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A re-examination of the space debris problem using systems thinking

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Abstract

Artificial satellites have enormous advantages, resulting in a massive increase in launches. As of January 2022, approximately 4852 operational satellites were orbiting Earth, assisting humans in communication, technology development, space observation, and earth science. Among the cataloged objects in space, only 20% are operational satellites, with the rest being debris. This debris poses a danger to active satellites and limits the orbital space for new satellite launches. These non-functional, fast-moving debris pieces may trigger collisions and potentially create new fragments of space junk. Most countries striving to exploit outer space have neglected the long-term consequences as explained by the tragedy of the Commons archetype. This study examines how the space race led to the specific issue of orbital debris using a systems thinking approach. Using counter-intuitiveness, causal loop diagrams (CLD), systemigrams, and archetypes as systems thinking methods and concepts to explain the space debris challenge. The systems thinking tools used in this study attempt to highlight the current space debris problem and the lack of a clear policy framework to mitigate the severity of the problem. Even though many private organizations and some space agencies are conceptualizing ideas to remove debris from space, the major issues in resolving this problem are time, cost, and uncertainty. Our findings highlight the importance of addressing the issue at the technological, system engineering, and policy levels.

Keywords: Space debris, systems thinking, causal loop diagram, systemigram, archetypes

INTRODUCTION

Space debris, also known as space garbage, refers to artificial, defunct objects that have accumulated in near-Earth space and are orbiting and potentially colliding but are not useful for human purposes[1,2]. These objects include decommissioned, malfunctioning, and damaged satellites, as well as some of the spent rocket stages, *etc.* This orbital debris has become a threat to new launches and a hazard to active satellites in space, and it continues to occupy precious orbital resources[3-5]. Before the launch of satellites in the first half of the twentieth century, everyone thought space was such a vast expanse that any number of launches could succeed. Space debris has become a major challenge for satellite-launching countries; these debris pieces occupy precious orbital resources and also pose a significant threat to active satellites in space[6-9]. No nation could have predicted that space would become a garbage dump, but the situation has quickly escalated into an uncontrollable crisis[10]. In recent years, the number of launches to harness the benefits of space technology has increased dramatically. With a 29 percentage increase in 2021 over 2020, the number of successful satellite launches was the highest in the history of the space race[11]. Over the last 60 years, more than 30,000 pieces of debris, totalling 9300 tonnes, have been trapped in Earth's orbits, posing a serious threat to all active satellites in space[12,13]. Many studies reveal that the lower Earth orbit (LEO) region has already reached its critical density, making it difficult to allocate an orbital slot for new launches[14]. This LEO region will probably be filled with tiny debris objects due to collisions between debris objects. Although atmospheric drag helps us to withdraw debris fragments from space, planning new launches will be difficult in this orbit in the coming years[15-17].

Along with the numerous benefits these satellites can bring to improve the quality of life of human beings, these satellites also cause non-beneficial aspects such as increasing geopolitical tensions, violence intensification, destruction of satellites, *etc.* The recent Russia-Ukraine conflict has increased geopolitical tension, and Russia has announced plans to leave the International Space Station (ISS) before 2024. If the appropriate corrective actions are not taken, this will have a long-term negative impact on ISS maintenance[18]. These kinds of threats will affect future collaboration, research projects, funding for space activities, *etc.* Additionally, a nation's navigation and communication systems will be impacted by cyberattacks on satellites, making them more vulnerable to intrusion[19,20]. Despite numerous efforts, debris removal remains a major challenge for national and international space agencies, with the presence and lack of traceability of small debris parts posing new challenges. Many previous studies have attempted to examine the difficulties that space debris removal programmes face. Some studies have mentioned the lack of international space rules and agreements[21,22], inefficient debris removal technologies[23], insufficient debris-catching mechanisms[24], financial constraints[25], and design limitations[15] as the main obstacles to developing successful space debris removal activities.

Policy recommendations are influenced by the economic constraints in handling space debris. The following are some research findings from an economic management perspective. Using analytical models, Macauley[26] investigated how different economic and financial benefits would affect various strategies for debris mitigation. However, a lot of assumptions were taken into account for this study, and the uncertainty and probability distribution functions affecting the process of grave yarding had a big impact on the strategy for clearing out the debris. Zhu *et al.* tried to calculate the break-even costs of sending satellites into space, considering the costs of avoiding costs of orbital debris collisions, costs of space preservation, early replacement costs and commercial benefits obtained from satellites, *etc.*[27]. To determine the efficacy of mitigation and remediation options, this study conducts sensitivity analyses. If spacefaring communities comply with them as soon as possible, post-mission disposal (PMD) with a 90% success rate and the active removal of no more than five retired spacecraft annually will be sufficient and effective space preservation measures. They draw attention to the drawback that the timing and phases of global mitigation and remediation practices are dependent on the results of break-even analysis. Klinkrad[28] discussed space debris models and the risks associated with risk analysis because of the space debris environment that exists now and in the future. Shan *et al.* reviewed and compared active space debris trapping and removal techniques; this study broadly classified the space debris mitigation strategies into two categories, space-based and non-space-based[29]. This study also discovered that developing active debris removal strategies are difficult due to many technical and economic difficulties in capturing and removing a tumbling target or a space debris object with unknown physical properties.

