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IDENTIFYING CRITICAL LEO KINETIC SPACE SAFETY ACTIVITIES

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Companies and organizations have proposed best practices for space safety, policymakers are emphasizing the importance of space sustainability, regulators are re-examining satellite licensing conditions, and many member states of the UN COPUOS have endorsed guidelines for the long-term sustainability of outer space activities. In parallel, these organizations and others are engaging in a healthy conversation on the magnitude of the issue, developing proposals for near- and long-term solutions and addressing the challenges of gaining widespread acceptance. Space safety and sustainability have galvanized stakeholder communities, but specific, meaningful solutions remain largely elusive, despite frequent webinars and conferences dedicated to the issue. The authors gathered to examine specific solutions and pragmatic actions to enhance LEO kinetic space safety (i.e., all measures to minimize collision risk for current and future space systems). A forcing function for this paper was the LEO Kinetic Space Safety Workshop held in May 2022 in Lausanne, Switzerland. This event scrutinized individual space safety activities by benefit (positive outcomes for space safety), maturity (readiness of the solution for implementation), and cost (resources required to develop and implement a solution). However, while the authors used this event as a starting point for discussions, we were clearly focused on creating a forward-leaning position paper with specific recommendations for the priority of kinetic space safety activities. This paper focuses on communicating to operators, developers, space agencies, regulators, academia, and others to advance toward a safer LEO environment. It is hoped that this document will serve as a roadmap for prioritizing kinetic space safety activities by the global space community.

I. INTRODUCTION

The growing population of operational satellites, fragment clouds, and massive derelict objects in low Earth orbit (LEO) together create an environment where greater scrutiny on space safety is a must. This situation is complicated by the diversity of stakeholders that are actively engaged in the space ecosystem: international licensing entities, spacecraft manufacturers, satellite operators, commercial businesses, government regulators, and civil & military organizations that leverage space systems. As a result, it is difficult to define universally-acceptable space safety activities that can be implemented globally.

This paper strives to characterize operationally-relevant kinetic space safety[*] activities in LEO by (1) cost, (2) benefit, (3) technical maturity, and (4)

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[*] Kinetic space safety is used here to represent the component of space system failure/disruption attributable to collisions with artificial space objects.

operational feasibility to identify the most desirable space safety activities to encourage/execute.

One way of organizing the comprehensive suite of space safety activities is through the categorical breakdown depicted in Fig. 1. With kinetic space safety as the goal, a top-level distinction can be made between those activities focused on improving our ability to conduct missions successfully in a given collisional threat environment, labeled "Operational Resilience," and those activities aimed at managing the environment itself, which we are calling, "Environmental Stewardship." A subsequent breakdown of operational resilience might then distinguish surviving collisions (Impact Tolerance) from avoiding them (Collision Avoidance). Similarly, the next level for environmental stewardship might distinguish preventing growth of the environment (Debris Prevention) from taking active steps to reduce the environment (Debris Remediation).

Each of these four areas has a distinct effect on the mission-terminating collisional risk profile experienced by any given spacecraft in LEO. Fig. 2 illustrates this risk profile as a function of potential impactor size and indicates the portions of the profile most influenced by each of our four areas of safety activities. Enhancing impact tolerance, for example, reduces risk from small particles, while improving collision avoidance capabilities focuses on the threat from trackable objects at the larger end of the environmental spectrum. Meanwhile, debris prevention (i.e., debris mitigation) and remediation are the only practical means today for managing the lethal non-trackable environment in the middle.

A brief description of the four categories is provided here, and the rest of the paper delves more deeply into the activities within each.

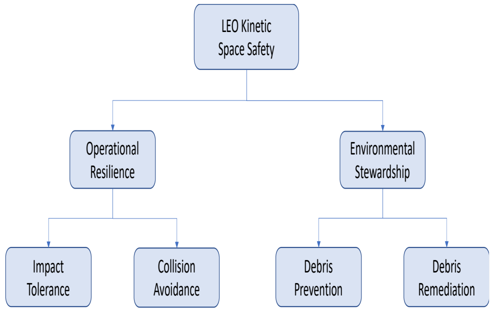

Fig. 1. Breakdown of kinetic space safety activities encourages a balanced approach.

Impact tolerance refers to our ability to design spacecraft to withstand collisions with small-particle debris. This may be the most direct means for addressing the most likely types of collisions in LEO, but there is a practical limit to the amount of protection this technique can afford. Additionally, poor community knowledge of the number, density, and shape of fragments too small to be tracked makes it difficult to know how effective these techniques are in practice.

Collision avoidance is the primary means to reduce the collision hazard from orbital debris large enough to be tracked and is often considered under the larger umbrella of space traffic management. Collision avoidance techniques are largely straightforward but are less effective if not used by all global space operators.

