Space Traffic Management: Addressing Challenges and Opportunities

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Space traffic management (STM) is a topic of great significance for the space community. Most of the objects that currently orbit Earth are inoperative satellites and debris. Companies are planning to place thousands of new satellites in low Earth orbit (LEO) which will vastly increase the risk of conjunctions and generate further debris. In this paper, the current methods for mitigating space traffic are explored. They include improved space situational awareness (SSA), end-of-life disposal, active debris removal (ADR), and collision avoidance maneuvers. The challenges that stand in the way of preventing space traffic are also outlined. Additionally, alternative methods such as the application of artificial intelligence, solar radiation pressure and solar electric propulsion, as well as the potential for inspiration from collision avoidance systems for swarms of drones are presented. The topic of STM is currently being researched, so this paper aims to highlight the available knowledge, the existing gaps in current measures, and what can be further done to improve the situation. Post-mission disposal, information sharing, and rules for maneuvers can help mitigate the issue.

Keywords: Space Traffic; Space Situational Awareness; Debris Removal; Collision Avoidance Maneuvers; Low Earth Orbit and Geostationary Equatorial Orbit; Short Range and Far Range Operations; End-of-Life Disposal

Introduction

Space traffic management attracts attention from the technical and law and policy aspects of the field[1]. Out of the growing number of objects that orbit the Earth, 90% are dead ones like inoperative satellites, sprent upper stages, and debris[2]. Within the next one or two decades commercial companies such as SpaceX, Theia, and Boeing have plans to place constellations of thousands of satellites in low Earth orbit. The implementation of these plans would increase the population of operational satellites in LEO to 16000 within the next one or two decades, doubling the objects tracked by the Space Surveillance Network (SSN)[2].Terms like NewSpace outline the trend of developing faster and more affordable access to space, which is different from government-driven security, political, and scientific activities[3]. This worsens the space debris environment, especially in LEO[3]. The debris is remnants of dead satellites, used rocket stages, and particles from the collision with other debris[4].

Each debris particle could have the ability to travel at 30,000km/h relative velocity, thus causing a great deal of damage[4]. Lastly, debris from LEO and geostationary equatorial orbit (GEO) collisions could have an effect on all orbital regimes, with a potential GEO collision having the ability to send debris fragments down to the surface of Earth and envelope a large amount of the GEO belt a day following the event[5]. In LEO altitudes specifically, the rate of collision between an active satellite and debris is significantly greater than the collision rate between two active satellites or debris-on-debris even though that could change given the number of proposed medium and large constellation satellites in the next decade[5].In GEO the situation differs given that the ratio of active satellites to debris is higher than in LEO, resulting in the likelihood of a collision between two active satellites and a collision between an active satellite and sizable debris being almost equal[5]. Because of this, GEO spacecraft operators normally understand that pooling their authoritative positional, physical, and observational satellite data allows them to mitigate a large amount of their collision risk.

Generally, when active-on-active collision rates are common, spacecraft operators benefit from exchanging their data with one another, whereas when collision rates between two debris objects or debris and an active satellite are prevalent, space data exchange between debris tracking SSA service and operators is of most use[5].

According to the definition in the United States Space Policy Directive, space traffic management is "the planning, coordination, and on-orbit synchronization of activities to enhance the safety, stability, and sustainability of operations in the space environment"[5]. The basis of STM systems is the space situational awareness of the space operating environment, with SSA being defined as the understanding and characterization of space objects and their operational environment to ensure secure and sustainable space activities. Supporting safe spaceflight has become a challenge, with at least a dozen collisions having occurred in LEO and indicators of at least five collisions in geosynchronous equatorial orbit. Nevertheless, a greater number of collisions in LEO and GEO that simply were not publicly announced could have occurred. A space collision or explosion can be incredibly far-reaching, with collision and explosion fragmentation events having an effect on the functionality and

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commercial viability in space across all orbital regimes and GEO longitude locations[5].

This paper aims to showcase how space traffic could be managed to ensure sustainable space operations and prevent collisions. It will go into detail on the current state of STM, existing frameworks and regulations in place, as well as specific challenges faced. Furthermore, various methods for regulating spacecraft traffic and case studies of successful STM practices will be analyzed. Lastly, a comparison of the effectiveness of different STM methods will be made, alongside a recommendation for future STM regulations and practices.

Background and Current State of Space Traffic Management

As industry and government agencies look to utilize the near-Earth space environment with satellite constellations, the total number of resident space objects (RSOs) is estimated to increase by a factor of five in the upcoming decade as over 20,000 new satellites in LEO and middle Earth orbit (MEO) are projected to be launched into orbit[6]. One key issue is that, of the 34,000 objects larger than 10 cm in orbit, only 20,000 are cataloged[7]. Out of those 20,000 large objects, only 2000 are operational, among which 1500 are maneuverable[7]. However, maneuvers can be performed only when at least one of two objects is maneuverable[7]. Therefore, 86% of collisions among cataloged objects are unavoidable in present times[7]. Collisions can destroy key space assets, lead to financial losses for satellite owners, and disrupt essential services for people on the ground such as communications, weather, or navigation[6]. To put it in perspective, the protection of satellites from debris could be very expensive due to design measures, surveillance and tracking, as well as the moving of satellites out of the way of potential collisions and even replacing them[8]. For geostationary orbit satellites, these costs could amount to 5-10% of the cost of the entire mission, meaning hundreds of millions of dollars. In LEO, the relative cost per mission could be an even larger amount[8]. They could also generate immense amounts of debris that would be an addition to the already 20,000 existing pieces of debris in orbit, thus further contributing to the likelihood of future collisions[6]. Therefore, this could turn into the Kessler syndrome, a self-sustaining collisional cascading process[9]. A main concern here is that reinforcing feedback loops could show up, which means that as more debris is present, more collisions will take place, further creating debris[9]. A depiction of this could be done through a simplified Causal Loop Diagram which is centered around collisions and their impact on populations that are modeled[9].

