Space Policy 47 (2019) 194–206

Contents lists available at ScienceDirect

Space Policy

journal homepage: www.elsevier.com/locate/spacepol

Review of Active Space Debris Removal Methods

C. Priyant Mark*, Surekha Kamath

Department of Instrumentation and Control Engineering, Manipal Institute of Technology, MAHE, Manipal, KA, India

ARTICLE INFO

Article history:
Received 6 February 2018
Received in revised form
22 November 2018
Accepted 31 December 2018
Available online 29 January 2019

Keywords:
Kessler syndrome
Space debris
Active debris removal
Trend analysis
Clean space

ABSTRACT

This article gives an overview of the active space debris removal methods that are currently in development. Orbital debris removal has become a very critical part of the commercial and scientific space management. It is an aggregating risk which needs to be immediately addressed to prevent loss of spacecraft to debris collision. The various concepts and methods which tend to bring the accumulating risk to a halt have been classified and reviewed. They are classified into collective, laser-based, ion-beam shepherd-based, tether-based, sail-based, satellite-based, unconventional, and dynamical systems-based methods. The dynamical systems-based method is a contemporary concept, which is developing at a rapid pace. Recent trends were analyzed to ascertain the evolution of the active space debris removal programs. State-of-the-art methods are essentially required to address the various sizes of space debris that need to be removed. This brings a huge opportunity in the area, which includes discovering commercially viable options, cleaning orbital regions, and optimizing crowded satellite orbits.

Contents

1. Introduction

The space environment beyond low Earth orbit (LEO) is teeming with space debris. These debris are mostly the remnants from human-made objects such as dead satellites, used rocket stages, and particles from the collision of other debris. Space debris was not considered an issue around 50 years ago because little was known about the practical applications of space above the stratosphere. Today, the world is different from what we knew back then. Satellite networks, for example, are an essential part of our life, and more and more satellites are required to enhance their coverage. These enhancements have not addressed the issue of accumulating space junk, which has been collecting in the belt of existing satellite orbits. It has, in fact, raised the risk for existing satellites because of the increasing possibility of collision, which will add even more debris into the belt. This build-up has been classified as the "Kessler

* Corresponding author.
E-mail address: priyant.mark.c@gmail.com (C.P. Mark).

https://doi.org/10.1016/j.spacepol.2018.12.005

Nomenclature

3D	Three Dimension
ACADS	Attitude Control and Aerodynamic Drag Sail
ADR	Active Debris Removal
ANCF	Absolute Nodal Coordinates Formulation
ATP	Area-Time-Product
CNES	Centre national d'études spatiales
DOF	Degrees of Freedom
EDT	Electrodynamic Tether
EOL	End of Life
FLI	Fast Lyapunov Indicators
GEO	Geosynchronous Earth Orbit
GNC	Guidance, Navigation and Control
H∞	H-infinity
IBS	Ion-Beam Shepherd
ICAN	International Coherent Amplification Network
ISS	International Space Station
LEO	Low Earth Orbit
LEOSWEEP	Low Earth Orbit Security with Enhanced Electric Propulsion
LODR	Laser Orbital Debris Removal
MEO	Medium Earth Orbit
RAAN	Right Ascension of the Ascending Node
SRP	Solar Radiation Pressure
SSO	Sun Synchronous Orbit
TDS	Telescopic Deployer System
TLE	Two Line Element
Δv	Delta-v

Syndrome", which might turn worse if left unresolved. Each debris particle has the potential to travel at 30,000 km/h relative velocity and can cause an immense deal of damage.

Kessler et al. (1978) [1] predicted the collision risk involved in Earth orbits and the threat's immense magnitude. This article popularized the term "Kessler Syndrome", commonly attributed to the build-up of orbiting space debris and its multiplication. The accumulation and the cascading effect were further described by Kessler et al. (2010) [2] to clarify the intended definition of the above said term. They discussed the frequency of collisions and the ensuing consequences, which could have a major impact worldwide. They also describe the common mitigation measures undertaken to avoid any catastrophe in the future. Pelton (2013) [3] explains the cascading effect of collisions and how debris generates debris. He describes the international standards that are in place for mitigating debris and for space traffic management, which could become the safety and operational standards for space and stratospheric missions and activities. Pelton (2015) [4] gives the current debris scenario, which is estimated to be around six metric tons and number about 22,000 tracked objects. There are two prominent debris addition events which have been recorded in recent history. These are the antisatellite missile test (2007) which downed the Chinese Fen Yun 1C satellite and the collision of Kosmos 2251 and Iridium 33 (2009). Despite the progress in developing the guidelines for debris mitigation, there is a serious lack of policy to outline the removal aspect. To have a clear picture of where the active debris removal (ADR) concepts stands, there arises a need for a compilation of all the recent work done. Hence, a review of all the major concepts has been compiled in this article.

The different methods which have been envisioned to clean the frequently used orbital regions are classified in Fig. 1 and are elaborated further below. Each method varies in the aspect of implementation, philosophy, and design. A limited set of literature in each category has been sampled and reviewed. The sampling was done based on the importance of the work done, which helped moved the concept forward. The sampled data does not represent the total papers on the concept published in a year. But all the methods have been carefully studied and classified based on their core competency. A highlight table is provided after the different methods to show the important parameters of the classification. The figures following the methods highlight the main aspect (milestones), which moved the concept forward with every paper.

2. Literature survey

2.1. Collective methods

Bonnal and Ruault (2013) [5] have compared the findings of different organizations working on ADR projects for centre national

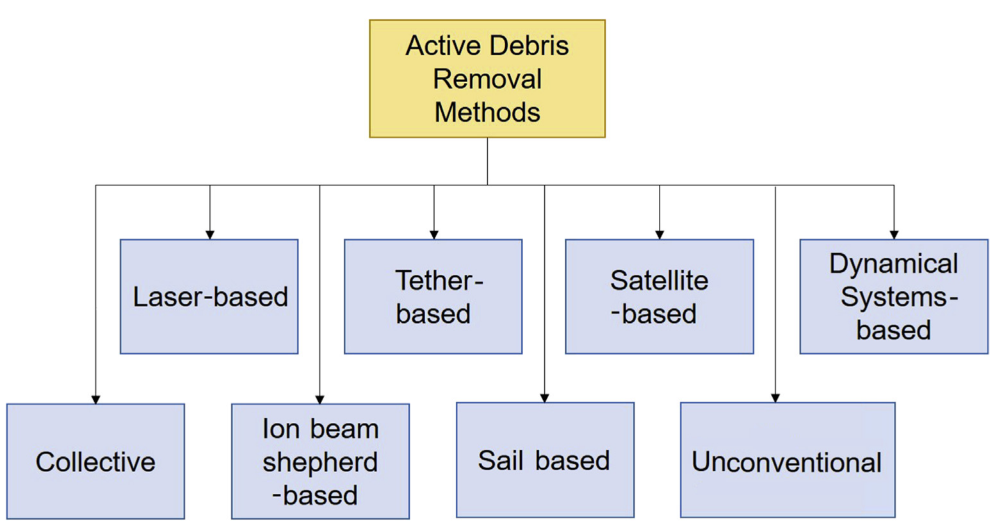

Fig. 1. Classification of active debris removal methods.

d'études spatiales (CNES). They discuss a strategy on sorting and prioritizing debris for removal which includes high-level functions for creating a removal model. Even though they try to answer the question of prioritizing the debris removal aspect, they could not settle on the answer for what has to be actually performed. This still leaves us with a major paradox to think about. They claim that no space agency will equally prioritize the ADR missions to the Earth observation missions. But things have changed. Now, even the International Space Station (ISS) is being used as a platform for debris removal experiments. They have further put an open question on the legal, political, financial, and international cooperation issues. This leaves us with a larger mandate to explore and find solutions. Emanuelli et al. (2014) [6] discuss the non-technical challenges associated with ADR. They have built the policy, legal, technical, and economic framework to deorbit debris based on scorecard method. They use a case study on "CleanSpace One" to elaborate on the concept addressing the issue. Even though they have discussed the economically, politically, and legally viable ADR concepts, they have not given a clear winner in that area. The scorecard method to determine an ADR concept is not practical in the terms of engineering perspective. A more robust method to determine the efficient ADR method is required. Petersa et al. (2016) [7] consider a concept of autonomous spacecraft to remove space debris. They have constructed an economically viable architecture for removal of debris using the lowest Δv budget. The principle architecture used for the spacecraft (Active Debris Removal Satellite # A) is constructed in-depth. They emphasize on the legal, policy, and funding framework as being the parameters that take forward the ADR concepts, but it may not be necessarily important. Their concept still has a lot of unsolved technical challenges. Shan et al. (2016) [8] explain the different phases and types of capturing and removal of space debris. They focus on the non-cooperative analysis of debris during the capture phase. Their comparison deals with contact and contact-less methods of debris removal methods. Even though their collation is comprehensive, the details were reserved for only the state-of-the-art of the methods. The non-cooperative analysis does not feature the updated methods and was focused on the methods existing during that time. Forshaw et al. (2017) [9] try to brief the "RemoveDebris" test mission which includes a sequence of removal methods to be tested in the space environment. It tends to prove the capability of existing technologies and provide the scalability of the same. They focus on the launch peculiarities, the testing philosophy, and the type of tests performed across payloads. Their demonstration of capture, navigation, and deorbiting capability is the first ever experiment conducted in space. This gives a lot of valuable insight into the challenges faced during a real ADR mission. Colmenarejo et al. (2018) [10] talk about ground validation of ADR techniques. They take a reference mission scenario known as ADR for a small satellite mission (AnDROiD) and describe the rendezvous and capture operations using a robotic arm and net system. They analyze three different types of target states namely cooperative, non-cooperative, and non-cooperative and tumbling. They define the control system architecture with hardware and software phases along with the chase guidance, navigation, and control (GNC) system. It uses visual-based navigation composed of image processing algorithms and monocular camera. They describe the control systems of 7-degrees of freedom (DOF) LEMUR robotic manipulator and test and simulate the systems. Many critical systems have been tested and validated, but it needs to be experimentally verified before operation.