Debris prevention (or mitigation) guidelines have been encouraged globally for over twenty years to limit the creation of debris through safer deployment and operations practices in addition to removing hardware after the end of its useful life. As in life, prevention is almost universally easier than dealing with issues of poor prevention (i.e., an ounce of prevention is worth a pound of cure). However, the success and scope of mitigation

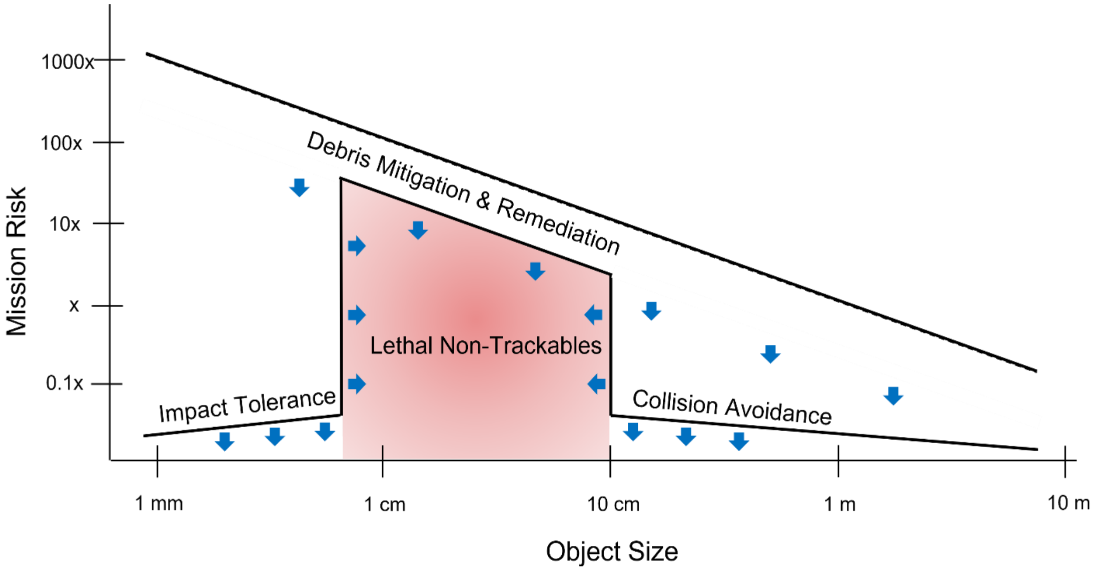

Fig. 2. Each of the space safety activities identified in Fig. 1 addresses the existing risk in a different way.

efforts have been debated much of late to determine how to strengthen mitigation guidelines at the same time as we experience a rapid increase in satellite launches, especially in LEO.

The last line of defense for enhancing kinetic space safety in LEO, debris remediation, is still in its infancy. Active debris removal (ADR) is seen as one of the leading ways to manage the growing debris population by removing derelict objects that both pose a collision hazard to operational spacecraft and represent a potential source of thousands more fragments, both trackable and nontrackable, in the event of a breakup.

Activities in these four categories are examined through the lens of four performance factors: cost, benefit, technical maturity, and operational feasibility. Each of these factors are heavily affected by the time at which their performance is realized. For example, the benefit of active debris removal may be considered very high, but it takes time to realize that benefit while collision avoidance measures provide immediate benefit of a collision averted (or at least reducing the probability of a collision).

Cost and benefit factors often are considered together in classic cost-benefit analysis with the clear positive outcome of favoring high benefit/low-cost activities over low-benefit/high-cost options. Even this apparent clear-cut breakdown has the complications that the costs and benefits may be applied to different stakeholders over varying periods of time. For example, having a very short post-mission disposal metric (e.g., one year versus the current 25 yr) will cost the spacecraft operator immediately but the (uncertain) benefit is accrued by the entire community over a long period of time.

The fourth term, operational feasibility, is included to consider potential political and cultural impediments to realizing the benefits that are not related to technical issues. For example, just-in-time collision avoidance (JCA) is a proposed debris remediation activity to nudge a derelict object out of the way of a potential impending collision with another derelict. Despite any cost, benefit, and technical maturity evaluation, there is some hesitance to embracing this solution as it has many of the major characteristics of a direct ascent anti-satellite mission and, as such, might meet some political resistance.

Each of the four technical dimensions for managing kinetic space safety in LEO will now be covered with a preamble on the importance of stakeholder perspective on this overall evaluation.

II. STAKEHOLDER PERSPECTIVE

An important consideration for recommending kinetic space safety activities is the wide variety of stakeholders who could be affected by collisions in space. They include not only the satellite operator, investors, and insurers that are directly at risk, but also the government regulators and policymakers that take on liability for systems they authorize and the consumers of the data and services being provided by that satellite. There may also be additional stakeholders further down the value chain who are in turn relying on additional products or services derived from the first-tier data and services. It is very likely that all of these stakeholders may not even be cognizant that they are reliant on a particular satellite, let alone aware of the potential risk of interruption to their business or service.

The stakeholder issue is becoming more complicated as a result of the growth and commercialization of the space sector. What was once largely dominated by a few governments and large government-funded programs has rapidly become commoditized as the cost of manufacturing, launching, and operating satellites falls. [1] Many more governments are getting involved in space activities and nearly all are reliant on the data, applications, and services derived from space systems. Those space systems are also increasingly operated by a diverse array of private sector entities, adding further complexity to the stakeholders involved in the system. An example of this is the Earth remote sensing sector, which was originally done by government civil programs but now includes dozens of commercial companies providing a wide variety of commercial products. These products are used not only for commercial reasons but also to support Earth science, climate modeling, and natural disaster response. The growth and complexity of the space sector makes it extremely difficult to measure the full economic impact of space debris and collisions.