Keeping the emerging problem in mind, this study uses a systems thinking approach to explain the root cause of the space debris problem. It is more of a philosophical approach than a set of tools and techniques. It entails taking apart and reassembling a problem to fully comprehend its components and feedback relationships[30]. Therefore, this article examines the policy gaps in addressing the problem of space debris and offers suggestions on how the global community can close these gaps. The article looks at orbital debris, the current legal system and policies surrounding it, as well as solutions to the issues with those systems that have been brought to light. The visualization and simulation are created using the Stella simulation software. Stella is a widely used system dynamic modelling tool that helps to develop conceptual diagrams and run simulation models based on the data[31].

Systems thinking approach and defining the problem

Figure 1 depicts the systems thinking approach to analysing the system and its dynamics. It restructures the problem to identify the system's causal relationships. The feedback loops are used to outline the component causalities. After the loops have been developed, the system's dynamics are learned by observing how the system reacts to changes in internal and external conditions. The effective application of the systems thinking approach will not only provide a clear understanding of the system but will also allow for the prediction of future problems and the explanation of past ones. Systems thinking is based on a circular understanding. It aids in the comprehension of the unintended consequences of our actions[32]. We want to understand the origins, progress, and future of the space debris problem by applying systems thinking concepts. We explain the source of the problem and make several policy-based recommendations at various technical and social levels using systems thinking concepts such as causal loop diagrams (CLD) and systemigrams.

Statement of the problem:

Intuitive Statement

▪ More satellites must be launched to support societal and economic development in space, and their orbital safety and stability are critical for their long-term operation.

Counter-Intuitive Statement

▪ Despite the allocation of a safe orbit for each satellite by the internationally authorised system, the threat to the safety and stability of the active satellite is increasing due to space debris.

RECENT EVENTS IN SPACE DEBRIS GENERATION

The recent geomagnetic storm that occurred in February 2022 caused catastrophic damage to Starlink's 40 satellites, as per official reports[33]. Although the company SpaceX stated that there is no threat to active satellites in the low Earth orbit due to Starlink's dead satellites, still the condition is unclear and uncertain,

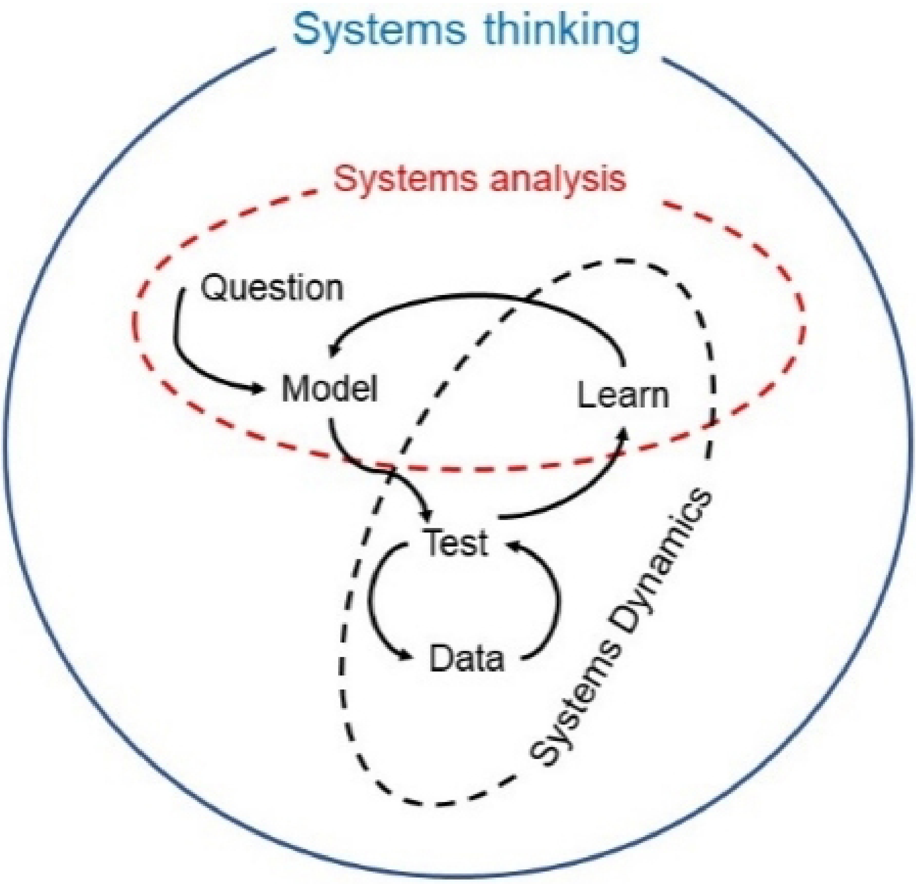

Figure 1. Systems thinking concept.

resulting in a financial loss of more than 20 million USD[34]. The anti-satellite tests in recent times have also increased the number of debris in space. In the ASAT process, an active satellite or rocket physically collides with target satellites (mostly defunct or dead satellites) to alter the satellite's course or destroy it, scattering numerous tiny pieces of debris in the process. On March 27, 2019, the India Space Research Organisation (ISRO) conducted an anti-satellite (ASAT) test on its defunct satellite Microsat-R[35]. Although ISRO officials stated that the debris fell back into the Earth's atmosphere within 45 days of the test, more than 400 pieces of debris were produced. NASA strongly criticized the attempt because this experiment significantly increased the risk of collision with the ISS by 44%[36]. China, the United States, and the Soviet Union have all conducted ASAT tests, with the resulting debris fragments threatening the functioning of the ISS and other active satellites in orbit. Table 1 presents the details of ASAT tests performed by various countries.

The effects of these anti-satellite tests limit orbital capacity because debris has become a permanent threat to active satellites, and the operational satellites in outer space face significant risks due to the high velocity and momentum of these debris pieces[43]. These objects may collide with each other and with active satellites, potentially causing an exponential increase in space debris[44].