The concept of collective method involves various ADR methods which has been clubbed together to build a robust system which can carry out the tasks in synchronization. As the set of papers explain, it begins with the strategy on prioritizing debris, sorting non-technical challenges, using autonomous spacecraft, non-cooperative analysis, a prototype experiment, and ground validation. These ideas have contributed significantly to the knowledge of collective methods. Table 1. gives the highlights and Fig. 2 shows the milestones achieved in the collective methods.

2.2. Laser-based methods

Phipps (2011) [11] describes a high-power pulsed laser system which shoots plasma jets from ground on the objects to slow them down. He adds on the advances made in the laser orbital debris removal (LODR) systems to make the method to be cost-effective. The LODR is definitely found to be effective in removing both large and small debris. It has the capability to handle tumbling or uncooperative debris. Even though the system is found to be cost effective, the readiness and response of the system is not up to the mark. Target acquisition is also an issue in the above method. Soulard et al. (2014) [12] discuss the architecture of the laser developed by International Coherent Amplification Network (ICAN). They propose to install the system in space which can be used for the purpose of tracking and deorbiting small-scale hyper-velocity space debris. Using the laser for both shooting and scanning and tracking is a very compact approach for such a system. The system is efficiently designed for taking down hyper-velocity objects. Even though it is extremely efficient, moving and assembling the system poses an issue in reality, which has to be addressed in the future. Shuangyan et al. (2014) [13] talk about laser irradiation to ablate part of the debris material to provide an impulse in order to deorbit the debris. A 100 Hz space-based laser system which could be used for protecting the ISS is demonstrated. They have estimated the laser repeat frequency for ablation. It is found to be very low for any actual debris. The angle of irradiation is found to be very effective. The protection for ISS can be scaled up to a major removal project. Schmitz et al. (2015) [14] developed a parametric mission performance model using Nd:YAG space-based laser. The model was simulated to quantify the range of performance of the system, and they also emphasize the requirement of a target catalog for the smooth operation of the

Table 1
Highlights of collective methods.

Collective methods	
Core competency	Major programs involving multiple ADR methods
Pros	Uses the strengths of every method collectively
Cons	No single method is used in-depth
Latest discovery	AnDROiD mission

ADR, active debris removal.

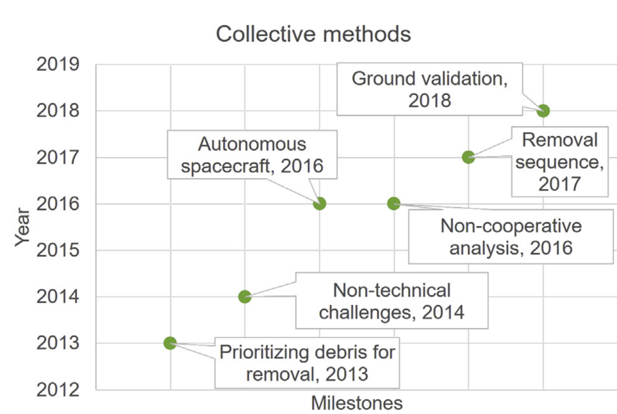

Fig. 2. Milestones in collective methods.

laser. They have identified the system drivers of laser-based missions as laser maximum operating range, beam tracking velocity or mirror agility, and power supply. They discuss creating a catalog of debris object for the laser to operate but express uncertainties of the approach. There will also be other issues such as energy consumption and waste heat generation which needs to be addressed. The promising performance claims need to be proved to have an actual estimate. Yang et al. (2016) [15] focus on the "LightForce" concept simulation approach to assess the long-term impact. It is a ground based off the shelf laser which uses photon pressure to perturb the orbit of a debris object. They perform two conjunction analysis including short-term approach and long-term approach and establish the results. The simulation gives an insight into the working of the concept for a year, which is very valuable to evaluate the efficiency of the system. The reduction in the number of collisions from the simulated results does look promising, but it has to be validated in a real-time scenario. Wen et al. (2017) [16] researched on the hybrid operation of ground-based laser and space-based laser to achieve optimum performance on debris removal. They use the ablation impulse coupling model to perform the deorbiting sequence, and the same was numerically simulated to verify the efficiency of operation. The sequence of deorbiting debris involves a gap between ground and space-based laser systems, which works only if the former could not complete the task. This can be optimized to function together to perform efficiently. This method can only remove small-scale debris, which is not very optimistic for the amount of debris present in orbit. Gambi and García del Pino (2017) [17] focus on a strategy to shoot down medium-sized space debris using space-based laser. They calculate the laser intercept point at position in which the relative velocity of the object with respect to the laser system is apparently zero. They discuss different combinations to shoot a piece of debris. Even with different calculations and optimizations, it takes 8 min and 3.7 km/s on an average to deorbit a piece of debris. This seems to be impractical with existing technologies. It also houses huge errors in the targeting model. Shuvalov et al. (2017) [18] bring about the simulation of dynamic action of plasma-beam high-energy ions on an object and study its long-term effects. They intend to use a space-borne ion thruster to produce the laser beams and mount it on a satellite to target space debris. They work on the long-term exposure of a coating material to high-energy ions. The results were computed experimentally, gathering valuable data on the reaction. It has to be implemented in real-time to observe the actual effects, which will vary drastically. This experiment was connected with the Low Earth Orbit Security with Enhanced Electric Propulsion (LEOSWEEP) project. Wen et al. (2018) [19] study about the impact of the orbital elements on a space-based laser station due to debris removal. They model the target and the station in a circular orbit and use momentum transfer to understand the relationship. They categorize the impacts with change in inclination and right ascension of the ascending node (RAAN). The elimination window is connected with the plane and is affected by inclination. Shared RAAN will require less power for elimination. The impacting parameters are more than inclination and RAAN, which has to be researched.

The laser-based ADR concept involves high-power laser used to sublimate the debris, either from ground or space. As the papers describe, the LODR program initiated the concept, ICAN brought the laser to space, laser ablation to deorbit, cataloged target deorbiting with Nd:YAG laser, perturbation with photon pressure, shooting strategies from ground, high-energy ion interaction, and impact of orbital elements on a station. These breakthroughs have propelled the concept of laser-based method forward. Table 2 gives the highlights and Fig. 3 shows the milestones achieved in the laser-based methods.

Table 2
Highlights of laser-based methods.

Laser-based methods	
Core competency	Involves a laser to shoot debris from ground or space
Pros	Low cost and very much feasible
Cons	Range and angle of operation is limited
Latest discovery	Orbital elements impact on a laser station

2.3. Ion-beam shepherd-based methods

Bombardelli and Pelaez (2011) [20] visualize the ion-beam shepherd (IBS) concept, which emits a beam of quasi-neutral plasma toward a target to impart a propulsive force on it. They discuss the capability of the system, which can operate only in close-range due to beam divergence effects and pointing errors. They further optimize mass to produce constant thrust for the system. The concept of momentum transfer for deorbiting debris is sufficiently ineffective, considering the mass of the debris and the thrust produced. It holds many issues such as sputtering and backflow, which needs to be addressed. Merino et al. (2013) [21] develop the IBS concept into a sustainable model wherein, they add a secondary propulsion system to stabilize shepherd satellite. They calculate the propulsive requirements and the forces and torques transmitted by the beam onto the debris. They further explore the controllability aspect of the system. The plasma plume interaction between the spacecraft and the debris was studied, but the fallout from the interaction could affect the health of the shepherd spacecraft. Controlling the complex debris system remains to be unchallenged, and only a simple controller was designed. Kitamura et al. (2014) [22] propose the IBS concept for geosynchronous Earth orbit (GEO) by re-orbiting the debris into disposal orbits. They use two ion engines in the opposite sides of the spacecraft to push the debris into disposal orbit. They study the effects of ion-beam irradiation, contamination, and non-cooperative target rendezvous. Even though simulations of beam convergence, back-sputtering and non-cooperative rendezvous give a desired result, the real-time flight data should be obtained for conclusion. Ruiz et al. (2014) [23] describe the FP7 LEOSWEEP project aimed at major advances in the analysis, implementation, and applicability of advanced electrical propulsion concepts in ADR methods. They focus on the efficiency of actuation and control of the shepherd spacecraft to align the beam on the target. The ion-beam divergence was limited to be as small as possible to keep a safe distance

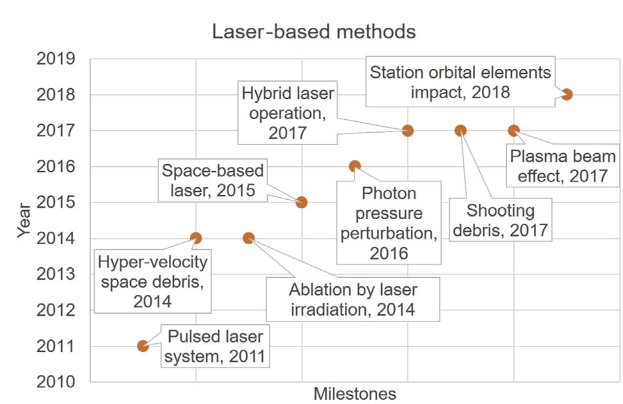

Fig. 3. Milestones in laser-based methods.