Overall, global space market revenues have increased steadily from about $176 billion in 2005 to about $337 billion in 2021, with the vast majority of the growth in commercial activities. Most of the revenues of the commercial satellite industry are generated with satellite navigation (50%) and communication (41%). [2] Reports by Goldman Sachs, Morgan Stanley and Bank of America Merrill Lynch project a $1 to 2.7 trillion space economy in the 2040s. [3] These space-derived data and services support jobs and revenues within the space sector but also provide cost savings and efficiency and productivity gains outside of the space sector. However, it is extremely difficult to get very precise numbers on this reliance, in large part due to the complexity involved. [4]

To deal with this issue, the space community should undertake efforts to engage with the broader set of stakeholders outside the space community on both the reliance on space and the subsequent risk from space debris and collisions in space. Raising awareness around the issue in the broader society could also help create more acknowledgement of the risk among policymakers and trigger policy action.

National policymakers themselves are increasingly focused on the orbital debris and collision risk issue. A growing number of governments have put in place national policies or regulatory frameworks that include orbital debris mitigation and spaceflight safety, and many more are actively discussing policies for potential implementation. For example, New Zealand recently implemented a national space law regime in 2017. [5]

However, policymakers face several key challenges in being able to quickly implement such policies or regulatory frameworks. The first challenge is trying to keep pace with the rapid changes in the space sector, including the aforementioned commercialization. Government processes by nature move slowly, and multilateral, intergovernmental negotiations having even more difficulty keeping pace with that of technology advancements and accelerating launch rates. For example, multiple national space agencies came together through the Inter-Agency Space Debris Coordination Committee (IADC) to publish the first set of international orbital debris mitigation standards in 2007. [6] These standards have only evolved incrementally since then, despite massive changes in the level of space activity and the diversity of space applications being deployed, and a number of trends are not yet even covered by current national policies and licensing practices.

The second challenge is that many of the existing frameworks dealing with orbital debris and collisions, including the IADC guidelines, are voluntary in nature. The increase in number of countries involved in space, and their diverse incentives, rationales, and politics, have made it extremely difficult to develop new, international, binding agreements. Thus, the focus has been on voluntary measures, such as guidelines, norms of behavior, and codes of conduct. While useful in many regards, they also limit the incentive for countries to go beyond the bare minimums and lead to unequal adoption based on national needs and desires.

The third challenge is the lack of solid evidence that can be used as a foundation for policymaking efforts on orbital debris and collisions. While there is a growing scientific literature on the risk posed by orbital debris and many proposed concepts for mitigating it, there is far less literature evaluating those proposals to determine which ones would be the most effective in reducing the risks posed by orbital debris. An example of this phenomenon can be seen in the U.S. Federal Communications Commission’s proposed rulemaking “Mitigation of Orbital Debris in the New Space Age.” The Commission opened the Notice of Proposed Rulemaking (NPRM) in November 2018 to get public comment on a series of proposals for mitigating orbital debris and collision risks from large constellations of non-geostationary satellite systems (NGSO). [7] In the final report and order issued in April 2020, the Commission adopted several additional disclosure requirements for NGSO constellations but avoided implementing requirements on the more substantive proposals, instead deferring judgment on those to a further NPRM. That subsequent NPRM remains open more than two years after the initial ruling.

This issue needs to be addressed urgently as part of the increased stakeholder engagement discussed above. It is our hope that this paper will accelerate the process of bringing the technical and scientific community together to assess the current state of knowledge and existing gaps and forming that knowledge into a set of coherent recommendations that policymakers can implement. The technical community also needs to identify the remaining gaps in our understanding and work with policymakers to secure appropriate funding to conduct additional research that will address those gaps in a timely manner.

III. IMPACT TOLERANCE

Impact Tolerance is the branch of Fig. 1 that presumes a space asset is struck by another object. The question then is, "What can we do to maximize the chances for the asset to survive the impact and continue its mission?" Obviously, whether an operational asset remains partially or totally functional after such an event is dependent on a wide range of factors. Chief among them is whether critical components are in the direct line of fire or within a cone of collateral damage, but the extent of damage will depend also on the particular impact location, angle, and velocity; the mass, size, and material makeup of the impactor; and the fragility of the satellite's components.

While the quantitative threat an asset encounters will be specific to the particular asset and its orbital environment, the following is true more generally. At some point on the small-particle end of the environment, a satellite will be resilient to impact (see Fig. 2). As we move to larger sizes, a satellite will become vulnerable, and impact(s) may result in functional degradation (e.g., peppering of solar arrays), loss of some capability entirely (e.g., a reaction wheel), or even loss of the whole mission.

The potential for damage and loss increases with impact energy - and therefore impactor mass - but the factors mentioned above can make a big difference. For example, an unlucky satellite could be completely disabled by a particle less than a centimeter across if a particularly sensitive and critical element is struck. Conversely, it is also possible for a satellite to survive macro-collisions, as was the case in 1996 when Cerise, a French reconnaissance satellite, was hit by a piece of debris from an Ariane rocket large enough to be cataloged. Had it struck the satellite's main body, Cerise would certainly have been completely destroyed, but it merely clipped the satellite's gravity gradient boom, and after re-engineering the attitude control system, the satellite was restored nearly to its full operational capability. [8]

In the case of a collision, there isn't much we can do to protect a satellite against a cataloged object, but there are ways to press the left end of the risk profile in Fig. 2 down and to the right. That is, there are techniques available to satellite manufacturers to both minimize the potential for damage when a strike does occur, as well as ones to help withstand minor damage if protection mechanisms are insufficient. These two branches constitute the next level of breakdown from Fig. 1, as illustrated in Fig. 3 below.