Impact of Space debris

When debris collides with an active satellite, the active satellite may cease to function and turn into debris, but this is a rare occurrence that depends on the size, velocity, and condition of the colliding object (debris)

Table 1. List of anti-satellite tests conducted by different nations

Country	Mission name	Year	Target satellite	Source
Soviet Union	Orbital ASAT	1963-1971	Soviet satellites	[37]
USA	US ASAT	1985	American satellite	[38,39]
China	SC-19 ASAT	2007	FY-1C Chinese weather satellite	[38]
USA	Operation Burnt Frost	2008	USA-193	[40]
India	Mission Shakti ASAT	2019	Microsat-R, Indian satellite	[35,36,41]
Russia	Kosmos 1408	2021	Kosmos 1408	[42]

and the size of the active satellite. After each impact, a debris cloud (sometimes a small one) is spread and distributed to different orbits, which may be close to or further away from the object impacted, depending on the impact energy. NASA, ESA, and JAXA data on previous launches and space debris statistics provide insight into the current issue. The debris in orbit (1/10 mm) is capable of causing optical surface erosion, permanently damaging telescope mirrors, and reducing the efficiency of solar cells[43]. The 1 mm size of debris can cause craters, dents, and pits on the surface of satellites and make them non-operational. An example showing the impact of debris on active satellite can be seen in Figure 2. If the debris is large enough, it can alter the satellite's orientation in space[45]. NASA proposed that satellites' outer surfaces be shielded. To reduce debris impact, the ISS has been shielded with two hard metal sheets separated by 10 cm. If the debris is not removed and preventive measures are not taken, the comforts offered by satellites may not be available due to the shortage of satellites and services[46]. Humanity will be drawn back to the situation that existed 50 years ago.

Using historical space debris data, Liou and Johnson[47] developed a three-dimensional physical model for the evolution of space debris populations [Figure 3], assuming no rocket launches after December 2004 and no future disposal manoeuvres for existing spacecraft . In the next 200 years, an average of 18.2 collisions (10.8 catastrophic, 7.4 non-catastrophic) is expected[40]. In this orbital region, objects of 10 cm and larger triple in size every 200 years, resulting in a 10% increase in collision probabilities. We have collected space debris data from various sources, including the ESA[12] and NASA's website[48], to plot the trend of space debris from 1957 to 2019. The trend line in Figure 4 shows a clear exponential growth of debris in recent years, so there is an urgent need to tackle the space debris issue.

SYSTEMS THINKING CONCEPT IN SPACE RESEARCH ACTIVITIES

Systems thinking concepts are rarely applied in understanding the holistic view of the space debris problem. El-Rashid *et al.* used the closed-loop systems thinking concept to propose a conceptual model called "space vulture", which aims to capture space debris and re-use the materials to manufacture different objects[49]. They have mentioned that engineering-based approaches always think linearly, whereas systems thinking also considers social and cultural implications. Estable *et al.* have implemented systems thinking tools such as loops, federated networks, and operability models to optimise the communication process in developing a complex system for space debris removal[50]. Allworth[13] has mentioned some key techniques for calculating space debris, highlighting the importance of observational curve data. In recent studies, Mark and Kamath[51] and Lewis and Marsh[52] used the deep time analysis thinking concept to determine the long-term consequences of space debris. They predicted that the space debris would continue to grow using natural simulation models and that it has nearly reached its orbit-carrying capacity. There is an immediate need to address this issue by removing the existing debris using sustainable measures and taking a systems approach. Many space debris removal projects remain in the conceptual and experimental phases due to the high cost of production and operations that slow down the feasible and sustainable removal of debris[49]. Madi and Sokolova[53] mentioned in the Space Debris Peril book that space debris removal has many

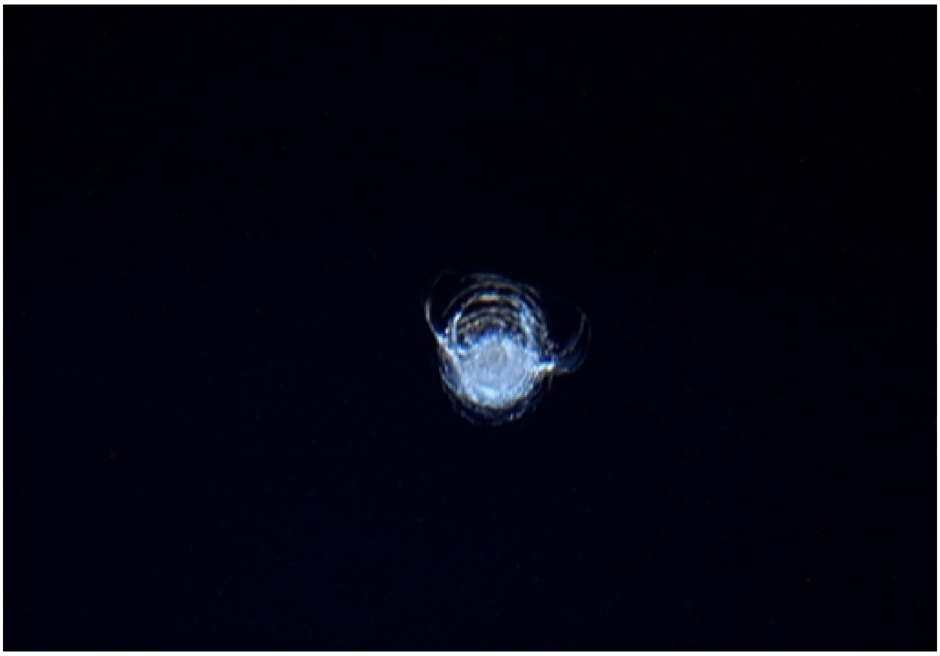

Figure 2. A debris impact chip in a Space Station window (Source[12]).