between the target and the shepherd. The laboratory tests are only proposed to validate numerical data. Those test results will be crucial for the technology development. Schaub and Sternovsky (2014) [24] propose a similar concept to IBS for GEO which uses electrostatic forces to re-orbit the debris. They model the forces between the tug and debris and optimize the potentials. Using craft charging model, they neutralize the current between them to produce thrust. They numerically simulate the charging to study the potentials. Determining craft separation distance using potentials is a state-of-the-art method, which is very valuable for any application. They claim that an equal potential condition will produce a better performance, but building a tug equal to the size of debris is not feasible. Cichocki et al. (2016) [25] propose to optimize the electric propulsion subsystem in IBS concept. They discuss the propulsion subsystem constraints with current available technology. They further model the momentum transfer efficiency by building a plume solution and study the interaction with the target. Finally, they optimize the propulsion subsystem by considering a few assumptions. Even though they have used design performance models to obtain optimized results, experimental techniques will provide accurate results. They claim that the plume physics will substantially affect the design choice with divergence angle and operational voltage, but they used only a single type of thruster (radio-frequency ion thrusters) for study, and hence, it cannot be proven. Aslanov and Ledkov (2017) [26] develop a mathematical model of the debris to study its attitude motion under the influence of ion flow. They use the planar equations to model and calculate the force and torque. They utilize plasma plume expansion and fully diffused ion reflection models to simulate the data. They find that the motion of the debris around its center of mass has a significant effect on the removal time which is a possible state to be considered during the removal process. The study of oscillations around the stable equilibrium point will significantly contribute to enhance the design. Shuvalov et al. (2017) [27] study the long-term dynamics of the debris due to the influence of ion beam. They conduct an experiment with space debris object coating material system to study sputtering and momentum transfer. The sputtering yields were collected by equating exposure regimes in orbit and the experiment. The dynamics are governed by the forces of ion and electron bombardment, material sputtering, and Coulomb interaction. The interaction of sputtering yield and high-energy ion normal and tangential momentum accommodation coefficients with bombarding particle energy gives a valuable insight into the dynamics of the system. Cichocki et al. (2018) [28] study the interaction of plasma plume on the spacecraft and debris by simulating using a code. They model the plume with back scattering and sputtering. Further, they create a sheath model with dielectric and conductive materials to calculate the current density. Then, the forces and torques were computed based on the linear momentum of impacting and emitted macroparticles, electron linear momentum, and electric forces. Sensitivity analysis was carried out on the results based on the change in electron cooling rate, ambient plasma, collisions, and debris position. They claim that heavier species produce back scattering, along with contamination of spacecraft, plasma plume electrical connection, and force contribution, which has to be validated to get a clear understanding. Hakima and Emami (2018) [29] focus on the use of IBS in LEO. They calculate the time required to deorbit the debris. They use three thrusters to model the spacecraft. They point out the importance of keeping a safe distance and the dangers of contamination. They further compare the performance with other ADR methods and asses mission cost and risk. The Monte Carlo analysis to analyze performance of methods is not sufficient to determining facts. Any conclusion has to be verified experimentally to confirm. Ledkov and Aslanov (2018) [30] determine the effects of IBS, considering atmospheric effects on the debris. They build a mathematical model, considering gravity, aerodynamic, and ion-beam forces and torques. The space debris is modeled as a cylindrical rigid-body. Then they simulate the debris removal using the model. They find that the presence of atmosphere significantly reduces the time of descent. They claim that when the debris orientation is perpendicular to the beam, it is effective, and the amplitude of oscillations affect the operation. This has to be verified experimentally to be proven.

The IBS concept involves stationing a chaser satellite and projecting ion beams onto the debris to push and deorbit it. As the papers describe, the quasi-neutral plasma beam initiates the IBS concept, secondary propulsion system for stability, IBS for GEO, LEOSWEEP concept aimed at alignment, electrostatic forces to re-orbit, electric propulsion subsystem, attitude motion under ion flow, dynamics of debris during beam targeting, interaction of plasma plume, IBS in LEO, and atmospheric effects of IBS. These ideas have moved the concept forward, at a priority. Table 3 gives the highlights and Fig. 4 shows the milestones achieved in the IBS-based methods.

2.4. Tether-based methods

Sanmartin et al. (1993) [31] propose an electron collection concept for electro dynamic tethers (EDT). They use bare-wire anode for the tether. They expose the anode end to the plasma as the emitter. They calculate the potentials in generator mode and thruster mode for different exposed area of the wire. The electrodynamic tether claimed by the author is multikilometer long, and hence the technical feasibility has to be ascertained. The concept is promising, but efficiency has to be improved. Kawamoto et al. (2009) [32] chose an orbit of 1000 km altitude and 83-degree inclination to study the distribution of space debris for implementing a plan to remove them. They propose the use of EDT to attract the debris and slow them down to deorbit them back into the atmosphere to let it burn. They further simulate the mission to identify orbital changes and tether stability. They claim to use piggyback satellites for debris removal. But the legal issues are not explored in the context. Its shown that an EDT of 5–10 km can

Table 3
Highlights of IBS-based methods.

IBS-based methods	
Core competency	Projects ions onto debris to push it
Pros	Quicker and feasible
Cons	Requires more power
Latest discovery	Atmospheric effect on IBS

IBS, ion-beam shepherd.

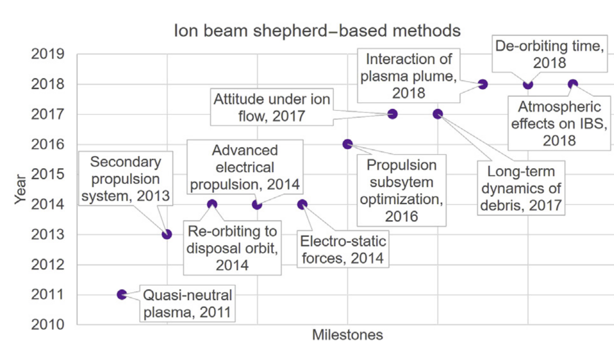

Fig. 4. Milestones in IBS-based methods.

remove a piece of debris within a year. This is a very optimistic target and cannot be proven until it is analyzed in real-time. Guang et al. (2012) [33] focus on debris present in the geostationary orbit. They analyze the debris composition to determine the best trajectory to perform the rendezvous. They design a space-based tether-net system intended to capture debris and bring it to a graveyard orbit, which eventually decays and burns. They also design the mission architecture along with the controls. Although the mission was designed, there were neither case studies nor experimental results to validate the method. Benvenuto et al. (2015) [34] explore the possibilities in the use of throw-nets and tow-tethers. They discuss the challenges faced during the different phases of operation of flexible tethered-net systems from the GNC point of view. They use multibody simulation to understand flexible ADR systems. The simulations give a broad understanding of the tether-net system. It gives precise data to design the actual mission. The experimental results help in validating the data and support the discussion. Dudziak et al. (2015) [35] carried out empirical testing and numerical modeling of a harpoon to secure debris. Initially, they characterized the targets to imitate experimental targets for tests. A medium velocity gas gun was used to shoot the harpoons onto the targets. They further tested the blunt and conical types of projectile for impact, penetration, and secondary debris creation. The lock-on systems and penetration onto obstructive structures were tested along with microgravity environment. The preliminary results are promising, and it gives a detailed idea to establish the harpoon technology. Other detailed updates will be necessary to finalize the results. A damper system will be required to handle the recoil, and their future work presents it. Huang et al. (2016) [36] propose an adaptive control strategy for space debris removal using tethered space robot. They derived the dynamics of base, tether, and target to model the system for control. They modified the adaptive controller to accommodate the complex dynamics of the system. Then they test the controller for its performance and efficiency for the removal of debris. Even though they could modify the controller for the complexities, it is uncertain how effective it would be in real-time. Converging results will also house errors which cannot be determined. Testing in an actual system is required to remove the uncertainties. Shan et al. (2017) [37] explain the dynamics of flexible tethered-net deployment using the absolute nodal coordinates formulation (ANCF) method. They compare the mass-spring model, and the ANCF model used for multibody dynamics in the perspective of net deployment. The simulation of the deployment process was performed to understand the dynamics. They figured out that the two models differ below 10%. Using the different driving parameters in a net system to investigate the dynamics gives a deep insight into the system. But the proven ANCF model, being computationally expensive, is not reliable for multiple simulations. The dynamics has to be eventually verified by experimental methods for uncertainties. Sharf et al. (2017) [38] focus on the net closing mechanism of a tether-net capture system. They designed a tether-net closure model, which is actuated by the main tether and secures the debris. Furthers, they designed a test-bed for simulation, which was used for testing the net under the influence of gravity. The system was modeled in a multibody dynamics tool to simulate contact dynamics. The net deployment dynamics was experimentally verified. The concept simulation and experimental verification establishes the dynamics of the model. Even with multiple validation, the performance of the mechanism has to be verified in actual environment to observe the behavior. Sanchez-Arriaga and Chen (2017) [39] talk about low-work-function tethers using photoemission effects. They mathematically model the system, including the current produced by the photoelectrons. The plasma contact model was incorporated for the current source. Then, the electrodynamic performance was evaluated, and the optimum material was selected based on the performance. The replacement of cathode by passive elements gives considerable efficiency. The photoelectric and thermionic effects play a considerable role in the system, and it was incorporated into it, improving the accuracy. The model has to be used in a real-time mission to be validated. Chu et al. (2018) [40] propose a hybrid tension control method for tumbling debris. They use a space tug with tether for debris capture and removal. The dynamical model was constructed with three reference frames, and the orbital motion was incorporated. Further, a hybrid control system was designed with fuzzy adaptive method for stability. Then, numerical simulation was carried out to ascertain the states with the impact of sway on tether windings. The proposed coordinated control method has been proved to control the relative motion between the target and the spacecraft. But still, the algorithm has to be optimized for shorter time to control.