A study was done by Thomas J. Colvin, John Karcz, and Grace Wusk where they analyzed that debris increases the costs of space operations[10]. This is primarily due to the fact that it is necessary to shield around or maneuver around the debris and that it could make orbits unusable. Debris also puts astronauts and satellites in danger and hinders the ability to launch spacecraft[10]. The costs and benefits of debris mitigation and tracking are known. Uncertainties also lie when it comes to the costs and benefits of debris remediation[10]. The cost of remediation is not known and the positive outcomes of it may not materialize for years[10].

In the study, both large debris remediation and small debris remediation were analyzed[10]. For the first, the benefits of removing the 50 most concerning derelict objects in LEO were considered, while for the latter one, the benefits of removing 100 000 pieces of 1-10 cm debris from altitudes between 450 km and 850 km were considered[10]. In both cases, all debris was assumed to be remediated upfront[10].

The main findings of the study were the following:

1. Eliminating small debris and nudging large debris to prevent collisions are the best remediation methods[10].
2. The recycling of space debris does not appear more risk-advantageous to other methods[10].
3. Both controlled and uncontrolled reentry through a reusable remediation servicer could be beneficial for spacecraft operators[10].

If there was a set of formal maneuver guidelines, it is hypothesized that the space environment could be managed and able to sustain current growth patterns[6]. Nevertheless, there are no formal or widely accepted maneuver guidelines to ensure the effective management of a future crowded LEO and MEO environment. If a conjunction event is predicted, satellite operators are expected to act independently, and there is no requirement for coordination with other operators or agencies[6].

Objects in the current catalog are tracked by the U.S. Space Surveillance Network (SSN)[3]. However, the current SSN LEO catalog only contains objects greater than 10 cm, and it is accepted that an impact in LEO with an object larger than 1 cm in size will cause damage to the satellite's mission which will be of significant damage. Therefore, unobserved debris poses a large risk[3].

On June 18, 2018, the U.S. National Space Council released the U.S. Space Policy Directive - 3 (SPD-3), highlighting the necessity of safety standards and practices to control space traffic[11]. Furthermore, it stated that improving space situational awareness data standards, developing standard techniques for mitigating collision risks, and promoting norms in space operations are of significance, identifying more than 40 necessary STM-related standards, guidelines, and practices. Examples of new regulations include rules for object trackability, information sharing, orbit selection, post-mission disposal reliability, etc. Still, there is tension between the government's need to protect the safety and sustainability of the space environment, on the one hand, and the industry's desire to have minimal, consistent regulatory constraints, on the other[11]. The reason for this is that space industry players know that having more regulatory constraints could increase design and operational costs, as well as hinder innovation and future investments. This is why so far there is one three-step process to stabilize the space

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environment which stakeholders around the world agree on. The first step involves gathering a community of space actors, government officials, organizations and academia to outline voluntary, technical, and operational standards, guidelines, and practices. The second aspect is to have the agreed-upon measures accepted by stakeholders and then have governments build them into domestic law and licensing criteria. Lastly, an international consensus should come up regarding the most appropriate and sustainable way for space activities to take place, which is grounded on congruent domestic law and customary practice[11].

Methods

The topic of this paper is being researched thoroughly with new ideas coming up. Still, the available material was not of significant substance, so careful selection of sources was required. The main approach involved adhering only to trusted journals, books, and websites after filtering by keywords such as "Space Traffic", "Space Traffic Management", "Collision-avoidance maneuvers", "Space Situational Awareness", "Active Debris Removal", "Debris", and "Disposal". For each source, the publication date and study design were evaluated to ensure that the information is up-to-date and relevant to the goal of this paper which is to present the current state and potential solutions to space traffic. Therefore, a great deal of time was spent reading through different studies, looking at data ranging from 2014 - 2024, comparing and contrasting. All available methods for managing space traffic were researched and compared across resources in order for the information included in this paper to be encompassing.

The writing approach of this paper was to first make a detailed review of the existing and applicable literature. Then, overlaps in the information were examined and based on that, the main issues with space traffic and the current ways in which it is tackled were selected. The organization of the paper follows the theme of introducing the concept of space traffic and outlining the background information and current state. It then naturally follows into methods for regulation and the challenges of overcoming the issue. Lastly, it wraps up with a discussion on future prospects, including innovative solutions.

Discussion

The present international space sustainability and orbital debris mitigation guidelines and standards do not have binding regulatory mandates, monitoring and enforcement[5]. Due to this, space operators and industry stakeholders have taken action to address collision risk and promote space safety by aiming to implement current guidelines and standards such as the Inter-Agency Space Debris Coordination Committee (IADC) guidelines, the United Nations Committee on the Peaceful Uses of Outer Space (COPUOS) guidelines, the International Standards Organization space debris mitigation standards, and the Consultative Committee for Space Data Systems standards, as well as more aspirational space sustainability practices[5].