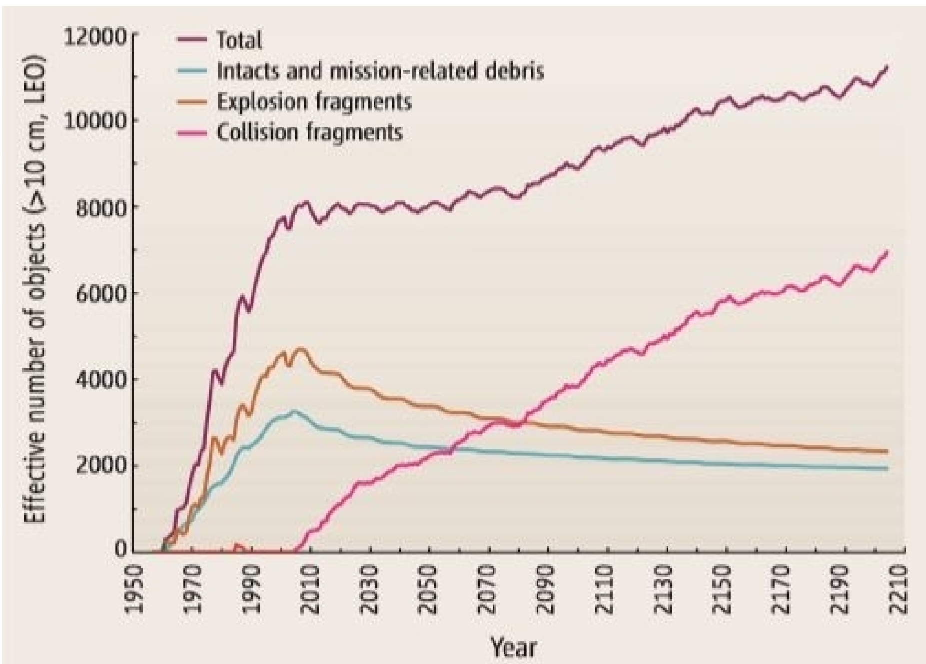

Figure 3. Simulation of space debris growth rate (Adapted from source[47]).

technical challenges and that it is almost impossible to remove tumbling objects and small pieces. Keeping this critical issue in mind, we attempted to provide insight into the current state of the problem and suggest some solutions for space debris control in this study.

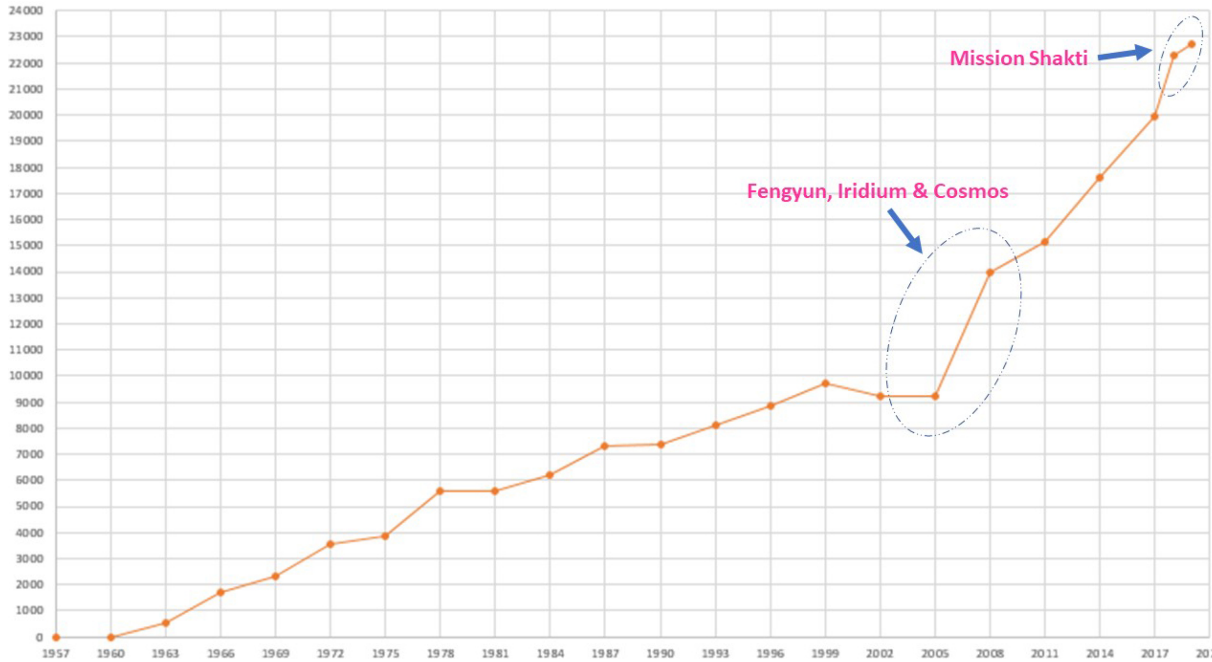

Figure 4. Analysis of Space debris (1957-2019).