The tether-based ADR concept involves attaching a long wire to a piece of debris and letting the Earth's magnetic field act on it to slowly pull it back into the atmosphere. As the papers describe, the electron collection concept was initiated, the use of EDT in a specific LEO, push GEO debris to graveyard orbit, use of throw-nets and tow-tethers, harpooning EDT, adaptive control strategy, flexible tethered-net deployment, net closing mechanism, low-work-function tethers, and hybrid tension control method. These ideas have improved the tether-based method. Table 4 gives the highlights and Fig. 5 shows the milestones achieved in the tether-based methods.

2.5. Sail-based methods

Romagnoli and Theil (2011) [41] explore the area of solar sails in the application of deorbiting space debris. They model the orbital dynamics of the sail, including the various perturbations. They derived the attitude kinematics and dynamics equation, assuming the sail-craft to be a rigid body. A simulation of both orbital and the attitude dynamics was performed to determine its state after a few days. It was found that the spacecraft successfully deorbited after a few months. They claim that the solar sail can

Table 4
Highlights of tether-based methods.

Tether-based methods	
Core competency	Involves a charged tether attached to debris
Pros	No power nor maintenance
Cons	Very slow in action
Latest discovery	Tension control for tumbling debris

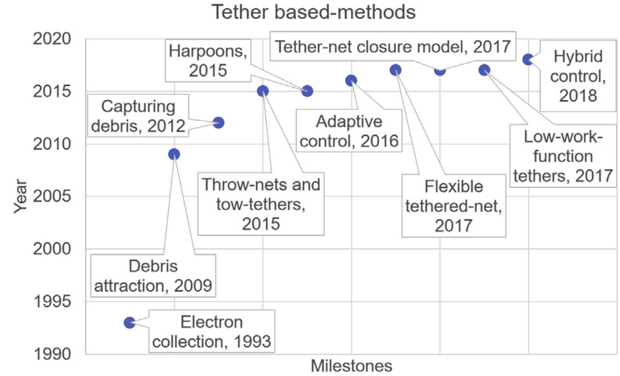

Fig. 5. Milestones in tether-based methods.

reduce the deorbiting time of a spacecraft than performing only by using its surface. Even though its advantageous to use a sail, the collateral effects could be far more severe in real-time. Aerobraking can lead to causing lift, which can extend the lifetime of a spacecraft in orbit. Pfisterer et al. (2011) [42] design a spacecraft named as KnightSat II and its sail mechanism known as attitude control and aerodynamic drag sail system. The project's main aim is to deploy a gossamer sail to reduce the time for deorbiting end-of-life satellites. The system was simulated and analyzed for load and drag. They claim that a satellite in orbit at around 600 km altitude will be deorbited within 6 months, but it cannot be proven due to various uncertainties in real-time conditions. Further, coupling with an electrodynamic tether will be useful for a faster deorbit rate. Fernandez et al. (2014) [43] propose a gossamer deorbiter sail system which utilizes drag and solar radiation pressure (SRP) for removal of debris. They analyze the mission details such as orbits, collision, re-entry, and thermal loads. The design was based on telescopic deployer system, which extends and unfurls to deploy the sail. Further, they test the sail focused on sail material and the static and dynamic structural properties of deployment booms. Then, qualification tests were performed to ascertain the performance in real-time environment. They analyzed several scenarios of potential application of the sail system, which included full-scale model functional tests and performance scalability. Their results show significant decrease in deorbit time and increase in ceiling altitude for sail-based deorbiting platform. The Gossamer de-orbiter has to be tested in an actual flight condition to know the environmental behavior and fragmentation risk. Visagie et al. (2015) [44] focus on the reduction of collision risk using a deployable drag-sail which uses drag augmentation to deorbit space debris. They perform a comparison analysis using area-time-product and collision risk analysis to cover missing factors. The system was modeled to analytically estimate the drag area for a given deorbit time. Further, the collision probability of the sail satellite during deorbit phase is determined. The usage of appropriate atmospheric models during orbit decay improves prediction accuracy. The importance of deorbit start epoch, which has been highlighted, is a major factor for deorbit time. Even if different noises exist, the model has been predicted with precision. Ham et al. (2016) [45] study a space system consisting of an inflatable magnetic sail. They use KnightSat II as their spacecraft, and it consists of magnetic torque coils imprinted upon the a Kapton film. They manufacture a prototype to test the system along with the supporting mechanism and bus subsystems. They claim to apply the sail to rapidly deorbit satellites and use for attitude control. The ground prototype was used to prove the effectiveness, which also produced valid results. Kelly et al. (2018) [46] explore the possibility of removing debris from GEO using sails. They model the satellite dynamics using SRP. Using that, they optimize the sail orientation and control it by rotating the sail perpendicular to the incoming sunlight. The “TugSat”, installed with the sail and used for pushing the debris, will glide to the target orbit and push it to a graveyard orbit. They analyze the various parameters affecting the orbit, including semi-major axis, eccentricity, inclination, longitude targeting, and simulate the deorbit. The viability of using SRP wholly for controlling satellites have to be investigated further.

The sail-based method involves using a large surface fabric to trap SRP and use it as a method of propulsion or control. As the papers describe, its starts with the analysis of sail's deorbit time, using KnightSat II concept for attitude control, gossamer deorbiter sail, deployable drag sail, inflatable magnetic sail, and using sails in GEO. These ideas have taken forward the concept of sail-based ADR method. Table 5 gives the highlights, and Fig. 6 shows the milestones achieved in the sail-based methods.

Table 5
Highlights of sail-based methods.

Sail-based methods	
Core competency	Uses SRP to augment drag with a large surface area
Pros	No external fuel or power
Cons	Very slow and uncontrollable
Latest discovery	Sail control from incoming sunlight

SRP, solar radiation pressure.

2.6. Satellite-based methods

Nishida et al. (2009) [47] discuss a space debris removal system using microsatellites. They study the method to remove satellites from their respective orbits. The strategy for removing satellites from Sun-synchronous LEO was discussed. The satellites use a robotic extensible arm to capture the debris. They claim to use EDT for orbital transfer, but its effectiveness is very slow, and moving between orbits is considered time consuming. Nishida and Kawamoto (2011) [48] highlights the strategy for orbital debris, which includes designing safe space systems and removing existing debris. Their removal method uses a micro sat, piggy-backed on a common mission and deployed to attach EDT onto the debris. They exemplify the key technologies required for such a composition. It includes approach, rendezvous, orbit changes, capture, and arm control. A satellite is used to maneuver into position, and a robotic arm with a brush-contactor is used to secure the debris. They simulate the capture system to identify possible bottlenecks. Adding autonomous technologies will increase the safety aspect of a mission, but all the intricate details of the complexity of space have to be incorporated for a successful maneuver. The braking simulations were yielding good results, but experiments have to be performed and compared. Castronuovo (2011) [49] envisages a prospect of deorbiting 35 large objects in 7 years using a chaser satellite. Initially, he categorizes interested debris objects for mission planning. Then, the phases of the mission were described, which includes free-flight, orbit phasing, far range rendezvous, close range rendezvous, mating, and deorbit device attachment. The mission would be to launch a satellite holding a number of deorbiting devices within it, which are attached to the debris and deorbited. He has also done a sample mission with a specific launch configuration date. The debris categorization analysis provides a deep insight into the different types of debris, orbiting the commercial orbits. The concept of orbiting warehouse for re-supply missions will be very useful for long-term missions. The author claims to remove 35 debris in a 7-year period. It can be only proven with a real-time mission. Levin et al. (2012) [50] explore into the frontier of debris

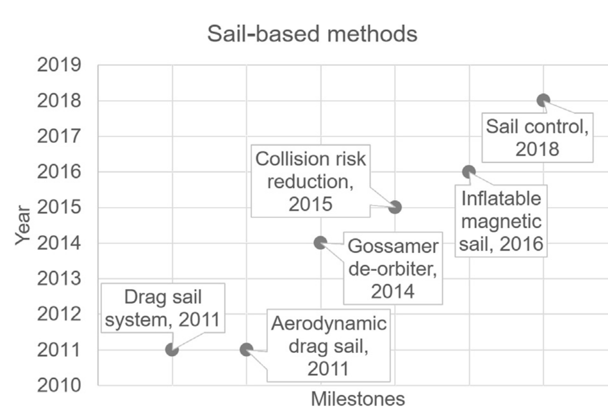

Fig. 6. Milestones in sail-based methods.

