in LEO where atmospheric drag is significant. This involves reorienting the satellite to change its frontal area in the velocity direction, altering the atmospheric drag experienced by the spacecraft, and resulting in a trajectory change over time.

[0032] Attitude Changes for Minimal Cross-Section: For spacecraft lacking propulsion or unable to use differential drag effectively, changing the attitude to present a minimal cross-section can reduce collision risk. This involves reorienting the satellite so that its smallest projected area faces the direction of the approaching object, minimizing the likelihood of collision.

[0033] Propulsive Maneuvers: These maneuvers involve using the satellite's thrusters to alter its trajectory, with planning typically beginning about three days before the time of closest approach (TCA). A maneuver trade-space plot determines the optimal burn intensity and timing, aiming to reduce the probability of collision by at least one and a half orders of magnitude below the mitigation requirement of 1E-04. Different propulsion modes may be used depending on the required velocity change.

[0034] Ephemeris Data Sharing: Sharing accurate orbital data with other spacecraft operators is crucial for coordinated collision avoidance maneuvers and improving overall space situational awareness and safety.

[0035] Design Considerations: Effective implementation of these strategies requires considering collision avoidance capabilities during the mission planning and spacecraft design phases, selecting an appropriate mission orbit that balances operational requirements with collision risks, and incorporating necessary hardware and software for supporting collision avoidance operations.

[0036] Finally, the system undergoes System Evaluation and Optimization, where its performance is continuously evaluated using metrics such as detection rates and false alarm rates. The system is optimized by leveraging residuals derived from observational noise, ensuring accurate maneuver detection and enhanced Space Domain Awareness (SDA). This integrated approach not only mitigates collision risks but also contributes to long-term orbital sustainability by reducing false alarms, operator workload, and maneuver estimation costs, thus addressing the growing threat of space debris effectively.

[0037] While the foregoing describes various embodiments of the invention, other and further embodiments of the invention may be devised without departing from the basic scope thereof. The scope of the invention is determined by the claims that follow.

[0038] The invention is not limited to the described embodiments, versions, or examples, which are included to enable a person having ordinary skill in the art to make and use the invention when combined with information and knowledge available to the person.

CLAIMS

We claim,

1. A system and method for AI-driven collision avoidance in satellites operating in Low Earth Orbit (LEO) and Geostationary Earth Orbit (GEO): The invention relates to enhancing satellite safety and operational efficiency through the integration of advanced technologies, such as LiDAR sensors, reinforcement learning (RL), and artificial intelligence (AI) models. The system addresses the growing threat of space debris, providing a comprehensive solution for real-time detection, tracking, and collision avoidance.

2. The invention claimed in claim 1 includes LiDAR sensors: These sensors provide high-resolution, real-time data on the position and movement of space debris within a range of Specified kilometers. This technology enables the precise detection and tracking of debris, including objects smaller than 10 cm, overcoming the limitations of traditional ground-based systems.

3. Integration of reinforcement learning (RL) and AI models: The system leverages RL and AI models to analyze collision risks and optimize satellite trajectory adjustments. These models continuously learn from past data and real-time conditions, enhancing decision-making accuracy and efficiency for collision avoidance.

4. Object detection and identification using PointNet and TensorFlow: The system implements PointNet for real-time object detection and identification

of space debris. Kalman and Unscented Kalman Filters (UKF) are integrated for tracking debris trajectories, ensuring accurate and reliable detection.

5. Advanced data processing frameworks: The invention utilizes Python and C++ frameworks such as Open3D and the Point Cloud Library (PCL) for LiDAR point cloud processing. These frameworks filter noise, segment, and cluster LiDAR data to extract essential debris features for further analysis.

6. Maneuver detection and trajectory estimation: The system includes maneuver detection algorithms supported by models like Long Short-Term Memory (LSTM) and Transformer architectures. These algorithms predict necessary trajectory adjustments and enable the satellite to autonomously execute collision avoidance maneuvers.

7. Autonomous decision-making and maneuver execution: Upon detecting collision threats, the satellite autonomously decides and executes trajectory adjustments to avoid debris and returns to its operational orbit post-threat. This capability reduces operator workload and improves operational efficiency.

8. System evaluation and optimization: The invention continuously evaluates system performance using metrics such as detection rates and false alarm rates. Residuals derived from observational noise are leveraged for improved maneuver detection, ensuring accurate and efficient collision avoidance.

9. Enhancement of Space Domain Awareness (SDA): The system implements AI-driven detection and timestamping techniques to enhance SDA, reducing

false alarms and mitigating operator workload. This comprehensive approach contributes to long-term orbital sustainability and addresses the growing threat of space debris.

10. Additional mitigation strategies: These include differential drag, which modifies the satellite's path without propellant by reorienting it to use atmospheric drag in LEO. Attitude changes reduce collision risk by presenting the smallest area to the approaching object. Propulsive maneuvers, planned a few days before the closest approach, use thrusters to adjust the trajectory, optimizing fuel use and minimizing risk. Sharing accurate orbital data with other operators enhances coordinated collision avoidance and space situational awareness. Effective implementation requires planning these features during mission design, incorporating necessary hardware and software for mitigation.

ABSTRACT

SYSTEM AND APPARATUS FOR AI-ENHANCED SATELLITE DEBRIS DETECTION AND COLLISION MITIGATION

The increasing number of satellites in Low Earth Orbit (LEO) and Geostationary Earth Orbit (GEO) has led to a rise in space debris, posing serious threats to satellite operations. Traditional tracking systems relying on ground-based radar and optical telescopes are insufficient due to the volume and velocity of debris and often lack real-time precision. This invention integrates LiDAR sensors with reinforcement learning (RL) and artificial intelligence (AI) models to enable real-time detection and tracking of debris, including objects smaller than 10 cm. The system employs advanced data processing frameworks such as Open3D and the Point Cloud Library (PCL) for LiDAR point cloud processing. Object detection is facilitated by PointNet in TensorFlow, while FilterPy integrates Kalman and Unscented Kalman Filters (UKF) for tracking debris trajectories. Autonomous decision-making algorithms, supported by Long Short-Term Memory (LSTM) and Transformer models, predict and execute collision avoidance maneuvers. Additionally, the system incorporates differential drag, attitude changes for minimal cross-section, propulsive maneuvers, and ephemeris data sharing, ensuring comprehensive mitigation strategies. LiDAR sensors will be mounted on satellite faces, based on their size, to provide comprehensive coverage. This approach enhances Space Domain Awareness (SDA), reduces false alarms, and ensures satellite safety and efficiency.