Chen[44] investigated the quantity, size, spatial distribution, source, and threat of space debris to satellites. It also discusses how debris formation control is critical for the long-term use of space, including developing debris mitigation measurements, active debris removal, and space traffic control, as well as how debris formation control is critical for the long-term use of space[54-56]. Some studies looked into the current state of the space debris problem and solutions, as well as the technical challenges and scientific difficulty of removing space debris with a pulsed laser system, and recommended that a space-based laser be developed in the future[57,58]. Haroun *et al.* examined policy gaps related to the problem of space debris, such as the lack of an international legal framework, responsibility and penalty for debris formation, and the distinction of debris from space objects, and proposed remedies to close the policy gap, including the application of environmental law concepts to space debris[59]. To emphasise the problem's criticality and urgency, Murtaza *et al.* reviewed the space debris issue, including the causes, quantity, potential threats, and sizes of orbital debris, counter-strategies with their current status, and legal issues[60]. All of th0 concerns and threats were also reviewed, and efforts to meet this challenge have been inadequate until now. Mironov and Murtazov[61] studied the difficulties of monitoring space debris, particularly hazardous meteoroids, clogging near-Earth space using optical meteor astronomy methods. They mentioned that in the next 50 years, space junk will worsen and no further launches into the orbits will be possible. A careful examination of published literature reveals that many authors have suggested conceptual, empirical models for removing the debris, but none of them tried to approach the root cause of the space debris problem using systems thinking concepts. As mentioned in many previous studies[49,52,58], the system approach will provide a holistic view of understanding the problem. We explore the advantages of the systems thinking concept to find out the root cause of this emerging space debris problem.

Understanding the problem using systems thinking tools

Causal Loop Diagram and Archetypes

The interaction between variables and nodes of a system is visualised using a causal loop diagram (CLD)[62]. It completely explains the relationship between the variables, what causes what, and how it affects either positively or negatively, but it does not explain why it happens. It provides a comprehensive view of the system, ensuring that nothing is overlooked. We identified the variables that caused the space debris problem using data from NASA, ESA, and other space agencies. We created a causal loop diagram based on the number of satellite launches, successful and failed launches, and the number of satellites carried by each mission. To create causal loop diagrams, Vensim software is used[63]. The CLD depicts how the various variables interact. The CLDs between the variables will help in the identification of recurring behaviour and the development of archetypes in the system. Archetypes are recurring behavioural patterns that reveal the structures that drive systems[64]. In the systems thinking approach, there are two types of reactions between the variables in a system dynamics. Balancing feedback slows or balances the process to close the gap between the actual and desired states. Reinforcing feedback, like a catalyst in chemical reactions, accelerates the ongoing process. In many cases, the introduction of reinforcing feedback prevents the relationship between the two variables from continuing, resulting in damage or destruction. An archetype is made up of a mix of reinforcing (positive) and balancing (negative) feedback. A balancing loop or self-correcting loop attempts to move the current state to the desired state. An archetype is named based on the number of positive and negative feedback in the system, as described in Braun's study[65]. The overall CLD of the space debris problem is depicted in Figure 5, where two red and two green colour borders explain the existence of two archetypes in the developed space debris system. The limit to growth archetype is represented by archetypes one (1) and three (3), while the tragedy of the Commons archetype is represented by archetypes two (2) and four (4).

The CLD aids in visualising the sequence of events in space launch activities as well as how the debris problem has arisen unexpectedly. Initially, humankind hoped to improve our quality of life with the help of satellites by bringing socio-economic developments such as communication, imaging, weather alerts, networking, geographic information systems (GIS), and navigation systems including GPS. Since the first satellite launches brought significant benefits to humanity, such as radio communication, navigation, investigation of the Earth's magnetic field, and weather monitoring, all nations have begun to invest in satellite activities to reap the benefits of these satellites. Countries competed to launch the most satellites, which started the space race. It was necessary to launch more satellites into orbit to receive greater and greater benefits and gain a dominant position in the space race. However, increasing the number of launches is reducing orbital capacity. To avoid collision damage from other satellites orbiting in space, each orbit has a set number of satellites. These satellites become debris when they reach the end of their life cycle, posing a threat to active satellites. Both the self-removal and external removal methods are expensive because we need to keep enough fuel in the rocket body to move inactive satellites into the LEO region after the completion of their life cycle. For the external removal method, a new spacecraft needs to be launched to remove the current space debris. Since these debris fragments are no longer functional, it is challenging to manoeuvre them into low orbits where atmospheric drag can gradually reduce the orbital energy until they finally reach LEO. These dead parts, spent rocket stages, *etc*., continue to orbit and have the potential to increase the number of smaller, harder-to-observe debris fragments through collisions. The following section explains the archetypes found in the above CLD, which aid in understanding the root cause and severity of the space debris problem.

Understanding the reduction in orbit capacity using Limits to growth

The limits to the growth archetype consist of a reinforcing loop whose growth is offset by the action of a balancing loop after some success. This means that being successful is never good enough to play. Any organisation that enjoys consistent success is overworking its current system. Any system that experiences slowing action as a result of a limiting factor is experiencing growth limits. Figure 5 shows two growth archetypes with their respective limits (1, 3). There is a reinforcing loop between variables "collision