Regarding steps to combat collision avoidance, the European Space Agency (ESA) has made efforts to contribute[12]. It released a unique real-world dataset that includes a time series of events outlining the evolution of collision risks in connection to actively monitored satellites. The main source of information on the collision avoidance process at ESA is grounded on conjunction data messages (CDMs), which are ASCII files produced by the United States based Combined Space Operations Center (CSpOC). Each conjunction has information on a close approach between a monitored space object, known as the "target satellite", and another space object, known as the "chaser satellite", with multiple attributes of the approach being contained like the identity of the satellite, the object type of the potential collider, the time of closest approach (TCA), the positions and velocities of the objects, as well as associated uncertainties. Following the first CDM, regular CDM updates are provided, and as time goes on, there are fewer uncertainties about the object positions as the knowledge of the close encounter is refined[12].

Normally, a time series of CDMs spanning one week is produced for each unique close approach, with around three CDMs becoming available each day. For a specific near approach, the most recent CDM can be assumed to be the most accurate regarding the probable collision and the state of the two objects in issue. If the predicted collision risk for an event is near to or greater than the reaction threshold (e.g., 10^{-4}), the Space Debris Office will notify control teams and start working on an avoidance maneuver a few days before the close approach, in addition to having a discussion with the flight dynamics and mission operations teams. The Space Debris Office at ESA assigns a risk rating to each CDM, yet still has not tried to propagate the risk value into the future. As a result, a practical baseline for the current best estimate would be using the latest risk value as the final prediction[12].

Generally, to assess how effective an STM regime is, the main metric is the reduction in the number of conjunctions after the regime is carried out in comparison to other STM systems[13]. Finding conjunctions makes it necessary to compare each resident space object to every other one at each time step in order to determine whether the pair is within an established maximum range of the nearest approach, which is also called Rcr, or if they passed within this range between the preceding and current time steps[13]. Below are outlined several key methods for managing space traffic that are currently mainly focused on.

Improved Space Situational Awareness (Technological Strategy)

The improvement of SSA and data sharing is a crucial step in combating the issue of space traffic. What is currently being implemented are S-Band radar systems by the United States in the Pacific Ocean region, which is called the space fence[14]. The

U.S. Defense Advanced Research Projects Agency (DARPA) is further ready to ship a new optical tracking system for operation in Australia, which would cover Southern Hemisphere debris tracking operations. Moreover, Germany has developed a radar system for debris tracking, involving a 34 m dish radar installed at the Research Establishment for Applied Science. These current efforts contribute to more precise space situational awareness, with a greater number of optical tracking systems being installed in several locations [14]. The Space Data Association (SDA) has now developed increased capability to prevent conjunctions with the use of tracking information supplied by its membership, which has grown to twenty commercial organizations and space system operators [14]. Nevertheless, the idea is not solely to expand the SSA capabilities using S-band radar, optical tracking and the sharing of spacecraft tracking data among satellite fleet operators, but also to have dependable means to share this data with those operating satellites, particularly ones in polar orbits and operating networks in the 300 km - 1500 km range [14]. Not to mention that orbital estimation through optical tracking could be challenging because of the relatively limited field of view that the sensors offer and the subsequent extremely short observation arc [15]. Still, this issue could be addressed through the use of a multi-spacecraft approach, a concept that makes use of a formation of coordinated spacecraft to work in synergy and compile tracking and estimation data to acquire more precise situational awareness [15]. Lastly, the capability to deliver timely alerts in regard to potential collisions is also becoming increasingly prevalent [14].

Overall, governmental systems and other national space agency capabilities, private SSA capabilities, and international commercial systems for sharing probable collisions of space objects have to continue developing ways to efficiently share information and avoid collisions [14]. National systems for information exchange regarding orbital collision risk and SSA will remain the main technique of risk avoidance until further mechanisms are developed. Nevertheless, technical capabilities, national security concerns and cost sharing arrangements for SSA activities and risk warning exchanges persist as central problems that hinder the establishment of a functioning international system for risk of collision information exchange [14].

What is important to note about improved SSA is that it will require collaboration and timely collision alerts. The sharing of useful information between governments and the private sector can facilitate the prevention of collisions. Therefore, it is necessary to work on the current technical limits and national security concerns that stand in the way of SSA.

End-of-Life Disposal (Policy Strategy)

Geosynchronous Disposal Guidelines

The Inter-Agency Space Debris Coordination Committee (IADC) has stated that spacecraft with terminated missions have to be maneuvered away from GEO so as not to cause interference with spacecraft or orbital stages still in geostationary orbit [15]. The spacecraft should be placed in an orbit that is above the GEO-protected region following the maneuver. Successful post-mission GEO disposal maneuvers can be achieved through the implementation of two conditions. The first is a minimum increase in perigee altitude of:

$$235km + (1000 \cdot C_{SRP} \cdot \frac{A}{m}) \tag{1}$$

where 235km is the sum of the upper altitude of the GEO-protected region (200km) and the compensation needed for altitude minimization due to luni-solar and geopotential perturbations (35km), C_{SRP} is the solar radiation pressure, and A/m is the aspect area to dry mass ratio. The second condition is a re-orbit eccentricity which fulfills these requirements:

1. An eccentricity ≤ 0.003, or
2. An eccentricity vector which is pointed in a way that the longitude of periapsis, ϖ , is pointed toward the winter or summer solstice. Therefore,

$$\varpi = \omega + \Omega \approx 90^\circ \text{ or } 270^\circ \tag{2}$$

where ω is the argument of periapsis and Ω is the longitude of the ascending node. If these requirements are carried out, the space vehicle will not reenter the protected zone for 40 years [15].