removal from LEO at a wholesale rate. They ranked the debris and determined the best one to start with. They contemplate the different methods to remove debris using a satellite. It includes drag devices, rockets, electrodynamic systems, recycling, and a method for traffic coordination. They analyzed the LEO and the possibilities to determine electrodynamic propulsion as the best suitable method to remove debris from it. They proved that the cost factor of removal will eventually establish wholesale active removal of debris, which is absolutely commendable. Covello (2012) [51] designs a mission at systems level using electrical propulsion for the satellite used for removing debris. The debris was classified and selected based on feasibility of removal. He uses two concepts, one for moving debris to disposal orbit by the satellite and the other by attaching a removal device. Then, he focuses on the electric propulsion viability. He also did a trade-off study between electrical and chemical propulsion to prove the economically viable option. The advantages of using electric propulsion are enormous, which was shown in the discussion. He prioritizes the satellite-moving concept as the preferable one, but the causes are not proven. Eventually, he concludes that the deorbit devices concept will be more economical. This concept is a proven technology and using it will be more viable, as stated. Missel et al. (2013) [52] provide a path optimization strategy for space debris removal using “Sling-Sat (4S) mission” satellite which captures and ejects debris plastically. They simulate the procedure with medium-to-small debris in LEO. Sling-Sat is modeled as a spinning satellite with collectors at the end of arms. Once the mission loop was finalized, they applied genetic algorithm to optimize the trajectory. They modularized the mission into several parts to simplify the subroutines. Finally, the optimized solution was applied to the mission. The simulation of real debris orbits gives an accurate fit for a mission, which was precisely performed. Fuel efficiency and shorter time period is in fact an advantage in this type of mission. Sahara (2014) [53] focuses on a three-dimensional (3D) satellite constellation to remove space debris. The orbital transfer problem was solved using the Lambert's equation, and the required Δv was calculated. Then he analyzes the potential for 3D positioning of the satellites in a constellation to work together. The initial analysis of 38 satellites unable to remove all the debris shows the complexity of positioning a swarm of satellites in a debris environment. Even with a two-stage strategy, it is not possible to clear the orbit completely. This method has to be optimized to have a higher efficiency. Rybus et al. (2014) [54] have designed an unmanned spacecraft equipped with manipulators which aid in securing tumbling debris. They model the system dynamics, formulate the problem, and solve it with rapidly exploring random trees algorithm. The satellite system model was considered as a rigid body with variable inertia tensor and analyzed with rotational motion. They analyze the results to find that the rotational energy is converted to heat and lost during the capture of a tumbling debris. The work involved finding a trajectory to minimize the rotational energy loss. Using a dual system will be difficult to control, and the mission may lead to a loss. The methodology has to be enhanced to stop the rotation and perform linear motions. Dubanchet et al. (2015) [55] propose a controller for a robotic arm mounted on a satellite to capture massive debris including dead satellites or launch vehicle upper stages. It uses dynamic models which rely on an adapted Newton-Euler algorithm and control algorithms based on the fixed-structure H_∞ synthesis. They model the robotic arm with 6-DOF and control the dynamics. Then they design the controller with two architectures, namely free-flying and free-floating type. A lower processing requirement controller was chosen to work in the space environment, and it was simulated. The effect of the arm movements will be felt on the base, and its attitude can change. This has serious consequences on the control of the satellite and needs to be incorporated for better results. Ruggiero et al. (2015) [56] propose an electric propulsion platform for deorbiting space debris. The mission scenario was planned in stages, and the satellite was designed based on the payload capacity of small-satellite launchers. They analyze the debris present in LEO and the possible approach of removing them efficiently. The usage of Hall effect thruster-based propulsion system is more efficient than chemical propulsion and will lead to a larger coverage area. But its effect on real objects has not been analyzed. Sufficient data can only be obtained by using the system on a real debris. Wenbin et al. (2016) [57] have designed a 7-DOF redundant manipulator for clearing large space debris mounted on a satellite. They have developed a kinematic model of the manipulator to simulate the operation and verified it with an inverse kinematics optimization algorithm. The optimization is based on weighted least-norm algorithm, which improves tracking accuracy. The system was simulated based on the kinematics formula. The kinematics model gives an accurate prediction based on microgravity environment, but it needs to be validated before deployment. Aslanov and Yudintsev (2018) [58] talk about using Coulomb force to control the motion of satellite tug. Using this technique, they have ascertained that pushing the target would give optimum results. They describe the motion of the system in a relative frame and model the equations. The feedback control law was designed considering minimum propellent mass. The stability analysis was carried out, and the parameters were numerically simulated with the effects of disturbances on it. The propulsive forces encountered during stabilizing maneuvers obtained from simulated data are not enough to prove the mass requirement, and other disturbances have to be considered.

The concept of satellite-based ADR method involves an attachment on a satellite (like a manipulator arm) which grapples the debris and pushes it around. As the papers describe, the concept initiates with microsatellites in LEO, piggy-backed micro sat with EDT, deorbiting devices in a satellite, wholesale removal, electric propulsion, capturing and ejecting debris with Sling-Sat (4S) mission, 3D satellite constellation, spacecraft with manipulators, controller for a robotic arm on a satellite, Hall effect thrusters, 7-DOF redundant manipulator, and Coulomb force-based satellite tug. These concepts have moved the concept forward, significantly. Table 6 gives the highlights, and Fig. 7 shows the milestones achieved in the satellite-based methods.

2.7. Unconventional methods

Andrenucci et al. (2011) [59] devise a new method of drag augmentation known as expanding foam system which promises to cover and deorbit debris. The mission scenario was analyzed, and the methodology was devised. The foam is supposed to be ejected from a platform, stick to the target surface, grow in volume, and cover the debris. They have modeled the system and used it for expansion analysis, which includes pressure difference and foam viscosity. They assessed the deorbiting time and impact probability. The size of the foam during re-entry plays a crucial role. It has to be tested for effectiveness before the actual mission. Ganguli et al. (2012) [60] propose a method to remove small debris by injection

Table 6
Highlights of satellite-based methods.

Satellite-based methods	
Core competency	Involves attachment to satellite, performing tasks
Pros	Can use multiple methods
Cons	Very complex
Latest discovery	Coulomb force control

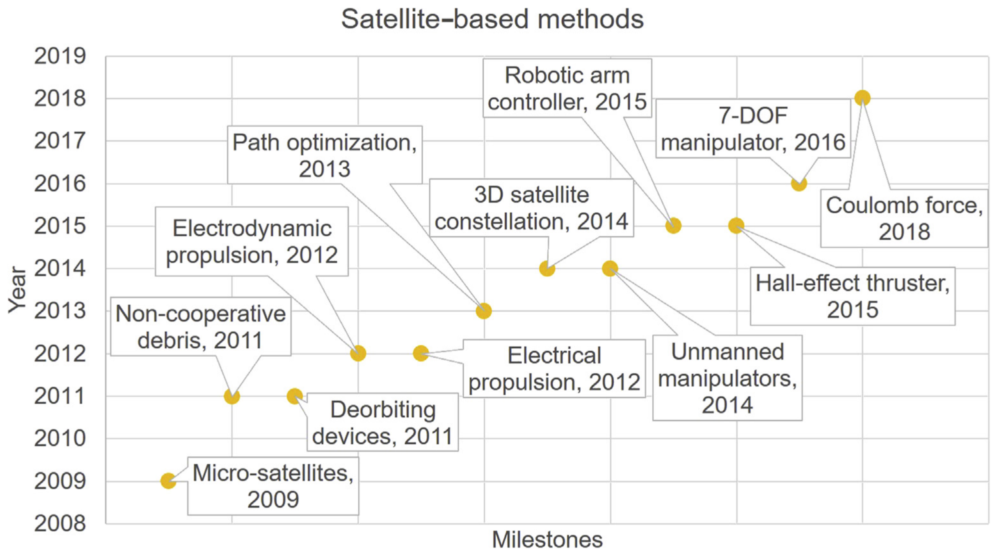

Fig. 7. Milestones in satellite-based methods.

of micron-scale dust over a narrow altitude band to accumulate mass on the debris and hence deorbit it. The dust will be injected in polar orbits to minimize precession due to gravitational anomaly. The dust will sweep the small debris and bring it to a lower altitude, where drag acts and the debris re-enters. They also analyzed the risks involved in using the method and the cost effectiveness of the concept. The dust injection concept is a cost-effective method to clear orbits, but the maintenance of the cloud has to be analyzed to effectively predict the consequences. Technology demonstration has to be performed to certify its usage in real-time environment. DeLuca et al. (2013) [61] discuss the use of an attachable hybrid propulsion module to remove space debris from LEO. The module is transferred from a satellite to the debris by means of a robotic arm so as to perform a controlled disposal. They select the target based on debris density in specific orbits and types. The mission concept is proposed based on rendezvousing with the debris, using an electroadhesive to mate with it, and deorbiting. They calculate the system mass budget by optimizing the removal trajectory. The mechanisms have to be experimentally tested for its functions to ascertain its performance in space environment. Wormnes et al. (2013) [62] talk about the “CleanSpace” initiative which broadly classifies into pushing, pulling, and contact-less maneuver to deorbit space debris. It involves attaching tethers, using throw-nets and shooting harpoons in pulling techniques, capture before touch strategy in pushing technique, and IBS and gas exhaust thruster in contact-less techniques. They further focus on a deorbitational mission planning to remove large and strategically chosen debris. Some of the exotic developments involve solid propulsion systems, GNC systems, expanding foams, and hybrid sails. Before a potential mission is planned, these concepts have to be proved to establish their capability. Bazzocchi and Reza Emami (2016) [63] try to apply asteroid redirection methods to orbital debris removal. The problem was formulated based on the cataloged two line elements data of debris in LEO and GEO. Some of the methods assessed include tugboats, laser sublimation, and ion beam. They have utilized analytical hierarchy process to assess the viability of each method based on re-entry of debris. The performance charts have projected tug boat and ion beam as viable methods. But more research is expected to certify the aggregated data. Chopra and Chandra (2018) [64] propose a method to deorbit debris using magnetic field–controlled plasma. They analyze the small satellite launches, predict the debris amount to get accumulated, and determine the clearing orbit. The system was designed for a small satellite with a plasma controller. The hardware configuration analysis was done to ascertain and fit it into a CubeSat module. It consists of electromagnetic coils, which are capable of producing directional magnetic fields, and a controller. The deorbiting maneuvers were analyzed with perturbations and torque control and simulated. The functioning of a magneto-plasma propelled system in a space environment has to be deeply investigated and experimentally analyzed before any mission.

The concept of unconventional methods includes abnormal ideas which help in the removal of debris, which cannot be achieved by existing techniques. As the papers describe, it initiates with expanding foam, micron-scale dust, attachable hybrid propulsion module, CleanSpace initiative with different maneuvers, asteroid redirection methods, and magnetic field-controlled plasma. These are the main ideas which have contributed to the concept's advancement. Table 7 gives the highlights, and Fig. 8 shows the milestones achieved in the unconventional methods.

2.8. Dynamical systems-based methods

Rosengren et al. (2015) [65] describe the chaotic growth of the eccentricity in navigation satellite systems due to perturbed motion of the moon. The chaos in orbit ensues when resonances overlap and onsets the dynamical instability of an object in space. The secular interactions were studied by averaging out the short periodic terms. This chaos plays a significant role in the disposal strategies of the orbit. The analysis of the stability of a graveyard orbit has given a significant insight into the disposal method. The point of instability in active orbits have to be researched to ascertain any threats due to the same chaos. Celletti and Gales (2015) [66] study the dynamics of space debris in regions corresponding to minor

Table 7
Highlights of unconventional methods.