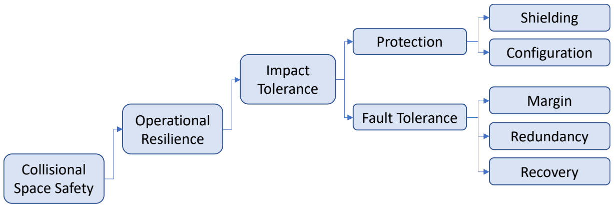

Fig. 3. Detailed breakdown of Impact Tolerance branch of kinetic space safety activities.

Further, within the protection branch, we can include the use of shielding and techniques for configuring the physical layout of a satellite to protect critical components from debris strikes. On the fault tolerance side, we can make spacecraft more robust by increasing performance margins; including hardware and software redundancies; and running fault detection, isolation, and recovery (FDIR) algorithms onboard to monitor and respond to anomalous conditions.

In the following paragraphs, brief descriptions of each of these five techniques will be provided in terms of our four assessment metrics: cost, benefit, maturity, and feasibility.

Spacecraft Shielding

The purpose of debris shielding is to intercept incoming projectiles and either stop them entirely, or to pulverize them as they penetrate protective layers to reduce and spread the subsequent impact loading on interior components. The cost of shielding comes principally in the forms of materials, integration costs, and an associated increase in launch costs related to the mass of shielding added to the spacecraft. Overall, cost is largely proportional to the added mass, an amount which is dependent on the area to be covered and the projectile size being designed for. Similarly, benefit also scales with shielding mass, although strategic placement in order to protect the most critical components from the most likely directions (+/- 60˚ from ram, in the local horizontal plane) will also make for the most cost-effective implementation.

Shielding technology has been developed over decades, extensively tested, and deployed in various forms on many of the world's most valuable space assets. This technique is therefore considered very mature and has limited potential for additional performance improvements. The current limits of shielding protection are in the range of ~1cm debris at hypervelocity speeds at a cost of adding 10-30 kg/m^2 of mass to one's spacecraft. [9] Feasibility is therefore a matter of risk tolerance, budget, and any satellite design constraints that might apply.

Spacecraft Configuration

Configuring the layout of a spacecraft with the debris environment in mind is a very inexpensive means of protecting critical components. When considered early in the design phase, the placement of such components in the interior, or towards the aft end of the structure, can usually be accommodated with only minor implications for other subsystems (e.g., thermal). This technique is not technically complex, so we can consider it to be mature and highly feasible for all but the smallest of spacecraft (which don't have much room to move pieces around!).

Performance Margins

Adding performance margins to spacecraft budgets is one way to mitigate damage to functions that become compromised by small-particle impacts. For example, reductions in power generation caused by the sand-blasting effect of particulate impacts on solar arrays can be overcome by overdesigning the power system. This obviously carries a cost proportional to the margins desired, but this is an effective way to mitigate the effects of the small end of the debris risk profile and requires no new technology development. Feasibility is a matter of being able to absorb the cost, size, and weight implications of the additional margins.

HW and SW Redundancies

Incorporating functional redundancies into the design of one's spacecraft is another effective way to mitigate the effects of impact damage. Redundancies can be of hardware or software and can be on hot or cold standby. The cost of implementation includes the direct cost of redundant components, the secondary costs (e.g., launch) associated with any added mass, and the cost of any software development needed to manage failover processes. The benefit of including redundancies over simply adding margins is that the spacecraft can overcome the complete loss of a component or function, and it can do this regardless of whether the loss is caused by debris impact or some other failure. Adding redundant components is a well-trod path, so this technique is very mature, carries little technical risk, and is relatively straightforward to implement. The feasibility is really driven by cost. Low-budget, small-scale development efforts will likely adopt a single-string design approach, whereas larger, more expensive development programs are more likely to be able to afford this type of mitigation.

Fault Detection, Isolation, and Recovery

An FDIR system provides a way for the satellite to self-monitor health and status of its various functions and to take corrective action when conditions stray from nominal. FDIR algorithms are not new, but they are unique to a satellite platform (if not mission), so there is some development cost associated with this technique. It can be an effective way to react to impact damage, although to work around permanent damage, FDIR algorithms will often have to work in conjunction either with some performance margins or component redundancies to restore functionality. In terms of implementation feasibility, most satellites already plan to have some form of FDIR processing onboard. Feasibility, effectiveness, and cost are really a matter of the sophistication of the algorithms used and the onboard resources one has to work with.

Overall, techniques for improving impact tolerance are fairly mature, technically straightforward, and very cost-effective against the portion of the environment that dominates kinetic threats to mission operations - the lower size end of the spectrum. Compared to other branches of activities depicted in Fig 1, the cost of implementation is modest, particularly in light of the fact that the debris population increases dramatically with decreasing size. Therefore, a small improvement in the risk profile on the left side of Fig. 2 affords a substantially outsized benefit to space safety. In addition, improvements to impact tolerance may contribute to better post mission disposal compliance.