LEO Disposal Guidelines

To achieve a balance between collision risk due to the extension of post-mission life and the cost of reducing it, the IADC has stated the following: post-mission lifetime has to be limited to 25 years for any spacecraft that passes through or could interfere with the LEO region [15]. Direct re-entry following a mission would be the successful way to reduce LEO traffic here, yet it imposes a weight fraction penalty on mission design. Therefore, the exploitation of natural orbital perturbations is recommended as the method to execute re-entry and complete burnup. In order to adhere to the 25-year policy, post-mission disposal has to be fully considered when spacecraft and missions are thought out, especially the propellant mass fraction affiliated with required maneuvers [15]. The lower the altitude, the stronger the atmospheric drag is, so the efficacy of atmospheric drag in decaying a space object's orbit depends on the final perigee after the post-mission maneuver. Therefore, spacecraft in the outer periphery are imposed with heavier propellant weight penalties to ensure that the space object eventually re-enters the atmosphere [15].

Currently, spacecraft have to showcase a high probability of successful disposal and high reliability throughout their design lifetime, with critical parameters monitored and contingency actions put in place [16]. Besides this, if an unplanned event were to occur or if a mission is extended, reassessments have to

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be done. These requirements are mainly to incentivize proper disposal of LEO spacecraft given that statistical studies have indicated that most LEO spacecraft do not comply with the 25-year rule[16]. It is also not an option to dispose of a LEO spacecraft above the LEO region in order not to create a hazardous graveyard region, and restrictions have been added on the number of orbital stages and debris objects a launch vehicle can release. Lastly, any spacecraft or orbital stage that cannot perform collision avoidance maneuvers by design needs to be removed from LEO within 25 years of its injection into orbit, not 25 years following the end of mission[16].

Active Debris Removal (Technological Strategy)

Active debris removal is an essential part in stabilizing the growth of space debris[17]. A space mission for active space debris capturing and removal comprises several phases[18]. They include Launch and Early Orbit Phase (LEOP), far range rendezvous phase, close range rendezvous phase, capturing phase, as well as removal phase. These can be performed autonomously or remotely where they are controlled by ground-based mission operations. The capturing phase is of significance in the complete mission process. In general, methods for space debris capturing can be divided into two categories: contact and contactless capturing methods[18]. Contactless capturing methods use electrostatic forces or gravitation and are mainly regarded for asteroid orbit deflection. Still, there is not a capturing method that can deal with all kinds of space debris. On the other hand, removal methods differ fundamentally from the capturing ones, and in some cases, removal is performed following capturing. However, most of the time, removal methods avoid capturing[18].

There needs to be further research done on effective capturing methods for each type of debris, as well as information about their cost and success rate.

The most developed ADR architecture that is preferred for efficiency is moving the debris to a lower altitude to reduce its lifetime and associated orbital collision risk[19]. The important aspect to optimize the missions is selecting which derelicts need to be deorbited given the need to maximize the retired debris risk[19].

A large focus has been put on ADR mission planning and how they are done using evolutionary algorithms[19]. D. Zona et al. use a genetic algorithm with multiple crossover and mutation operators in order to quantify their impacts on choosing debris targets while taking into account fuel and constraints regarding timing[19]. Shen et.al had a similar approach to the ADR issue where the focus was on optimization for the usage of fuel and timing constraints[19]. The J_2 perturbation was employed to ensure that the orbit of the servicer spacecraft line up with the derelict orbit. This lessens the dependence on spacecraft fuel to change the servicer's orbit. The problem was developed as a Mixed Integer Nonlinear Problem (MINLP) and solved through ant colony optimization. Nevertheless, these methods are applied to specific inclinations and altitudes of LEO. That is either in current debris clouds or preselected orbits[19].

Static characteristics such as mass, inclination, and lifetime contribute to the clear definition that a space object (SO) poses[19]. These characteristics outline the amount of energy that will exist in a collision and which SOs present with the highest collision risk. The Criticality of Spacecraft Index (CSI) is a static risk index that takes into account the orbital elements and geometric properties of the SO[19]. Recently, an open-source MIT Orbital Capacity Assessment Tool (MOCAT) was created to carry out Monte Carlo (MC) simulations to propagate every SO to extract metrics about its future risk[19]. The MOCAT-MC is combined with the CSI to obtain the MIT Risk Index (MITRI), which quantifies the risk posed by an SO. This risk index, along with spacecraft fuel constraints, can be used in the planning of an optimal ADR mission[19].

Up to now, the development and implementation of ADR has included preliminary research and development, yet there is now a transition towards a focus on support for technical demonstration missions[19]. Companies in various countries such as the United States, United Kingdom, Switzerland, and Japan are working on ADR technologies that focus on debris removal missions. The commercialization of these technologies is of importance when it comes to the transition to operational ADR capability while increasing efficiency and scalability, lowering costs, and working pay for ADR, low technical readiness levels, and unresolved policy issues around objects with unknown ownership and liability[19].

For on-orbit space debris removal, a chaser satellite encounters target debris based on autonomous maneuvers and particular sensors used in each phase of the rendezvous process[20]. When it comes to the far range rendezvous phase, the chaser satellite needs to be located in a position farther than 5 km from the target[20]. In the close range phase, the chaser satellite should be between 5 m and 5 km away from the target. For the final approach, which is the last phase of the rendezvous, the chaser would be within 5 m to the target. Nevertheless, these boundary locations between different phases could change depending on the sensor system and its performance, as well as the approach strategies for distinct missions[20].