Unconventional methods	
Core competency	Unusual ways to deorbit
Pros	Highly efficient
Cons	Not feasible
Latest discovery	Magnetic field-controlled plasma

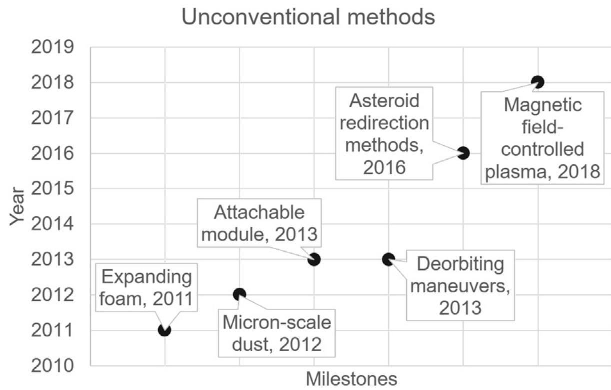

Fig. 8. Milestones in unconventional methods.

resonances. The mathematical model of the debris was treated with Cartesian and Hamiltonian formalism, which includes Earth's gravitational influence, the geopotential, the solar attraction, the lunar attraction, and the SRP. Then, the size of the resonant islands was studied, and the superposition of resonances were detected. The *trans*-critical bifurcations were obtained from minor resonances. They verified using fast Lyapunov indicators (FLIs) including various Cartesian variables. The claim of no modification of main characteristics due to minor resonances has been well established and supported. Daquin et al. (2016) [67] study the dynamical structure of the medium Earth orbit (MEO) region. They explore the effect of luni-solar resonances on the orbital region by examining the width of the chaotic layer from the overlap of nearby resonances. Then, they use the heuristic Chirikov criteria with 2.5-DOF approach to define the resonance centers. Further, they present an atlas of stability maps based on dynamical structures appearing in the MEO. The FLI stability was analyzed for hyperbolicity and predictability. The transport property was defined based on the exploration of phase-space domain. When analyzing, the reduction from 2.5-DOF to 1-DOF presents considerable inaccuracies. It has to be revamped to have a finer detailed model. Gkolias et al. (2016) [68] look into the effect of perturbations on an Earth's satellite orbit. The system was modeled based on Kepler's problem with doubly averaged potential. It involves non-autonomous Hamiltonian with 2-DOF motion. They study the secular dynamics of the MEO and GEO system by means of FLI and confirm the transition from order to chaos in orbits. The lunar nodal precession was deeply linked, and its effects were described in detail. But the exclusion of octupole-order secular interactions will have drastic changes in the results. Klima et al. (2016) [69] analyze the space debris removal efforts from a game theory perspective. The empirical estimate of orbit decay was obtained from a simulated system. They build a collision model with Cube approach and breakup with NASA's standard model. They simulate new launches with past data and validate with spatial density in different altitude angles. They investigate the strategic properties and equilibria of the efforts to determine the effective solution to the problem. Using game theory to predict future evolution of space debris with simplification is not accurate, as different variables come into existence. Celletti et al. (2017) [70] explore the possible causes for the onset of chaos in space debris dynamics. They create a mathematical model of the space debris including all the influencing disturbances and apply Cartesian, Delaunay, Milankovitch, and epicyclic variables to study the effects. The resonances were trapped to analyze the harmonic effects including the effect of J2, tesseral, secular, and semisecular. They identify the onset of chaos in a conservative regime with overlapping tesseral resonances and luni-solar secular resonances. Using the results to design disposal strategies is a fine task, but it has to be built on more simulated and experimental data. Suryanarayanan (2017) [71] focuses on predicting debris collisions using dynamical systems theory and chaos theory. The collision probability was detected using both the theories, and convergence in phase-space was defined. He builds a debris trajectory based on phase-space model and studies the influence of the disturbances on the body. The simulated results of the approach prove the improved accuracy of the prediction model. The claim on higher accuracy due to the application of improved prediction model cannot be proven unless it uses real-time data. Efimov et al. (2018) [72] explore the long-term attitude dynamics of debris in sun synchronous orbits (SSO). They mathematically model the rotational dynamics of a debris object in SSO. The secular effects in the dynamics was examined with the analysis of fast rotations evolution. The influence of gravity gradient torque and orbital evolution on the rotational motion was studied using conservative evolution. The evolution equations describing the eddy-current torque impact was derived and averaged along Cassini cycles. The system was numerically simulated to obtain exponential deceleration and chaotic stabilization along with evolution of angular momentum direction. The application of the system on a real debris object has to be investigated to utilize the phenomenon.

The dynamical systems-based ADR method involves deorbiting the debris by altering the orbital parameters by various

Table 8
Highlights of dynamical systems-based methods.

Dynamical systems-based methods	
Core competency	De-stabilizing debris by using perturbations
Pros	Very simple
Cons	Takes more computational time
Latest discovery	Rotational dynamics of debris in SSO

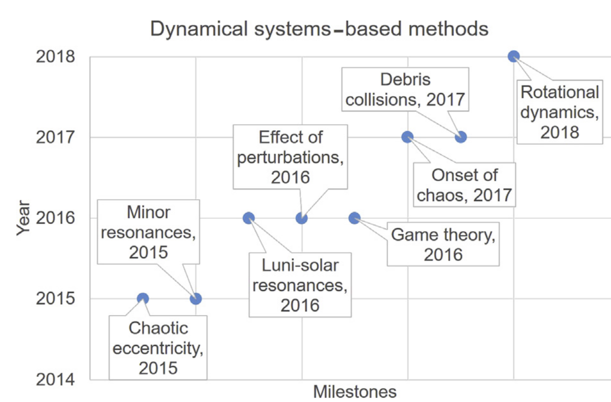

Fig. 9. Milestones in dynamical systems-based methods.

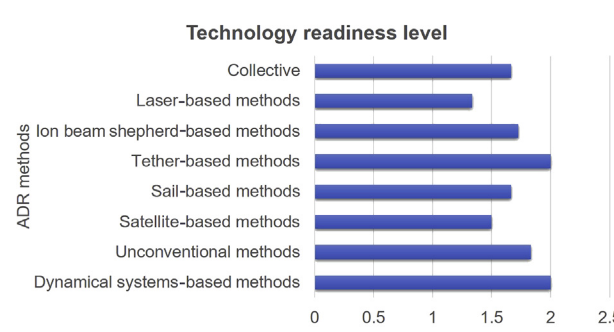

Fig. 10. Technological readiness level of the methods. ADR, active debris removal.

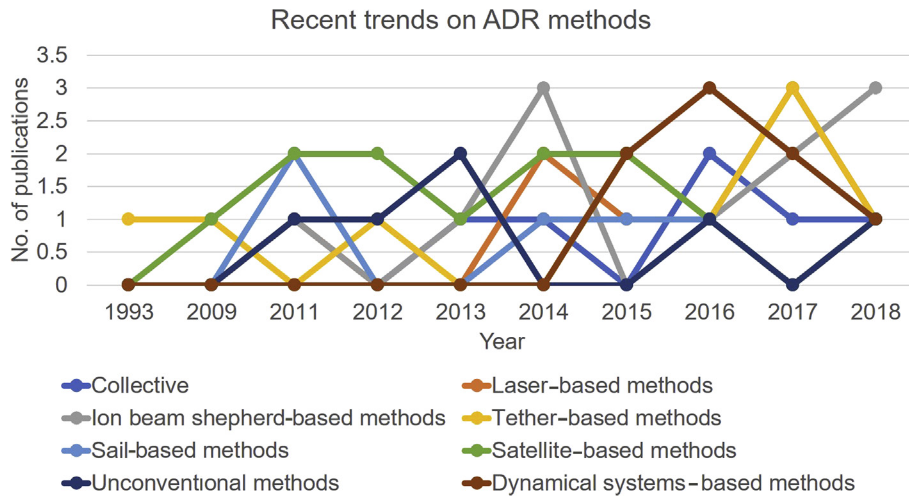

Fig. 11. Recent trends on active debris removal methods. ADR, active debris removal.

perturbations, both natural and artificial. As the papers describe, it initiates with chaotic growth of the eccentricity due to the moon, debris in regions of minor resonances, dynamical structure of MEO, perturbations on Earth's satellite, using game theory, causes for onset of chaos, predicting debris collisions, and dynamics of debris in SSO. All of these concepts have made a significant contribution, driving the concept forward. Table 8 gives the highlights, and Fig. 9 shows the milestones achieved in the dynamical systems-based methods.

3. Observations

Observing the ideas incorporated in every method, the review has thrown light on the important aspects moving the ADR concept forward. Based on the study, significant progress has been accomplished in proving the various concepts associated with the methods, such as collective method, laser-based method, IBS-based method, tether-based method, sail-based method, satellite-based method, unconventional method, and dynamical systems-based method, in the domain of space debris removal. Each concept has been advanced, and more knowledge has been recorded with every passing year. Furthermore, the methods have matured into experimental and prototype testing phase. This has established a highly equipped space sector, which can achieve a standalone ADR system. Yet, a substantial amount of research is required to bring the prospective systems into place.