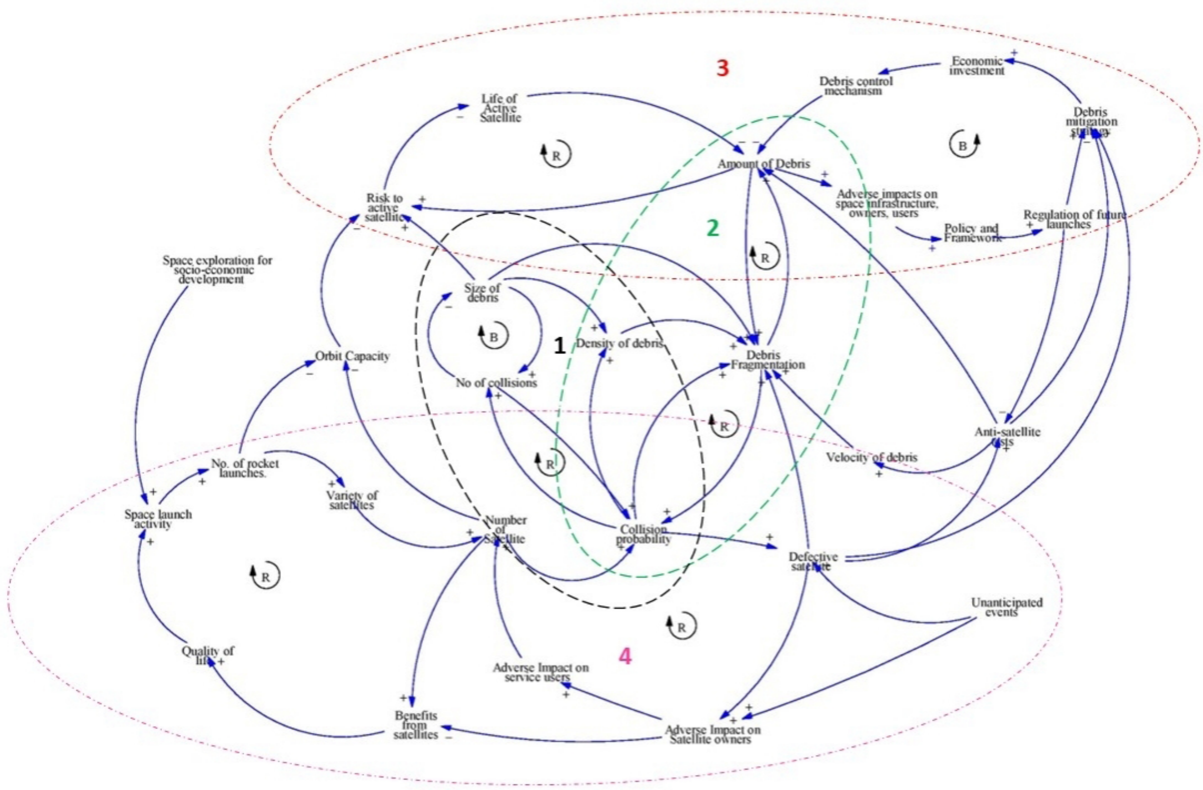

Figure 5. Causal Loop diagram of space debris problem.

probability" and "collisions" in the one (1) numbered archetype. As the collision probability rises, so does the number of collisions. As the number of collisions increases, the collision fragments will collide with already accumulated debris and active satellites, and the size of the debris will decrease to subcritical sizes that would be difficult to label or catalogue[12]. The relative velocity of debris depends on its population[66], its distribution or spread in orbit, as well as the orbital mechanics[67]. This is a balancing loop. As the size of the debris decreases, the number of particles in space increases, increasing the likelihood of a collision. Despite successful rocket technology and capital investments, the presence of growth limits explains why in-orbit capacity is decreasing. Because of the high likelihood of collisions between debris particles, the orbit becomes clogged with these dead objects. Due to the high likelihood of collisions, a new launch of satellites into this orbit may not be possible.

As the amount of debris in orbit grows, the threat to active satellites in that orbit grows as well. The life of active satellites decreases as the threat grows. Active satellites eventually become debris when they collide with debris particles. We began with the assumption that the amount of debris would increase and ended with an increase in the amount of debris. A reinforcing loop is indicated by this. As the number of pieces of debris grows, we'll need more robust and dynamic policies to keep it under control from the start, focusing on existing debris mitigation strategies. Future launches will be governed by policies, such as including a return mechanism once satellites have served their purpose. Otherwise, we must concentrate on debris-removal strategies. All of this contributes to a reduction in orbital debris. We began with the assumption that debris would increase and ended with the assumption that debris would decrease. It indicates that a balancing loop exists. As a result, the growth archetype has yet another limit.

Understanding the debris generation problem using the Tragedy of commons

The phrase "tragedy of the commons" refers to a situation where people who have access to a shared resource (also known as a common) act in their own interests and eventually deplete the resource[68]. This archetype explains how people who want to maximize their gains often end up at the expense of the common good. The tragedy of the Commons archetype has been used in recent years to draw attention to problems with resource exploitation, including air and water pollution, deforestation, climate change, sustainability, *etc.*[69,70]. Researchers identified some underlying causes of issues, such as a lack of coordination, poor communication, and acting against the interests of all users, which can help us better understand social dilemmas. This archetype occurs when two reinforcing loops are dependent on a common, limited resource. The space debris problem is explained by two tragedies of the common archetypes, represented as numbers two (2) and four (4) in the above CLD. The loop between debris fragmentation and the amount of debris is a reinforcing loop. It clearly says that as the number of debris increases, the debris collision rate increases and fragmentation takes place, and vice versa. There is one more reinforcing loop between debris fragmentation and collision probability. As fragmentation increases due to a greater number of smaller pieces, the collision rate also increases. Serial number 4 also emphasizes the presence of a tragedy of the Commons archetype. When the number of satellites increases, it directly increases the number of benefits from the satellites. As the benefits increase, the quality of life also increases. Space launch activity and the number of rocket launches also increase, which ultimately increases the number of satellites in space. We began with an assumption of satellite increases and ended with an increasing number of satellites; this indicates the presence of a reinforcing loop. As collision probability increases, the number of defective satellites in orbit also increases, which causes a more adverse impact on satellite owners and users. The greater the adverse impact, the greater demand for new satellites, and the launch of new satellites will increase the probability of collisions. This indicates a reinforcing loop. This is also explained by the tragedy of the Commons archetype.