Regarding the far range phase, the position of the target in the orbit is cataloged and known by surveillance systems, yet there is always a percentage of errors in the real location[20]. It is important to have accuracy in the debris location so that sudden collisions and the waste of power and fuel resources from the chaser are avoided. Because of this, the long distances in this phase require microwave radar and optical sensor suits[20].

For the close range phase, the precision of the measurements grows with the decrease of the range. In this case, the use of a laser range sensor would be appropriate[20]. The chaser in a close range or final approaching rendezvous phase is normally controlled automatically by on-board computers, yet it could be managed by astronauts on the chaser or telecontrolled by operators on the target or in the mission control center[21].

Lastly, when the chaser satellite is at the final approach phase

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and near to capture the debris, it is at the closest and most dangerous phase[20]. Therefore, it is of importance to have a quick object detection system and to use minimum power resources. An example of a good sensor would be the photonic mixer device (PMD)[20]. It has a lower mass and power requirements, which makes it suitable for the final rendezvous phase, obtaining a non-ambiguous range of around 7 m. Furthermore, the frame rate of a PMD sensor is greater than that of others, and the increment in images made per second could contribute to the overall safety[20]. For example, a target could be rotating around one of its axes at a rate faster than the sensor frame rate, which could show up as a blur in the image and lead to a bad attitude calculation. However, the PMD sensor operation on-orbit and performance in the space environment have yet to be reviewed[20].

Case Studies

The RemoveDEBRIS mission is the first of its kind to showcase in-orbit technologies for active space debris removal[22]. Several technologies were tested. Two of them, a net and a harpoon, were analyzed for the capture of the debris. A LiDAR camera and software was used for the observation of the debris which was valuable in determining various parameters like distance and spinning rates[22]. Such parameters play a vital role during the rendezvous and debris capture. Lastly, the dragsail was utilized for de-orbiting at the end of life.

It is necessary to perform in-orbit demonstrations because it is not possible to execute fully representative tests on the ground[22]. The satellite in the mission was put in orbit through a two-stage process. It was first taken to the International Space Station (ISS) during a Space X periodic resupply mission. Afterwards, with the use of the Japanese module airlock, the satellite was transferred outside the ISS and released in-orbit by the space station's robotic arm. Following that, the mission was executed. Regarding hardware, it was made up of a satellite platform that hosted the payloads which performed the demonstrations[22]. When the platform was in-orbit, it released two 2U CubeSats. These were space debris and served as targets for the net capture and VBN technology demonstration. The harpoon was fired from the platform at a target which was about 1.5 meters away at the end of a deployable boom. Lastly, the dragsail had to be deployed from the platform[22]. This was made up of an inflatable mast which was 1-m long and which supported a mechanism that deploys 4 booms. The booms unfurl 4 quadrants of sail. Following the deployment, the sails form a square (3×3 meters) and the deployable booms are the square's diagonals. The inflatable mast holds the assembly from the centre with the distance from the platform being 1 metre. Given that the craft is in LEO, the residual atmosphere enables the sail to produce drag which slows down the satellite and contributes to the de-orbiting process[22].

Besides RemoveDEBRIS, a mission known as Clearspace-1 is set to launch and be the ESA's first mission to showcase how to remove space debris from Earth's orbit[23].

Autonomous Rendezvous

One experiment was done for autonomous rendezvous with two Astrobee robots on the International Space Station[24]. For the experiment, one robot was the autonomously controlled "Chaser" and the other - the unknown "Target". The Astrobee robots are free-flying robots which operate aboard the ISS[24]. They allow microgravity autonomy research because of a suite of sensors and three reconfigurable general-purpose processors. The Astrobees have sensors for navigation including cameras and an inertial measurement unit (IMU).

The autonomous rendezvous problem considers a close proximity rendezvous maneuver between two of the Astrobees[24]. The proximity is analogous to the last $\sim$ 20–40 m of an on orbit approach operation and the aim is to reach a predetermined offset point known as the mating point (MP), which is fixed in the body frame of the tumbling Target. In order to achieve this, in the motion planning computation, an artificial hull similar to the shape of Envisat is superimposed on the Target[24].

To successfully complete the tumbling target rendezvous task, three things need to be done[24]. The first step is to decide the Target's tumble, which includes its attitude and angular velocity, and, potentially, its inertia tensor. The second step is to have a motion plan that considers collision-avoidance, constraints, and conserves fuel. The third step is to perform precise control that ensures robustness against current uncertainty levels[24].

Collision Avoidance Maneuvers (Operational Strategy)

After discovering that a collision is likely to happen, RSOs need to be maneuvered, and presently, the maneuver that is used is an orbital phasing one[13]. It alters the time of perigee while leaving the RSO in the same orbital track, thus changing the time at which either one or both of the RSOs will reach the conjunction point. A change of velocity, the direction of which will align with the RSO's current velocity vector, is required to enter an orbit that will move the RSO by a specific angle, ϕ. Following an orbit, a change in velocity (δv) that is of the same magnitude is applied in the opposite direction[13]. When the conjunction has passed, this method is done a second time with a negative value of ϕ. The process is improved to increase the period between the first and second burns to be as large a number of orbits as possible prior to the collision[13]. Overall, collision avoidance maneuvers are normally very small, including changes in velocity less than 1 m/s[25]. Most of the time they can performed without the waste of propellant resources. Nevertheless, 99% of the risks to operational spacecraft arise from conjunctions with objects that are not large enough to be tracked routinely, meaning smaller than 5-10 cm[25].