IV. COLLISION AVOIDANCE

One of the avenues to achieving flight safety and sustainability is by conducting collision avoidance between pairs of active spacecraft, or between an active spacecraft and debris. The risk of collision has increased greatly in the past two decades as the number of active spacecraft and the number of debris objects occupying certain orbital regimes (altitude vs inclination) have led to a five-fold increase in close approaches in the last five years alone. [10] Large-scale fragmentation events stemming from preventable collisions underscores the need for improvements in this area. Additionally, although condemned as a practice, ASAT testing and other debris generating events that are “planned” (and avoidable) will need to be considered as debris proliferation that must be factored into planning, sizing, and processes when conducting collision avoidance.

Collision avoidance processes require conjunction assessments that produce decision-quality results that are comprehensive, timely, transparent, readily available, and standardized, and that service all orbital regimes. Yet despite recent advances in global SSA capabilities to track space objects, we are still unable to track Lethal Non-Trackable objects (LNTs) ranging in size from perhaps one to five or ten centimeters. Collision avoidance processes face many technical and policy challenges because they rely on an entire chain of elements spanning the SSA system, policies, sensors, data aggregation, spacecraft metadata, owner/operator process maturity and analytics, and a failure in even a single element of that chain can cause the collision avoidance process to fail.

Enhance communication globally

Spacecraft operators have been largely proactive in sharing their space data (including their positional information or “ephemerides” and planned maneuvers), directly with one another when conjunctions arise, and more broadly on existing space data sharing and/or exchanges such as the 18 SDS Space-Track website [11], the Space Data Association [12], EU SST [13], and others. And some operators indicated a willingness to share even more information, to potentially include spacecraft mass and dimensions, covariance, and raw astrometric observations. Seemingly simple steps such as sharing operator contact information facilitates global communication and enhances SSA. Yet for all this progress, much remains to be done. Where observations from a single SSA provider or single sensor are insufficient, the use of data fusion techniques is encouraged to address undersampling, data deficiencies, and coverage or observability limitations. Operators have also highlighted the difficulties of sharing or exchanging space data with operators from certain other countries, particularly Russia and China. [14] A meeting facilitated by the Secure World Foundation (SWF) on the margins of the Paris Peace Forum [15] began important dialogues between U.S. and Chinese operators, and SWF is looking to expand upon these soon. Finally, as LEO continues to be an area of increased economic utility (and, thus, more entrants), additional collision avoidance best practices and standards will need to be developed to help manage the use of this increasingly populated regime.

Space data sharing/exchange formats

Per international policies and guidelines, space operators are encouraged to use existing international technical standards, including those published by the International Organization for Standardization (ISO), the Consultative Committee for Space Data Systems and national standardization bodies. During the course of space operations operators specifically discuss and promote the widespread use of Conjunction Data Messages and Orbit Data Messages in flight safety operations. Further, both message types (the CDM and ODM) are currently being revised and updated so operationally-related discussions help to refine these standards. Establishing a space sharing agreement with the Combined Space Operations Center (CSpOC) is an excellent first step to getting access to data catalogs. However, as this function is eventually transitioned to the US Department of Commerce, it is envisioned that other entities will start to have improved sensing and aggregation capabilities and it will be important to ensure the information aperture is opened fully to allow data sharing of critical items such as propagated ephemerides and maneuver plans [16].

Data sharing is also a critical feature for logging of impact-related mission-degrading or mission-terminating events that relate to impact tolerance and space population modeling that are essential to understanding the priorities for enhancing kinetic space safety.

Activities to improve identification and quantification of imminent collision risk

Today, spacecraft operators use a variety of collision risk metrics, associated thresholds, and procedures to mitigate risk. Several spacecraft operators stated that they use not only the conjunction warnings freely provided on space-track.org, but also augment them by participation in the Space Data Center or subscriptions to commercial SSA services. It has been noted in operational dialogues that some of the key elements of information required to estimate collision probability and resulting risk are often unavailable and, in some cases, had to be estimated or assumed by the analyst such as positional covariance, hard body radius, and miss distance. The European Space Agency's DISCOS Database is a useful source for such information, while other commercial SSA providers have been working to create their own databases. We suggest that such efforts be further prioritized, standardized, and where possible crowdsourced and curated, maintaining a provenance trail for each data element, to optimize the usability and veracity of such data.

Automated collision avoidance

The sheer number of conjunctions that large constellations face highlights the benefit of automated collision avoidance approaches to mitigate collision risk by minimizing human error and enabling a greater data flow rate. At least one operator has an automated process for avoiding collisions with other space objects, which can be viewed as a good approach as long as the automated behavior is communicated to other operational systems with which it interacts. For such automation schemes to be effective, the accuracy of SSA data feeding the analysis must be of sufficient accuracy and timeliness to enable collision avoidance maneuvers [17, 18]. As well, it will be important as more large constellations are launched to ensure that the automation schemes are coordinated to address collision risk scenarios that those operators may jointly face. In order to be scalable, the automation process must address the condition where two active spacecraft that perform automated collision avoidance are conjuncting; what should be the protocol for such a situation?