The causal loop diagram clearly explains the source of the space debris problem, the number of new satellite launches, orbital capacity, collision probability, and the impact of debris on satellite benefits to humankind.

Understanding the root cause of space debris problem using systemigrams

Systemigrams[71] provide context for complex problems and are an effective tool for systems thinking and practice. Systemigrams are taken directly from the author's writing. They focus on linear thinking and are memoryless[72,73]. Figure 6 shows the systemigram used to explain the root causes of the space debris problem. A systemigram's interpretation usually begins at the top left corner and moves down to the bottom right. The richness of perspectives in systemigram analysis is increased by including multiple viewpoints and participants. To improve the presentation, we used colour coding to group similar items together.

Figure 6 shows a systemigram with nodes representing key concepts and links between them representing relationships. The bottle on the left in the figure shows six different types of legends, each of which represents a sub-family of concepts used to explain the space debris problem. Figure 6 depicts and summarises how the space debris problem exhibits the characteristics of emergence, connectivity between variables, autonomy, belonging, and diversity. Human life has greatly benefited from space exploration, which has improved our communication systems and quality of life. We start with the top left corner of the systemigram; more satellites must be launched to gain more benefits from space. At the end of the 1990s, satellites had an average lifespan of about 8.6 years[74], but due to recent technological advancements, this is now gradually rising to an average of 15 years[75]. It is challenging to generalise the average lifespan of an active satellite because it depends on factors such as orbital position, atmospheric drag, radiation exposure, design, and build quality. New satellites must be launched to maintain existing systems and ensure that the

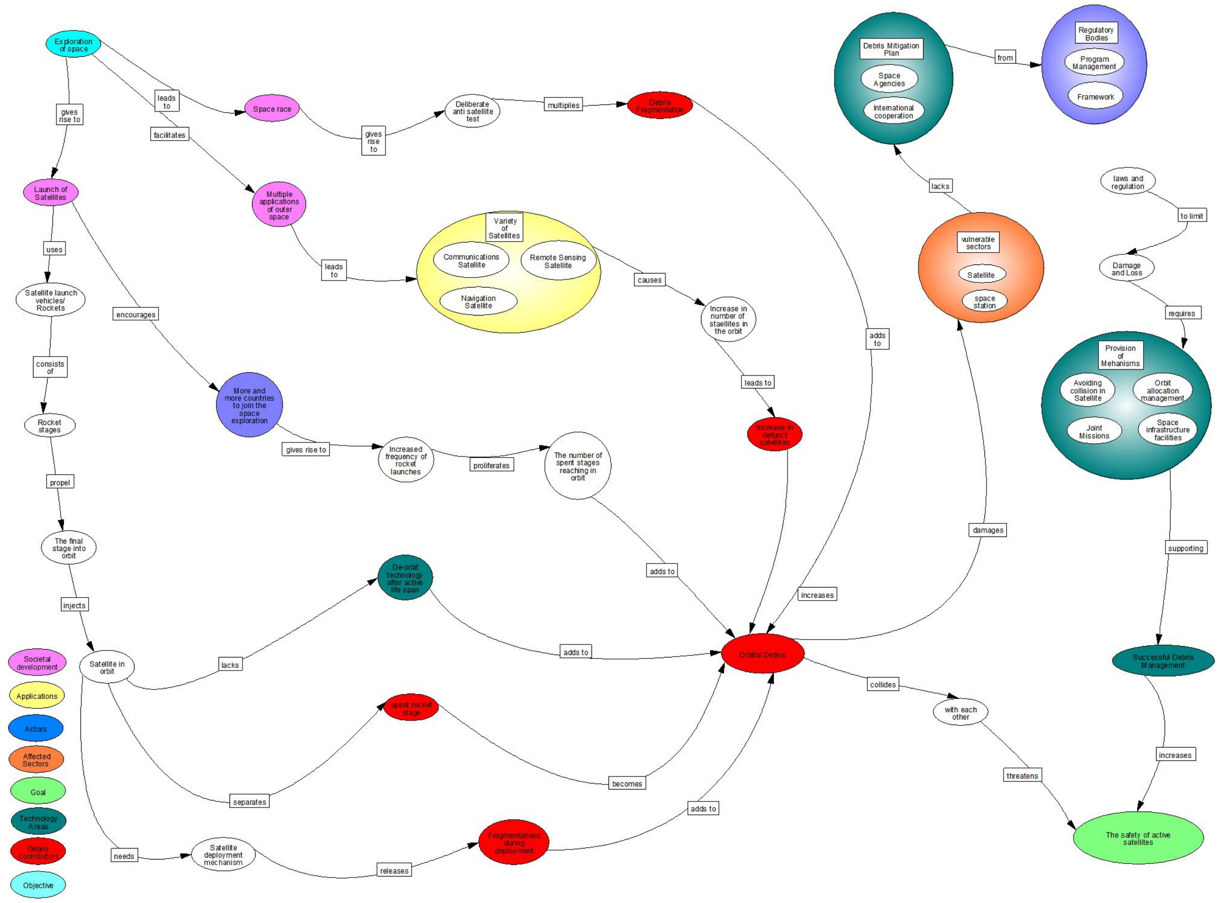

Figure 6. Systemigram of space debris problem (see online version for colours).