The heavy-weight novel programs such as “CleanSpace”, “RemoveDebris”, “AnDROiD”, etc. can boost the revolution to provide a cleaner space. The majority of the methods have a lack of experimental verification phases, which is very essential in the growth of the concept. Others are mired in technological challenges, various noises to be incorporated, physical effects, and unreliable data. Based on the technological readiness and maturity level within the sample, an analysis was conducted to ascertain which method can reach the production phase with current knowledge (Fig. 10). The readiness level was calculated by assigning points based on three criteria (model, simulation and experiment) for all the publications in each method. Then, the aggregate score based on the sampled count on a particular method was determined. The results showed that tether-based method and dynamical systems-based method have excelled in their capacity. Looking into the future, all the methods could develop at a different pace. But the relatively newer concepts of unconventional and dynamical systems approach can bring a drastic change to the ADR world. A trend analysis was also carried out to have a glimpse of the papers sampled (Fig. 11).

In the future, the possibility of commercializing the venture is also being probed. The required standards and policies for the governance of space traffic management is also being setup. This can lead to freeing up more space for better utilization of the aerial resource. The development of any new method is impending, while the issue worsens day by day. The research on this domain is projected to plunge forward the existing methods into a fully established system supplying with all the relevant information to tackle the huge issue of cleaning up the orbital region.

4. Conclusion

It has been determined that all the ADR systems are at a conceptual/experimentation phase and require more study to be established into commercially viable platforms. Different ventures have already capitalized on the emerging trends to start standalone ADR programs. Based on the focus of research and observations, the tether-based method and dynamical systems-based method are at the forefront. Further on, the concept of a mixture of methods is also catching on. Some of the extraordinary concepts such as unconventional and dynamical systems approach will be in the spotlight for surprising changes. But any newer approach, which is more efficient is emphatically required to bring a major overhaul in the domain of space debris removal.

References

[1] D.J. Kessler, B.G. Cour-Palais, Collision frequency of Artificial satellites: the creation of a debris belt, J. Geophys. Res. 83 (A6) (1978) 2637–2646.

[2] Donald J. Kessler, Nicholas L. Johnson, J.C. Liou, Mark Matney, The Kessler Syndrome: Implications to Future Space Operations, American Astronautical Society, Breckenridge, Colorado, 2010. AAS 10-016.

[3] J.N. Pelton, Space Debris and Other Threats from Outer Space, SpringerBriefs in Space Development, 2013, pp. 17–23, https://doi.org/10.1007/978-1-4614-6714-4_2.

[4] J.N. Pelton, New Solutions for the Space Debris Problem, SpringerBriefs in Space Development, 2015, pp. 1–9, https://doi.org/10.1007/978-3-319-17151-7.

[5] Christophe Bonnal, Jean-Marc Ruault, Marie-Christine Desjean, Active debris removal: recent progress and current trends, Acta Astronaut. 85 (2013) 51–60, https://doi.org/10.1016/j.actaastro.2012.11.009.

[6] M. Emanuelli, G. Federico, J. Loughman, D. Prasad, T. Chow, M. Rathnasabapathy, Conceptualizing an economically, legally, and politically viable active debris removal option, Acta Astronaut. 104 (2014) 197–205, https://doi.org/10.1016/j.actaastro.2014.07.035.

[7] Susanne Petersa, Christoph Pirzkall, Hauke Fiedler, Roger Förstner, Mission concept and autonomy considerations for active Debris removal, Acta Astronaut. 129 (2016) 410–418, https://doi.org/10.1016/j.actaastro.2016.10.006.
[8] Minghe Shan, Jian Guo, Eberhard Gill, Review and comparison of active space debris capturing and removal methods, Prog. Aero. Sci. 80 (2016) 18–32, https://doi.org/10.1016/j.paerosci.2015.11.001.
[9] Jason L. Forshaw, Guglielmo S. Aglietti, Thierry Salmon, et al., Final payload test results for the RemoveDebris active debris removal mission, Acta Astronaut. 138 (2017) 326–342, https://doi.org/10.1016/j.actaastro.2017.06.003.
[10] P. Colmenarejo, M. Graziano, G. Novelli, D. Mora, P. Serra, A. Tomassini, K. Seweryn, G. Prisco, J.G. Fernandez, On ground validation of debris removal technologies, Acta Astronaut. (2018), https://doi.org/10.1016/j.actaastro.2018.01.026.
[11] Claude R. Phipps, Clearing Space Debris with Lasers, SPIE Newsroom, 2011, pp. 1–3, https://doi.org/10.1117/2.1201112.004076.
[12] Rémi Soulard, Mark N. Quinn, Toshiki Tajima, Gérard Mourou, ICAN, A novel laser architecture for space debris removal, Acta Astronaut. 105 (2014) 192–200, https://doi.org/10.1016/j.actaastro.2014.09.004.
[13] Shuangyan Shen, Jin Xing, Hao Chang, Cleaning space debris with a space-based laser system, Chin. J. Aeronaut. 27 (4) (2014) 805–811, https://doi.org/10.1016/j.cja.2014.05.002.
[14] Manuel Schmitz, Stefanos Fasoulas, Jens Utzmann, Performance model for space-based laser debris sweepers, Acta Astronaut. 115 (2015) 376–383, https://doi.org/10.1016/j.actaastro.2015.05.032.
[15] Yang Fan, Bron Nelson, Jonathan Aziz, et al., LightForce photon-pressure collision avoidance: efficiency analysis in the current debris environment and long-term simulation perspective, Acta Astronaut. 126 (2016) 411–423, https://doi.org/10.1016/j.actaastro.2016.04.032.
[16] Quan Wen, Liwei Yang, Shanghong Zhao, Yingwu Fang, Yi Wang, Removing small scale space debris by using a hybrid ground and space based laser system, Optik 141 (2017) 105–113, https://doi.org/10.1016/j.ijleo.2017.05.075.
[17] J.M. Gambi, M.L. García del Pino, Autonomous shooting at middle size space debris objects from space-based APT laser systems, Acta Astronaut. 131 (2017) 83–91, https://doi.org/10.1016/j.actaastro.2016.11.026.
[18] Valentin A. Shuvalov, NikolaiB. Gorev, Nikolai A. Tokmak, Galina S. Kochubei, Physical simulation of the long-term dynamic action of a plasma beam on a space debris object, Acta Astronaut. 132 (2017) 97–102, https://doi.org/10.1016/j.actaastro.2016.11.039.
[19] Q. Wen, L. Yang, S. Zhao, Y. Fang, Y. Wang, R. Hou, Impacts of orbital elements of space-based laser station on small scale space debris removal, Optik-International Journal for Light and Electron Optics 154 (2018) 83–92, https://doi.org/10.1016/j.ijleo.2017.10.008.
[20] C. Bombardelli, J. Pelaez, IBS for contactless space debris removal, J. Guid. Contr. Dynam. 34 (3) (2011) 916–920, https://doi.org/10.2514/1.51832.
[21] M. Merino, E. Ahedo, C. Bombardelli, H. Urrutxua, J. Peláez, IBS satellite for space debris removal, Progress in Propulsion Physics 4 (2013) 789–802, https://doi.org/10.1051/eucass/201304789.
[22] S. Kitamura, Y. Hayakawa, S. Kawamoto, A reorbiter for large GEO debris objects using ion beam irradiation, Acta Astronaut. 94 (2) (2014) 725–735, https://doi.org/10.1016/j.actaastro.2013.07.037.
[23] M. Ruiz, I. Urdampilleta, C. Bombardelli, E. Ahedo, M. Merino, F. Cichocki, The fp7 leosweep project: improving low earth orbit security with enhanced electric propulsion, in: Space Propulsion Conference (No. 2980908), 2014.
[24] H. Schaub, Z. Sternovsky, Active space debris charging for contactless electrostatic disposal maneuvers, Adv. Space Res. 53 (1) (2014) 110–118, https://doi.org/10.1016/j.asr.2013.10.003.
[25] F. Cichocki, M. Merino, E. Ahedo, M. Smirnova, A. Mingo, M. Dobkevicius, Electric propulsion subsystem optimization for "IBS" missions, J. Propul. Power 33 (2) (2016) 370–378, https://doi.org/10.2514/1.B36105.
[26] V.S. Aslanov, A.S. Ledkov, Attitude motion of cylindrical space debris during its removal by ion beam, Math. Probl Eng. (2017), https://doi.org/10.1155/2017/1986374.
[27] V.A. Shuvalov, N.B. Gorev, N.A. Tokmak, G.S. Kochubei, Physical simulation of the long-term dynamic action of a plasma beam on a space debris object, Acta Astronaut. 132 (2017) 97–102, https://doi.org/10.1016/j.actaastro.2016.11.039.
[28] F. Cichocki, M. Merino, E. Ahedo, Spacecraft-plasma-debris interaction in an IBS mission, Acta Astronaut. 146 (2018) 216–227, https://doi.org/10.1016/j.actaastro.2018.02.030.
[29] H. Hakima, M.R. Emami, Assessment of active methods for removal of LEO debris, Acta Astronaut. 144 (2018) 225–243, https://doi.org/10.1016/j.actaastro.2017.12.036.
[30] A.S. Ledkov, V.S. Aslanov, Attitude motion of space debris during its removal by ion beam taking into account atmospheric disturbance, in: Journal of Physics: Conference Series, vol. 1050, No. 1, IOP Publishing, 2018, p. 012041, https://doi.org/10.1088/1742-6596/1050/1/012041.
[31] J.R. Sanmartin, M. Martínez-Sánchez, E. Ahedo, Bare wire anodes for electrodynamic tethers, J. Propul. Power 9 (3) (1993) 353–360, https://doi.org/10.2514/3.23629.
[32] Satomi Kawamoto, Yashushi Ohkawa, Shoji Kitamura, Shin-ichiro Nishida, Strategy for active debris removal using electrodynamic tether, in: Trans. JSASS Space Tech. Japan, vol. 7, No. ists26, 2009. Pr_2_7-Pr_2_12.
[33] Zhai Guang, Jing-rui Zhang, Space Tether Net System for Debris Capture and Removal, 4th International Conference on Intelligent Human-Machine Systems and Cybernetics, 2012, https://doi.org/10.1109/IHMSC.2012.71, 258-161.
[34] Riccardo Benvenuto, Samuele Salvi, Michèle Lavagna, Dynamics analysis and GNC design of flexible systems for space debris active removal, Acta Astronaut. 110 (2015) 247–265, https://doi.org/10.1016/j.actaastro.2015.01.014.
[35] Dudziak Roger, Sean Tuttle, Simon Barraclough, Harpoon technology development for the active removal of space debris, Adv. Space Res. 56 (2015) 509–527, https://doi.org/10.1016/j.asr.2015.04.012.
[36] Panfeng Huang, Fan Zhang, Zhongjie Meng, Zhengxiong Liu, Adaptive control for space debris removal with uncertain kinematics, dynamics and states, Acta Astronaut. 128 (2016) 416–430, https://doi.org/10.1016/j.actaastro.2016.07.043.
[37] Minghe Shan, Jian Guo, Eberhard Gill, Deployment dynamics of tethered-net for space debris removal, Acta Astronaut. 132 (2017) 293–302, https://doi.org/10.1016/j.actaastro.2017.01.001.
[38] Inna Sharf, Benjamin Thomsen, Eleonora M. Botta, Arun K. Misra, Experiments and simulation of a net closing mechanism for tether-net capture of space debris, Acta Astronaut. 139 (2017) 332–343, https://doi.org/10.1016/j.actaastro.2017.07.026.
[39] G. Sanchez-Arriaga, X. Chen, Modeling and performance of electrodynamic low-work-function tethers with photoemission effects, J. Propul. Power 34 (1) (2017) 213–220, https://doi.org/10.2514/1.B36561.
[40] Z. Chu, J. Di, J. Cui, Hybrid tension control method for tethered satellite systems during large tumbling space debris removal, Acta Astronaut. 152 (2018) 611–623, https://doi.org/10.1016/j.actaastro.2018.09.016.
[41] D. Romagnoli, S. Theil, De-orbiting satellites in LEO using solar sails, in: Proc. International Symposium on Space Flight Dynamics, 2011, pp. 1–13.
[42] Michael Pfisterer, Kevin Schillo, Christopher Valle, Kuo-Chi Lin, Chan Ham, The development of a propellantless space debris mitigation drag sail for LEO satellites, in: Proc. 15th World Multi-Conference on Systemics, Cybernetics and Informatics, WMSCI, 2011, pp. 19–22.
[43] Juan M. Fernandez, Lourens Visagie, Mark Schenk, et al., Design and development of a gossamer sail system for deorbiting in low earth orbit, Acta Astronaut. 103 (2014) 204–225, https://doi.org/10.1016/j.actaastro.2014.06.018.
[44] Lourens Visagie, Vaios Lappas, Sven Erb, Drag sails for space debris mitigation, Acta Astronaut. 109 (2015) 65–75, https://doi.org/10.1016/j.actaastro.2014.12.013.
[45] Chan Ham, Kuo-Chi Lin, Study of a gossamer sail and its application to LEO spacecraft for space debris mitigation and attitude control, Frontiers in Aerospace Engineering 5 (1) (2016) 38–48, https://doi.org/10.12783/fae.2016.0501.04.
[46] P.W. Kelly, R. Bevilacqua, L. Mazal, R.S. Erwin, TugSat: removing space debris from geostationary orbits using solar sails, J. Spacecraft Rockets 55 (2) (2018) 437–450, https://doi.org/10.2514/1.A33872.
[47] Shin-Ichiro Nishida, Satomi Kawamoto, Yasushi Okawa, Fuyuto Terui, Shoji Kitamura, Space debris removal system using a small satellite, Acta Astronaut. 65 (2009) 95–102, https://doi.org/10.1016/j.actaastro.2009.01.041.
[48] Shin-Ichiro Nishida, Satomi Kawamoto, Strategy for capturing of a tumbling space debris, Acta Astronaut. 68 (2011) 113–120, https://doi.org/10.1016/j.actaastro.2010.06.045.
[49] M. Marco, Castronuovo, Active space debris removal—a preliminary mission analysis and design, Acta Astronaut. 69 (2011) 848–859, https://doi.org/10.1016/j.actaastro.2011.04.017.
[50] Eugene Levin, Jerome Pearson, Joseph Carroll, Wholesale debris removal from LEO, Acta Astronaut. 73 (2012) 100–108, https://doi.org/10.1016/j.actaastro.2011.11.014.
[51] Fabio Covello, Application of electrical propulsion for an active debris removal system: a system engineering approach, Adv. Space Res. 50 (2012) 918–931, https://doi.org/10.1016/j.asr.2012.05.026.
[52] Jonathan Missel, Daniele Mortari, Path optimization for Space Sweeper with Sling-Sat: a method of active space debris removal, Adv. Space Res. 52 (2013) 1339–1348, https://doi.org/10.1016/j.asr.2013.07.008.
[53] Hironori Sahara, Evaluation of a satellite constellation for active debris removal, Evaluation of a satellite constellation for active debris removal, Acta Astronaut. 105 (2014) 136–144, https://doi.org/10.1016/j.actaastro.2014.08.026.
[54] Tomasz Rybus, Karol Seweryn, Jurek Z. Sasiadek, Optimal Detumbling of Defunct Spacecraft Using Space Robots, IEEE, 2014, pp. 64–69, 978-1-4799-5081-2/14.
[55] Dubanchet Vincent, David Saussié, Daniel Alazard, Caroline Bérard, Catherine Le Peuvédic, Modeling and control of a space robot for active debris removal, CEAS Space J (7) (2015) 203–218, https://doi.org/10.1007/s12567-015-0082-4.
[56] A. Ruggiero, P. Pergola, M. Andrenucci, Small electric propulsion platform for active space debris removal, IEEE Trans. Plasma Sci. 43 (No. 12) (2015) 4200–4209, https://doi.org/10.1109/TPS.2015.2491649.
[57] Wenbin Yan, Ningning Qi, Jialin Ai, Lei Sun, A redundant manipulator design for active space debris removal, in: Proc. 35th Chinese Control Conference July 27-29, 2016, Chengdu, China, 2016, pp. 4585–4590.
[58] V. Aslanov, V. Yudintsev, Motion control of space tug during debris removal by a Coulomb force, J. Guid. Contr. Dynam. (2018) 1–9, https://doi.org/10.2514/1.G003251.