Enhanced tracking and processing

Recent analyses have shown that the SSA data relied upon by operators for flight safety purposes may not be sufficiently accurate to achieve a system that minimizes the number of collision avoidance maneuvers while maintaining a set level of safety (e.g., maneuver to reduce risk to below say 1E-4). [19] Further, as was shown in Figure 2, our space object tracking enterprise has always had the Lethal Non-Trackable (LNT) gap where sensors are globally not capable of tracking objects that are of sufficient size and mass to severely impact or terminate a mission and, just as importantly, create additional debris (both trackable and LNT). More must be done to deploy and operate sensors and use sensor phenomenologies and data fusion capabilities that, when taken in aggregate, are capable of tracking not only smaller objects, but also allow orbit determination processes to generate high accuracy SSA information in a timely manner.

V. DEBRIS PREVENTION

For nearly fifty years, space industry experts have recognized the need to prevent the generation of debris from space activities. As early as 1978, NASA presented specific recommendations on passivation and end-of-life disposal. [20] Today, industry groups, international organizations, space agencies, and governments around the world have endorsed specific measures to prevent debris, but breakups continue unabated. Debris prevention can be achieved through a number of active measures such as bans on anti-satellite (ASAT) testing, passivation of pressurized systems, end-of-life disposal, and space traffic management.

ASAT test bans

The U.S. government announced its unilateral commitment not to conduct destructive, direct-ascent ASAT missile testing on April 18, 2022. [21] Other countries agreed to support this commitment, including Canada and New Zealand. ASAT tests by China (2007), India (2019), and Russia (2021), as well as the intentional destruction of a U.S. government satellite in orbit (2008) generated over 5,600 tracked debris fragments. Of these, over 3,500 remain in orbit, all from the Chinese and Russian ASAT tests, representing 14% of catalogued on-orbit objects. [All figures in this section are from space-track.org retrieved July 6, 2022] The commitment to not conduct ASAT tests is a simple and efficient measure for preventing debris and should be embraced by all nations.

Passivation of pressurized systems

Pressurized systems on spacecraft include propulsion tanks and lines, battery cells, payload units, and even complete bus structures. These systems can fracture due to fatigue or can be punctured by MMOD and can lead to the catastrophic fragmentation of a satellite. Notable instances in LEO include battery anomalies on several NOAA and DMSP meteorological satellites, which have contributed 780 tracked fragments currently on orbit.

Passivation is commonly performed on satellites in GEO, as that orbit is a limited resource and operators are aware of the threat from fragmentation debris to their high-value assets. Still, several operational satellites in GEO have suffered breakups in the last five years. These satellites are typically at or beyond the end of their operational life, but, as they are still able to generate revenue, operators are hesitant to re-orbit them to the GEO graveyard orbit. In fact, there are currently over 120 satellites in GEO that are kept in operation even though they are beyond their design life, some up to 25 years beyond their specified lifetime.

Launch vehicle upper stages that remain in orbit are typically vented to alleviate stored energy, though residual propellant remains and can have sufficient stored energy to cause breakups. Older stages were not vented and represent a significant ongoing hazard. Fragmentations include those from the U.S. (2650 debris objects still in orbit), Russia (1903), China (737), Europe (380), India (73) and Japan (21).

Post-mission disposal (PMD)

Disposal of satellites soon after the end of their operational lifetime, or autonomously after their failure in orbit, ensures that these objects do not present an ongoing hazard to safe space operations. The 25-yr rule has been a “standard” for 20 years for many nationalities, however, the associated reliability threshold has varied over time and by specific organization. Overall, compliance with both time and reliability parameters by the various national and international requirements, guidelines, and best practices is poor.

Despite poor compliance to the current PMD guidelines, the trends toward a more congested orbital environment with a greater diversity of satellite operators, and more capable satellite technology suggests a need to re-investigate these limits (both time and reliability). Current dialogue has revolved around 1-yr and 5-yr time options with evidence that new electric propulsion (EP) systems can enable this PMD performance with a small mass margin and high reliability. [22] It is suggested that a 5-yr PMD time limit with a 90% reliability is a cogent compromise at this time.

Space traffic management

Space traffic management (STM) currently includes collision avoidance during launch and on-orbit operations. The primary source of collision data messages (CDMs) has been the U.S. Space Force (USSF) 18th Space Defense Squadron (18 SDS), using their Space Surveillance Network (SSN). As the USSF focuses their attention on critical national security missions, they have supported commercial space situational awareness (SSA) data providers in the dissemination of CDMs to satellite operators. Indeed, some of these providers have deployed their own sensors to enhance the timeliness and accuracy of CDMs. These CDMs can be further enhanced with sharing of ephemerides and maneuver data by satellite operators. Some operators are reluctant to share such data, due to competitive or national security concerns. Demonstrating the importance of data sharing can allay such concerns and contribute to debris prevention. The 2009 collision of the active Iridium 33 satellite and the derelict Cosmos 2251 satellite generated over 2,300 tracked fragments, of which over 1,000 remain in orbit 13 years later, presenting a persistent collision hazard. [23]

Looking ahead

Debris prevention requires specific and intentional actions by space operators. Space agencies, legislators, industry groups, and even insurance companies can collaborate to insist on requirements for preventing debris generation. The issues discussed above represent a small subset of the threats and opportunities in debris prevention.