benefits of space technology continue to be available. New satellites require orbital space to launch, so if an orbit has slots for positioning the satellite, it can be launched without difficulty. However, the dead satellites, spent rocket stages, mission-related debris, and fragmentation debris orbiting in space pose a threat to new and active satellites. More countries have recently developed satellite launch technologies, and private companies have begun to send people into space via space tourism. The demand for a wide range of applications, such as communication, remote sensing, defence services, weather monitoring, television, and internet access, drove up the number of launches. Uncontrollable satellite launches, contrary to popular belief, have a negative side. The launch of a large number of satellites has resulted in space debris or space junk. Because there is no system in place to remove space junk, all satellites launched to date will become junk in the coming years. The debris collides with active satellites and other debris fragments regularly. These collisions regularly produce tiny debris particles. International collaboration, a clear framework, guidelines, and a future vision are all lacking in the debris mitigation system. Some countries have recently proposed space junk removal plans, but none have proven to be successful. Successful debris management is essential for a long-term space programme. Exploration of space leads to a race between countries in terms of satellite variety, launch rate, and other factors, all of which contribute to the formation of orbital debris. It is clear from the systemigram that the formation of orbital debris is influenced by a variety of factors. Orbital debris is primarily caused by satellite deployment mechanisms, deorbit technologies, and competition between countries for space. Various vulnerable sectors, such as space stations and active satellites, are directly affected by orbital debris. Only through space regulatory bodies and various mechanisms can successful debris management be accomplished.

CONCLUSION

The space race has resulted in the launch of several operational satellites, which are currently providing tremendous benefits to humanity. Many satellites become defunct due to their short lifespans, and there is currently no system in place to remove these satellites from orbit. Satellite ancillary parts such as screws, nuts, bolts, outer covers, rocket bodies, defunct satellites, and debris fragments rotate in orbit with the dead satellites, posing a serious threat to active satellites. The threat of debris and reduced orbital capacity are making it more difficult to launch new satellites as explained by the reinforcing loop in the limits to growth archetypes [Figure 5]. Debris removal is being delayed due to a lack of clear laws, rules, and regulations, as well as practical solutions. In this context, we want to use systems thinking concepts to figure out the cause of the space debris problem in the first place. The problem is more peculiar due to unplanned initial satellite launches, the lack of reusable satellite launch engines, and the lack of a responsible orbit allocation system, according to findings from CLD and systemigrams. To begin with, space agencies around the world should coordinate mitigation programmes aimed at reducing the creation of new space junk. The second method is to remove debris using either human-made systems or natural processes such as atmospheric drag. Atmospheric drag, post-mission-disposal, controlled reentry, and other factors have reduced much debris, but there is no efficient human-made system in place to remove space debris or junk. We recommend that changes be made during the satellite design phase to avoid the creation of space junk. The reusable rocket launcher Falcon developed by SpaceX uses a benign separation system that reduces the debris generated during the mission separation phase[76], which could be a good example of how to address the ever-increasing problem of space pollution as the organization tries to maximize the usage of this reusable rocket engine. Also, one more practical option for satellites and orbital stages within or close to the geostationary ring is to re-orbit into a "graveyard orbit" after the mission is complete. This ensures that the re-orbited object will never cause a problem for active GEO satellites. But this process also requires a considerable cost to send an active satellite or rocket to manoeuvre the inactive satellites to grave orbit[77]. While numerous proposed active space debris removal concepts, such as space-based lasers, electrodynamic tethers, adhesive techniques, solar sails, orbital transfer vehicles, and drag augmentation devices, all these necessitate international collaboration, financial support, and the relaxation of some international laws to aid in the development of a cumulative solution to remove space debris. To be specific, it is necessary to draw more precise rules and enforcement methods to mitigate the space debris problem, which was illustrated by the tragedy of Commons archetype [Figure 5]. Furthermore, the cooperatives must take international space law's responsibility and liability into account. The concepts of fault, negligence, and causation should be defined properly, and an internationally binding agreement should be created to track, assign and monitor the events in space debris generation[59]. Many contend that these ideas should be interpreted in light of adherence to codes of conduct and space traffic rules, as explained by the tragedy of commons in Figure 5 of this study. The operational and technical requirements of satellites should also be standardised. Particularly, launches must include both effective post-mission disposal plans and collision avoidance mechanisms, as mentioned by Zhu *et al.*[27]. When the tax laws and subsidies are linked to the commitment to remove debris (of that particular satellite) after the completion of the lifecycle, the debris generation problem can be mitigated at the ground level. To avoid congestion in certain orbits and reduce the likelihood of collisions, space traffic laws should be developed. To avoid explosions, binding production standards should be imposed. Intentional explosions in orbits where the debris does not dissipate quickly should be avoided. For particular areas, the duty to remove outdated satellites from orbit at the end of their useful lives should be adopted. Since the same technology used to remove debris can also be used to disable functional space objects, there is a risk that technologies used to clear up debris will become militarized. This might create a lack of security and a lack of cooperation might create unintended perceived safety concerns for the countries who own/operate satellites. The spacefaring countries must also take into account how private businesses and people are involved in space exploration and exploitation in addition to the aforementioned factors. The private sector's contribution to the space industry must be reflected in a system that fairly distributes the duties of debris prevention and remediation.

DECLARATIONS

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Authors' contributions

Conceptualization, methodology, analysis, writing: Verma VK
Conceptualization, drafting, methodology, data collection: Gangadhari RK
Supervision, reviewing: Pandey PK

Availability of data and materials

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Consent for publication

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