Challenges

One key issue is that presently, only 4% of the LEO space population and 4% of the GEO space population sized 1 cm

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and larger are tracked by the Space Surveillance Network, which means that 96% of objects in LEO and GEO are untracked[26]. Therefore, there is not enough situational awareness. Furthermore, it is approximated that one hundred million tiny fragments down to 1 mm are present[26].

In all regimes, spacecraft operators experience difficulty in figuring out which conjunctions are "too close"[27]. Operators with spacecraft operating in a low-risk orbital regime can carry out simple, ultra-conservative collision avoidance strategies that are not costly in regards to fuel or operations. Operators with spacecraft operating in high-risk regimes need to be realistic in their collision avoidance methods as to not exhaust their fuel budget and overtax their fight dynamics teams[27]. Still, while there is a large amount of collision avoidance maneuver Go/No-Go criteria, operators struggle to secure the metrics and data types needed to populate the most suitable criteria. Furthermore, the algorithms used to populate these criteria can contain assumptions like using linearized relative motion and spherical object shape approximations which are not valid since more sophisticated formulations are necessary[27]. An example of this is the paper referenced in the Collision Avoidance Maneuvers section of this paper which outlines several of these assumptions when discussing how the probability of a collision is calculated; the relative motion between two RSOs during a conjunction is assumed to be linear, and the RSOs are modeled as spheres[13].

Finally, another central issue today is that there is not sufficient accuracy of the orbital parameters of cataloged objects, especially smaller ones, and of the orbital propagation[28]. Normally, if you have knowledge of the position of a 20 cm cubesat with an accuracy of $\pm$ 1 km along the velocity vector, this could result in an incredibly scattered evaluation of a collision probability. Therefore, the thresholds reviewed for the collision avoidance criteria need to be strict, which means that maneuvers have to be commanded whenever the risk goes above a 1 in a 1000 probability. Because of this, a main priority is the improvement of orbital data accuracy. This will aid in handling the expected rapid increase of catalog sizes, which result from the launch of constellations and the progress in radar sensitivities[28].

Challenges Associated with ADR Spacecraft for Debris Capture

At the beginning of environment remediation, several points need to be addressed[29]. Those include where the most critical region for the remediation is, the short and long-term objectives of the mission, what debris should be removed first, as well as how to carry out the operations.

An end-to-end ADR operation has various parts such as launch, ground support, propulsion, proximity operations, rendezvous, docking, as well as deorbit or graveyard maneuvers[29]. When it comes to cost, several ADR systems per launch or secondary payload design are better[29].

Central challenges for the removal of debris from LEO that are between 5 and 10 mm are connected to the dynamic nature of small debris and how many of them there are in the environment[29]. When it comes to proximity operations such as guidance, navigation and control, alongside rendezvous and capture/attachment of ADR targets, new technologies are necessary as targets can be noncooperative or not designed for docking. A main issue lies in how a rapid spin or tumble motion of the target can be handled[29]. There is not sufficient data, but the currently available one suggests that several of the ADR targets could have tumble rates larger than 1 rpm. The tumble states of targets and how these states might change can be characterized and determined with the use of ground-based radar or optical observations. New technologies will be necessary to stabilize a target if physical contact with it is needed during removal operations[29].

Lastly, when a target is captured by an ADR system or when it is attached to a device, there are two end results - reentry or a graveyard orbit[29]. There are ADR concepts in which a high altitude target could be maneuvered to a graveyard orbit above 2000 km altitude. However, this is not a lasting solution given the fact that the cumulative debris mass will create an environment issue via collisions in the graveyard orbit. The most optimal end result for an ADR operation is to have the target brought down[29]. The challenges with this option include the necessity of assessing reentry risks and the fact that if a controlled reentry is required, the ADR operational options will be limited and the overall cost will increase greatly[29].

Challenges during the far range and close range rendezvous phases

In order to actively remove a target from orbit, a vehicle has to be placed in the same orbit plane and eventually connect to the body[30]. However, in cases like this, the target is not designed for rendezvous and capture, so it will not have absolute navigation sensors or specific interfaces for relative navigation[30]. It also will not have specific interfaces for capture and physical connection. Moreover, the incapacitated spacecraft could rotate about unknown axes[30]. Therefore, it is of great importance to be aware of the steps needed for a successful capture. The orbital parameters of the target need to be determined from the ground. The chaser needs to be placed into an orbital plane close to that of the target and guided to a range from the target from where relative navigation can begin. The chaser should be close to the target so that it can assume conditions related to position, altitude, and rate that would allow for capture by a mechanical capture device. Following the capture, there has to be a connection between the chaser and target that would facilitate a controlled deorbitation and allow for altitude and trajectory control[30].

The main challenges that need to be mastered are the following[30]. One is how to determine the most optimal distance to the target before beginning relative navigation by sensors on the chaser based on measurements from the ground for position and velocity. A second challenge concerns what types of sensors would be the best for relative navigation measurements between the chaser vehicle and the target, from far range down to a range where it can be captured, when the target does not provide any sensor interfaces. The third issue regards how the position of the chaser can be controlled at a very close range when the attitude of the debris object is not determined and when it is rotating with unspecified rates about unspecified axes[30]. The fourth challenge is how to determine the best approach for capturing an incapacitated spacecraft or another debris object, which was not designed for this or which has fragile structures on its surface like solar panels and antennas. Lastly, it is necessary to consider how a stiff enough structural connection between the chaser and target can be established so that it allows for a controlled deorbitation[30].