VI. DEBRIS REMEDIATION

Debris remediation comprises all activities that enhance kinetic space safety by removing the collision risk from debris already abandoned by space missions. As such, the immediate observation is that poor debris mitigation performance makes debris remediation solutions even more critical, and poor debris remediation, in turn, increases pressure for effective collision avoidance. Figure 4 outlines how debris remediation (lower half of figure) relates to debris mitigation/prevention and collision avoidance (upper half of the figure).

Above the horizontal line, debris mitigation and collision avoidance are under the purview of operators executing their missions. Below the horizontal line, the general categories of debris remediation (i.e., active debris removal (ADR), sweeping up fragments, nano-tug, and just-in-time collision avoidance (JCA)) are detailed from left to right.

ADR solutions are being developed and tested by several entities such as ClearSpace, Astroscale, and others. [24] This work has shown the clear (but delayed) benefit to space safety from the removal of massive derelict objects and the technical maturity of these solutions is fairly high (at the subsystem level) but not yet fielded operationally. Further, many studies show that

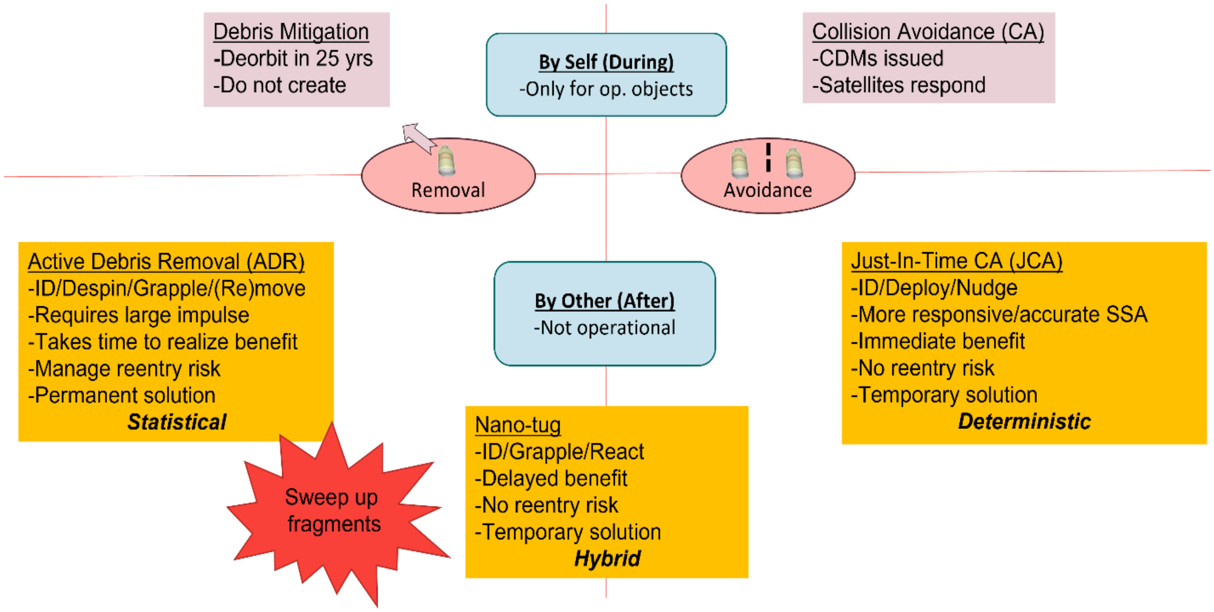

Fig. 4. Debris remediation is about reducing the risk of debris already abandoned on-orbit from affecting the safety of operational space assets.

the current LEO environment has already reached a point where the debris population is unstable, and growth will continue in spite of implementing the commonly-adopted mitigation measures. Remediation measures, such as ADR, should be considered to stabilize the future LEO environment. [25]. The permanence of the solution (i.e., will not have to act on the same object more than once) is a positive aspect relative to the other remediation options, however, it is a process that is complicated by the target's mass, tumbling behavior, and external physical configuration (e.g., a cylindrical rocket body might be easier to grapple than a payload with large solar arrays).

Although it is difficult to predict which debris objects will collide in the future, removal of a few higher-risk objects per year reduces the potential for LNT generation and the burden of collision avoidance [26]. Large debris in crowded orbits whose consequences are significant are proposed as the most cost-effective candidates for remediation [27].

Not all collisions can be prevented by a few derelict removals, but it is necessary to evaluate how much risk can be reduced and at what cost in order to get consensus on the overall value afforded by ADR. This also includes consideration of the potential risk created when approaching and capturing debris objects in crowded orbits. This can be managed by improving our knowledge through the accumulation of observation data on the attitude and rotational dynamics of targets and how environmental exposure might affect the integrity of a target and complicate the safety of capture operations.

It is likely that the benefit of ADR will be increased if the result of an ADR mission is to immediately deorbit the object, not just moving it to an orbit compliant with the 25-yr rule. However, lowering the orbit to a 25-year lifetime orbit would still be effective in reducing the predicted collision rate of crowded orbits and suppress collisional cascading [28], while the cost to require controlled reentry is significant. Large objects intentionally abandoned in orbit were originally left to reenter the atmosphere randomly, so leaving them to do so after reducing their orbital lifetimes would still be an improvement.