[59] M. Andrenucci, P. Pergola, A. Ruggiero, Expanding Foam Application for Active Debris Removal, Thesis, Advanced Concepts Team, ESA, 2011.
[60] Gurudas Ganguli, Christopher Crabtree, Leonid Rudakov, Chappie Scott, Active Debris Removal by Micron-Scale Dust Injection, IEEE, 2012, pp. 1–9, 978-1-4577-0557-1/12.
[61] L.T. DeLuca, F. Bernelli, F. Maggi, et al., Active space debris removal by a hybrid propulsion module, Acta Astronaut. 91 (2013) 20–33, https://doi.org/10.1016/j.actaastro.2013.04.025.
[62] K. Wormnes, R. Le Letty, L. Summerer, et al., ESA Technologies for Space Debris Remediation, White Paper - Advanced Concepts Team, ESA, 2013.
[63] Michael C.F. Bazzocchi, M. Reza Emami, Application of Asteroid Redirection Methods to Orbital Debris Removal, IEEE, 2016, pp. 1–10, 978-1-4673-7676-1/16.
[64] C. Chopra, R. Chandra, Small satellite deorbital system using magnetic field controlled plasma, in: 2018 SpaceOps Conference, 2018, p. 2705, https://doi.org/10.2514/6.2018-2705.
[65] Aaron J. Rosengren, Elisa Maria Alessi, Alessandro Rossi, Giovanni B. Valsecchi, Chaos in navigation satellite orbits caused by the perturbed motion of the Moon, Mon. Not. R. Astron. Soc. 000 (2015) 1–6, arXiv:1503.02581v1.
[66] Alessandra Celletti, Catalin Gales, Dynamical Investigation of Minor Resonances for Space Debris, Celestial Mechanics and Dynamical Astronomy, 2015, pp. 1–31, https://doi.org/10.1007/s10569-015-9636-1.
[67] Jérôme Daquin, J. Aaron, Rosengren, Elisa Maria Alessi, et al., The dynamical structure of the MEO region: long-term stability, chaos, and transport, Celest. Mech. Dyn. Astron. 124 (2016) 335–366, https://doi.org/10.1007/s10569-015-9665-9.
[68] Ioannis Gkolias, Daquin Jerome, Fabien Gachet, Aaron J. Rosengren, From Order to Chaos in Earth Satellite Orbits, astro-ph.EP, 2016, pp. 1–30, arXiv:1606.04180v2.
[69] Richard Klima, Daan Bloembergen, Rahul Savani, Karl Tuyls, Daniel Hennes, Dario Izzo, Space debris removal: a game theoretic analysis, Games 7 (20) (2016) 1–18, https://doi.org/10.3390/g7030020.
[70] Alessandra Celletti, Christos Efthymiopoulos, Fabien Gachet, et al., Dynamical models and the onset of chaos in space debris, Int. J. Non Lin. Mech. 90 (2017) 147–163, https://doi.org/10.1016/j.ijnonlinmec.2016.12.015.
[71] Aswath Suryanarayan, Determining orbits for collision prediction using dynamical systems theory, in: Proc. 7th European Conference on Space Debris, 2017, pp. 18–21. Darmstadt, Germany.
[72] S. Efimov, D. Pritykin, V. Sidorenko, Long-term attitude dynamics of space debris in Sun-synchronous orbits: Cassini cycles and chaotic stabilization, Celest. Mech. Dyn. Astron. 130 (10) (2018) 62, https://doi.org/10.1007/s10569-018-9854-4.