Far Range

The range where relative navigation needs to start is dictated by the accuracy of ground measurements and by safety considerations[30]. The target will not provide aids for the rendezvous sensors, so only sensors which can detect the reflections of the surface of the target object or the radiation of the body due to its temperature would be suitable. Also, if no external illumination can be used, the power requirements for sensors without dedicated interfaces will be high. Rendezvous and capture operations with incapacitated spacecraft would be possible if the chaser can offer enough resources to operate a skin-tracking radar with a range of more than 20 km and an accuracy of at least 1% of range[30]. An example scenario of this was with the Space Shuttle on flight STS-51-A in November 1984. Then, the Orbiter retrieved two communication satellites, PALAPA B-2 and WESTAR VI because they were stuck in LEO[30]. The Ku-band radar of the Shuttle weighed more than 130 kg and had a greater power consumption than 400 W in the skin tracking mode; this gave a maximum range of 22 km. Still, the power requirements for such sensors increase[30].

Normally, spacecraft, which cannot return to ground, can operate only in one particular orbital plane without being able to change that plane[30]. Therefore, for each removal, a new servicing spacecraft will be required, which will put financial strains as sufficient resources will be needed to support a heavy and power demanding radar installation for such a range. Moreover, laser range finder and light detection and ranging (LiDAR) type of sensors for ranges of more than a few kilometres would not be of good use as they would lead to problems concerning power consumption and safety[30]. Due to this, there is a gap between the effective range for ground-based absolute navigation measurements and the range from which navigation by laser range finder and LiDAR type of instruments becomes useful[30].

Regarding the far range phase, there have been different approaches for trajectory design[31]. When it comes to cooperative targets, the optimal approaches leverage the experience gained from the Automated Transfer Vehicle (ATV) missions and the Orbital Express and Engineering Test Satellite No. 7 (ETS-VII) demonstration missions. The v-bar approach is mainly used to reduce the separation and rendezvous with the target[31]. When it comes to uncooperative targets, the v-bar approach is not sufficient. Spiralling approaches which use the relative Eccentricity and Inclination (E/I) vector separation have been taken into account because of the inherent independence on the along-track component of the navigation solution[31]. This ensures the security of the trajectory regarding target-servicer collision avoidance[31].

Short Range

When it comes to short range rendezvous operations, they have to bring the chaser into close vicinity of the target[30]. They also need to align the capture tool with the entire target or with a specific feature on its surface. This process could include flyarounds so that the target object is inspected, suitable features for capture are decided, attitude rates are identified, and features that would need to be captured are accessed. For safety concerns, when it comes to ranges from two or three kilometers downwards, there needs to be sustained measurement of relative position or of range with an accuracy larger than 1% of range[30]. In GEO, cameras can be used down to significantly close range (even to contact), yet in LEO, the sensors need to provide illumination so that the measurements over the entire orbit are known[30]. But RF-type of sensors do not provide enough accuracy in close range and the use of cameras comes with significantly high power requirements for illumination of the entire field of view (FOV)[30]. Because of this, for the short range approach, the most optimal choice would be scanning laser range finder or LiDAR type of sensors. During the approach down to the near vicinity of the target, Sun illumination will be enough for the measurements of the sensors. Nevertheless, at significantly close ranges, the body of the chaser vehicle could cast a shadow on the features of the target that will be assessed. In this case, artificial illumination for the camera or a LiDAR type of sensor could be required[30].

Finally, when it comes to short range, disturbances such as the drag of the residual atmosphere in LEO and solar pressure in GEO influence the evolution of the trajectory[30]. Their presence and strength make it necessary for short range trajectories to be controlled first by mid-course corrections and then by a closed loop control[30].

Potential Solutions

Application of Artificial Intelligence (AI)

As evidenced by the contents of this paper, current measures in place for space traffic management are reliant on human experts to determine whether an event is high or low risk, as well as to decide a maneuver approach to avoid conjunctions[32]. Nevertheless, this is a time-consuming task for satellite operators, especially with the increase in space objects, which includes active satellites and debris. Wrong classification, human error,

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and difficulties in pricing of insurance premiums are possible outcomes given the complexity of the assessment of the risk exposure. These issues could be addressed through the adoption of AI and cognitive technologies. The company Neuraspace strives to improve space traffic management through data fusion, AI and machine learning, and maneuvering automation[32]. One aspect of their innovative approach includes producing self-learning software to aid operations teams. The second aspect is examining various data sets from distinct sources fused into one Data Warehouse in order to evaluate risk exposure and reduce the rates of false positives and false negatives. This will result in action being taken only when necessary given the significance of the risk exposure[32]. The third point is introducing automated classification of events which will ensure that time is spent solely on cases of high risks. The fourth aspect is automated analysis and optimisation of potential maneuvers and their costs. This will be outlined based on strategies that align with the needs of operators and the requirements of each mission. The final point is autonomy of satellites and objects in orbit. With all of these measures, the goal is to ensure a sustainable space environment and the autonomization of space activities[32].