Sweeping up small debris fragments has been proposed but the cost is very uncertain and likely very large while the technical maturity of such solutions is very low. Rendezvousing with each fragment is impractical, so proposals for direct remediation of small debris typically employ sweeping techniques in which spacecraft are designed to capture particles through high-velocity impact absorption. [29]

The concept of a nano-tug is to attach a small system (e.g., a 6U cubesat) to a large derelict object, such as a spent rocket body. [30] Such a nano-tug might include a GPS receiver, accelerometers, and several electric thrusters resulting in a system that provides the capability to sense the dynamic motion of the rocket body in order for the thrusters to stabilize the rocket body and then the GPS receiver can determine its location. Further, if a collision avoidance maneuver is deemed necessary, the electric thrusters may also be used to perform an evasive maneuver.

Just-in-time collision avoidance (JCA) will require exquisite knowledge of the conjuncting objects and a global network of launching systems to deploy super-fine particulate clouds to impart a small impulse to one of two massive derelict objects in order to reduce the probability of collision. [31] This “nudging” might also be done by a laser (either ground-based or space-based). JCA, with all of the infrastructure in place, could be very responsive but this would be a costly endeavor with only a temporary effect as the large derelict objects reman on orbit. [32]

In conclusion, ADR should be seen as the primary means for remediation of the space environment and it is hoped that the three major spacefaring countries that have contributed to the bulk of the massive derelicts in LEO (i.e., the US, Russia, and China) will become active in this capacity to supplement the leadership shown by JAXA, ESA, and ESA in funding and pursuing ADR efforts.

Further, it is recommended that a joint effort by these three countries would serve to catalyze the ADR industry that has been jumpstarted by studies and initial service contracts by JAXA, ESA, and the UKSA. [33]. In addition to ADR, it is proposed that nano-tugs are the best complement to ADR for debris remediation.

The technology maturity is moderate and the political headwind to their use is likely less than for JCA and has lower technical risk than proposed fragment sweepers. It is suggested that nano-tugs might be optimally applied to the most massive objects located in the highest orbits.

In addition, the benefits of nano-tugs are measurable and immediate though temporary in nature since the nano-tug will have a finite lifetime.

VII. CLOSING COMMENTS

Figure 5 summarizes the critical recommendations for the four kinetic space safety categories These are not meant to be comprehensive but rather identify key efforts that need further emphasis.

The authors propose that all four of these categories of kinetic space safety activity are important; this balanced approach to attacking each of these dimensions is a major observation of this examination. While none of these suggested activities individually are novel, this collection of technical/policy directives provide a compelling framework for a comprehensive response to improving kinetic space safety in LEO. One of the key impediments to gaining momentum in adopting these space safety activities as norms is that frequency and severity of the possible massive collisions between derelicts are uncertain. Indeed, the most likely event to occur is likely to not be the next event to occur due to the flat probability distribution function of these events (i.e., there are many moderate probability events, not a few high probability events and many low probability events).

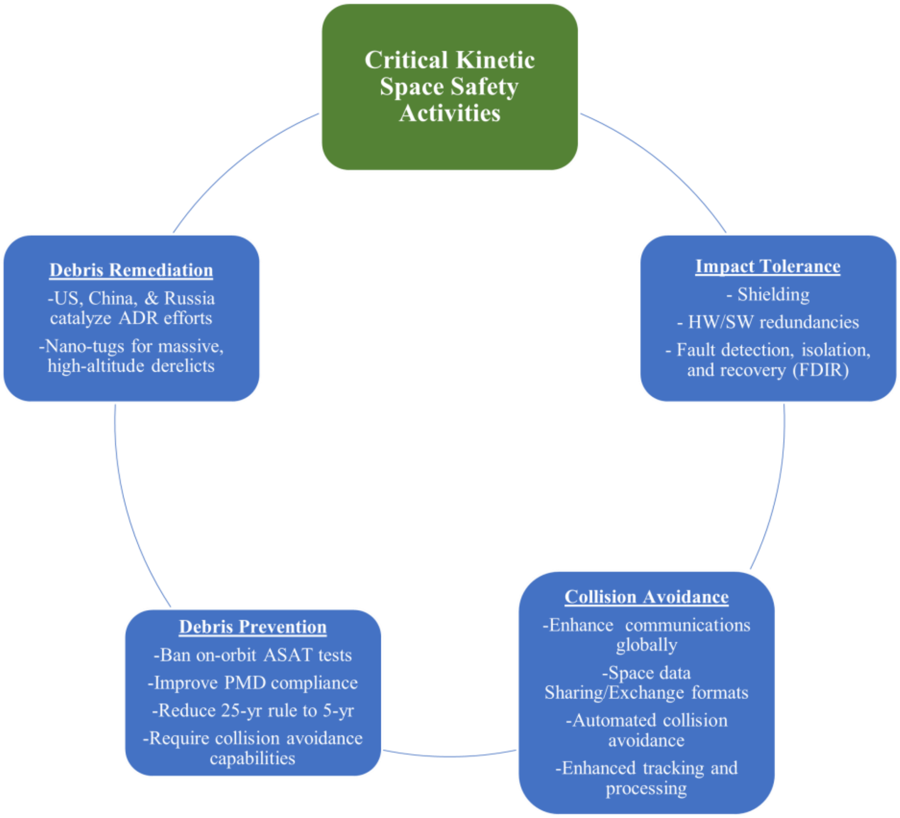

Fig. 5. The priority kinetic space safety activities provide a roadmap for immediate action by commercial, civil. and government organizations.

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