Solar Radiation Pressure and Solar Electric Propulsion

The use of electric propulsion has been explored in great detail because of its propellant use, which has been showcased by missions like Deep Space 1, Hayabusa, Dawn, and Hayabusa2[33]. Electric propulsion enables time-consuming trajectory maneuvers. However, they are propellant-efficient. This is especially useful for small spacecraft since the mass budget is limited in those cases. Low-power ion thrusters for use in small spacecraft have also been developed. Besides this, in the past ten years, there have been propositions regarding deep space exploration missions by small spacecraft using electric propulsion[33]. Overall, solar electric propulsion (SEP) has had a grand impact on the design and economics of communications satellites[34]. Its initial use was connected with station-keeping operations of geostationary satellites. However, now SEP has been adopted for orbit raising, either in collision with a chemical propulsion system or exclusively by electric means[34]. Moreover, SEP has become important regarding the deployment of large satellite constellations into low earth orbit due to its capacity to reduce the mass to orbit and correspondingly increase how many satellites are carried during a single launch. So in the context of STM, it would be important to explore the role of solar electric propulsion in collision avoidance maneuvers given how it offers high propellant utilization efficiency[34].

Going more specifically into collision avoidance maneuvers, they are performed using the satellite's propulsion system[35]. However, without propulsion, orbital maneuvers can be achieved through solar radiation pressure (SRP) and drag. The maneuver is done through the orientation of the satellite such that the merged effect of both forces adds up to ensure the change of the semimajor axis from the nonmaneuver case[35]. This has been studied, and there have been various works that focus on the design of spacecraft with large solar sails. More recently, there have been proposals to use SRP for formation control of Earth satellites; drag was also explored with work in the formation flying field[35].

Drawing Inspiration from Collision Avoidance Systems for Swarms of Drones

In this section, the methods from collision avoidance systems for swarms of drones will be explored given that they could serve as inspiration for potential innovations in STM. When considering navigation in a swarm of drones, two main issues arise: the formation and maintenance of the swarm and collision avoidance[36]. With collision avoidance, the attention is put on path planning of the individual drones in order to mitigate conjunctions between the drones, as well as between the drones and other objects in the environment. However, the location of each drone is defined with reference to the drones in a formation[36].

Another proposed approach in the field is energy-efficient formation morphing for collision avoidance (EFMCA), which merges formation control and collision avoidance to enable autonomous swarm navigation[37]. For this idea, a novel algorithm, which consists of two feedback-based algorithms for formation control and collision avoidance, is developed. Collision radius and formation distance make up the feedback for the controller of each drone, with the end result being the minimization of differences between observed and reference values[37]. The angular error, which is the variance between the required and observed angle, showcases how much the node should turn in order to keep its position with respect to its neighbor. On the other hand, the distance error, which is the variance between the measured distance from the reference distance, showcases how much and the way the node should move with respect to its neighbor[37]. Furthermore, if there is no feedback by the on-board sensor system, this means that there is not an external object in the surrounding area and that the algorithm conserves the formation through dynamic checks and adjustments of the distance of the drone to its neighbors. The distance should be larger than the collision radius, yet not vastly different from the pre-specified formation distance[37]. Finally, when an obstacle is detected, the algorithm increases the priority of the collision avoidance aspect; this aspect normally gets the largest priority when the unmanned aerial vehicle (UAV) gets close to the minimum safe distance from an obstacle. Once the obstacle is passed, a Failsafe/Fault-Tolerance check is implemented to ensure that the UAV has connection with its leader[37].

Finally, there are some other approaches for UAVs that need to be outlined. One includes using artificial potential fields (APFs)[38]. They are applicable due to their simplicity, computational efficiency and straightforward trajectory generation. The APF algorithm can be equated to a magnetic field where the neighboring drones can each be considered a repulsive magnet and the desired target – an attracting magnet[38]. The

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resultant force from the magnets leads the drones to the target without making them come together with one another[38]. To ensure that the drones do not collide, a control barrier function (CBF) was examined. From formation control and guidance, the drones each receive a nominal control signal. In the final step, a quadratic programming problem is put together which reduces the error between the control signal and the nominal control signal that addresses safety limitations from the CBF[38]. These methods serve as examples of the ways space traffic management could become more efficient, ensuring a safe and sustainable space environment. Moreover, they could be implemented simultaneously.

Conclusion

Overall, this paper explores the key aspects of STM and the growth of space objects in LEO. Space traffic is a central issue, especially with the emergence of commercial companies and concepts such as space tourism. Large constellations with a significant number of satellites are expected to be launched in LEO, and the risk of conjunctions increases. However, there are no universal guidelines for how satellite operators should act if a conjunction event is predicted and no requirement for coordination with other operators and agencies[6]. Responses to high-risk conjunctions expect resources from the owner such as tracking resources, analyst attention, fuel, etc., so it is also important to avoid false alarms, which is increasingly difficult given that currently objects are tracked to levels several orders of magnitude larger than them[2]. Therefore, operational decisions and insufficient accuracy of the orbital parameters of cataloged objects and of the orbital propagation are key issues that need to be addressed[28]. The paper highlighted current methods for space traffic management like debris removal, end-of-life disposal, collision avoidance maneuvers, and better SSA, yet there is still a necessity for a universal approach to the issue and better collaboration. Examples of potential methods for improvement are the application of AI and solar radiation pressure and solar electric propulsion. Both are outlined in the paper, alongside the collision avoidance systems for swarms of drones to serve as further inspiration in the field. An effective STM is of great importance, and this paper aims to present the current state of the issue, what is being done, and potential ways in which the situation could be improved upon in the future. The best way to overcome the issue is to ensure efficient SSA and collision avoidance maneuvers, proper tracking of space objects and debris, and end-of-life disposal guidelines.

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